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Evaluating methane emissions from oil and gas transport facilities in Nigeria – exploring innovative ways to mitigate environmental consequences.

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Abstract

Climate change impacts are increasingly becoming more evident through heavy rainfall episodes and subsequent flooding, elevation of mean annual temperature, heat waves and so on. Methane is a significant greenhouse gas that has been linked to these climate change impacts and the oil and gas industry is a major source of anthropogenic methane emission. Recent studies have suggested that the tropical regions (*e.g. Nigeria*) hold some unexpectedly high methane concentrations and that the recent changes in the global methane burden is poorly understood, partly because methane monitoring outside the major nations is rare. Therefore, this paper presents a first effort to quantify methane emissions from one of the most vulnerable oil and gas infrastructures in Nigeria (a tropical rainforest country and the largest oil and gas producer in Africa). A combination of the IPCC tier-1 approach and an adapted GREET model was used to estimate methane emissions from the system 2C pipeline. We tested the hypothesis of no significant change in methane emission trend from the pipeline over a six-year period using the between group t test inferential analysis. Key findings include: (a) a crude oil throughput of 8.7 to 238 (10^3 m^3) emitted methane ranging from 4,734 x 10^{-8} to 1,288 x 10^{-6} (Gg) respectively, with a cumulative methane release of 1,149 x 10^{-6} (Gg) in January 2005 to 4,397 x 10^{-5} (Gg) in December 2012; and (b) surprisingly, methane emissions along the system 2C transport pipeline seem to have continued without significant change (p = 0.7327 at 95% confidence interval) between 2005, and 2008 to 2012 despite the low crude oil throughput in 2009. This article has provided some first estimates of methane release from oil and gas infrastructure in Nigeria, and indicated the likelihood of continuous but rising methane emissions, as suggested by recent international studies. These findings are unique and contribute to the current debate on methane emissions from the largely unmonitored tropical region of which Nigeria is key. Therefore, we recommend that stakeholders should set up and agree a study plan for the identification and continuous monitoring of methane emissions from across the key Nigerian oil and gas infrastructure. Meaningful corporate engagement in international schemes such the Natural Gas STAR program, Climate and Clean Air Coalition, Global Methane Initiative etc. would promote strategic and measurable methane reduction plans in Nigeria.

Keywords: methane emission, oil and natural gas, transportation, climate change, environmental impact, Nigeria

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<Stakeholders should set up and agree a study-plan for the identification of, and continuous monitoring of, methane emissions from the key oil and gas infrastructures in Nigeria>

1. Introduction

Methane (CH_4) is one of the six greenhouse gases (GHGs) being mitigated under the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). The others are carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Atmospheric concentration and sources of CH_4 are not particularly well understood or well quantified, and they are highly disputable (Frankenberg et al., 2005, Miller et al., 2013). Also, official inventories underestimate actual CH_4 emissions (Brandt et al., 2014) despite, yet again, a rising global trend of CH_4 (Nisbet at al., 2014).

Although CO_2 emissions account for 55-60% of present man-made radiative forcing (IGSD, 2013), recent studies have identified non-CO_2, but short-lived, climate pollutants such as CH_4, black carbon aerosols (BC), tropospheric ozone (O_3) and HFCs as equally important in reducing climate change impacts (e.g. IGSD, 2013; Xu et al., 2013). Radiative forcing is caused when CH_4 and CO_2 absorb thermal radiation from the earth system (Frankenberg et al. 2005). Approximately 20% of the increase in radiative forcing by anthropogenic GHGs since 1750 is due to CH_4 emissions (Nisbet et al., 2014). According to the Intergovernmental Panel on Climate Change (IPCC) (2007), the global atmospheric concentration of CH_4 rose from a pre-industrial value of 715 parts per billion (ppb) to 1,732 ppb in the early 1990s and 1,774 ppb in 2005, i.e. a rise of about 150%. This is of concern given that the lifetime of CH_4 once released into the atmosphere is about 12 years (Xu et al., 2013), and it is 25 times more potent at trapping atmospheric heat than CO_2 over a 100-year timescale (IPCC, 2007). Clearly, methane is crucial in the mitigation of global warming as its reduction will support an average global temperature rise of not greater than 2^0C (US EPA, 2013a).

However, the United Nations Environment Program/World Meteorological Organisation (2011) projected an increase in CH_4 emissions due to rising oil and gas extraction, production and transportation, growth in agricultural activities, population boom, and municipal waste generation. For instance, Nigeria is the largest oil producer in Africa with an average of 2.68 million barrels per day (Idemudia, 2012), and an estimated 180 trillion cubic feet of natural gas reserve (BP, 2014) – one of the largest in the world. In addition, Nigeria's potential natural gas reserve is put at 600 trillion cubic feet (KPMG, 2014). Also, Nigeria's high population (about 170 million) is accompanied by intensive agricultural systems in most of the country's rural and peri-urban areas (Maconachie, 2012) and farming is a key source of

CH_4 emissions (e.g. Nie et al., 2010); especially with unregulated manure/fertilizer application in developing countries (see Thu et al., 2012). China is another prominent developing country ranked amongst the largest fossil consumers in the world and the second largest GHG emitter – with a 46.6% reliance on oil importation as of 2007, large-scale agricultural systems and organic fertilizer utilisation (Zhang et al., 2012; Wang et al., 2014). China has the largest population in the world; and according to Wan et al. (2014) it has the single largest natural gas reserve and a technically recoverable volume put at 67% more than that of the US.

Furthermore, as microorganisms decompose plant and animal residues in soils, the organic mineralization process is further enhanced in warm and moist tropical climates thereby releasing CH_4, CO_2 and nitrogen but this process is hindered in temperate and arctic climates due to limited microbial activities (Wiloso et al., 2014). This occurs mostly during agriculture / soil cultivation and land transformation (Bartl et al., 2011). Other sources of global CH_4 emissions include animal husbandry, landfills, coal mining, wastewater treatment plants, and stationary and mobile combustion (Miller et al., 2013; Suberu et al., 2013). Wetlands, biomass burning and termites are some of the sources of tropical methane (Frankenberg et al., 2005). Enteric fermentation from livestock and feeding on rain grown tropical pastures lead to CH_4 emissions (Bartl et al., 2011; Nahed-Toral et al., 2013). However, northern Nigeria is predominantly known for traditional pastoral cattle production while goat/sheep rearing is common in the south. Also CH_4 emissions from feedlot manure and enteric fermentation in temperate regions (e.g. the highlands and coast of Peru; and, part of the US) contribute to global CH_4 budget but emission data are very scarce and uncertain in tropical and arid regions (Bartl et al., 2011; Dudley et al., 2014).

The majority of emission models is designed for industrialised states and temperate climates (Bartl et al., 2011). Unlike in developing countries, more detailed studies in the arctic region have shown that rising temperatures which thaw permafrost could generate more CH_4 emissions (Shaefer et al., 2011; NRC, 2011). Methane emissions from semi-arid and desert biomes appear to be least researched of all regions of the world but Hou et al., (2012) suggest that wetted desert soils temporarily increase CH_4 uptake in a short period. However, irrespective of biomes or regions, global mean temperature by 2100 is likely to be twice as warm as the last 100 years (IPCC, 2007) and mean yearly precipitation is expected to increase with variability in volume and intensity by region (Meehl, 2007). The loss of ice from Antarctic and Greenland could contribute a further 1 foot to sea level rise (NRC, 2011). There are, however, some innovative climate engineering or geoengineering approaches that could mitigate these climate change impacts (Zhang et al., 2014). Geoengineering is a scheme that artificially cools the earth (Royal Society, 2009) and may include carbon-dioxide removal and/or solar radiation management deployable on land, ocean, atmosphere and space (Zhang et al., 2014). Geoengineering has different impacts on regional climate patterns (Niemeier et al., 2013) but solar radiation management provides greater opportunity for impact mitigation though its discontinuation may lead to extremely rapid climate warming called termination effects (Keller et al., 2014; Zhang et al., 2014).

Oil and natural gas systems are a significant source of anthropogenic CH_4 emissions, especially as upstream pipelines (see Anifowose et al., 2014) are highly susceptible to leaks due to corrosion and abrasion, and are not frequently inspected, thereby making them one of the largest sources of CH_4 emissions in the gas industry (Fernandez et al., 2005). Some studies have identified oil and natural gas transportation systems as one of the main sources of CH_4 emissions (e.g. Dlugokencky et al., 2011; Burnham et al., 2012; Miller et al., 2013).

The IPCC (2006) details emission sources of fugitive CH_4 throughout the oil and gas value chain (see Figure 1). As shown in Table 1, the transportation and distribution industry sectors alone constitute more than 60% and 48% of total CH_4 emissions from natural gas and crude oil industries' emissions sources, respectively. Of particular significance are emissions from compressor stations, pneumatic devices, pipeline maintenance, pipeline accidents such as interdiction (see Anifowose et al. 2012), transportation tanker operations, and crude oil storage tanks. The inadequate knowledge of what controls the global atmospheric CH_4 budget, and its poorly understood recent changes (Nisbet et al., 2014), as well as the claim by Dlugokencky et al. (2011) that a reduction in CH_4 emissions would rapidly benefit the earth's climate, are a vital impetus for this present research.

Therefore, this paper focuses on CH_4 emissions, broadly from transportation and distribution systems within the oil and gas industry, with particular reference to Nigeria. We focus on Nigeria for two distinct reasons viz: (i) recent studies have suggested that the tropical region (e.g. Nigeria, Cuba, Burma) and East Asia hold some unexpectedly high CH_4 concentrations (see Frankenberg et al., 2005; Nisbet et al., 2014) which may have contributed to its poor understanding and quantification; and, (ii) Nigeria is characterised by vast oil and gas developments (Agha et al., 2002; Nwokeji, 2007) and remains a key location for extreme oil pollution and environmental impacts, particularly in the Niger Delta (UNDP 2006, UNEP 2011, Anifowose et al., 2012). Hence, there is the need to address synergistic impacts that may arise from a combination of extreme oil pollution and GHG emissions (e.g. CH_4) which could lead to an impact greater than the sum of their individual impacts. Samarakoon and Gudmestad (2011) argue that there is now an amplified pressure on governments and oil companies to minimize negative environmental impacts.

Inset Table 1; Inset Figure 1

1.1 Research Gap

The absence of systematic direct measurements at designated sites along an oil and gas infrastructure limits the opportunity to evaluate cost-effective CH_4 emission reduction strategies (see Fernandez et al., 2005; Burnham et al., 2012). Clearly, there is limited understanding of emission rates from oil and gas transportation, distribution and storage facilities, including in the United States (Howarth et al., 2011). The first in a series of CH_4 emission studies involving more than 90 partners (e.g. research facilities, universities, scientists, and oil and gas companies) in the US has recently been published by Allen et al. (2013). To date, there has been no similar study to gather scientific estimates, or locate specific sites of emission along oil and gas infrastructures in Nigeria. Although there have been studies of climate change vulnerability, adaptation and qualitative assessment in Nigeria (e.g. Fasona and Omojola, 2005; Yusuf and Oyewunmi, 2008; Adebimpe, 2011; Oni and Oyewo, 2011), these tended to focus mainly on gas flaring as the primary source of GHGs. There is currently no study of CH_4 emission rates and trends from oil and gas transportation and distribution systems. Therefore, we present a modest first effort to address this research gap by analysing CH_4 emissions and providing estimates from the System 2C crude oil transport pipeline (Figure 2) as a vital component of the transportation, distribution and storage network in Nigeria.

Nigeria’s First National Communication under the UNFCCC published in November 2003 recognised the dire need for good quality data, local emission factors and activity-based data collection (Federal Ministry of Environment, 2003) but nothing appears forthcoming to date.

However, the UNDP-supported UNFCCC Second National Communication started in February 2006 with an expected end date of April 2012.

Insert Figure 2

1.2 Study Aim and Objectives

This study aims to evaluate methane emission trends from a rather less considered, but potentially significant emission source in the oil and gas industry (section 1.1). The set objectives are to:

(a) Analyse the nominal and cumulative crude oil throughput from the System 2C pipeline (Figure 2) between 2005 and 2012;
(b) Assess CH_4 emissions using a combination of the IPCC emission factor approach and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model;
(c) Investigate the statistical mean difference between the estimated CH_4 emissions in the earlier (2005, 2008, 2009) and the later (2010, 2011, 2012) years of data availability.

1.3 Study Significance and Scope

Without a comprehensive understanding of CH_4 emission patterns and trends, it will be difficult to develop effective strategy(s) to mitigate CH_4 emissions from the oil and gas value chain. This is even more important for developing countries since they are most vulnerable to climate change impacts, largely resulting from continuous emissions of GHGs (see Adger and Barnett, 2007; Challinor et al., 2007; Hallegatte et al., 2013) of which CH_4 is key.

This study focuses solely on the System 2C transport pipeline as shown in Figure 2. As of 2009, the NNPC reported 74 damage points on the 60 km Escravos –Warri segment of the System 2C pipeline alone. The System 2C pipeline constitutes approximately 13% of the Nigeria National Petroleum Corporation (NNPC)/Pipelines and Product Marketing Company (PPMC) managed pipeline network, while it represents only about 5% of the entire oil and gas pipeline network in Nigeria. Yet, the 2C pipeline has potential to contribute additional emissions to the global methane budget.

2. Materials and Methods

The analyses in this paper utilised the monthly crude oil throughput received from Escravos at the Kaduna Refinery through the 674 km System 2C transport pipeline (Figure 2). The data were retrieved from the NNPC Monthly Petroleum Information which covers the following crude streams: Forcados Blend; Escravos Light; Bonny Light; Arabian and/or Basra light (NNPC, 2005-2012). The data period is from 2005 to 2012, but year 2006 (which has less than 50% of the throughput data) and 2007 (which has no data for the 12-month period) were excluded. In addition to the 2006-2007 missing data, not all the monthly throughput data are available between 2008 and 2011 partly due to interdiction and maintenance issues. However, we have employed the monthly crude oil throughput data in this study because: (a) crude oil pipeline is a subcategory under 'Oil transport' as an industry segment in the activity summary list of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; and (b) they are the only accessible data, at the moment, that can satisfy the study aim. Table 2 shows some detailed characteristics of the System 2C crude oil pipeline.

Mean monthly temperature data (Celsius) were retrieved from the World Bank Group's Climate Change Portal. These historical temperature data show baseline climate and seasonality by month for Nigeria between 1900 and 2009 as produced by the Climate Research Unit of the University of East Anglia. It is assumed that the dataset is fairly representative of the prevalent environmental condition between 2005 and 2012.

2.1 Methods

For scenarios where no direct measurement of emissions exists, such as in Nigeria, the API (2009) and IPCC (2006) provide methodologies that can be used. This article utilised the methodology from the latter, based on accessible crude oil throughput data, but this, like other approaches, is susceptible to possible under or overestimation (see Brandt et al., 2014). The API approach, which is more rigorous, would require key infrastructure data (e.g. number and types of facilities; and, amount and type of equipment in use (see IPCC, 2006; API, 2009), which are not readily available.

To supplement the IPCC (2006) emission factor approach, we adapted the latest edition of the GREET model (October 2013 version) for life cycle assessment of methane emissions from the System 2C pipeline and its associated facilities. The GREET model is a well-documented methodology (e.g. see Miller and Theis, 2006; Jindan et al., 2010; Burnham et al., 2012) for estimating CO_2, CH_4 and N_20 emissions amongst others.

2.1.1 The Emission Factor Tiered Approach

Figure 3 illustrates the systematic process followed in choosing the method of analysis to address part of objectives (b) and (c) in this paper (section 1.2). The IPCC (2006) provides a three-tiered approach for estimating CH_4 emissions, including other GHGs, as follows:

Tier 1 – Top-down Average Emission Factor Approach. This is the most straightforward and is relatively less data-intensive. It utilises predefined default emission factors for aspects of the oil and gas value chain. The size of oil and gas activities in a country has a direct relationship with the importance of its fugitive emissions, and the larger the size, the more reliable are the Tier-1 emission factors, according to the IPCC (2006:4.41). However, there is a degree of uncertainty with the Tier-1 approach but it nevertheless provides indicative insights for data-sparse scenarios such as in the Nigerian case. The throughput data (section 2) is the minimum required activity data for the Tier-1 approach.

Tier 2 – Mass Balance Approach. This appears the most relevant approach (e.g. for Nigeria which flares the majority of its associated gases), especially when taking a holistic view of mitigating CH_4 emissions. The mass balance approach considers volume of associated and solution gases to account for conserved, re-injected and utilised volumes on a country-specific basis (IPCC, 2006).

Tier 3 – Rigorous Bottom-up Approach. It is the most rigorous of the three-tier approaches, requiring direct calibration of emissions, infrastructure, and detailed production accounting data. It is mostly practiced in developed countries where, typically, most data may be available and/or accessible at individual facility level.

For the reasons summarised in section 2.1, we are unable to employ either the Tier 2 or Tier 3 approach in this first effort at estimating CH_4 emissions from transport pipeline systems in Nigeria. Hence the choice of the Tier 1 emissions factor approach.

Inset Figure 3

2.1.1.1 Calculation and Application of the IPCC Tier 1 Approach

The IPCC Tier 1 approach was applied by inputting the following equation (IPCC, 2006) into Microsoft Excel worksheet:

$$E_{\text{oil transport}} = A_{\text{pipeline\_throughput}} \text{ x } EF_{\text{GH4\_pipeline}}$$

Where:

$E_{\text{oil\_transport}}$ = monthly emissions (Gg)
$A_{\text{pipeline\_throughput}}$ = volume of crude oil transported (bbl)
$EF_{\text{GH4\_pipeline}}$ = emission factor (Gg per unit of volume transported)

2.1.1.2 Hypothesis Testing

To address objective (c) in section 1.2, we formulated and tested the hypothesis that there is no statistically significant mean difference in methane emission trends from the System 2C pipeline during the six-year period under study i.e. H_O ($\mu_1=\mu_2$).

The estimated methane emissions data span a 72 month period, and are grouped as follows (Table 3) for the purpose of testing the hypothesis:

Inset Table 3

A 95% confidence interval was used in setting the decision rules, with the degree of freedom calculated in Excel, and using the *t* distribution table (two-tailed), the critical value is 2.0017. Therefore:

If $t_{\text{obs}} \leq -2.0017$ or $t_{\text{obs}} \geq 2.0017$, then reject H_O.
If $t_{\text{obs}} > -2.0017$ and $t_{\text{obs}} < 2.0017$, then do not reject H_O.

To calculate the observed *t* value (t_{obs}) between groups, the *t*-test equation was applied (see Plonsky, 2012).

2.1.2 The Greenhouse-Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model

The GREET applies a multidimensional mathematical model by accounting for technologies and resources to calculate the energy and emissions associated with a sequence of stationary and transportation processes (Argonne National Laboratory, 2013). We used herein some default GREET assumptions, and built a conceptual frame for the System 2C pipeline by adding it as a new process and set up the localised parameters, i.e. distance (674 km, or 418.804 miles); share (100%); crude oil default ‘fuel share’ for the pump and booster stations; and energy intensity per unit length of crude oil pipeline (404 btu/mile/ton). The analyses only accounted for emissions from the transport of crude oil from Escravos to Kaduna refinery (Figure 2) and therefore omit emissions from production and other upstream processes. The reason for this omission relates to the difficulty associated with attributing emissions from a production well that produces both ‘natural gas’ and ‘crude oil’ using a life-cycle assessment approach (see Brandt et al., 2014).

After adding the transportation and stationary processes, a new pathway was created in order to calculate the life cycle emissions per 1 mmBtu of crude oil transported through the System 2C pipeline. The volume of crude oil flowing through the pipeline per unit of time in m^3 was used to alter the functional unit from mmBtu in GREET. The LCA mathematical model used to calculate emissions in GREET is as follows:

$$Em(f) = a(f)Em_{up}(f) + a(f)\sum_{t\in T} s\,(f,t)Ef(f,t) + Em_{other}$$

$$= a(f)\left(Em_{up}(f) + \sum_{t\in T} s\,(f,t)Ef(f,t)\right) + Em_{other}$$

Where:

Em = emissions vector (gram);
f = resource e.g. crude oil
$a(f)$ = amount of a resource f (joule – *j*, gram – *g*, or litre – *l*)
$Em_{up}(f)$ = energy vector associated with emissions to produce (*g/j, g/g, g/l*)
t = technology
T = set of technologies
s = percentage share
m = mode of transportation
E = energy vector

3. Results and Discussion

The estimated CH_4 emissions from the application of the IPCC Tier-1 emission factor approach and the GREET model are presented and discussed in this section.

3.1 IPCC Tier-1 and GREET Model estimates of methane from the System 2C pipeline

Figures 4A to F show the monthly crude oil transport/throughput (10^3 m^3) along the System 2C pipeline, and the corresponding estimated monthly CH_4 emissions including the monthly cumulative trend over a 6-year period (2005, 2008 to 2012). The throughputs range from 8.7 to 238 (10^3 m^3) while the corresponding CH_4 emissions range from 0.04734 to 1.288 Metric Tonnes (MT); and, the monthly cumulative ranges from 12.55 MT in December 2005 to 10.37 MT in December 2012, and the least was 1.77 MT in December 2009 (Figure 4). Generally, data on CH_4 emissions from oil and natural gas pipelines are scarce around the world. In fact, in a recent US study by Burnham et al. (2012), transmission (i.e. transportation), storage and distribution are aspects of the value chain noted as requiring further investigation into CH_4 emissions. It suggested that about ±2% of production gets emitted as CH_4 during transportation and distribution of conventional and shale gas. Methane from high northern latitudes is significant and in the US, for instance, natural gas production can release 6 to 12% to the atmosphere (Nisbet et al., 2014); and about 58% of this could come from 'superemitter' sources (Brandt et al., 2014). There is not much critical discussion on CH_4 emission quantification from oil and gas facilities in Europe but EC (2013) suggests that emissions from oil and gas systems is 8.9% of total EU emissions. However, a collaborative study involving the US EPA (1996) cited in Howarth et al. (2011), Harrison et al. (1996) and Kirchgessner et al. (1997) estimated the emission rate from natural gas transportation as 0.53% mean value, while loses from distribution was estimated as 0.35% of production in the US (Howarth et al., 2011). Based on the US EPA (1996) emission factor, Lelieveld et al. (2005) estimated an average loss rate of 1.4% (range 1% to 2.5%) for natural gas transportation, distribution and storage in Russia.

Following the GREET model approach, Figure 5 shows the minimum annual crude oil throughput of 327 (10^3 m^3) with a corresponding 12,988 kg of CH_4 emission in 2009 and a maximum of 2,324 (10^3 m^3) throughput with a corresponding emission of 92,202 kg (92.20

MT) in 2005. The cumulative crude oil throughput of 8,142 (10^3 m^3) yielded a total life-cycle emission of methane estimated to be 323,040 kg (323 MT) throughout the period under study.

Expectedly, both the IPCC Tier-1 approach and the GREET model show that the higher the crude oil throughput, the higher the potential CH_4 emissions and, by extension, arguably the more likely the climate change impacts, e.g. hydrological (such as higher rainfall/flood intensity and frequency), and climatological (such as drought, heat waves and increased temperature). Clearly, crude oil throughput by itself does not fully explain the changes in CH_4 emissions and the attendant climate change impacts. For instance, Heath et al., (2014) found that material quantities and their chemical components (e.g. binders vs. geopolymers) influence global warming potential of GHGs in the cement industry; while Nemecek et al. (2012) suggest different farming systems, climatic conditions, landuse change and inputs as key factors in agriculture.

Most important, these climate change impacts have implications for national infrastructure (roads, rails, hospitals, telecommunications, buildings and so on) – no matter how adaptive and innovative the design of these infrastructures. According to VDOT (2011), World Bank (2009) in Bruckner (2012) and CSIRO (2007), road damage, rail buckling, flooded drains and canals, and washing out of bridges, are some of the key impacts. Given the high global warming potential of CH_4 (25 times more potent than CO_2 over a 100-year timescale) and its significance in climate change impacts (Brandt et al., 2014; Xu et al., 2013), every opportunity to minimise its release into the atmosphere ought to be utilised.

Figures 4 and 5 only present estimates based on the System 2C crude oil pipeline, which is only one of many (section 1.3). A more robust approach involving ‘rigorous bottom-up assessment by primary source’ at individual facility level is essential to identify facilities where large leaks may otherwise go unnoticed over a long time period (see Fernandez et al., 2005, Picard 2010). Such bottom-up assessment study should cover as much of the value chain as possible, or in phases as in Allen et al. (2013), so as to engender evidence-based policymaking on climate change adaptation and mitigation in Nigeria. As an optimum approach, Brandt et al. (2014) suggest a combination of emissions inventories, including improved inventory validation, device-level measurements, and atmospheric science studies.

Geoengineering i.e. solar radiation management, though a relatively new concept, would be interesting for Nigeria. This has been trialled in few places in North America, UK and Asia but still requires substantial development in the areas of law, ethics, economics and social policy (Zhang et al., 2014). Carbon-dioxide removal through reforestation and afforestation programmes is well established in Nigeria.

Inset Figures 4 and 5

3.2 Uncertainties and Errors in estimated methane emissions from System 2C pipeline

The IPCC (2006) puts the range of uncertainties associated with CH_4 emissions estimation from crude oil transport pipeline at between -50% and 200%. Figure 6A shows the lower (-50%) and upper (200%) bands of the uncertainties associated with cumulative estimated emissions for year 2005 only. It ranges from 0.00 MT in the lower band, and 2.29 to 25.09 MT in the upper band (Figure 6A). Similar trends, as shown in Figure 6A, are observable in the data for 2008 to 2012 (Figures 4B to F). Inferential error bars for all mean monthly emissions are shown in Figure 6B. Cumming et al. (2007) suggest that large error is depicted by wide inferential bars while high precision is indicated by short inferential bars. Uncertainty estimates address errors from both systematic and random sources; hence they are a suitable way of assessing the accuracy of results, which is consistent with the International Standards Organisation’s guidelines on uncertainty estimation (e.g. see NDT Education Resource Centre, 2014; Coleman and Steele, 1995). However, Figure 6B shows an interesting pattern as both average monthly methane emission and mean monthly temperature rise from January to March with the former declining steeply between March and June while the latter increases until April before its gentle decline till August. The methane emission trend also declines sharply from September to December with a corresponding but gentle fall in temperature from October to December. A semi-arid study in Northern China by Hou et al., (2012) observed a linear correlation between temperature and the uptake of methane in the months of July and August with $R^2 = 0.8357$ and 0.6337 respectively. On the other hand, a UK experimental study in the Moor house Nature reserve (North Pennines) show that 98% of methane is retained at 5^0C but as temperature increased to 25^0C only 50% could be retained (Winden et al., 2012). An empirical study is fundamental to our understanding of how CH_4 might respond to temperature variability specifically in the tropics and this could be vital in determining the best possible geoengineering scheme to reduce temperature anomalies since it is impossible to control other parameters like precipitation, wind. The temperature data in Figure

6B is averaged over Nigeria; perhaps ambient temperature measurement along the system 2C pipeline (Figure 2) may have yielded a slightly different result.

Inset Figure 6

Burnham et al. (2012) assumed a rather conservative uncertainty range of ±30% and also used uncertainty values from Harrison et al. (1996) to estimate CH_4 emissions across various segments of the natural gas sector. The range of uncertainties from the System 2C pipeline (Figure 6) is not surprising given recent findings suggesting that official inventories and emission factors underestimate actual CH_4 emissions, especially in the US and Canada (Brandt et al., 2014), and in the tropical rainforest region (Frankenberg et al., 2005). Clearly, the Tier-1 emission factor (section 2.1.1) was derived from measurement data based on studies conducted in developing countries such as Uzbekistan, Romania and China, and the IPCC 1996 revised methodology manual (IPCC, 2006). Also, the GREET model is primarily developed using data from the US oil and gas systems, although some default conditions were altered with data from the System 2C pipeline (section 2.1.2) in this paper. The variation in data sources and focus in both the IPCC Tier-1 approach and the GREET model is responsible for some of the disparity in the results of estimated CH_4 emissions as shown in Figures 4 and 5.

To enhance the accuracy of estimates, a more rigorous evaluation (e.g. as in API (2009) or IPCC (2006) Tier-3) at activity level, together with top-down atmospheric studies, are essential in Nigeria. According to IPIECA, API and CONCAWE (2009) the complexity of oil and gas industry operations, its large geographical extension and the use of average emission factors, amongst others, make the estimation of fugitive gases, such as CH_4, exhibit the highest degree of uncertainty. This argument is further buttressed by Nisbet et al. (2014) which claim that recent changes in atmospheric methane burden are poorly understood.

3.3 Cumulative methane emissions and oil transport throughput

Figure 7 provides a more direct comparison (using the same unit of measurement) between cumulative monthly throughput and estimated monthly cumulative emissions ($0.858\ m^3 = 1$ metric tonne). A cumulative monthly crude oil throughput of 9,490 metric tonnes from Escravos to Kaduna Refinery (Figure 2) over the six-year period gave a monthly cumulative methane emission figure of about 44 metric tonnes (Figure 7) or 44×10^{-3}.

Inset Figure 7

The potential implication of Figure 7 is as discussed in section 3.1. However, Picard (2000) and IPCC (2006) suggest fugitive emissions from gas transportation and distribution systems can also be related to the lengths of pipeline in addition to throughput data (e.g. as explained in section 2). This provides an opportunity for future research, where the length of the transport pipeline network could be considered a factor in estimating CH_4 emission trends. A thorough analysis and monitoring of the transport distribution system have great potential for a full understanding of the greenhouse impacts associated with the industry (Nisbet et al., 2014), as well as helping to address the environmental impacts of oil and natural gas production and transportation (Burnham et al., 2012).

3.4 Inferential analysis of mean difference in methane emissions over time

The between group *t*-test analysis carried out to examine the mean difference in CH_4 emission trends, based on Table 3, yielded a p value = 0.7327. Also the t_{obs} was 0.3523 and this does not fall within the critical region as determined by the t_{crit} of ±2.0017 and the p value of 0.7327 is greater than 0.05, therefore we fail to reject the null hypothesis H_O (section 2.1.1.2). This non-statistically significant result suggests that no change occurred in methane emission trend from the System 2C transport pipeline during the six-year period under study – signifying the likelihood of continuous but rising methane emissions. Assuming the null hypothesis is indeed true, the probability of arriving at a t_{obs} value as large as 0.3523 is defined by a high p value of 0.7327.

This non-statistically significant result is very surprising given that in 2009 (Table 3) the quantity of crude oil transported between the Escravos – Warri section (Figure 2) was highly impaired as a result of interdiction (see Figure 5). In that year alone, the NNPC reported 74 damage points on this 60 km stretch of the pipeline. Perhaps the absence of crude oil throughput data for years 2006 and 2007 may have influenced both the tested hypothesis and its final result. As the majority of the Nigerian pipeline network infrastructure dates back to the 1970s and 1950s, it is not unlikely that most of it may have been built from cast iron and unprotected steels. According to US EPA (2013b), cast iron and unprotected steels are prone to increased GHG emissions, including methane gas. This further compounds the potential severity of the continuous upward trend in CH_4 emissions (p value = 0.7327 at 95% confidence interval) from the System 2C pipeline, and most likely from other pipeline networks not covered in this paper, especially the upstream natural gas systems and flowlines within the Niger Delta.

4. Conclusions

A number of contemporary studies have suggested that the tropical region (which has countries like Nigeria, Cuba, Brazil, West Bengal, Burma and so on) hold some unexpectedly high methane concentration and that the recent changes in global methane burden is poorly understood for many reasons, including a lack of methane monitoring outside the major developed nations. This paper, therefore, presents a first effort to quantify methane emissions from one of the most vulnerable oil and gas infrastructures in Nigeria, and highlights the need for further bottom-up and top-down studies including the areas of well completions and workovers, liquid unloadings, well equipment leakage and venting, processing, transportation, storage, and distribution.

This study found that:

(a) a crude oil throughput range of 8.7 to 238 (10^3 m^3) had a corresponding methane emission ranging from 0.04734 to 1.288 MT respectively, with a monthly cumulative methane release of 12.55 MT in December 2005 to 10.37 MT in December 2012, and

Surprisingly, it was discovered that:

(b) methane emissions along the System 2C transport pipeline seem to have continued without significant change ($p = 0.7327$ at 95% confidence interval) between 2005 and 2008 to 2012 despite the low crude oil throughput in 2009;

The above findings are unique and contribute to the current debate on methane emissions from the largely unmonitored tropical region (NB: Nigeria is only one of many countries in this region). Although the study results only provide insights into methane emissions from a crude oil pipeline in Nigeria, further study is required to cover other sources including oil and gas facilities and in other countries within the tropical region to reasonably understand the level of CH_4 concentration and proffer tailored mitigation. The study approach and its results readily find applicability in developing countries who are producers of oil and gas within the tropics and beyond. The study indicates the likelihood of continuous but rising methane emissions; and it may be that similar trend is observable throughout the tropical region.

Nisbet et al., (2014, p.494) averred that in the tropics… ‘unwelcome methane surprises may lurk, but watchers are few’ and findings from our paper re-emphasize the danger of ‘business as usual’ as CH_4 emissions appear to have continued (i.e. from one of numerous sources in Nigeria) without significant change over the six year period. Though each country can identify sources of methane but the impact is beyond the borders of any nation; instead, the impact is worldwide.

Hitherto, the focus has been on GHG emissions from gas flare sites with little or no attention to releases from oil and gas transportation facilities, which could range between 48% and 63% for methane (see Table 1). This article therefore hopes to advance scientific and policy debate on methane (and other) emissions throughout the oil and gas value chain in Nigeria and internationally, and engender best possible mitigation strategies through evidence-based policymaking. Given the high global warming potential of methane; uncertainties and limited knowledge surrounding its trend (section 3.2); and, its significance in climate change impacts, mainly discernible through flood disasters, drought, heat waves, and so on, we suggest the following key recommendations:

a) that stakeholders including the Federal Ministry of Environment, the Department of Petroleum Resources, multinational oil companies and indigenous oil companies, the NNPC/PPMC, the Nigerian Institute of Transport Technology and other relevant intergovernmental agencies, should set up/agree a study-plan for the identification and continuous monitoring of methane emissions from key oil and gas infrastructures in Nigeria, and ensure its standardised reporting (e.g. Jung et al., 2001);
b) step up coordinated participation in national and international stakeholder forums such as the Natural Gas STAR Program, the Climate and Clean Air Coalition of the United Nations Environment Programme, and the Global Methane Initiative amongst others through which many developing oil and gas producing countries (e.g. Ecuador, Indonesia, India, Colombia, Mexico) have been able to evolve strategic and measurable methane reduction plans; and
c) explore opportunities for the budding climate engineering schemes especially land-based geoengineering given the vast landmass in Northern Nigeria; atmosphere and space-based geoengineering; and carbon-dioxide removal. Best practices can be learnt from the National Key Science Program for Global Change Research

"Geoengineering" (e.g. Zhang et al., 2014); and, the first major framework for climate engineering experiments recently launched by Oxford Geoengineering Programme.

These recommendations are equally applicable to developing nations in Africa, Asia, South America and Eastern Europe *inter alia*. To be 'climate-smart', implementing these recommendations is vital and would also demonstrate a nation's commitment to climate change impact mitigation for the benefit of future generations, and guarantee longer-term innovative and adaptive national critical infrastructures.

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References

Adebimpe, R.U. 2011. Climate Change Related Disasters and Vulnerability: An Appraisal of the Nigerian Policy Environment. *Environmental Research Journal* 5(3), 97-103

Adger, W.N. and Barnett, J. 2007. Climate change, human security and violent conflict. *Political Geography* 26, 639-655

Adger, W.N., Huq, S., Brown, K., Conway, D. and Hulme, M. 2003. Adaptation to climate change in the developing world. *Progress in Development Studies* 3(3), 179–195

Allen, D.T., Torres, V.M., Thomas, J., Sullivan, D.W., Harrison, M., Hendler, A., Herndon, S.C., Kolb, C.E., Fraser, M.P., Hill, A.D., Lamb, B.K., Miskimins, J. Sawyer, R.F. and Seinfeld, J.H. 2013. Measurements of methane emissions at natural gas production sites in the United States. DOI: www.pnas.org/lookup/suppl/doi:10.1073/pnas.1304880110/-/DCSupplemental.

Anifowose, B.A., Lawler, D.M., van der Horst, D., and Chapman, L.C. 2012. Attacks on oil transport pipelines in Nigeria: a quantitative exploration and possible explanation of observed patterns. *Applied Geography* 32, 636-651.

Anifowose, B.A., Lawler, D.M., van der Horst, D. and Chapman, L.C. 2014. Evaluating interdiction of oil pipelines at river crossings using Environmental Impact Assessments. *Area* 46(1), 4-17.

API, America Petroleum Industry, 2009. Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry. Washington, DC.

Argonne National Laboratory, 2013. GREET Life-Cycle Model. Centre for Transportation Research, Energy Systems Division, Argonne National Laboratory, Chicago.

Bartl, K., Gómez, C. and Nemecek, T. 2011. Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru. *Journal of Cleaner Production* 19, 1494-1505.

BP, 2014. Statistical Review of World Energy. Available at: http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf. Accessed on: 3 August 2014.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.D., Eardley, D. and Harriss, R. 2014. Methane Leaks from North American Natural Gas Systems. *Science: Energy & Environment*, 343(6172), 733-735

Bruckner, M. 2012. Climate change vulnerability and the identification of least developed countries. United Nations Development Policy and Analysis Division Department of Economic and Social Affairs, New York.

Burnham, A., Han, J., Clark, C.E., Wang, M., Dunn, J.B. and Rivera, I.P. 2012. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum. Environ. Sci. Technol. 46, 619-627

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P. and Kassam, A. 2007. Assessing the vulnerability of food crop systems in Africa to climate change. *Climatic Change* 83(3), 381-399

Coleman, H.W. and Steele, W.G. 1995. Engineering application of experimental uncertainty analysis. *AIAA Journal* 33(10), 1888-1896

CSIRO 2007. Infrastructure and climate change risk assessment for Victoria, Commonwealth Scientific and Industrial Research Organisation.

Cumming, G., Fidler, F. and Vaux, D. 2007. Error bars in experimental biology. *Journal of Cell Biology* 177(1), 7-11.

Dlugokencky, E. J., Nisbet, E. G., Fisher, R., and Lowry, D. 2011. Global atmospheric methane: budget, changes and dangers, Phil. Trans. R. Soc. A, 369, 2058–2072, doi:10.1098/rsta.2010.0341.

Draft inventory of U.S. Greenhouse Gas Emissions & Sinks: 1990-2010 (February 2012). Sourced online from: http://www.epa.gov/outreach/reports/03-naturalgas.pdf. Accessed on: 3 May 2012.

Dudley, Q., Liska, A., Watson, A. and Erickson, G. 2014. Uncertainties in life cycle greenhouse gas emissions from U.S. beef cattle. *Journal of Cleaner Production* 75, 31-39

EC 2013. European Commission Global Methane Reduction Actions. Available at: https://www.globalmethane.org/documents/EC_GMI_reduction_actions.pdf. Accessed on 4 Oct 2014.

Fasona, M.J. and Omojola, A.S. 2005. Climate Change, Human Security and Communal Clashes in Nigeria. Paper presented at the International Workshop on Human Security and Climate Change, Holmen Fjord Hotel, Asker, near Oslo, 21–23 June.

Federal Ministry of Environment 2003. Nigeria's First National Communication under the United Nations Framework Convention on Climate Change. Federal Republic of Nigeria, Abuja

Fernandez, R., Petrusak, R., Robinson, D. and Zavadil, D. 2005. Cost-Effective Methane Emissions Reductions for Small and Midsize Natural Gas Producers. *Journal of Petroleum Technology* 6, 34-42

Frankenberg, C., Meirink, J.F., van Weele, M., Platt, U. and Wagner, T. 2005. Assessing Methane Emissions from Global Space-Borne Observations. *Science* 308(5724), 1010-1014.

Hallegatte, S., Green, C., Nicholls, R.J. and Corfee-Morlot, J. 2013. Future flood losses in major coastal cities. *Nature Climate Change* 3, 802-806

Harrison, M.R., Shires, T.M., Wessels, J.K. and Cowgill, R.M. 1996. Methane emissions from the natural gas industry. Executive summary, vol. 1. EPA-600/R-96-080a. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC

Heath, A., Paine, K. and McManus, M. 2014. Minimising the global warming potential of clay based geopolymers. *Journal of Cleaner Production* 78, 75-83

Hou, L., Wang, Z., Wang, J., Wang, B., Zhou, S. and Li, L. 2012. Growing season in situ uptake of atmospheric methane by desert soils in a semiarid region of northern China. *Geoderma* 189–190, 415–422.

Howarth, R.W., Santoro, R. and Ingraffea, A. 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Climatic Change*, 106, 679–690.

Idemudia, U. 2014. The resource curse and the decentralization of oil revenue: the case of Nigeria. *Journal of Cleaner Production* 35, 183-193.

IGSD, Institute for Governance & Sustainable Development, 2013. Primer on Short-Lived Climate Pollutants. Washington, DC.

IPIECA, API, and CONCAWE 2009. Addressing Uncertainty in Oil and Natural Gas Industry Greenhouse Gas Inventories: Technical Considerations and Calculation Methods. Prepared by the LEVON Group, LLC and URS Corporation, pp.186.

IPCC, Intergovernmental Panel on Climate Change, 2006. Fugitive Emissions - Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy, Institute for Global Environmental Strategies, Japan.

IPCC, Intergovernmental Panel on Climate Change, 2007. Climate Change Synthesis Report - An Assessment of the Intergovernmental Panel on Climate Change. Working Group contributions to the Fourth Assessment Report.

Jindan, D., Weijian, H. and Yinghong, P. 2010. Life cycle greenhouse gases, energy and cost assessment of automobiles using magnesium from Chinese Pidgeon process. *Journal of Cleaner Production* 18(2), 112-119

Jung, E., Kim, J. and Rhee, S. 2001. The measurement of corporate environmental performance and its application to the analysis of efficiency in oil industry. *Journal of Cleaner Production* 9, 551–563.

KPMG, 2014. Oil and Gas in Africa – Reserves, Potential and Prospects of Africa. Available at:http://www.kpmg.com/Africa/en/IssuesAndInsights/Articles-Publications/General-Industries-Publications/Documents/Oil%20and%20Gas%20in%20Africa%202014.pdf. Accessed on: 3 August 2014.

Keller, D., Feng, E. and Oschlies, A. 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. Nature Communications 5, 3304.

Kirchgessner, D.A., Lott, R.A., Cowgill, R.M., Harrison, M.R. and Shires, T.M. 1997. Estimate of methane emissions from the US natural gas industry. *Chemosphere* 35, 1365–1390

Lelieveld, J., Lechtenbohmer, S., Assonov, S.S., Brenninkmeijer, C.A.M., Dinest, C., Fischedick, M. and Hanke, T. 2005. Low methane leakage from gas pipelines. *Nature* 434, 841–842

Maconachie, R. 2012. Reconciling the mismatch: evaluating competing knowledge claims over soil fertility in Kano, Nigeria. *Journal of Cleaner Production* 31, 62-72.

Meehl, G., Stocker, T., Collins, W., Friedlingstein, P., Gaye, A., Gregory, J., Kitoh, A., Knutti, R., Murphy, J., Noda, A., Raper, S., Watterson, I., Weaver, A. and Zhao, Z. 2007. Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis*.

Miller, S.A. and Theis, T.L. 2006. Comparison of Life-Cycle Inventory Databases: A Case Study Using Soybean Production. *Journal of Industrial Ecology* 10 (1-2), 133 -147

Miller, S.M., Wofsy, S., Michalak, A., Kort, E., Andrews, A., Biraud, S., Dlugokencky, E., Eluszkiewicz, J., Fischer, M., Janssens-Maenhout, G., Miller, B., Miller, J., Montzka, S., Nehrkorn, T. and Sweeney, C. 2013. Anthropogenic emissions of methane in the United States. *Proceedings of the National Academy of Sciences of the United States of America* 110(50), 20018–20022, doi: 10.1073/pnas.1314392110

Nahed-Toral, J., Sanchez-Muñoz, B., Mena, Y., Ruiz-Rojas, J., Aguilar-Jimenez, R. and Castel, J., de Asis Ruiz, F., Orantes-Zebadua, M., Manzur-Cruz, A., Cruz-Lopez, J. and Delgadillo-Puga, C. 2013. Feasibility of converting agrosilvopastoral systems of dairy cattle to the organic production model in southeastern Mexico. *Journal of Cleaner Production* 43, 136-145.

NCP/BPE. (2008). Environmental audit of Pipelines and Products Marketing Company Limited (PPMC). Abuja, Nigeria: Commissioned by the National Council on Privatization (NCP)/Bureau of Public Enterprise (BPE).

NDT Education Resource Centre 2014. Accuracy, Error, Precision, and Uncertainty. Available at: http://www.ndt-ed.org/GeneralResources/ErrorAnalysis/UncertaintyTerms.htm. Accessed on: 07 May 2014.

Nemecek, T., Weiler, K., Plassmann, K., Schnetzer, J., Gaillard, G., Jefferies, D., García-Suárez, T., King, H. and Canals, L. 2012. Estimation of the variability in global warming potential of worldwide crop production using a modular extrapolation approach. *Journal of Cleaner Production* 31, 106-117.

Niemeier, U., Schmidt, H., Alterskjær, K. and Kristjansson, J. 2013. Solar irradiance reduction via climate engineering-impact of different techniques on the energy balance and the hydrological cycle. *Journal of Geophyical Research* 118, 11905-11917.

Nie, S., Gao, W., Chen, Y., Sui, P. and Eneji, A. 2010. Use of life cycle assessment methodology for determining phytoremediation potentials of maize-based cropping systems in fields with nitrogen fertilizer over-dose. *Journal of Cleaner Production* 18, 1530-1534.

Nisbet, E.G., Dlugokencky, E.J. and Bousquet, P. 2014. Methane on the Rise—Again. *Science: Atmospheric Science* 343(6170), 493-495

NNPC 2005 – 2012. Monthly Petroleum Information. Corporate Planning & Development Division, NNPC Towers, Central Business District, Herbert Macaulay Way, Abuja, Nigeria.

NRC 2011. *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*. National Research Council. The National Academies Press, Washington, DC, USA.

Oni, S.I. and Oyewo, M.A. 2011. Gas Flaring, Transportation and Sustainable Energy Development in the Niger-Delta, Nigeria. *Journal of Hum Ecol* 33(1), 21-28

Picard, D. 2000. Fugitive Emissions from Oil and Natural Gas Activities. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

Picard, D. 2010. Directed Inspection & Maintenance. Methane to Markets Partnership - Technology Transfer Workshop, Moscow, Russia.

Plonsky, M. 2012. Psychological Statistics – Hypothesis Testing: Continuous Variables (2 Sample). Available at: http://www4.uwsp.edu/psych/stat/11/hyptest2s.htm#III23. Accessed on: 12 December 2013.

Rella, C.W., Crosson, E., Jacobson, G., Karion, A., Petron, G. and Sweeney, C. 2013. Quantifying the relative contribution of natural gas fugitive emissions to total methane emissions in Colorado and Utah using mobile $d^{13}CH_4$ analysis. Available at: http://www.picarro.com/sites/default/files/Rella%20IG4%20-%20S4.12%20-%20BG1.4%20-%2020130411%20-%200845.pdf. Accessed on: 17 Oct. 2013.

Royal Society, 2009. Geoengineering the Climate: Science, Governance and Uncertainty. Available at: https://royalsociety.org/~/media/Royal_Society_Content/policy/publications/2009/8693.pdf. Accessed on: 4 Oct. 2014.

Samarakoon, S.M.K and Gudmestad, O.T. 2011. The IPPC directive and technique qualification at offshore oil and gas installations. *Journal of Cleaner Production* 19, 13-20.

Shaefer, K., Zhang, T., Bruhwiler, L. and Barrett, A. 2011. Amount and Timing of Permafrost Carbon Release in Response to Climate Warming. *Tellus B* 63(2), 165-180

Suberu, M., Bashir, N. and Mustafa, M. 2013. Biogenic waste methane emissions and methane optimization for bioelectricity in Nigeria. *Renewable and Sustainable Energy Reviews* 25, 643–654.

The World Bank Group. Mean monthly temperature data (1990-2009) for Nigeria. Climate Change Knowledge Portal. Available at: http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisRegion=Africa&ThisCCode=NGA. Accessed on: 6 Oct. 2014.

Thu, C., Cuong, P., Hang, L., Chao, N., Anh, L., Trach, N. and Sommer, S. 2012. Manure management practices on biogas and non-biogas pig farms in developing countries e using livestock farms in Vietnam as an example. *Journal of Cleaner Production* 27, 64-71.

UNEP/WMO 2011. Integrated assessment of black carbon and tropospheric ozone: summary for decision makers. United Nations Environment Programme and the World Meteorological Organization, Nairobi.

USEPA, US Environmental Protection Agency, (u.d.). Natural Gas STAR Program. Available at: http://www.epa.gov/methane/gasstar/basic-information/index.html. Accessed on: 12 February 2012.

USEPA, US Environmental Protection Agency, 2012. Global Anthropogenic Non-CO_2 Greenhouse Gas Emissions: 1990-2030. EPA 430-R-12-006. Washington, DC: USEPA.

USEPA, US Environmental Protection Agency, 2013a. Global Mitigation of Non-CO_2 Greenhouse Gases: 2010-2030. EPA-430-R-13-011. Washington, DC: USEPA.

USEPA, US Environmental Protection Agency, 2013b. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011 (Environ Protect Agency, Washington, DC). EPA 430-R-13-001.

van Winden, J., Reichart, G., McNamara, N., Benthien, A. and Damsté, J. 2012. Temperature-Induced Increase in Methane Release from Peat Bogs: A Mesocosm Experiment. *PLoS ONE* 7(6): e39614. doi:10.1371/journal.pone.0039614

VDOT, Virginia Department of Transportation, 2011. Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure. Hampton Roads Virginia Pilot, Virginia Department of Transportation.

Wan, Z., Huang, T. and Craig, B. 2014. Barriers to the development of China’s shale gas industry. *Journal of Cleaner Production* xxx, 1-6.

Wang, X., Chen, Y., Sui, P., Gao, W., Qin, F., Wu, X. and Xiong, J. 2014. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. *Journal of Cleaner Production 65,* 234-245

Wiloso, E., Heijungs, R. and Huppes, G. 2014. A novel life cycle impact assessment method on biomass residue harvesting reckoning with loss of biomass productivity. *Journal of Cleaner Production* xxx, 1-9.

World Bank (2009). The Economics of Adaptation to Climate Change. A Synthesis Report. Washington, DC: World Bank.

Xu, Y., Zaelke, D., Velders, G.J.M. and Ramanathan, V. 2013. The role of HFCs in mitigating 21st century climate change. *Atmos. Chem. Phys.,* 13, 6083–6089

Yusuf, R.O. and Oyewunmi, M.O. 2008. Qualitative Assessment of Methane Generation Potential from Municipal Solid Wastes: A Case Study. *Environmental Research Journal* 2 (4), 138-144

Zhang, Z., Moore, J., Huisingh, D. and Zhao, Y. 2014. Review of geoengineering approaches to mitigating climate change. *Journal of Cleaner Production* xxx, 1-10

Zhang, L., Song, B. and Chen, B. 2012. Emergy-based analysis of four farming systems: insight into agricultural diversification in rural China. *Journal of Cleaner Production* 28, 33-44

Figure captions

Figure 1: Conceptual diagram of a typical oil and gas value chain. Source: adapted from US EPA (u.d.)

Figure 2: Nigeria showing the system 2C crude oil pipeline transport network and its associated facilities. Source: adapted from Anifowose et al. (2014).

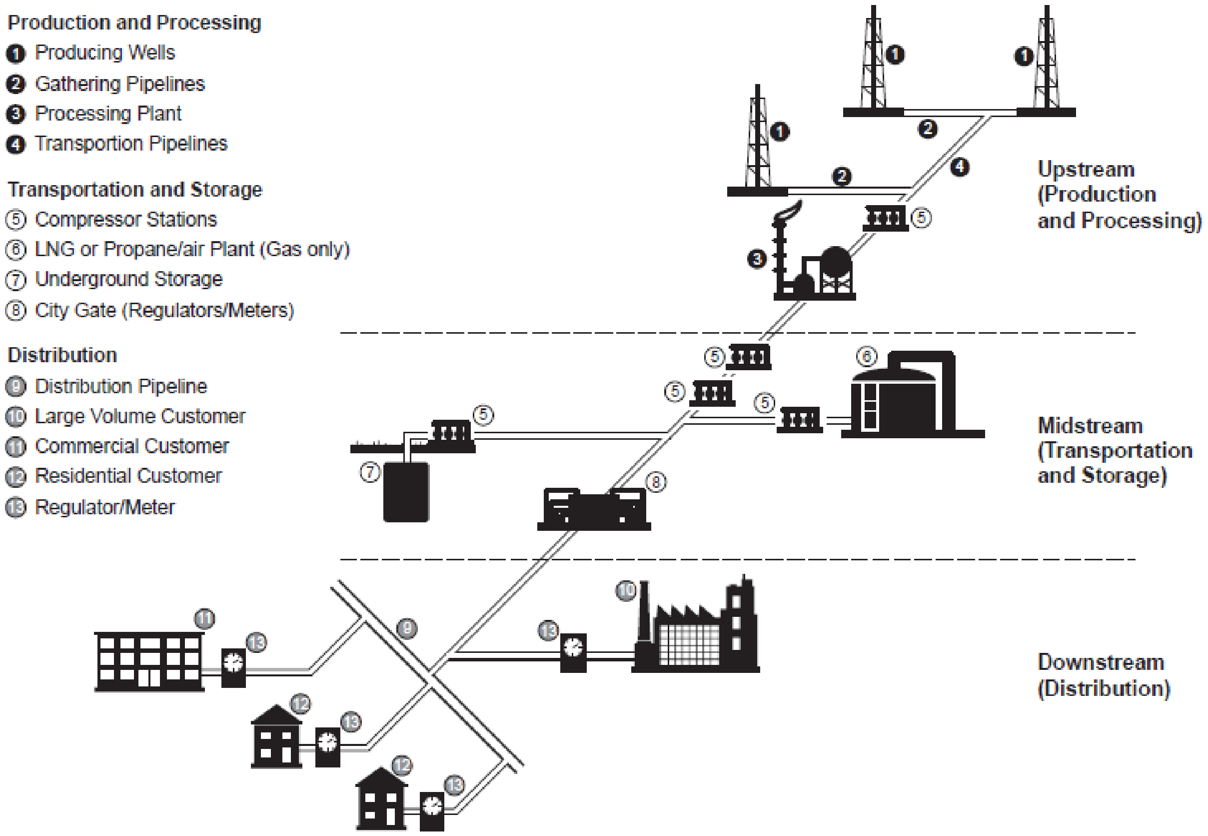
Figure 3: Decision tree for crude oil transport, refining and upgrading. Source: IPCC (2006, p.4.40)

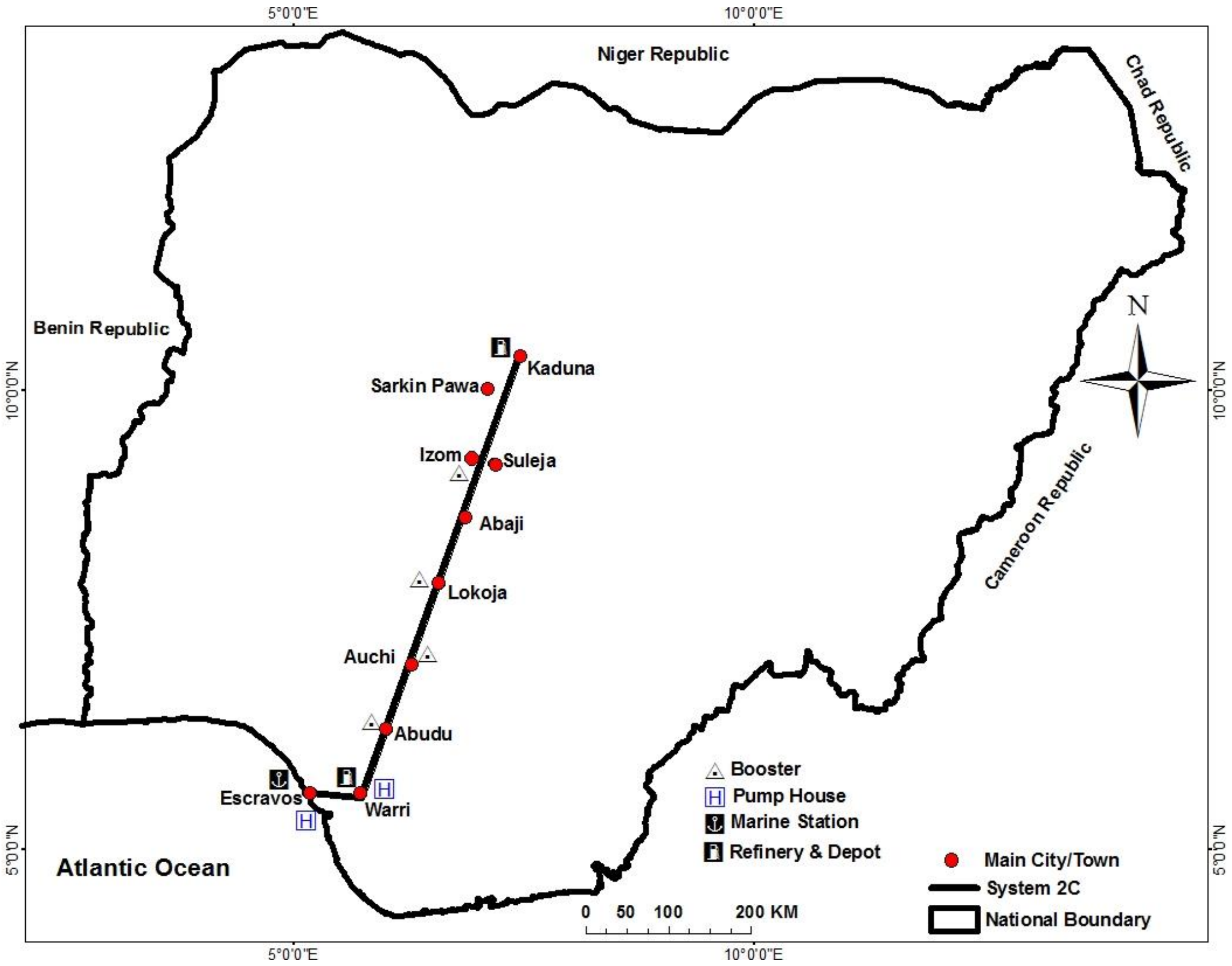
Figure 4: Monthly crude oil transport/throughput (10^3 m^3) along the system 2C pipeline (2005 and 2008 to 2012), the estimated monthly CH_4 emissions and the cumulative values.

Figure 5: Yearly crude oil throughput (m^3) and its corresponding estimated methane emissions (kg and Gg) from the GREET model (2005, 2008 to 2012 along the system 2C pipeline)

Figure 6: Estimated monthly uncertainties (lower and upper bands) associated with cumulative CH_4 emissions along the system 2C pipeline in 2005.

Figure 7: Cumulative methane emissions (Metric Tonnes, MT) and oil transport throughput (MT) along the system 2C pipeline in 2005, 2008 to 2012


Production and Processing
❶ Producing Wells
❷ Gathering Pipelines
❸ Processing Plant
❹ Transportion Pipelines
Transportation and Storage
⑤ Compressor Stations
⑥ LNG or Propane/air Plant (Gas only)
⑦ Underground Storage
⑧ City Gate (Regulators/Meters)
Distribution
⑨ Distribution Pipeline
⑩ Large Volume Customer
⑪ Commercial Customer
⑫ Residential Customer
⑬ Regulator/Meter
Upstream (Production and Processing)
Midstream (Transportation and Storage)
Downstream (Distribution)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Izom
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Abaji
Lokoja
Auchi
Abudu
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Warri
Booster
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Refinery & Depot
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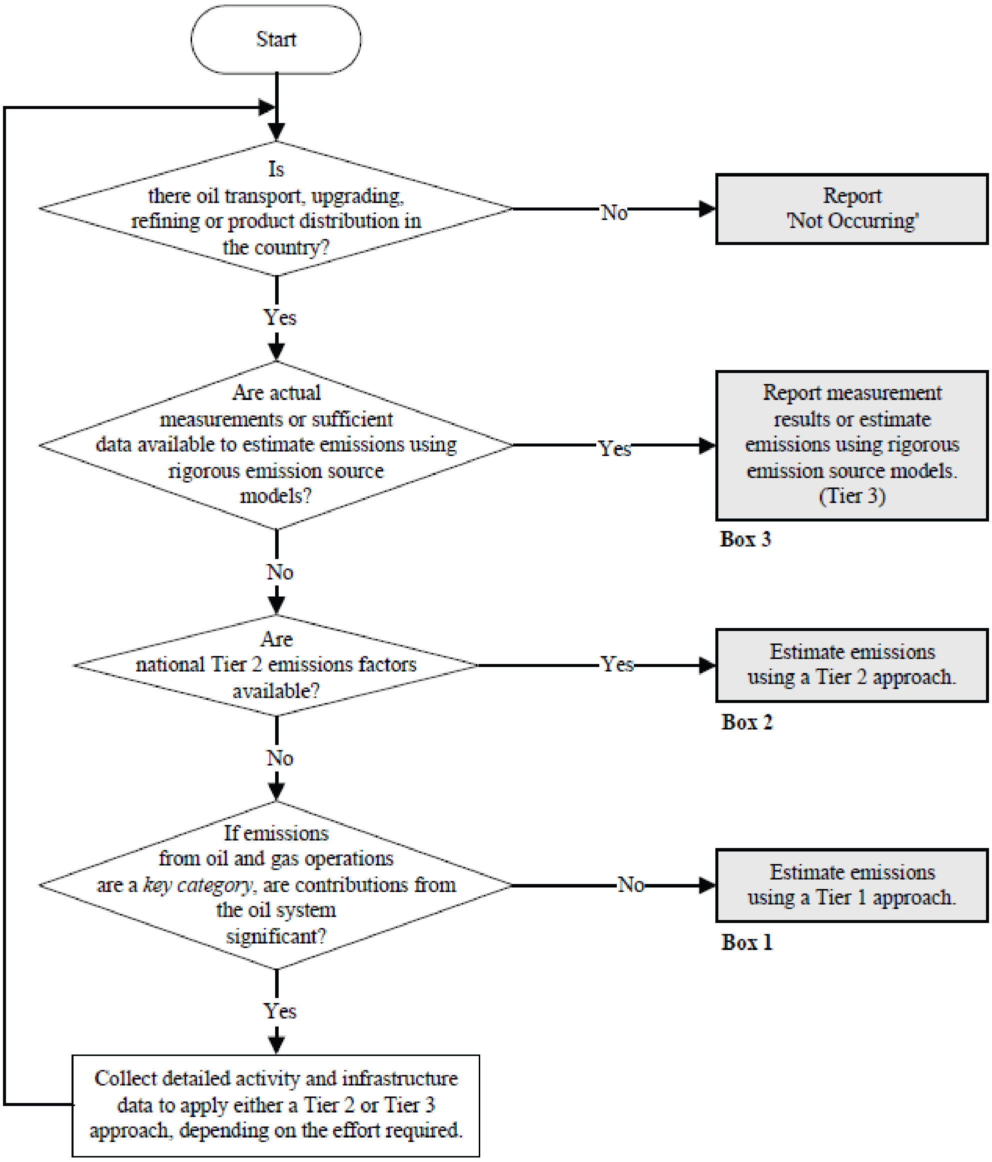
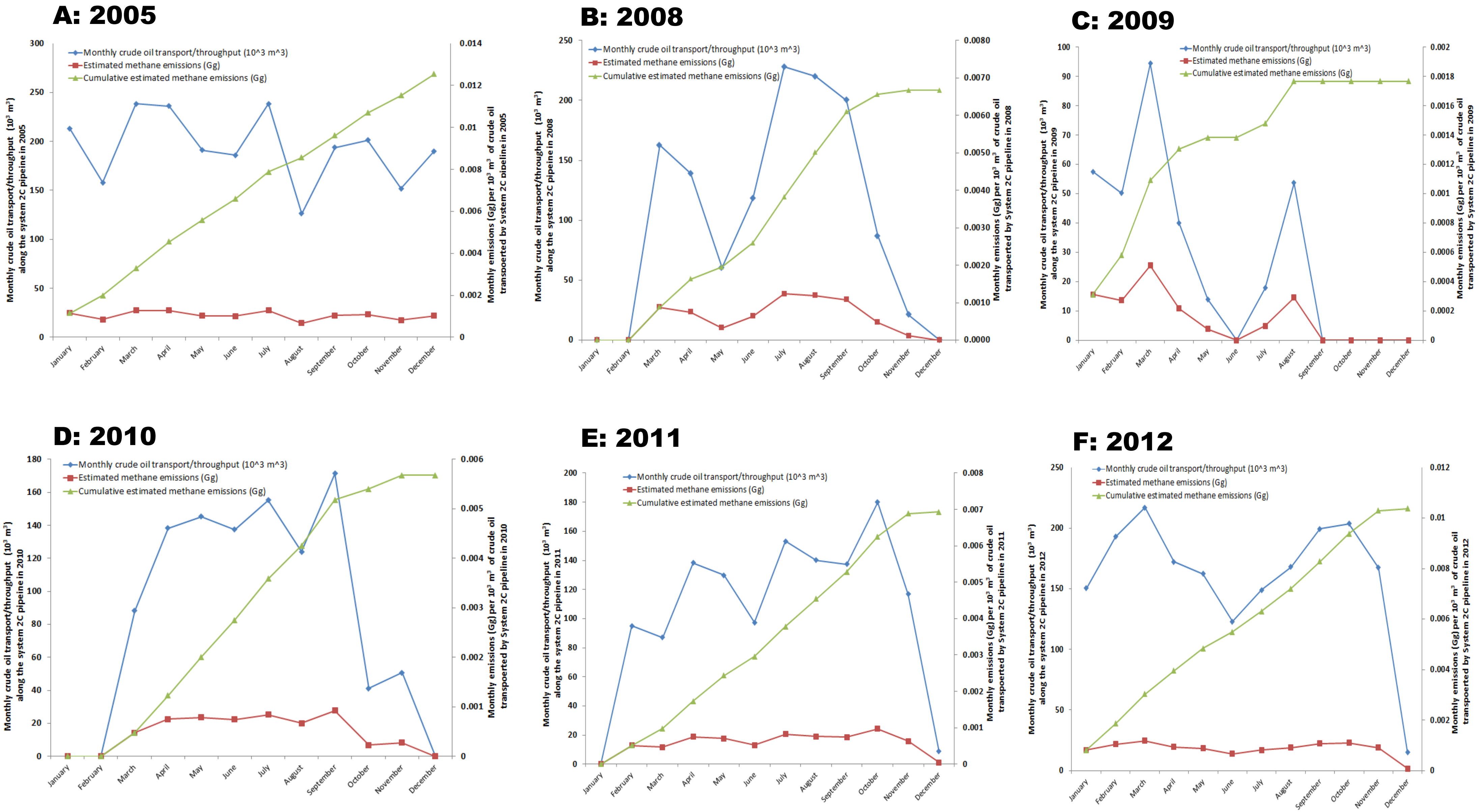

Start
Is there oil transport, upgrading, refining or product distribution in the country?
No
Report 'Not Occurring'
Yes
Are actual measurements or sufficient data available to estimate emissions using rigorous emission source models?
Yes
Report measurement results or estimate emissions using rigorous emission source models. (Tier 3)
Box 3
No
Are national Tier 2 emissions factors available?
Yes
Estimate emissions using a Tier 2 approach.
Box 2
No
If emissions from oil and gas operations are a key category, are contributions from the oil system significant?
No
Estimate emissions using a Tier 1 approach.
Box 1
Yes
Collect detailed activity and infrastructure data to apply either a Tier 2 or Tier 3 approach, depending on the effort required.


A: 2005
B: 2008
C: 2009
D: 2010
E: 2011
F: 2012
Monthly crude oil transport/throughput (10^3 m^3)
Estimated methane emissions (Gg)
Cumulative estimated methane emissions (Gg)
Monthly crude oil transport/throughput (10^3 m^3) along the system 2C pipeine in 2005
Monthly emissions (Gg) per 10^3 m^3 of crude oil transpoerted by System 2C pipeline in 2005
Monthly crude oil transport/throughput (10^3 m^3) along the system 2C pipeine in 2008
Monthly emissions (Gg) per 10^3 m^3 of crude oil transpoerted by System 2C pipeline in 2008
Monthly crude oil transport/throughput (10^3 m^3) along the system 2C pipeine in 2009
Monthly emissions (Gg) per 10^3 m^3 of crude oil transpoerted by System 2C pipeline in 2009
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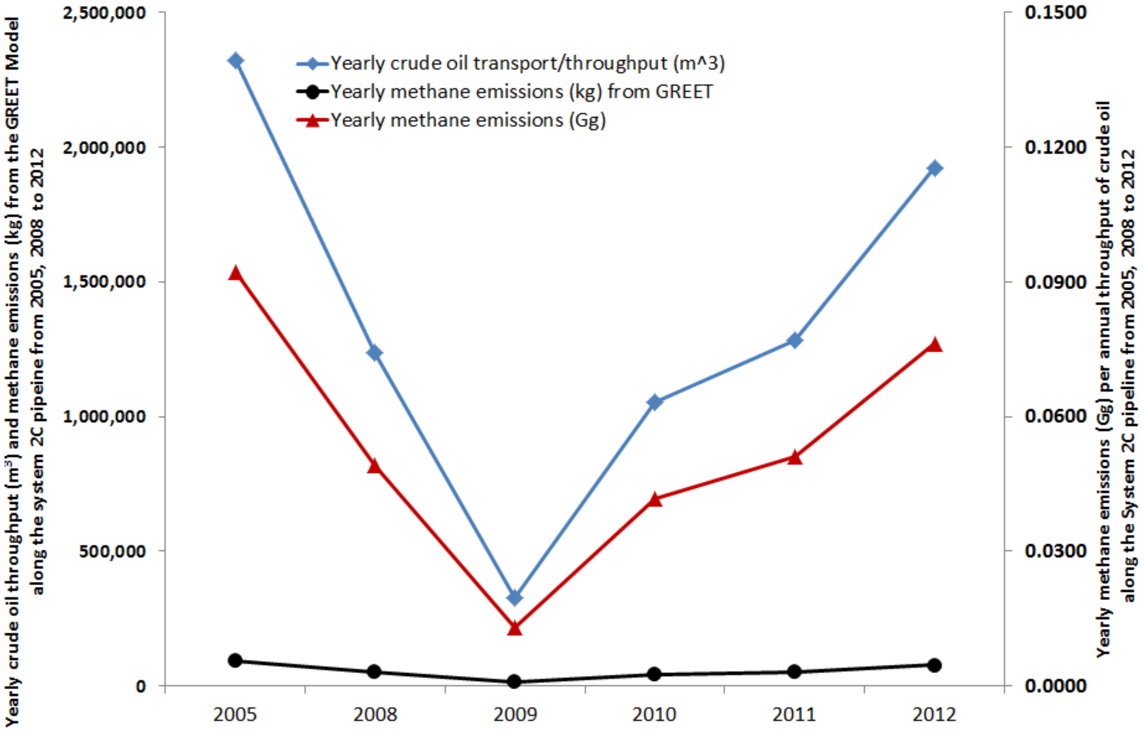
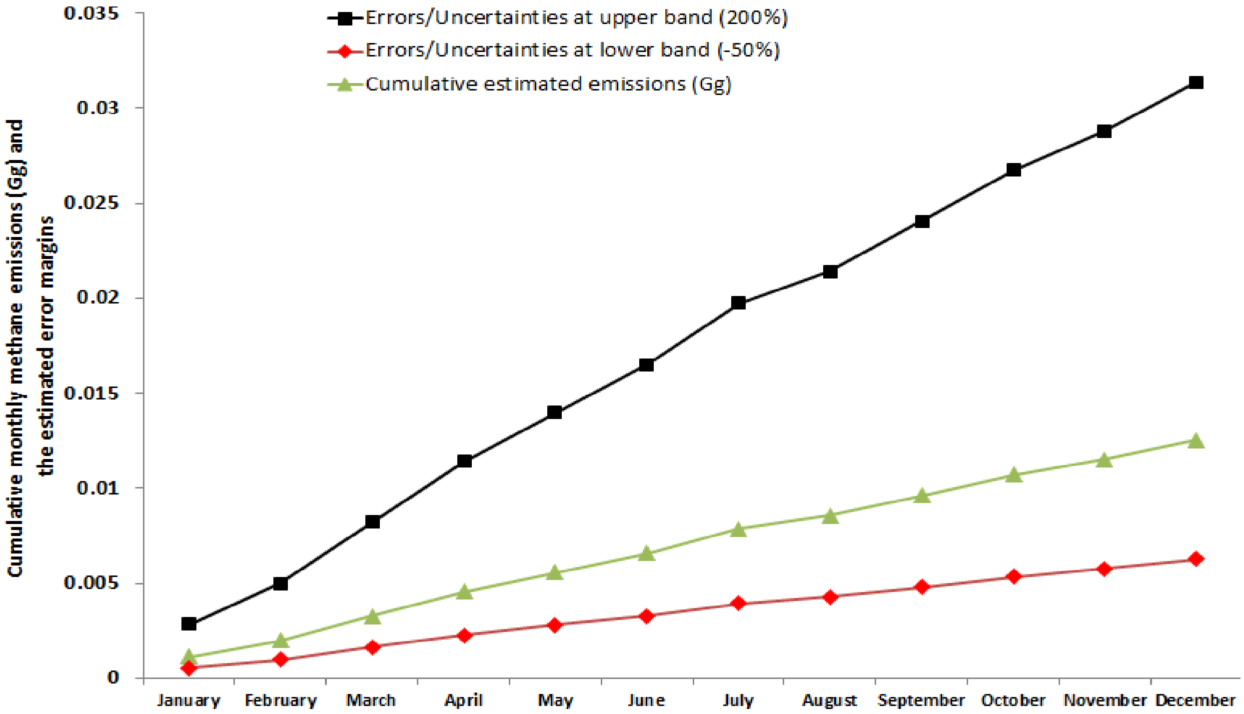
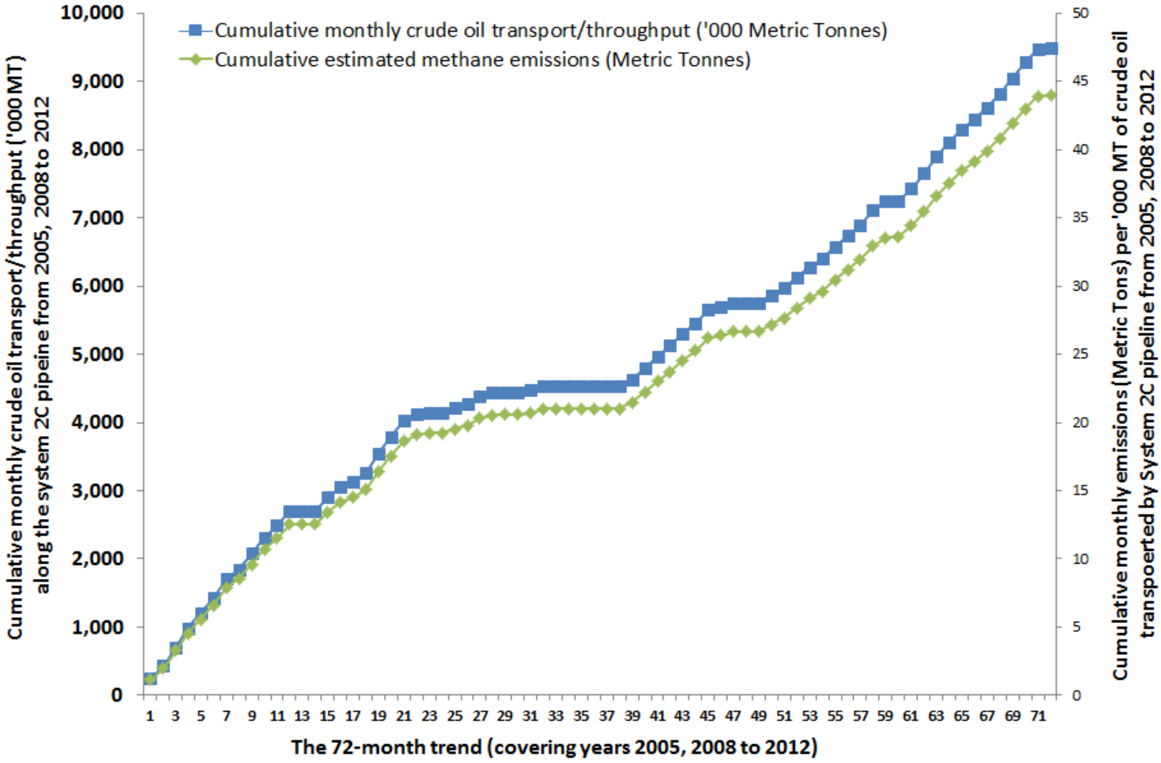
Monthly emissions (Gg) per 10^3 m^3 of crude oil transpoerted by System 2C pipeline in 2011
Monthly crude oil transport/throughput (10^3 m^3) along the system 2C pipeine in 2012
Monthly emissions (Gg) per 10^3 m^3 of crude oil transpoerted by System 2C pipeline in 2012
January
February
March
April
May
June
July
August
September
October
November
December


Yearly crude oil throughput (m³) and methane emissions (kg) from the GREET Model along the system 2C pipeine from 2005, 2008 to 2012
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
Yearly crude oil transport/throughput (m^3)
Yearly methane emissions (kg) from GREET
Yearly methane emissions (Gg)
2005
2008
2009
2010
2011
2012
0.1500
0.1200
0.0900
0.0600
0.0300
0.0000
Yearly methane emissions (Gg) per annual throughput of crude oil along the System 2C pipeline from 2005, 2008 to 2012


Cumulative monthly methane emissions (Gg) and the estimated error margins
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Errors/Uncertainties at upper band (200%)
Errors/Uncertainties at lower band (-50%)
Cumulative estimated emissions (Gg)
January
February
March
April
May
June
July
August
September
October
November
December

Cumulative monthly crude oil transport/throughput ('000 Metric Tonnes)
Cumulative estimated methane emissions (Metric Tonnes)
Cumulative monthly crude oil transport/throughput ('000 MT) along the system 2C pipeine from 2005, 2008 to 2012
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Cumulative monthly emissions (Metric Tons) per '000 MT of crude oil transpoerted by System 2C pipeline from 2005, 2008 to 2012
50
45
40
35
30
25
20
15
10
5
0
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
57
59
61
63
65
67
69
71
The 72-month trend (covering years 2005, 2008 to 2012)

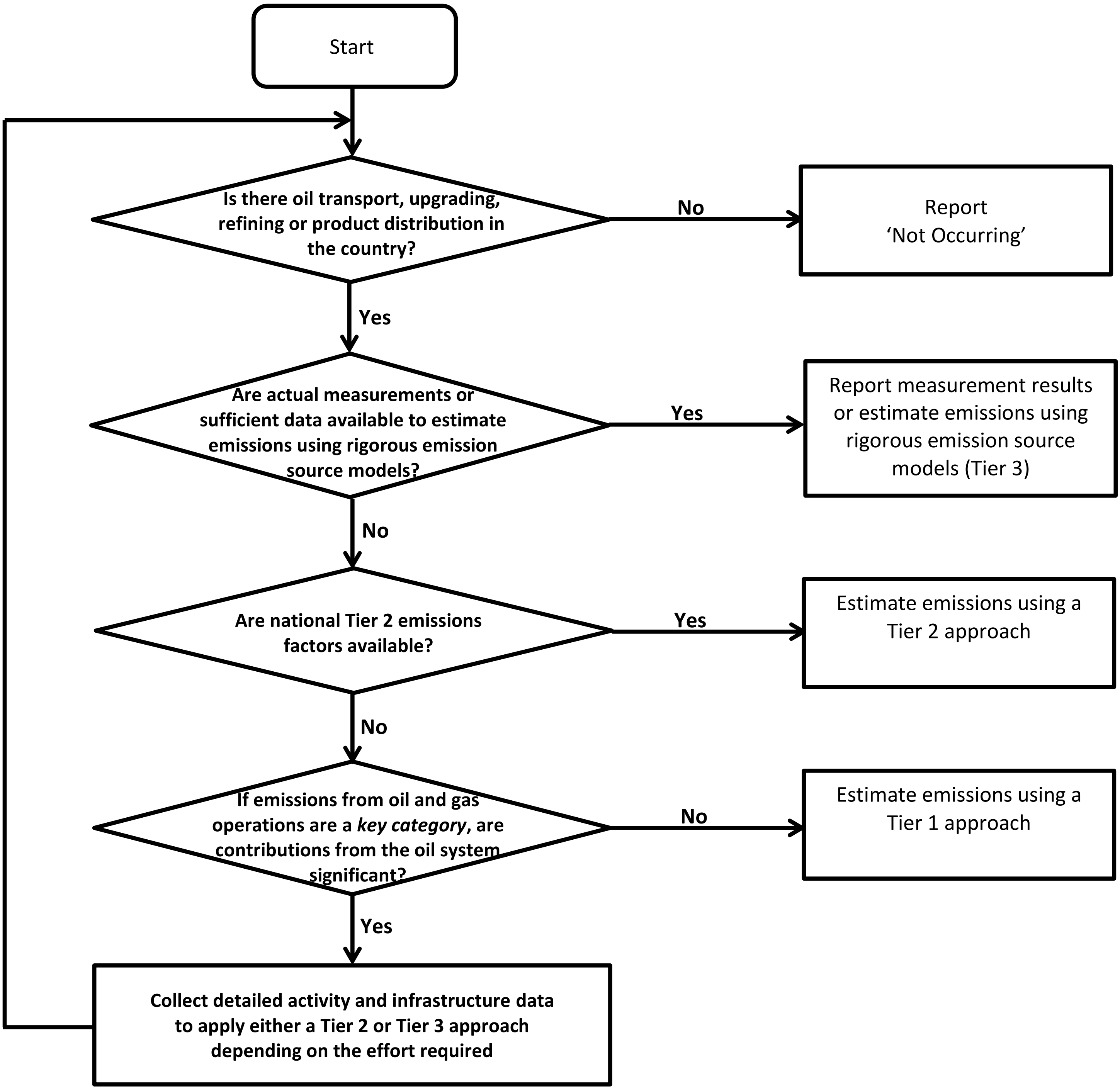


Figure 3: Decision tree illustrating the systematic process followed in choosing a method for estimating methane emissions from crude oil transport, refining and upgrading processes. Source: after, IPCC (2006, p.4.40)

Table 1: Sources of Methane Emissions from Oil and Gas Activities

Industry sector	**Natural Gas Industry: Sources of Emissions**	**% of total & Amount**	**Crude Oil Industry: Sources of Emissions**	**% of total & Amount**
Production	Wellheads, dehydrators, separators, gathering lines and pneumatic devices	25% 8.4 MMTCE or 1.5 Tg	Wellheads, separators, venting and flaring, other treatment equipment	49% 0.7 MMTCE 0.13 Tg
Processing	Compressors and compressor seals, piping, pneumatic devices, and processing equipment	12% 4.1 MMTCE or 0.7 Tg	Waste gas streams during refining	2% 0.1 MMTCE or 0.01 Tg
Transportation & Storage	Compressor stations, pneumatic devices, pipeline maintenance, accidents, injection/withdrawal wells, and dehydrators	37% 12.4 MMTCE or 2.2 Tg	Transportation tanker operations, crude oil storage tanks or tankfarms, crude oil pipelines (e.g. Picard 2000, IPCC 2006)	48% 0.7 MMTCE or 0.13 Tg
Distribution	Gate stations, underground non-plastic piping (cast iron mainly) and third party damage (e.g. See Anifowose et al. 2012)	26% 8.6 MMTCE or 1.5 Tg	Not applicable	
	TOTAL	33.5 MMTCE or 5.8 Tg		1.6 MMTCE or 0.27 Tg

Source: after, Draft inventory of U.S. Greenhouse Gas Emissions & Sinks: 1990-2010 (February 2012)

Table 2: Characteristics of the System 2C Crude Oil Transport Pipeline. NB: This table is best read alongside Figure 2.

System	PIPELINE SECTION	DISTANCE KM	SIZE INCHES	CAPACITY M^3	DESIGN FLOW RATE M^3/HR	
					Min	Max
2C	Escravos to Warri	60.0	16”	16,080	1,500	1,650
	Warri to Abudu	89.6	16”	10,820	360	640
	Abudu to Auchi	89.5	16”	10,810	360	640
	Auchi to Lokoja	103.9	16”	12,550	360	640
	Lokoja to Abaji	100.2	16”	12,100	360	640
	Abaji to Izom	81.5	16”	9,840	360	640
	Izom to Sarkin Pawa	90.8	16”	10,965	360	640
	Sarkin to Kaduna	58.0	16”	7,005	360	640

Source: adapted from NCP/BPE (2008).

Table 3: Grouping of resulting emission data

Earlier Years:	Latter Years:
Group 1	Group 2
2005, 2008, 2009	2010, 2011, 2012