Petroleum and Coal

Article **Open Access**

Development of a Conceptual Framework for the Application of Circular Economy in the Nigerian Refining Industry

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Received August 18, 2023; Accepted November 13, 2023

Abstract

The refining industry is confronted with challenges ranging from environmental pollution to high market volatility. Effective methods to quantify and monitor the potential environmental impacts of the refining process are lacking in the industry. In this study, the refining process is examined from the perspective of the circular economy (CE). The objective is to identify the primary environmental damage caused by the refining process and identify potential solutions. This study made use of an inventory and quantitative analysis of the Fluid Catalytic Cracking Unit. A portion of the environmental impact of the refining process is attributable to processes involving fuels, working fluids, and auxiliary materials. Improving the utilization of steel resources, adopting best maintenance practices, and improving the utilization efficiency of resources and energy is helpful to reduce the environmental hazards of the refining process system. This research focuses on the existing refinery configuration; it highlights areas where CE has already been well-thought-out and seeks to instigate pragmatic solutions to identified areas in need of improvement. The study attempts to proffer alternative solutions which could be implemented to bridge identified gaps when operating existing refineries, rehabilitating old refineries, or embarking on new refinery projects.

Keywords: *Circular Economy; Fluid Catalytic Cracking Unit; Life Cycle Assessment; Recycling; Refinery.*

1. Introduction

The crude oil refining and processing industry is crucial in the production of various types of fuels, and its refining process involves several complex physical and chemical processes. The industry produces a wide range of products, including petrochemicals, lubricants, asphalt, and paraffin wax. The refining industry is a complex structure that involves various stakeholders and processes that affect the performance of the entire system. The circular economy aims to develop new business models that increase the value and life of materials, products, and assets and design out waste from production and consumption. Refineries utilize resources to transform crude oil and its derivatives into products, and the efficient utilisation of these resources has been a challenge to the industry. Effective refinery operations should deliver superior value at minimal cost while considering social and environmental factors. Refinery operations generate waste products, and poor management of these waste products may lead to a severe loss of lives and property. The circular economy aims to decouple economic growth from the rate of increase in environmental impact by arranging direct reuse, repair, refurbishment, and remanufacturing. The Figure 1 show the major CE factors in Nigerian refineries.

1.1. The circular economy concept

The CE is an industrial system that was intended to be restorative or regenerative by design. This idea seeks to eliminate waste through the superior design of materials, products, systems, and within that, business models. Additionally, it switches to using renewable energy, abandons hazardous chemicals (which prevent reusing), and does away with toxic chemicals [1].

Walter Stahel and Genevieve Reday promoted the idea of an economy in a loop and its implications for job creation, economic competitiveness, resource savings, and waste prevention in the 1976 research report of the European Commission titled "The Potential for Substituting Manpower for Energy" [2-5].

This concept, published in 1982, is known as the Circular Economy (CE). CE is a model kind of production and consumption, which looks at re-using, repairing, refurbishing, and recycling existing waste materials from the production process [6-9]. The universe is sensing the need to rely increasingly on research based on the idea of a circular economy for effective resource usage and waste management [10-11].

The CE is an answer to the need for sustainability in the face of mounting production and consumption pressures on the planet's resources and environment [12]. It is advantageous to use best maintenance practises, increase the use of steel resources, and improve resource and energy efficiency, as well as a CE framework designed to reduce environmental risks associated with the refining process system. The Circularity notion has, however, not been implemented in the way that was intended despite its widespread popularity [13]. This study focuses on the configuration of an existing refinery in Nigeria. It identifies areas where CE has already been carefully considered and seeks to spark practical solutions to those areas. The study attempts to suggest alternative solutions that could be used to close gaps when operating existing refineries in Nigeria, restoring previous refineries, or starting new refinery projects. The study seeks to safeguard the environment while also boosting efficiency throughout the product life cycle, in contrast to a linear economy. It can also be viewed as a closed economic model in which waste and resource consumption is reduced during the production of goods [14].

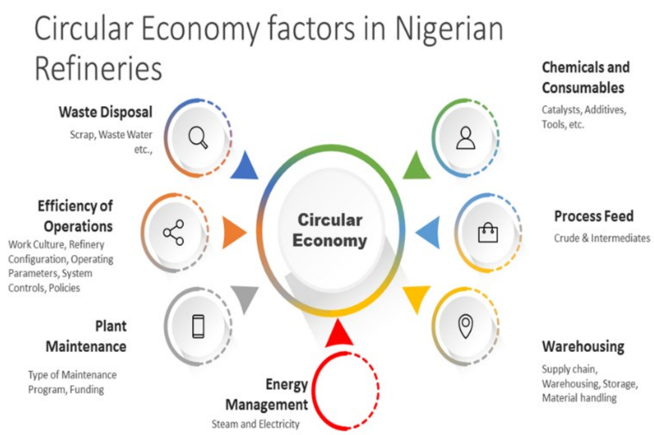

Figure 1. Key circular economy factors in Nigerian Refineries

CE transcends recycling because it is based on a rehabilitating industrial system that will lead to the eradication of waste [15]. Recycling can be regarded as the outer layer of the CE, needing more energy than the inner layer, which includes, among other things, repair/modification, reuse, and treatment [16]. CE refers to an economy that leaves no waste to be landfilled and one that maintains the continuous loop of materials and resources through reuse, redesign, and material/ energy recovery [17]. Current practices have seen the CE concept being embraced in the policy of developed nations as well as developing nations [18].

According to [19], a CE focuses on virgin materials, hazardous chemicals, and waste streams that create unique issues to maximize the value of materials that circulate within the economy while simultaneously attempting to limit material consumption such as plastics, food, electricity and electronic goods [20].

1.2. Existing adaptations of CE in the oil and gas industry

Merli *et al.* [21] stated that an economic model must tend toward a circular system for sustainable growth, particularly in the sector of waste management. Their research focuses on valorising spent FCC catalysts from oil refineries, which produce 400,000 metric tons of spent catalyst each year, most of which is disposed of in landfills. The research community has shown interest in the catalyst employed in the refining process [22].

The economic performance of the project is also described using other indices, such as the Gross Margin Ratio (GMR) and Return on Investment (ROI), by the metric used in the balance sheet. The analysis of the research is conducted in a baseline with alternative scenarios and varying critical variables. Some studies focused on new processes for recycling the catalyst used in the FCCU of Oil Refineries [23-24].

Considering the key circular economy factors, this study seeks to contribute to developing a conceptual framework for the application of CE in the refining Industry in Nigeria, bridging the information gap, and creating a platform for further studies on the subject matter.

2. Theoretical considerations

The following are a few illustrations of mathematical expressions that could be used to illustrate various aspects of the CE:

1. **Material flow:** In a CE, materials are cycled through the economy in a continuous loop, rather than being extracted, used, and discarded. One way to represent this material flow mathematically is with a mass balance equation, which describes the movement of a particular material between different parts of the system. For example, the equation might describe how much of a particular material is being extracted from the environment, how much is being used in production, and how much is being returned to the environment through waste treatment or recycling processes. The material flow model can be expressed as follows:

Considering a dynamic economy which consists of a representative consumer with preferences over consumption on n different types of functionalities $c_{1,t} \geq 0$, with $i = 1, 2, 3, \ldots\ldots n, and\ t,$ denoting time, running from 1 to T. Preferences are represented by a strict concave instantaneous utility function, $\grave{u}_{,t}(c_{1,t}, c_{2,t}, \ldots. c_{n,t})$ satisfying ${\partial u_t}/{\partial_{\grave{c}_{i,t}}} > 0^3 \ldots..$

For optimal behaviour, we characterize the optimal behaviour of the material flows of the system. The maximization problem of the economy subject to technological constraints can be expressed in Lagrangian notation as:

$$\mathcal{L} = \sum_t \boldsymbol{u_t} \left(\boldsymbol{z_t^1} (\boldsymbol{c_{1,t}}, \ldots.., \boldsymbol{c_{1,t-h_1}}), \ldots \ldots (\boldsymbol{c_{n,t}}, \ldots.., \boldsymbol{c_{n,t-h_n}}) \right) + \sum_t \sum_j \left(\boldsymbol{q_{j,t}^v} (\boldsymbol{m_{1,t}^j}, \boldsymbol{m_{2,t}^j} \ldots.., \boldsymbol{m_{n,t}^j}) + \boldsymbol{q_{j,t}^r} (\boldsymbol{r_{1,t}^j}, \boldsymbol{r_{2,t,}^j} \ldots.., \boldsymbol{r_{n,t}^j}) \right) + \sum_t \boldsymbol{\lambda_t^c} \left(\boldsymbol{c_{i,t}} - \boldsymbol{f_{i,t}} \left(\boldsymbol{m_{i,t}^j}, \boldsymbol{m_{i,t}^j} \ldots.., \boldsymbol{m_{i,t}^N}, (\boldsymbol{r_{i,t}^1}, \boldsymbol{r_{i,t,}^2} \ldots.., \boldsymbol{r_{i,t}^N}, \boldsymbol{k_{i,t}}) \right) + \sum_t \sum_i \sum_j \boldsymbol{\lambda_{i,j,t}^{rv}} \left(\boldsymbol{r_{i,t}^{v,j}} - \boldsymbol{g_{i,t}^{v,j}} \left(\boldsymbol{m_{i,t-h_i}^j}, \boldsymbol{k_{i,t}^{v,j}} \right) \right) + \sum_t \sum_i \sum_j \boldsymbol{\lambda_{i,j,t}^{rv}} \left(\boldsymbol{r_{i,t}^{v,j}} - \boldsymbol{g_{i,t}^{v,j}} \left(\boldsymbol{r_{i,t-h_i}^j}, \boldsymbol{k_{i,t}^{r,j}} \right) \right) + \sum_t \boldsymbol{\lambda_t^k} (\boldsymbol{K_t} - \sum_i \sum_j (\boldsymbol{k_{i,t}^{v,j}} + \boldsymbol{k_{i,t}^{r,j}}) - \sum_i \boldsymbol{k_{i,t}})) + \sum_t \boldsymbol{\lambda_t^w} (\boldsymbol{W_t} - \boldsymbol{W_t}) \tag{1}$$

Proposed metric

Having characterized the optimal flow of virgin and recycled materials, we proceed to build some auxiliary metrics.

We define the *endogenous* recycling rate of material type *j* in sector *i* at time $\boldsymbol{t}(\boldsymbol{\alpha_{j,t}^i})$ as $\boldsymbol{\alpha_{j,t}^i} = \frac{\boldsymbol{r_{i,t}^j}}{\boldsymbol{m_{i,t}^j} + \boldsymbol{r_{i,t}^j}} \in [\mathbf{0}, \mathbf{1}]$, and the size of optimal recycling activity of material type *j* in sector *i* at time $\boldsymbol{t}(\boldsymbol{R_{i,j,t}^*})$ as $\boldsymbol{R_{i,j,t}^*} = \left(\boldsymbol{\Sigma_{s=0}^{h_i}} \frac{\boldsymbol{\partial u_{i+s}^*}}{\boldsymbol{\partial_{z_{i+s}}^*}} \frac{\boldsymbol{\partial f^*_{s,i}}}{\boldsymbol{\partial r_{s,i}^j}} \right) \boldsymbol{\alpha_{jt^*}^i}$ (2)

where asterisks denote optimal levels.

Thus metric (2) measures the marginal benefit of recycled material $\boldsymbol{r_{i,t}^j} \ldots$

2. **Economic value**: In a CE, economic value is generated through the reuse and recycling of materials, rather than through the extraction and use of new resources. This can be represented mathematically by calculating the net economic value generated through different circular activities, such as recycling or refurbishment, and comparing it to the net

economic value generated through traditional linear activities, such as resource extraction and disposal.

3. **Environmental impact:** The CE aims to reduce the environmental impact of economic activity by reducing the use of virgin resources and minimizing waste. This can be represented mathematically by calculating the environmental impact of different activities, such as resource extraction, production, and disposal, and comparing them to the environmental impact of circular alternatives, such as recycling or refurbishment.
4. **System dynamics:** The CE is a complex system with many interdependent parts and understanding how these parts interact and influence each other is important for designing and managing the system effectively. Mathematical models can be used to represent the dynamics of the circular economy, such as how different materials flow through the system, how economic value is generated and distributed and how different activities impact the environment.

3. Methodology

This study focuses on the refining industry with Warri Refinery and Petroleum Company (WRPC) FCC Plant as a case study. This order was followed:

1. Explore the circularity concept in the refining industry and identify areas for enhancement concerning recycling, reuse, recovery, and useful life extension in various refinery subunits.
2. Create plans to implement the circular economy in the refining sector.
3. Assessing the anticipated outcome of putting the developed strategy in WRPC.

3.1. The refinery from a CE Perspective

Various measures for determining circularity have been proposed such as the number of materials consumed, the quantity of energy consumed, the quantity of organic waste from processes, efficiency in the use of raw materials, ecological design of process plants, extension of useful life (Level of recycling and reuse), level of implementation of Circular Business Models and amount of investment in CE driven projects.

3.2. Retained environmental value approach to measurement of circularity

Haupt & Hellweg [25] proposed the use of retained environmental value (REV) as an impact-based measure for the circular economy as a holistic approach to circularity. It calculates how much of the original environmental impact may be preserved in nature through value preservation. This approach uses the formula below:

$$\mathrm{REV} = \frac{\sum_{j=1}^{n}\left(\mathrm{EI}_{\mathrm{disp},j} - \mathrm{EI}_{\mathrm{vrp},j}\right) - \mathrm{EI}_{\mathrm{surplus}}}{\sum_{i=1}^{n}\left(\mathrm{EI}_{\mathrm{original},i}\right)} \tag{3}$$

where: REV *(Retained Environmental Value),* EI_{disp} *(Environmental Impact of Displaced Product),* $EI_{surplus}$ *= Environmental Impact of Alternative Primary Product,* $EI_{original}$ *(Environmental Impact of Original Product),* EI_{vrp} *(Environmental Impact for Remanufacturing, Recycling).*

A REV of 0% implies that no net environmental value is kept in the product, whereas a REV of 100% shows that the material has the complete original environmental value and is ready for further use. The REV can be used as an indicator to relate to a variety of important impact or damage categories, including climate change, biodiversity loss, human health consequences, and cumulative energy [26]. Most materials used in the refining process are provided by design without alternatives that hurt the product output. This research proposes a set of variables that are both practical and appropriate for the Nigerian refining sector.

3.3. Current level of circularity in WRPC

Key components which contribute to the level of circularity in WRPC's FCC unit include: wastewater treatment plant; fuels plant and petrochemical plant incinerators for solid waste; co-boiler; catalyst regeneration; heat exchange (heat exchangers, heat recovery steam generators, pipe design). Table 1 shows the annual metals and non -metals use in WRPC.

Table 1. Annual material usage (metals and non-metals).

SNO	Materials	Quantity (kg)	Percentage
1	Metals (Scrap)	1132017.60	63.54%
2	Chemicals (Non-Metals)	67994.40	3.82%
3	Catalyst (Powder)	536550.00	30.12%
4	Hydrocarbons (Non-Metals)	44928.00	2.52%
		1781490.00	100%

4. Results and discussion

The results of the study with regards to the federate, chemical consumption, and solid waste generation are presented.

4.1. The feed rate and chemical consumption for the Warri refinery

The design feed rate in the WRPC FCCU is 120m^3/hr. Chemical consumption in the FCC is mainly dependent on operations. Replenishment may be due to varying factors such as maloperations or leakages. Table 2 shows the federate and product output at the FCCU.

Table 2. Feed rate and product output.

S/N	Product	Quantity (m3/hr)	Density (kg/m^3)	Mass (kg/hr)
1	Gasoline	75	800	60,000
2	Light Cycle Oil	20	973.6	19,472
3	Methane	3.5	0.657	2.3
4	Fuel Gas			

4.2. Solid waste generation

Multiple interconnected subunits make up refineries. The expansion of solid waste over numerous components calls for further thought. Table 3 shows how much waste was generated by the FCC Unit during the course of 18 months. The entire mass density of the steel turnaround maintenance at the Warri Refining and Petrochemical Company was calculated to be 251,300,888 grammes (the approximate density of steel being 128.64g/inch^3).

Table 3. Intervention measures to maximize circularity in the FCC Unit.

Item	Category	Material Class	Reuse	Repare	Refurbishment	Remanufacturing	Useful Life Extention	Recovery	Benefits/Value Retention
Pipes	INPUT	SOLID		■		■	■		over 251,000 kg of steel pipes is to be replaced during WRPC's rehab
Valves	INPUT	SOLID	■	■	■	■	■		40% cost savings when valve recycling
Columns	INPUT	SOLID		■			■		Mainly determine by corrosion rate
Drums	INPUT	SOLID		■			■		Mainly determine by corrosion rate
Pumps & Motors	INPUT	SOLID	■	■	■	■	■		effective maintenance programs, design considerations and other factors significantly increases retention value

Item	Category	Material Class	Reuse	Repare	Refurbishment	Remanufacturing	Useful Life Extention	Recovery	Benefits/Value Retention
Feed (Heavy Gas Oil / Vacuum Gas Oil)	INPUT	FLUID						■	Efficient operations allow for 20-35% value retention
Flue-Gas/CO (For Heaters)	INPUT	FLUID	■				■	■	CO reused as fuel for the CO Boiler
Catalyst	INPUT	POWDER	■		■		■	■	99% recovery possible using electrostatic precipitator
Scrap	OUTPUT	SOLID	■	■	■	■	■		Estimated 500,000Kg of scrap generated per annum
C4	OUTPUT	FLUID						■	Effective compression in 16-K-02 compressors significantly retains C4 streams
Gasoline	OUTPUT	FLUID						■	Effective compression in 16-K-02 compressors significantly reduces release to flare
Light Gas Oil	OUTPUT	FLUID						■	Effective compression in 16-K-02 compressors significantly reduces release to flare
Off-spec Products	OUTPUT	FLUID	■	■				■	Efficient operations, and good maintenance programs engenders high value retention
Wast Water/Effluent	OUTPUT	FLUID	■				■	■	Less oily effluent, less charges due to environmental pollution
Flare Gases	OUTPUT	FLUID	■					■	Maloperation, design, and implementation of maintenance program influence gas flaring
Air	OUTPUT	FLUID		■			■	■	Process air through air blower.
Catalyst-release	OUTPUT	POWDER	■	■	■	■	■	■	Use of electrostatic precipitator can give 99% catalyst recovery
Light Cycle Oil (LCO)	OUTPUT	FLUID						■	Effective compression in 16-K-02 compressors significantly reduces release to flare

Item	Category	Material Class	Reuse	Repare	Refurbishment	Remanufacturing	Useful Life Extention	Recovery	Benefits/Value Retention
Methane (C3)	OUTPUT	FLUID	■					■	Effective compression in 16-K-02 compressors significantly reduces release to flare
Fuel Gas (FG)	OUTPUT	FLUID	■					■	Effective compression in 16-K-02 compressors significantly reduces release to flare
High Pressure Steam Output	INPUT	FLUID	■				■	■	HP Steam from compressor discharge used to drive process increasing retention value
Monoethanol Amine	INPUT	FLUID					■		Effective operations increase value retention
Philmplus	INPUT	FLUID	■				■	■	Effective operations increase value retention
Caustic (NaOH)	INPUT	FLUID	■				■	■	Effective operations increase value retention
Mekor	INPUT	FLUID	■				■	■	Effective operations increase value retention
Phosphate	INPUT	FLUID	■				■	■	Effective operations increase value retention

5. Conclusion and recommendations

An ideal framework for the CE must consider vital variables and align with business strategic goals. These factors include waste management, the efficiency of operations, maintenance program, design feed, warehousing/material management and chemical consumption (e.g., catalyst). Without these factors in play, a wholesome measure of circularity cannot be determined. Figure 2 summarizes the average resource consumption per annum used in the Fluid Catalytic Cracking Unit.

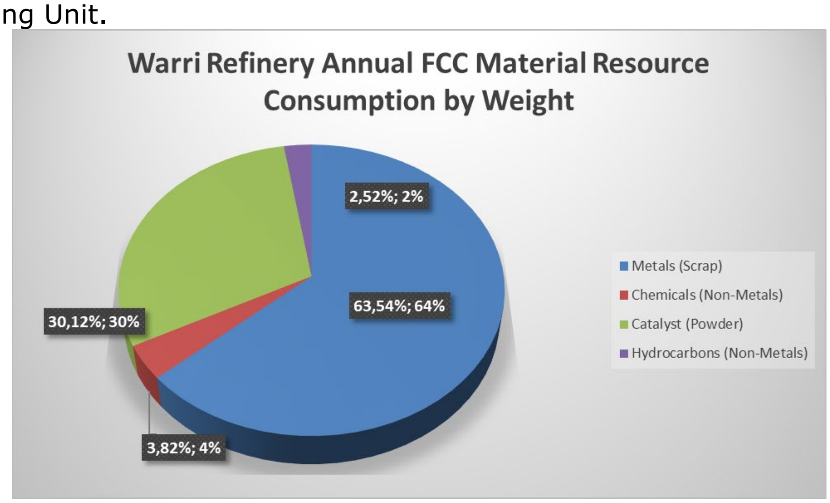

Figure 2. Estimated annual WRPC FCC material usage.

Focus on the key circularity factors in refining leads to significant gains, the following recommendations can significantly improve circularity in Nigerian Refineries: 99% reduction in catalyst loss by redesigning the FCC Unit to use the electrostatic precipitator. Over 63.54% of scrap material generated in Nigerian Refineries are metals. Improved circularity levels can be attained by improved maintenance programs and renegotiating contracts on the purchase of valves to adopt free valve recycling initiatives offered by leading valve manufacturers. Deploying advanced process controls limits losses due to maloperation. Hence limiting the accidental release of toxic chemicals into the environment.

Acknowledgements

The authors acknowledge the WRPC for allowing us to conduct our study in their company.

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