Sustainability Benefits of Valorizing Associated Flare Gas for the Production of Transportation Fuels

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Sustainability Benefits of Valorizing Associated Flare Gas for the Production of Transportation Fuels

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A Thesis in the Field of Sustainability
for the Degree of Master of Liberal Arts in Extension Studies

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Abstract

Associated gas is a form of natural gas primarily comprised of methane. The gas is released when the crude oil is extracted from the ground. However, the collection and aggregation of this associated gas for commercial applications has mainly been cost-prohibitive. Thus, drillers usually combust this associated gas (known as flaring) as an act of economic expediency. The global gas flaring has been hovering around 150 billion cubic meters annually for the last quarter-century, equivalent to Sub-Saharan Africa's total annual gas consumption in 2019.

Gas flaring contributes to global warming and climate change, with more than 400 million tons of CO_2 equivalent emissions every year, approximately 1% of anthropogenic carbon dioxide emissions globally. Gas flaring also emits air pollutants that are detrimental to human health. For instance, fine particulate matter particles (i.e., $PM_{2.5}$) can travel and penetrate deeply into the respiratory tract and therefore constitute a risk for health by increasing mortality from respiratory infections and diseases, lung cancer, and selected cardiovascular diseases. Furthermore, gas flaring has also been a significant waste of fossil energy, an unsustainable natural resource.

Therefore, this study aims to demonstrate that, instead of flaring, associated gas utilization by directly converting associated flare gas to transportation fuels at wellheads can be an attractive approach to mitigate climate change, decrease fossil resource depletion, and improve environmental well-being.

This study adopted a holistic approach to investigate the three core aspects of sustainability to quantify benefits: economic, environmental, and social. Specifically, methods combined various analyses, including cost-benefit analysis, life cycle assessment, and climate and health benefits assessment. Some critical data needed were gas flaring volume, capital costs, operating costs, emission factors, social cost of carbon, ambient air pollution attributable mortality rates, and population. In addition, the study also considered the impact of geographical differences on these benefits by comparing the United States, Russia, Nigeria, and China.

The results from this study provided a complete picture of the sustainability benefits of using associated gas for the production of transportation fuels. The benefits for valorizing one billion cubic meters of associated gas at wellheads were determined to be 1) economic—between \$209 million (Nigeria) and \$639 million (China); 2) climate—2.05 million metric ton CO_2 equivalent averted (all countries); and 3) health—between 25 (the United States) and 461 (Russia) avoided mortality. The potential combined economic, climate, and health benefits present a three-in-one value proposition that can persuade the industry to switch from gas flaring to liquid fuel production and provide regulators guidance to set policies that favor associated gas utilization. Additionally, the results confirmed that countries that are more polluted and higher in mortality rates could potentially reap more significant health benefits due to converting associated gas to liquid fuels. In terms of avoided mortality, the potential benefits could help convince international financial institutions such as the World Bank to provide low-interest loans and grants to support the construction of small-scale facilities to valorize associated gas to produce transportation fuels.

Dedication

“He who has a *why* to live for can bear almost any *how*.”

Friedrich Nietzsche (1844 – 1900)

I dedicate this thesis to my parents, of course.

I also dedicate this work to my wife and children. They witnessed my enthusiasm and passion in the field of sustainability and constantly put up with my seemingly perpetual restlessness throughout the journey of this worthy endeavor.

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Acronyms and Abbreviations

BAU: business-as-usual

bbl: 42-gallon barrel

bcm: billion cubic meters

BCR: benefit-cost ratio

CAP: criteria air pollutants

CI: confidence interval

CO2e: carbon dioxide equivalent

CRF: capital recovery factor

CSCC: country-level social cost of carbon

C_v: coefficient of variation

CVD: cardiovascular diseases

DALYs: disability-adjusted life years

DQI: data quality index

Eq: equivalent

FCI: fixed capital investment

FOC: fixed operating cost

GGE: gasoline gallon equivalent

GGFR: the World Bank's Global Gas Flaring Reduction Partnership

GHG: greenhouse gas

GNI: gross national income per capita

GSD: geometric standard deviation

GTL: gas-to-liquids

GWP: global warming potential

iF: intake fraction, the ratio of the mass of a pollutant inhaled or ingested to the mass of the pollutant emitted

LCA: life cycle assessment

LHV: lower heating value

HHV: higher heating value

MCC: mortality cost of carbon

MMSCFD: million standard cubic feet per day

Mt: million metric ton

NOAA: the US National Oceanic and Atmospheric Administration

PM_{10}: particulate matter with diameters that are 10 micrometers and smaller

$PM_{2.5}$: particulate matter with diameters that are 2.5 micrometers or less

ROI: return on investment

SCC: social cost of carbon

scf: standard cubic feet

TCI: total capital investment

TDC: total direct cost

TIC: total installed cost

tCO_2: a metric ton of CO_2

USD: the US dollars

VOC: volatile organic compounds

VMR: value of mortality risk

VSL: the value of a statistical life

WTW: well-to-wheel

Chapter I

Introduction

There are ample unrealized opportunities to enable the low carbon transition and mitigate climate change and other sustainability challenges with fossil energy. Waste-to-energy is one example of such an opportunity. The waste here refers to the associated flare gas at wellheads. The global gas flaring has been hovering around 150 billion cubic meters (bcm) annually for the last quarter-century (GGFR, 2020a). Today, associated gas is still mainly flared in the oil industry for reasons such as technical challenges, the absence of regulations on gas flaring, or economic constraints (Elvidge et al., 2018). Gas flaring generates greenhouse gas and other air emissions and represents potential economic opportunity loss. Moreover, emissions from gas flaring cause respiratory-related and other diseases and trigger hundreds of millions of dollars in health costs and various environmental impacts (Blundell & Kokoza, 2020; Nwosisi et al., 2021; Soltanieh et al., 2016).

Associated gas utilization can be an attractive approach to mitigating climate change, such as directly converting flare gas to transportation fuels at wellheads. Associated gas utilization involves tapping into the energy and economic resource that would otherwise be wasted by flaring—the valorization (i.e., making something "worthless" to something with monetary value). The potential extra revenue incurred can be especially impactful in the local economy of countries with a relatively low gross national income (GNI) per capita. Of course, the feasibility of associated gas utilization will be contingent upon its economic value proposition.

In addition to the potential economic benefit, associated gas utilization will reduce air emissions (i.e., greenhouse gas and criteria air pollutant emissions). For example, conventional gasoline and diesel displacement with associated gas-derived synthetic fuels exhibit lower transportation life cycle emissions (Tan et al., 2018). This reduction in greenhouse gas emissions can help fight global warming and mitigate climate change. Further, minimizing air pollutant emissions can provide health benefits and save lives. Ambient air pollution is linked to numerous adverse health effects (Brauer et al., 2012), such as premature death in people with heart or lung disease (Dockery, 2009). There is also a direct correlation between air pollution and mortality rates. Exposure to airborne particulate matter with aerodynamic diameters less than or equal to 2.5 μm ($PM_{2.5}$) could increase morbidity and death resulting from cardiovascular disease (CVD) (Feng et al., 2021; Guo et al., 2021). Therefore, gas flaring countries with relatively high air pollution can significantly benefit from air emission reduction through associated gas utilization from the environmental and health-benefit perspectives.

Research Significance and Objectives

The significance of this study is it adopted a holistic approach to investigate the three core aspects of sustainability (namely, economic, environmental, and social) associated with the valorization of associated gas for the production of transportation fuels. In addition, the study also considered the impact of geographical differences on these benefits. Combining all these elements to evaluate the proposed associated flare gas utilization approach will allow the stakeholders (e.g., petroleum industry, governments, and regulators) to see the gas flaring practice differently (i.e., as new opportunities).

The main objectives of this study were:

- To provide a complete picture of the sustainability benefits, that is, the three-in-one value proposition, that may stimulate an interest in the industry to switch from gas flaring to liquid fuel production.
- To quantify and assess the sustainability benefits of utilizing associated gas for the production of transportation fuels, including performing a cost-benefit analysis, carrying out life-cycle assessment (LCA) comparisons, quantifying the averted emissions, and assessing the environmental impacts.
- To determine if countries that are more polluted, higher in mortality rates, and lower in gross national income (GNI) per capita will reap more significant health benefits due to converting associated gas to liquid fuels.

Background

Energy consumption underpins every facet of the global economy and modern life. Energy production and end-use generate large environmental footprints, causing substantial detrimental effects on the environment. Significant environmental sustainability consequences are climate change, resource depletion, and ecosystem and human health damages. For example, increased greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), in the atmosphere can trap more heat from the sun via the greenhouse effect (Feldman et al., 2015). This greenhouse gas effect leads to an increase in global temperature and causes climate change, as evidenced by rising sea levels and increased extreme weather events (IPCC, 2014).

In 2014 the US transportation sector alone contributed 1,815 million metric tons (or 33%) of the total energy-related CO_2 emissions (U.S. Department of Energy, 2015).

In addition to GHG emissions, the combustion of fuels in power plants and vehicle operations also emits criteria air pollutants. Criteria air pollutants include particulate matter (PM), sulfur oxides (SOx), and nitrogen oxides (NOx). For instance, a gasoline vehicle operation can emit 0.026 g/MJ of NOx, 0.005 g/MJ of PM_{10}, and 0.002 g/MJ of $PM_{2.5}$ in the US (Argonne National Laboratory, 2020). Similarly, a conventional and low-sulfur diesel vehicle operation in the United States can emit 0.035 g/MJ of NOx, 0.006 g/MJ of PM_{10}, and 0.003 g/MJ of $PM_{2.5}$. Moreover, there is an association between these air pollutants and human health. An increase of 10 $\mu g/m^3$ in $PM_{2.5}$ concentration (including primary $PM_{2.5}$ and secondary $PM_{2.5}$ from precursors such as SOx and NOx) could potentially increase the overall cardiovascular mortality by 9% (Dockery et al., 1993).

Fossil fuels like coal, natural gas, and crude petroleum oils will continue to be the primary energy source for the foreseeable future. For example, fossil fuels supplied 83% of US energy in 2014 (U.S. Department of Energy, 2015). In the same year, the transportation sector accounted for 27% of the total energy supply, of which 95% came from fossil fuels (92% from petroleum products and 3% from natural gas). The US domestic fossil energy production and consumption will continue to grow (U.S. Energy Information Administration (EIA), 2020a). Unfortunately, fossil fuels are not renewable. Their reserves will inevitably diminish over time, though their diminishing rates will depend on multiple factors, including world consumption and fossil fuel price (Shafiee & Topal, 2009). Overall, slowing down net fossil fuel depletion is also a sustainability challenge.

Opportunities exist within the fossil energy system to contain its environmental sustainability challenges. One leverage point to intervene in our largely petroleum-driven economy is to alter the associated flare gas's fate, considered a "waste" in the oil and gas industry. The utilization of associated gas to produce transportation fuels is one such opportunity to alleviate fossil fuel depletion, enable the low carbon transition, and mitigate climate change.

Associated Flare Gas

Associated flare gas is a form of natural gas primarily comprised of methane. The gas is co-produced when the crude oil is extracted from the ground. However, the collection and aggregation of this associated gas for commercial applications has mainly been cost-prohibitive. Thus, drillers usually combust (known as flaring) this associated gas, as illustrated in Figure 1. In 2019, global gas flaring was 150 billion cubic meters

Figure 1. Associated gas flaring at an oil field.
Source: (Collins & Adams-Heard, 2019).

(bcm), equivalent to Sub-Saharan Africa's total annual gas consumption (GGFR, 2020a). About 45% comes from Russia (23.21 bcm), Iraq (17.91 bcm), the United States (17.29 bcm), and Iran (13.78 bcm), the top four gas flaring countries (Figure 2). Moreover, the oil boom, enabled by hydraulic fracturing (also known as fracking), led to a 23% increase in the US gas flaring volume between 2018 and 2019. This increase in flaring was primarily attributed to the rapid expansion of oil production, which likely outpaced the construction and deployment of pipelines and ancillary systems to transport associated gas from oil wells to market (Caulton et al., 2014).

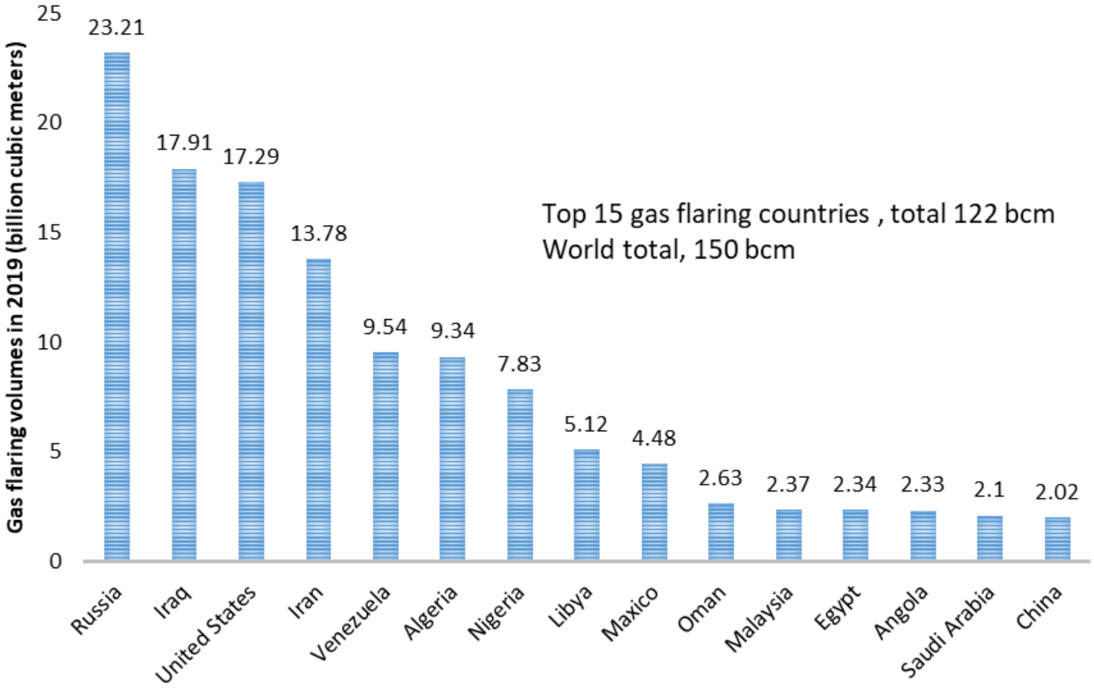


Figure 2. Gas flaring volumes for the top 15 countries in 2019.
Created with data from (GGFR, 2020a).

Note that there are three types of gas flaring: downstream flaring of the oil and gas refineries and petrochemical complex, upstream flaring of the associated gas from oil wells, and industrial flaring at coal mines, landfills, etc. (Comodi et al., 2016; Elvidge et al., 2018; Nezhadfard & Khalili-Garakani, 2020). The most important source is upstream flaring of associated gas from oil wells, which makes up about 90% of all flaring (Elvidge et al., 2018).

Resource and Economic Opportunity Loss

Due to a high depletion rate in oil production, many wells are often drilled over a large area during a short time, and it is not economically viable to plan the appropriate infrastructure for the commercialization of associated gas (Tan et al., 2018). Therefore, associated gas flaring has inevitably been an act of economic expediency (Schade, 2020). Consequently, global gas flaring has been a significant waste of a valuable fossil resource and a tremendous amount of energy (Nezhadfard & Khalili-Garakani, 2020). For example, in 2018, flaring wasted $750 million worth of natural gas in the US Permian Basin alone (Chapa, 2020). Hence, gas flaring is readily a resource and economic opportunity loss.

Flare Gas Recovery and Utilization

Various methods of flare gas recovery and utilization technologies and options have been explored, such as associated gas injection into oil wells for enhanced oil recovery (EOR) or pipelines, liquefied natural gas (LNG), gas-to-liquid production, gas-to-methanol, and other chemicals (e.g., ethylene, dimethyl-ether (DME), ammonia, etc.), electricity generation with a gas turbine or solid oxide fuel cell, and compressed natural gas (Bauer et al., 2012; GGFR, 2004; Khalili-Garakani et al., 2021; Mousavi et al., 2020; Nezhadfard & Khalili-Garakani, 2020; Nwaoha & Wood, 2014; Odumugbo, 2010; Rahimpour et al., 2012; Saidi et al., 2014).

There are also a limited number of commercial success examples. Haldor Topsoe recently completed and commissioned a world-scale gas-to-gasoline plant in Ashgabat, Turkmenistan, based on TIGAS technology. This plant converts about 160 million standard cubic feet per day (MMSCFD) of associated gas into 15,500 barrels per day (bpd) of high octane gasoline (GGFR, 2020c). Pioneer Energy (Denver, CO) has numerous commercial operations. Also, it has a broad, fully integrated portfolio of flare gas monetization, converting flare gas to LNG, methanol, and dimethyl ether (DME), with a scale ranging from 1 MMSCFD (mini) to 100+ MMSCFD (world-scale) (GGFR, 2020c). Still, associated gas is mainly flared in the oil industry due to technical challenges and economic constraints (Elvidge et al., 2018). Besides, regulators would rather have drillers flaring associated gas instead of venting it. The reason for this practice is that methane released from venting has significantly higher global warming potential than the carbon dioxide emitted due to flaring (U.S. Energy Information Administration (EIA), 2020b).

Gas Flaring Environmental and Health Impacts

Associated gas flaring generates two types of pollutants: global greenhouse gas emissions and local air pollution (Agerton et al., 2020). Local air pollution includes criteria air pollutants, such as particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NOx), which are known to be detrimental to human health.

Gas flaring contributed approximately 1% of anthropogenic carbon dioxide emissions globally (Schade, 2020). Global gas flaring has resulted in more than 400 million tons of CO_2 equivalent emissions every year (GGFR, 2020a). For instance, the global warming potential (GWP) over a 100-year horizon for capturing one metric ton (t) of associated gas (i.e., displacing natural gas as a form of utilization) is 2.74 tCO_2, compared to 5.49 tCO_2 for flaring or 36.74 tCO_2 for venting (Calel & Mahdavi, 2020). The utilization of associated gas via combined heat and power (CHP) or heat boilers, by displacing marginal production of heat and electricity instead of flaring, can significantly reduce life cycle greenhouse gas (GHG) emissions by about 319% or 123%, respectively (Rajović et al., 2016). Further, the life cycle GHG emissions for the synthetic fuels derived from associated gas at oil wells could exceed by more than half compared to conventional petroleum fuels (Tan et al., 2018).

Besides GHG emissions, criteria pollutant emissions and various environmental impacts of gas flaring have been reported (Soltanieh et al., 2016). For example, strong associations existed between air pollutants and respiratory and dermal diseases (Nwosisi et al., 2021). A 1% increase in the amount of flared natural gas in North Dakota increased the respiratory-related hospital visitation rate by 0.0012 (0.7%) (Blundell & Kokoza, 2020). The resulting health costs were $400 million (in U.S. dollars) from 2007 to 2015, at roughly $30,000/t for SO_2, $25,000/t for $PM_{2.5}$, $5,500/t for NOx, $1,200/t for volatile organic compounds (VOCs), and $17/t for CO (Blundell & Kokoza, 2020).

Using associated flare gas to produce transportation fuels can potentially lower air emissions and benefit the environment. A 20 vol% of the synthetic fuel blended with petroleum diesel could have noticeably reduced criteria air pollutant emissions: PM (-18%), CO (-24%), and NOx (-5.5%) from 1996 to 2015 diesel vehicles compared to petroleum diesel (Tan et al., 2018). Still, there is virtually no report in the recent literature on the health benefits associated with the averted local pollutant emissions (such as $PM_{2.5}$

and SO_2) in terms of avoided premature deaths from cardiovascular disease and lung cancer and the value for a statistical life saved.

Global Ambient Air Pollution and Mortality Rates

Ambient air pollution results from emissions from industrial activity (e.g., gas flaring) and vehicle exhaust consists of pollutants that are harmful to health (World Health Organization (WHO), 2018). Of all these pollutants, fine particulate matter has the most significant effect on human health. These particles can travel and penetrate deeply into the respiratory tract and therefore constitute a risk for health by increasing mortality from respiratory infections and diseases, lung cancer, and selected cardiovascular diseases (World Health Organization (WHO), 2021). As evident in Figure 3, the extent of ambient air pollution varies noticeably from country to country. For example, the 2016 annual mean $PM_{2.5}$ concentration for the United States was 7.4 $\mu g/m^3$, compared to 61.73 $\mu g/m^3$ (about 8.3 times higher) for Nigeria.

Similarly, the mortality rate attributed to ambient air pollution varies spatially, as shown in Figure 4. The corresponding death rate for the US and Nigeria is 24.07 and 75.57 per 100,000 people, respectively. Therefore, assessing the environmental and health benefits of the globally associated gas valorization to produce transportation fuels should consider geographical differences.

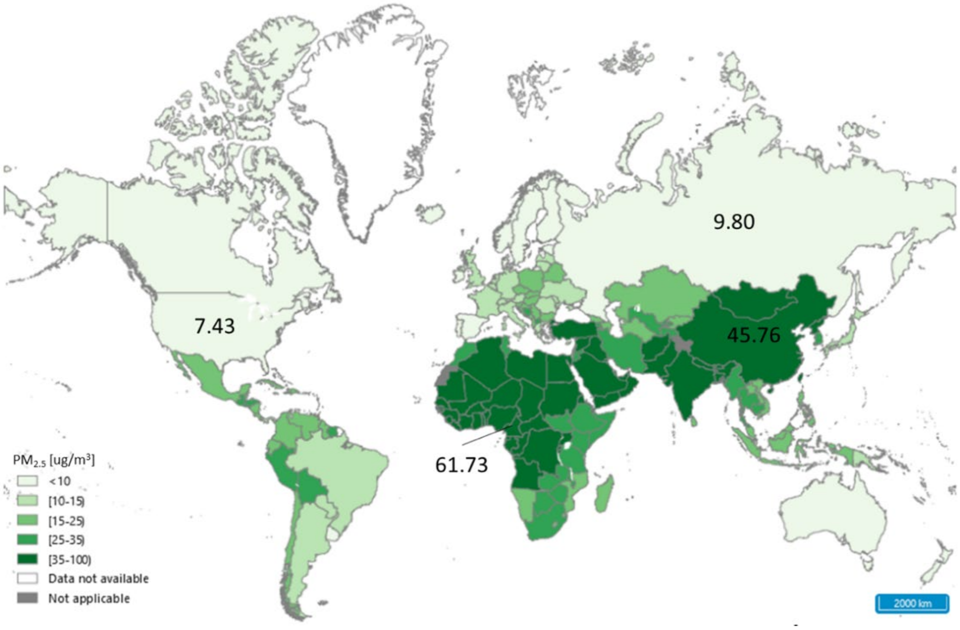


Figure 3. Concentration of fine particulate matter (PM$_{2.5}$ in µg/m^3) in countries.
Source: (World Health Organization (WHO), 2021). Values for the selected countries are added to the original figure.

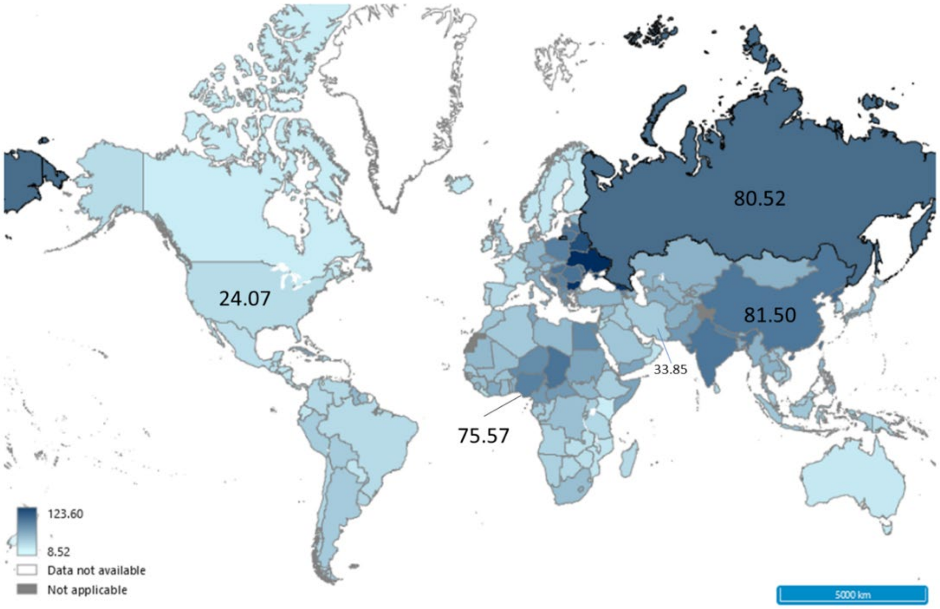


Figure 4. Ambient air pollution attributable death (per 100,000 population).
Source: (World Health Organization (WHO), 2018). Values for the selected countries are added to the original figure.

Gas-to-Liquids (GTL) Technology

On-site utilization of associated flare gas to produce transportation fuels necessitates reliable and cost-effective technologies to convert flare gas to fuel at wellheads. Gas-to-liquids (GTL) can potentially be the technology of choice for converting associated gas to liquid fuels. The GTL process includes two primary operations: converting associate gas to synthesis gas, or “syngas,” via steam reforming or autothermal reforming followed by a Fischer-Tropsch (FT) synthesis process. Syngas is a fuel mixture consisting primarily of hydrogen and carbon monoxide. FT synthesis is a catalytic conversion step that converts syngas into a mixture of reaction products which could be refined to synthetic fuels, lubricants, and petrochemicals (Sahir et al., 2019). One of the essential advantages that the FT process offers is its capability of producing liquid hydrocarbon fuels directly from syngas, which are nearly free from sulfur and relatively low in aromatic content. Reduced sulfur content and aromatic content are two fuel properties essential for clean combustion (Hosseini et al., 2010). Aromatics are responsible for higher NOx emissions in conventional diesel engines because they produce higher combustion temperatures (Jeihouni, Pischinger, Ruhkamp, & Koerfer, 2011).

Furthermore, GTL plants have four size categories (gas feed-rate in million standard cubic feet per day [MMSCFD]/production rate in barrels per day [bpd]): world-scale (>100MMSCFD/>10,000bpd), small-scale (~>10MMSCFD/>1000bpd), mini-GTL (~/> 1MMSCFD/>100bpd, and micro-GTL (~/>0.1MMSCFD/>10bpd), in which 0.01MMSCF of gas yields ~1bbl of oil/diesel/gasoline (GGFR, 2019). Traditional GTL plants are world-scale which are built to process substantial amounts of gas, thereby producing over 30 thousand barrels of fuels per day (Lipski, 2013). This design feature would be a challenge for associated gas utilization as it would necessitate gathering gas from a large number of wells (hundreds or even thousands) required for a large-scale GTL plant. Additionally, it would require building gas collection facilities at the oilfields and constructing an extensive pipeline network to carry the gas to the GTL facility (Rahimpour et al., 2012).

Planning the appropriate infrastructure is an expensive proposition for the commercialization of associated gas (Tan et al., 2018). To put this in perspective, the combined gas flaring in Bakken (North Dakota) and Permian Basin and Eagle Ford (both in Texas) has a combined total area of hundreds of square miles. In these areas, a total of 1,300 MMSCFD of associated gas were flared in 2019, representing 85% of the reported vented and flared gas of the year in the United States (U.S. Energy Information Administration (EIA), 2020b). Therefore, small-scale GTL technologies are required to provide a feasible option to monetize smaller gas volumes.

Advantages associated with small GTL plants (<2,000 bbl/day) are that they are less complex, require smaller capital investment, incur lower financial risk, and could provide easy access to remote locations (de Klerk, 2012). New technologies, such as Velocys' (Houston, TX) microchannel FT reactors (Lipski, 2013), allow GTL plants to be scaled down. Among many notable small-scale GTL developers are CompactGTL (London, UK), Emerging Fuels Technology (Tulsa, OK), GasTechno Energy & Fuels (Walloon Lake, MI), Greyrock Energy (Sacramento, CA), and Primus Green Energy (Hillsborough, NJ) (GGFR, 2020b). Some of these companies are the current leading GTL technology providers with commercial offers for associated gas conversion, including Greyrock Energy, which has Mini-GTL and Micro-GTL plants in the US and Canada (GGFR, 2019).

The synthetic liquid fuels produced by these small GTL plants can then be transported by truck to a nearby central location and subsequently distributed to local fueling stations. The final product can also be synthetic crude oils that can be injected into an oil pipeline without being transported by truck (GGFR, 2020b).

Potential Economic Benefit of Flare Gas Utilization

A comparative economic evaluation of associated gas utilization approaches, namely gas-to-liquids (GTL) production and electricity generation with a gas turbine, showed GTL can produce about 48 barrels per day of synthetic transportation fuels (Rahimpour et al., 2012). This process also generated roughly 2,100 MW of electricity from the 357 million standard cubic feet per day (MMSCFD) from gas flared from the Asalooye Gas Refinery in Iran. These are potential economic benefits from not flaring the associated gas. The synthetic fuels were zero-sulfur, fully fungible, and compatible with existing liquid fuels. The corresponding rate of return for capacity increment (ROR) for GTL and electricity production was 125% and 21%, respectively, suggesting that the associated gas utilization approaches are potentially economically feasible (Rahimpour et al., 2012).

In the United States, up to 5.30 billion liters (or 1.4 billion gallons) of synthetic fuels could be produced each year from associated gas (Tan et al., 2018), corresponding to a 3.5 billion dollar economic potential (assuming an average fuel price of $2.50/gal).

Moreover, suppose the gas flared in the Permian Basin during the third quarter of 2019 alone was captured and liquified. In that case, it could yield as much as 4.8 million tonnes per year of exportable liquified natural gas (LNG). At an average of $250/tonne in value, this would be a 1.2 billion dollar per year economic opportunity (Collins, 2019).

This points out how the oil and gas industry can play a critical role in mitigating climate change, decreasing fossil resource depletion, and improving environmental well-being by reducing associated gas flaring.

The value proposition of valorizing associated gas will primarily dictate the extent to which the industry is willing to change its practice. However, no reported studies combine economic, climate, and health benefits and consider how geographical differences can impact the valorization of flare gas for transportation fuel production. Including all these aspects in the sustainability assessment can provide a comprehensive picture of the evaluated approach to utilize associated flare gas.

Research Questions, Hypotheses, and Specific Aims

The research questions of this study were: What are the sustainability benefits (i.e., value propositions) of utilizing associated gas for the production of transportation fuels instead of flaring? Specifically, will the fuel production cost be lower than the wholesale price of conventional fuels? What are the environmental benefits? What are the health benefits? And what are the impacts of geographical differences on the health benefits?

In addressing these questions, this study examined the following hypotheses:

- Conversion of associated gas to transportation fuels can be economically feasible. The investment would be justified for all countries, that is, having a benefit-to-cost ratio (BCR) > 1.0, especially when taking the climate (carbon credits) and health benefits (e.g., the Value for Statistical Life Saved) into consideration.

- Liquid fuels derived from associated gas will exhibit lower GHG emissions by at least 50% and criteria air pollutants, e.g., PM, SO_2, and NOx, by greater than 25% compared to flaring and conventional petroleum fuels.
- Countries that are more polluted, higher in mortality rates, and lower gross national income (GNI) per capita will reap relatively greater health benefits from converting associated gas to liquid fuels.

Specific Aims

To show that flare gas valorization for transportation fuels potentially offers overall sustainability benefits, the specific aims of this research were to:

1. Perform cost-benefit analysis and calculate the economic benefit associated with the production of transportation fuels from associated gas (i.e., the quantity of fuel produced and the associated economic values)
2. Perform life cycle assessment and quantify life cycle greenhouse gas and criteria emissions of transportation fuel produced from the associated gas (compared to flaring and conventional petroleum fuels)
3. Determine climate change benefits (i.e., the equivalent carbon credits)
4. Estimate health benefits of pollution reduction (i.e., lives saved and mortality damages)
5. Evaluate geographical differences on health impact assessments

Chapter II

Methods

To answer the research question and address the hypotheses on the sustainability benefits of utilizing associated gas to produce transportation fuels instead of flaring, this study performed a combination of various analyses and used different data obtained from the literature, i.e., journal publications and reports from multiple organizations. The analyses encompass cost-benefit analysis, life cycle assessment (LCA), and health benefits assessment. Detailed descriptions of each analysis and approach are provided below. Examples of data needed are gas flaring volume, GTL capital and operating costs, air emission attributable mortality rates, environmental characterization factors, financial data (income tax, interest rate, etc.), carbon credits, population, and gross domestic product per capita.

Additionally, GTL plants can be somewhat different in many ways. The differences can be attributed to a variety of factors, for instance, reactor types, catalysts used, carbon conversion efficiency, utility consumption, operating costs, and production capacity, as indicated by my previous work (Tan et al., 2018, 2021; Zhang et al., 2018). Hence, my experience in converting fossil and renewable feedstocks to liquid transportation fuels via GTL helped guide this study.

Economic Benefits Calculation

The steps to determine the economic benefit associated with the production of transportation fuels from associated gas involve associated flare gas data collection, determination of synthetic fuel production and fuel production cost, and cost-benefit analysis.

Associated Flare Gas Data Collection

The quantity of synthetic fuel produced via the gas-to-liquids (GTL) technology will depend on the associated gas's availability and quality. The data needed for this study include both the quantity and compositions of the flare gas at a specific location or country. The World Bank's Global Gas Flaring Reduction Partnership (GGFR) provides the latest global gas flaring volume data (GGFR, 2020a, 2021). The 2020 report includes the gas flaring volume data up to 2019 (GGFR, 2020a), and the latest 2021 report (GGFR, 2021) also consists of the 2020 data. 2020 was unprecedented due to the COVID-19 pandemic, which dampened oil demand, prices, and production. Consequently, from 2019 to 2020, there was an 8% decline in oil production, and gas flaring dropped by 5%. Thus, this study used the 2019 gas flaring volume (GGFR, 2020a), complied according to the satellite data collected by the US National Oceanic and Atmospheric Administration (NOAA)'s satellite mounted Visible Infrared Imaging Radiometer Suite of detectors (VIIRS) (GGFR, 2021). Flare gas volumes were estimated using the heat generated by the gas burning in the flare, as illustrated in Figure 5. There is a linear relationship between radiant heat and flare volume (Figure 6), with a correlation coefficient of 0.85 (World Bank, n.d.-a).

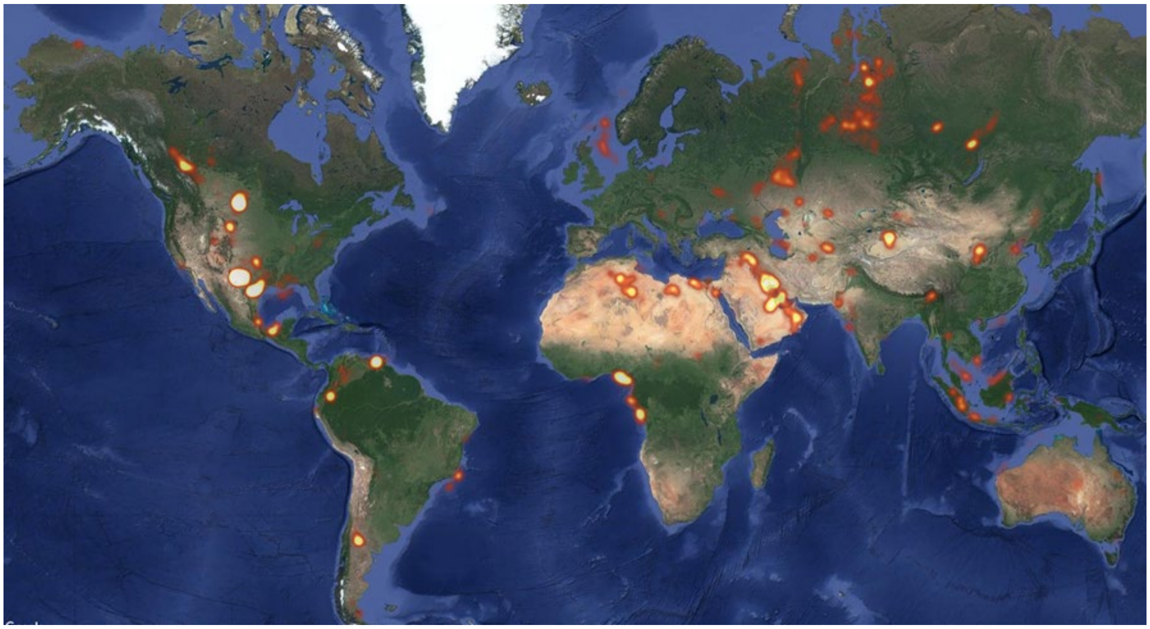


Figure 5. Satellite image of gas flaring volume for 2020.
Source: (GGFR, n.d.)

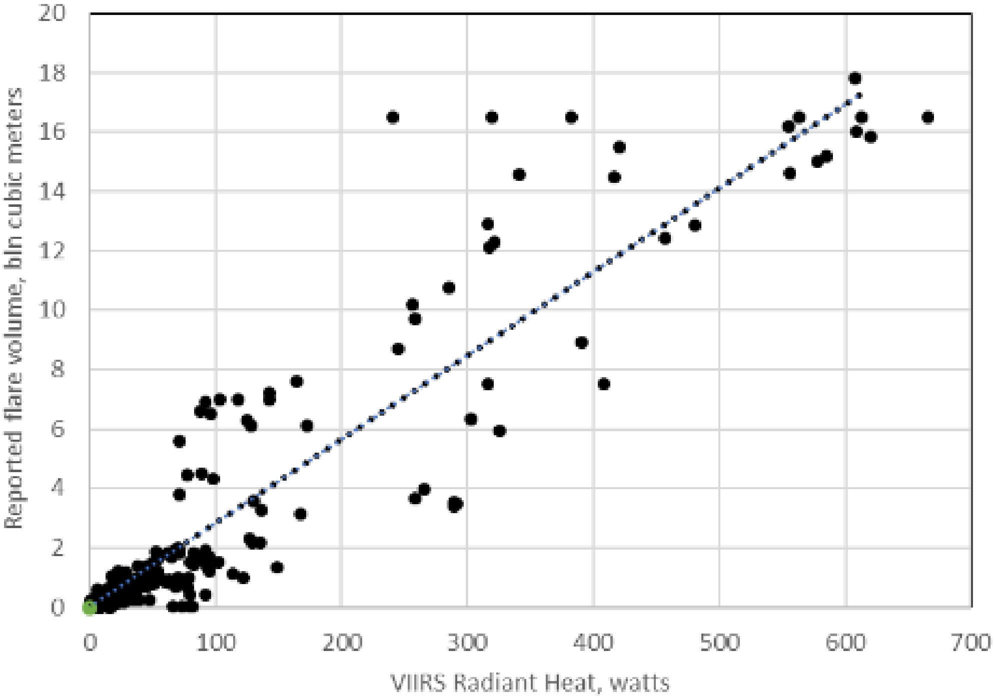


Figure 6. Correlation between Cedigaz reported flare volumes and VIIRS radiant heat estimates.
Obtained from (World Bank, n.d.-a). The correlation coefficient is 0.85, and from the least-squares regression: Satellite flare volume estimate = 0.0281 x VIIRS radiant heat.

As with flare gas volume, flare gas composition also depends on the area of production and the specific properties of the oil field (Vorobev & Shchesnyak, 2019). While flare gas volumes can be precisely quantified and allocated to the country where the flaring occurs (World Bank, n.d.-a), it is more difficult to obtain the flare gas composition data. Therefore, this study used the flare gas composition found in the literature. The average associate gas composition from oil wells selected for this study were from the United States (Burruss & Ryder, 2014), China (Zhu et al., 2014), Nigeria (Anosike et al., 2016), and Russia (New Generation, 2013), as summarized in Table 1. The heating values for the average gas composition were determined and used to determine synthetic fuel production and associated emissions. The uncertainty related to the composition was characterized and presented in Appendix 1 and Figure 26.

Table 1. Average associated flare gas composition from oil wells at various global locations.

Well locations	Ohio		Texas		China		Nigeria		Russia		Average	
Constituent	vol%	wt%	vol%	wt%	vol%	wt%	vol%	wt%	vol%	wt%	vol%	wt%
Methane (CH_4)	87.98	76.50	85.40	73.87	93.91	85.85	79.01	60.77	81.27	61.15	85.52	70.62
Ethane (C_2H_6)	5.61	9.14	11.00	17.84	0.72	1.23	10.49	15.12	4.65	7.78	6.67	10.08
Propane (C_3H_8)	2.10	5.02	2.90	6.90	0.08	0.20	4.63	9.79	5.85	13.70	3.26	7.02
Butane (C_4H_{10})	1.00	3.15	nd	nd	0.02	0.07	1.76	4.92	3.77	10.94	1.36	4.70
Pentane (C_5H_{12})	0.30	1.17	nd	nd	0.01	0.04	0.89	3.09	1.37	4.75	0.52	2.23
Carbon dioxide (CO_2)	0.50	1.19	0.40	0.95	4.60	11.54	2.60	5.48	0.17	0.35	1.65	3.85
Nitrogen (N_2)	2.50	3.80	0.30	0.45	0.60	0.96	0.61	0.82	0.99	1.32	1.00	1.45
Hydrogen sulfide (H_2S)	0.01	0.01	nd	nd	0.06	0.11	0.001	0.002	0.00	0.00	0.01	0.04
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	98.1	100.0	100.0	100.0
Higher heating values (HHV), MJ/kg	51.85		53.70		48.44		50.43		52.59		51.37	
Lower heating values (LHV), MJ/kg	46.89		48.59		43.67		45.75		47.77		46.51	

nd not determined

Synthetic Fuel Production Estimation

The GTL technology selected for this study was a Greyrock Flare-to-Fuels™ process, developed by Greyrock Energy (Sacramento, CA), which has recently emerged as a leader in small-scale GTL technologies (GGFR, 2018, 2019, 2020b, 2020c). The analysis assumed that all associated gas currently flared can be sent to GTL plants. The GTL requires 56% of the associated gas energy for plant operation (heating). The remaining gas will be converted to synthetic fuels, corresponding to an energy conversion efficiency of 44% (Tan et al., 2018).

Synthetic Fuel Production Cost Estimation

When calculating the synthetic fuel production cost (or levelized costs of fuel production), this study followed the method of economic analysis used in the literature, which requires five primary inputs: capital costs, operating costs, plant utilization, capital intensity, and a capital recovery factor (CRF) (Keith et al., 2018; Sagues et al., 2019). CRF is a levelized annual charge on capital divided by the overnight capital cost. The synthetic fuel production cost includes annualized capital and fixed and variable operating expenses. The cost of a Greylock micro-GTL plant processing up to 500 MMSCFD of flare gas is between \$65,000 to \$100,000 per 42-gal barrel per day (GGFR, 2020b). This study considered a plant size at 1,000 bbl per day (corresponding to a feed of 12.9 MMSCFD of associated flare gas) at a capital cost of \$65,000/bbl/d.

The levelized capital cost is the product of the overnight capital cost and the capital recovery factor (CRF). CRF is a function of the project life (*N*), and the weighted average cost of capital (*i*), i.e., interest on debt capital and return on equity capital (Sagues et al., 2019), determined using Equation 1.

$$CRF=\frac{i(i+1)^N}{(1+i)^N-1} \tag{1}$$

Equation 2 indicates how to calculate the levelized capital cost:

$$Levelized\ capital\ cost = capital\ intensity\ x\ \frac{CRF}{utilization} \tag{2}$$

The variable operating costs are attributed to catalysts and utilities, and this analysis used the estimate of \$5.83/bbl (Tan et al., 2021). The feedstock for the fuel production was associated gas, considered as "free" because it would otherwise be flared and wasted and did not contribute to the variable operating cost. The fixed operating expenses include labor costs which will vary in different countries. This study assumes that the fixed operating costs (FOC) were 5% of the fixed capital investment (FCI). The FOC for each country was approximated using Equation 3,

$$FOC_i = FOC_{US}\ x\ \left(\frac{GNI_i}{GNI_{US}}\right)^{\eta} \tag{3}$$

where FOC_i and FOC_{US} are the costs in country "i" and the United States, respectively. GNI_i and GNI_{US} are the gross national income per capita for country "i" and the United States. The elasticity (η) of 0.7 was used here. Additionally, since GTL is a capital-intensive technology (de Klerk, 2012; Lipski, 2013), the capital recovery factor (CRF) is a crucial variable. The labor costs and loan interest rates will also differ from country to country. The production cost is in US dollars per gasoline gallon equivalent (GGE) or \$/GGE. GGE is based on the lower heating value (LHV) of gasoline blendstock (i.e., 116,090 Btu/gal or 32,356 kJ/L) (Argonne National Laboratory, 2020).

Cost-Benefit Analysis

Finally, the cost-benefit analysis was performed after determining the total fuel production costs and the overall benefits. The revenue from the fuel sales was determined using the local wholesale fuel price. The project will be profitable if the wholesale price exceeds the production cost (i.e., the breakeven price). Profit calculations also considered the climate and health benefits; their methods of calculation and analysis are delineated below.

Life Cycle Assessment

This study carried out a life cycle assessment (LCA) to determine the climate and health benefits associated with using associated gas for transportation fuel production. Benefits come from quantifying reductions in greenhouse gas (GHG) and criteria air pollutant emissions (e.g., $PM_{2.5}$, SOx, NOx) due to synthetic fuel production. Figure 7 shows the "well-to-wheel” (WTW) LCA system boundaries.

A conventional transportation fuel pathway was used as the baseline for comparison. The life cycle stages include crude oil production, fuel production, fuel distribution, and vehicle operation. Similarly, the life cycle stages considered for the associated gas-to-transportation fuels encompass associated gas production, synthetic fuel production, fuel transportation and distribution, vehicle operation, and the gas flaring stage, which accounts for the avoided flaring emissions in the life cycle. The functional unit for this study was one megajoule (MJ) of transportation fuel. All emissions were expressed in grams per megajoule (g/MJ). The LCA accounted for the direct emissions from all life cycle stages. The global warming potential (GWP), represented in grams of CO_2-equivalents (CO2e), was estimated based on a 100-year time horizon (IPCC, 2014).

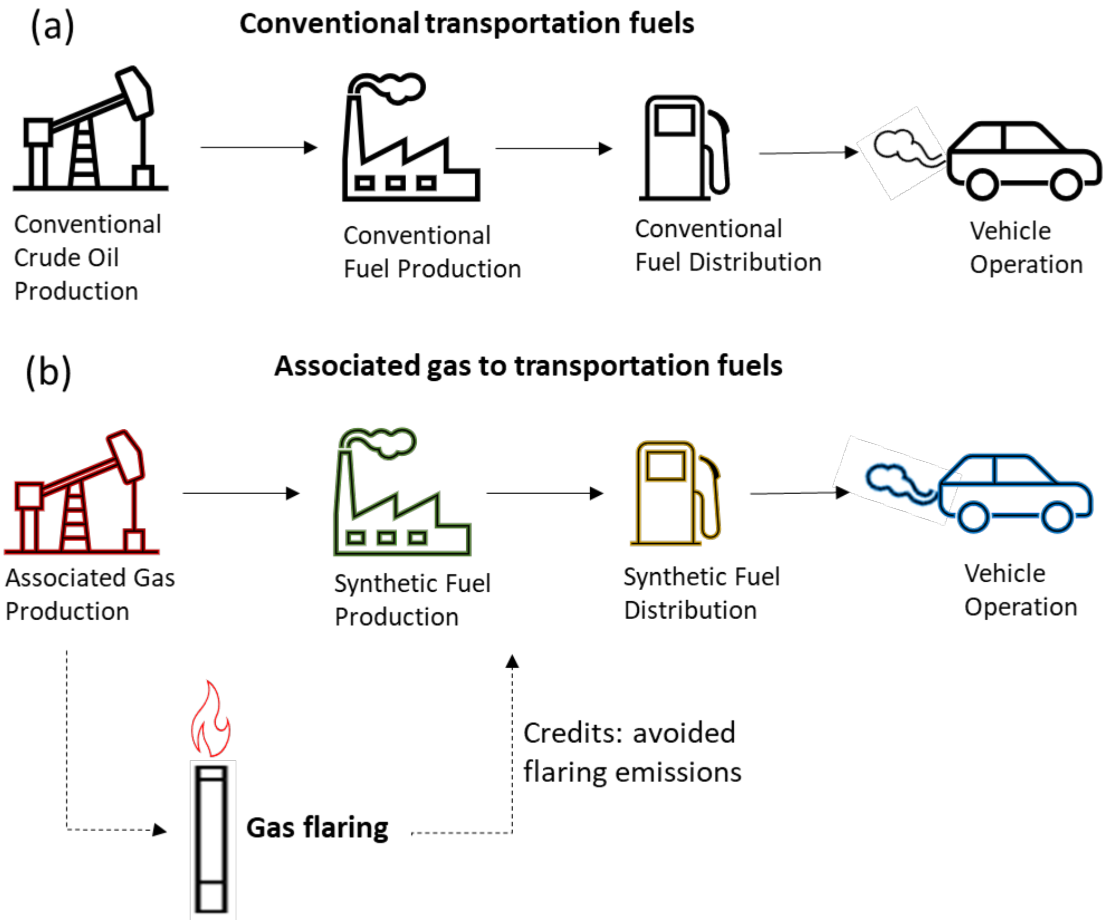


Figure 7. "Well-to-wheel" system boundaries for (a) a conventional transportation fuel pathway and (b) the current associated gas-to-transportation fuel scenario.

Reductions of GHG and criteria pollutant emissions were quantified and evaluated for the selected countries according to their respective gas flaring volume and associated gas compositions. In addition to GWP, the LCA also evaluated other impact categories (such as photochemical smog and acidification). This information was an input to perform human health and environmental (ecosystems) damage assessment using the ReCiPe impact assessment method (Huijbregts et al., 2017). The steps in Table 2 represent a guide to derive the life cycle emissions and quantify the health and environmental impacts. Details on assumptions and calculations for each life cycle stage emission are provided below.

Table 2. Steps for deriving life cycle emissions and quantifying impact categories and human health and ecosystems damages.

Step	Description
1	Obtain associated gas volume and composition for the interest countries
2	Determine heating values of the associated gas
3	Calculate GHG for each life cycle stage
4	Calculate CAP and other emissions for each life cycle stage
5	Determine GWP using a 100-year time horizon using results from Step 3
6	Determine other impact categories based on emission results from Steps 3 and 4 using the ReCiPe impact assessment method (midpoint)
7	Determine health and environmental impacts using the ReCiPe impact assessment method (endpoint)
8	Summarize results for the direct conversion of associated gas to fuels scenario
9	Quantify emissions for the conventional transportation fuels
10	Determine the reductions in emissions and quantify health and environmental benefits based on results from Steps 9 and 10

Associated Gas Production Emissions

The oil production processes are oil drilling and gas collection and transfer to the co-located synthetic fuel production plant. The emissions associated with the associated gas production are mainly the fugitive emissions (CH_4 and CO_2) at wellheads, where oil production takes place. The typical average total fugitive emissions of associated gas generated during the oil drilling and collection were 0.163 g/MJ of flare gas for the CH_4 and 2.01 g/MJ for the CO_2 (Tan et al., 2018). This study adopted these emission factors to calculate the associated gas production emissions for all scenarios.

Associated Gas Flaring Emissions

Associated gas flaring emissions were determined using the approaches published in the literature. The flare combustion efficiency can vary moderately, depending on the flare design and operating conditions. This study used the flare combustion efficiency of 95% to estimate the associated gas flaring CH_4 and CO_2 emissions using the mass balance concept (Ismail & Umukoro, 2016; Tan et al., 2018). Criteria emissions for associated flare gas can be estimated using various methodologies. The flared-generated particulate matter (PM), which is predominantly black carbon (BC), was calculated using the emission factor of 0.061 g/MJ, an average value from different sources (Weyant et al., 2016). The emission of nitrogen oxide (NOx) from associated gas flares is primarily a function of the gas composition, the air-to-fuel ratio, the combustion temperatures, pressures, and residence time in the combustion zone. In this study, the LCA model used the emission factor of 6.67 g/MJ, corresponding to flaring condition at 0.90 lambda (the mass combustion ratio of air and fuel) and 95% efficiency, and was derived based on the kinetic models developed by Ismail and Umukoro (2016). Sulfur dioxide (SO_2) emissions assumed that all hydrogen sulfides (H_2S) were oxidized to SO_2 in the flare stoichiometrically. Table 3 summarizes these emission factors.

Fuel Production Emissions

In addition to being a feedstock for synthetic fuel production, associated gas is also used as a fuel for heat and power generation for the GTL plant. The LCA model used the air emissions factors for the Greylock GTL plant, summarized in Table 4 (Tan et al., 2018).

Table 3. Associated gas production and flaring emission factors.

Associated gas production emissions	Values	Remarks
Methane (CH_4)	0.163	g/MJ of flare gas; fugitive emissions at wellheads
Carbon dioxide (CO_2)	2.01	g/MJ of flare gas; fugitive emissions at wellheads
Associated gas flaring emissions	**Values**	**Remarks**
Methane (CH_4)	95%	combustion efficiency; mass balance
Carbon dioxide (CO_2)	95%	combustion efficiency; mass balance
Particulate ($PM_{2.5}$)	0.061	g/MJ, the average value from literature
Nitrogen oxides (NOx)	6.67	g/MJ, 0.90 lambda, 95% efficiency
Carbon monoxide (CO)	3.62	g/MJ, 0.90 lambda, 95% efficiency
Sulfur dioxide (SO_2)	100%	all hydrogen sulfides (H_2S) in flare gas oxidized to SO_2 stoichiometrically

Table 4. GTL plant air emission factors.

Plant air emissions	g/MJ of associated gas as fuel
Methane (CH_4)	$9.16x10^{-4}$
Carbon dioxide (CO_2)	$5.20x10^{2}$
Carbo monoxide (CO)	$6.20x10^{-4}$
Particulate matter (PM)	$7.75x10^{-4}$
Nitrogen oxides (NOx)	$1.03x10^{-3}$
Non-methane hydrocarbons (NMHC)	$4.38x10^{-3}$

Fuel Distribution and Vehicle Operation Emissions

This study assumed the synthetic fuels are transported to regional storage and distributed based on Argonne National Laboratory's GREET processes (Argonne National Laboratory, 2020). The fuels are then used in vehicle operation. Diesel emissions were based on GREET model values for a compression ignition direct injection (CIDI) vehicle using conventional and low-sulfur diesel. Gasoline emissions were based on GREET values for a gasoline vehicle (spark-ignition engines) using conventional gasoline. Gasoline vehicles have an on-road fuel economy of 0.34 km/MJ (26.08 miles per gallon [MPG]), and diesel vehicles have an on-road fuel economy of 0.41 km/MJ (31.30 MPG) based on a gasoline-equivalent volume. Table 5 and Table 6 summarize the associated emission factors. There was no SOx emission related to the vehicle operation as the synthetic fuels are sulfur-free. The synthetic fuel distribution was 18.6% gasoline and 81.4% diesel on an energy basis. This LCA study used the weighted emission factors obtained based on the energy distribution for the fuel distribution and vehicle operation.

Table 5. Emission factors for the fuel distribution life cycle stage.

	Gasoline	Diesel	Weighted Average
Methane (CH_4)	1.36E-04	3.91E-04	3.44E-04
Carbon dioxide (CO_2)	0.0998	0.292	0.256
Particulate matter (PM_{10})	9.10E-06	7.65E-05	6.39E-05
Particulate matter ($PM_{2.5}$)	5.02E-06	6.51E-05	5.39E-05
Nitrogen oxides (NOx)	2.47E-04	0.00173	0.00145
Carbo monoxide (CO)	1.04E-04	4.15E-04	3.57E-04
Sulfur dioxide (SO_2)	8.84E-06	2.81E-04	2.30E-04
Volatile organic compounds (VOC)	3.46E-05	1.12E-03	9.19E-04

Table 6. Emission factors for the vehicle operation life cycle stage.

	Gasoline	Diesel	Weighted Average
Methane (CH_4)	0.00190	0.0275	0.0227
Carbon dioxide (CO_2)	71.6	73.6	73.2
Particulate matter (PM_{10})	0.00516	0.00622	0.00602
Particulate matter ($PM_{2.5}$)	0.00207	0.00256	0.00247
Nitrogen oxides (NOx)	0.0264	0.0347	0.0332
Carbo monoxide (CO)	0.596	0.742	0.715
Sulfur dioxide (SO_2)	--	--	--
Volatile organic compounds (VOC)	0.0526	0.0324	0.0362
Sulfur dioxide (SO_2) (only for conventional fuels)	0.000432	0.000361	0.000375

Climate Change Benefits

After quantifying the life cycle GHG emissions, the study determined the potential GHG reduction from the elimination of flaring and synthetic fuel use in vehicle contribution to climate change. The study also calculated the carbon credits associated with the potentially avoided GHGs. Climate change benefits were monetized using the social cost of carbon. However, instead of converting the GHG reduction to dollar values using the World Bank's Social Cost of Carbon (SCC) (World Bank, n.d.-b), this study determined the carbon credits based on the country-level social cost of carbon (CSCC). This country-level information accounts for the heterogeneous geography of climate damage and differences in country-level contributions to the global social cost of carbon, as depicted in Figure 8 (Ricke et al., 2018).

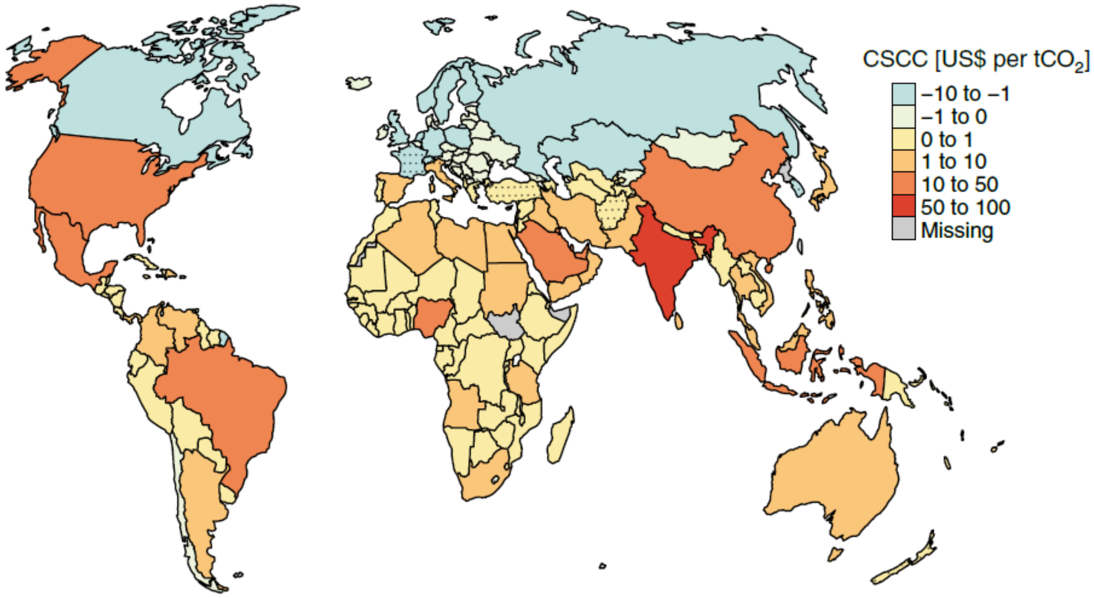


Figure 8. Spatial distribution of estimates of the country-level social cost of carbon (CSCC).
Source: (Ricke et al., 2018).

Health Benefits

The health benefits associated with the air emission reduction relate to the number of lives saved and mortality damages. As mentioned in the background section, associated gas flaring generates two types of pollutants: global greenhouse gas emissions and local air pollution (Agerton et al., 2020). Local air pollution includes criteria air pollutants, encompassing particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NOx), that are known to be detrimental to human health. Additionally, this study assumed that approximately half of PM_{10} is $PM_{2.5}$; this proportion was reported in several metropolitan areas (Das et al., 2006; Khodeir et al., 2012; Kong et al., 2017; Lawrence et al., 2016; Pey et al., 2013).

The potential local emissions reduction from the elimination of flaring and synthetic fuel used in vehicles contributing to health effects were determined using the Intake Fraction (iF) model and the literature's data (Apte et al., 2012). Intake fraction is the ratio of the mass of a pollutant inhaled or ingested to the mass of the pollutant emitted (atmospheric emissions) and is a function of emissions and exposure concentrations. With the estimate of the change in exposure concentration, the health benefits from reducing pollution in terms of lives saved per year can be estimated using the correlation established by Dockery and colleagues (Dockery et al., 1993). Note that the positive health impacts from eliminating flaring will benefit the residents near the gas flaring stations the most (Nwosisi et al., 2021), and the positive health impacts from synthetic fuel use in vehicles will benefit the general population. The primary data needed for health benefits calculation are mortality rate, population, and change in exposure concentration (primary and secondary $PM_{2.5}$). The number of annual lives saved or avoided mortality was determined using Equation 4:

$$Lives\ saved = \frac{\Delta C \ x\ Y\ x\ 1E09}{365\ x\ Q\ x\ P}\ x\ \frac{CVD\ x\ P\ x\ \Phi}{\Omega} \tag{4}$$

where ΔC (in kg/MJ) is the $PM_{2.5}$ emission change between the synthetic fuels and the conventional fuels, Y is the annual synthetic fuel production (in MJ/yr), Q is the average breathing rate (in m^3/person/d), P is the population (or the number of people exposed), CVD is the number of deaths associated with the cardiovascular diseases per person, and Φ is the percentage of cardiovascular diseases rate increase per Ω change in $PM_{2.5}$ concentration (in $\mu g/m^3$). This study used the assumption that an increase of 10 $\mu g/m^3$ in the concentration of $PM_{2.5}$ would increase the overall cardiovascular mortality by 9% (95% Confidence Interval: 3%, 16%) (Dockery et al., 1993), assuming the average breathing rate is 20 m^3 per person per day.

The lives saved were then monetized by estimating the value for a statistical life (VSL), which were calculated or obtained for the studied countries using Equation 5 derived from the literature (Hammitt & Robinson, 2011; Narain & Sall, 2016; Viscusi & Masterman, 2017):

$$VSL_i = VSL_{US}\ x\ \left(\frac{GNI_i}{GNI_{US}}\right)^{\eta} \tag{5}$$

where VSL_i and VSL_{US} are the value for a statistical life in country "i" and the United States, respectively. VSL_{US} of \$9 million per statistical death per year was used in this study (Viscusi & Masterman, 2017). GNI_i and GNI_{US} are the gross national income per capita for country i and the United States, respectively (Table 7). The elasticity (η) of 0.7 was used here.

Geographical Difference Impacts

This study also evaluated geographical differences on health impact assessments to test the hypothesis that countries that are more polluted, higher in mortality rates, and lower in gross national income per capita will reap greater health benefits due to converting associated gas to liquid fuels. Four countries out of the top 15 gas flaring countries, namely, the United States, Russia, Nigeria, and China, were selected for this study. The United States was the baseline country for comparison. In addition to annual flaring volume, other criteria for country selection were geographical region, gross national income per capita, population, mortality rate, and availability of the data needed for this study. Table 7 summarizes input data for the key variables used to assess the impact of geographical differences on the health benefits. The study used emission intake fraction values for the cities identified as the sample locations close to the gas flaring sites (Figure 9).

Table 7. Data for key variables used to study the geographical differences in the health benefits.

Country	**United States**		**Russia**		**Nigeria**		**China**	
Geographical region	North America		South America		West Africa		East Asia	
Gross national income per capita, USD	55,980		11,450		2,820		7,930	
Cardiovascular diseases (CVD) mortality rate, deaths/100,000 people	243		855		110		305	
Population	City	Population	City	Population	City	Population	City	Population
City 1	Abilene, TX	107,000	Noyabrsk	100,100	Owerri	183,400	Qinyang, Henan	160,200
City 2	Odessa, TX	111,400	Nizhnevartovsk	239,400	Calabar	418,600	Yulin, Shaanxi	409,500
City 3	Fargo, ND	142,500	Surgut	279,000	Warri	486,700	Pingliang, Gansu	444,200
City 4	Lubbock, TX	202,200	Tyumen	505,400	Port Harcourt	846,000	Yinchuan, Ningxia	586,000
City 5	Corpus Christi, TX	293,900	Orenburg	548,900	Benin City	918,000	Baotou, Inner Mongolia	1,319,000
Intake Fraction (iF), PM$_{2.5}$ (transportation)	City	iF	City	iF	City	iF	City	iF
City 1	Abilene, TX	2.40E-06	Noyabrsk	6.22E-06	Owerri	1.13E-05	Qinyang, Henan	9.33E-06
City 2	Odessa, TX	2.72E-06	Nizhnevartovsk	1.23E-05	Calabar	3.79E-05	Yulin, Shaanxi	2.12E-05
City 3	Fargo, ND	4.09E-06	Surgut	1.56E-05	Warri	2.39E-05	Pingliang, Gansu	2.78E-05
City 4	Lubbock, TX	4.14E-06	Tyumen	2.21E-05	Port Harcourt	3.88E-05	Yinchuan, Ningxia	3.63E-05
City 5	Corpus Christi, TX	3.17E-06	Orenburg	1.93E-05	Benin City	6.30E-05	Baotou, Inner Mongolia	2.08E-05

Gross national income (GNI) per capita (Viscusi & Masterman, 2017). Background mortality rates for cardiovascular disease, urban population, and global intraurban intake fractions for primary air pollutants from vehicles data source (Apte et al., 2012).

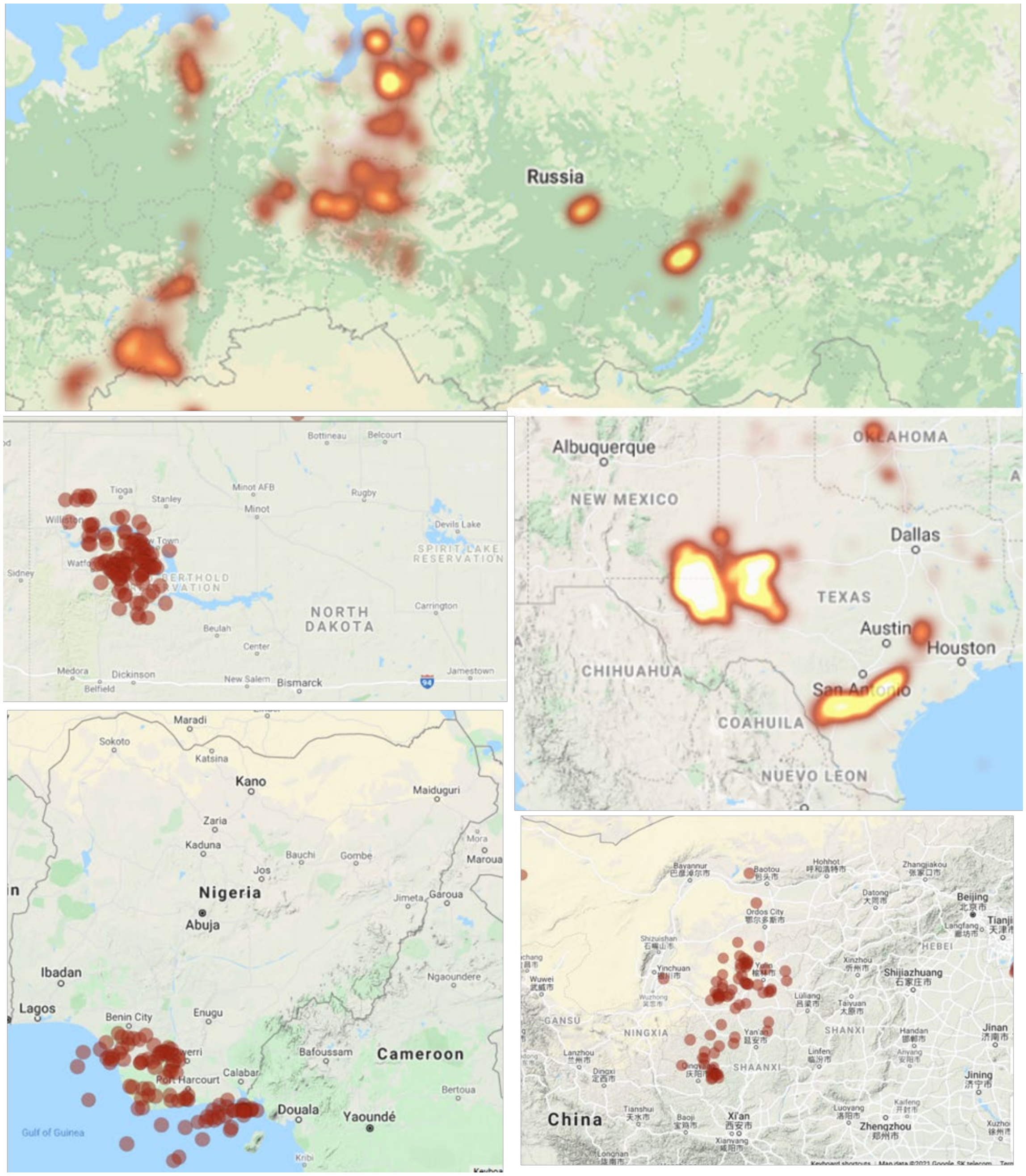


Figure 9. Compiled map showing main cities in the vicinity of the gas flaring sites. *Source: Created from (GGFR, n.d.).*

Chapter III

Results

This chapter presents the important findings of the sustainability benefits of valorizing associated gas for the production of transportation fuels instead of flaring using small-scale GTL processing plants.

Synthetic Fuel Production Economic Analysis

For this study, plant size was 1,000 bbl per day (processing 12.9 MMSCFD of associated flare gas) at a total installed cost (TIC) of $65,000/bbl/d (Table 8). The annual production was 346,750 barrels or 17.5 million GGE using the 95% plant utilization. The indirect costs (non-manufacturing fixed capital investment costs) were estimated using factors based on the total direct cost (TDC), for example, site development and additional piping. The factors are the percentages of TIC and total direct cost (TDC). The fixed capital investment (FCI) was determined to be $122.7 million, equal to the sum of TDC and all the indirect costs (such as project contingency, start-up, and permits). The total capital investment (TCI) was $128.9 million and included 5% working capital. The resulting capital intensity was $7.38/GGE; this is the overnight capital cost and does not depend on the geographical location. Table 8 presents a summary of these calculations.

Figure 10 shows the synthetic fuel production cost for each evaluated country. The United States and Russia exhibited the lowest and the highest production cost, $1.09/GGE and $1.27/GGE, respectively. The difference in levelized capital cost and fixed operating costs caused variations between the studied countries. The levelized capital cost was the most significant cost contributor. All countries showed higher levelized capital cost ($1.04/GGE) than the United States ($0.62/GGE), attributing to higher capital recovery factor (CRF), which was due to a higher loan interest rate (12%) compared to the United States (8%). The Russia, Nigeria, and China markets are viewed as riskier than the United States, thus having higher borrowing costs.

Table 8. Capital intensity calculation for a 1,000 barrels per day GTL plant.

Plant size	bbl/d		1000
	MMSCFD		12.90
Plant utilization			95.0%
Synthetic fuel production, bbl/y			346,750
Synthetic fuel production, at 50.36 GGE/bbl, GGE/y			17,462,330
Feedstock cost (associated flare gas), $/y		$	-
Total installed cost (TIC), at 65000 $/bbl/d		$	65,000,000
Warehouse	4% of TIC	$	2,600,000
Site development	9% of TIC	$	5,850,000
Additional piping	5% of TIC	$	3,250,000
Total direct cost (TDC)		$	76,700,000
Prorateable Expenses	10% of TDC	$	7,670,000
Field Expenses	10% of TDC	$	7,670,000
Home Office & Construction Fee	20% of TDC	$	15,340,000
Project Contingency	10% of TDC	$	7,670,000
Other Costs (Start-Up, Permits, etc.)	10% of TDC	$	7,670,000
Fixed capital investment (FCI)		$	122,720,000
Working capital	5% of FCI	$	6,136,000
Total capital investment (TCI)		$	128,856,000
Capital intensity per GGE		**$**	**7.38**

Conversely, all countries' fixed operating costs (related mainly to the labor costs) were lower than that of the United States ($0.35/GGE) as they were adjusted based on GNI relative to the United States using Equation 3. The variable operating costs were identical for all countries ($0.12/GGE). Table 9 presents a summary of these calculations.

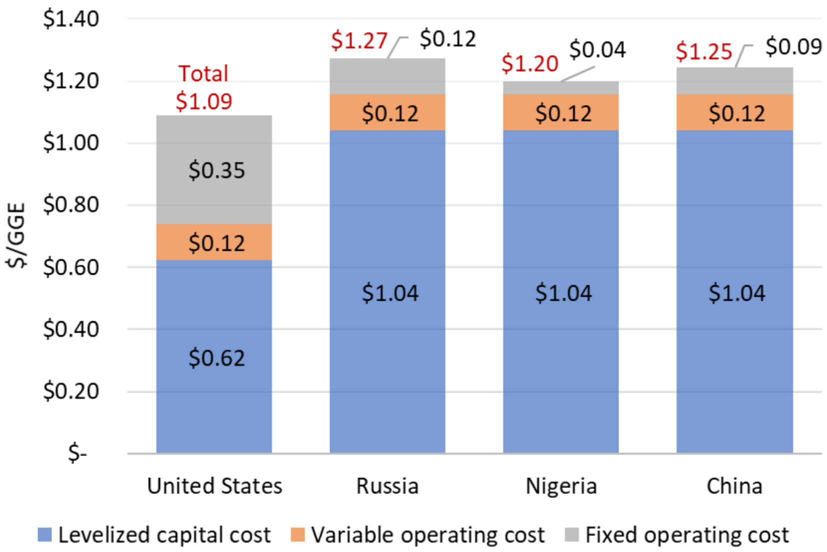


Figure 10. Synthetic transportation fuel production cost comparison.

Net Profits of the Operation

The wholesale prices of the road transportation fuels varied from country to country, namely, $3.68/GGE in the United States, $2.67/GGE in Russia, $1.52/GGE in Nigeria, and $4.63/GGE in China at the time of this study (Gasoline prices around the world, 2021). All countries had positive gross profits as the wholesale prices were greater than the fuel production costs. The corporate taxes are also different for each country, the United States (25.8%), Russia (20.0%), Nigeria (30.0%), and China (25.0%) (Bray, 2021). Consequently, the net profits are the results of the interplay among the fuel production costs, wholesale fuel prices, and tax rates, and increased in the order: China ($2.54/GGE) > the United States ($1.92/GGE) > Russia ($1.12/GGE) > Nigeria ($0.22/GGE), as shown in Figure 11. The return on investment (ROI) profile without any fiscal incentives, climate, and environmental benefits, ranging from 3.0% to 34.4%, was consistent with the net profits. The calculations are shown in Table 9.

Table 9. Synthetic fuel production cost calculation.

		United States	Russia	Nigeria	China
Capital intensity per GGE		$ 7.38	$ 7.38	$ 7.38	$ 7.38
Project life, years		20	20	20	20
Weighted average cost of capital (i.e., interest on debt and return on equity capital)		5.0%	12.0%	12.0%	12.0%
Capital recovery factor (CRF)		8.0%	13.4%	13.4%	13.4%
Levelized capital cost per GGE		**$ 0.62**	**$ 1.04**	**$ 1.04**	**$ 1.04**
Feedstock (associated flare gas)		$ -	$ -	$ -	$ -
Variable operating costs		$ 2,021,948	$ 2,021,948	$ 2,021,948	$ 2,021,948
Gross national income (GNI) per capita		$ 55,980	$ 11,450	$ 2,820	$ 7,930
GNI per capita relative to the United States		1.00	0.20	0.05	0.14
Fixed operating costs (adjusted to GNI per capita)	5% of FCI	$ 6,136,000	$ 2,020,348	$ 757,594	$ 1,562,261
Net operating costs		$ 8,213,929	$ 4,053,746	$ 2,782,362	$ 3,592,139
Net operating costs per GGE		**$ 0.47**	**$ 0.23**	**$ 0.16**	**$ 0.21**
Total synthetic fuel production costs per GGE		**$ 1.09**	**$ 1.27**	**$ 1.20**	**$ 1.25**
Wholesale price per GGE		$ 3.68	$ 2.67	$ 1.52	$ 4.63
Annual gross profits		$ 45,087,254	$ 24,389,184	$ 5,565,535	$ 59,091,667
Gross profits per GGE		$ 2.58	$ 1.40	$ 0.32	$ 3.38
Corporate tax rate		25.77%	20.00%	30.00%	25.00%
Annual tax		$ 11,618,985	$ 4,877,837	$ 1,669,661	$ 14,772,917
Net profits after tax		$ 33,468,269	$ 19,511,347	$ 3,895,875	$ 44,318,751
Net profits after tax per GGE		**$ 1.92**	**$ 1.12**	**$ 0.22**	**$ 2.54**
Return on investment (ROI) - excluding climate benefits		**26.0%**	**15.1%**	**3.0%**	**34.4%**

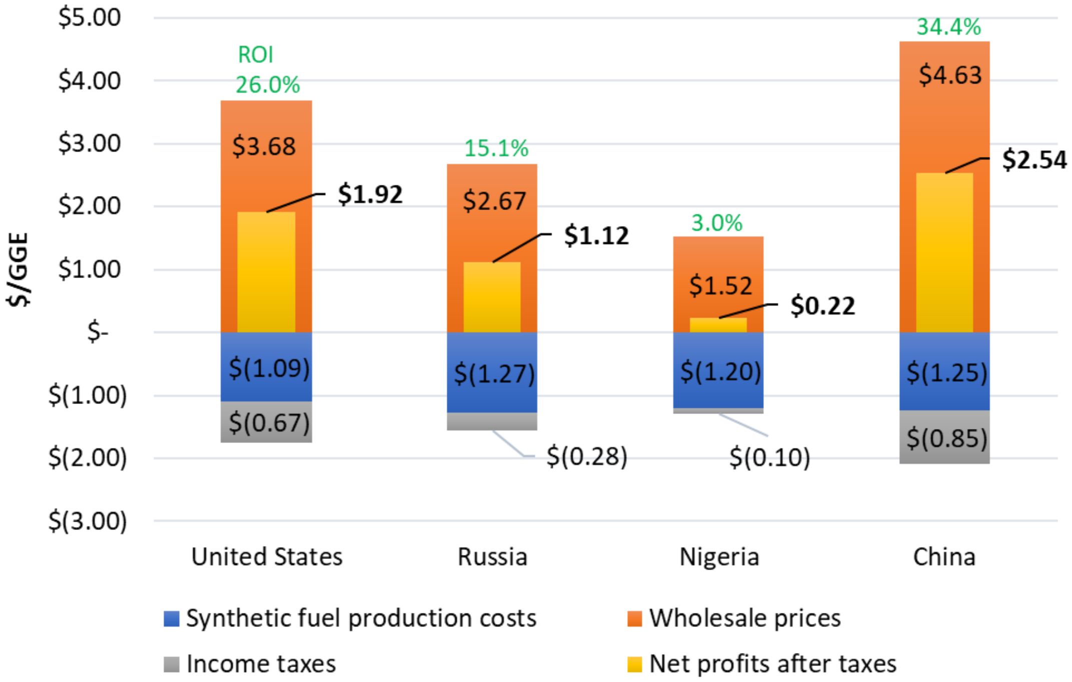


Figure 11. Net profit of the production of synthetic transportation fuel from associated gas.

Synthetic Fuel Production and Economic Benefits

Global gas flaring has been a significant waste of a valuable fossil resource and a tremendous amount of energy. The associated gas volume in 2019 was 17.3 billion cubic meters per year (bcm/y) in the United States, 23.2 bcm/y in Russia, 7.8 bcm/y in Nigeria, and 2.0 bcm/y in China (Figure 2 and Table 10). These amounts of associated gas could have been converted to liquid transportation fuels using the current mini-GTL technology. With the conversion efficiency of 44.3% using the current mini-GTL technology, the United States could have produced 37.4 million barrels (MMbbl) of synthetic diesel and 9.9 MMbbl of synthetic gasoline, for a total of 2,384 MMGGE of fuel (Table 10). Since the total fuel production is directly proportional to the associated gas volume, the possible total fuel production increased in the order: Russia (3,201

MMGGE) > the United States (2,384 MMGGE) > Nigeria (1,080 MMGGE) > China (279 MMGGE). The number of 1,000 bbl/d GTL plants required to process all the associated gas for the countries were determined to be 184, 137, 62, and 16, respectively. This analysis estimated that the corresponding economic values are between $1.3 and $8.8 billion (Table 10). These are the potential economic benefits of associated gas valorization for the production of transportation fuels.

Table 10. Economic values from the associated gas valorization for transportation fuel production.

Associated gas volume in 2019	United States	Russia	Nigeria	China
bcm/y	17.3	23.2	7.8	2.0
Mt/y	14.2	19.0	6.4	1.7
bMJ/y	659	885	299	77.0
Associated gas conversion via GTL				
100% associated gas valorization, bMJ/y	659	885	299	77.0
Plant operation, bMJ/y	367	493	166	42.9
Fuel production, bMJ/y	292	392	132	34.1
Synthetic fuel production				
Synthetic diesel, MMbbl/y	37.4	50.2	16.9	4.4
Synthetic gasoline, MMbbl/y	9.9	13.4	4.5	1.2
Total, MMbbl/y	47.3	63.6	21.4	5.5
Total, bbl/d	129,723	174,139	58,747	15,156
Total, MMGGE/y	2,384	3,201	1,080	279
Potential economic opportunity				
Gasoline price, $/GGE	$3.68	$2.67	$1.52	$4.63
Economic value, MM$/y	$8,764	$8,542	$1,640	$1,290
Number of plants, at 1000 bbl/d and 95% utilization	137	184	62	16

Synthetic fuels: a) in energy: 81.4% diesel and 18.6% gasoline; b) in volume: 79% diesel and 21% gasoline.

Life Cycle Assessment Results

This study quantified the emissions of the two fuel production systems to compare the WTW life cycle environmental impacts between synthetic fuels and conventional fuels. This analysis is based on the assumptions and approaches outlined in Chapter II.

Life Cycle Emission Inventory

Table 11 presents the emission results. Emissions for life cycle stages [C] – [H] are weighted based on energy: 81.4% diesel and 18.6% gasoline. The emissions are in grams per megajoule of fuels (g/MJ).

Associated gas production emissions are fugitive emissions generated during the oil drilling and collection [A], and this analysis also quantified flaring emissions [B]. Since associated gas would otherwise be flared and emitted to the atmosphere, the avoided flaring emissions at wellheads ([B]) were included as credits in the synthetic fuel "well-to-wheel" (WTW) LCA. At each life cycle stage, the fossil energy consumption was also estimated to perform the fossil resource scarcity assessment. The WTW fossil energy demand for the synthetic fuel system was determined to be 0.00352 MJ/MJ, which includes the flaring credit of 2.26 MJ/MJ. In comparison, the WTW fossil energy demand for the conventional fuel baseline was 1.19 MJ/MJ, a 99.7% higher.

Table 11. Life cycle stage emissions for conventional fuels and synthetic fuels from associated gas.

Synthetic gasoline and diesel from associated gas

Emissions (g/MJ of synthetic fuels)	Associated gas production [A]	Associated gas flaring [B]	Synthetic fuel production [C]	Fuel distribution [D]	Vehicle operation [E]	Associated gas flaring at wellhead [A] + [B]	WTW synthetic fuels [A]+[C]+[D]+[E]-[B]
Methane (CH_4)	3.68E-01	1.71E+00	1.06E-03	3.44E-04	2.27E-02	2.08E+00	-1.32E+00
Carbon dioxide (CO_2)	4.54E+00	1.24E+02	6.02E+01	2.56E-01	7.32E+01	1.29E+02	1.38E+01
Particulate matter (PM_{10})	--	--	--	6.39E-05	6.02E-03	--	6.09E-03
Particulate matter ($PM_{2.5}$)	--	1.38E-01	7.80E-04	5.39E-05	2.47E-03	1.38E-01	-1.34E-01
Nitrogen oxides (NOx)	--	1.51E+01	9.74E-04	1.45E-03	3.32E-02	1.51E+01	-1.50E+01
Carbo monoxide (CO)	--	8.17E+00	1.30E-03	3.57E-04	7.15E-01	8.17E+00	-7.46E+00
Sulfur dioxide (SO_2)	--	3.76E-02	2.10E-02	2.30E-04	--	3.76E-02	-1.64E-02
Voltatile organic compounds (VOC)	--	--	--	9.19E-04	3.62E-02	--	3.71E-02
Fossil energy (MJ/MJ)	--	2.26E+00	1.26E+00	3.52E-03	1.00E+00	2.26E+00	3.52E-03

Conventional gasoline and diesel

Emissions (g/MJ of conventional fuels)	Conventional crude oil production [F]	▨	Conventional fuel production [G]	Fuel distribution [D]	Vehicle operation [H]	▨	WTW conventional fuels [F]+[G]+[D]+[H]
Methane (CH_4)	8.31E-02	▨	1.58E-02	3.44E-04	2.27E-02	▨	1.22E-01
Carbon dioxide (CO_2)	4.89E+00	▨	7.93E+00	2.56E-01	7.32E+01	▨	8.63E+01
Particulate matter (PM_{10})	6.85E-04	▨	7.89E-04	6.39E-05	6.02E-03	▨	7.56E-03
Particulate matter ($PM_{2.5}$)	5.71E-04	▨	6.66E-04	5.39E-05	2.47E-03	▨	3.76E-03
Nitrogen oxides (NOx)	1.50E-02	▨	6.47E-03	1.45E-03	3.32E-02	▨	5.61E-02
Carbo monoxide (CO)	7.47E-03	▨	4.30E-03	3.57E-04	7.15E-01	▨	7.27E-01
Sulfur dioxide (SO_2)	4.45E-03	▨	2.68E-03	2.30E-04	3.75E-04	▨	7.74E-03
Voltatile organic compounds (VOC)	3.51E-03	▨	6.21E-03	9.19E-04	3.62E-02	▨	4.69E-02
Fossil energy (MJ/MJ)	5.78E-02	▨	1.29E-01	3.52E-03	1.00E+00	▨	1.19E+00

Life Cycle Impact Assessment

The emission results in Table 11 are the life cycle inventory that was further classified and characterized using the ReCiPe 2016 v1.1 impact assessment method (Huijbregts et al., 2017). The impact categories are global warming (in kg CO2 eq), ozone formation-human health (in kg NOx eq), fine particulate matter formation (in kg PM2.5 eq), ozone formation-terrestrial ecosystems (in NOx eq), terrestrial acidification (in CO2 eq), and fossil resource scarcity (in kg oil eq). The term "eq" is the abbreviation of equivalent. This study also assessed other impact categories in the ReCiPe Midpoint (H) method, but they are not shown here due to zero scores.

Synthetic fuel production at the GTL plant and vehicle operating were the significant contributors to global warming and fossil resources scarcity environmental impact categories (Figure 12). Other impacts were primarily attributed to the vehicle operation. Flaring credits largely offset all impacts because they were greater than the burdens for all categories except the resource scarcity. Thus, the associated gas-to-fuels system exhibited more favorable environmental impacts when compared to the conventional fuel system. However, synthetic fuel production via the current GTL technology requires more energy input (Table 11), resulting in higher global warming and fossil resource scarcity impacts, as shown in Figure 13 for the case without the flaring credits.

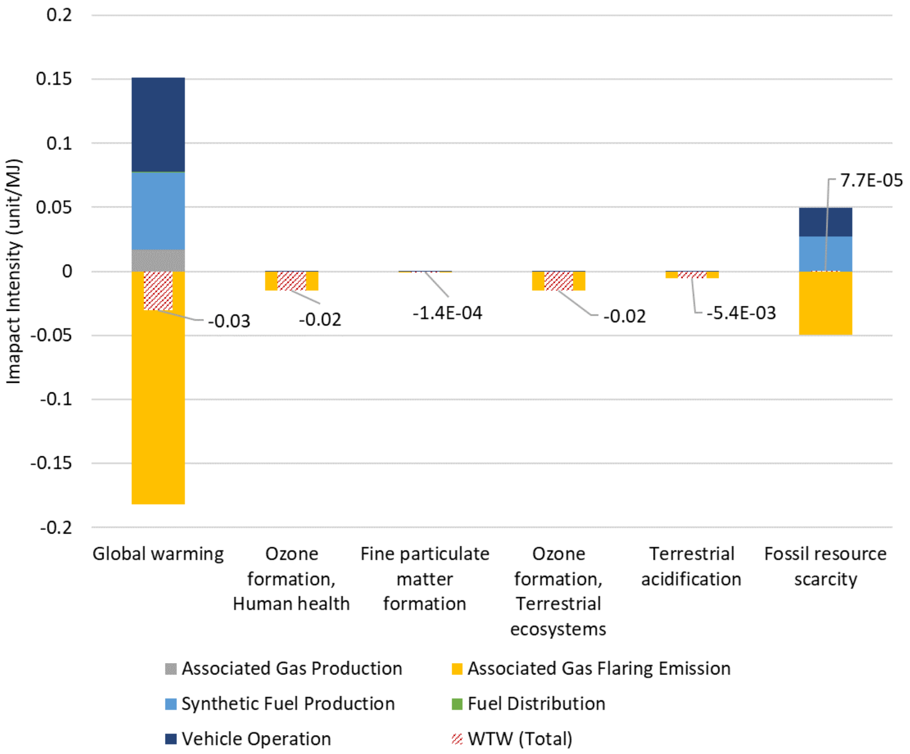


Figure 12. Life cycle impact assessment using ReCiPe Midpoint (H) method for 1 MJ of synthetic fuel.

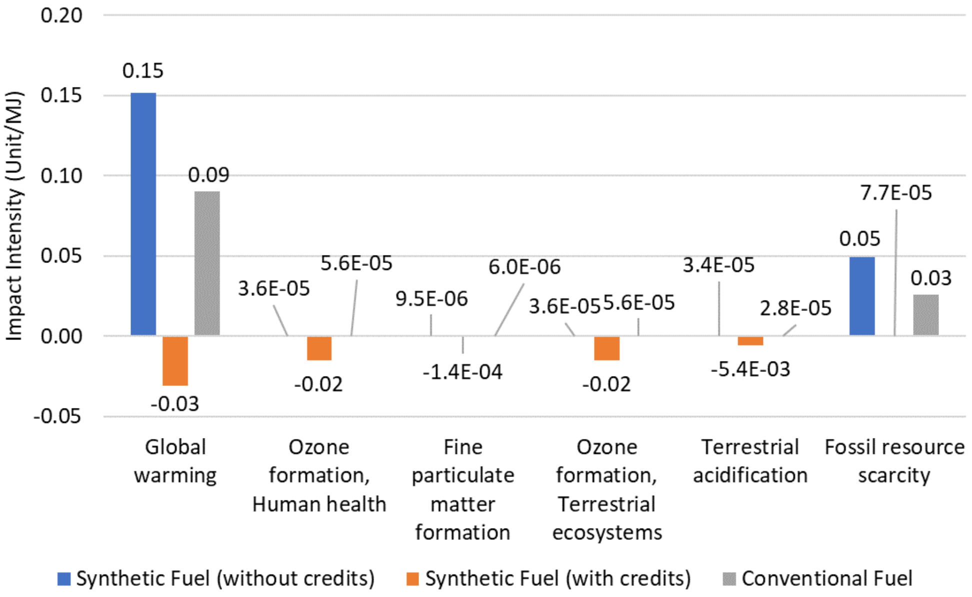


Figure 13. Comparison of the WTW life cycle impacts between the synthetic fuel pathway (with and without flaring credits) and the conventional fuel pathway for 1 MJ of fuels.

Health and Environmental Impacts

This analysis combined the midpoint impact indicators into human health damage (Figure 14), ecosystem damage (Figure 15), and resource depletion costs (Figure 16) using the ReCiPe Endpoint (H) method (Huijbregts et al., 2017). The results were for a 1,000 bbl/d facility with 95% utilization and an annual fuel production capacity of 2,139 million MJ (or 17.5 MMGGE/y). To produce 2,139 million MJ of synthetic fuels will require the processing of 0.127 bcm of associated gas. Flaring this amount of associated gas will cause 1,026 DALYs of human health damage (Figure 14), 7.84 species/yr of ecosystem damage (Figure 15), and $48 million of fossil resource depletion (Figure 16).

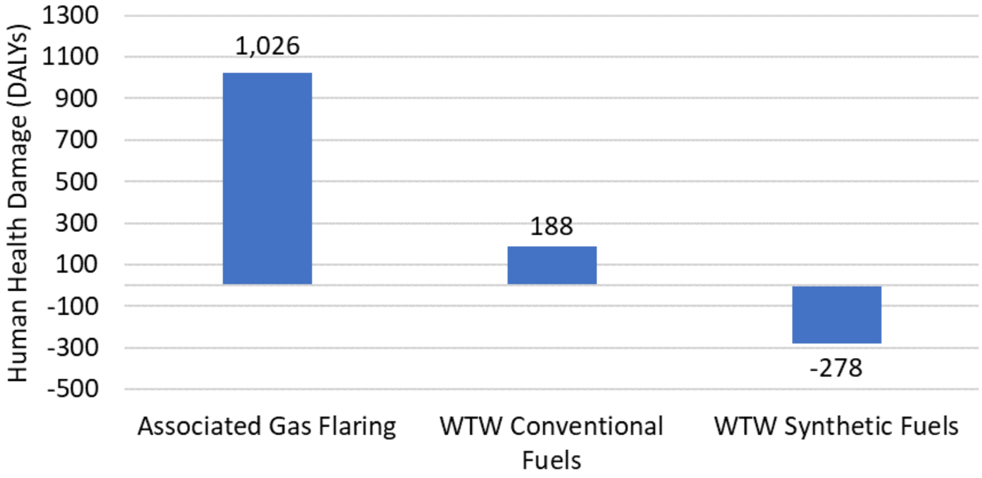


Figure 14. Comparison of damage to human health in disability-adjusted life years (DALYs) for 2,139 million MJ of fuels (the annual production capacity of a 1,000 bbl/y plant).

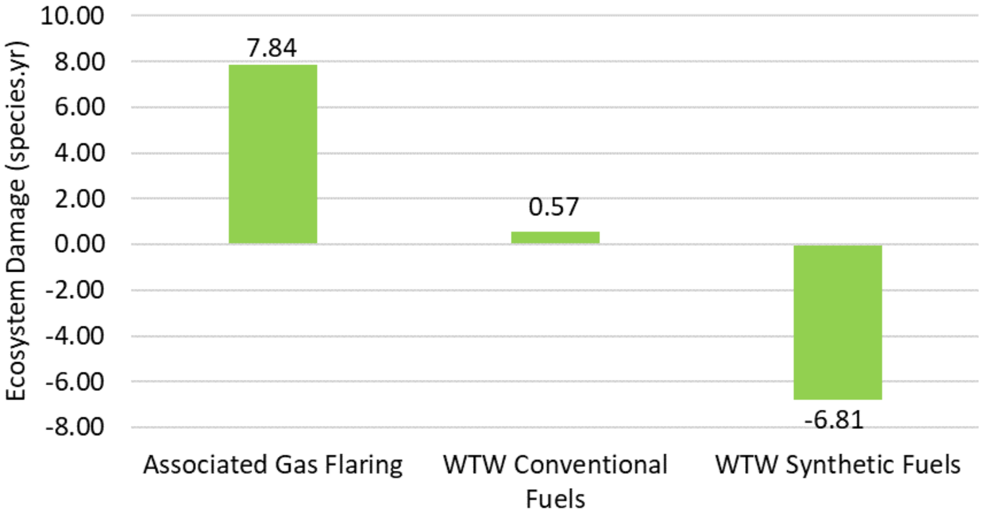


Figure 15. Comparison of damage to the ecosystem in species year (Sp.yr) for 2,139 million MJ of fuels (the annual production capacity of a 1,000 bbl/y plant).

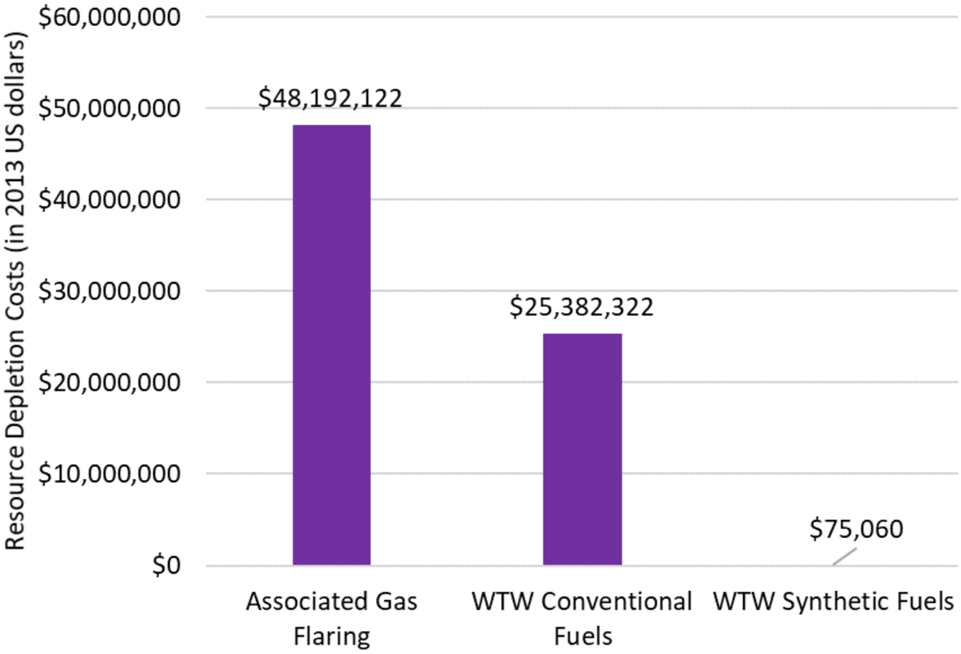


Figure 16. Resource depletion costs in 2013 US dollars for 2,139 million MJ of fuels (the annual production capacity of a 1,000 bbl/y plant).

On the other hand, the synthetic fuels derived from the associated gas exhibited more favorable health and environmental impacts compared to the conventional fuels: -

278 versus 188 DALYs in human health damage, -6.81 versus 0.57 species.yr in ecosystem damage, and $75,060 versus $25.4 million in resource depletion costs. Therefore, the valorization of associated gas for the production of synthetic fuels at wellheads that substitute the conventional transportation fuels can potentially lower the resource depletion costs by 134%, reduce the greenhouse gas emissions by 100%, and decrease the ecosystem and human health damages by 1,295% and 248%, respectively (Figure 17).

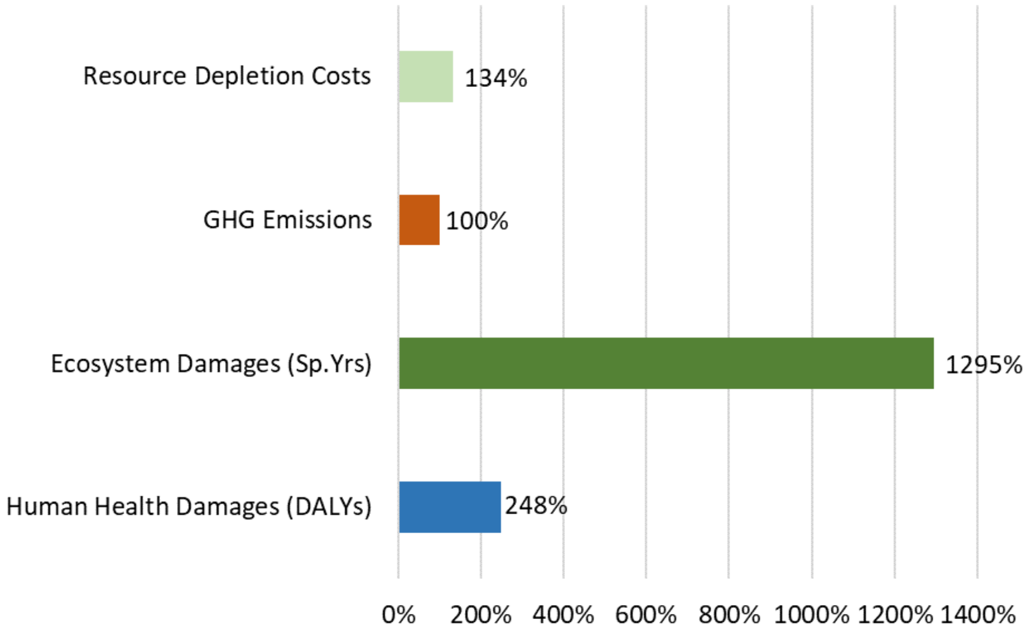


Figure 17. Reductions in resource scarcity damages, GHG emissions, health, and environmental damages due to the substitution of conventional fuels with synthetic fuels.

Furthermore, Table 12 summarizes the impact benefits to health and the environment when displacing conventional fuels with synthetic fuels at the country level, assuming that the study valorized all associated gas for synthetic fuels. The annual total avoided impacts are human health damage (7,447 – 85,645 DALYs), ecosystem damage

(118 – 1,357), resource depletion costs ($0.4 - $4.7 billion), and greenhouse gas emissions (4.1 – 47.6 million metric tons of CO2e). The extent of the benefits is directly proportional to the total amount of the annual associated gas being flared (Table 10); hence, Russia and China showed the highest and lowest, respectively, in each category.

Table 12. Potential avoided health and environmental impacts if all associated gas were converted to synthetic fuels and replaced the conventional fuels.

		Basis	United States	Russia	Nigeria	China
Number of plants, at 1000 bbl/d and 95% utilization		1	137	184	62	16
Impact category	Unit	Avoided Impacts				
Human health damage	DALYs	465	63,768	85,645	28,858	7,447
Ecosystem damage	species.yr	7.38	1,010	1,357	457	118
Resource depletion costs	USD 2013 (millions)	25	3,467	4,657	1,569	405
Carbon emissions	Metric tons of CO2e (thousands)	259	35,465	47,632	16,050	4,142

Climate Benefits

The amount of greenhouse gas averted for a single 1,000 bbl/d GTL plant was estimated to be 259 thousand metric tons per year (Table 12). The baseline climate change benefits were determined using the country-level social cost of carbon (CSCC), which has a higher geographical resolution (country level) than the global social cost of carbon (SCC) (Figure 18). The mean CSCC for the countries per metric ton of CO_2 equivalent (tCO_2) were the United States ($46/$tCO_2$), Russia (-$5.5/tCO_2), Nigeria ($30/$tCO_2$), and China ($24/tCO_2). The magnitude of CSCC varied considerably (i.e., large confidence intervals), stemming from the uncertainties associated with climate system response to CO_2 and the expected climate change-related economic harm (damage function) (Ricke et al., 2018).

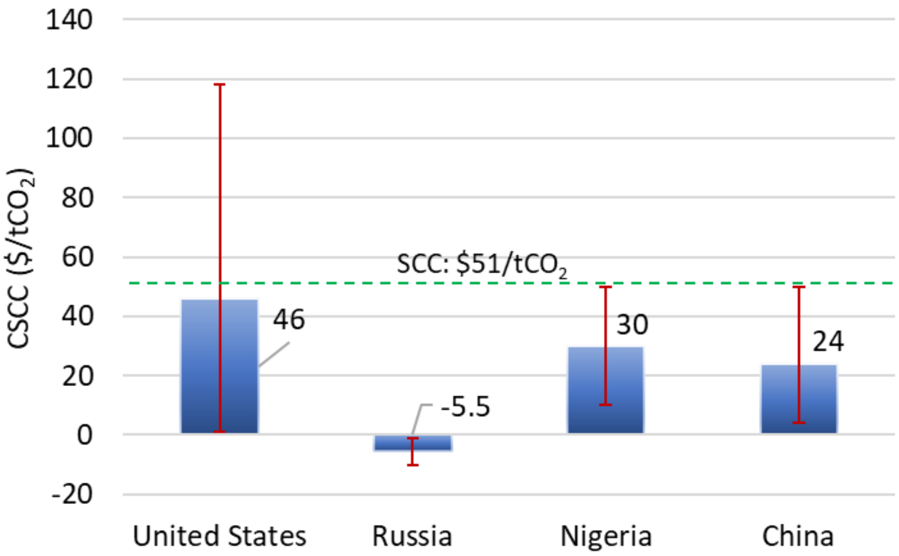


Figure 18. Country-level social of carbon for the selected countries (CSCC) and the social carbon cost (SCC).
CSCC source: (Ricke et al., 2018). The "error bars" represent 65% confidence intervals.
SCC source: (Rennert et al., 2021).

The climate benefits determined using the CSCC values (Figure 19) increased in the order (before-tax and after-tax in parentheses): the United States ($0.71/GGE, $0.53/GGE) > China ($0.44/GGE, $0.33/GGE) > Nigeria ($0.36/GGE, $0.25/GGE) > Russia (-$0.08/GGE, -$0.07/GGE). Russia had a negative CSCC value because its additional CO_2 emissions lead to marginal benefit as opposed to marginal damage. With negative CSCC values, Russia would be penalized for cutting GHG emissions, which is rather nonsensical.

Climate benefits used the global SCC value ($51/t$CO_2$) (Rennert et al., 2021) as a sensitivity study. This is a commonly used value but essentially treats each country as the same, in terms of heterogeneous geography of climate damage and differences in country-level contributions, as well as climate and socio-economic uncertainties (Ricke et al., 2018). All countries' climate benefits before tax were identical ($0.76/GGE). After-tax benefits were Russia ($0.60/GGE) > China ($0.57/GGE) > the United States ($0.56/GGE) > Nigeria ($0.53). The differences in the after-tax benefits were entirely attributed to the different tax rates (see Table 9).

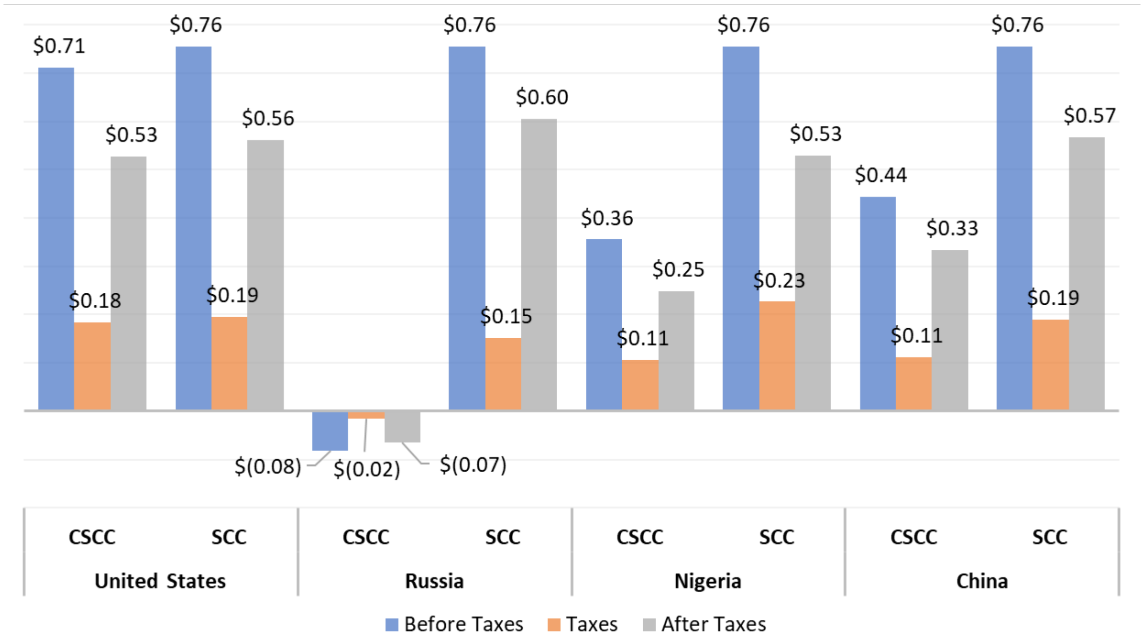


Figure 19. Estimated climate benefits based on the country-level cost of carbon (CSCC) and social cost of carbon (SCC) in $/GGE.

Health Assessment and Monetization

Substituting conventional fuels with synthetic fuels reduced $PM_{2.5}$ emission by 1.5 g/MJ (Figure 13). The changes in the $PM_{2.5}$ concentration due to 17.5 million GGE per year (the annual production of a 1,000 bbl/d GTL plant) and the corresponding avoided mortality related to cardiovascular diseases (CVD) were determined using

Equation (4) and data in Table 7, including the population numbers, CVD mortality rates, and the intake fraction (iF) values for the studied communities. The intake fraction (iF) is the ratio of the mass of a pollutant inhaled to the mass of the pollutant emitted and is a function of emissions and exposure concentrations. It varies from country to country but generally increases with a larger urban population. Consequently, avoided mortality is directly proportional to the urban population (Figure 20). However, the number of lives saved is less smooth for certain cities as some iF values are less accurately correlated with the city population. The five-city population-weighted average avoided mortality numbers were 58.2 (Russia), 28.6 (China), 17.7 (Nigeria), and 3.2 (the United States) (Figure 20 and Table 13).

The results were also normalized based on a per one million population to assess and compare the impact of geographical difference on the health benefits. The avoided mortality rates are generally higher for the lower population areas (Figure 21). The population-weighted avoided mortality rates ranged from 17.9 to 148 lives saved per one million people, increasing in the order: Russia (148) > Nigeria (25.8) > China (46.3) > the United States (17.9) (Figure 21 and Table 13). The lives saved are also directly proportional to the underlying background CVD mortality rates.

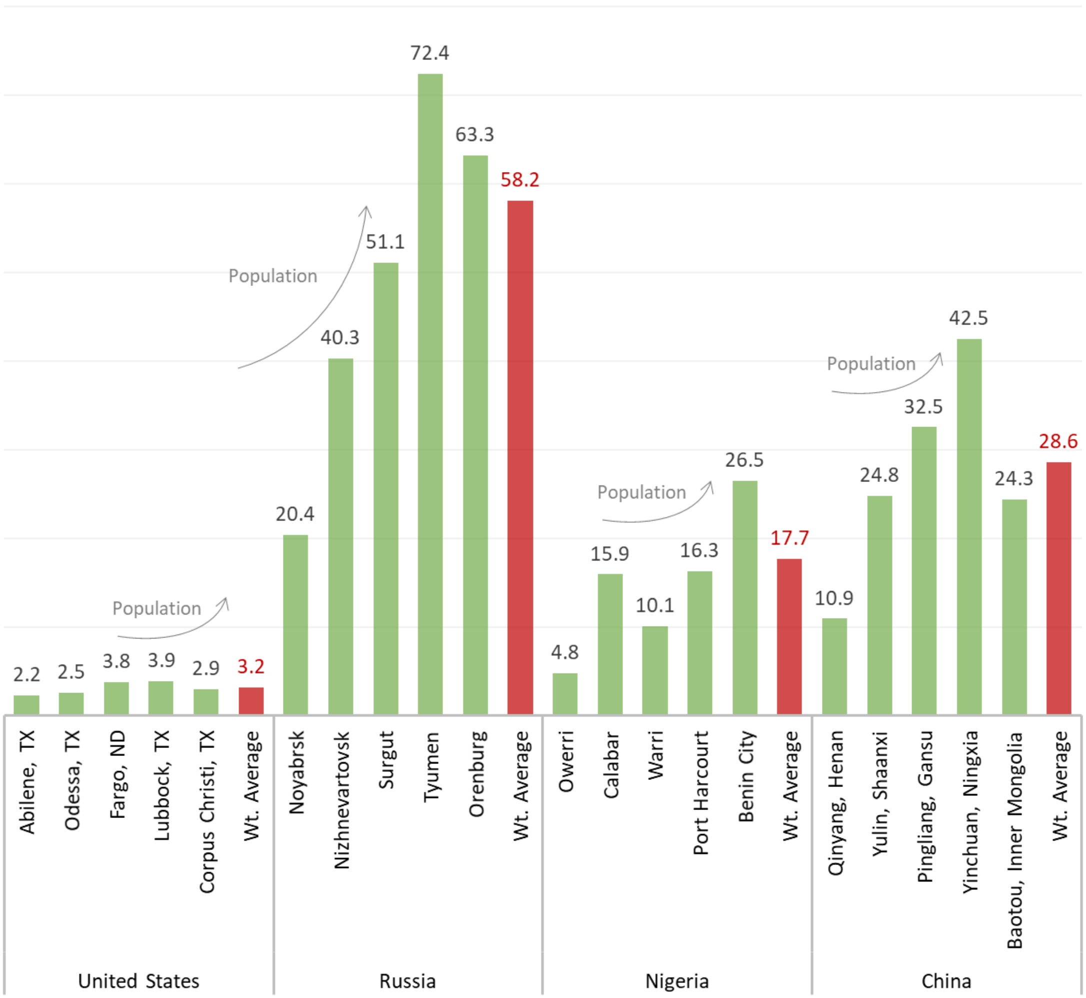


Figure 20. Avoided CVD-related mortality (lives saved) per year for selected cities in each chosen country per city's population due to displacing conventional fuels with synthetic fuels (17.5 million GGE).

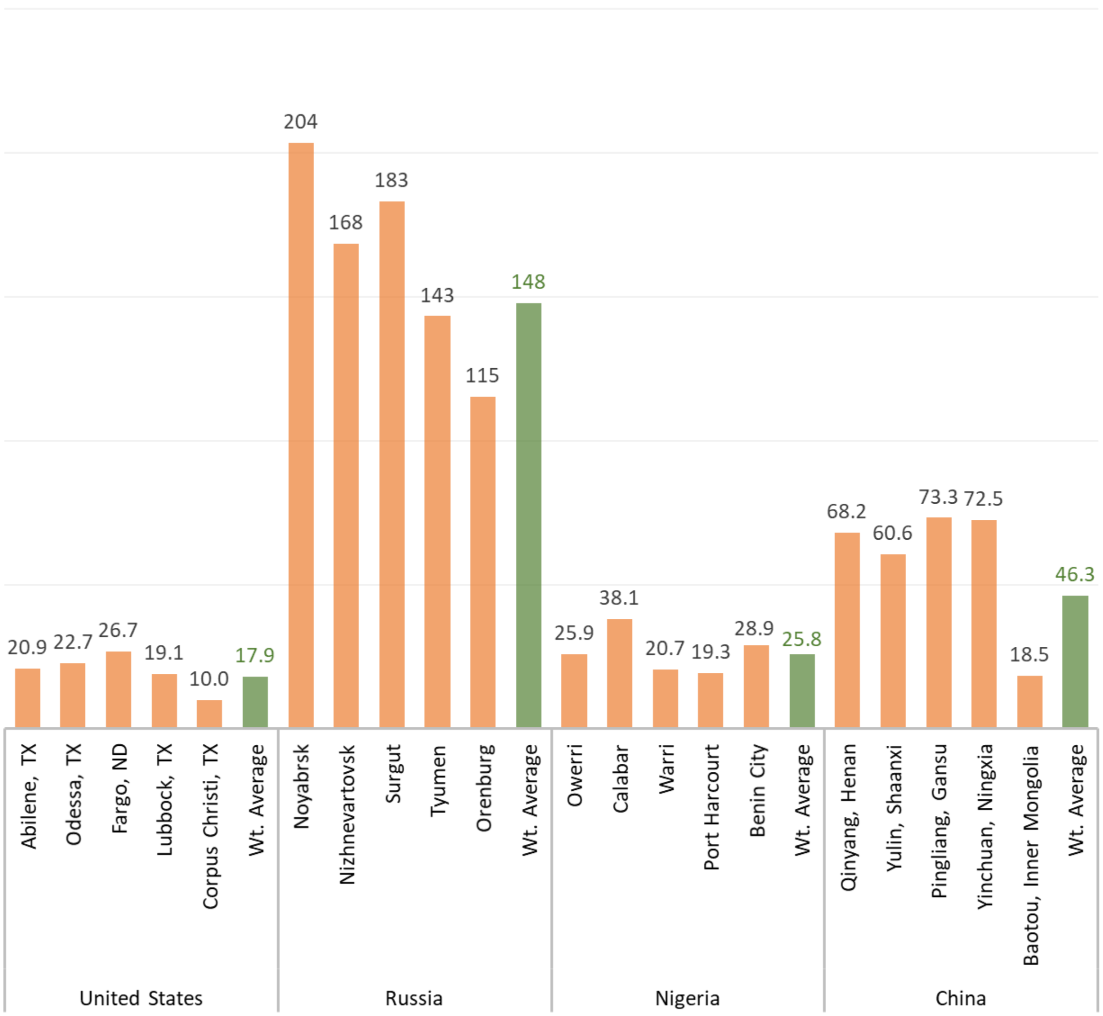


Figure 21. Avoided CVD-related mortality (lives saved) per year for selected cities in each chosen country per 1 million population caused by displacing conventional fuels with synthetic fuels (17.5 million GGE).

The number of lives saved or avoided mortality per year caused by the reduction in $PM_{2.5}$ concentration were monetized by estimating the value for statistical life saved (VSL). The VSL for the United States was $9 million per life saved. VSLs for other countries were determined using Equation (5) and the respective gross national income (GNI) per capita given in Table 7. The VSLs for Russia, Nigeria, and China were $2.96, $1.11, and $2.29 million per statistical life, respectively (Figure 22 and Table 13).

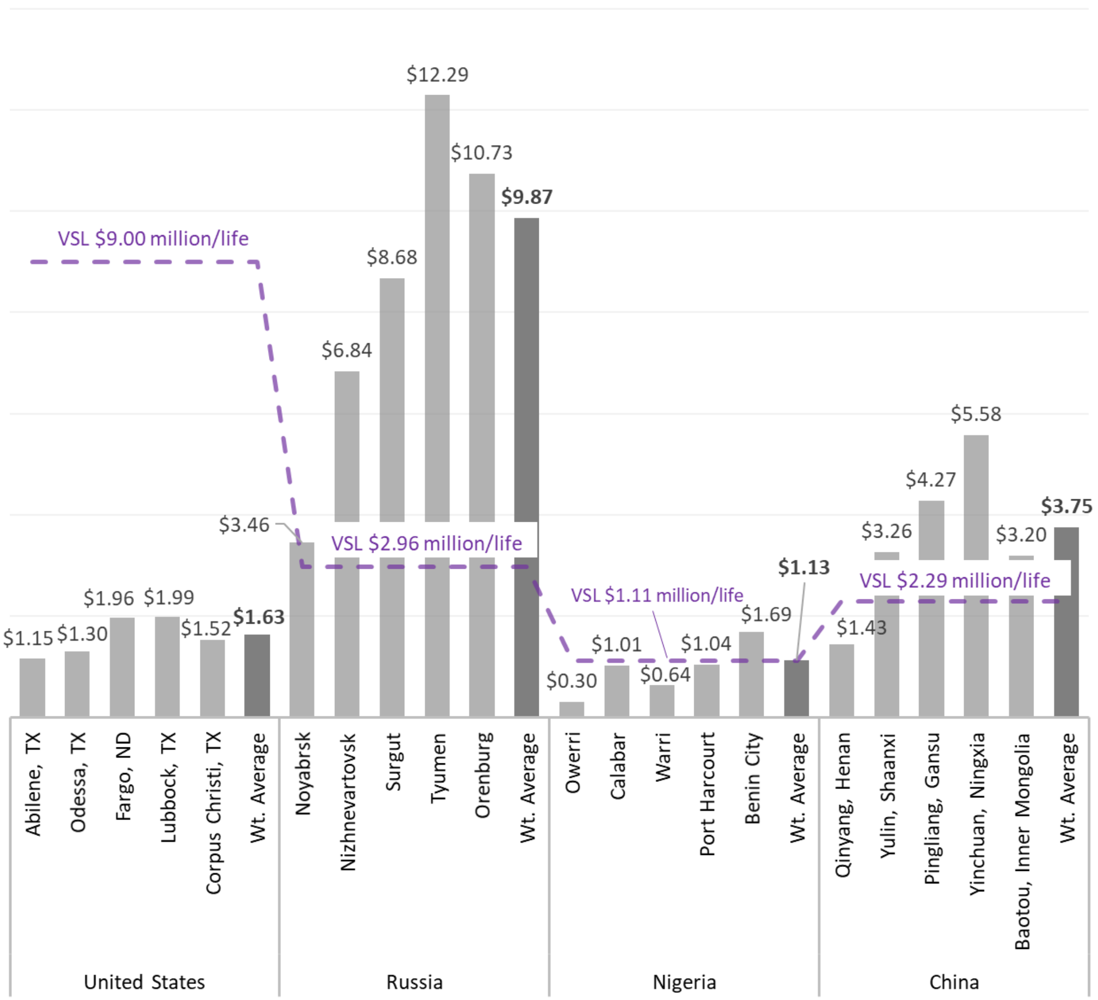


Figure 22. Monetized health benefits in \$/GGE and the value of a statistical life (VSL) in \$ millions per life saved per year.

Thus, a 1,000 bb/d GTL plant (17.5 million GGE synthetic fuel production capacity) in the United States potentially saves approximately 3.2 lives per year. With the VSL of \$9 million per life, the corresponding annual health benefits are roughly \$28.5 million or \$1.63/GGE. For simplicity, only the population-weighted average values are used for comparison and discussion.

Similarly, the annual health benefits for the other three countries were Russia ($172.3 million or $9.87/GGE), Nigeria ($19.7 million or $1.13/GGE), and China ($65.5 million or $3.75/GGE). The normalized $/GGE values indicate that the associated gas valorization for synthetic fuel production benefits most to Russia, followed by China, the United States, and Nigeria.

Table 13. Summary of health benefits from a 1,000 barrels per day GTL plant.

	United States	Russia	Nigeria	China
Background information				
Intake fraction (iF)[1]	3.40E-06	1.77E-05	4.21E-05	2.44E-05
Background CVD mortality rate (per 100,000)	243	855	110	305
Value of statistical life (VSL) ($ millions)	9.00	2.96	1.11	2.29
Change in $PM_{2.5}$ concentration				
$PM_{2.5}$ concentation reduction (μg/m^3)[1]	0.82	1.92	2.61	1.69
Avoided mortality				
Lives saved (per year)[1]	3.16	58.2	17.7	28.6
Lives saved (per 1 million per year)[1]	17.9	148.0	25.8	46.3
Lives saved (per million GGE)[1,2]	0.18	3.33	1.01	1.64
Health benefits				
Annual health benefits ($ millions)[1]	28.5	172.3	19.7	65.5
Annual health benefits ($/GGE)[1,2]	1.63	9.87	1.13	3.75

Notes

[1] Population weighted average

[2] Annual synthetic fuel production capacity 17.5 million GGE

Cost-Benefit Analysis Results

This study performed a cost-benefit analysis to assess and compare the value propositions of valorizing associated gas for transportation fuel production. The results can also help answer which country would benefit the most from the project investment. The synthetic fuel produced from associated gas via GTL technology included capital recovery charges, variable operating costs, and fixed operating costs, between $1.09 and $1.27 per GGE (Figure 23). The different product costs were due to differences in fixed operating costs (primarily labor costs and adjusted using GNI) and capital recovery charges (higher loan interest rates for emerging markets and developing countries compared to the United States).

The economic benefits are compared based on the net revenues, the net profits determined using each country's wholesale price of the fuels, and corporate tax rates (Table 14). China exhibited the highest economic benefits stemming from its relatively high fuel price ($4.63/GGE) and reasonable corporate tax rate (25%). In contrast, Nigeria’s low fuel price ($1.52/GGE) and high corporate tax rate (30%) hampered the country’s economic benefits from associated gas valorization (a mere $0.22/GGE). Consequently, the net revenues (economic benefits alone) increased in the order: China ($2.54/GGE) > the United States ($1.92/GGE) > Russia ($1.12/GGE) > Nigeria ($0.22/GGE).

Russia had the highest cardiovascular disease (CVD) mortality rate (855 deaths per 100,000 population) (Table 13). The substitution of conventional fuels with synthetic fuels potentially leads to lower $PM_{2.5}$ concentrations that help prevent cardiovascular diseases. Countries and communities with higher CVD-related mortality rates would benefit from the $PM_{2.5}$ concentration reduction more. Thus, associated gas valorization for transportation fuel production provided Russia with the highest potential health benefits. Besides the CVD mortality rate, the adjusted VSL also plays a significant role in health benefits quantification, as discussed in the next section on the United States and Nigeria comparison.

The climate benefits resulting from the averted greenhouse gas emissions were estimated using the country-level social cost of carbon (CSCC) (Table 14). The climate benefits shown in Figure 23 are after-tax benefits, the United States ($0.53/GGE), Russia (-$0.07/GGE), Nigeria ($0.25/GGE), and China ($0.33/GGE). The differences in country-level carbon prices and tax rates contributed to the differences in the climate benefits (Table 14). The United States had the highest climate benefits ($0.53/GGE). On the other hand, Russia exhibited a negative climate benefit (-$0.07/GGE), suggesting that the country would be penalized for facilitating climate mitigation or rewarded for releasing more greenhouse gases.

As a sensitivity analysis, climate benefits were also calculated using the global social cost of carbon (SCC). The inset in Figure 23 shows the results for this sensitivity analysis. Russia had a positive climate benefit of $0.60/GGE when using the SSC carbon price. Since the carbon price is identical for all countries ($51/t$CO_2$), the climate benefits were similar for the nations, and the differences are solely caused by the difference in tax rates.

The overall benefits presented in Figure 23 are the sum of economic benefits, health benefits, and climate benefits. The associated gas valorization benefited the countries to various extents, with the combined benefits increasing in the order: Russia ($10.92/GGE) > China ($6.62/GGE) > the United States ($4.07/GGE) > Nigeria ($1.60/GGE). The overall benefits for the scenario with climate benefits determined using SCC pricing are highlighted in red dash boxes for comparison.

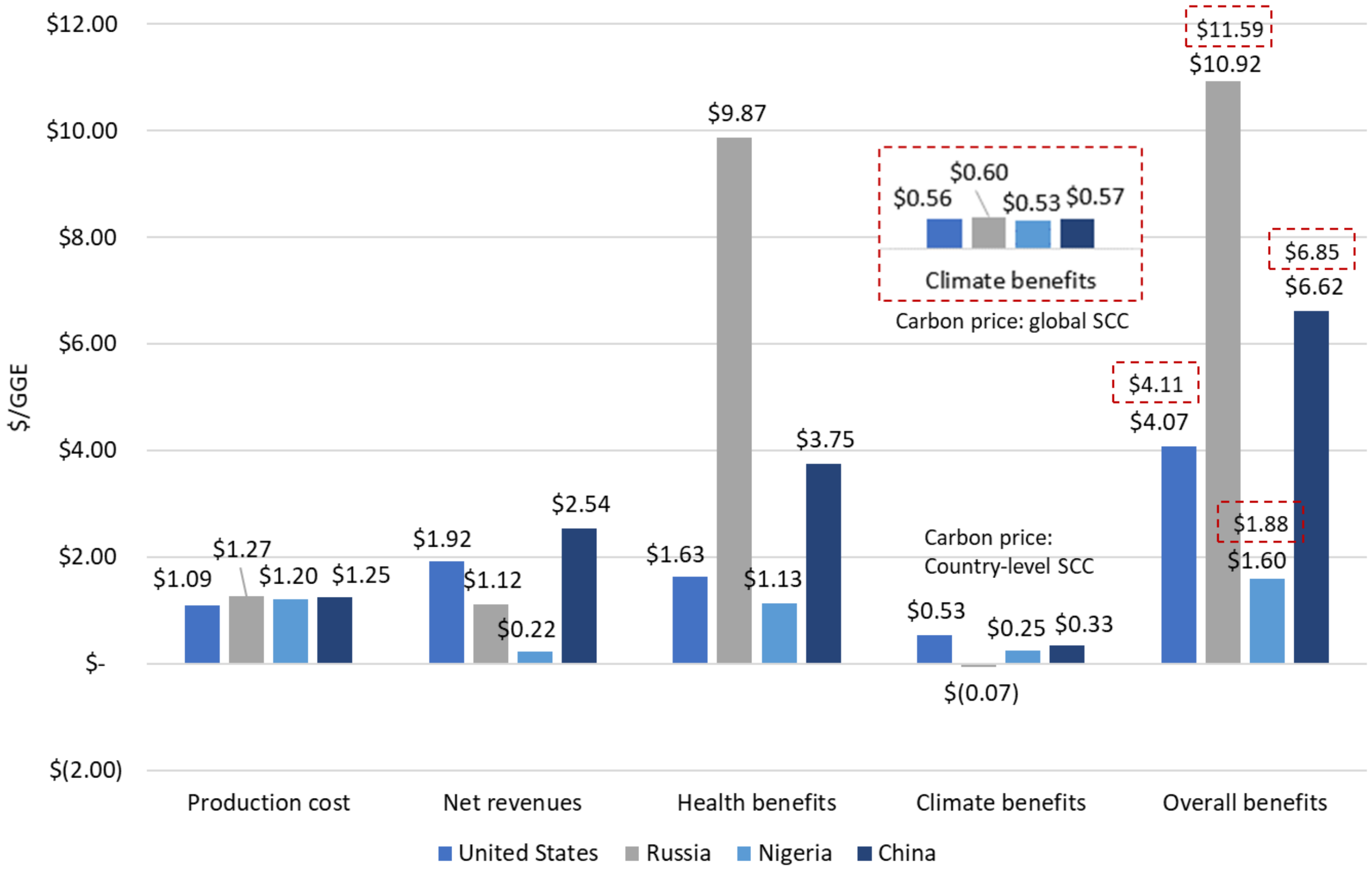


Figure 23. Breakdown of costs and benefits per GGE for associated gas valorization to synthetic fuels.
Climate benefits using global SCC and resulting overall benefits are highlighted in red dash line boxes.

Table 14. Summary and comparison of benefit-to-cost ratios (BCR).

	United States	Russia	Nigeria	China
Fuel wholesale price (\$/GGE)	3.68	2.67	1.52	4.63
Adjusted VSL (\$ millions/stastical life)	9.00	2.96	1.11	2.29
Corporate tax rates (%)	25.8	20.0	30.0	25.0
Country-level social cost of carbom (CSCC) (\$/tCO_2)	48.0	-5.5	24.0	30.0
Global social cost of carbom (SCC) (\$/tCO_2)	51.0	51.0	51.0	51.0
Benefit-to-cost ratio (BCR)				
BCR (economic benefits only)	1.75	0.88	0.19	2.04
BCR (economic + climate benefits)				
Cost of carbon: Country-level (CSCC)	2.24	0.83	0.39	2.31
Cost of carbon: global SCC	2.27	1.35	0.63	2.49
BCR (economic + climate + health benefits)				
Cost of carbon: Country-level (CSCC)	3.73	8.59	1.33	5.31
Cost of carbon: global SCC	3.76	9.11	1.57	5.50

Without the health and climate benefits (i.e., economic benefits only), the benefit-to-cost ratios (BCR) for the United States and China were 1.75 and 2.04, respectively (Figure 24 and Table 14). A BCR greater than 1.0 suggests that economic benefits are greater than the costs of the projects. On the other hand, the BCRs for Russia (0.88) and Nigeria (0.19) were below 1.0. The wholesale fuel prices for Russia (\$2.67/GGE) and Nigeria (\$1.52/GGE) were not high enough to generate enough revenues to cover the production costs.

The addition of climate benefits helped Russia to achieve BCR > 1.0 at 1.35 if using global SCC carbon price but did not help Nigeria's BCR, which remains below the threshold (BCR = 1.0) (Table 14).

The health benefits would be particularly significant to Russia and Nigeria, making the associated gas valorization project in Russia and Nigeria a good investment (BCR > 1.0). With the inclusion of health benefits, the BCR for all countries increased significantly. When considering all benefits, Russia had the highest BCR (8.59 or 9.11), followed by China (5.31 or 5.50) and the United States (3.73 or 3.76). Nigeria exhibited the lowest BCR (1.33 or 1.57). The first and second values in the parenthesis are for climate benefits obtained using CSCC and SCC carbon prices, respectively.

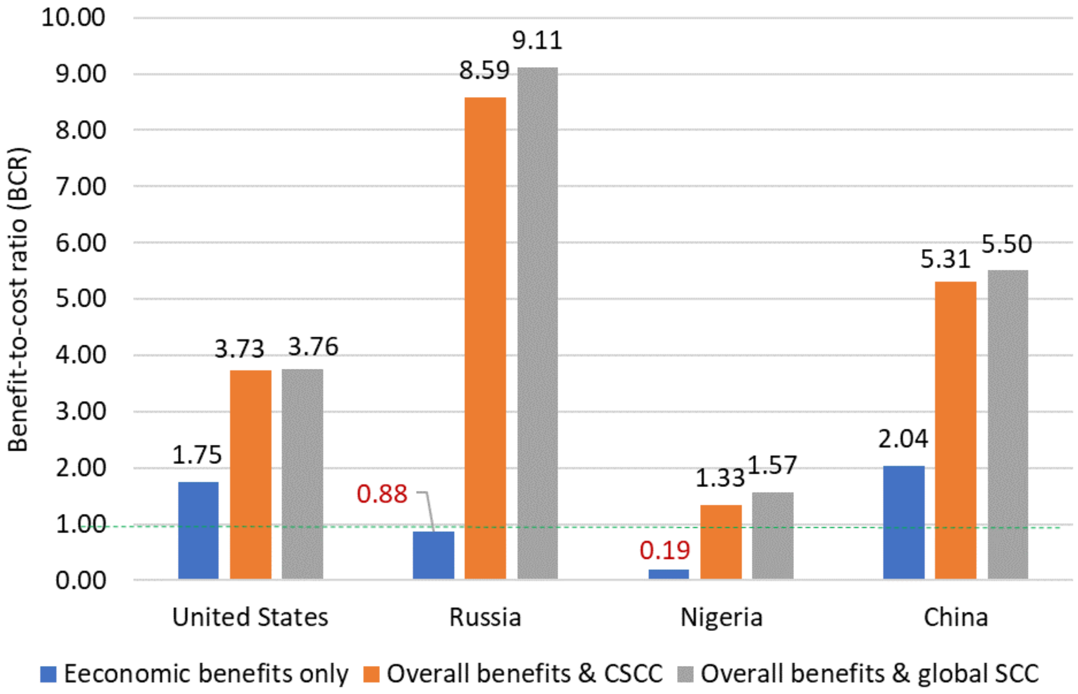


Figure 24. Benefit-to-cost ratio comparison.

Chapter IV

Discussion

Given the assumptions of this modeling, the conversion of associated gas to transportation fuels can be economically feasible for all evaluated countries, with positive revenues after tax. However, the positive after-tax revenues (or economic benefits) alone do not justify a good investment for all countries. The consideration is that an investment is justified if it has a benefit-to-cost ratio (BCR) > 1.0. Only the United States and China exhibited BCR > 1.0. Both Russia and Nigeria had BCR < 1.0. The local wholesale fuel prices for Russia and Nigeria were not high enough to generate enough revenues to cover the production costs. At the time of the study, China had the highest transportation fuel price ($4.63/GGE), and Nigeria has the lowest ($1.52/GGE). Nigeria will need to have a wholesale price of $2.91/GGE (about 192% of the current price) to achieve the BCR equal to one. Similarly, Russia's BCR breakeven wholesale price (to meet BCR = 1.0) is $2.86/GGE, a 107% increase from the current price. While fuel prices can be volatile at times, it would still be unusual for the prices to double in a short time.

Climate benefits, and to a much larger extent, health benefits, increase the value proposition for valorizing the associate gas for synthetic production. When considering all benefits, the BCRs for all countries exceeded 1.0. Both climate and health benefits come from the monetization of adverted greenhouse gas and criteria pollutant emissions. Liquid fuels derived from associated gas exhibit lower WTW lifecycle GHG emissions by nearly 100% and criteria air pollutants, e.g., PM, SO_2, and NOx, by greater than 300% compared to conventional petroleum fuels.

The baseline climate benefits were quantified using the country-level social cost of carbon (CSCC). CSCC accounts for the heterogeneous geography of climate damage and differences in country-level contributions to the global social cost of carbon, as well as climate and socio-economic uncertainties (Ricke et al., 2018). Therefore, the high country-level resolution is desirable because it allows for a more accurate evaluation of the impact of GHG reduction and is pertinent to the geographical impact comparison study. However, the negative CSCC carbon prices for countries like Russia (about 10% of the world population has a negative CSCC (Ricke et al., 2018)) because the expected benefits associated with additional GHG emissions lead to an unexpected conclusion, that is, negative climate benefits. Penalizing Russia for cutting CO_2 emissions to fight climate change suggests that climate change is good, which in essence, is illogical. Russia's negative climate benefits appear to be a technical artifact, and the country may need to have a minimum carbon cost. Thus, as a sensitivity study, the climate change benefits were monetized using the global social cost of carbon (SCC) (\$51/tCO_2), which is the same for all countries and is commonly employed to assess the expected economic damages from GHG emissions (Rennert et al., 2021). Future studies on climate benefit monetization can also consider the carbon prices that incorporate the costs of human mortality caused by climate change. For example, future studies can accomplish this by employing the new metric, the mortality cost of carbon (MCC), that estimates the number of deaths caused by every additional metric ton of CO_2 (Bressler, 2021).

In addition to climate benefits, this study also monetized avoided CVD-related mortality in terms of the value of a statistical life saved (VSL). The number of lives saved or avoided mortality per year results from reducing $PM_{2.5}$ concentration. The $PM_{2.5}$ concentration reduction is a function of intake fraction (iF), which positively correlates to the pollutant emitted (atmospheric emissions). More polluted countries tend to have higher iF and underlying CVD mortality rates. Therefore, at a given averted life cycle $PM_{2.5}$ emission, the extent of the $PM_{2.5}$ concentration reduction is more substantial and impactful for more polluted countries and consequently benefits these countries more in terms of the number of lives saved. Hence, the number of avoided mortalities is a function of both a country's background mortality rate as well as the $PM_{2.5}$ concentration reduction (see Table 13).

However, there is a lack of equivalence between the number of lives saved and the corresponding monetization of health benefits. While countries that are more polluted and higher in mortality rates will reap more significant health benefits in terms of lives saved due to converting associated gas to liquid fuels, countries with lower gross national income (GNI) per capita gain less in monetary terms. For example, Nigeria showed a 5.61 times higher avoided mortality than the United States, i.e., 17.7 versus 3.16 per year for a 1,000 bbl/d plant or 1.01 versus 0.18 per million GGE (Table 13 and Figure 25). Still, its health benefits were only 69% of the United States ($1.13/GGE versus $1.63/GGE). The asymmetry or disparity between lives saved and health benefits is attributed to the difference in the countries' different VSL values, $9 million per life for the United States and $1.11 million per life for Nigeria (nearly 88% lower) (Table 13). It is not disputable that human lives saved are more important than money. It is more important to emphasize the benefits of lives saved than in dollar equivalents. The latter can be deceiving and is likely to misinterpret the actual health impact comparison, highlighting the limitation of using country-level adjusted VSL (based on gross national income per capita) as a metric for health benefits. The US EPA has attempted to change the terminology when valuing changes in mortality risk, from "value of statistical life" (VSL) to "value of mortality risk" (VMR) (US EPA, 2014). This attempted change is to convey the health risk changes better, and also avoid confusion (i.e., a study sets a "price" on the individual lives). VSL and VMR use different units to aggregate and report the risk changes. VSL uses dollars per statistical death per year, and VMR uses dollars per micro-risk per person per year, where a "micro-risk" means a one in a million chance of dying.

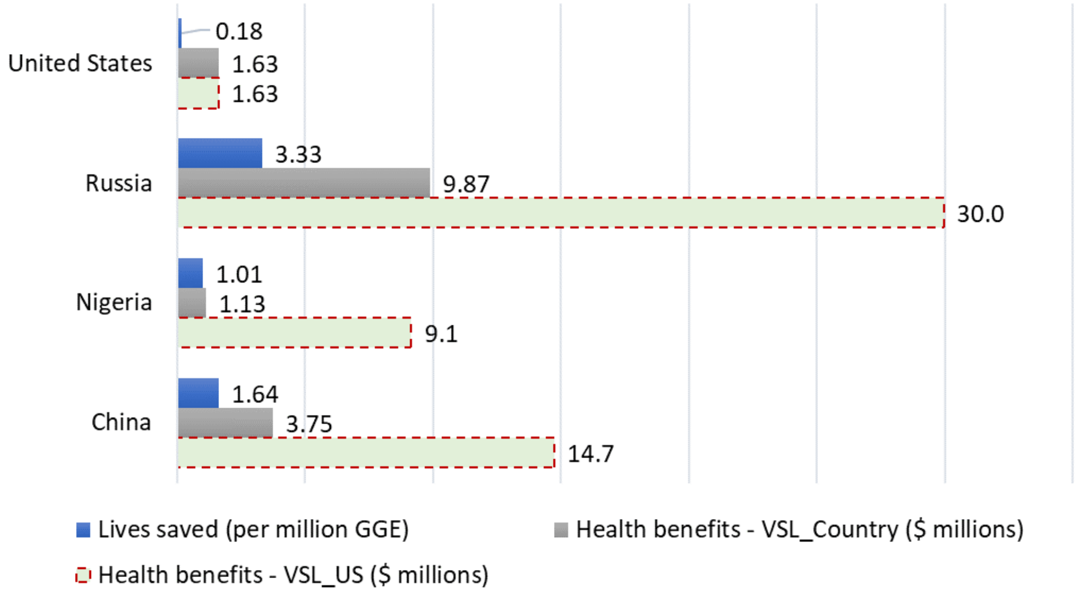


Figure 25. Asymmetry between lives saved and health benefits in monetary terms. *Comparison of health benefits obtained based on individual country's VSL and the assumption that all countries have the same VSL as the United States ($9 million/life).*

Research Limitations

The research limitations of this study were mainly related to data availability. For instance, the current gas compositions for gas flares are not readily available. Associated gas compositions from wellheads in this study were obtained from the literature and limited to selected geographical areas. The average derived compositions likely might deviate from the exact compositions for the local wellheads. Other important data, such as flaring efficiencies, emission data, and GTL performance, also needed to rely on assumptions and results from published literature to fill the data gaps. Thus, the uncertainty for the critical data was characterized (Appendix 1).

Although this study could benefit from more accurate local data, and the results are subject to a range of assumptions and uncertainties, the study answered the critical research questions on the sustainability benefits (i.e., value propositions) of utilizing associated gas for the production of transportation fuels instead of flaring, and the impacts of geographical differences on the health benefits.

Conclusions

This study investigated the three core aspects of sustainability (economic, environmental, and social) associated with the valorization of associated gas to produce transportation fuels. The study also considered the impact of geographical differences on these benefits by comparing the United States, Russia, Nigeria, and China. The cost-benefit analysis results demonstrate that the conversion of associated gas to transportation fuels can be a feasible economic proposition. Moreover, the contribution from the climate (carbon credits) and health benefits are critical.

The LCA results show that direct associated gas conversion to fuels exhibit lower life cycle GHG and criteria air pollutant emissions than gas flaring. More importantly, countries that are more polluted and higher in mortality rates reap greater health benefits from converting associated gas to liquid fuels that displace the conventional fuels.

China benefited the most from the economic benefits due to higher fuel selling prices. Conversely, Nigeria's relatively low fuel price impeded its economic benefit potential. The synthetic fuel production costs were similar for all countries; the differences are primarily attributed to labor costs. Additionally, the climate benefits were similar for all countries if the study used the global social cost of carbon to monetize adverted GHG emissions; the differences are due to different tax rates. However, when using the country-level social cost of carbon, the climate benefits were drastically different due to carbon prices and tax rates.

Furthermore, health benefits were directly proportional to local air pollution levels, CVD mortality rates, and population density. All compared countries benefited from reducing $PM_{2.5}$ concentration, leading to avoided mortality, ranging from about 18 lives saved per million people in the United States to 148 lives saved per million in Russia. When assessing and comparing the health benefits, the focus should be more on the number of avoided mortality than the value of the statistical lives saved, which can be deceiving as it ties to the country's economic strengths and standard of living (i.e., gross national income).

The overall sustainability benefits may encourage the industry to switch from gas flaring to liquid fuel production and provide regulators guidance to set policies that favor associated gas utilization. The results, especially the potential lives saved, could also convince international financial institutions such as the World Bank to offer low-interest loans and grants to facilitate retrofits in the oil sector. The flaring countries, particularly those that are more polluted and less developed, could use these loans or grants to construct more small-scale facilities to valorize associated gas to produce transportation fuels.

Appendix 1

Uncertainty Characterization

Input data used in this study were obtained from various sources and could influence the reliability and applicability of the results. Therefore, this study performed an uncertainty analysis to assess the critical data quality's uncertainty using a data quality pedigree matrix with five data quality indicators: reliability, completeness, temporal, geographical, and technological correlations (Weidema & Wesnæs, 1996). The approach assumes a lognormal distribution, which a standard deviation can characterize. For a lognormal distribution, the geometric standard deviation (GSD) covers the 95% confidence interval (CI), often reported as 95% CI [LL, UL], with LL as the lower limit and UL as the upper limit of the interval. LL and UL are the mean value divided by the GSD and the mean value times the GSD, respectively. GSD can be estimated according to the pedigree matrix developed by Weidema (1996) using Equation 6.

$$(1 + C_V) = \exp[\ \sqrt{([\ln(U_1)]^2 + [\ln(U_2)]^2 + [\ln(U_3)]^2 + [\ln(U_4)]^2 + [\ln(U_5)]^2 + [\ln(U_6)]^2 + [\ln(U_b)]^2}\ ] \qquad (6)$$

C_V is the coefficient of variation. The factors $U_1 - U_6$ refer to the uncertainty factors of reliability (1), completeness (2), temporal correlation (3), geographical correlation (4), technology correlation (5), and sample size, respectively. U_b refers to the basic uncertainty factor (see Table 15).

Table 15. Pedigree matrix with five data quality indicators.

Indicator score	1	2	3	4	5
Reliability (U_1)	Verified data based on measurement	Verified data is partly based on assumptions or non-verified data based on measurements.	Non-verified data is partly based on assumptions.	Qualified estimate (e.g., by an industrial expert)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
Completeness (U_2)	Representative data from a sufficient sample of sites to even out normal fluctuations over an adequate period.	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from a sufficient number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites or shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
Temporal correlation (U_3)	Less than three years of difference to the year of study	Less than six years difference	Less than ten years difference	Less than 15 years difference	Age of data unknown or more than 15 years of difference
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
Geographical correlation (U_4)	Data from the area under study	Average data from a larger area in which the area under study is included	Data from a place with similar production conditions	Data from a site with slightly similar production conditions	Data from an unknown area or an area with very different production conditions
	1.00	**1.01**	**1.02**	**1.05**	**1.10**
Technological correlation (U_5)	Data from enterprises, processes, and materials under study	Data from processes and materials under investigation but from different enterprises	Data from processes and materials under study but from other technology	Data on related processes or materials but the same technology	Data on related processes or materials but different technology
	1.00	**1.10**	**1.20**	**1.50**	**2.00**
Sample size (U_b)	>100, continuous measurement, the balance of purchased products	> 20	>10, aggregated figure in an environmental report	≥ 3	Unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

Source: (Weidema & Wesnæs, 1996). Values in bold are the default uncertainty factors applied together with a matrix of data quality indicators.

Table 16. Uncertainty characterization of associated gas composition at wellheads.

Item	Mean	Source	Statistical Distribution	Data Quality Index	Geometric Standard Deviation (1 + Cv)	2.5th Percentile	97.5th Percentile	Standard Deviation in the Risk Solver System
Methane (CH_4), wt%	70.62	Weighted average	Lognormal	(2,2,3,2,2)	1.167	60.52	82.41	11.78
Ethane (C_2H_6), wt%	10.08	Weighted average	Lognormal	(2,2,3,2,2)	1.167	8.64	11.76	1.68
Propane (C_3H_8), wt%	7.02	Weighted average	Lognormal	(2,2,3,2,2)	1.167	6.02	8.19	1.17
Butane (C_4H_{10}), wt%	4.70	Weighted average	Lognormal	(2,2,3,2,2)	1.167	4.03	5.49	0.78
Pentane (C_5H_{12}), wt%	2.23	Weighted average	Lognormal	(2,2,3,2,2)	1.167	1.91	2.60	0.37
Carbon dioxide (CO_2), wt%	3.85	Weighted average	Lognormal	(2,2,3,2,2)	1.167	3.30	4.49	0.64
Nitrogen (N_2), wt%	1.45	Weighted average	Lognormal	(2,2,3,2,2)	1.167	1.24	1.69	0.24
Hydrogen sulfide (H_2S), wt%	0.04	Weighted average	Lognormal	(2,2,3,2,2)	1.167	0.04	0.05	0.01
Lower heating value (LHV), MJ/kg	46.51	Weighted average	Lognormal	(2,2,3,2,2)	1.167	39.86	54.27	7.76
Higher heating value (HHV), MJ/kg	51.37	Weighted average	Lognormal	(2,2,3,2,2)	1.167	44.02	59.94	8.57

Data quality index (DQI) was obtained according to the pedigree matrix. The standard deviation in the risk solver system is equal to the mean times the coefficient of variation (C_V).

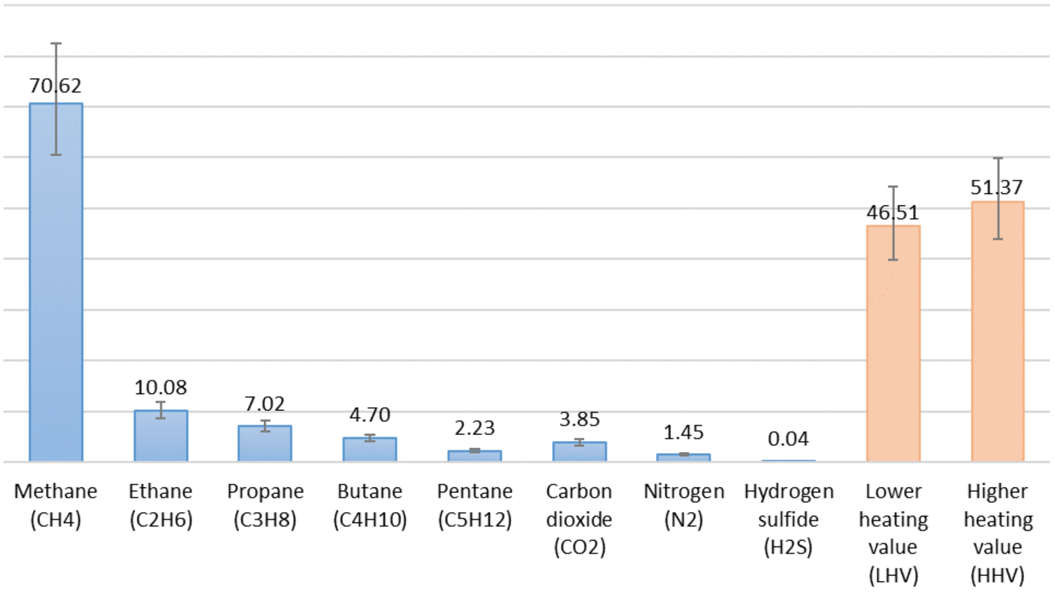


Figure 26. Average associated flare gas composition and heating values.
The "error bars" of the gas composition (in wt%) and heating values (in MJ/kg) represent the 95% confidence intervals around them.

Table 17. Uncertainty characterization of key input data associated with GTL synthetic fuel production costs and revenues, costs of carbon, and health benefits.

Item	Mean	Source	Statistical Distribution	Data Quality Index	Geometric Standard Deviation (1 + Cv)	2.5th Percentile	97.5th Percentile	Standard Deviation in the Risk Solver System
Associated gas to synthetic fuels energy conversion efficiency (%)	44.29	Average	Lognormal	(2,3,3,3,1)	1.139	38.88	50.47	6.17
Specific GTL capital cost ($ thoudsans per barrel per day)	65.00	Average	Lognormal	(4,3,3,2,1)	1.244	52.26	80.84	15.84
Capital recovery factor (CRF) - the United States (%)	8.02	Average	Lognormal	(3,5,5,1,1)	1.580	5.08	12.68	4.66
Capital recovery factor (CRF) - other countries (%)	13.39	Average	Lognormal	(3,5,5,1,1)	1.580	8.47	21.16	7.77
GTL variable operating costs ($ millions per year)	2.02	Average	Lognormal	(2,3,3,3,1)	1.139	1.77	2.30	0.28
Fuel wholesale price - the United States ($/GGE)	3.68	Average	Lognormal	(1,1,2,1,1)	1.062	3.46	3.90	0.23
Fuel wholesale price - Russia ($/GGE)	2.67	Average	Lognormal	(1,1,2,1,1)	1.062	2.51	2.83	0.17
Fuel wholesale price - Nigeria ($/GGE)	1.52	Average	Lognormal	(1,1,2,1,1)	1.062	1.43	1.61	0.09
Fuel wholesale price - China ($/GGE)	4.63	Average	Lognormal	(1,1,2,1,1)	1.062	4.36	4.92	0.29
Corporate tax rate - the United States (%)	25.77	Average	Lognormal	(1,1,2,1,1)	1.062	24.26	27.37	1.60
Corporate tax rate - Russia (%)	20.00	Average	Lognormal	(1,1,2,1,1)	1.062	18.83	21.24	1.24
Corporate tax rate - Nigeria (%)	30.00	Average	Lognormal	(1,1,2,1,1)	1.062	28.24	31.87	1.87
Corporate tax rate - China (%)	25.00	Average	Lognormal	(1,1,2,1,1)	1.062	23.54	26.56	1.56
Country-level social cost of carbon (CSCC) - the United States ($\$/tCO_2$)	48.00	Average	Lognormal	(2,2,1,2,2)	1.129	42.51	54.19	6.19
Country-level social cost of carbon (CSCC) - Russia ($\$/tCO_2$)	-5.50	Average	Lognormal	(2,2,1,2,2)	1.129	-4.87	-6.21	-0.71
Country-level social cost of carbon (CSCC) - Nigeria ($\$/tCO_2$)	24.00	Average	Lognormal	(2,2,1,2,2)	1.129	21.26	27.10	3.10
Country-level social cost of carbon (CSCC) - China ($\$/tCO_2$)	30.00	Average	Lognormal	(2,2,1,2,2)	1.129	26.57	33.87	3.87
Social cost of carbon (SCC) - all countries (t/CO_2)	51.00	Average	Lognormal	(2,2,1,2,2)	1.129	45.17	57.58	6.58
Infraction ($PM_{2.5}$, transportation) - the United States	3.40E-06	Weighted Average	Lognormal	(2,2,3,2,2)	1.167	2.91E-06	3.96E-06	5.67E-07
Infraction ($PM_{2.5}$, transportation) - Russia	1.77E-05	Weighted Average	Lognormal	(2,2,3,2,2)	1.167	1.52E-05	2.07E-05	2.96E-06
Infraction ($PM_{2.5}$, transportation) - Nigeria	4.21E-05	Weighted Average	Lognormal	(2,2,3,2,2)	1.167	3.61E-05	4.92E-05	7.03E-06
Infraction ($PM_{2.5}$, transportation) - China	2.44E-05	Weighted Average	Lognormal	(2,2,3,2,2)	1.167	2.09E-05	2.85E-05	4.07E-06
Cardiovascular diseases - the United States (per 100,000 popuation)	242.63	Average	Lognormal	(2,2,3,2,2)	1.167	207.94	283.12	40.48
Cardiovascular diseases - Russia (per 100,000 population)	854.56	Average	Lognormal	(2,2,3,2,2)	1.167	732.36	997.15	142.59
Cardiovascular diseases - Nigeria (per 100,000 population)	109.65	Average	Lognormal	(2,2,3,2,2)	1.167	93.97	127.94	18.30
Cardiovascular diseases - China (per 100,000 population)	305.22	Average	Lognormal	(2,2,3,2,2)	1.167	261.58	356.15	50.93
Average breathing rate (m^3/person/day)	20.00	Average	Lognormal	(2,2,3,2,2)	1.167	17.14	23.34	3.34
Percent increase of CVD mortality of 10 $\mu g/m^3$ of $PM_{2.5}$ concentration	9.00	Average	Lognormal	(2,2,3,2,2)	1.167	7.71	10.50	1.50

Table 18. Uncertainty characterization of the emission factors for the WTW life cycle stages of synthetic fuels (in g/MJ).

Item	Mean	Source	Statistical Distribution	Data Quality Index	Geometric Standard Deviation (1 + Cv)	2.5th Percentile	97.5th Percentile	Standard Deviation in the Risk Solver System
Associated gas production								
Methane (CH_4)	0.37	Average	Lognormal	(2,2,3,3,2)	1.168	0.32	0.43	0.06
Carbon dioxide (CO_2)	4.54	Average	Lognormal	(2,2,3,3,2)	1.168	3.89	5.30	0.76
Associated gas flaring								
Methane (CH_4)	1.71	Average	Lognormal	(3,4,3,3,2)	1.220	1.40	2.09	0.38
Carbon dioxide (CO_2)	124.40	Average	Lognormal	(3,4,3,3,2)	1.220	101.98	151.75	27.35
Particulate matter ($PM_{2.5}$)	0.14	Average	Lognormal	(3,4,3,3,2)	1.220	0.11	0.17	0.03
Nitrogen oxides (NO_x)	15.06	Average	Lognormal	(3,4,3,3,2)	1.220	12.34	18.37	3.31
Carbo monoxide (CO)	8.17	Average	Lognormal	(3,4,3,3,2)	1.220	6.70	9.97	1.80
Sulfur dioxide (SO_2)	0.04	Average	Lognormal	(3,4,3,3,2)	1.220	0.03	0.05	0.01
Synthetic fuel production								
Methane (CH_4)	1.06E-03	Average	Lognormal	(3,4,3,1,1)	1.189	8.92E-04	1.26E-03	2.01E-04
Carbon dioxide (CO_2)	60.19	Average	Lognormal	(3,4,3,1,1)	1.189	50.61	71.57	11.39
Particulate matter ($PM_{2.5}$)	7.80E-04	Average	Lognormal	(3,4,3,1,1)	1.189	6.56E-04	9.27E-04	1.48E-04
Nitrogen oxides (NO_x)	9.74E-04	Average	Lognormal	(3,4,3,1,1)	1.189	8.19E-04	1.16E-03	1.84E-04
Carbo monoxide (CO)	1.30E-03	Average	Lognormal	(3,4,3,1,1)	1.189	1.09E-03	1.55E-03	2.46E-04
Sulfur dioxide (SO_2)	0.02	Average	Lognormal	(3,4,3,1,1)	1.189	0.02	0.02	3.97E-03
Fuel distribution								
Methane (CH_4)	3.44E-04	Average	Lognormal	(3,5,2,4,1)	1.246	2.76E-04	4.28E-04	8.46E-05
Carbon dioxide (CO_2)	0.26	Average	Lognormal	(3,5,2,4,1)	1.246	0.21	0.32	0.06
Particulate matter (PM_{10})	6.39E-05	Average	Lognormal	(3,5,2,4,1)	1.246	5.13E-05	7.97E-05	1.57E-05
Particulate matter ($PM_{2.5}$)	5.39E-05	Average	Lognormal	(3,5,2,4,1)	1.246	4.33E-05	6.72E-05	1.33E-05
Nitrogen oxides (NO_x)	1.45E-03	Average	Lognormal	(3,5,2,4,1)	1.246	1.16E-03	1.81E-03	3.57E-04
Carbo monoxide (CO)	3.57E-04	Average	Lognormal	(3,5,2,4,1)	1.246	2.87E-04	4.45E-04	8.79E-05
Sulfur dioxide (SO_2)	2.30E-04	Average	Lognormal	(3,5,2,4,1)	1.246	1.85E-04	2.87E-04	5.66E-05
Voltatile organic compounds (VOC)	9.19E-04	Average	Lognormal	(3,5,2,4,1)	1.246	7.38E-04	1.15E-03	2.26E-04
Vehicle operation								
Methane (CH_4)	0.02	Average	Lognormal	(3,5,2,4,1)	1.246	0.02	0.03	0.01
Carbon dioxide (CO_2)	73.23	Average	Lognormal	(3,5,2,4,1)	1.246	58.78	91.24	18.01
Particulate matter (PM_{10})	6.02E-03	Average	Lognormal	(3,5,2,4,1)	1.246	4.84E-03	7.51E-03	1.48E-03
Particulate matter ($PM_{2.5}$)	2.47E-03	Average	Lognormal	(3,5,2,4,1)	1.246	1.98E-03	3.08E-03	6.08E-04
Nitrogen oxides (NO_x)	0.03	Average	Lognormal	(3,5,2,4,1)	1.246	0.03	0.04	0.01
Carbo monoxide (CO)	0.71	Average	Lognormal	(3,5,2,4,1)	1.246	0.57	0.89	0.18
Voltatile organic compounds (VOC)	0.04	Average	Lognormal	(3,5,2,4,1)	1.246	0.03	0.05	0.01

Table 19. Uncertainty characterization of the emission factors for conventional fuels' WTW life cycle stages (in g/MJ).

Item	Mean	Source	Statistical Distribution	Data Quality Index	Geometric Standard Deviation (1 + Cv)	2.5th Percentile	97.5th Percentile	Standard Deviation in the Risk Solver System
Conventional crude oil production								
Methane (CH_4)	8.31E-02	Average	Lognormal	(2,1,2,2,1)	1.081	7.68E-02	8.98E-02	6.76E-03
Carbon dioxide (CO_2)	4.89E+00	Average	Lognormal	(2,1,2,2,1)	1.081	4.52	5.29	0.40
Particulate matter (PM_{10})	6.85E-04	Average	Lognormal	(2,1,2,2,1)	1.081	6.33E-04	7.41E-04	5.57E-05
Particulate matter ($PM_{2.5}$)	5.71E-04	Average	Lognormal	(2,1,2,2,1)	1.081	5.28E-04	6.18E-04	4.65E-05
Nitrogen oxides (NO_x)	1.50E-02	Average	Lognormal	(2,1,2,2,1)	1.081	1.39E-02	1.62E-02	1.22E-03
Carbo monoxide (CO)	7.47E-03	Average	Lognormal	(2,1,2,2,1)	1.081	6.91E-03	8.08E-03	6.09E-04
Sulfur dioxide (SO_2)	4.45E-03	Average	Lognormal	(2,1,2,2,1)	1.081	4.11E-03	4.81E-03	3.62E-04
Voltatile organic compounds (VOC)	3.51E-03	Average	Lognormal	(2,1,2,2,1)	1.081	3.25E-03	3.80E-03	2.86E-04
Conventional fuel production								
Methane (CH_4)	1.58E-02	Average	Lognormal	(2,1,2,2,1)	1.081	1.46E-02	1.71E-02	1.29E-03
Carbon dioxide (CO_2)	7.93E+00	Average	Lognormal	(2,1,2,2,1)	1.081	7.33E+00	8.57E+00	6.45E-01
Particulate matter (PM_{10})	7.89E-04	Average	Lognormal	(2,1,2,2,1)	1.081	7.30E-04	8.53E-04	6.42E-05
Particulate matter ($PM_{2.5}$)	6.66E-04	Average	Lognormal	(2,1,2,2,1)	1.081	6.16E-04	7.20E-04	5.42E-05
Nitrogen oxides (NO_x)	6.47E-03	Average	Lognormal	(2,1,2,2,1)	1.081	5.98E-03	7.00E-03	5.27E-04
Carbo monoxide (CO)	4.30E-03	Average	Lognormal	(2,1,2,2,1)	1.081	3.97E-03	4.64E-03	3.50E-04
Sulfur dioxide (SO_2)	2.68E-03	Average	Lognormal	(2,1,2,2,1)	1.081	2.48E-03	2.90E-03	2.18E-04
Voltatile organic compounds (VOC)	6.21E-03	Average	Lognormal	(2,1,2,2,1)	1.081	5.74E-03	6.72E-03	5.06E-04
Fuel distribution								
Methane (CH_4)	3.44E-04	Average	Lognormal	(3,5,2,4,1)	1.246	2.76E-04	4.28E-04	8.46E-05
Carbon dioxide (CO_2)	2.56E-01	Average	Lognormal	(3,5,2,4,1)	1.246	0.21	0.32	0.06
Particulate matter (PM_{10})	6.39E-05	Average	Lognormal	(3,5,2,4,1)	1.246	5.13E-05	7.97E-05	1.57E-05
Particulate matter ($PM_{2.5}$)	5.39E-05	Average	Lognormal	(3,5,2,4,1)	1.246	4.33E-05	6.72E-05	1.33E-05
Nitrogen oxides (NO_x)	1.45E-03	Average	Lognormal	(3,5,2,4,1)	1.246	1.16E-03	1.81E-03	3.57E-04
Carbo monoxide (CO)	3.57E-04	Average	Lognormal	(3,5,2,4,1)	1.246	2.87E-04	4.45E-04	8.79E-05
Sulfur dioxide (SO_2)	2.30E-04	Average	Lognormal	(3,5,2,4,1)	1.246	1.85E-04	2.87E-04	5.66E-05
Voltatile organic compounds (VOC)	9.19E-04	Average	Lognormal	(3,5,2,4,1)	1.246	7.38E-04	1.15E-03	2.26E-04
Vehicle operation								
Methane (CH_4)	2.27E-02	Average	Lognormal	(3,5,2,4,1)	1.246	1.82E-02	2.83E-02	5.58E-03
Carbon dioxide (CO_2)	7.32E+01	Average	Lognormal	(3,5,2,4,1)	1.246	58.78	91.24	18.01
Particulate matter (PM_{10})	6.02E-03	Average	Lognormal	(3,5,2,4,1)	1.246	4.84E-03	7.51E-03	1.48E-03
Particulate matter ($PM_{2.5}$)	2.47E-03	Average	Lognormal	(3,5,2,4,1)	1.246	1.98E-03	3.08E-03	6.08E-04
Nitrogen oxides (NO_x)	3.32E-02	Average	Lognormal	(3,5,2,4,1)	1.246	2.66E-02	4.14E-02	8.17E-03
Carbo monoxide (CO)	7.15E-01	Average	Lognormal	(3,5,2,4,1)	1.246	5.74E-01	8.90E-01	1.76E-01
Sulfur dioxide (SO_2)	3.75E-04	Average	Lognormal	(3,5,2,4,1)	1.246	3.01E-04	4.67E-04	9.21E-05
Voltatile organic compounds (VOC)	3.62E-02	Average	Lognormal	(3,5,2,4,1)	1.246	2.91E-02	4.51E-02	8.91E-03

Appendix 2

Sensitivity Analysis of Global Warming Time Horizon

Global warming potentials (GWPs) are relative to CO_2, and as a result, GWPs based on a shorter timeframe is larger for gases with shorter lifetimes than CO_2. For example, greenhouse gas methane (CH_4), which has a relatively short atmospheric lifetime and is more potent compared to CO_2, its GWP value for the 100-year is 35, which is much smaller than the 20-year GWP value of 85 according to IPCC Fifth Assessment Report (IPCC, 2014). As methane emissions are a key contributor to climate change and the ongoing debate on using a 100-year time frame to quantify its impact (Balcombe et al., 2018), GWPs based on both 20-year and 100-year time horizons were determined (for comparison and result robustness (using GREET (Argonne National Laboratory, 2020). The displacement of conventional fuels with synthetic fuels derived from associated gas will result in a GWP reduction of 222% for GWP (20-year) and 141% for GWP (100-year), as depicted in Figure 27.

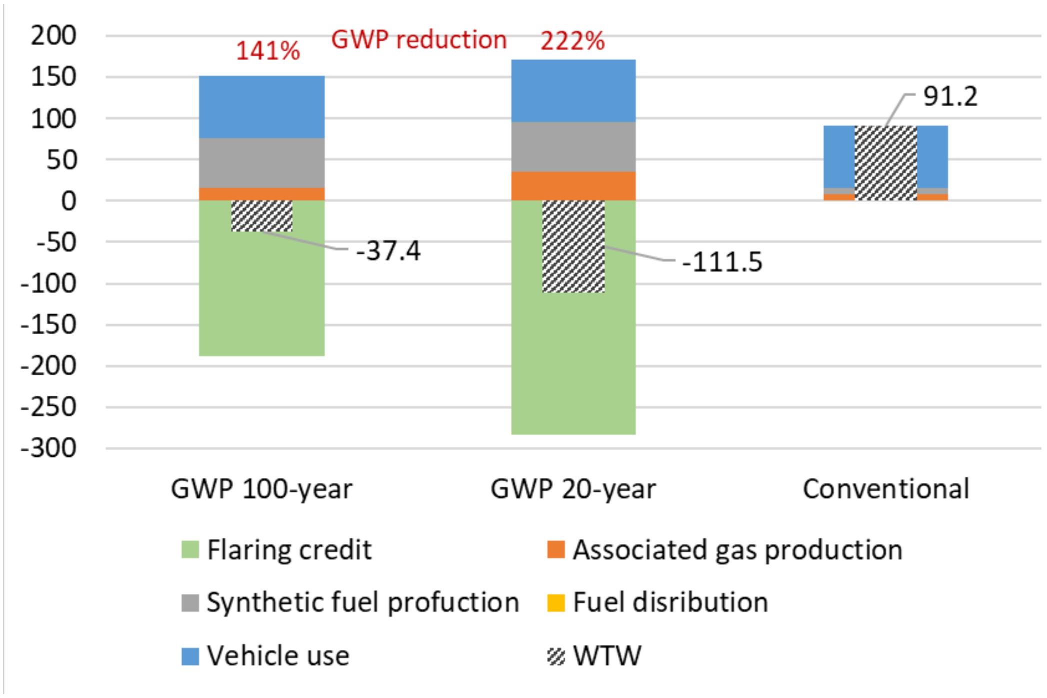


Figure 27. Sensitivity analysis on GWPs based on both 20-year and 100-year time horizons.

Appendix 3

Supplementary Information

Table 20. Associated gas properties, synthetic fuel properties, and GTL production assumptions.

Associated gas properties	Values	Units
Lower heating value (LHV)	46.51	MJ/kg
Density	0.82	kg/m^3 (1 atm, 60 ºF)
Energy density	38.13	MJ/m^3 (1 atm, 60 ºF)
Synthetic fuel properties	**Values**	**Units**
Synthetic gasoline	6352.92	MJ/bbl
Synthetic diesel	5471.38	MJ/bbl
Synthetic fuel (weighted average)	6167.67	MJ/bbl
	50.36	GGE/bbl
GTL synthetic fuel production	**Values**	**Units**
Baseline plant size	1,000	bbl/d
	6,167,670	MJ/d
	50,356	GGE/d
Associated gas feed	12.90	MMSCFD
GTL plant use (heating)	55.71	%
Synthetic fuel production	44.29	%
Synthetic fuels		
Synthetic gasoline	21.01	% (volume)
	18.64	% (energy)
Synthetic diesel	78.99	% (volume)
	81.36	% (energy)

Table 21. Health assessment and monetization inputs and results.

United States	Abilene, TX	Odessa, TX	Fargo, ND	Lubbock, TX	Corpus Christi, TX	Wt. Average
Population	107,000	111,400	142,500	202,200	293,900	
Population (% of five cities)	12.49%	13.00%	16.63%	23.59%	34.29%	
iF $PM_{2.5}$ (transportation)	2.40E-06	2.72E-06	4.09E-06	4.14E-06	3.17E-06	3.40E-06
CVD Mortality (deaths)	259.6	270.3	345.8	490.6	713.1	
Change in $PM_{2.5}$ Concentration ($\mu g/m^3$)	**-0.96**	**-1.04**	**-1.22**	**-0.87**	**-0.46**	
Lives saved	**-2.23**	**-2.53**	**-3.81**	**-3.85**	**-2.95**	**-3.16**
Annual Health Benefits ($ millions)	**20.10**	**22.78**	**34.25**	**34.67**	**26.55**	**28.45**
Russia	Noyabrsk	Nizhnevartovsk	Surgut	Tyumen	Orenburg	Wt. Average
Population	100,100	239,400	279,000	505,400	548,900	
Population (% of five cities)	5.98%	14.31%	16.68%	30.21%	32.81%	
iF $PM_{2.5}$ (transportation)	6.22E-06	1.23E-05	1.56E-05	2.21E-05	1.93E-05	1.77E-05
CVD Mortality (deaths)	855.4	2,045.8	2,384.2	4,319.0	4,690.7	
Change in $PM_{2.5}$ Concentration ($\mu g/m^3$)	**-2.65**	**-2.19**	**-2.38**	**-1.86**	**-1.50**	**-1.92**
Lives saved	**-20.39**	**-40.31**	**-51.13**	**-72.43**	**-63.26**	**-58.16**
Annual Health Benefits ($ millions)	**60.41**	**119.46**	**151.51**	**214.64**	**187.45**	**172.34**
Nigeria	Owerri	Calabar	Warri	Port Harcourt	Benin City	Wt. Average
Population	183,400	418,600	486,700	846,000	918,000	
Population (% of five cities)	6.43E-02	1.47E-01	1.71E-01	2.97E-01	3.22E-01	
iF $PM_{2.5}$ (transportation)	1.13E-05	3.79E-05	2.39E-05	3.88E-05	6.30E-05	4.21E-05
CVD Mortality (deaths)	201.1	459.0	533.7	927.6	1,006.6	
Change in $PM_{2.5}$ Concentration ($\mu g/m^3$)	**-2.63**	**-3.86**	**-2.09**	**-1.95**	**-2.92**	**-2.61**
Lives saved	**-4.75**	**-15.94**	**-10.05**	**-16.32**	**-26.49**	**-17.72**
Annual Health Benefits ($ millions)	**5.28**	**17.71**	**11.17**	**18.13**	**29.44**	**19.69**
China	Qinyang, Henan	Yulin, Shaanxi	Pingliang, Gansu	Yinchuan, Ningxia	Baotou, Inner Mongolia	Wt. Average
Population	160,200	409,500	444,200	586,000	1,319,000	
Population (% of five cities)	5.49%	14.03%	15.22%	20.08%	45.19%	
iF $PM_{2.5}$ (transportation)	9.33E-06	2.12E-05	2.78E-05	3.63E-05	2.08E-05	2.44E-05
CVD Mortality (deaths)	489.0	1,249.9	1,355.8	1,788.6	4,025.9	
Change in $PM_{2.5}$ Concentration ($\mu g/m^3$)	**-2.48**	**-2.21**	**-2.67**	**-2.64**	**-0.67**	
Lives saved	**-10.92**	**-24.82**	**-32.54**	**-42.49**	**-24.35**	**-28.57**
Annual Health Benefits ($ millions)	**25.03**	**56.87**	**74.57**	**97.37**	**55.79**	**65.46**

Values in bold are results for displacing conventional fuels with synthetic fuels derived from associated gas (per 2,139 million MJ of fuels = annual production capacity of a 1,000 bbl/y plant).

Table 22. Well-to-wheel life cycle health and environmental impacts for conventional fuels and synthetic fuels derived from associated flare gas (per 1 million MJ).

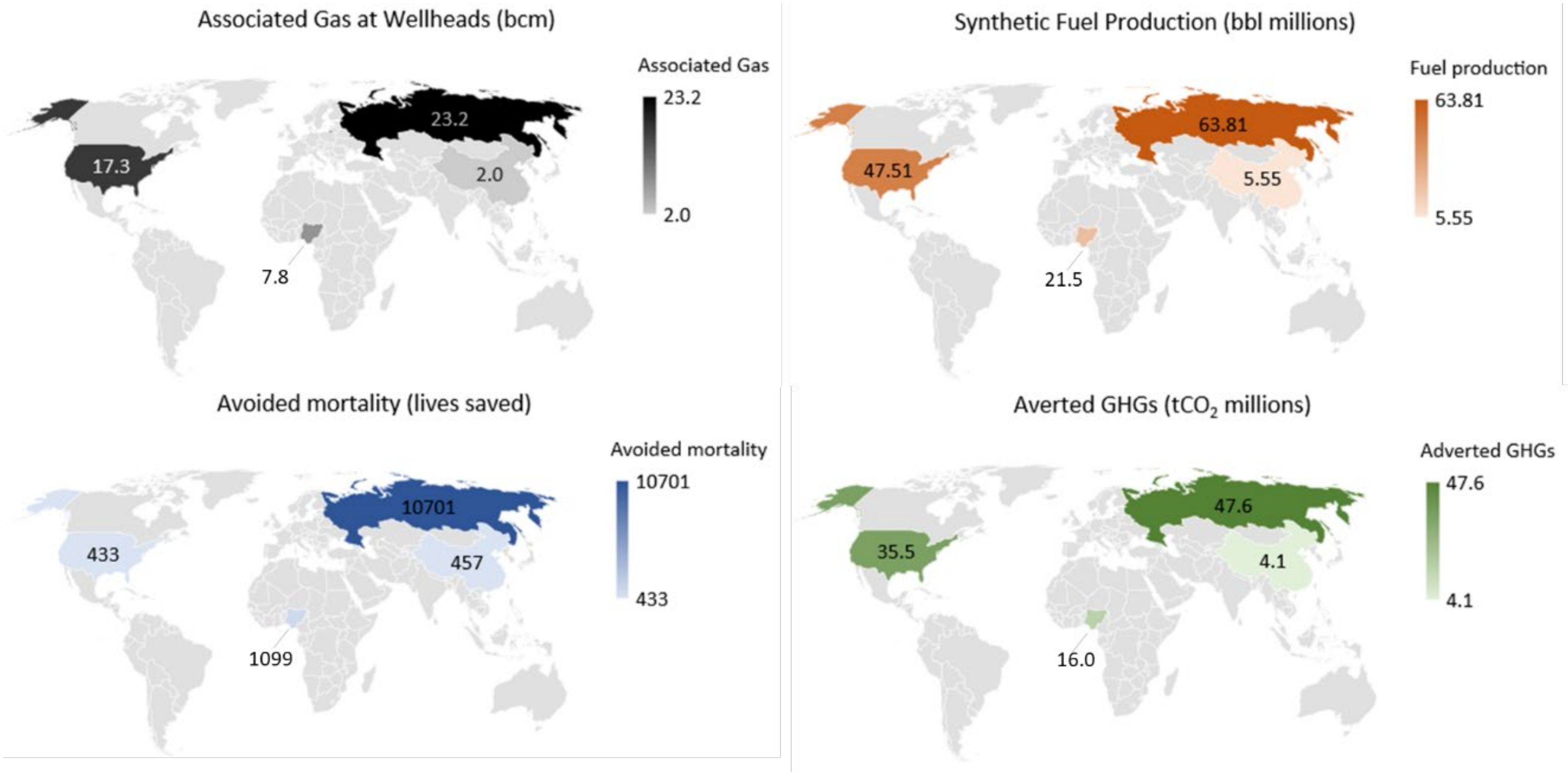
Scenarios	Human Health in Disability Adjusted Life Years (DALYs)	Ecosystem Damages in Species.Years (Sp.yr)	Resource Depletion Costs in 2013 US Dollars	Carbon Emissions (tCO_2)
Associated Gas Flaring (BAU)	0.48	0.0037	$22,532	199
WTW Conventional Fuels	0.088	0.00027	$11,867	90.4
WTW Synthetic Fuels	-0.13	-0.0032	$35.094	-30.6

Associated gas flaring is the business-as-usual (BAU) scenario. BAU's impacts are per 2.1 MMSCF of flare gas (i.e., the amount to produce 1 million MJ of synthetic fuels).

Table 23. Benefits for the valorization of 1 billion cubic meters (bcm) of associated gas at wellheads.

	United States	Russia	Nigeria	China
Synthetic fuel production, GGE millions	138.4	138.4	138.4	138.4
Economic benefits, $ millions	507	368	209	639
Health benefits, $ millions	225	1366	156	519
Avoided mortality, lives saved	25.0	461	140	226
Adverted GHGs, tCO_2 millions	2.05	2.05	2.05	2.05
Climate benefits (CSCC carbon price), $ millions	1.70	-0.26	0.38	0.12
Climate benefits (SCC carbon price), $ millions	104.3	104.3	104.3	104.3

* All $ benefits are before tax.



Associated Gas at Wellheads (bcm)

Synthetic Fuel Production (bbl millions)

Avoided mortality (lives saved)

Averted GHGs (tCO_2 millions)

Figure 28. Summary of benefits for the valorization of all associated gas at wellheads.
Associated gas volumes are for 2019 (GGFR, 2020a). All values are per annum.

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