METHANE REDUCING TECHNOLOGIES

Efficiency, Effectiveness, and Reception

By
Jack Robertson
University of Colorado at Boulder

A thesis submitted to the
University of Colorado at Boulder
In partial fulfillment
of the requirements to receive
Honors designation in
Environmental Studies
December 2017

Thesis Advisors:

Nicholas Flores, Economics Department, Committee Chair
Leaf Van Boven, Psychology Department
Dale Miller, Environmental Studies Department

Abstract

This topic brings together many of the areas that I have studied throughout my education at the University of Colorado Boulder, where I studied Environmental Studies and Economics. I was originally interested in pursuing technology and policy options for methane reductions because methane is a potent greenhouse gas that is often overlooked in the decision-making process. The issues surrounding methane emissions in the United States represents a tremendous inefficiency in our society. There exist solutions that bring developed innovations together to benefit industry, the economy, the environment, and human health. These innovations allow our current technologies, systems, and choices to become more efficient and cost-effective.

Contents

INTRODUCTION 1

BACKGROUND 3

Methane 3

Climate Change 7

Lowest Hanging Fruit Principle 9

Recent Actions Taken to Reduce Greenhouse Gas Emissions 11

The Oil and Natural Gas Industry 12
- Movement Away from Coal-Fired Energy Generation 12
- Natural Gas Production 16
- The Scope of Methane Leaks in the Oil and Gas Industry 18
- Locating Methane Leaks in the Oil and Gas Industry 21
- Reducing Methane Emissions in the Gas and Oil Industry Currently 22
- Vapor Recovery Unit 24
- Example of Vapor Recovery Unit 28

Landfill Gas Utilization 29
- The Basics 29
- Wells 29
- Feasibility 30
- Methods to Create Energy from Landfill Gas 31
- Available Incentives 31
- Current Usage 32
- Example of WTE 32

Livestock Animal Farms 33
- The Basics 33
- Anaerobic Digestion 34
- Feasibility 35
- Available Incentives 36
- Examples of Anaerobic Digestion 36

Other Studies on Methane Reducing Techniques 38

Social Costs of Methane 42

Policy Options 44

METHODS 49

Methane Reducing Technologies 49

Survey 51

RESULTS 54

Natural Gas Industry- Vapor Recovery Unit 54
- Payment per year ($) 54
- Methane reduction per year (tons) 55
- Benefit to producers per year ($) 56

Social benefit of methane reductions per year ($) ... 57
Total benefit per year ($) ... 57
Net benefit per year ($) ... 57
Dollars per ton of methane reduction ($/ton) ... 58

Landfill Industry- 3MW Gas Turbines ... 58
Payment per year ... 58
Methane reduction per year (tons) ... 59
Benefit to producers per year ($) ... 60
Social benefit of methane per year ($) ... 62
Total benefit per year ($) ... 62
Net benefit per year ($) ... 62
Dollars per ton of methane reduction ($/ton) ... 63

Livestock Industry- 5000-Ton Anaerobic Digester ... 63
Payment per year ... 63
Methane reduction per year (tons) ... 64
Benefit to producers per year ($) ... 65
Social benefit of methane per year ($) ... 66
Total benefit per year ($) ... 66
Net benefit per year ($) ... 66
Dollars per ton of methane reduction ($/ton) ... 67

Survey Results ... 67
Qualifying Questions ... 67
Regulation/ Subsidy Questions ... 68
Preference Questions ... 70
Demographic Questions ... 71
Significance Results ... 73

ANALYSIS OF RESULTS ... 74

Table 1 Analysis ... 74

Table 2 Analysis ... 76
Efficiency ... 77
Effectiveness ... 79
Benefits ... 80

Survey Results Analysis ... 81

RECOMMENDATIONS ... 85

Natural Gas VRUs ... 85

Landfill 3MW Gas Turbines ... 86

Livestock Animal Farms Anaerobic Digesters ... 87

AREAS FOR FURTHER RESEARCH ... 88

APPENDIX 89

Appendix 1: Survey 89

BIBLIOGRAPHY 99

Introduction

Methane emissions damage human health and lead to climate change. As more people accept the adverse effects of climate change, the importance of reducing emissions will increase. The United States is the world's second largest greenhouse gas emitter, and second per capita emitter. As the United States falls behind other country's commitments to greenhouse gas reductions, our reduction tactics must become further calculated. Incorporating the social cost of methane into cost-benefit analyses for methane reducing technology allows us to create a more comprehensive model. This model can be used to determine the methane reducing technology that is the most efficient, effective, and that creates the most benefits. This information is to be used in determining the first steps of implementing such technologies into the market.

My first research question is, what technology is most efficient, effective and creates the most benefits while reducing methane emissions? So far nobody has investigated and compared individual methane reducing technologies, while considering the social costs of methane. I have created economic models of three different technologies that reduce methane emissions, while creating monetary and social benefits. These benefits arise through methane gas capture. The captured methane gas is converted into natural gas or electricity. The first technology is vapor recovery units in the natural gas industry. The second technology is 3MW gas turbines in the landfill industry. And, the third technology is 5000-ton anaerobic digesters in the livestock animal farm industry. I found that natural gas vapor recovery units are the most efficient in reducing methane emissions. Following the lowest hanging fruit principle, vapor recovery units should be implemented first into the market. I found that livestock animal farms anaerobic digesters should be subsidized to reach zero net benefit. And, I found that landfill 3MW gas turbines create massive benefits for producers and society.

My second research question is, are Colorado citizens supportive of using policies to encourage industries to implement methane reducing technologies? Industries often do not take it upon themselves to use methane reducing technologies, largely because of fears of inconvenience and intensive capital requirements. The economics of methane reducing technologies are used to craft policies that best suit all stakeholders. Therefore, I created a survey to see if Colorado citizens would be supportive of placing policies on industries for the implementation of methane reducing technologies. I found that Colorado citizens were moderately supportive of all policies to reduce methane emissions. Citizens that believe climate change is a very serious problem are much more supportive of the policies to reduce methane emissions than citizens that believe climate change is less of a problem.

The first and second research questions work together to offer insight into the most viable technology and policy options to reduce methane emissions.

Background

Methane

Methane (CH4) is a greenhouse gas that is much worse for the environment and human health than the same amount of carbon dioxide. Global methane levels have risen from 772 parts per billion (ppb) in preindustrial times to 1800 ppb in 2011 (IPCC, 2013), which is the highest level in at least 800,000 years (IPCC, 2013). According to the U.S. Energy Information Administration (EIA), in 2009 (most recent available data), the U.S. produced 29.24 million metric tons of methane (EIA, 2012). The Environmental Protection Agency (EPA) says, in 2015, methane accounted for about 10 percent of all United States (U.S.) greenhouse gas (GHG) emissions by weight from human activities (EPA, 2017). Methane emissions in the U.S. are only a small chunk of the total GHG emissions, but since methane has a high global warming potential, even a small amount of methane released into the atmosphere can cause large damages to the environment and to human health. Global warming potential is a relative measure of how much heat a greenhouse gas traps in the atmosphere. Methane doesn't linger as long in the atmosphere as carbon dioxide, but it absorbs far much more heat when present. During the first 20 years after methane's release into the atmosphere it is 84 times more potent than carbon dioxide and 28 times more potent over 100 years (Shepstone, 2012). The high heat trapping ability of methane has led it to be estimated to account for about 25% of manmade global warming (IPCC, 2014).

Methane emissions in the U.S. decreased by 16 percent between 1990 and 2015, as seen in *Figure 1* (EPA, 2017). During this time, methane emissions increased from agricultural activities, while emissions decreased from landfills, coal mining, and the distribution of natural gas and petroleum products (EPA, 2017).

Figure 1: U.S. Methane Emissions, 1990-2015

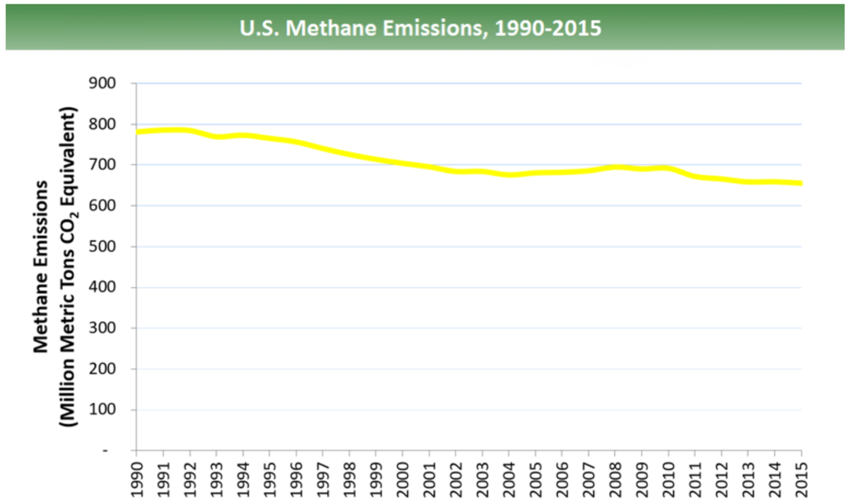


Figure 1: The x-axis is years, starting in 1990 and ending in 2015. The y-axis is the methane emissions (million metric tons CO2 equivalent). The CO2 equivalent of methane is calculated by multiplying the amount of methane emissions by the global warming difference between methane and carbon dioxide. The graph shows a consistent decrease in methane emissions in the U.S between 1990 and 2015.

The concerns around methane has led to the EPA laying out a variety of ways to reduce methane emissions. The EPA has voluntary programs for reducing methane emissions, in addition to regulatory initiatives. The EPA also supports the Global Methane Initiative, an international partnership encouraging global methane reduction strategies (EPA, 2017).

The natural gas and oil industry accounts for about 31% of U.S. methane emissions, according to *Figure 2*. Methane is the primary component of natural gas. Methane is released into the atmosphere during the production, processing, storage, transmission and distribution of natural gas. Natural gas is often found near petroleum, therefore the production, refinement, transportation, and storage of crude oil is also a source of methane emissions (EPA, 2017). Methane emissions can be reduced in the natural gas and oil industry by upgrading the equipment used to produce, store, and transport oil and gas. Methane from coal mines can be captured, converted, and used for energy to power the mines. The EPA started the Natural Gas STAR program, which is a voluntary partnership with oil and gas companies to encourage them to adopt cost-effective technologies and practices that improve operational efficiency and reduce methane emissions (EPA, 2017). The Coalbed Methane Outreach Program, by the EPA, works cooperatively with the coal mining industry to reduce methane emissions (EPA, 2017).

Agriculture methane emissions are mostly from enteric fermentation, which is livestock animal flatulence, belching. Another major methane emitting process from agriculture is manure management. These two sources account for about 35% of methane emissions in the U.S., according to *Figure 2.* Domestic livestock animals such as cattle, buffalo, sheep and goats produce methane as a part of their natural digestion process. Also, when manure is stored in holding tanks methane is produced. Since humans raise livestock animals for food and other products, the emissions are considered to be human related. Methane can be reduced in agricultural systems by improving manure management strategies and livestock animal feeding practices (EPA, 2017). The EPA has a program called AgSTAR, that promotes the use of biogas recovery systems to reduce methane emissions from livestock waste, as well as achieve other social, environmental, agricultural and economic benefits, like producing electricity (EPA, 2017).

According to *Figure 2,* Landfills account for about 18% of U.S. methane emissions. Methane is created in landfills when municipal solid waste (MSW) decomposes. Emissions are also created in the process of treating wastewater at landfills (EPA, 2017). Emission controls that capture landfill methane, or landfill gas (LFG), are an effective reduction strategy. The EPA started the Landfill Methane Outreach Program, which is a voluntary program that works cooperatively with industry stakeholders and waste officials to reduce or avoid methane emissions from landfills (EPA, 2017).

Figure 2: 2015 U.S. Methane Emissions, By Source

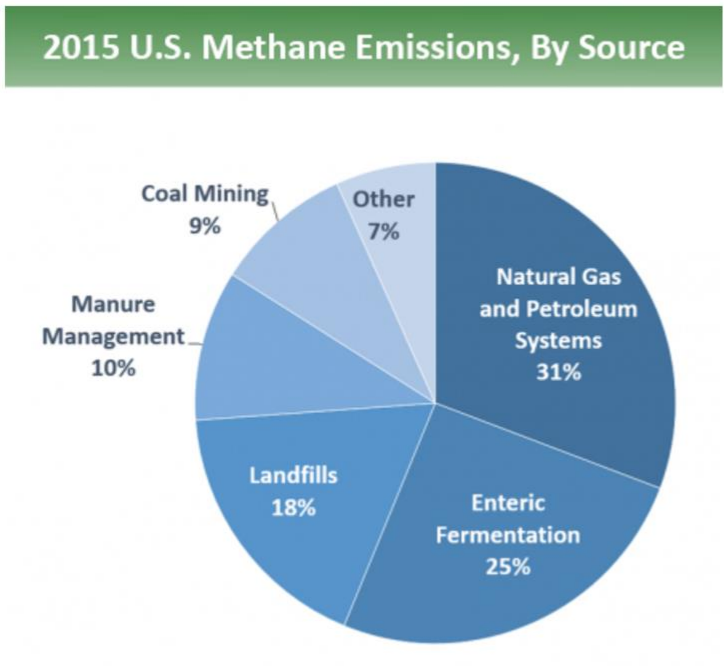


Figure 2: Natural gas and petroleum systems account for the largest amount of U.S. methane emissions, followed by enteric fermentation and landfills, coal mining and other smaller sources.

Climate Change

Scientific evidence for warming of the climate system is unequivocal

-Intergovernmental Panel on Climate Change (IPPC)

Since the late 19th century, the planet's average surface temperature has risen about 2 degrees Fahrenheit (1.1 degrees Celsius) (NASA, 2017). This rise in temperature is driven mostly by increased carbon dioxide and other human made GHG emissions (NOAA, 2017). In *Figure 3,* the correlation between global temperature and carbon dioxide (CO2) concentrations are shown to be tremendously strong. The change in global temperature is accelerating as more GHG are released into the atmosphere. Most of the 2 degree Fahrenheit change has happened within the last 35 years, with 16 of the 17 warmest years on record occurring since 2001 (NASA, 2017). 2016 was the warmest year ever recorded (NASA, 2017).

Figure 3: Global Temperature and Carbon Dioxide

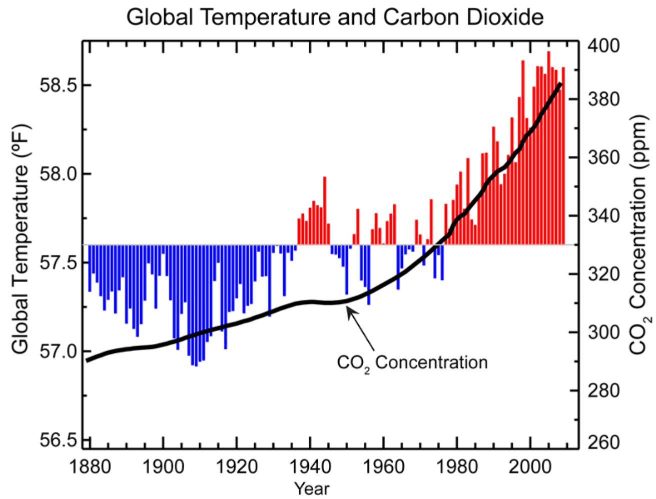


Figure 3: The x-axis is years, starting in 1880 and ending in 2016. On the left y-axis is the global temperature (degrees Fahrenheit). On the right y-axis is carbon dioxide concentration (parts per million). The graph shows that CO2 and global temperature are highly correlated. When CO2 concentrations increase, global temperature increase too.

The International Panel on Climate Change (IPCC) is the world's foremost collection of climate scientists. Recent reports from the IPCC exposed that the impacts of climate change are already "widespread and consequential" (IPCC, 2017). The first installment of the IPCC's Fifth Assessment Report determined the amount of carbon dioxide emissions we can emit while still having a likely change of limiting global temperature increase to 2 degrees Celsius above pre-industrial levels (WRI, 2017), this is called the "carbon budget". Deciding the "carbon budget" for each country was a major step forward in limiting climate change. "If emissions continue unabated, the world is on track to exceed [2°C] in only about 30 years—exposing communities to increasingly dangerous forest fires, extreme weather, drought, and other climate impacts," says the World Resources Institute (WRI).

The signs of global warming are everywhere and are more complex than just rising temperatures. The planet is already suffering from some of the impacts of global warming.

For example, ice is melting worldwide, species are having to relocate and some are going extinct, the sea level is rising, precipitation (rain and snowfall) has increased across the globe, invasive species are thriving, floods and droughts are more common, and hurricanes and storms are becoming more powerful. As global emissions raise the plant's temperature, the effects of global warming will become more intense and dangerous.

Lowest Hanging Fruit Principle

The lowest hanging fruit principle is a commonly used metaphor for doing the simplest or easiest work first or for a quick fix that produces ripe, delectable results. Although the metaphor may seem tacky, it is an extremely important lesson in economics. The principle says, in general, rational producers will always take advantage of their best opportunities first, moving on to more difficult or costly opportunities only after their best ones have been exhausted. We will be interested in finding the technology that is the lowest hanging fruit, which provides methane reductions at the lowest cost. The technology that reduces methane emissions at the lowest cost per ton of reduced methane is the most efficient option.

This principle is reinforced by the law of diminishing returns, which is the decrease in the marginal output of a production process as the amount of a single factor of production is incrementally increased, while the other factors remain constant, as shown in *Figure 4*. In figure below, as inputs are increased, results increase, until the point of diminishing returns. As inputs are continued to be increased after reaching the point of diminishing returns, results are not realized at the same rate as they were before the point of diminishing returns. Returns continue to diminish as inputs continue to increase, until the point of negative returns is realized. Inputs should never be increased to the point of negative returns. Inputs should stop being increased somewhere between the point of diminishing returns and the point of negative returns. The lowest hanging fruit is found where the rate at which results increase by an additional unit of input is highest, otherwise known as the highest marginal output.

Figure 4: Law of Diminishing Returns

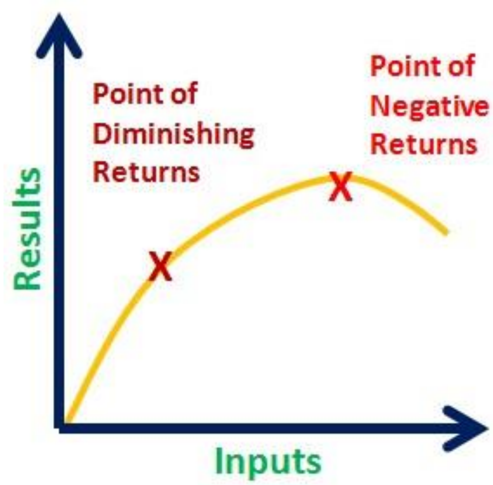


Figure 4: The x-axis is inputs. The y-axis is results. The graph shows that you receive a high amount of results with few inputs at the beginning. As you continue using more inputs, the amount of results you receive starts to decrease, until you receive no results, and eventually negative results with additional inputs.

Al though picking the lowest hanging fruit may not always solve the bigger problem, it is the most efficient way to go about a specific task. In our case, reducing methane emissions is the task. Choosing the lowest hanging fruit is imperative because that is where the inputs (time, money, etc.) are being used most efficiently. As we will see, certain technologies are more efficient than others at reducing methane emissions than others. Each technology has its own curve like in *Figure 4.* The most efficient methane reducing technology will achieve more results with less inputs. As inputs in that technology increase, the rate of results will eventually decrease to the point where choosing another technology will provide a more efficient use of inputs.

Recent Actions Taken to Reduce Greenhouse Gas Emissions

The United Nations Framework Convention on Climate Change (UNFCCC) on October 5th, 2016, established the Paris Agreement. The Paris Agreement entered into force on November 4th, 2016 (UNFCCC, 2017). The Paris Agreement is a battle against climate change. World leaders from across the world met to, for the first time ever in history, legally ratify action against pollution through the United Nations Framework Convention. Countries have the option to attend or not, Syria and Nicaragua were the only countries not to attend the Agreement. Countries also have the option to pledge to the Agreement or not. As of October 15th 2017, 168 countries have ratified the Agreement, out of the 197 countries to attend the Convention. The United States is the largest country that has not accepted, nor ratified the Paris Agreement. The Agreement has a loose framework to allow individual countries to develop their own global temperature reduction strategies. This way, individual countries can choose their own lowest hanging fruit. The Agreement is being enforced by making polluters financially responsible for their contribution to climate change. The Agreement is laid out so that bigger polluters pay higher costs. The typical rate is set at $150 per ton of carbon dioxide emitted. The framework of the Agreement focused largely on the transparency of countries, to make sure they are staying on track. If all the countries stay on track, the Agreement would keep global temperatures below a 1.5 degree

Celsius rise from pre-industrial levels. Which would reduce the risks and impacts of climate change (Simon-Lewis, 2017).

The Clean Power Plan (CPP) is a policy that was created during Obama's presidency. The CPP was a large factor in the green movement in the U.S. Obama's CPP was designed to cut the power industry's carbon emissions by 32 per cent by 2030. Doing so would be a large step towards staying on track of the Paris Agreement's goals (Simon-Lewis, 2017). The current U.S. president, Donald Trump, has openly announced to retract the CPP.

Right now, in the United States, there is a lack of policies encouraging a reduction in GHG. A possible remedy to the lack of climate policy could be to propose policies that are cost-effective for all parties. This way, climate policies do not hurt businesses, and instead they help them see more profits and create more jobs, while simultaneously helping the environment and human well-being.

The Oil and Natural Gas Industry

Movement Away from Coal-Fired Energy Generation

In 2015, coal accounted for 21% of electricity production, but also 71% of carbon dioxide emissions. The energy generation to emissions ratio reveals how coal is an outdated and inefficient energy source. The byproducts of coal-fired energy generation make it a very undesirable energy source when trying to stay below the 2 degree Celsius threshold.

The shift away from coal has happened much quicker than expected in the United States. Coal-fired generation of electricity in the U.S. fell 25 percent between 2007 and 2013, which decreased carbon dioxide emissions by 500 million tons annually (Kaffine, 2017). At the same time, a substantial increase in natural gas supply has made natural gas much more affordable. The decrease in natural gas prices are largely due to the expansion of hydraulic fracturing extraction techniques used throughout the United States. The high level of availability, low prices, and low GHG emissions of natural gas have led to U.S. market forces favoring natural gas to be used for energy generation over coal. In *Figure 5* you can see the recent movement away from coal and towards natural gas (EIA, 2016).

Figure 5: U.S. Electricity Generation by Source 1950-2016

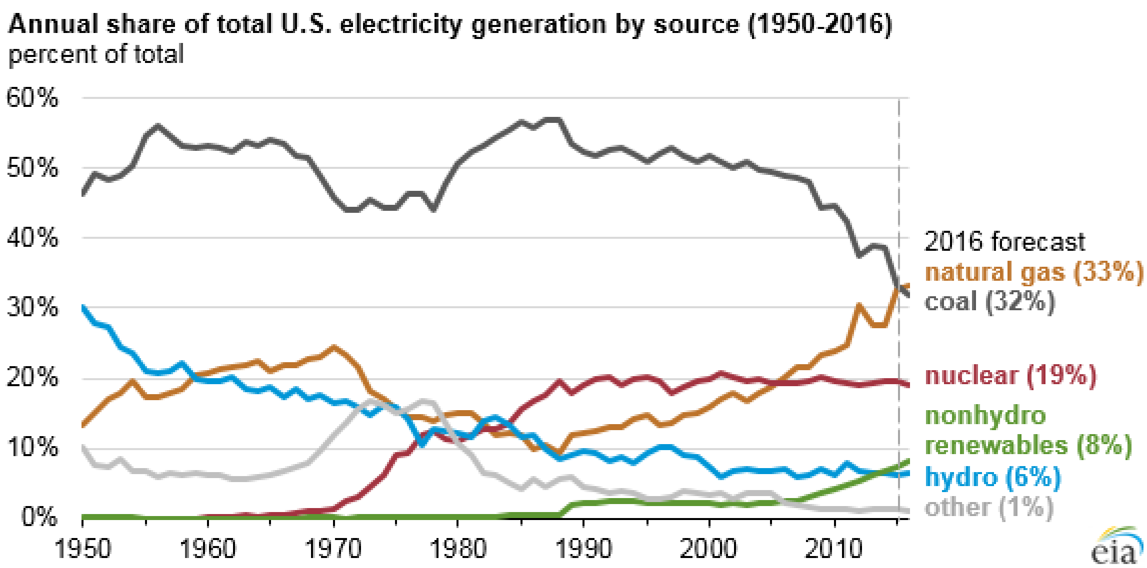


Figure 5: The x-axis is years, starting in 1950 and ending in 2016. The y-axis is annual share of total U.S. electricity generation by source. The graph shows that coal and hydro U.S. electricity generation has been decreasing, natural gas and nuclear have been increasing in the recent years.

Much of the progress in moving away from coal is due to four main sources. They are: the retirement of coal-fired power plants, natural gas' higher energy generation to emissions ratio, the reduction in subsidies given to coal producers, and the increased supply of natural gas in the U.S.

40GW (Gigawatts) of coal-burning power plants have been disconnected, while only 19GW have been installed since 2005 in the U.S. (Bloomberg, 2015). The average home uses about 11,000 kWh per year (EIA, 2016). A typical 1-gigawatt power plant generates about 7,700 GW of energy a year. The amount of energy production from a single GW coal-fired power plant can power about 7,000,000 homes a year. The decrease in coal-fired power plants has allowed room for cleaner forms of energy generation to take its place in the market.

The second factor in the movement away from coal-fired electricity generation is that natural gas provides a higher energy generation to emissions ratio, making natural gas a useful resource in potentially keeping the global temperature below a 2 degree Celsius increase. But, natural gas is not completely greenhouse gas emission free. Natural gas is made almost completely of methane (CH_4). When methane is combusted for energy production it releases only carbon dioxide and water. Natural gas emits much less CO_2 than coal, in fact, natural gas emits 50 to 60 percent less carbon dioxide when combusted in a new, efficient natural gas power plant compared to emissions from a typical new coal plant (NETL, 2010). Being able to produce the same amount of energy through burning natural gas as coal, yet having less GHG emissions is a large factor leading the U.S. energy market away from coal-fired electricity generation and toward natural gas fired electricity generation.

The third factor in the movement away from coal is the reduction in subsidies that are provided for federal fossil fuels. It was estimated in an EIA report, that federal fossil fuel subsidies had fallen from $3.3 USD billion in 2007 to an estimated value of $561 USD million in 2010. The decrease in subsidies is all encompassing for fossil fuels of all types.

The coal industry was more harshly affected than other fossil fuel industries. The coal industry relied heavily on government subsidies to keep their costs and prices low. Because coal represented such a large portion of the market for electricity generation, the coal industry is experiencing the biggest loss in subsidy amount. The reduction in coal subsidies increase production costs of coal extraction, production and refraction. The producers must sell the coal for more than before, because it costs them more to produce. With the increase in the price of coal, we see more innovation and acceptance of other, cheaper forms of energy, like natural gas.

The fourth factor in the movement away from coal in the United States is the increased supply of natural gas. In 2015 natural gas production and storage inventories reached all-time highs (Bloomberg, 2015). The efficiency and expansion of fracking has led to incredible increases in the amount of natural gas drilling sites in the United States, from 2005 to 2013 there were at least 80,000 new wells drilled or permitted (Ridlington et al., 2013). An enlarged supply of natural gas has made electricity generation more efficient, cost-effective and has helped lower the United States' annual level of greenhouse gas emissions. "Natural gas prices in 2015 sank to their lowest levels since 1999 and natural gas plants displaced generation previously provided by retiring coal plants, natural gas consumption in the power sector exceeded 10quads for the first time ever (Bloomberg, 2015)." The decrease in coal-fired power plants, natural gas' high energy to emissions ratio, the decrease in coal subsidies, and the increase in natural gas supply has led the United States to away from coal and towards natural gas for electricity generation.

Natural Gas Production

Natural gas prices have dropped dramatically because of the boom in natural gas production and supply, which has been assisted by the discovery of previously unknown shale oil and tight oil reservoirs underground. The process of hydraulic fracturing, otherwise known as "fracking", captures these reserves. Natural gas captured through fracking is called "unconventional gas." "Hydraulic fracturing produces fractures in the rock formation that stimulate the flow of natural gas or oil, increasing the volumes that can be recovered (EPA, 2017)." These wells are typically drilled vertically hundreds to thousands of feet underground and these wells may include horizontal sections that extend for thousands of feet.

Fractures are created by pumping fluids at high pressure down a well and into the target rock formation. The fluid that is pumped into the well is typically a mix of water and chemicals that help create larger fractures for the oil and gas to escape through. The oil and gases then move up towards the surface through a tube that was extended down into the fracture. When the oil and gas reach the surface, it is captured and stored in on-site storage tanks, to be later distributed for energy production. Take a look at *Figure 6* below for a visual description of how fracking wells work and the technology that they use. Hydraulic fracturing systems are often just off of main roads, *Figure 7* is a real life look at one, so you may be able to recognize one next time you drive past.

Figure 6: Diagram of Hydraulic Fracturing

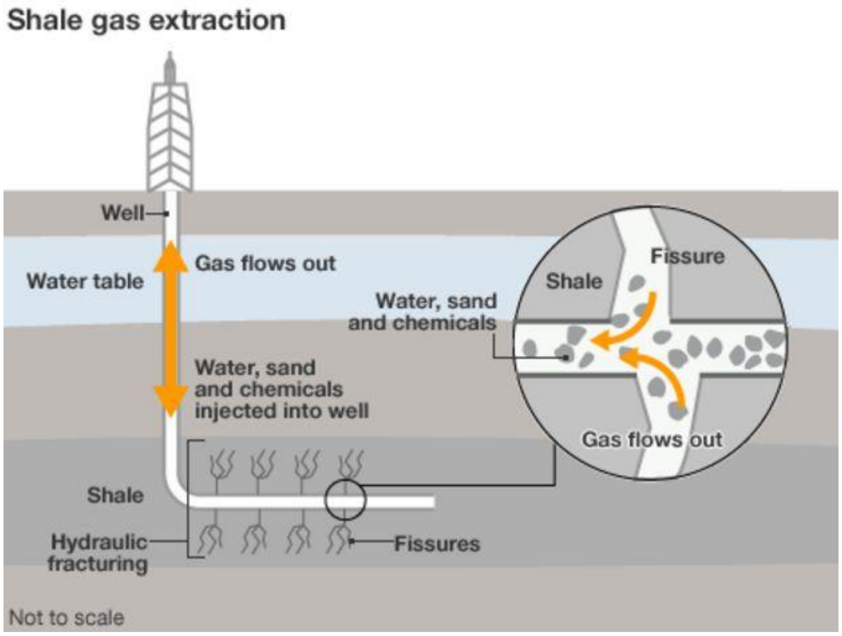


Figure 6: This diagram is provided to establish a sense of how hydraulic fracturing works.

Figure 7: A Real Life Look at a Hydraulic Fracturing System

Figure 7: Hydraulic fracturing systems can often be seen just off of main roads.

Unconventional gas is a relatively new method of fossil fuel extraction. Coalbed methane production began in the 1980s; shale oil extraction is even more recent. Coalbed methane (CBM) was originally extracted as a safety measure to reduce the probability of an explosion in coalmines. The main enabling technologies, hydraulic fracturing and horizontal drilling, have opened new areas for oil and gas development, with a focus on natural gas reservoirs such as shale, coalbed and tight sands (EPA, 2017). Shale oil extraction has expanded the areas where oil or gas extraction can take place throughout the United States. Tight sands must be captured through hydraulic fracturing to release the gas that is found in fine-grained sandstones or carbonates with low permeability. The increased number of fracking wells has allowed natural gas to become a cheap and desirable resource for energy production.

The Scope of Methane Leaks in the Oil and Gas Industry

The largest source of methane emissions is the oil and gas industry (Shepstone, 2012). Much of the methane emissions from the oil and gas industry arise from, "leaks and releases that occur throughout the natural gas supply chain (EPA, 2012)." Methane emissions from the gas and oil industry must be reduced to curb the extensive amount of climate change we are experiencing.

Natural gas has the capability to lead the United States into a generation of low emissions and cheap power, but the problem of methane leakage from the fracking process and throughout the supply chain may undermine the benefits associated with natural gas. As put by the Environmental Defense Fund (EDF), the problem with natural gas is, "If not better mitigated, methane leaks and releases could undermine the greenhouse gas advantage natural gas offers and spell major trouble for the climate."

The amount of methane that leaks from the production process is largely unknown, but there have been a few recent estimates on the topic. Harvard researchers used new satellite data and surface observations from remote sensing systems to confirm previous data and observations: "United States methane emissions are considerably higher than the official numbers from the Environmental Protection Agency (EPA) (Turner et al., 2016)." The EPA estimates the value of the leaked gases from gas and oil storage tanks to be between $30,300 and $608,810 per year, depending on the size of the tank and the amount of gas and oil that goes through it (flow rate) per year. The EPA numbers are based on industry-provided estimates, and not from actual measurements. The EPA's numbers are most likely lower than the real leakage numbers because the oil and gas industry is incentivized to under estimate the amount of emissions to avoid possible repercussions of high levels of emissions.

The Harvard research also found a 30 percent increase in United States methane emissions from 2002-2014. The research did not find specifically where the sources of the increase in methane emissions were coming from. Cornell professor Robert Howarth said that the increase in methane emissions "almost certainly must be coming from fracking and from the increase in use of natural gas. (Howarth, 2014)." This was determined by comparing the increase in natural gas production to the increase of atmospheric methane. Howarth goes on to mention that even with the movement away from coal we are still headed towards 2°C warming around 2050, because of the fugitive methane emissions from fracking. "Fugitive emissions" are emissions that are not measured and not associated with any specific point in the production process. The EDF estimates that about 109,000 metric tons of methane has leaked between October 23rd and February 11th of 2016 from a single storage tank leak (EDF). A leak of 109,000 metric tons of methane causes the same amount of damage to the environment as about 9,156,000 metrics tons of carbon dioxide. This is equivalent to about 1,948,085 average American cars driving for a year (EPA, 2017). Methane leaks have devastating effects on the environment, as methane is a much more powerful short-term greenhouse gas than carbon dioxide.

A study from 2011 by Tom Wigley of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado said, "unless leakage rates for new methane can be kept below 2%, substituting gas for coal is not an effective means for reducing the magnitude of future climate change (Wigley, 2011)." Research has shown that the methane leaks that are occurring sets us at a level much above the 2% limit. Researchers from NOAA and the University of Colorado at Boulder led a study that found we are losing much more than 2% of natural gas through leaks, "estimates that natural gas producers in an area known as the Denver-Julesburg Basin are losing about 4% of their gas to the atmosphere- not including additional losses in the pipeline and distribution system (Tollesfon, 2012)." It is noted that individual drilling sites may very likely have different levels of methane leakage. Some sites could be experiencing even more leakage than the Denver-Julesburg Basin area. Gabrielle Petron, an atmospheric scientist at NOAA and at the University of Colorado at Boulder says, "I think we seriously need to look at natural gas operations on the national scale. (Petron, 2012)."

Locating Methane Leaks in the Oil and Gas Industry

The EDF says that their research has shown, "methane is leaking at every stage of the gas and oil supply chain." The research also shows that leaks are happening in all sizes of drilling sites, from large oil and gas facilities and fields to neighborhoods. Studies have shown that leaks are occurring at: drilling sites, along pipelines, at compression stations, and at storage facilities (Aschwanden, 2016). So, this begs the question, "Where do we start reducing methane emissions from the gas and oil industry?"

A good place to start looking are the gas and oil storage tanks. As mentioned in the previous section, the EPA estimates that storage tanks lose thousands of dollars a year in methane leaks. There are about 500,00 underground storage tanks across the United States. Many of these storage tanks, "seem to have fallen through the cracks in terms of regulation (EIA, 2008)." The Aliso Canyon Gas Storage Field methane leak is an example of the methane leakage problem in gas and oil storage tanks. The Aliso Canyon Gas Storage Field, in California, is located underground and is the largest underground gas and oil storage facility in the western United States. The leak was called a 'blowout,' which is defined by the Dictionary of Petroleum Terms as, "an uncontrolled flow of gas, oil, or other well fluids." The blowout was discovered on October 23rd 2015. The estimated loss was 97,100 tons of methane. This single blowout event increased atmospheric methane by approximately .002% (Conley et al., 2016). It is predicted that the blowout had occurred weeks before it was found.

Reducing Methane Emissions in the Gas and Oil Industry Currently

Leaks of methane from gas and oil storage tanks aren't always unnoticed, some gas is leaked on purpose. For example, oil and gas producers are flaring, or burning, natural gas from storage tanks, see *Figure 8* for an example of flares from a natural gas and oil refinery.

Figure 8: Flares from Natural Gas and Oil Refinery

Figure 8: Flares coming from a natural gas and oil refinery. The flares burn light gases that are hard to capture or transport. Before the gases are flared they are stored at the top of storage tanks. There is typically a vent on the top of storage tanks that allows light gases to escape the storage tank and be brought to the top of the towers to be flared.

The industry's standard practice is to burn off methane and other gases that can't be captured or transported easily. The burning of methane through flaring is typically done at sites where natural gas is a byproduct of oil production. Christopher Elvidge, a physical scientist at NOAA's Earth Observation Group in Boulder, Colorado estimates that in 2012 flares burned 143 billion cubic meters of gas. "The flared gas represents 3.5 percent of global natural gas consumption and 19.8 percent of the United States natural gas consumption: enough gas to power 74 million automobiles driving 13,476 miles a year (Elvidge et al., 2015)." This gas should be captured and used, rather than wasted as a byproduct of oil and gas production and storage.

The gas and oil industry is working to limit the amount of methane leakage from their facilities. Driven by safety concerns and the fears of costly infrastructure repairs, some of the oil and gas industry has optimized innovations in well integrity technology. For instance, advances in anticorrosive tubing, cement chemistry, and computer imaging of subsurface conditions have been developed to improve well integrity (Boling et al., 2015). These innovations will help reduce the chance of leaks occurring, as well as help notice them sooner. The industries movements towards limiting methane emissions have been driven by market forces, and not by regulation or policy. The companies are mostly worried about the loss in profits from the leaks, rather than the externalities the leaks create.

The EPA has created a voluntary methane reduction program for oil and gas producers. This program gives recommendations on possible techniques for reducing the amount of methane and gases that are lost throughout the production of oil and natural gas. The program also notices and recognizes oil and gas producers that are taking steps to reduce their methane emissions. The Natural Gas STAR Methane Challenge Program started with 41 founding partners at the Global Methane Forum on March 30, 2016 (EPA, 2016). There is no monetary incentive set up by the program to further encourage methane reducing actions, but there are benefits that are associated with being part of the program. For example, Methane Challenge partners have the benefit of: sharing information and technology with one another that the EPA facilitates. Peer networking, voluntary record of reductions, and public recognition helps the partners be recognized as industry leaders and allows them to showcase their commitments to reducing methane emissions.

The EPA lays out many options for reducing methane. All of the options include information on costs of purchasing, implementing and managing each system. There are many categories of recommended technologies including: Compressors/Engines dehydrators, directed inspection and maintenance, pipelines, pneumatics/controls, valves, wells, tanks, and other. These options range from $0 to >$50,000.

As discussed earlier, oil and gas storage tanks are responsible for much of leakage that happens throughout the process of extracting, refining and transporting oils and natural gas. Instruments that are added to storage tanks have a direct and measurable impact on reducing methane and other emissions. The flaring of natural gas and other gases is widely used. Gas that is flared is valuable gas for the producer and carries high global warming potential when released in the atmosphere.

Vapor Recovery Unit

One methane control instrument recommended by the EPA is a Vapor Recovery Unit (VRU). The VRU system is used on storage tanks. A real life example of a VRU is shown in *Figure 9.* This process redirects emissions that would be typically vented or flared. The emissions are reused or recycled to the inlet line of a separator, to a sales gas line, or to some other line carrying fluids for beneficial use, such as use a fuel (EPA, 2013). Vapor recovery units have been shown to reduce gas emissions from storage vessels by over 95 percent (EPA, 2006). When operating properly, VRUs generally approach 100 percent efficiency. The EPA used proposed state-only revisions to a Colorado regulation to estimate the cost of a VRU system. Total capital investment of the system is estimated to cost $171,538 in 2012 dollars. Capital recovery with 7 percent interests and 15-year equipment life shows that the total annual costs (without savings) are $28,230 per year (Brown, 2013).

Figure 9: Real Life Look at a Vapor Recovery Unit

Figure 9: This picture is a real life example of a VRU. The VRU is shown on the right side of the picture, it is attached to three crude oil storage tanks, that are shown on the left side of the picture. Refer to *Figure 10* for a diagram on how the VRU is attached and works with the storage tanks.

A small unit costs about $35,000, while a large unit costs about $130,000 over its lifetime. The costs of buying, installing and maintaining these units discourages oil and gas producers using VRUs. The economic conditions must be favorable for each individual scenario for a company to install VRUs. A large unit saves approximately 96,000 McF per year of vapor. McF is an abbreviation denoting a thousand cubic feet of natural gas. One McF is equal to about 1,000,000 Btu (British thermal units) of energy. Colorado households consume an average of 103 million Btu per year (EPA, 2009). This means that one unit saves enough energy to power about 930 homes per year. Remember that there are over 500,000 storage tanks in the United States. At the market price for natural gas ($3.50 per McF), a large unit saves oil and gas producers $319,000 a year. The return on investment can be paid back in full in about 3 months. Rate of return on investment increases with VRU size. A diagram of a typical VRU is shown in *Figure 10.*

Figure 10: VRU Diagram

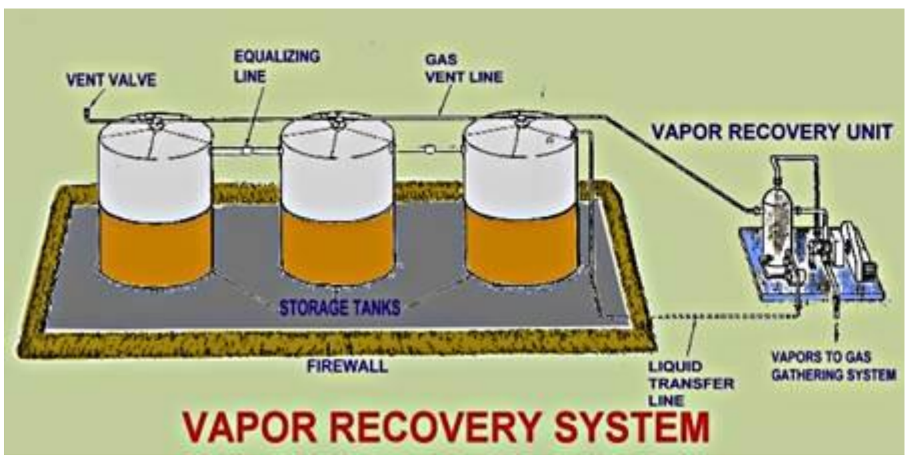


Figure 10: This diagram is provided to give a better look of what a VRU looks like and how it is attached to a storage tank.

Underground crude oil and gases are brought to the surface to be processed then distributed for use in the markers. Many of the lighter gases, and water, are removed through a series of separators. The crude oil and gas is then injected into a storage tank to await sale and transportation off site. The remaining gases in the oil are emitted as vapors into the tank. These vapors are often emitted by being flared or recovered by VRU systems. Loses of the remaining gases happen in three ways: 1) Flash losses occur when the gas and oil is put into the storage tanks. 2) Working losses occur when gas is released because of the changing fluid levels and there is no room in the storage tank. 3) Standing losses occur with daily and seasonal changes in temperature. These gas vapors contain higher energy content than pipeline quality natural gas.

VRUs work by drawing out gas vapors out of the storage tanks, when the gases would typically be flared or just released into the atmosphere. Please refer to *Figure 11* below to follow along with the description. The gases are captured by the suction line and moved to a separator (Suction Scrubber) to collect any liquids that condense out. The liquids (heavy matieral) are recycled back to the storage tank. The vapors (light material) are metered and removed from the VRU system for pipeline sale or onsite fuel supply (EPA, 2013). The vapors (light material) are converted into natural gas through the VRU system and can be sold or used for onsite fuel supply (EPA, 2013). For a more detailed look at a VRU, consult *Figure 11* below.

Figure 11: Standard Stock Tank Vapor Recovery Unit

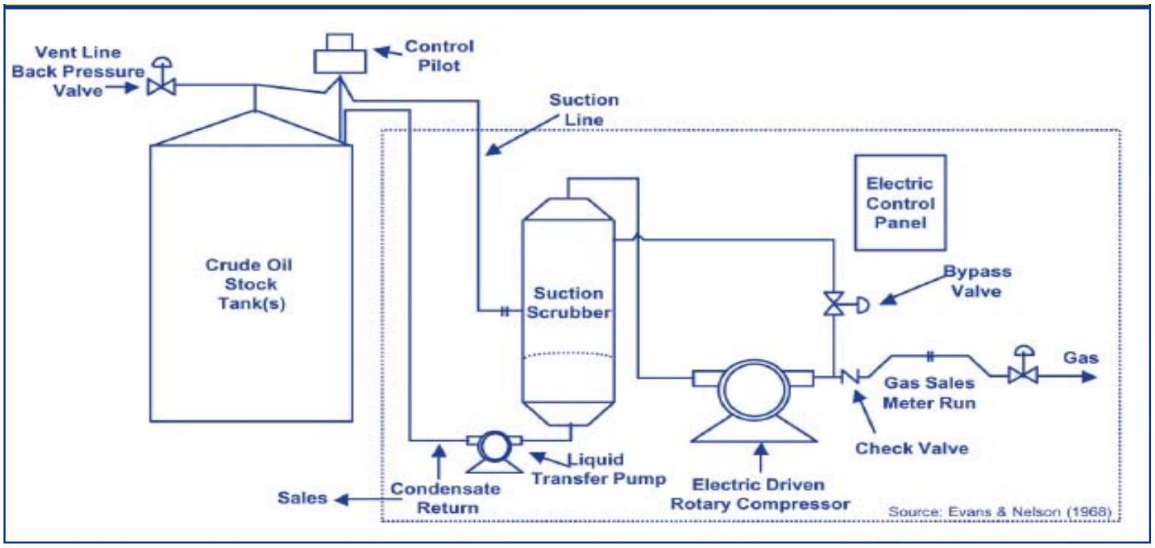


Figure 10: This diagram shows the technicalities of a VRU. On the left is the storage tank that holds crude oil. The line that leads to the VRU is attached where the flare would typically be. In the box, on the right side of *Figure 8*, is the VRU. The VRU is a fairly complex system that takes the natural gas that would typically be flared and condenses it to be put back into the crude oil storage tank. The condensate return line is at the bottom left of the box, and is the line that leads to condensed natural gas back into the storage tank.

Example of Vapor Recovery Unit

The EPA offers an example of one of their partner's experience using a VRU. The partner was Chevron USA Production Company. They installed eight VRUs in 1996 on crude oil storage tanks. Chevron calculated the methane emissions reductions, which equaled about 21,900 Mcf per year from each unit. A total methane emission reduction of about 175,200 Mcf per year. The gas prices that they used were at $7 per Mcf, but todays gas prices are about half of $7, $3.50. Using todays gas prices, Chevron realized about $613,200 per year for all eight units. The capital and installation costs were estimated to be about $393,400 in 2017 dollars (BLS, 2017). This project would have realized a full payback in just under 3 months (EPA, 2006).

Landfill Gas Utilization

The Basics

Landfill gas utilization system are also known as waste-to-energy (WTE) systems, MSW-to-energy systems, LFG-to-energy systems. These systems produce useful energy and reduce greenhouse gas emissions. Landfill gas utilization is a process of gathering, processing, and treating the methane gas emitted from municipal waste (garbage) to produce electricity, heat, and fuels. These projects collect methane gases that are typically lost into the atmosphere, then treat and use them for electricity or pipeline-grade gas. Landfill gas projects have become much more popular in the last few years.

Gas is produced at landfills through the decomposition of biodegradable waste. This biodegradable waste is usually from food waste, paper, and cardboard. The gases that are produced in landfills with anaerobic conditions (no oxygen) produce about 60% methane and 40% carbon dioxide. Landfills often reach their maximum gas production rate at about 5 years, then start to decline.

Wells

These systems are usually accomplished through the installation of wells installed vertically and/or horizontally in the landfill where the waste is located. Design standards for vertical wells call for about one well per acre of landfill surface, whereas horizontal wells are normally spaced about 50 to 200 feet apart on center (EPA, 2009). Efficient gas collection can be accomplished at both open and closed landfills, but closed landfills have systems that are more efficient. On average, closed landfills have gas collection systems that capture about 84% of produced gas, compared to about 67% for open landfills (Powell, 2015). For an illustration on landfill WTE basics, consult *Figure 11* below.

Figure 12: Landfill Waste-to-Energy System Diagram

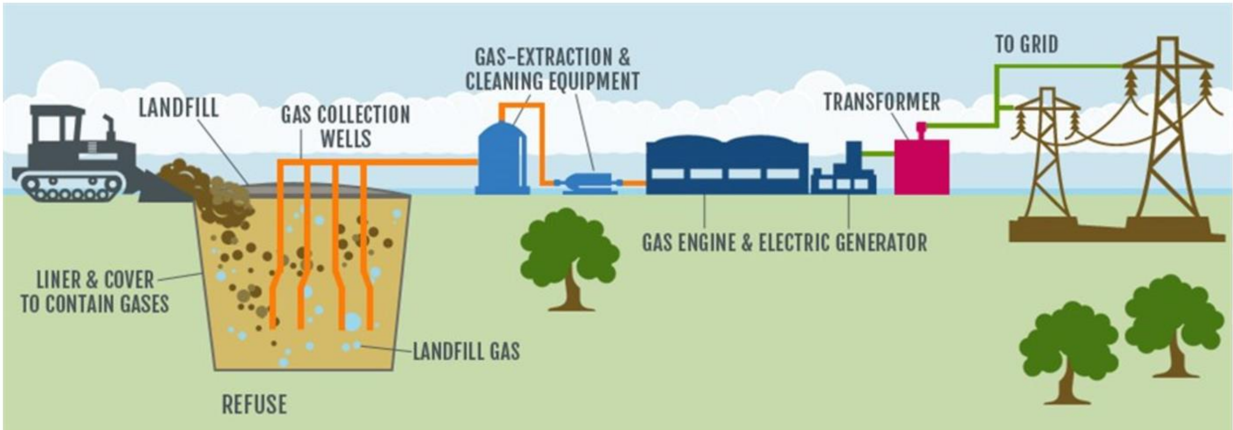


Figure 12: This image is provided to give a clear look at the basic processes that go on during landfill waste-to-energy systems. The beginning of the process is in the bottom of the landfill. The landfill gas is captured by gas collection wells. Then, the gas is extracted and cleaned by a near-site facility. Next, the cleaned gas goes to a gas engine to produce electricity. A transformer makes the electricity available for distribution through the grid and to be used in homes.

Feasibility

The feasibility of using a WTE system depends of each landfill. Each landfill is different, and so are the systems involved. The systems may have different designs and technology depending on the landfill, but similarities do exist. The similarities will be a key assumption in considering the effectiveness and efficiency of WTE systems. Each system will have an active gas collection system (blowers/vacuums), possibly a treatment system, and an individual energy recovery system. The effectiveness and efficiency depend on if the landfill has a liner, how much waste the landfill has (impacts gas production), how long the landfill has been or was in operation and the closure date of the landfill.

Methods to Create Energy from Landfill Gas

Electricity generation is the most common use of landfill gases. This can be accomplished through internal combustion engines, gas turbines, and micro turbines. There are three different uses of the gas.

Direct use of landfill gases is often the cheapest and easiest method of using landfill gases to create energy. These systems use the gases to fuel boilers or other equipment, like fueling kilns, thermal dyers, boilers, infrared heaters, and greenhouses. These systems accounted for about one third of WTE systems in the United States in 2012. Direct use is often chosen for landfills with lower flow rates, but they can also work in landfills with high flow rates as well (EPA, 2012).

Landfill gas can also be converted to liquid natural gas. The gas needs to be a certain percentage of methane, oxygen, and nitrogen for this to be feasible. Most landfills that process landfill gas to natural gas can use the gases to fuel waste collection trucks.

Landfill gases can also be used in a cogeneration system, that creates heat and power. These systems are typically the most efficient, achieving around 90% efficiency. This is possible because the heat that is created through the electricity generation process is also used to heat buildings. Cogeneration systems require a high flow rate.

Available Incentives

Typically, incentives are in the form of tax credits, bonds, or grants. For example, the Renewable Electricity Production Tax Credit (PTC) gives a corporate tax credit of 1.1 cents per kWh (kilowatt hour) for landfill projects above 150 kW (kilowatt) (Powell, 2015). Various states and private foundations give incentives to landfill gas projects. A Renewable Portfolio Standard (RPS) is a legislative requirement for utilities to sell or generate a percentage of their electricity from renewable sources, which includes landfill gas. Some states require all utilities to comply, while others require only public utilities to comply (Powell, 2015).

Current Usage

In 2005, 166 million tons of MSW were discarded to landfills in the United States (Kapla, 2009). Roughly 120 kg of methane is generated from every ton of MSW. Around 4 to 10 percent of landfill gas escapes the collection system of a typical landfill with a gas collection system (EPA, 2009). 450 of the 2,300 landfills in the United States have operational landfill gas utilization projects as of 2007, leaving a large space for improvements. It is estimated by the EPA that approximately 520 additional landfills that currently exist could utilize landfill gas (enough to power 700,000 homes). Landfill gas projects also decrease local pollution, and create jobs, revenues and cost savings (EPA, 2009). Of the roughly 450 landfill gas projects operational in 2007, 11 billion kWh of electricity was generated and 78 billion cubic feet of gas was supplied to end users. These totals amount to the annual emissions from about 14,000,000 passenger vehicles (EPA, 2009).

Example of WTE

The first example of a WTE system is for a closed landfill in Sumter County, Georgia. The information used in this example was put together by students at the University of Georgia (Wilson, et al., 2012). This landfill collected about 172,000 metric tons of waste between 1987 and 1995. The landfill became too full and was closed in 1995. The peak of emissions was reached in 1996. The peak total emissions rate is estimated at 155 cubic feet per minute (cfm). The peak total emissions rate in 2012 is estimated at 69.7 cfm. The rate decreases quickly because the waste in the landfill emits most of its gases in the first few years of being in the landfill.

The relatively low flow rate of the Sumnter County landfill is a major constraint for installing WTE systems. For electricity generation, micro turbines producing 30 to 250 kW per turbine are feasible, but internal combustion engines and gas turbines are not. For direct use, creating medium-BTU pipeline-quality gas is feasible, but not High-BTU pipeline-quality gas, cogeneration or liquid natural gas.

Microturbine system's initial capital costs for the gas collection and flare system would be about $521,500, and $230,660 for the micro turbine system, which leads to a total capital cost of $752,100, with the average operation and maintenance costs of $99,910. Implementing a micro turbine system in 2014 and operating it until 2023 would produce an average yearly loss of $174,740 in the case of the Sumnter County landfill.

For direct use, the initial capital costs are $521,500 for the gas collection and flare system, $794,500 for the compressor and dehydration unit, $86,700 for the pipeline form the landfill to the use-site, which adds up to a total capital cost of just over $1.4 million dollars. The operation and maintenance costs are $116,740, and $124,740 per year in miscellaneous fees. Implementing a direct use system would lead to an annual average loss of $215,587 for the landfill.

Livestock Animal Farms

The Basics

Livestock contribute 37% of world anthropogenic methane emissions (Hanson, 1998). The Global Methane Initiative estimates that 26% of anthropogenic methane is produced by enteric fermentation. Enteric fermentation is the digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal. Of this 26%, about 90% is produced by cattle (including both beef and dairy). The process of enteric fermentation leads to livestock animals creating a large amount of gas, mostly composed of methane. This gas is released by the animal through belching or by flatulating. Enteric fermentation creates about 70% of methane emissions from livestock, while gases from manure creates about 30% of methane emissions from livestock.

Anaerobic Digestion

Many farms already use methane as a power source. Most use anaerobic digestion of livestock manure. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. One of the end products is biogas, which is combusted to generate electricity and heat, or can be processed into renewable natural gas and transportation fuels (American Biogas Council, 2014). The other byproduct is fertilizer that can used on the farm, or it can be solid or given away. Anaerobic digesters in the livestock industry work to reduce methane emissions, odors, pathogens and produce biogas. For more information on the anaerobic digestion process, consult *Figure 13* below.

Figure 13: Anaerobic Digestion

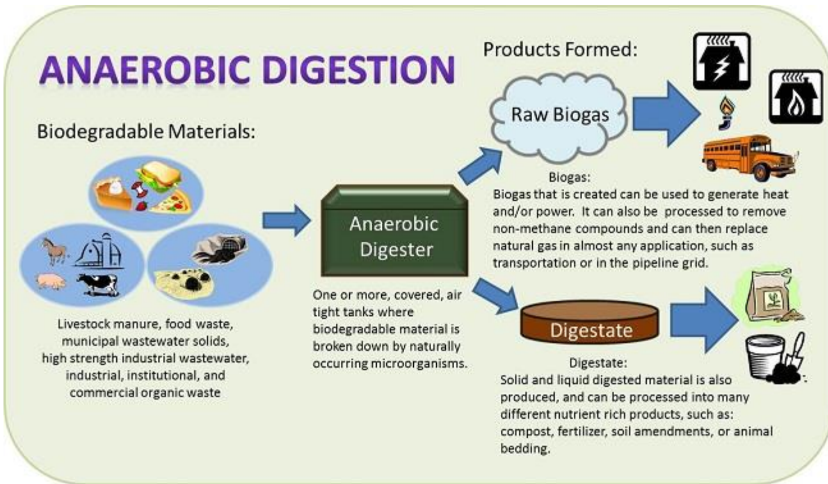


Figure 13: This diagram gives a clear look at the process that is used to turn biodegradable materials into raw biogas and digestate. The process starts on the left with normal landfill garbage. The garbage goes through anaerobic digestion and is converted into raw biogas and digestate.

Feasibility

A digester is a major capital investment, and calls for a careful engineering and economic analysis of the situation. Consultants and computer decision tools are available to assist with the analysis. Published digester economic assessments tend to show that the most successful digesters are those that have generated added value from separated manure fiber, charged tipping fees from accepting off-farm food processing wastes, or had a nearby high-value use for the biogas or electricity. Pathogen reduction is another frequently-cited benefit of digestion. Electricity sales alone are not usually enough to cover costs. Even an unprofitable digester may be regarded as successful if it provides nonmonetary benefits such as odor control (Lazarus, 2015).

Available Incentives

The federal government and many states offer incentives for installing anaerobic digesters. The 2008 Farm Bill included two grant and loan programs that cover digesters – the Rural Energy for America Program (REAP) and the Value-Added Producer Grant Program. REAP provides grants of up to 25 percent of project cost and loan guarantees of up to $25 million. The Value-Added Producer Grants can provide planning costs and working capital. Utilities will also sometimes underwrite part of the cost of the electrical generating equipment (Lazarus, 2015).

Examples of Anaerobic Digestion

A typical dairy farm milking an average of 500 cows per day can produce 30,000 - 50,000 cubic feet of biogas daily. With this volume of gas, a 70-kW generator can produce 1000 - 1,400 kWh of electricity per day, along with significant heat recovery from the engine. When deciding on the size of generators, each operation should do their own evaluation based on number of animals, the type of digester and other factors unique to the farm. However, as broad guidelines, a 70-kW generator has been recommended for a 500-cow herd. A larger farm that has 2,300 dairy cows installed a 750-kW generator. Estimated engine maintenance for an on-farm biogas generator engine, including periodic engine overhaul, was $3,700 per year in one case, for about 1,800 milking cows (Lazarus, 2015).

In another example, in 1998, AgSTAR, a collaborative effort of various federal agencies, including the EPA, selected the 1,000-acre, four-generation Haubenschild family farm near Princeton, Minnesota, to demonstrate the effectiveness of an on-farm digester operation. The Haubenschild's digester receives, on average, 20,000 gallons of manure per day, producing 72,500 cubic feet of biogas, most of which is used to power a 135-kW generator. Waste heat recovered from the generator's cooling jacket is used to heat the barn. As an added benefit, the Haubenschilds can supply enough electricity for an additional 70 households, and by December 2005, the farm had generated a total of 5.8 million kWh (Nationwide, 2012).

The energy produced by the digester prevents the equivalent of burning 50 tons of coal per month. Because it reduces methane emissions, the Haubenschild Farm can sell 90 to 100 tons of carbon credits per week through the Environmental Credit Corporation (ECC). The farm has also saved an estimated $40,000 in fertilizer costs because they use resulting "digestate" as a soil amendment (Nationwide, 2012). The capital requirements to install a digester will vary widely depending on digester design chosen, size, and choice of equipment for utilization of the biogas and/or for separating out manure fiber. The current capital cost range for complete digester systems is estimated at $1,000 to $2,000 per cow depending on herd size, with the cost to maintain an engine-generator set at $0.015 to $0.02/kWh of electricity generated. An AgSTAR regression of investments made versus herd size at nineteen recent dairy farm digesters gave a result of $566,006 + $617 per cow in 2009 dollars. Other items that may be included in charges are for connecting to the utility grid and equipment to remove hydrogen sulfide, which could add up to 20 percent to the base amount. Figuring the other items at 10 percent, the investment works out to $1.2 million for a 700-cow dairy operation, going up to $2.7 million for 2,800 cows. A similar regression for thirteen digesters gave $320,864 + $563 per cow.

There is considerable interest in digester designs that are economically feasible for smaller farms, but some digester components are difficult to scale down. A complete mix digester with separator installed on a 160-cow Minnesota dairy farm in 2008 cost

$460,000, or $2,875/cow. Another recent study found that if the biogas can be used for heating rather than to produce electricity the systems can become more efficient (Lazarus, 2015).

Other Studies on Methane Reducing Techniques

Reducing methane emissions at a cost-savings is an exciting idea. Information presented in the paper *management of tropospheric ozone by reducing methane emissions* states that, "identified global abatement measures can reduce about 10% of anthropogenic methane emissions at a cost-savings." The strategies that lead to cost-saving methane reductions are efficient and represent the lowest hanging fruit for reducing methane emissions. If all 10% of abatement techniques were implemented the U.S. production of methane would be reduced by about 2.9 million metric tons.

The EIA report *building the cost curves for the industrial sources of non-CO2 greenhouse gases* has a list of cost-effective methane reducing options. These are the options that the EIA say can reduce methane emissions at a lower price than the money that they make. This information is presented in the *Figure 14* below.

Figure 14: Cost-Effective Methane Reducing Options

Greenhouse Gas Sector	Sub Sector	Abatement Option
Methane		
Coal mining		Methane drainage combined with injection into a natural gas pipeline
Natural Gas Production, transmission and Distribution		a) Revised maintenance procedures for gas compressors b) Equipment surveying to identify leaks and direct maintenance/repairs c) Installation of dry seals on compressors d) Reduced glycol circulation rates in dehydrators e) Installation of low-bleed pneumatic devices on compressors
Solid waste management		a) Anaerobic digestion with compost production b) Use of landfill gas in existing boilers for heat production
Waste water management		Electricity generation from recovered methane

Figure 14: Options that are cost-effective in reducing methane emissions in multiple sectors. Vapor recovery units in the natural gas production, transmission and distribution sector are part of option a. Anaerobic digesters are part of solid waste management and are part of option a. WTE systems are part of solid waste management too, and part of option b.

This table also reinforces my decision to look at the natural gas and oil industry, landfill industry, and livestock animal farm industry. The table mentions all three of the technology options that I have chosen to analyze.

The article, *the social costs of methane: theory and applications* (2017), by Shindell, Fuglestvedt and Collins, focuses on calculating an updated social cost of methane and the application of the social cost of methane to various industries for the use of methane reducing technologies. The article says that any technology that leads to net benefits may be useful to pursue at the local level, but to provide the largest global impact a few industries standout. "With the perspective of a private investor, improving coal mine ventilation systems, separation and treatment of biodegradable waste, and reducing gas pipeline leakage are the top three measures." Pursuing methane reductions in the previously mentioned areas are the best, because of the total net benefits they create. The costs and benefits that it would take to reduce one ton per industry is presented in *Figure 15.*

Figure 15: Private Cost-Benefit Analysis

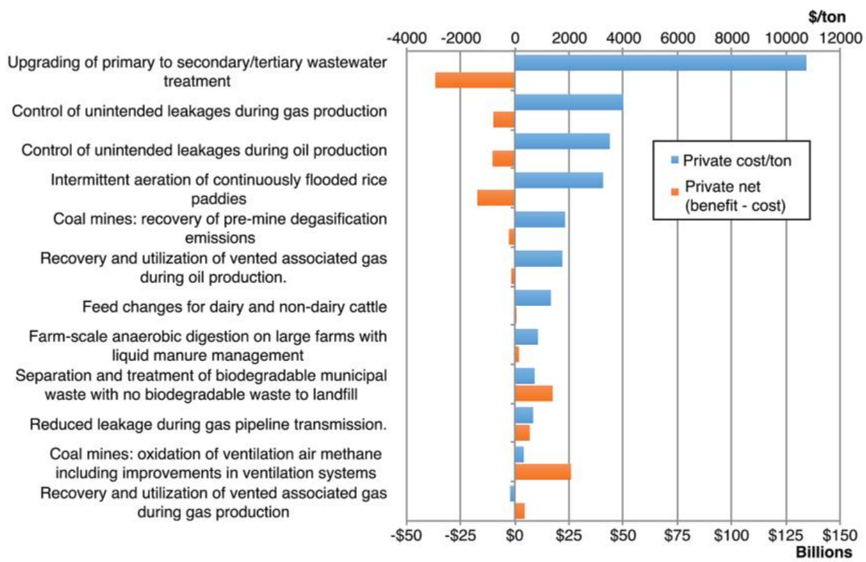


Figure 15: The mitigation costs (blue bars; $ per ton methane on upper axis) and net social costs (orange bars; benefits minus implementation costs on lower axis) for the studied emissions reduction measures. The values are evaluated from the perspective of a private investor (10% discount rate).

The article goes into an analysis of the energy sector and its methane emissions. This section of the article is designated to calculate the real costs of electricity production in the U.S. They consider their updated social cost of methane, which is about $3,000 per ton. $3,000 per ton of methane is much higher than most of estimates, mentioned later in the *Social Costs of Methane* section. Typically, natural gas and wind power have similar costs per kWh and are relatively cheap, while solar power is relatively expensive. When the social costs of methane are added to the cost per kWh, coal becomes the most expensive energy production process, with natural gas second. The total costs of natural gas-fired electricity generation, including the social cost of methane, would be far less than coal, comparable to and even slightly less than current solar, but still much more expensive than wind. *Figure 16* shows the cost per kWh and the separated costs for electricity production through coal, gas, nuclear, solar and wind.

Figure 16: Electricity Production Costs in the U.S.

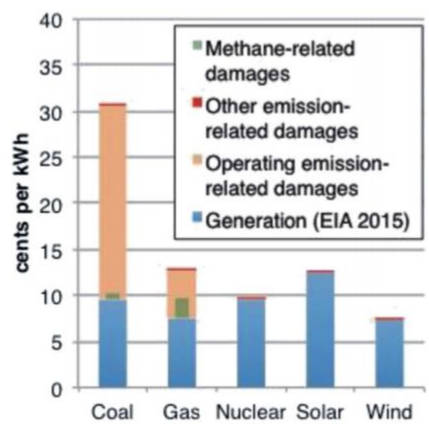


Figure 16: Electricity production costs in the U.S. for various sources. The social cost of methane (green) are a portion of total operating emission-related damages for coal and gas. Other emission-related damages are from emissions associated with construction and facility retirement over the life-cycle of the power source (Shindell, 2017). The total height of the bars for each option is the cents per kWh of electricity generation, with all social costs included.

From the journal article, *a cost curve for greenhouse gas reduction,* the authors state that agricultural and waste disposal in developing economies have a large potential for reducing "greenhouse gases such as methane and nitrous oxide" at a price "no more than 40 euros [~$46 USD (United States Dollars)] a ton." They say that a shift to fertilization and improved tillage techniques in agriculture and capturing methane from landfills would cost less than 40 euros a ton. The information provided by the journal article is helpful to get a sense of the expenses that greenhouse gas emissions cost, but they are not looking specifically at methane emissions. Methane emissions are only a percentage of the GHG. Therefore, reducing methane would be more expensive per ton than the price of reducing GHG stated in this article.

Drew Shindell, a climate scientist at NASA's Goddard Institute for Space Studies, recently led a global team of scientists in analyzing seven methane-reduction strategies, from draining rice fields to capturing the gas that escapes from landfills and gas wells. Shindell's group found, the benefits of methane controls outweigh the costs by at least 3 to 1, and in some cases by as much as 20 to 1 (UNEP, 2011). According to this research, it makes sense to work on reducing methane emissions immediately, before methane poses a bigger problem to society and the environment than it already does.

Social Costs of Methane

It is important to compare the costs of methane reducing technologies to the social costs of methane reductions. Social costs are calculated by determining the total cost to society that each ton of methane emissions produce.

Research has led to the determination of the social cost of methane to be much higher than the social cost of carbon dioxide. This represents that methane has harsher impacts on the humans and the environment per ton of carbon dioxide. A study from 2006 shows the social cost of methane to be $105 USD per ton (Hope, 2006). This finding came from a new model of the PAGE model; PAGE2002 estimated the marginal impacts of methane, based on Scenario A2 of the IPCC (Intergovernmental Panel on Climate Change). The marginal impacts of methane far outweigh the marginal impacts of carbon dioxide, which is estimated to be at $19 USD per ton (Hope, 2006). Nicholas Z. Muller, Robert Mendelson, and William Nordhaus concluded that, "at a price of $65 a ton of carbon, the total damages from natural gas are more than double its value-added (Muller et al., 2011)." This study shows that the social cost of methane is more than $130 USD, which is fairly well aligned with Hope's determination of $105 USD. Newer research may prove to show that the social cost of methane is continuing to rise, as more of it is released into the atmosphere, and natural gas production continues to expand.

An article mentioned in the last section (Other Studies on Methane Reducing Techniques), written by Shindell, Fuglestvedt, and Collins named, *The Social Cost of Methane: Theory and Applications,* explains that the when "calculating the social cost of methane using consistent temporal treatment of physical and economic processes and incorporating climate- and air quality-related impacts, we find large social costs of methane values, e.g. ~$2,400 per ton and ~$3,600 per ton with 5% and 3% discount rates respectively." The social cost of methane values that this study found are 50 to 100 times greater than typical social costs of methane estimates. "The results indicate that efforts to reduce methane emissions via policies spanning a wide range of technical, regulatory and behavioral options provide benefits at little or negative net cost." The social cost of methane may reach this price one day, if it continues to go largely unabated. At this time, this estimate is overreaching and disproportionate to the social costs of other greenhouse gases.

Policy Options

As earlier discussed, atmospheric methane should be quickly and dramatically reduced. Most industries will not pay for the implementation of methane reducing instruments or techniques because of fears of inconvenience and intensive capital requirements. The initial capital cost of most instruments in large industries are very expensive.

Policy-makers have two broad types of instruments available for changing consumption and production habits in society. The same principles can be applied to our case of reducing methane emissions. They can use traditional regulatory approaches (command-and-control) that set specific standards across polluters. Or they can use economic incentives or market-based policies that rely on market forces to correct for producer and consumer behavior.

There are two basic types of traditional regulatory approaches to policy. The first type is a technology standard that mandates specific control technologies or production processes that polluters must use to meet an emission standard. The second type is a performance-based standard that also requires that polluters meet an emissions standard, but it allows them to choose any available method to meet that standard. The performance-based standard is often preferred to the technology standard option, because the technology standard may not reduce pollution at an efficient level for all polluters. Polluters may have more efficient ways to reduce pollution, which would only be able to be pursued in the performance-based standard option.

Traditional regulatory approaches, like technology and performance based standards, are widely used and accepted policy tools for environmental problems, but incentive based policies are becoming increasingly popular as tools for addressing a wide range of environmental issues (EPA, 2017). Incentive based approaches create encouragement for polluters to incorporate pollution abatement into the production decisions. There are four main types of incentive/market based policies: marketable permit systems, emission taxes, subsidies and tax-subsidy combinations.

There are two types of marketable permit systems in the United States. The first is an Emission Reduction Credits (ERCs) program that allows polluter as to earn credits by reducing their pollution below a certain rate. The credits can be redeemed as tax credits. The largest criticism of ERCs is that there is no ceiling on total emissions, so if more polluters join the market there could actually be more pollution. The second type of marketable permit system is the Capped Allowance System, otherwise known as a cap-and-trade system, which sets a maximum allowable ceiling on total emissions. The cap is equal to the total number of allowances allocated to a group of polluters. Each polluter has the decision to sell their allowances to other polluters if they make more money doing so than by polluting, or they can save their allowances and pollute. This system allows for very high efficiency in reducing pollution.

Emissions taxes are widely used and place a per unit monetary charge on pollution emissions to reduce the overall quantity (EPA, 2017). The main critique is that there is no promised quantity of emissions reductions. Emissions taxes address the failure of free markets to consider environmental impacts (EPA, 2017). Ecotaxes are an example of a Pigouvian tax, which are taxes that attempt to make the polluters feel the social burden of their actions. Many times, a pollution tax may attempt to maintain overall tax revenue by proportionately reducing other taxes.

An emissions tax was enacted in Germany in three laws in 1998, 1999, and 2002. The first law introduced a tax on electricity and petroleum, at variable rates based on environmental considerations. The second law adjusted the taxes to favor efficient conventional power plants. The third law increased the tax on petroleum. At the same time income taxes were reduced. The ecotaxes effects were extremely beneficial for the country of Germany and its people. The Federal Environmental Bureau highlighted the effects in early 2002, when it stated that by the end of that year, its projections showed that ecotaxes would have reduced CO_2 emissions by more than 7 million tons and created 65,000 new jobs (WRI, 2014).

A subsidy is defined as, "monetary assistance granted by a government to a person or group in support of an enterprise regarded as being in the public interest. (Yager, 2015)." The EPA says that subsidies work different than taxes on emissions, "rather than charge a polluter for emissions, a subsidy rewards a polluter for reducing emissions (EPA, 2017)." The EPA also explains that, subsidies have been used for a wide variety of purposes, including: brownfield development after a hazardous substance contamination; agricultural grants for erosion control; low-interest loans for small farmers; grants for land conservation; and loans and grants for recycling industrial, commercial and residential products. While subsidies offer incentives to reduce emissions similar to a tax, they also encourage market entry to qualify for the subsidy (EPA, 2017). The entry into the market by new firms has the potential to limit the amount of progress in reducing methane emissions. Even if there is a reduction in emissions per firm, enough new firms joining the market have the capability to lead to more emissions.

A previous example of a subsidy being used for emissions reductions was the National Clean Diesel Rebate Program in 2012, which provided financial assistance to public and private fleet owners for the replacement of older school buses with new, cleaner school buses (EPA, 2012). Over 1000 school bus fleets applied for the EPA's 2012 School Bus Rebate Program, requesting over $70 million in funding (EPA, 2017). Unfortunately only $2 million was allocated to the applicants at the top of the list. The rest of the applicants were placed on the applicant wait list. Although not all of the applicants received funding in 2012, there were also clean diesel rebates in 2014, 2015, and 2016. It is unknown exactly how much carbon dioxide emissions this program reduced, but it has been said, by the EPA, that the benefits have been shown to strongly outweigh the costs of the program (EPA, 2017).

The oil and gas industry already receives many subsidies provided by the government. The Organization for Economic Cooperation and Development reported that 40 countries subsidized the cash cost of motor fuel by $548 USD billion in 2014 (OECD, 2015). The large number of subsidies that the gas and oil industry receives has had some backlash by activists, researchers, and citizens. Some people believe that gas and oil companies should not be given monetary assistance, because it promotes the production and use of fossil fuels, which creates adverse effects on human health and the environment. This is contrary to the polluter pays principle, where the guilty party is responsible for correcting (and paying for) the negative externality they produce (Hanley, 2001).

For example, David Kelly, from the National Bureau of Economic Research says that, "Previous work in partial equilibrium shows that subsidies to environmentally sensitive industries increase output and pollution emissions." He believes that, "reducing some subsidies may offer a path to sustainable development by raising income and at the same time improving the environment." Kelly's research is focused on where the subsidies are going. If subsidies are provided to emissions intensive industries, the amount of emissions will go up, but if the subsidies are provided to cleaner industries, the emissions will decrease. He says that natural gas subsidies may not reduce emissions as much as subsidies towards other renewable fuels (Kelly, 2009).

Methods

My methods are to go as far as economic analysis can take me with the current research on: methane reducing technologies in the natural gas and oil industry, landfill industry, and livestock animal farm industry. The full equations used to determine the statistics of each methane reducing technology can be seen in the Results section. Along with consulting prior research, I have created and implemented a survey asking Colorado citizens about their opinions on the three methane reducing technologies that I have laid out, and policies on such technologies. I have created a focus on methane because the EIA says that, "the largest reductions [in GHG] can be obtained by abating emissions from methane sources (EIA, 2003)." I have chosen these three industries because they are the largest three methane emitting industries in the United States and offer the most promise in limiting global warming. The EIA greenhouse gas research and development program says that, "most of the potential cost-effective reductions can be achieved in the wastewater management sector, followed by solid waste management, and the natural gas sector (EIA, 2003)." Wastewater management includes wastewater from multiple sectors, including: residential wastewater, landfill wastewater, and farm wastewater. It is important to focus on the largest emitters first, because they have the most room for improvement and typically contain the lowest hanging fruit for pollution reductions.

Methane Reducing Technologies

I gathered information on the costs of the three methane emissions reducing technologies from various online resources. The cost information for the VRUs is provided by Natural Gas STAR partners and VRU manufacturers. The cost information for 3MW gas turbines is provided by The Global Methane Initiative. The cost information for 5000-ton anaerobic digesters is provided by Marathon Equipment (Clarke, 2014). For all technologies, actual costs might be greater or lower depending on expenses for shipping, site preparation, supplemental equipment, etc. The costs of each technology were compared to multiple other sources to make sure the numbers were aligning (Hy-bon, 2017) (EESI, 2013) (RWI, 2013).

The costs will be compared to the benefits of the technology in a cost-benefit analysis. The benefits for each individual technology depends on many factors, including: flow rate, pressure, efficiency, leaks, types of recovered material, processing equipment, etc. The benefits to producers through the VRUs are assumed to be equal to $3.50 per Mcf (million cubic feet) of recovered gases (EIA, 2017). The benefits to producers through 3MW gas turbines and 5000-ton anaerobic digesters are equal to 6 cents per kWh from electricity buyback programs (EPA, 2017). The costs of each technology are in present value terms. Present value is the value in the present of a sum of money, in contrast to some future value it will have when it has been invested and compound interest. The costs solutions found through the present value of payments equation illustrate the amount of money producers can expect to pay per year in present value terms. The costs are reduced at a 2% discounting rate per year. A 2% discounting rate was chosen because it is a practical rate for discounting for benefit cost analyses (Phaneuf, 2005).

Benefits to producers of each technology are added to the social benefit of each technology to arrive at the total benefit. The social benefit of reducing one ton of methane is equal to $105 (Hope, 2006). This number was developed by comparing the damages from each ton of methane to each ton of carbon dioxide. I looked at the amount of methane reductions that each technology is capable of. All methane emissions reductions were converted into tons. The larger the decrease in methane emissions, the more effective a technology is. I took the amount of methane emissions reduced and multiply that number by the social costs of methane ($105) to find the total social benefit of implementing methane reducing technologies. If the technology passes the cost-benefit test, then it may be recommended for implementation to reduce methane emissions in its respective industry.

Next, I divided the cost of the methane reducing technology, in present value terms, by the total reduction in methane in tons. This number represents the cost per ton of methane reduction. This number will be important for determining the most efficient technology in reducing methane emissions. The lowest hanging fruit principal says that the most efficient technology should be used to reduce methane emissions first. The efficiency of all three technology options increases as the size of the technology unit increases. This makes larger facilities more practical for implementation of methane reducing technologies. For the purpose of this study, we are focusing on the average costs of each technology, so the efficiency ranging in size is not an important decision-making factor in choosing the lowest hanging fruit.

Survey

I have created a survey that asks Colorado voters which of the three methane reducing technologies they prefer. Then I ask about respondent's preferences of providing subsidies or command and control regulations, and which policy they prefer for each individual technology. The layout of the survey is as follows: three questions asking if people would vote for subsidies for each of the three methane reducing technologies, three questions asking if people would vote for regulations for each of the three methane reducing technologies, what technology they prefer, what policy they occur, demographic questions – including two questions on opinions on global warming, and one question on political affiliation. This information will allow me to gauge people's acceptance of using for methane emissions control. I compared the results and the results lead to correlations between responses. The information gathered through the survey shows people's preferences on which industry policy should be implemented upon. This information is very important at making a policy decision of enacting methane reducing technologies.

Before submitting the survey, I had students in my senior thesis class, at the University of Colorado at Boulder, complete my draft survey and give criticisms and comments. After receiving eight responses, I made the necessary changes, and submitted my updated survey to my faculty advisors. Then, I made additional changes, which completed the survey is its entirety. I needed to complete the necessary Institutional Review Board (IRB) certifications for human subject's surveys. These certifications were completed to certify myself as a surveyor, and certify the survey itself. To certify myself I completed CITI Training. To certify the survey, I followed the eRA Submission Guidelines by completing the initial application. The initial application includes the protocol and the initial application forms. I did not need to complete a waiver form, because the results of the survey are anonymous and there is no sensitive questions or information in the survey. Once I received my certification, I moved on to making sure the survey would be collecting all of the results that were needed to create a reasonable view on Colorado voter's opinions. I worked with Qualtrics to submit the survey to 250 Colorado voters. The survey was created and distributed through the Qualtrics website.

To analyze the survey results I looked at the response percentages to determine how popular each choice was. I then ran a regression through Microsoft Excel to determine if any of the results made a significant difference on the other results. Before completing the regressions, I needed to change the word answers into numerical answers. I did so through the find and replace feature on Excel. I then sorted by number to eliminate the "unsure" answers from the data for each regulation/ subsidy answer. At this point I ran the regressions and determined a few significant results, that can be seen in the Results section below.

For the recommendation section, I looked at the results from the statistics of each technology separately, then I looked at the results from the survey data separately, then finally, I looked at the results from each section together. I made the recommendation as if I was responsible for determining whether to subsidize, regulate, or leave each industry in next year's budget. I made the recommendations based on the assumption only one industry could be subsidized, only one be regulated, and only one be left as is for next year's policies.

Results

For each of the three systems, the numbers and calculations that were used to find the payment per year, benefits per year, methane reduction per year, and dollars per ton of methane reduction will be shown. Results for the natural gas industry's VRUs will be provided first. The results for the landfill industry's 3MW gas turbines will be provided second. And, the results for livestock animal farm's 5000-ton anaerobic digesters will be provided third. After the calculations are shown and explained, the survey results will be shown.

Natural Gas Industry- Vapor Recovery Unit

For all calculations on VRUs we must establish some assumptions. We assume: API gravity = 38 degrees, separator pressure = 40 psi , oil cycled = 1,000 barrels/year, vapor emissions rate = 43 scf/barrel

Quantity of hydrocarbon vapor emissions =

*43 scf/barrel * 1,000 barrels/day = 43 Mcfd* (thousand cubic feet per day)

Payment per year ($)

The average payment per year for an average sized VRU system is **$**14,479 in present value terms.

To find the present value of the costs, I found the average capital costs, average installation costs, average operation and management (O&M) costs, average lifetime of the system, and chose the discount rate:

Average capital cost ($) = 36,082

Average installation cost ($) = 30,637

Average capital cost + average installation cost ($) (X)= 66,719

Average O&M cost ($) = 10,903

Discount rate= .02

A= 1 , T= 24 years, r= .02

The equation to find present value of capital and installation costs:

(A*(1+r)/r*(1-(1+r)^(-T+1)))/ (X)

(1(1.02)/.02*(1-(1+.02)^(-24+1)))/ (66,719) = $3,576 per year*

I took the present value of capital and installation costs plus the average O&M costs per year to find the present value of payments per year.

$3,576 + $10,903 = $14,479

Methane reduction per year (tons)

The average amount of methane reduction per year is 374 tons. Through the EPA website on VRUs provided me with 43 Mcf as the average amount of gas captured by VRUs per day (EPA, 2006). Mcf is an abbreviation for a thousand cubic feet of natural gas. The EPA assumes 95% of the annual volume of gas lost can be recovered using a VRU. To calculate the annual amount of gas captured by VRUs we multiply the Mcf of gas captured by .95 efficiency.

$$43\ Mcfd * .95 = 41\ Mcfd$$

The average savings from VRU technology is equal to the Mcfd times 365 days

$$41\ Mcfd * 365\ days = 14{,}965\ Mcf\ per\ year$$

Next, I converted Mcfe to Btu. A Btu is an abbreviation for a British Thermal Unit. There are 1027 Btu in each Mcf of natural gas, on average (EIA, 2012).

$$14{,}965\ Mcf * 1000 * 1027\ Btu/Mcf = 1.53 * 10^{10}\ Btu$$

There are 41,102,000 Btu of natural gas in a ton (Hofstrand, 2014). The tons of methane reductions per year on average for natural gas VRUs equals the Btu saved for VRUs divided by the amount of Btu per ton.

$$1.53 * 10^{10}\ Btu / 41{,}102{,}000\ Btu/ton = 374\ tons$$

Benefit to producers per year ($)

The benefit to producers per year for natural gas VRUs is $52,378. Assumes $3.50 per Mcf. The average Mcf savings per year is 14,965 (from above). The benefit to producers per year for natural gas VRUs is equal to the total amount of Mcf reductions multiplied by the cost per Mcf of natural gas.

*14,965 Mcf * $3.50 = $52,378*

Social benefit of methane reductions per year ($)

The social benefit of methane reduction per year for natural gas VRUs is $39,270. The social cost of methane is $105 per ton (Hope, 2006). The average methane reduction of natural gas VRUs per year is 374 (from above). The social benefit of methane reduction per year for natural gas VRUs equals the average methane reduction of natural gas VRUs multiplied by the social cost of methane.

*374 tons * $105/ton = $39,270*

Total benefit per year ($)

The total benefit per year for natural gas VRUs is $91,648. The total benefit per year for natural gas VRUs is the benefit to producers (from above) added to the social benefit of methane reductions per year (from above).

$52,378 + $39,270 = $91,648

Net benefit per year ($)

The net benefit per year form natural gas VRUs is $77,169. Net benefit per year for natural gas VRUs is calculated by subtracting the payment per year (from above) from the total benefit per year (from above).

$91,648 - $14,479 = $77,169

Dollars per ton of methane reduction ($/ton)

The dollars per ton of methane reduction for natural gas VRUs is $39 per ton of methane reduction for natural gas VRUs. The dollars per ton of methane reduction is calculated by dividing the payment per year (from above) by the tons of methane reduction per year (from above).

$14,479 / 374 tons = $39

Landfill Industry- 3MW Gas Turbines

Payment per year

The average payment per year for a 3MW gas turbine is $513,428 in present value terms. To find the present value of the costs, I found the average costs of 3MW gas turbines, average lifetime of the system, and chose the discount rate:

Average total cost ($) = $6,340,000

Discount rate= .02

A= 1 , T= 15 years, r= .02

The equation to find present value of capital and installation costs:

(A*(1+r)/r*(1-(1+r)^(-T+1)))/ (X)

(1(1.02)/.02*(1-(1+.02)^(-15+1)))/ (6,340,000)= $513,428 per year*

Methane reduction per year (tons)

The average amount of methane reduction per year is 2,316 tons. The Environmental and Energy Study Institute provided me with the information that one million tons of landfill waste emit approximately 432,00 cubic feet of LFG (landfill gas) per day, which is enough to produce .78 MW of electricity (EESI, 2013). I then had to convert cubic feet of LFG per day into cubic feet of LFG per hour. To find the cubic feet per hour of gas is equal to the cubic feet of LFG per day divided by 24 hours.

432,000 cubic feet LFG / 24 hours = 70,629 cubic feet per hour

Landfill gas is composed of approximately 50% methane (EESI, 2013), the other half is almost completely CO2- which we disregard, because we are focused on methane reductions. The amount of methane released by the landfill per hour is equal to the cubic feet of gas per hour multiplied by 50% methane.

*70,629 cubic feet/hour * 50% methane = 35,314.5 cubic feet of methane/hour*

Gas turbines usually meet an efficiency of 20 to 28 percent at full load with LFG. We will use the average efficiency of 24% to find the cubic feet of methane reductions to create electricity by the 3MW gas turbines.

*35,314.5 cubic feet of methane/ hour * 24% = 8,475.48 cubic feet of methane per hour*

Now we must find the weight of the methane being used. The density of methane = .0624 lbs/ft^3. To find the weight of methane reductions in pounds per hour we must convert cubic feet of methane to weight by multiplying it by the density of methane.

*8,475.48 cubic feet of methane * .0624 lbs/ cubic feet of methane = 529 lbs/hour*

Convert pounds per hour of methane reductions to tons by taking the pounds per hour of methane reductions by the weight of a ton (2000 lbs).

529 lbs / 2000 lbs = .26 tons per hour

Convert the tons per hour of methane reductions to tons of methane reductions per year by multiplying the tons per hour of methane reductions by 24 hours and 365 days to find the tons of methane reductions by 3MW gas turbines per year. We assume that the turbines are operating all year at full capacity.

*.26 tons/hour * 24hours * 365days = 2,316 tons*

Benefit to producers per year ($)

The average benefit to producers per year for 3MW gas turbines is $1,865,880. Incentive programs vary by landfill type, location, state regulations. We must convert 3MW to MW per year by multiplying 3MW by 24 hours and 365 days.

*3MW * 24hr * 365 days = 26,280MW/year*

To convert MW per year to kWh per year we must take the MW per year multiplied by 1000 MW per year per kWh per year.

*26,280MW * 1000MW/kW = 26,280,000 kWh/ year*

In the EPA's LFG Energy Project Development Handbook, they estimate 6 cents per kWh of electricity for buyback programs (EPA, 2017). The amount of revenue created through 3MW per year is equal to the cost of electricity in buyback programs multiplied by the kWh per year produced by 3MW gas turbines.

*.06 $/kWh * 26,280,000 = $1,576,800*

The Renewable Electricity Production Tax Credit (PTC) pays .011 $/ kWh (energy.gov, 2017). To calculate the revenue of 3MW through Renewable Electricity PTC we multiply the PTC by the kWh produced per year by 3MW gas turbines.

*.011 $/kWh * 26,280,000 = $289,080 per year*

To calculate the total benefit to producers we add the benefits from the 6 cent buyback program to the benefits from the Renewable Electricity PTC.

$1,576,800 + $289,080 = $1,865,880

Social benefit of methane per year ($)

The social benefit of methane reductions by 3MW gas turbines is $234,180. To arrive at the social benefits of methane per year we multiply the social costs of methane by the average methane reduction of 3MW gas turbines per year. The social cost of methane is $105 per ton (Hope, 2006). The average methane reduction of landfill 3MW gas turbines per year is 2,316 tons (from above).

*2,316 tons * $105/ton = $243,180*

Total benefit per year ($)

The total benefit per year for 3MW gas turbines is $2,109,060. The total benefit per year for landfill 3MW gas turbines is the benefit to producers (from above) added to the social benefit of methane reductions per year (from above).

$1,865,880 + $243,180 = $2,109,060

Net benefit per year ($)

The net benefit per year to landfills from 3MW gas turbines is $1,595,632. Net benefit per year for landfill 3MW gas turbines is calculated by subtracting the payment per year (from above) from the total benefit per year (from above).

$2,109,060 - $513,428 = $1,595,632

Dollars per ton of methane reduction ($/ton)

The dollars per ton of methane reduction created by 3MW gas turbines is equal to $222 per ton of methane. The dollars per ton of methane reduction is calculated by dividing the payment per year (from above) by the tons of methane reduction per year (from above).

$513,428 / 2,316 tons = $222 per ton

Livestock Industry- 5000-Ton Anaerobic Digester

Payment per year

The average payment per year for a livestock animal farm 5000-ton anaerobic digester is **$**131,310 in present value terms. The cost information is provided by Marathon Equipment (Clarke, 2014). Actual costs might be greater depending on expenses for shipping, site preparation, supplemental equipment, etc.

To find the present value of the costs, I found the average capital costs, and average operation and management (O&M) costs, average lifetime of the system, and chose the discount rate:

Average capital cost ($) = $2,450,000

Discount rate= .02

A= 1 , T= 24 years, r= .02

The equation to find present value of capital and installation costs:

(A*(1+r)/r*(1-(1+r)^(-T+1)))/ (X)

(1(1.02)/.02*(1-(1+.02)^(-15+1)))/ (2,450,000) = $131,310 per year*

Methane reduction per year (tons)

The methane emission reductions from 5000-ton anaerobic digesters per year is $502 tons per year. According to Lormor, et al., a 1,400 pound dairy cow is about an average sized dairy cow in the U.S. The average 1,400 pound dairy cow produced 120 pounds of manure each day. To calculate the kilograms (kg) per year from a 5000-ton anaerobic digester is equal to 907 kg (1 ton= 907 kg) per ton multiplied by 5000 tons per year.

*5000 tons/year * 907kg/ton = 4,535,000 kg/year*

Kougias, of the Technical University of Denmark says the typical biogas yield from anaerobic digestion of cattle manure is equal to 0.21 m^3/kg of volatile solids, 65% of which being methane. To calculate the weight of methane emissions from a cubic meter of manure we multiply the biogas yield from anaerobic digestion of cattle manure by the percent of the biogas that is methane.

*0.21 m^3/kg * 65% = .14 m^3/kg*

To calculate the methane emission per year in cubic meters from 5000 tons of manure we multiply the kg per year of manure by the weight of methane emissions from a cubic meter of manure.

*4,535,000 kg/year * .14 m^3/kg = 634,900 m^3 of methane emissions/year*

From here we calculate the weight of methane emissions per year from 5000 tons of manure by taking methane's density (0.717 kg/m^3) by the cubic meters of methane emission per year.

*634,900 m^3/year * 0.717kg/m^3 = 455,223 kg of methane/year*

Now, we convert kg per year to tons per year. We do so by multiplying the kg per ton (907 kg in a ton) by the kg of methane emissions per year.

455,223 kg of methane/year / 907 kg/ ton = 502 tons per year

Benefit to producers per year ($)

The average benefit to producers per year for 5000-ton anaerobic digesters is $105,966. Marathon Equipment says that a 5000-ton anaerobic digester can produce 203 kWh/ton on average, while running at full capacity. To calculate the kWh per year we multiple the tons per year by electricity production per ton.

*5000 tons/year * 203 kWh/ton = 1,015,000 kWh/year*

As stated before, the EPA estimates that producers of electricity can expect to receive 6 cents per kWh from buyback programs through energy suppliers. To calculate the benefit to producers per year from 5000-ton anaerobic digesters we multiply the kWh per year by the electricity buyback price.

*1,015,000 kWh/year * .06 $/kWh = $60,900 per year*

Social benefit of methane per year ($)

The social benefit of methane reductions per year from 5000-ton anaerobic digesters is $52,710. The social cost of methane is $105 per ton (Hope, 2006). The average methane reduction of 5000-ton anaerobic digesters per year is 502 tons (from above). To calculate the social benefit of methane reduction per year we multiply the tonnage of methane reductions by the social cost of methane.

*502 tons * $105/ton = $52,710*

Total benefit per year ($)

The total benefit per year from 5000-ton anaerobic digesters is $113,610. The total benefit per year for 5000-ton anaerobic digesters is equal to the benefit to producers (from above) added to the social benefit of methane reductions per year (from above).

$60,900 + $52,710 = $113,610

Net benefit per year ($)

The net benefit of 5000-ton anaerobic digesters per year is -$17,700. The net benefit per year for 5000-ton anaerobic digesters is calculated by subtracting the payment per year (from above) from the total benefit per year (from above).

$113,610 - $131,310 = -$17,700

Dollars per ton of methane reduction ($/ton)

The dollars per ton of methane reduction per year from 5000-ton anaerobic digesters is $262. The dollars per ton of methane reduction is calculated by dividing the payment per year by the tons of methane reduction per year.

$131,310 / 502 tons = $262 per ton

Survey Results

The entire survey be viewed in *Appendix 1.* Please refer to *Appendix 1* for any questions about the specifics of the survey. I will write out the questions in this section as well. I start by giving the results of the qualifying questions, then regulation/ subsidy questions, then industry questions, and finally demographic questions. After the survey results are displayed, I will give the significant regression results of the demographic questions on the regulation/ subsidy questions.

Qualifying Questions

The first three questions on the survey are qualifying questions. These questions were added to the survey to make sure the respondents were actually reading and understanding the information presented prior to the completion of the survey. The first question, "Which of the three technologies costs the least to reduce methane emissions per ton," had 61.4% of the respondents respond with the correct answer "Natural gas vapor recovery units." The second qualifying question is, "The most net benefit per year comes from which of the three presented technologies." Respondents got the answer right 62.5% of the time with the answer of "Landfill gas 3MW gas turbines." The third qualifying question is, "Which of the three technologies reduces methane emissions the most." The respondents said that, "Landfill gas 3MW gas turbines" reduced the most emissions only 45.8% of the time.

Regulation/ Subsidy Questions

This section will display the survey results from the regulation/ subsidy portion of the survey. There are six questions in this section. The respondents were asked if they would vote yes or no to regulation or subsidies to each industry and the corresponding technology. The questions were laid out as such, "Suppose we held a referendum on regulating or subsidizing natural gas, landfill, or livestock animal producers, requiring them to install VRUs, 3MW gas turbines, or anaerobic digesters. The businesses would pay for the VRUs, 3MW gas turbines, or anaerobic digesters. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made." The results were as follows:

VRU regulation:
- Yes= 143 (56.5%)
- No= 47 (18.6%)
- Unsure= 63 (24.9%)

VRU subsidy:
- Yes= 127 (50.2%)
- No= 58 (22.9%)
- Unsure= 68 (26.8%)

3MW gas turbine regulation:
- Yes= 140 (55.3%)
- No= 47 (18.6%)

- Unsure= 66 (26.1%)

3MW gas turbine subsidy:

- Yes= 133 (52.4%)
- No= 57 (22.4%)
- Unsure= 64 (25.2%)

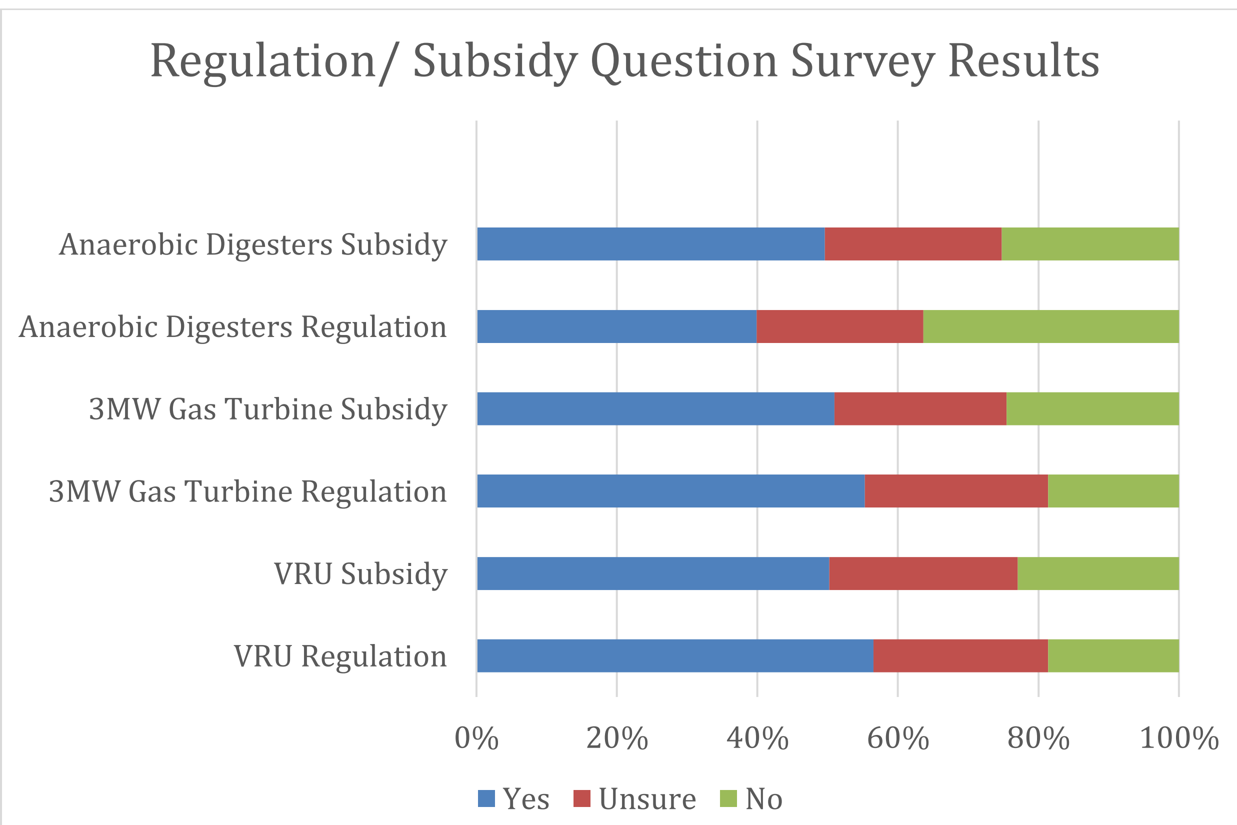
Anaerobic digesters regulation:

- Yes= 101 (39.9%)
- No= 92 (36.4%)
- Unsure= 60 (23.7%)

Anaerobic digesters subsidy:

- Yes= 126 (49.6%)
- No= 64 (25.2%)
- Unsure= 64 (25.2%)

Graph 1: Regulation/ Subsidy Question Survey Results



Graph 1: Shown in the graph above are the answers to the regulation/ subsidy question survey answers. The blue portion represents the “Yes” answers, the red portion represents the “Unsure” answers, “No” answers are represented in the green. This graph shows the differences in the percentage of answers for each regulation/ subsidy question.

Preference Questions

The next portion of the survey asked Colorado citizens what industry they would prefer to put regulations, subsidies, and reduce methane emissions in. The results are as follows:

What industry would you most prefer to provide subsidies to?

- Natural gas= 56 (22.1)
- Landfill= 73 (28.9)
- Livestock animal farm= 73 (28.9)
- None= 15 (5.9)
- Unsure= 36 (14.2)

What industry would you most prefer to put regulations on?

- Natural gas= 62 (24.5)
- Landfill= 89 (35.2)
- Livestock animal farm= 47 (18.6)
- None= 25 (9.9)
- Unsure= 30 (11.8)

I would prefer that methane is reduced in the:

- Natural gas= 53 (20.9)
- Landfill= 107 (42.3)
- Livestock animal farm= 49 (19.4)
- None=10 (4)
- Unsure= 34 (13.4)

I think that the policy option that should be used to reduce methane emission in the industry I chose in number 12 is:

- Subsidies= 78 (30.8)
- Regulations= 85 (33.6)
- None= 22 (8.7)
- Unsure= 68 (26.9)

Demographic Questions

The demographic questions come at the end. This section also asks questions on the respondent's individual political ideology, and views on climate change. The results are as follows:

Education:

- Less than high school= 5 (2%)
- High school or GED= 50 (19.8%)
- Some college= 84 (33.2%)
- 2 year degree= 25 (9.9%)
- 4 year degree= 59 (23.3%)
- Professional degree= 29 (11.4%)
- Doctorate= 1 (.4)

Gender:

- Male = 37 (14.6%)
- Female= 214 (84.6%)
- Do not wish to identify= 2 (0.8%)

Ethnicity:

- African American=8 (3.1%)
- African/Black/Caribbean= 3 (1.2%)
- Asian/ Pacific Islander= 3 (1.2%)
- Caucasian= 186 (73.2%)
- Hispanic/Latino= 39 (15.4%)
- Native American= 5 (2%)
- Other= 10 (3.9%)

What is your income range:

- 0-30= 74 (29.2%)
- 30-60= 86 (34%)
- 60-90= 43 (17%)
- 90-120= 31 (12.3%)
- 120+= 19 (7.5%)

What is your age range:

- 0-20= 16 (6.3%)
- 20-40= 115 (45.3%)
- 40-60= 95 (37.4%)

- 60-80= 28 (11%)
- 80+= 0

What is your political ideology:

- Very conservative= 15 (5.9%)
- Conservative= 46 (18.1%)
- Moderate= 81 (31.9%)
- Liberal= 61 (24%)
- Very liberal= 15 (5.9%)
- No opinion= 36 (14.2%)

I currently live within one mile of a natural gas plant:

- Yes= 15 (5.9%)
- No= 238 (94.1%)

I currently live within one mile of a landfill:

- Yes= 26 (10.2%)
- No= 228 (89.8%)

I currently live within one mile of a livestock animal farm:

- Yes= 54 (21.3%)
- No= 200 (78.7%)

What is your view on climate change:

- Warming is due to human activity= 166 (65.4%)
- Warming is due to natural changes= 40 (15.7%)
- No solid evidence earth is warming= 23 (9.1%)
- Unsure= 25 (9.8%)

Global warming is:

- Very serious problem= 160 (63%)
- Somewhat serious= 42 (16.5%)
- Not too serious=21 (8.3%)
- Not a problem= 17 (6.7%)
- Unsure= 14 (5.5%)

Significance Results

I have determined some significant results between respondent's demographic answers and how they answered the regulation/ subsidy questions. The P-value of a variable must be under .05 for the results to be significant. The results are as follows:

Q3: 3MW gas turbine regulation

- Q24 (Global warming is) is significant, with a P-value of .000205.
- Q18 (Age range) is significant, with a P-value of 0.044316.
- Q14 (Education) is significant, with a P-value of 0.017115.

Q4: 3MW gas turbine subsidy

- Q24 (Global warming is) is significant, with a P-value of 0.030347.
- Q19 (Political ideology) is significant, with a P-value of 0.047983.

Q5: Anaerobic digesters regulation

- Q24 (Global warming is) is significant, with a P-value of 0.031358.

Q6: Anaerobic digester subsidy

- Q24 (Global warming is) is significant, with a P-value of 0.013012

Analysis of Results

Table 1 Analysis

Table 1: The Cost, Effectiveness and Efficiency of Each Technology

Industry	Methane Reduction System	Payment per year (Cost) ($)	Methane reductions per year (tons)	Dollars per ton of methane reduction ($)
Natural gas	VRU	14,479	374	39
Landfill	3MW gas turbine	513,428	2,316	222
Livestock farms	5000-ton Anaerobic digesters	131,310	502	262

The payment per year ($), from table 1, is how much it costs each year to purchase and operate each system on average. This tells us how expensive each system is. The payments are in present value terms. The payments are set up to be paid until the end of the average lifetime of each system, at a discounting rate of 2% per year. The average lifetime of VRUs and 3MW gas turbines is 24 years, while 5000-ton anaerobic digesters have an average lifetime of 15 years (Hy-Bon, 2016) (Elsasser, 2006). VRUs are respectively cheap technologies, they cost the least amount of money to install and operate per year. 5000-ton anaerobic digesters are the second cheapest. 3MW gas turbines are respectively expensive and are the third cheapest out of the three technologies above. Typically, cheaper systems are more convenient for use.

Methane reductions per year (tons), from table 1, is the number of tons of methane the average system saves in a year. The more methane that is being reduced from the atmosphere leads to benefits for the environment and human health. It is important to know the size of the reductions, so that you can compare the effectiveness of each system in their abilities to reduce methane emissions. 3MW gas turbines reduce much more methane per year than VRUs or 5000-ton anaerobic digesters. 5000-ton anaerobic digesters reduce the second most methane per year. VRUs reduce relatively little methane, making them the least effective at reducing methane emissions compared to the other two technologies.

Dollars per ton of methane reduction ($), from table 1, tells us the efficiency of each technology. It is the amount of money it costs to reduce one ton of methane through each technology. VRUs are the most efficient way to reduce methane emissions. The dollars per ton of methane reduction for VRUs is less than the social cost of methane, making it a very efficient technology for reducing methane emissions. Landfills are the second most efficient, and livestock farms are the third most efficient in reducing methane emissions of the three technologies. Landfills cost much more per ton of methane reductions than the other technologies, making it a relatively inefficient technology in reducing methane emissions.

Table 2 Analysis

Table 2: Benefits of Each Technology

Industry	Methane Reduction System	Benefit to Producers per year ($)	Social Benefit of Methane per year ($)	Total Benefit per year ($)	Net Benefit per year ($)
Natural gas	VRU	52,378	39,270	91,648	77,169
Landfill	3MW gas turbine	1,865,880	243,180	2,109,060	1,595,632
Livestock farms	5000-ton anaerobic digester	60,900	52,710	113,610	-17,700

The benefits to producers per year ($), from table 2, is how much money the producers make by using each system. VRUs, 3MW gas turbines, and 5000-ton anaerobic digesters all make money by selling electricity produced by the gases that the systems capture. As discussed, each technology can be used to create energy that can be used on-site. The on-site energy usage creates larger benefits to producers for each technology. The average cost of selling energy in a buyback program is estimated to be 6 cents per kWh by the EPA (EPA, 2017). The average cost of buying electricity is estimated to be around 10 cents per kWh (Clarke, 2014). The benefits to producers per year is maximized by each technology when the energy is used on-site. For this study, we will be assuming each technology produces energy to be sold back to energy producers at 6 cents per kWh. On-site usage may include additional costs.

Social benefit of methane reductions per year is equal to $105 per ton of methane reduced (Hope, 2006). The price of methane is a measure of long-term damage done by a ton of methane emissions in each year. This is a comprehensive estimate of climate change damages and includes changes in agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased cost for air conditioning (EPA, 2017). The technologies that can most effectively reduce methane emissions lead to the largest social benefit of methane reductions. Because 3MW gas turbines in landfills reduce the most methane emissions, they also create the largest social benefit. 5000-ton anaerobic digesters reduce methane emissions the second most of the three technologies, therefore they create the second largest social benefit of methane emission reductions per year. Natural gas VRUs reduce the least methane emissions of the three technologies, which leads to the lowest amount of social benefit created through the three technologies.

Total benefit per year is equal to the benefit to producers per year plus the social benefit of methane reductions per year. This gives us the total amount of benefits that are created through using each individual system for one year. These benefits are accomplished throughout the lifespan of the equipment.

The net benefit per year is calculated by subtracting the payment per year from the total benefit per year. The net benefits of all systems outweigh the costs for natural gas VRUs and 3MW gas turbines. 5000-ton anaerobic digesters do not have a positive net benefit. This means that 5000-ton anaerobic digesters are not cost-effective technologies in reducing methane emissions.

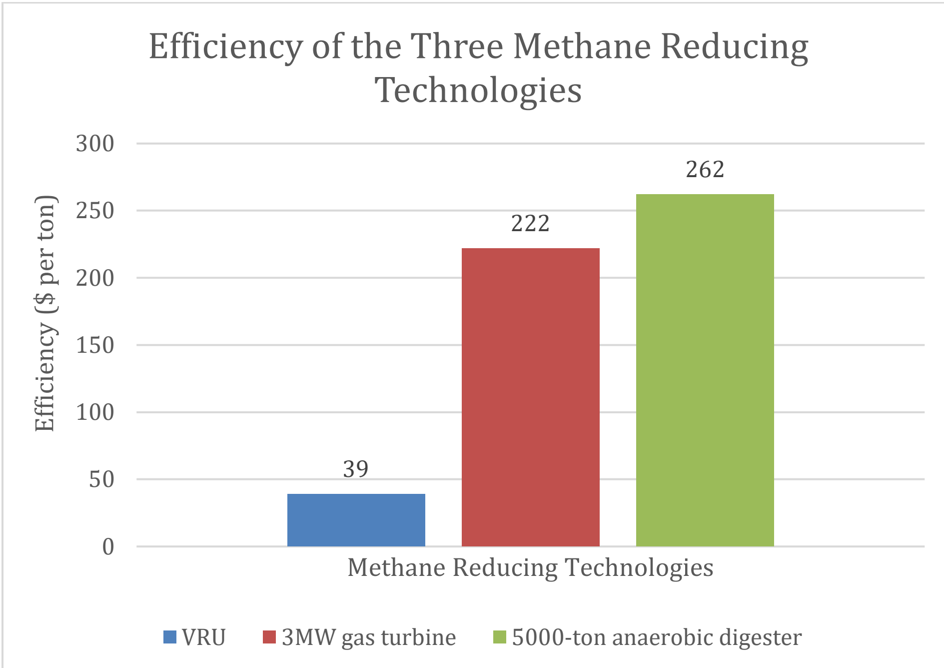
Efficiency

To work most efficiently we are most concerned with finding the technology that provides the lowest hanging fruit for reducing methane emissions per ton. Consult *Graph 1* to have a visual of the most efficient and lowest hanging technology. The lowest hanging fruit is the most viable method for reducing methane emissions to start with. The lowest hanging fruit is the natural gas VRUs. This technology reduces methane emissions at only

39 dollars per ton of methane emissions on average. The cost of reducing methane emissions by using VRUs is less than the social cost of the methane, making the VRUs a very efficient and cost-effective technology.

In a typical industry, as methane reductions increase, the cost of reducing methane will increase as well. When the cost of reducing methane emissions reaches a point where there are other technologies that do so at the same cost or cheaper, the focus will then shift to a cheaper technology. For example, assume every cost presented in *Table 1* does not change, and the benefits in table two do not change. Also assume that natural gas VRUs, landfill 3MW gas turbines, and 5000-ton anaerobic digesters are the only technologies for reducing methane emissions. Here, methane would first be reduced in the natural gas industry through VRUs. VRUs would continue to be used until every natural gas storage tanks use VRUs. The next lowest hanging fruit is landfill 3MW gas turbines. This technology would then be used for reducing methane emissions, until all landfills used 3MW gas turbines. Then, livestock animal farms 5000-ton anaerobic digesters would be used, because they are the highest hanging fruit of the three technology options.

Graph 2: Efficiency of the Three Methane Reducing Technologies



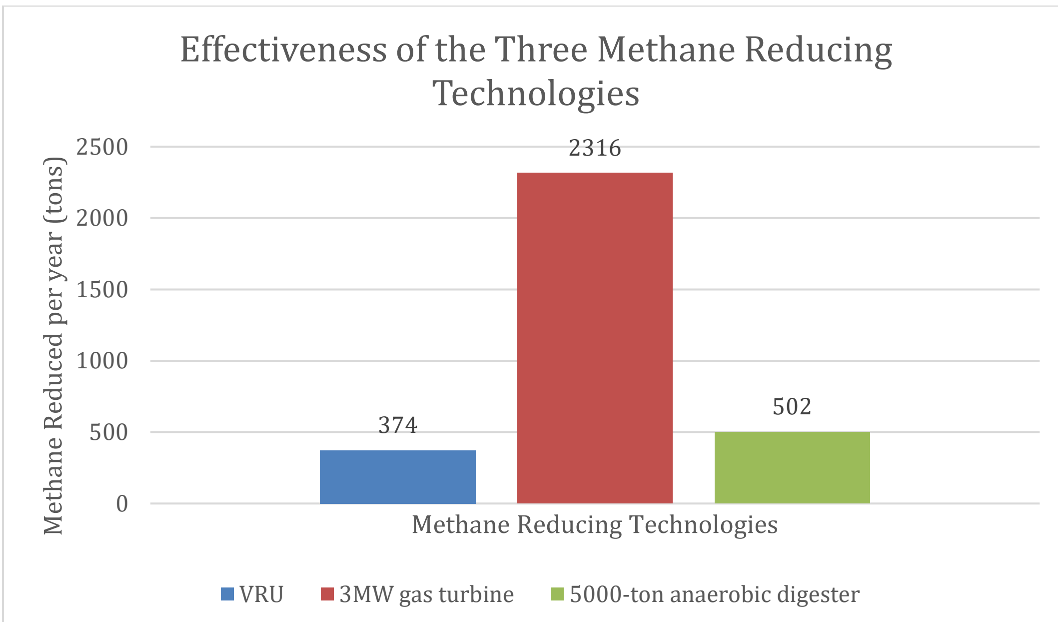
Graph 2: This graph highlights the efficiency of each methane reducing technology.

Effectiveness

Landfill 3MW gas turbines are the most effective technology at reducing methane emissions by a factor of more than four, consult *Graph 3* for a visual on the effectiveness of each technology. We are concerned with reducing as much methane emissions as possible. It is important to note the technologies methane reduction ability, so we can reduce the largest amount of methane being released into the atmosphere. Al though landfill 3MW gas turbines reduce the most methane emissions, this technology may not be the first technology to be used, because it is not quite as efficient in reducing methane emissions as natural gas VRUs. If we were concerned with reducing as much methane emissions per technology landfill 3MW gas turbines would be used. The landfill industry produces 18% of

U.S. methane emissions, while the natural gas and petroleum industry produces 31% of U.S. methane emissions, according to *Figure 2*. This means that the natural gas and petroleum industry has the highest potential to reduce the largest amount of methane emissions through methane reducing technologies.

Graph 3: Effectiveness of the Three Methane Reducing Technologies

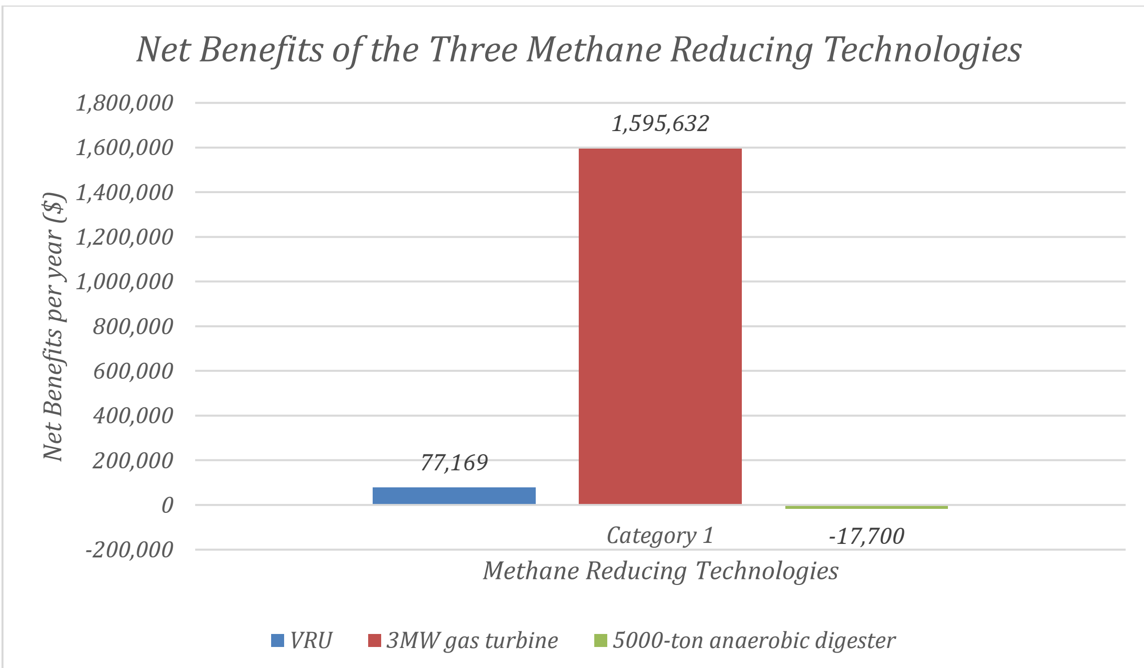


Graph 3: This graph shows the amount of methane reduced per year (tons) for each of the three methane reducing technologies.

Benefits

A technology that creates benefits for producers, the environment, and human health is a sign of a valid technology option. Landfill 3MW gas turbines create more total benefits than the other two technologies by nearly a factor of 20, consult *Graph 4* for a visual of the net benefits of each technology. This technology should be used by landfills on their own. Landfills should not need government encouragement and policy to implement this methane reducing strategy. The massive benefits that a 3MW gas turbine creates a very fast return on investment of the 3MW gas turbine. Businesses are typically concerned about the bottom line. That is, will the technology make money? In the case of landfill 3MW gas turbines, that answer is yes. Natural gas also creates benefits, which help business' bottom lines.

Graph 4: Net Benefits of the Three Methane Reducing Technologies



Graph 4: This graph shows the net benefits per year ($) of each of the three methane reducing technologies.

Survey Results Analysis

The results of the qualifying questions were much lower than I anticipated. This means that the questions were too hard, the information was not presented clearly enough, or the respondents did not take time to read thoroughly through the information before answering the survey questions. Because of the low amount of correct answers, and the inability to determine who answered all three questions correctly, while keeping the data comprehensive, I decided to not focus on the results of the qualifying questions.

The six regulation/ subsidy questions offered interesting results. Overall, the results for each question were similar. But there were intricate differences. For example, respondents preferred to regulate the natural gas industry more than subsidize it. This result comes as expected, because, generally, people believe that the natural gas and oil industry already receives enough subsidies. On average, respondents believed that the landfill industry should have policies put in place on it more than the natural gas or livestock animal farm industries. This result makes sense, since the 3MW gas turbines reduce much more emissions per year compared to vapor recovery units or anaerobic digesters. More respondents thought that the livestock animal farms should receive subsidies than regulations. I was hoping to find these results, because without subsidies, in my model, anaerobic digesters do not create a positive net benefit. Overall, the results seemed consistent with what I was anticipating. But, the results were much more consistent across questions than I expected.

The same number of respondents said that they would most prefer to provide subsidies to the landfill and livestock animal farm industry. I believe people would want to provide subsidies to the landfill industry so that more landfills are encouraged to implement 3MW gas turbines, since they reduce so much methane. The respondents that preferred to provide subsidies to livestock animal farms most likely wanted to help farms reach a positive net benefit. Most people wanted to put regulations on the landfill industry, which makes sense, because it's 3MW gas turbine technology reduces the most methane emissions. Most respondents would prefer that methane is reduced in the landfill industry.

Again, this is probably because of the large amount of methane that 3MW gas turbines reduce.

An interesting finding was that there were no significant results between people's proximity to natural gas plants, landfills, or livestock animal farms and their preferences on any of the other questions. I expected that people that lived close to natural gas plants, landfills or livestock animal farms would prefer to reduce emissions from the source that they live close to. This could be because of a small sample size, or that people don't notice the emissions during their daily lives.

For the demographic questions there were a few very interesting results that stuck out. This was that 84.6% of respondents were female. The large gender gap could provide some insights into the results, as well as cause biases. Another interesting result was that only 65.4% of respondents believe that climate change in due to human activity. I previously thought that more Colorado citizens would think warming is due to human activity. Also, only 63% of respondents said that global warming is a very serious problem. 16.5% said that it is a somewhat serious problem. These percentages added together (79.5%) believe global warming is a problem. This number (79.5%) is much higher than the 65.4% of respondents that think climate change is due to human activity. So, even if the respondents don't believe climate change is due to human activity, they do believe it is a problem.

The main finding of the regressions was that global warming had a very significant impact on how people answered the regulation/ subsidy questions. The global warming question was significant in four out of 6 regulation/ subsidy questions. The results show that people that think global warming is a very serious problem also think that there should be regulations or subsidies for the landfill and livestock animal farm industries. The results were not significant for the natural gas industry (P-value of .06 for VRU regulation). The people that think global warming is not a problem significantly vote to not put regulations or subsidies on any industries. This shows that people that do not believe global warming is a problem, do not want any policies put in place to reduce emissions. There was no significant correlation between respondent's political ideologies and their thoughts on global warming.

From the survey results on their own, it seems that the respondents would prefer that emissions are reduced in the landfill industry most. They would most prefer to regulate the landfill industry. They would want to subsidize the livestock animal farm industry. And the results aren't very clear about how they would want to act on the natural gas industry. So, the natural gas industry would be left as is.

Recommendations

When making recommendations, I must consider the costs, benefits, efficiency, effectiveness, and net benefits of each technology. I must also consider Colorado citizen's preferences that were determined through the survey. To make realistic and appropriate recommendations, I must consider all factors. A policy is not feasible if it doesn't meet economic and social approval.

Natural Gas VRUs

Natural gas VRUs are the most efficient in reducing methane emissions, making VRUs the lowest hanging fruit. VRUs should be used first to reduce methane emissions, because they do so most efficiently. Along with being efficient, they also create net benefits, the cost of the VRUs is outweighed by the benefits they create. The natural gas and petroleum industry is the biggest producer of methane emissions in the U.S., according to the EPA. Natural gas VRUs are the most efficient, create net benefits, and have the largest potential to reduce methane emissions in the U.S. For these reasons, the U.S. government should regulate the usage of VRUs. Every natural gas and crude oil storage tanks should be required to have VRUs installed and used. The producers of natural gas and crude oil would pay for the units, as required by the government. The survey results give strength to this recommendation for natural gas VRUs. The respondents were largely split on how to act upon the natural gas industry, but VRU regulation did receive a 56.5% "yes" vote. Presenting Colorado citizens with more information could help increase this number even more.

Landfill 3MW Gas Turbines

Landfill 3MW gas turbines create the largest methane reductions per technology and create the largest net benefits of the three presented technologies. The 3MW gas turbines in the landfill industry create such large net benefits that landfills should use this technology themselves. There is no need for regulation or subsidies to the landfill industry for the usage of 3MW gas turbines now. Subsidies should not be used to encourage the implementation of this technology. When VRUs are an exhausted resource to reduce methane emissions, then landfill 3MW gas turbines should then be regulated by the government. This should be the case because 3MW gas turbines are already a cost-effective methane reducing technology, therefore no subsidy needs to be provided. Regulation should be used to force landfills to install 3MW gas turbines after VRUs are regulated. The respondents in the survey believed highly that the landfill industry should be regulated, or subsidized, so that 3MW gas turbines are used to reduce methane emissions. I do also believe that methane emissions should be reduced in the landfill industry, but 3MW gas turbines are not as efficient as natural gas VRU units. Therefore, 3MW gas turbines in the landfill industry are not the lowest hanging fruit. The landfill industry should be pressured to implement methane reducing technology by citizens, organizations, and the government. But, I believe it is too early to regulate the landfill industry, there are more efficient reduction technologies to be regulated first. The landfill industry should also not receive a subsidy because there is no need for it. The implementation of 3MW gas turbines already create massive benefits. The subsidy money should be saved for another technology that creates less benefits and is less cost effective.

Livestock Animal Farms Anaerobic Digesters

Livestock animal farms 5000-ton anaerobic digesters produce a variety of benefits, like reduction in methane, additional profit streams, and reduction in smell. Al though they do produce benefits, they do not create net benefits. 5000-ton anaerobic digesters do not help businesses bottom line, so this technology option would be best paired with a subsidy, to even the costs and benefits of the technology. If the subsidies paid the difference between net benefits and 0, the 5000-ton anaerobic digesters would create a net 0 benefit. A net 0 benefit is exactly even between costs and benefits. At zero total net benefit, the livestock animal farms would be able to make a decision on whether to implement anaerobic digesters or not. The decision will depend on farm specifics, and if the farm believes it can gain extra recognition or sales because of their environmentally friendly behavior. 5000-ton anaerobic digesters are the highest hanging fruit of the three technologies presented, so the subsidies paying for this technology should only be used when natural gas VRUs have been added to every natural gas and crude oil storage tanks, 3MW gas turbines added to all landfills, and all other lower hanging fruit options have been exhausted. Colorado citizens largely agree with this recommendation. Al though only 49.6% of respondents voted "yes" to subsidizing anaerobic digesters, that number is much higher than the percentage that voted to regulate them (39.9%). Respondents were also asked, "What industry would you most prefer to provide subsidies to?" For this question, 73 people voted for the landfill industry and 73 people voted for the livestock animal farm industry.

Areas for Further Research

Of course, I could not cover each and every industry technique or technology that is used to reduce methane emissions. It would be beneficial to my research to be able to look into other ways of reducing methane emissions. The costs, benefits, efficiency, and effectiveness of other techniques and technologies could be compared to the ones that I have studied in order to create a more comprehensive analysis of types of methane reduction. It would also be beneficial to be able to look at more individual cases for each technology, and not rely as heavily on the averages. A case study may produce more accurate results, because there are so many variables associated with all three technologies.

It would also be interesting to research if other greenhouse gases have lower abatement cost curves. Carbon dioxide is an intensely studied greenhouse gas, and compared the costs, benefits, efficiency, and effectiveness across different types of greenhouse gases would be largely beneficial to know where to focus.

Appendix

Appendix 1: Survey

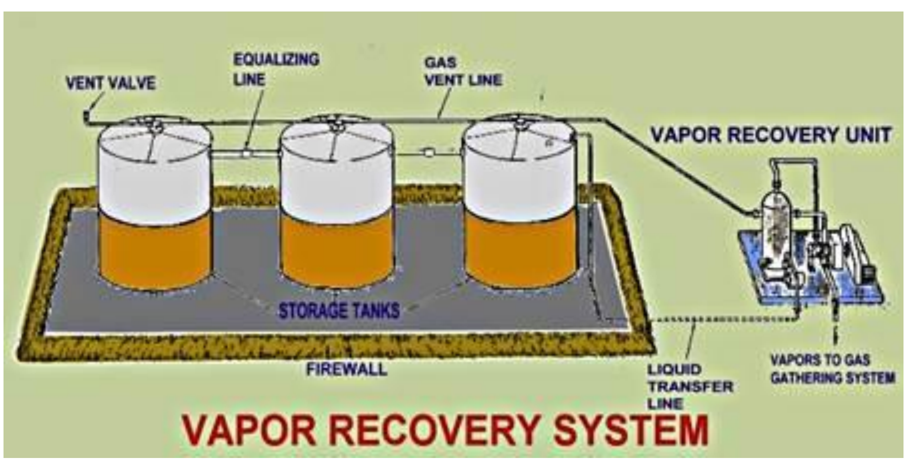
Methane Reducing Technologies Survey

Background Information:
There will be information regarding methane emissions, three methane reducing technologies, and policy options below. You will be asked about which methane reducing technology you prefer. You will also be asked about which policy you prefer.

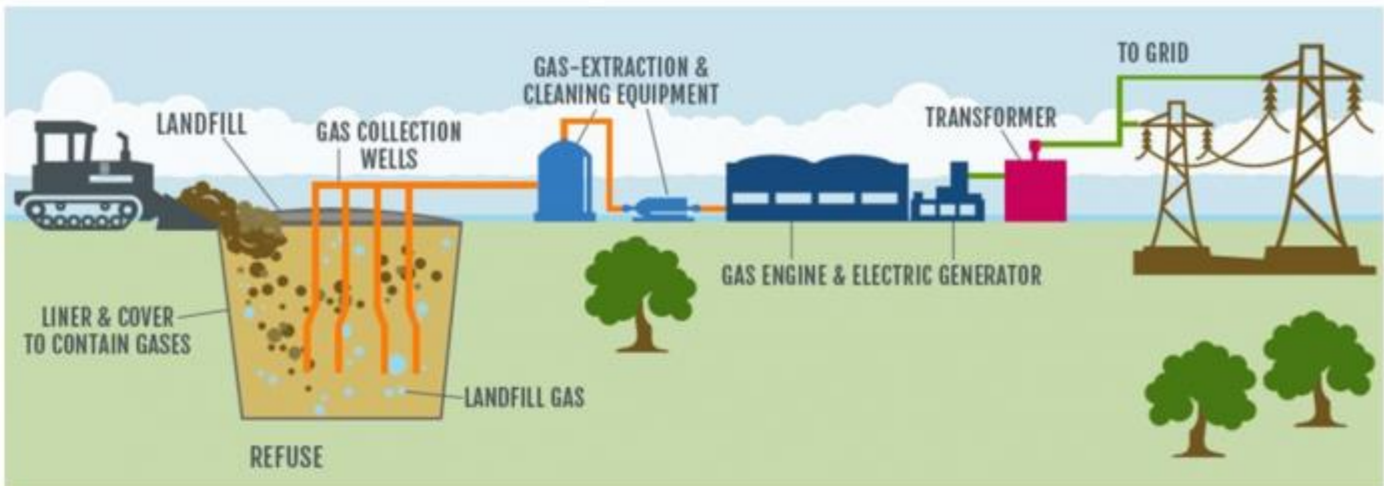
Methane and Climate Change: Methane is a greenhouse gas that is much worse for the environment and human health than the same amount of carbon dioxide (about 25 times worse). In 2015, methane accounted for about 10 percent of all U.S. greenhouse gas emissions from human activities. Methane is estimated to account for about 25% of man made global warming. The signs of global warming are everywhere and are more complex than rising temperatures. The planet is already suffering from some of the impacts of global warming. For example, ice is melting worldwide, species are having to relocate and some are going extinct, the sea level is rising, precipitation (rain and snowfall) has increased across the globe, invasive species are thriving, floods and droughts are more common, and hurricanes and storms are becoming more powerful. As global emissions raise the planet's temperature, the effects of global warming will become more intense and dangerous.

Three Methane Reducing Technologies:

Natural Gas- Vapor Recovery Unit (VRU): After natural gas is extracted from the ground it is put into storage tanks. These storage tanks leak methane gas. VRUs capture the gas that leaks from storage tanks. Once the gas is captured by the VRUs, it is put back into the storage tank when there is room. VRUs make more money for the natural gas producers because they can sell the captured gas. VRUs also reduce methane emissions by capturing the gases before they are released into the air.



Landfills- Gas Utilization: 3 Megawatt (MW) Gas Turbines: Garbage in landfills releases gases when the garbage is decomposing. Methane is one of the gases released. Landfill gas utilization captures the gas that garbage releases and uses it to make useful energy. 3MW (Megawatt) gas turbines turn the landfill gas into energy. Landfills can sell this energy for extra money. This gas is bad for air quality, so capturing it is good for the environment.



Livestock Animal Farms- 5000-ton Anaerobic Digesters: Livestock animals like pigs and cows create a lot of greenhouse gases through their manure. When manure is left in a field it releases methane. One way to reduce methane emissions is to collect the waste and put it into tanks where the waste is broken down by naturally occurring microorganisms. When the waste is broken down it creates a gas that can be used to create heat or power, rather than being released into the air.

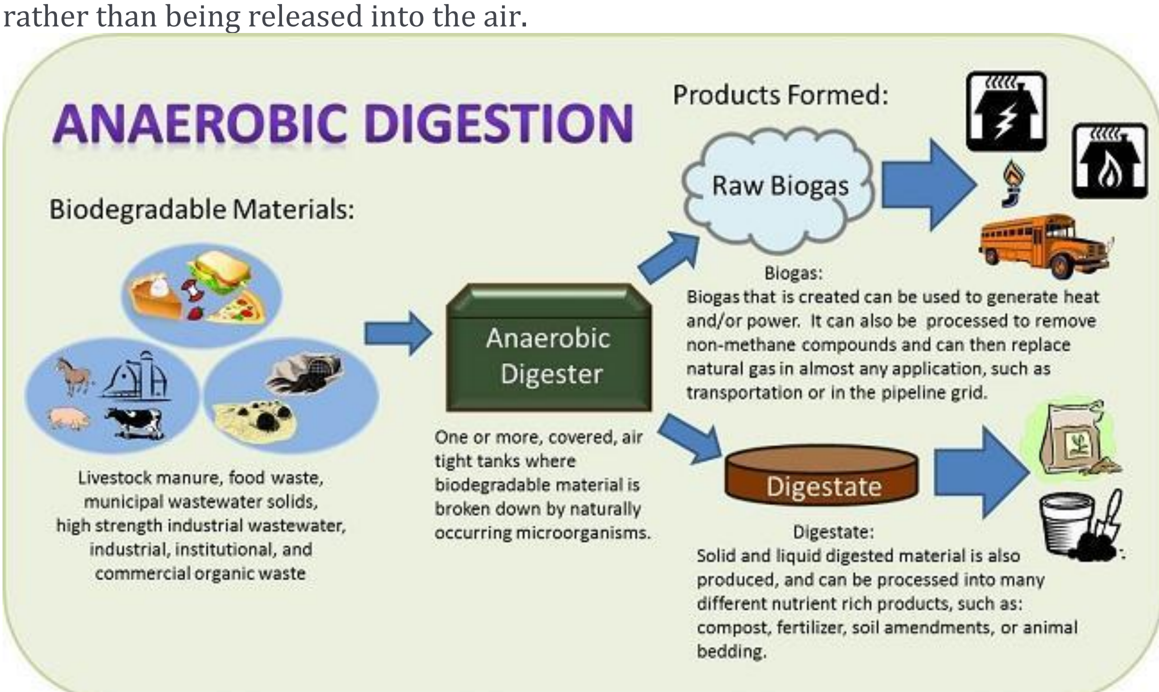


Table 1: Cost, Effectiveness and Efficiency of Each Technology in Reducing Methane Emissions

Industry	Methane Reduction System	Payment per year (Cost) ($)	Methane emissions reductions per year (tons)	Cost per ton of methane emissions reductions ($)
Natural gas	VRU	14,479	202	159
Landfill	3MW gas turbine	513,428	9,652	656
Livestock farms	5000-ton Anaerobic digesters	131,310	753	3,254

Table 1 Analysis:
The payment per year ($) is how much it costs each year to purchase and operate each methane reducing technology on average. This tells us how expensive each system is. Natural gas VRUs are the cheapest. Landfill 3MW gas turbines are the most expensive.

Methane emissions reductions per year (tons) tell us the effectiveness of each technology. It is the number of tons of methane the average system saves from being released into the air each year. Landfill 3MW gas turbines are the most effective in reducing methane emissions. Natural gas VRUs are the least effective in reducing methane emissions.

Dollars per ton of methane emissions reductions ($) tells us the efficiency of each technology. It is the amount of money it costs to reduce one ton of methane through each methane reducing technology. Natural gas VRUs are the most efficient way to reduce methane emissions. Livestock animal farms 5000-ton anaerobic digesters are the least efficient way to reduce methane emissions.

Table 2: Benefits

Industry	Methane Reductio n System	Benefit to producer s per year ($)	Social benefit of methane emissions reductions pe r year ($)	Total benefit per year ($)	Net benefit per year ($)
Natural gas	VRU	212,359	15,439	227,798	213,319

Landfill	3MW gas turbine	1,865,880	1,013,447	2,879,327	2,365,899
Livestock farms	5000-ton anaerobic digester	105,966	79,049	185,015	53,705

Table 2 Analysis:
Benefits to producers per year ($) is how much money the producers make by selling electricity produced by the gases that the technologies capture. Landfill 3MW gas turbines make the most money per year. Livestock animal farms 5000-ton anaerobic digesters make the least amount of money per year.

Social benefit of methane emissions reductions per year ($) is equal to the amount of tons of methane reduced per year multiplied by $105 per ton. The price of methane is a measure of long-term damage done by a ton of methane emissions over its lifetime. Landfill 3MW gas turbines reduce the most methane, therefore they create the most social benefit in methane emissions reductions. Natural gas VRUs reduce the least methane, therefore they create the least social benefit in methane emissions reductions per year.

Total benefit per year ($) is equal to the benefit to producers per year ($) plus the social benefit of methane emissions reductions per year ($). This gives us the total amount of benefit that is created through using each individual system for one year. These benefits are accomplished throughout the lifetime of the equipment. Landfill 3MW gas turbines create the most total benefit per year. Livestock animal farm anaerobic digesters create the least amount of total benefit per year.

Net benefit per year is calculated by subtracting the payment per year (Cost) ($) (from Table 1) from the total benefit per year ($). The net benefits of natural gas VRUs and landfill 3MW gas turbines outweigh the costs; therefore, these two systems are cost-effective at reducing methane. Livestock animal farm 5000-ton anaerobic digesters have a negative net benefit, so they are not a cost-effective technology at reducing methane.

Policy Options:
Policies are used to encourage industries to use the methane reducing technologies just discussed (VRU, landfill gas, anaerobic digesters).

Subsidies: One policy option is for the government to provide a subsidy to businesses that buy and install the relevant technology. A subsidy is where the government helps an industry or business pay for the technology. For the survey, the subsidy will pay for 100% of the cost of purchasing and installing the equipment in each industry. So, the methane reducing technology is free to businesses.

Command and Control Regulations: The second policy option is command and control regulation. Command and control regulations would require businesses to purchase and install the relevant technology. That is to say, command and control regulations would be used to force the businesses to use the methane technologies. The businesses would pay for the methane reducing equipment themselves.

Table 3: Policy Options for Reducing Methane Emissions

Policy	Subsidy	Regulation/ Command and Control
Who Pays:	Government pays	Business pays
Who Benefits:	Benefits everybody	Benefits everybody

Survey Questions

Instructions: Please mark the appropriate box next to your answer choice. Please answer all the questions truthfully and to the best of your ability. All answers are 100% anonymous.

1. Which of the three technologies costs the least to reduce methane emissions per ton (efficiency):

- (●) Natural gas Vapor Recovery Units
- ( ) Landfill 3MW
- ( ) Livestock animal farm anaerobic digesters
- ( ) I am not sure

2. The most net benefit per year comes from which of the three presented technologies:

- ( ) Natural gas Vapor Recovery Units
- ( ) Landfill 3MW gas turbines
- ( ) Livestock animal farm anaerobic digesters
- ( ) I am not sure

3. Which of the three technologies reduces methane emissions the most (effectiveness):

- ( ) Natural gas vapor recovery units
- ( ) Landfill 3MW gas turbines
- ( ) Livestock animal farm anaerobic digesters
- ( ) I am not sure

4. Policy Question: VRU Regulation

Suppose we held a referendum on regulating natural gas producers, requiring them to install VRUs. The businesses would pay for the VRUs. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

5. Policy Question: VRU Subsidy

Suppose we held a referendum on providing subsidies to natural gas producers. The government would pay for the VRUs. The businesses would not pay for the VRUs. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

6. Policy Question: 3MW Gas Turbine Regulation

Suppose we held a referendum on regulating landfills, requiring them to install 3MW gas turbines. The businesses would pay for the turbines. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

7. Policy Question: 3MW Gas Turbine Subsidy

Suppose we held a referendum on providing subsidies to landfills. The government would pay for the 3MW gas turbines. The businesses would not pay for the turbines. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

8. Policy Question: Anaerobic Digesters Regulation

Suppose we held a referendum on regulating livestock animal farms, requiring them to install anaerobic digesters. The businesses would pay for the digesters. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

9. Policy Question: Anaerobic Digesters Subsidy

Suppose we held a referendum on providing subsidies to livestock animal farms. The government would pay for the anaerobic digesters. The businesses would not pay for the digesters. If we held the referendum, how would you vote? Please answer as if this were the *only* decision being made.

- I would vote Yes
- I would vote No
- I am not sure

10. What industry would you most prefer to provide subsidies to?

- Natural gas
- Landfill
- Livestock animal farm
- None of the above
- I am not sure

11. What industry would you most prefer to put regulations on?

- Natural gas
- Landfill
- Livestock animal farm
- None of the above
- I am not sure

12. I would prefer that methane is reduced in the:

- Natural gas industry
- Landfill industry
- Livestock animal industry
- None of the above
- I am not sure

13. I think that the policy option that should be used to reduce methane emissions in the industry I chose in question 12 is:

- Subsidies
- Command and control regulation
- None of the above
- I am not sure

14. Education:

- Less than high school
- High school or GED
- Some college
- 2 year degree
- 4 year degree
- Professional degree
- Doctorate

15. Gender:

- Male
- Female
- Do not wish to identify

16. Ethnicity:

- African American
- African/Black/Caribbean
- Asian/ Pacific Islander
- Caucasian
- Hispanic/Latino
- Native American
- Other

17. What is your income range:

- 0-30,000
- 30,000-60,000
- 60,000-90,000
- 90,000-120,000
- 120,000+

18. What is your age range:

- 0-20
- 20-40
- 40-60
- 60-80
- 80+

19. What is your political ideology:

- Very conservative
- Conservative
- Moderate
- Liberal
- Very liberal
- No opinion

20. I currently live within one mile of a natural gas plant:

- Yes
- No

21. I currently live within one mile of a landfill:

- Yes
- No

22. I currently live within one mile of a livestock animal farm:

- Yes
- No

23. What is your view on climate change:

- Warming is due to human activity
- Warming is due to natural changes
- No solid evidence earth is warming
- I am not sure

24. Global warming is:

- Very serious problem
- Somewhat serious
- Not too serious
- Not a problem
- I am not sure

Bibliography

78 FR 58416, September 23, 2013. The EPA issued final updates to its 2012 VOC performance standards for storage tanks used in crude oil and natural gas production and transmission. The amendments reflected updated information that responded to issues raised in several petitions for reconsideration of the 2012 standards.

Alex Morales. (2010, July 29). Fossil Fuel Subsidies Are Twelve Renewables Support. Bloomberg.

American Biogas Council. (2014). What Is Anaerobic Digestion? www.americanbiogascouncil.org/biogas_what.asp

Amon, T., et al. (2007). Biogas Production form Maize and Dairy Cattle Manure- Influence of Biomass Composition on the Methane Yield. Agriculture, Ecosystems & Environment, 118(1), 173-182.

Aschwanden, C. (2016, February 03). Methane Is Leaking All Over The Place. https://fivethirtyeight.com/features/methane-is-leaking-all-over-the-place/

Bade Shrestha, S.O, et al. (2008). Landfill Gas with Hydrogen Addition a Fuel for SI Engines. Fuel. 87.17/18: 3616-3626.

Bianco, Nicholas. (2014, October 10). World Resources Institute. By the Numbers: How the U.S. Economy Can Benefit from Reducing Greenhouse Gas Emissions. www.wri.org/blog/2014/10/numbers-how-us-economy-can-benefit-reducing-greenhouse-gas-emissions.

Brown, Heather. (2013). Memorandum prepared for Bruce Moore, EPA/OAQPS/SPPD/FIG. Revised Analysis to Determine the Number of Storage Vessels Projected to be Subject to New Source Performance Standards for the Oil and Natural Gas Sector.

Clark. (2014). Anaerobic Digestion What Are the Economics. Marathon Equipment. www.marathonequipment.com/news/2014/08/anaerobic-digestion-what-are-economics

Conley et al. (2016). Methane Emissions from the 2015 Aliso Canyon Blowout in Los Angeles, CA. Science.

Cooperative Institute for Research in Environmental Sciences. (2012, March 01). Colorado Oil and Gas Wells Emit More Pollutants Than Expected. http://cires.colorado.edu/news/colorado-oil-and-gas-wells-emit-more-pollutants-expected

Dorsey, Priccirilli. (2013, April 23). Fact Sheet- Landfill Methane. Environmental and Energy Study Institute. www.eesi.org/papers/view/fact-sheet-landfill-methane

El-Mashad, H., et al. (2010). Biogas Production from Co-digestion of Dairy Manure and Food Waste. Bioresource Technology. 101(11), 4021-4028.

Elsasser, Shaun. (2006, May). Anaerobic Digester Use in Dairy Farms in the United States. UNLV Theses, Dissertations, Professional Papers, and Capstones, University of Nevada Las Vegas, digitalscholarship.unlv.edu/cgi/viewcontent.cgi?article=1323&context=thesesdissertations

Elvidge, C., Zhizhin, M., Baugh, K., Hsu, F., & Ghosh, T. (2015). Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data.

Ge, Mengpin, et al. (2014, November 25). 6 Graphs Explain the World's Top 10 Emitters. World Resource Institute. wri.org/blog/2014/11/6-graphs-explain-world%E2%80%99s-top-10-emitters.

Inside Gov. (2017). 2017 United States Budget Estimate. Rate Limited.

Hanson, R., et al. (1996). Methanotrophic bacteria. Microbiological reviews, 60(2), 439-471.

Hanley, Nick. Jason F. Shogren, and Ben White. (2001). Introduction to Environmental Economics. Oxford University Press, NYC. Global Subsidies Initiative (GSI).

Hofstrand, Don. (2014). Natural Gas and Coal Measurements and Conversions. Iowa State University. www.extension.iastate.edu/agdm/wholefarm/html/c6-89.html

Hope, C. W. (2006). The Marginal Impacts of CO2, CH4, and SF6 Emissions. Climate Policy. http://www.tandfonline.com/doi/abs/10.1080/14693062.2006.9685619

Howarth, R. W. (2014). A Bridge to Nowhere: Methane Emissions and the Greenhouse Gas Footprint of Natural Gas. Energy Science & Engineering. doi:10.1002/ese3.35

Hy-Bon. (2016, February 24). Frequently Asked Questions about Vapor Recovery Units (VRUs). hy-bon.com/blog/faq-about-vapor-recovery-units/

International Panel of Climate Change. (2013). Climate Change 2013: The Physical Science Basis- Summary for Policymakers. Cambridge University Press.

Jewell, W.J., et al. (1997). Evaluation of Anaerobic Digestion Options for Groups of Dairy Upstate New York. Department of Agricultural and Biological Engineering, Cornell University. Ithaca, NY.

Kapalan, P., et al. (2009). Is it Better to Burn or Bury Waste for Clean Electricity Generation? Environmental Science & Technology. 43.6: 1711-1717

Kelly, D. (2009). Subsidies to Industry and the Environment. The National Bureau of Economic Research. http://www.nber.org/papers/w14999

Konschnik, K. E., & Boling, M. K. (2016). Shale Gas Development: A Smart Regulation Framework. Environmental Science & Technology. http://blogs.harvard.edu/environmentallawprogram/files/2014/03/Konschnik-NAS-Shale-Gas-Paper.pdf

Kougias, Panagiotis. (2014) How Much Methane than Can Be Produced per 1 Kg of Cow Manure Using Anaerobic Digestion? ResearchGate. www.researchgate.net/post/How_much_methane_than_can_be_produced_per_1_kg_of_cow_manure_using_anaerobic_digestion

Lassey, K., et al. (2007). Livestock Methane Emission: From the Individual Grazing Animal Through National Inventories to the Global Methane Cycle. Agricultural and forect meterology, 142(2), 120-132.

Lazarus, William. (2015, October 27). Economics of Anaerobic Digesters for Processing Animal Manure. Extension. University of Minnesota.

Lohila, Annalea, et al. (2007). Micrometeorological Measurements of Methane and Carbon Dioxide Fluxes at a Municipal Landfill. Environmental Science & Technology, 41.8 (2007): 2717-2722.

Lorimor, Jeff, et al. (2004). Manure Characteristics. MWPS. msue.anr.msu.edu/uploads/files/ManureCharacteristicsMWPS-18_1.pdf

NASA. (2017, August 10). Climate Change Evidence: How Do We Know? climate.nasa.gov/evidence/

National Climatic Data Center. (2017). Global Climate Change Indicators. National Oceanic and Atmospheric Association. www.ncdc.noaa.gov/monitoring-references/faq/indicators.php

Organization for Economic Co-operation and Development (OECD). (2015). Environmental Taxation.

Organization for Economic Co-operation and Development (OECD). (2015). OECD Inventory of Support Measures for Fossil Fuels 2015. http://www.oecd.org/about/secretary-general/oecd-inventory-of-support-measures-for-fossil-fuels-2015.htm

Phaneuf, Dan. (2005, August 10). Discount Rates for Benefit-Cost Analysis. Environmental Economics. www.env-econ.net/2005/08/discount_rates_.html

Renewable Waste Intelligence. (2013). Business Analysis of Anaerobic Digestion in the USA. www.renewable-waste.com/pdf/AnaerobicDigestionEbrief.pdf.

Powell, Jon T., et al. (2015, September 21). Estimates of Solid Waste Disposal Rates and Reduction Targets for Landfill Gas Emissions. Nature. ISSN 1758-6798. Doi:10.1038/nclimate2804

Richardson, R., Bradford, T., Dejonckheere, S., & Winegarden, W. (2017). Clean Tax Cuts for Green Bonds Charrette Report. Columbia University. Retrieved from http://cleantaxcuts.org/wp-content/uploads/char-rpt-greenbonds-170306.pdf

Ridlington, E., & Rumpler, J. (2013). Fracking by the Numbers: Key Impacts of Dirty Drilling at the State and National Level. Environmental America. http://www.environmentamerica.org/sites/environment/files/reports/EA_FrackingNumbers_scrn.pdf

Romm, J. (2016, February 17). Methane Leaks Erase Climate Benefit of Fracked Gas, Countless Studies Find. https://thinkprogress.org/methane-leaks-erase-climate-benefit-of-fracked-gas-countless-studies-find-8b060b2b395d

Shepstone, T. (2012, April 6). Turning Natural Gas into Water: Hydraulic Fracturing Doesn't Deplete Water Supplies. https://energyindepth.org/marcellus/turning-natural-gas-into-water-hydraulic-fracturing-doesnt-deplete-water-supplies-2/

Shindell, D. T., et al. (2017, January 25). The Social Cost of Methane: Theory and Applications. Faraday Discussions, The Royal Society of Chemistry. pubs.rsc.org/-/content/articlelanding/2017/fd/c7fd00009j/unauth#!divAbstract

Simon-Lewis, Alexandra. (2017, November 7). What Is the Paris Climate Agreement and Who Has Signed It" WIRED, WIRED UK. www.wired.co.uk/article/what-is-paris-agreement-on-climate-change

Tollefson, Jeff. (2012, February 7). Air Sampling Reveals High Emissions from Gas Field: Methane Leaks During Production May Offset Climate Benefits of Natural Gas. Nature.

Transportation and Climate Division Office of Transportation and Air Quality U.S. Environmental Protection Agency. (2012). National Clean Diesel Rebate Program. https://permanent.access.gpo.gov/gpo57556/420r12029.pdf

Turner, A., Et al. (2016). A Large Increase in U.S. Methane Emissions Over the Past Decade Inferred from Satellite Data and Surface Observations. AGU Publications. http://onlinelibrary.wiley.com/doi/10.1002/2016GL067987/abstract

United States Department of Agriculture and Natural Resources Conservation Service. (2007, October). An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities. directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22533.wba+

United States Department of Labor https://www.osha.gov/SLTC/etools/oilandgas/glossary_of_terms/glossary_of_terms_b.html

Urban, W, et al. (2009). Catalytically Upgraded Landfill Gas as a Cost-effective Alternative for Fuel Cells." Journal of Power Sources, 193.1: 359-366.

U.S. Energy Information Administration. Carbon Dioxide Uncontrolled Emission Factors. https://www.eia.gov/electricity/annual/html/epa_a_03.html

U.S. Energy Information Administration. (2008, December). Office of Oil & Gas, Natural Gas Division Gas, Gas Transportation Information System.

U.S. Environmental Defense Fund. (2017). Aliso Canyon Leak Sheds Light on National Problem. https://www.edf.org/climate/aliso-canyon-leak-sheds-light-national-problem

U.S. Environmental Defense Fund. (2012, April). The climate impacts of methane emissions. https://www.edf.org/energy/methaneleakage

U.S. Environmental Defense Fund. (2016). Methane: The other important greenhouse gas. Retrieved from https://www.edf.org/methane-other-important-greenhouse-gas

U.S. Energy Information Administration. (2017, November 7). How Much Electricity Does an American Home Use? www.eia.gov/tools/faqs/faq.php?id=97&t=3

U.S. Energy Information Administration. (2016, March 16). Natural Gas Expected to Surpass Coal in Mix of Fuel Used for U.S. Power Generation in 2016. Today in Energy. www.eia.gov/todayinenergy/detail.php?id=25392

U.S. Energy Information Administration. (2017, November 30). U.S. Natural Gas Wellhead Price (Dollars per Thousand Cubic Feet). www.eia.gov/dnav/ng/hist/n9190us3m.htm

U.S. Environmental Protection Agency. (2008, September). Adapting Boilers to Utilize Landfill Gas: An Environmentally and Economically Beneficial Opportunity.

U.S. Environmental Protection Agency. (2017, September 5). AgSTAR: Biogas Recovery in the Agriculture Sector. www.epa.gov/agstar.

U.S. Environmental Protection Agency. (2016, December 17). Climate Change Indicators: U.S. Greenhouse Gas Emissions. www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions

U.S. Environmental Protection Agency. (2017, November 29). Coalbed Methane Outreach Program (CMOP). www.epa.gov/cmop.

U.S. Environmental Protection Agency. (2017, April 17). Economic Incentives. https://www.epa.gov/environmental-economics/economic-incentives#subsidies

U.S. Environmental Protection Agency. (2017, November 16). EPA's Voluntary Methane Programs for the Oil and Natural Gas Industry. www.epa.gov/natural-gas-star-program

U.S. Environmental Protection Agency. (2008, November). Fueling the Economy and a Sustainable Energy Future While Improving the Environment.

U.S. Environmental Protection Agency. (2017, April 17). Household Energy Use in Colorado. U.S. Energy Information Administration.

U.S. Environmental Protection Agency. (2017, November 30). Landfill Methane Outreach Program (LMOP). www.epa.gov/lmop

U.S. Environmental Protection Agency. (2017, April 14). Overview of Greenhouse Gases. www.epa.gov/ghgemissions/overview-greenhouse-gases#methane

U.S. Environmental Protection Agency. (2017, January 9). The Social Costs of Carbon. 19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html

U.S. Environmental Protection Agency. (2017, January 09). The Process of Hydraulic Fracturing. https://www.epa.gov/hydraulicfracturing/process-hydraulic-fracturing

U.S. Environmental Protection Agency Office of Air and Radiation Office of Air Quality Planning and Standards. (2016). Control Techniques Guidelines for the Oil and Natural Gas Industry. https://www.epa.gov/sites/production/files/2016-10/documents/2016-ctg-oil-and-gas.pdf .

U.S. Environmental Protection Agency. (2006, October). Lessons Learned from Natural Gas STAR Partners. Installing Vapor Recovery Units on Storage Tanks. Natural Gas STAR Program.

U.S. Environmental Protection Agency. (2011). AP 42, Fifth Edition, Volume I, Chapter 13.5 Industrial Flares. Office of Air Quality Planning & Standards. 1991. UNEP. Towards an Action Plan for Near-term Climate Protection and Clean Air Benefits. UNEP Science-policy Brief. 17pp.

Weishar, Lee. (2013, November 1). The 5 Laws of Decline – (#4) The Law of Diminishing Returns. Leadership to Freedom. leadershiptofreedom.com/2013/11/01/the-5-laws-of-decline-4-the-law-of-diminishing-returns/

Wigley, T.M.L. (2011). Climate Change 108: 601. doi:10.1007/s10584-011-0217-3

World Resources Institute. (2016). Understanding the IPCC Reports. www.wri.org/ipcc-infographics

Yager, D. (2015, November 12). Is the Oil Industry Really Subsidized? http://oilprice.com/Energy/Energy-General/Is-The-Oil-Industry-Really-Subsidized.html