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ANALYSIS AND PROCESS EVALUATION OF THE SUSTAINABILITY AND IMPACT OF NATURAL GAS IN AFRICA

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ABSTRACT
Environmental concerns call for the need for the world to start running completely on cleaner energy sources. However, the advocacies from various quarters calling for quick jettisoning of any other energy sources and leaving only those with negligible or no carbon emission potentials in the energy mix is totally unrealistic, as even a gradual transition process is faced with various challenges. There is therefore, the need to holistically address the various issues in terms of social, economic, energy efficiency, technological switch and associated cost, and energy affordability. Natural gas is a cleaner alternative with minimal carbon emission and global warming potential (GWP). It is also cheaper to process and affordable to most of the populace than most other energy sources. It can therefore be inferred that the demand for natural gas remains high given to these benefits. These advantages of natural gas over other fossil fuels can be leveraged to address the challenges facing the complete transition to zero carbon energy sources. In this work, the key factors influencing transition to low carbon energy which has been discussed in the literature were reviewed, these include political, socioeconomic, and climate change. The work also considers how natural gas will contribute in the process of transiting to the use of cleaner energy sources. To further support and justify the views, which is this research focus, we developed mathematical models that closely describe natural gas production and demand patterns in Africa, and also conducted process Life Cycle Assessments (LCAs) to quantify and compare the environmental impacts of natural gas energy and other fossil fuels in the region, using their diesel equivalences. It was found that natural gas poses far lesser environmental consequences compared to other fossil energy sources. Specifically, the region could be saved of over 155 thousand metric tonnes of CO_2 emission daily if the current use of other fossil fuels are completely replaced with natural gas. Hence, if the main challenge associated with natural gas, which is methane leakage, is eliminated, natural gas will continue to play a vital role in the long term, in the future energy mix.

KEYWORDS:
Production and Demand Model, Environmental Life Cycle Assessment, Cradle to Grave, Process Engineering Approach, CO_2 Emission, Global Warming Potential.

1.0 INTRODUCTION

Complete transition to no carbon emission energy sources appears to be faced with a mix of challenges which can be said not to have been foreseen or seen with a blurred vision by most environmental campaigners. Like the UN's Sustainable Development Goals (SDGs) which is only imaginative, considering that it envisaged for just fifteen years ahead, most projections across countries that favour the full effect of zero carbon emission energy sources are only good to be true on paper and as such, too far from realisation. The world is working seriously towards goal number seven (Affordable and Clean Energy) of the SDG which is the major determiner of goals number eleven (Sustainable Cities and Communities) and thirteen (Climate Action) (UNDP, 2015). This is unarguably important to secure our world. However, some technological innovations that are meant to emit zero carbon still source their energy from sources that are not entirely clean, hence, this is just a shift of burden. Some of such projections that favour the total dependence on renewable sources in the transition process are: The World Wild Life Federation (WWF) report which revealed that a million onshore and a hundred thousand offshore wind turbines could meet one quarters of the world's energy demand by 2050 (Eric & Joanne, 2015); Renewable energy production from technologies that are readily available today, together with flexible power systems, is very sufficient to supply about 80% of the total U.S electricity need by 2050 (Hand, *et al.*, 2012)

However, the projection of the renewable energy system as being a stand-alone solution to a decarbonised energy future appears impracticable, taking social and economic factors into consideration while we are still much concerned about the environmental factor in the transition process. The energy mix ought to be considered as a whole to identify other possible non-renewable energy sources that could offer minimal or near zero negative environmental consequences, hence, can be regarded as cleaner sources as well; The question of affordability must also be sincerely addressed by employing relevant economic and statistical methods for a proper analysis of the available energy market data, especially the demand side. There should also be the concern about the fact that transition pace will vary by locality, region and country. Other low-carbon sources and energy technology mix will offer great opportunities for innovative solutions. Therefore, the one-model-fits-all problems type of solution being projected as a panacea to the no-carbon transition process requires a broader view, to accelerate actions in the short to medium term (Safari, *et al.*, 2019). Safari *et al.* (2019) also argued that natural gas presents a good option to compliment renewable energy sources for transition as that will provide innovative scope, various technological advancement, and choice, as a result of different resource endowment and short term priorities. In addition, to ensure that countries that solely depend on fossil fuel energy means are not under threat in the transition struggle, a smooth, socially and economically reasonable transition process needs to be initiated.

Environmental concerns regarding energy consumption together with economic growth are becoming more apparent, and the discourse concerning economic growth and its environmental impact has been on-going. A crucial parameter in the process of transition is the availability of modern energy conversion and transmission technologies. Challenges around access to energy and living condition have been complicated by the rate of increase in global population (Safari, *et al.*, 2019). The fact has been acknowledged that it is important to the world that these issues be handled with topmost priority, in an environmentally sustainable manner (UNDP, 2015). The discussion about SDGs has given rise to a various policies due to results from the integration of environmental elements into the economic activities at various and collective levels. Diversification and control of energy supply and consumption are considered as important mitigation policies for addressing the climate change problem (IPCC, 2007).

The parties to the Paris Agreement consented to ensure that the global temperature increase does not exceed 1.5ºC. The United Nations Development Programme's (UNDP's) adopted parallel SDGs framework of 2015 also shows differences in national priorities and how national priorities require simultaneous considerations in the short term (UNDP, 2015). The transition to low-carbon energy source has now become of great importance to the countries who participated regardless of their development status, alongside efficiency improvement of the total energy system with a rise in the consumption of renewable energy that has become popular across nations. The combustion reactions which fossil fuels undergo result in the emission of greenhouse gases (GHG) that contribute to global warming, a phenomenon not attributed to RES, hence, this positive impact makes renewable energy more important and popular across countries. It was reported by the International Renewable Energy Agency (IRENA) that about 2000GWs of energy was generated from renewable sources at the end of 2015 (IRENA, 2015). It was also reported the largest renewable energy capacity was installed in 2016, with wind and solar energy making the substantial part of it because of low cost of the technologies (Safari, *et al.*, 2018).

Energy is the major driving force of socio-economic development; it provides a substantial input in the fight toward poverty eradication, helps to increase the rate of food production and aids access to clean water, helps improve public health and education services, creates room for economic opportunities and empowerment. It has been demonstrated with fact, that the fight against climate change requires a fundamental change in the pattern of generation and use that should not be of negative impact to human progress and economic development. Access to affordable, clean and sustainable energy is also part of the agenda brought forward by UNDP, as spelt out by item seven of the SDGs. However, energy derived from fossil sources has tremendously increase carbon footprint generally. Affordability here, means economically viable while clean and sustainable mean environmentally friendly and reliable manners through conventional and unconventional energy sources. In this respect, low-carbon and clean energy policies have been suggested to mitigate energy insecurity and climate risk (INDC, 2015). Steady growth with insignificant adverse environmental effect can be achieved by decoupling emission from energy consumption and GDP growth (Ramanathan, 2006). The development pattern adopted by a nation sometimes results from the fragments of decisions made by various players of the economy and not always integrated into all sectors. The issue of climate change is not just an environmental problem, but also of great impact on socio-economic development. Countries are therefore coming to understand and see that the problem of climate change needs to be addressed by an integrated crosscutting policy approach (Safari, *et al.*, 2019). That is, there is need for it to be made a mainstream of the development planning. Numerous pathways for transition to reach the "low-carbon" goal have been proposed in the literature. Most researchers are of the opinion that achieving the ultimate result requires the use of a mix of low carbon content technology and energy sources (IPCC, 2014). Energy is a basic component of life and for any modern society, it directly affects every human activities and plays a major role in social and economic development. It is indeed, deeply rooted in all components of mankind development: economic, social and environmental (Tzanakis, *et al.*, 2012).

The quality of life is directly dependent on the access to energy from any energy source, and about 1.6 billion of the world's population have no access to modern energy services (Safari, *et al.*, 2018). Technical challenges, with inadequate or lack of infrastructure (that is, sufficient storage units), technical know-how and inconsistent sources of renewable energy (the most significant) are also sources of worry (Safari, *et al.*, 2019). Renewable energy sources are mostly periodic by nature, an undesirable characteristic in energy development and network system. Hence, renewable energy is not affordable and readily available for majority of the populace (IRENA, 2015). Besides poor access to energy and technical challenges, energy cost and access to modern infrastructure and economic consequences are part of the third aspect. Infrastructural development in countries or regions with poor infrastructure will be very costly. Lack of proper infrastructure in place therefore, implies a substantial cost of investment in renewable energy and makes it more reasonable to invest in non-renewable energy resources, as the cost associated with the development and production of renewable energy sources is relatively huge compared to that required for non-renewable resources (Safari, *et al.*, 2018). Solar and wind resources which appears less costly to develop and produce in the renewable energy mix, may be a better alternative to power generation from coal in terms of cost, but not to natural gas (EIA, 2018). Other disadvantages of renewable energy sources include: unreliability and storage difficulty, low level of generation and relatively higher cost per energy compared to other energy types (Safari, *et al.*, 2019).

A new energy model is needed to tackle the challenges mentioned. However, such model does not have a unique solution. The most pressing future challenge can be minimised with systems that make use of fossil fuel energy sources, developed and produced by efficient technology solutions. These can be used for competition and for the facilitation of the realisation of renewable energy resources. This would greatly increase the energy efficiency of both present and future conversion systems. Natural gas is the most dependable and the cleanest among all fossil fuels. It has been projected that its demand will rise by about 50% by 2035, and therefore, expected to overtake coal in the future global energy mix (OECD/IEA, 2011).

2.0 PRODUCTION AND DEMAND MODELS

This section is concerned with the development of empirical models that suite the regional demand and production trends of natural gas. As noted earlier, the demand for natural gas around the world has been on a steady increase primarily due to affordability, coupled with environmental efficiency, fuel diversity and energy security and economic growth. The current consumption trend of natural gas energy source in Africa, upon which the production trend depends closely follows the models developed here. Natural gas being a cleaner source of energy than coal and other fossil fuels, has also been seen and forecasted to have a higher demand growth rate after coal (EIA, 2007). This led to a forecast that the consumption of natural gas would almost double between 1999 and 2020, a projection that has been confirmed (Balat, 2005). Consequently, this has encouraged production and associated technological innovation.

In this work, a new model approach was developed to model natural gas production and demand trends in Africa. This approach was inspired by the International Gas Union (IGU) Expert View Scenario Data (IGU, 2009). Figure 1 below shows the region's gas production and demand past trend combined with the IGU forecast. The plots closely agree with the models developed here.

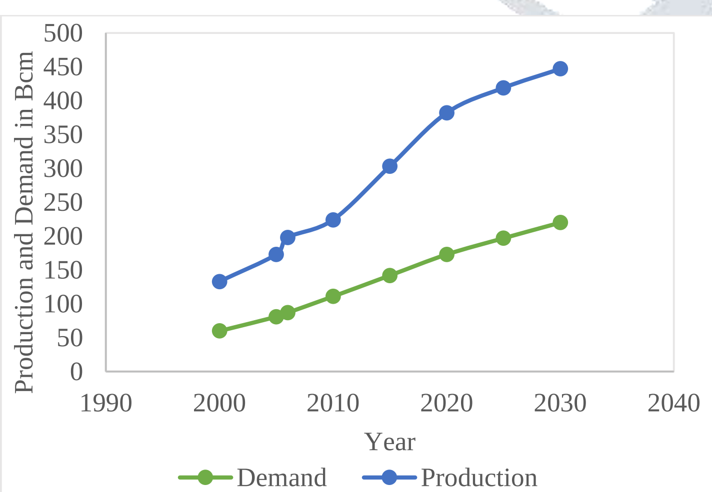

Figure 1 - Production and demand trends for Africa.

For production:

$$PNG = -0.0003A + 2.345B - 7035.9C + 9 \times 10^6 D - 5 \times 10^9 \qquad R^2 = 0.9960 \qquad (1)$$

For demand:

$$DNG = 5.5675y - 11078 \qquad R^2 = 0.9968 \qquad (2)$$

Where *A*, *B*, *C*, and *D* in (1) are functions of *y*. For the same year *y*,

$$A = 1.5676 \times 10^{13} + 5.6606 \times 10^9 DNG + 7.663 \times 10^5 DNG^2 + 46.11 DNG^3 + 1.04 \times 10^{-3} DNG^4 \qquad (3)$$

$$B = 7.88 \times 10^9 + 2.133 \times 10^6 DNG + 192.55 DNG^2 + 5.79 \times 10^{-3} DNG^3 \qquad (4)$$

$$C = 3.96 \times 10^6 + 715.13 DNG + 3.23 \times 10^{-2} DNG^2 \qquad (5)$$

$$D = 1989.8 + 0.1796 DNG \qquad (6)$$

The IGU expert view scenario forecast reveals a steady increase in natural gas demand over the next decade. The high demand rate can be explained by social, economic, efficiency and environmental factors.
The abundance of natural gas is an advantage that is currently being utilised for societal development in all parts of the world. Power can be easily and readily sourced from gas in all regions due to its availability, this in turn contributes to socio-economic development of the society at large. Solar and other forms of renewable energy resources are however regionally limited, that is, their availability and intensity vary across space and with season. Currently, the world sources a huge part of its energy use from fossil fuels. This is because these sources provide energy at a lower cost compared to most renewable energy sources and they are abundantly available. Natural gas in particular, is the cheapest and cleanest fossil fuel energy sources, it is not expensive to process and very affordable to an average consumer. In addition, it is widely available and fairly evenly distributed across regions and countries. Hence, there is no doubt that the availability and affordability of natural gas resource is the reason for the continuous rise in the demand.

3.0 ENVIRONMENTAL LIFE CYCLE ASSESSMENT

Products and systems should be evaluated for their environmental impacts as well as their technical and economic potentials. The environmental impact of a product or system can be conducted using Life Cycle Assessment (LCA). LCA is a tool for conducting a systematic analysis that describes the 'cradle-to-grave' environmental impacts of products, processes and services using Process Engineering Approach (Murphy, 2018). The increasing awareness for environmental protection has resulted in increased attention for LCA. LCA provides a systematic assessment of all environmental aspects related to a product or services to ensure that economic growth results in reduced environmental impact; that is, we want to make sure that economic growth is decoupled from environmental impact (Murphy, 2018). The aim of an LCA can be explained as to provide results which will help achieve the following objectives: identification of the interaction between a product or service with the environment and to analyse and quantify the environmental load; provision of information which help make informed decisions on prioritising environmental improvements; to provide a tool for evaluating the level of achieving target values and meeting regulatory requirements as part of companies efforts for environmental protection; effective communication with customers on the environmental quality of a product or service (Riva, *et al.*, 2006).

In this section, we conducted 'cradle-to-grave' LCAs for natural gas energy and other fossil fuel energy sources (petrol and diesel) from crude oil. The 'cradle-to-grave' processes of these fuel sources are similar in design because, they are extracted in similar ways and they share some other processes in common.

3.1 LCA for Crude Oil Sourced Fossil Fuels

The life cycle flow sheet for fossil fuels sourced from crude is shown in figure 2 below. The production phase here refers to activities carried out at the surface to ensure safe and economic extraction of the crude and other surface separation done before the crude is passed to the refinery for further processing.

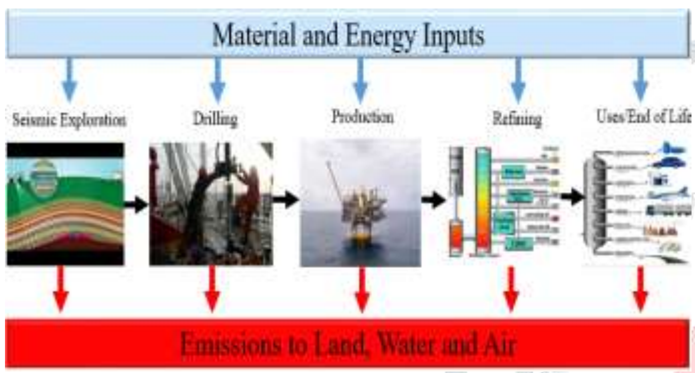

Figure 2 – Life cycle flow sheet for crude oil sourced energies. Sources: Megasco; Getty Images/Joe Raedle; Equinor; Pinterest; BPF

As illustrated in figure 2, the end products of refined crude find uses in the flowing sector: domestic, transportation, industry and construction.

The breakdown for energy requirement and associated emission for each stage is presented in table 1 below. The average energy requirements for each of the exploration, drilling and production operations is estimated for an average operation (IPIECA, 2013) and assuming each of these operations is implemented daily. The emissions for exploration, drilling and production were calculated for about 60 rigs currently located Africa (Faria, 2021). The diesel requirement for production operation is made to be slightly higher due to emissions not primarily from fuel consumption, e.g. emissions from desanding and dewatering/desalting systems. The average energy requirement for crude refining is estimated for the total current Africa's refining capacity of 3,712,000 *barrels/day* (Research and Markets, 2020). The end of life/uses of products is estimated for the continent's fossil fuel (diesel plus diesel equivalence of petrol and kerosene) consumption. The CO_2 emission was estimated at 10.180×10^{-3} *metric tons* CO_2/*gallon* of diesel (Federal Register, 2010), assuming all the carbon in the diesel are converted to CO_2 (IPCC, 2006) and using the volumetric conversion factor of 264.172 *gallons/cubic meter*. The average refinery emission rate was estimated based on the emission range of 0.8 to 4.2 *million* of CO_2 per year for a standard 300,000 *barrels per day* refinery (Straelen, *et al.*, 2009), and back calculations were made to arrive at the diesel fuel equivalence. The end of life/use is estimated based on the average crude demand of 3.1 *million barrels per day* in Africa (IEA, 2019). This is used to determine a rough estimate of the volume of diesel that could be produced from the knowledge that a typical U.S refinery will produce about 12 *gallons* of diesel from 42 *gallons* (1 *barrel*) of crude (EIA, 2021). The estimation ignores the transportation phase due to the complexity in accounting for that phase. However the aim here, which is to adjudge the comparative level of the impacts of natural gas and crude oil resources is achieved.

Table 1: Estimates of process energy requirements and CO_2 emission for crude sourced fossil fuels.

Stage	Average energy required per day (m^3/*day* of diesel)	Unit	Equivalent CO_2 emission (*metric tons* of CO_2 *per day*)
Exploration/Drilling	30	60	4,840.6877
Production	50	60	8,067.8129
Refining	31,500	1	84,748.8584
End of life/use	140,817	1	401,759.0121

3.2 LCA for Natural Gas Sourced Fuels

The environmental life cycle of natural gas energy is quite similar to that of other fossil fuels sourced from crude oil, especially the first three stages (seismic exploration, drilling and production). As noted in the previous subsection, the production cycle involves the extraction of natural gas from the subsurface and some surface preliminary operations which includes de-sanding and gas/liquid separation. The processing phase includes further field processes which include cryogenic separation, conditioning and sweetening, dehydration, compression, liquefaction and others.

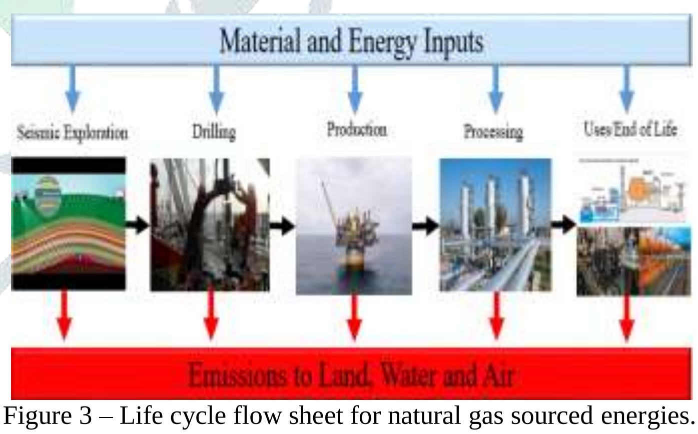

Figure 3 – Life cycle flow sheet for natural gas sourced energies. Sources: Megasco; Getty Images/Joe Raedle; Equinor; Petro Energy; Kepco; MET.

As illustrated in figure 3 above, natural gas energy finds its end use in the following sectors: power generation, domestic and industrial.

As similarly done for other fossil fuels, the breakdown for energy requirement and associated emission for each stage is presented in table 2 below. The average energy requirements for each of the exploration, drilling and production operations is estimated for an average operation. The average energy requirement for processing natural gas is considered to be considerably lesser than that required for processing an equivalent volume of crude oil as crude is comparatively complex in nature and much expensive to process to finished products. Considering that the equivalent volume of natural gas for the diesel equivalent volume rate of 31,500 m^3/day (198,129.0384 *barrels/day*) of the refinery capacity in table 1 above is to be processed. This volume rate of diesel will require an equivalent rate of about 1,103 $MMft^3/day$ natural gas to produce the same Heating Value (HV) (EIA, 2021). The end of life/use of products is estimated for Africa's fossil fuel (diesel plus diesel equivalence of petrol) consumption for natural gas volume equivalent to the 140,817 m^3/day (885,712.2795 *barrels/day*) of diesel in table 1; this will amount to a natural gas volume rate of about 4,930 $MMft^3/day$ (EIA, 2021) to produce the same HV. The CO_2 emission estimates for exploration/drilling and production phases remain as they were in sub-section 3.1. Using a CO_2 emission rate of 0.0548 *metric tons* CO_2/Mft^3 of natural gas (EPA, 2021), the emission rate for the processing and the end of life/use in table 2 were arrived at.

Table 2: Estimates of process energy requirements and CO_2 emission for natural gas sourced fossil fuels.

Stage	Average energy required per day (m^3/day of diesel)	Unit	Equivalent CO_2 emission (*metric tons* of CO_2 *per day*)
Exploration/Drilling	30	60	4,840.6877
Production	50	60	8,067.8129
Processing	31,500 (1,103 $MMft^3/day$)	1	60,444.4000
End of life/use	140,817 (4,930 $MMft^3/day$)	1	270,164.0000

4.0 DISCUSSION OF RESULTS

4.1 PRODUCTION AND CONSUMPTION TRENDS

The current consumption trend of natural gas energy source in Africa, upon which the production trend depends closely follows the models developed in section 2.0. Although sub-regional variations exist, there is closer agreement with the pattern in general. Natural gas being a cleaner source of energy than coal and other fossil fuels, has also been seen and forecasted to have a higher demand growth rate after coal (EIA, 2007). This was also supported by the IGU expert view scenario forecast (IGU, 2009).

The high demand rate can be explained by social, economic, efficiency and environmental factors:
The abundance of natural gas is an advantage that is currently being utilised for societal development in all parts of the world. Power can be easily and readily sourced from gas in all regions due to its availability, this in turn contributes to socio-economic development of the society at large. Solar and other forms of renewable energy resources are however regionally limited, that is, their availability and intensity vary across space and with season. Currently, the world sources a huge part of its energy use from fossil fuels. This is because these sources provide energy at a lower cost compared to most renewable energy sources and they are abundantly available (IEA, 2013). Natural gas in particular, is the cheapest and cleanest fossil fuel energy sources, it is not expensive to process and very affordable to an average consumer. In addition, it is widely available and fairly evenly distributed across regions and countries (Demirbas, 2002). Hence, there is no doubt that the availability and affordability of natural gas resource is the reason for the continuous rise in the demand.

Natural gas is also seen to be more efficient than renewable energy sourced energies. For instance, one gallon of gasoline has a potential of about 37kWh, which would require a slightly higher equivalent cubic feet of natural gas. This will require 185 hours of sunshine, which could take about a month for a consistent 6 hour of sunshine daily (Timmons, *et al.*, 2014).

Natural gas is also more environmental friendly compared to other fossil fuels. Issues of spillage resulting in environmental pollution which most times destroys aquatic and terrestrial lives are not commonly associated with natural gas.

4.2 ENVIRONMENTAL LIFE CYCLE

All energy resources have their environmental impact during their life cycle from exploration/production to end of life/use. Natural gas like other fossil fuels have similar life cycle structures since their processes from extraction to processing are sometimes related and similar. However, except for methane leakage to the atmosphere during drilling and pipeline transportation, which poses a serious greenhouse effect, natural gas is a cleaner source. In addition to high energy conversion efficiency, natural gas generally have a much lower global warming potential compared to coal and other fossil fuels. It is the cleanest and richest in hydrogen among all hydrocarbon. Natural gas also emit much lesser volume of CO_2 during combustion; with about 50% to 60% less by volume when it undergoes combustion in a new plant and efficient gas power plant compared to a typical new coal power plant (NETL, 2010).

The cradle to grave LCAs done in the previous section reveal that emission from natural gas is much more less compared to other fossils fuels, with results showing that the continent and of course, the world can be saved from over 155 thousand *metric tonnes* of CO_2 emission into the atmosphere per day if all current use of other fossil fuels of high GWP are replaced with natural gas energy. This figure can be said to be the least possible avoidable emission rate because: for processing, we have used the worst case scenario, that is, considering that the diesel equivalence of all CO_2 emission for Africa's total crude refinery capacity is converted to the natural gas volume rate which will produce the same HV and for end of life likewise, the diesel equivalence of the total demand for crude in Africa has been converted to the natural gas volume rate that will produce the same HV. However, in the real sense, a natural gas processing facility may probably even emit lesser volume of CO_2 compared to a crude processing facility of similar capacity. Typically, lower emission implies lesser energy wastage – which means better efficiency alongside lower pollution. It has been demonstrated in section 3.0 that, natural gas energy has a comparative advantage over other fossil fuels in terms of environmental performance. The application of LCA to natural gas and the diesel equivalence of other fossil fuels for energy generation, using the CO_2 emission criterion helped to prove this advantage. Hence, in addition to comparative cost advantage and availability over renewable energy technology and high energy conversion efficiency, natural gas which is the fossil fuel with minimal GWP promises to bridge the gap as a clean and efficient fuel in the transition to sustainable and clean energy sources.

5.0 CONCLUSION

Natural gas, being a cleaner energy source compared to other fossil fuels such as diesel and coal promises to be a lasting alternative for meeting the immediate to medium term global energy needs in the move toward full utilisation of zero carbon energy sources. Natural gas is also believed to continue in serving some energy needs in the long term in the future energy mix. Following this research, the following findings were arrived at:

- The demand for natural gas will continue to rise in the next decade, judging by past trends and current state of energy use.
- Although there is sub-regional variations in the demand and production patterns from the general models developed, most trends approximately correlate with the models.
- Political, socioeconomic and climate change factors are influencing the transition to the full utilisation of zero carbon energy sources.
- The almost instantaneous transition to no carbon emission which is being advocated by various models from various quarters is infeasible.
- While environmental performance is of the essence, socioeconomic impact ought to be given serious consideration in the move toward zero carbon energy. Affordable energy must be available to the society at large; poor and rich alike for uniform social development.
- Natural gas has a lower GWP compared to other fossil fuels, much lower technological cost (easy and cheaper to process than gasoline) and it is affordable to most consumers compared to other fossil fuels and renewable energy.

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