Research Article

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Optimizing Waste-To-Energy Boiler Performance in Kandy Industrial Park: A Comprehensive Life Cycle Assessment and Advanced Efficiency Enhancement Strategies.

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ABSTRACT

The scope of industrialization and energy usage requires efficient and environmentally friendly energy generation techniques to reduce the effects of energy production on the environment. This research specifically deals with enhancing the efficiency of the WtE boiler operating at the KIP while carting the industrial symbiotic phenomena between the apparel sector and the IV fluid Manufacturing facility located within the demarcated boundary for the KIP. This component has a comprehensive LCA and highly efficient boiler efficiency improvement techniques.

The present performance of the WtE boiler in terms of fuel utilization and emissions is evaluated and areas of optimization are examined. Using a combination of waste fuels including wood chips, fabric offcuts, cardboard, and paper the study assesses greenhouse emissions, resource utilization, and emissions to the air. Performance improvements proposed by the LCA involve a strategic fuel input, improvement in fuel burn rate, and exhaust emission through select catalytic reduction and better pollution control technologies. Moreover, this study also encourages industrial symbiosis in KIP by utilizing industries' waste as fuel sources, thereby encouraging sustainability and the circular economy. Therefore, these findings are favorable in decreasing the environmental impacts of energy production while enhancing business profitability.

Keywords : Waste to Energy Boiler, Life Cycle Assessment, Kandy Industrial Park, Industrial Symbiosis, Waste Management.

1. INTRODUCTION

The growth of industries and increased demands for energy sources have become paramount to integrating sustainable energy production for environmental and economic sustainability. In this context, the waste-to-energy (WtE) approach has gained traction as an innovative solution that addresses two significant global challenges: areas such as waste management and energy generation (Tabasová et al., 2012). In large-scale establishments for instance the Kandy Industrial Park (KIP) in Kandy; Sri Lanka, the increased power outputs within waste streams offer a window to improve performance and minimize adverse effects on the environment (Dharmasiri, 2019). This research aims to increase the efficiency of the WtE boiler within the KIP through a Life Cycle Assessment (LCA) in improving efficiency improvement strategies while addressing the anticipated environmental impact and subsequent effect on the natural resources.

1.1. Background of the Study

The Board of Investment of Sri Lanka (BOI), established in 1978, provides considerable impulse to industrial development through the nineteen Export Processing Zones (EPZs) nationwide and more than 600 outside enterprises operating under the BOI purview. These industrial clusters have played a significant role in the process of bringing FDI, generating employment, and increasing the economy. Nonetheless, the environmental impact of these industrial zones especially in the issues of waste and energy management has raised concern (Herath et al., 2023). Out of the EPZs, the Kandy IP is the most sensitive park managed by the BOI providing 5.6 Bn Sri Lankan rupees export value to the national economy.

Most of the large-scale industries within KIP are apparel manufacturing and produce approximately 2400kg/day of fabric waste. Further, the rest of the part produces general wastes including cardboard and paper that are subjected to the scope. In the context of the management of waste, the BOI incurred massive expenses as part of fabric waste is categorized under brand protection according to the Sri Lankan Custom law. Thereby, the only approved facility to manage such a quantity is obtaining a thermal destruction facility from the INSEE Eco cycle Pvt Ltd, which is located 140 km away from the KIP.

Simultaneously, in early 2023, Sri Lankan-only IV fluid manufacturing facility Kelun Life Sciences Pvt Ltd, which fulfilled 60% of local saline demand in the country distressed due to fossil fuel-dependent energy practices. The daily diesel consumption of the facility was 5000 l/day.

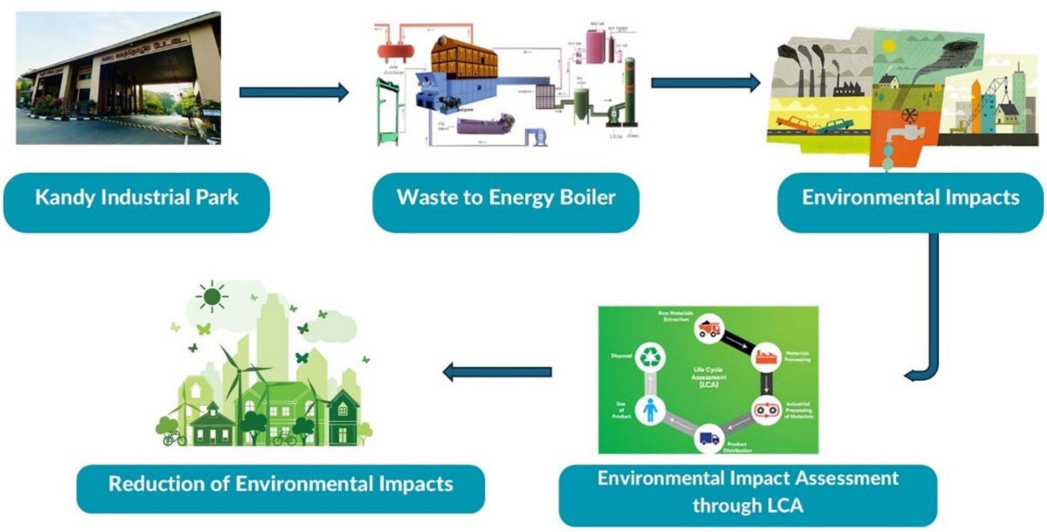
In response to the situation, the BOI has been at the forefront of developing an efficient system to deal with waste and reducing the uptake of fossil energy resources. These problems were properly mitigated through the win-win project created by BOI management in collaboration with the respective IV manufacturing company by applying an industrial symbiotic WtE Boiler over the land belonging to BOI.

1.2. Problem Statement

WtE is a sustainable technology that converts waste into energy useful to human beings in their daily life (Alao et al., 2022). It is still challenging to achieve optimal performance for WtE boilers because the sub-optimal conversion of energy can always be counterproductive to the functions of the systems (Spandan Basak Payel et al., 2023). Higher efficiency of boilers is the key factor in raising the effectiveness of heat recovery from various types of wastes, decreasing the usage of conventional energy resources, and, therefore, solving crucial environmental challenges (Men et al., 2021).

Inefficient WtE plant operations increase releases of pollutants such as particulate matter (PM), nitrogen oxides (NOx), sulfur oxides (SOx), dioxins, and furan to the environment, causing air pollution (Larki et al., 2023). To support the initiatives of the world moving toward sustainability, it is possible and necessary to create high-efficiency methods that reduce emissions and increase the efficiency of the energy produced (Filonchyk et al., 2024). The LCA for the WtE system and its environmental emissions is necessary to overcome these challenges. This will not only support discovering the inefficiencies but also help us understand ways that can enhance efficiency to reduce operation costs and environmental impacts drastically (Figure 1).

Figure 1: Problem statement of the research.



1.3. Objectives

The main concern of this analysis is to enhance the performance of the WtE boiler system at KIP through a comprehensive LCA and the formulation of an improved efficiency rate. The specific objectives assigned to the research scope are:

- Evaluate the current performance of the WtE boiler system: Compare its current operational efficiency, fuel consumption, and emission level.

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- Conduct an LCA: Identify and quantify the sustainable impacts of the WtE process through the LCA in terms of emissions to the atmosphere, resource usage & other waste generation.
- Identify key areas for efficiency enhancement: Review the life cycle data to identify thermal efficiency, rate of emissions, and fuel consumption challenges.
- Develop and propose advanced efficiency strategies: Findings on needful technical changes and practical measures to improve boiler efficiency, emission reduction, and efficient energy consumption.
- Promote industrial symbiosis within KIP: Discuss ways of cooperation of industries in KIP through using waste from one industry as an input to the boiler system, for instance, fabric offcuts from garment industries.

2. MATERIAL AND METHODS

2.1. Physical observations

In any LCA research, performing a site visit is usually the first and crucial approach because of the actual data gathering. As the name suggests it is used to evaluate the effect of certain operations, processes, or industries under review (Fnais et al., 2022). A research priority at the beginning of this study was a thorough tour of the boiler destination since this study focused on the environmental consequences of waste energy production. The first time offered significant information about the boiler facility's operating environment, physical space, and the unique attributes of the work setting. On this visit physical measurement of the facility was done, measurement of the capacities of the boiler for steam production besides the measurement of the volume of the waste that had been used daily, and the seasonal measure was done.

A critical analysis of the working dynamics and anatomy of the boiler such as the combustion process, energy conversion rates, and pollution control measures were assessed. This practical assessment was further augmented with interviews of the facility operators and maintenance personnel, giving a good practical perspective of the operations – efficient and effective, short-term and long-term. The background data collected during this visit was used for analysis and to form planning and data collection for the LCA. This phase of the research was crucial to the formation of the framework of the analysis so that the following data studies and analytics can be done competently (Hetherington et al., 2014).

Figure 2a: WtE boiler house

Figure 3a: Heat pipes of boiler

2.2. Preliminary assessment

A Preliminary assessment in LCA is an initial survey of a product, process, or system by adopting early-stage data to recognize areas where improvement is possible. It allows for a state of general expectations regarding the sustainability of a project before proceeding to other, more specific phases of LCA, to make decisions on material choice, and further optimization of processes (Židoniene and Kruopiene, 2015). In the primary analysis of the waste-fired steam boiler, the study examined the technical parameters and features of operation of the DZL 6-1,25-S model from Xuzhou Double Rings Machinery Co. This boiler has been engineered to accept a wide variety of biomass fuels, fabric waste, wood chip and cardboard which is in line with the goals of achieving sustainability in the study. The apparatus has a rated output capacity of 6 tons per hour of operation at a working pressure of 1.25 Mpa (12 bar) and a rated steam temperature of 191.6degC. A high thermal efficiency of 85.15% indicates that biomass fuels are effectively utilized in the boiler hence minimizing carbon emissions that would otherwise arise due to industrial-related processes.

The structure of the boiler includes a horizontal three-back water fire pipe combination type, which makes its operation and maintenance simple. It applies the light chain grate stoker for mechanical feeding. A draft fan and blower provide mechanical ventilation, and a scraper slag remover helps in ash removal. This not only guarantees the efficient burning of waste fuels, but it also relieves the operational burden which in turn improves the efficiency of the biomass energy generation processes. There is careful design of the boiler's body and economizer heating surfaces to ensure adequate heat transmission and thereby, enhance the combustion of the fuel.

Technical documentation, equipment quality assurance, and boiler scope of supply come as a complete package. This includes the body of the boiler and auxiliary equipment such as economizers, fans, pumps, and control box, all the valves, instruments, and accessories including spare parts. Quality control is hard and well managed with a bundle variety of inspecting equipment and mechanisms that are provided in the acceptable documents to make sure the operation of the boiler is safe and reliable (Ramadolela, 2018). Reaction to these problems such as inspection fuss, digital carbon analysis, sulfur analysis, self-ignition furnace testing with high and low speeds photometry, metallography, composite testing, hydrostatic multi-purpose testing apparatus, and total non-destructive testing increase the safety and reliability of the Pressure Vessel and its Components (Jeguirim and Khiari, 2023).

This WtE boiler represents a new direction in the field of energy conversion of waste to useful energy bringing perfect, clean technology for industrial heating (Song et al., 2023). The possession of an in-depth understanding of its parameters, construction, and operation gives a base to the further scope of the research we are conducting on the issues of the environmental effects as well as the effectiveness of biomass energy systems.

2.3. Life Cycle Assessment

2.3.1. Goal

LCA for a WtE boiler system aims at identifying, measuring, and comparing the different aspects of heat processing including its impacts on the environment at a specific stage of the process (Quinteiro et al., 2019). This model ensures that the total environmental impact of the installed boiler system including greenhouse gas Emissions, Energy use, Water,

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Waste, and other forms of adverse impact is synthesized comprehensively. It is shown that the LCA assesses from the life cycle consideration where positive environmental impacts or energy savings opportunities could be obtained, as well as increase the use of noble materials and technologies.

In addition, the rest of the LCA will allow the interested parties concerned persons, manufacturers or policymakers, or the end users themselves to make better choices about the design, functioning, or the choice of the boiler system leading the industry into sustainability (Khasreen et al., 2009). The goal of the evaluation in an LCA is not only to estimate the negative environmental consequences of some activity. It also aims at enabling changes in impractical and unsustainable societies to healthy and better energy systems by targeting strategies for wood-mixed boiler development and utilization, thereby contributing to the broader agenda of mitigating climate change and preserving natural resources for future generations (Quinteiro et al., 2019).

2.3.2. Objectives of the LCA

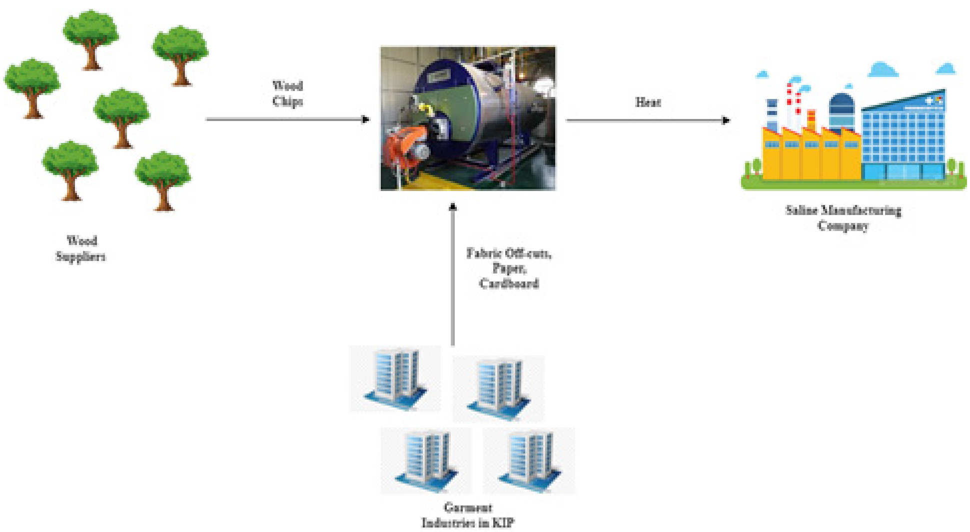
There are several objectives of this study which focus on systematically assessing the environmental and parts of social and economic impacts of WtE boilers through processing. Hence, the LCA aims to estimate the global warming potential of WtE boilers due to emissions of carbon dioxide, methane, and other emissions that harm climate change. Secondly, the boilers have been assessed in terms of resource consumption such as energy, water, and raw materials to the emissions that will include greenhouse gases, contaminants, and pollutants including a systematic evaluation of each stage of the boiler emissions lifecycle.

This integrated approach allows embracing the environmental advantages to have a point of reference and concentrate efforts on the current emission reduction and further other pollutants' emissions minimization. Also, the research will focus on the energy performance of the equipment including their use of resource potentials. The study seeks to offer practical recommendations built around these aims, all of which would be expected to influence the sustainability, efficiency, and social responsibility of the boiler systems.

2.3.3. Scope of the study

The boiler operates with different biomass inputs—wood chips from three suppliers, fabric off-cuts collected from the apparel factories within KIP, and paper and cardboard sourced from industries operating in the KIP. Through an LCA, the environmental impacts of each input are summarized considering raw material extraction and processing, transportation to the boiler, and conversion into heat. In this context, the life cycle phases considered extend from feedstock acquisition to operation of the boiler, including any emissions and resource consumption.

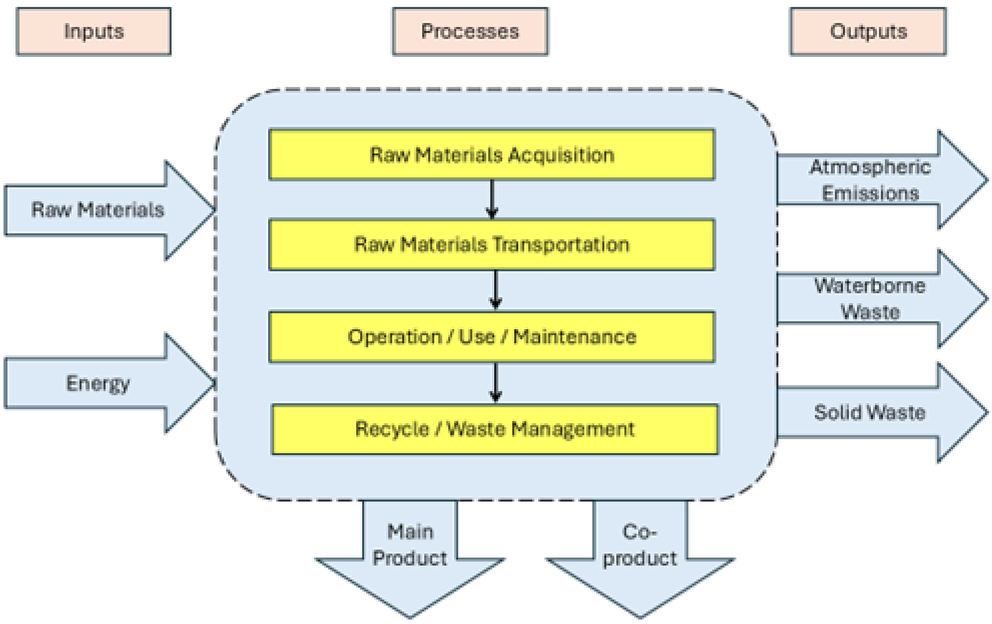
Figure 2b: Scope of the LCA



Case studies of the LCA will help to shed light on the sustainability implications of utilizing more than one type of fuel, specifically concerning waste-to-energy (WtE) practices and their potential contributions to circular economy goals (Nubi et al., 2024). The assessment also seeks to identify these relationships across industrial processes, for instance how waste outputs from the garment industry could be used as an input for fuel production helping achieve a self-sufficient closed-type model thus reducing the overall environmental burden.

More broadly, the results of this LCA may provide insights into the socio-economic dimensions that industrial symbiosis can tap to support its role in delivering economic prosperity with enhanced community and ecological resilience.

Figure 3b: IPO method of the LCA



2.3.4. Functional Unit

The functional unit of the study is taken as heat production by the WtE boiler per day. This functional unit is used as the reference point in measuring all inputs such as wood chips, fabric offcuts, paper as well as all the outputs especially the heat produced. In this case, through benchmarking the functional unit, the study develops a measure against which the environmental costs incurred in the daily use of the boiler can be done. This makes it possible to achieve the following: Detailed quantification of the overall efficiency of energy conversion in the boilers, the actual number of resources consumed for each day of operation, and the emissions produced. Therefore, the data collected and processed regarding this functional unit gives a clear understanding of the daily environmental impact of the boiler system so that optimization and sustainability improvements in the system can be determined (Quinteiro et al., 2019). In addition, the distribution of all data to the functional unit makes the LCA more methodical and minimizes the subjectivity of the results thus providing actionable information which serves as a directive for improving operations as well as policy formation.

2.3.5. System boundary

The gate-to-gate system boundary for the mixed boiler encompassed the boiler and associated equipment, such as a de-aeration tank, economizer, super-heater, water treatment, and emissions control. To maintain the sustainable wood supply chain disregarding the green cover depletions, the wood species for the wood chips have been restricted to the Gliricidia, Ipil Ipil, Rubber, Eucalyptus, and Acacia. Fabrics are not limited. However, using the importation details managed by the Investor Services department of BOI and the Sri Lanka custom dashboard has shown cotton as a prominent fabric material. Transportation was an input if the fuels were manufactured at another location and was achieved as a function of the green mass of the fuel and transport distance in terms of kilometers (km). Distances were more precisely measured; as for the quantity of purchased fuel, it was also possible to obtain highly accurate measurements, which were taken at the facility gates. Other potential feedstocks comprised of, for example, small quantities of natural gas/propane for start-up, and fuels for rail. All other inputs were not fuel inputs. These were known with high accuracy from the preliminary records of the purchasing invoices. Ash was an output destined for making cement bricks. The quantities of ash were determined with a high degree of certainty from the weights of the trucks that transported it out of the facility. From the boiler, the quantity of steam produced was either as stated in other surveys for use in dryers or presses or was based on an energy calculation based on the amount of water evaporated in other processes.

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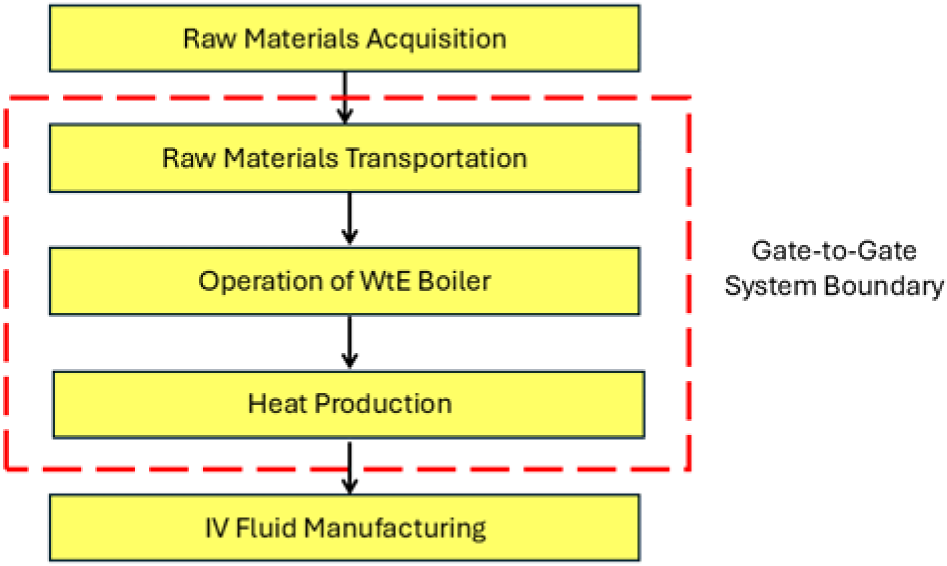
Figure 4: System boundary of the LCA.



2.3.6. Inventory Analysis

In this context, the aim is to determine the inputs and outputs of the boiler system and their environmental implications, mainly the conversion of waste substances into usable energy and the emissions associated with this procedure. The WtE boiler converts diverse waste streams into energy. The WtE boiler uses wood chips, fabric offcuts, lubricants, and other substances as inputs to generate heat at the same time while emitting diverse gases and particulates as outputs.

Table 1: Inputs of WtE boiler.

Inputs	Value	Unit	Calorific value
Wood Chips	6000	kg	3750 kcal/kg
Fabric offcuts	1500	kg	3800 kcal/kg
Paper	500	kg	3200 kcal/kg
Transport, combination truck, diesel-powered	90	L	10700 kcal/kg
Lubricants	0.33	L	
Engine oil	0.33	L	
Electricity	122.4	kWh	
Water, municipal, process, surface	270	m3	

LCA of the WtE boiler system is conducted through a comprehensive and multi-faceted method to ensure certain accuracy and relevance. The primary sources for the environmental and technical databases were developed by recording operational statistics, direct interviews with boiler operators, and consultations with different relevant stakeholders. Environmental and technical databases provided a sturdy foundation for the information collection procedure. Key databases were utilized to acquire standardized facts on inputs, emission elements, and energy intake related to WtE boiler operations. These databases are widely identified in the LCA network for quantitative and reliable datasets, which cover an extensive variety of industrial tactics and environmental effects.

Recorded statistics from the boiler's operational logs provided comprehensive information into the daily functioning and performance metrics of the WtE boiler. These covered measurements of fuel input quantities (e.g., wood chips, fabric offcuts), energy outputs (e.g., heat and strength produced), and emissions (e.g., CO_2, NOx, particulates). These logs are maintained as part of the recurring monitoring and compliance processes and provide an empirical basis for the LCA. Direct interviews with boiler operators were conducted to get qualitative insights and contextual knowledge of the operational practices, upkeep workouts, and any variability in the device's overall performance.

Table 2: Output flows of WtE boiler.

Outputs	Value	Unit
Products & co-products		
Heat	18452000	kJ
wood + fabric ash	30	kg
Air Emissions		
O2	17.4	%
CO2	11.6	%
CO	1360.7	mg/Nm3
NO	57.4	mg/Nm3
NO2	3	mg/Nm3
NOx as NO2	88	mg/Nm3
SO2	12.3	mg/Nm3
Particulate Matter	152.9	mg/Nm3
Dioxin & Furan	0.0000057	mg/Nm3
Primary Air Temperature	37	C
Stack Temperature	96.9	C
Emissions to water		
Suspended solids: unspecified	20	kg

A complete evaluation of the transportation of wood chips is performed to the boiler facility, focusing on the environmental effects related to this technique. The data series was executed through in-person interviews with the drivers accountable for transporting the wood chips. This approach enabled to gather statistics that are important for the accuracy and reliability of our assessment. The parameters measured at some point in these interviews blanketed the weights of the vehicles both empty and while loaded with timber chips, in addition to the mileage by way of each truck. This information has been essential in calculating the gross and net weights transported, thereby allowing an accurate assessment of the transportation performance and the related carbon footprint. Accordingly, the daily consumption of diesel for the transportation of wood chips is calculated. The quantity of diesel consumed per day is a key indicator of the environmental impact of the transportation process, as it directly contributes to greenhouse gas emissions and energy efficiency.
The inventory evaluation statistics and the boiler technique's precise inputs and outputs are simulated using the openLCA software.

Table 3: Inventory analysis of LCA.

Inputs					
Flow UUID	**Flow**	**Category**	**Sub-category**	**Unit**	**Result**
fe062094-9ab6-4166-a3fb-32b79c05c2c4	Electricity			kcal	105315.5
0e9d63cf-482c-4e7c-8a37-4fd30af8edc6	Engine oil			m3	0.00033
c0b6cfdc-5eb8-401f-a2bb-80c74f88ef91	Fabric offcuts			kg	1500
d5722901-c59c-4985-908b-96a0c48518ba	Lubricants			m3	0.00033
35cb4560-58e0-4262-8285-876e9ca561f2	Paper			kg	500
a6ff7058-1dfc-4f65-80f9-91bdff3ec196	Transport, combination truck, diesel-powered			m3	0.09

731bf2da-5ab2-450b-ac61-3b463aa3fe2b	Water, municipal, process, surface			m3	270
fc0a692f-397e-45b6-b854-357d41a4a88c	wood + fabric ash			kg	-30
fa054777-a6df-41c4-b862-2c133919e6b5	Wood Chips			kg	6000
Outputs					
Flow UUID	**Flow**	**Category**	**Sub-category**	**Unit**	**Result**
643975a8-03da-44bb-873f-4fe8e7740fe6	Carbon dioxide	Emission to air	high population density	kg	1.16E-05
620bc2f6-cf71-4dde-bba9-c6e8fdec5e23	Carbon monoxide	Emission to air	high population density	kg	0.001361
237a5f15-8119-472a-8988-88b7ecb42405	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	Emission to air	high population density	kg	5.7E-12
6cb27843-3de3-452f-b83b-ecf41df1a249	Nitric oxide	Emission to air	high population density	kg	5.74E-05
d9945575-a965-4bf3-9cd7-584263172abd	Nitrogen dioxide	Emission to air	high population density	kg	0.000003
d068f3e2-b033-417b-a359-ca4f25da9731	Nitrogen oxides	Emission to air	high population density	kg	0.000088
e661f08d-3606-3d13-aace-3842ee2cb46a	Oxygen	Emission to air	low population density	kg	1.74E-05
32295152-7da7-47cb-b4a2-60ca4f246a80	Particulates, < 10 um	Emission to air	high population density	kg	0.000153
8c52f40c-69b7-4538-8923-b371523c71f5	Sulfur dioxide	Emission to air	high population density	kg	1.23E-05
0ec1f82f-fd14-3b7a-8057-6e7ae1bd7889	Suspended solids, unspecified	Emission to air	unspecified	kg	20

2.4. Assumptions

This research also requires that all the necessary data concerning industry development will be given by the key stakeholders, including the BOI and industrial park operators. Based on this it is presumed that all the necessary resources –, financial, human, and technical resources, will be available for the execution of the comprehensive life cycle assessment as well as the adoption of the proposed strategies. The sampled data will reflect the situation and functioning of the waste-to-energy boiler now in KIP with sampling methods and techniques. The research hypothesis holds that using life cycle assessment together with qualitative and quantitative data collection methods, are relevant and adequate to address the research goals.

2.5. Limitation

This study has been carried out on the WtE boiler system at KIP and hence is only relevant to the region and might not apply to other industrial parks or other separate geographical regions, operational conditions, or types of waste. The limitation of the source may cause an issue for the research where the information is either lacking or in accurate form may create problems for the research if the industrial park or other stakeholders do not provide good records. The study could be constrained by funding and time, and this could affect the amount of work that could be done during the research, or the effectiveness of the strategies designed. The study may face challenges during the research due to the efficiency structure or operations of the WtE boiler system which may limit the achievement of actual increase in efficiency because some measures or operational efficiencies might be outdated and cannot be operationalized fully. The study may encounter difficulties in getting all the anticipated cooperation and involvement of the stakeholders on board which would impact the collection of data or the adoption of the recommended interventions.

3. RESULTS AND DISCUSSION

An Impact Assessment is an essential section within the Life Cycle Assessment (LCA) procedure, specializing in evaluating the environmental impacts related to the inputs and outputs diagnosed in the stock analysis (Larrey-Lassalle et al., 2017). This assessment will delve into various effect classes which include global warming potential, human toxicity, ecotoxicity, acidification, and resource depletion, amongst others, to provide complete information on the environmental footprint of the WtE boiler device (Sharaai et al., 2011).

The impact evaluation for the WtE boiler system involves several standardized strategies and classes to quantify the potential environmental effects. In generally, ReCiPe, CML, TRACI, and Eco-indicator 99 methods are used. (Speck et al., 2016). This assessment has been followed the ReCiPe method, which converts lifestyle cycle inventory results into impact factor of diverse environmental categories (Huijbregts et al., 2017).

The human carcinogenic toxicity effect category has the highest impact of 0.000526 kg 1,4-DCB. Human Toxicity Potential assesses the impact of toxic materials on human fitness (McKone and Hertwich, 2001). The emissions of concern from the WtE boiler encompass Dioxins and Furans, Carbon Monoxide, and Particulates (<10 μm). Dioxins and Furans are extremely toxic compounds even at very low concentrations (Schröder et al., 2021). Dioxins, measured at 5.7 x 10-6 mg (0.0000057mg), can cause excessive health issues, which include cancer, and reproductive and developmental problems. Carbon Monoxide (CO) is emitted at 1360.7 mg, CO is a toxic gas that may impair oxygen transportation in the human body, leading to severe fitness results, especially for humans with cardiovascular conditions (Raub, 1999). Fine particulate count (152.9 mg) can penetrate deep into the lungs, causing breathing and cardiovascular sicknesses.

Ecotoxicity Potential evaluates the impact of toxic substances on ecosystems (Schuijt et al., 2021). Key emissions from the WtE boiler affecting ecotoxicity encompass Heavy Metals and Dioxins, Sulfur Dioxide (SO_2), and Nitrogen oxide (NOx). Although specific heavy metals aren't indexed in the inventory, they're common in combustion emissions and can cause significant damage to aquatic and terrestrial ecosystems. Sulfur Dioxide (SO_2) and Nitrogen oxides (NOx) are emitted at 12.3 mg and 88 mg respectively, these gases can cause acidification of soils and water our bodies, harming plant and animal life (Sedyaaw Balasaheb Sawant Konkan Krishi Vidypeeth et al., 2024).

Global Warming Potential measures the impact of greenhouse gases (GHGs) on climate changes over a selected time horizon, commonly 100 years (Filonchyk et al., 2024b). GHGs emitted from the WtE boiler system consist of Carbon Dioxide (CO_2) and Nitrous Oxide (N2O). The WtE boiler emits 11.6 mg of CO_2. Despite its particularly low mass, CO_2 has a significant global warming potential due to its ability to increase the heat for a long period. (Golchin and Misaghi, 2024). The cumulative impact of those emissions outcomes is an extremely severe contribution to global warming, requiring upgrades in combustion performance and emission controls to mitigate the impacts. Acidification Potential measures the potential of emissions to acid rain, which can deliver extreme environmental impacts. The number one contributor encompasses Sulfur Dioxide (SO_2) and Nitrogen oxide (NOx). A giant acidifying compound, SO_2 emissions can result in the formation of sulfuric acid in the surroundings. Nitrogen Oxides (NOx) associated with Nitric acid, contributing to acid rain and harm to ecosystems (Sedyaaw Balasaheb Sawant Konkan Krishi Vidypeeth et al., 2024).

Photochemical Ozone formation of ground-stage ozone (smog) from emitted precursors which includes risky organic compounds (VOCs) and NOx. Nitrogen Oxides (NOx) are a key precursor to ozone formation, NOx emissions from the WtE boiler make contributions to photochemical smog, impacting human health and flora (Nguyen et al., 2022). Eutrophication Potential measures the effect of nutrient enrichment in water bodies, main to excessive growth of algae and the next depletion of oxygen. Nitrogen Oxides (NOx) make contributions to nitrogen enrichment in aquatic systems that could cause eutrophication. Although an issue for water fin, the strong residues (20 kg of suspended solids) from the WtE procedure can also contribute to eutrophication if now not managed well.

The result of 1.36x 10-5 kg of PM2.5 shows that the WtE boiler gadget contributes to the formation of first-rate particulate depend, which can have destructive outcomes on human health and the surroundings. Particulate emissions may be generated from diverse stages of the WtE technique, together with combustion, material coping, and transportation. These emissions can contribute to breathing troubles, visibility discounts, and climate impacts (Aminzadegan et al., 2022). Strategies to mitigate particulate count formation may additionally consist of improving combustion efficiency, implementing advanced air pollutants control technologies, and optimizing logistics and transportation.

The result of 0.000088 kg NOx for both ozone formation (Human Health and Terrestrial Ecosystems) effect classes suggest a meager contribution to the formation of floor-stage ozone. However, nitrogen oxide (NOx) emissions from the combustion technique can contribute to ozone formation, which could have terrible effects on human health and terrestrial ecosystems. Strategies to mitigate this impact may also include optimizing combustion situations, imposing selective catalytic reduction (SCR) technologies, and monitoring and controlling NOx emissions (Buruiana et al., 2021).

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Overall, the translation of the LCIA effects highlights the significance of addressing ability environmental influences, particularly in particulate count number formation, human carcinogenic toxicity, and global warming. Implementing techniques that include optimizing combustion conditions, enforcing superior emission manipulation technologies, and incorporating renewable strength assets can assist in mitigating those influences and decorating the sustainability of the waste-to-power boiler machine.

Table 4: Impact assessment of LCA.

Impact category	**"Reference unit"**	**Result**
"Fine particulate matter formation - ReCiPe 2016 Midpoint (H)"	kg PM2.5 eq	1.36E-05
Fossil resource scarcity - ReCiPe 2016 Midpoint (H)	kg oil eq	0
Freshwater eutrophication - ReCiPe 2016 Midpoint (H)	kg P eq	0
Freshwater eutrophication - ReCiPe 2016 Midpoint (H)	kg P eq	0
Global warming - ReCiPe 2016 Midpoint (H)	kg CO2 eq	1.16E-05
Human carcinogenic toxicity - ReCiPe 2016 Midpoint (H)	kg 1,4-DCB	0.000526
"Human non-carcinogenic toxicity - ReCiPe 2016 Midpoint (H)"	kg 1,4-DCB	0
Land use - ReCiPe 2016 Midpoint (H)	m2a crop eq	0
Marine ecotoxicity - ReCiPe 2016 Midpoint (H)	kg 1,4-DCB	2.02E-07
Marine eutrophication - ReCiPe 2016 Midpoint (H)	kg N eq	0
"Ozone formation, Human health - ReCiPe 2016 Midpoint (H)"	kg NOx eq	0.000088
Ozone formation, Terrestrial ecosystems - ReCiPe 2016	kg NOx eq	0.000088
Midpoint (H)	eq	
Terrestrial acidification - ReCiPe 2016 Midpoint (H)	kg SO2 eq	4.51E-05
Terrestrial ecotoxicity - ReCiPe 2016 Midpoint (H)	kg 1,4-DCB	2.24E-06
Water consumption - ReCiPe 2016 Midpoint (H)	m3	0

Figure 5: Impact contribution of each flow.

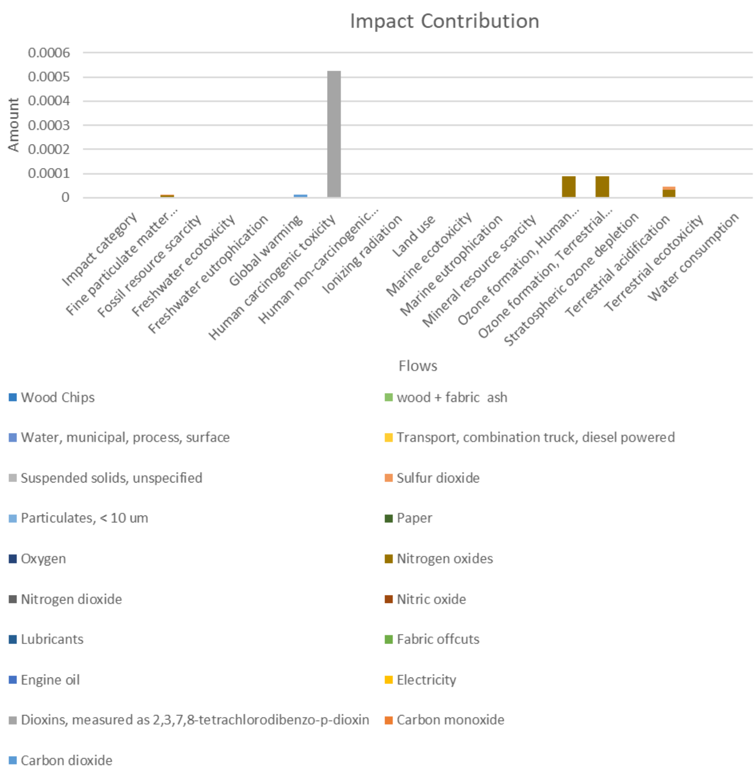

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Figure 6: Amount of each impact category

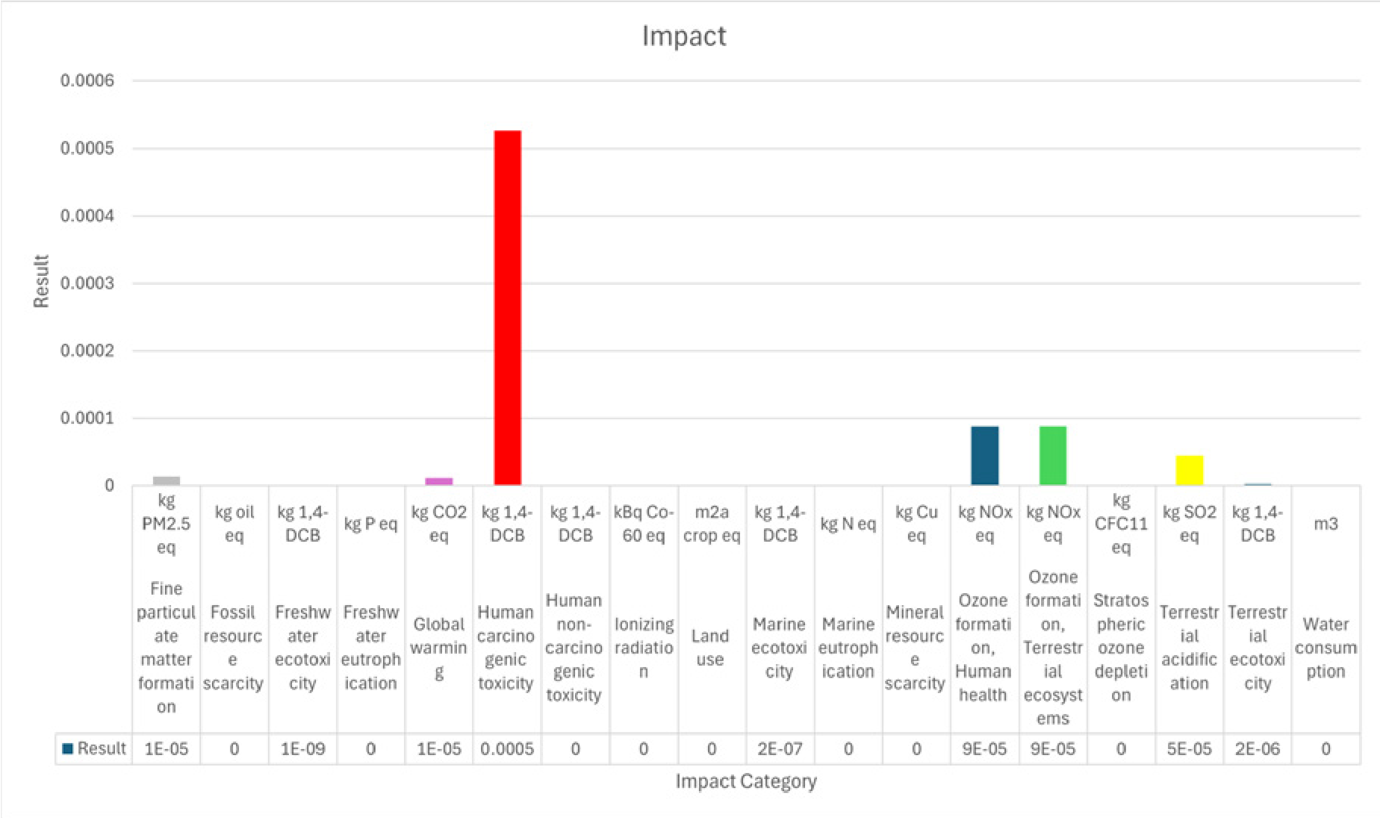

Figure 7: Contribution of flows for fine particulate matter formation

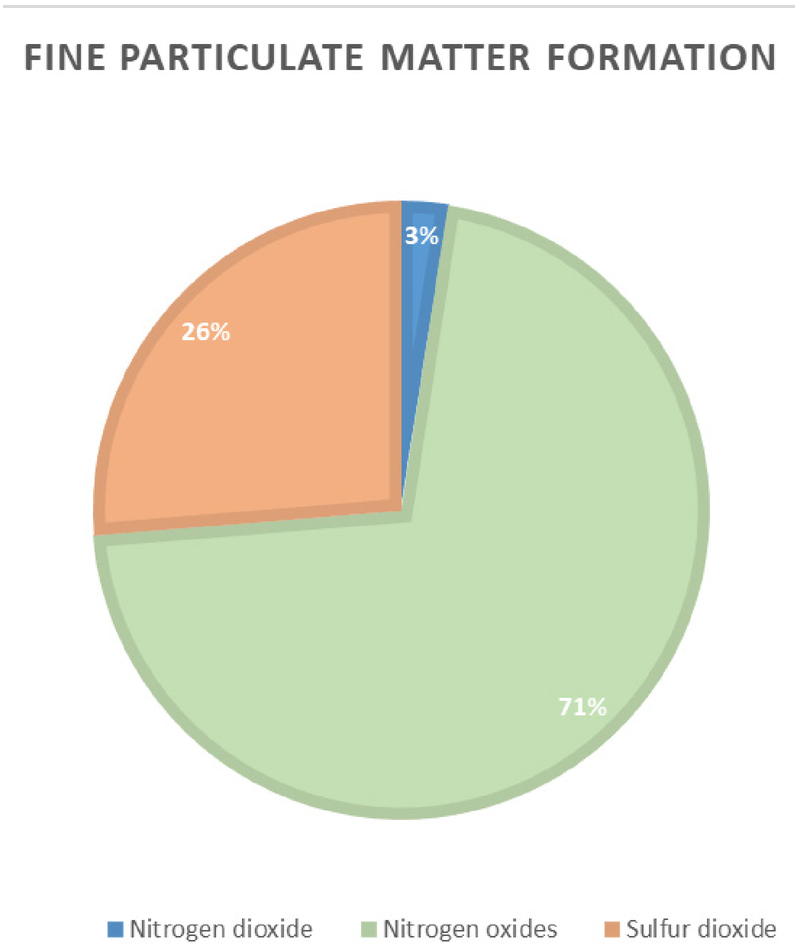

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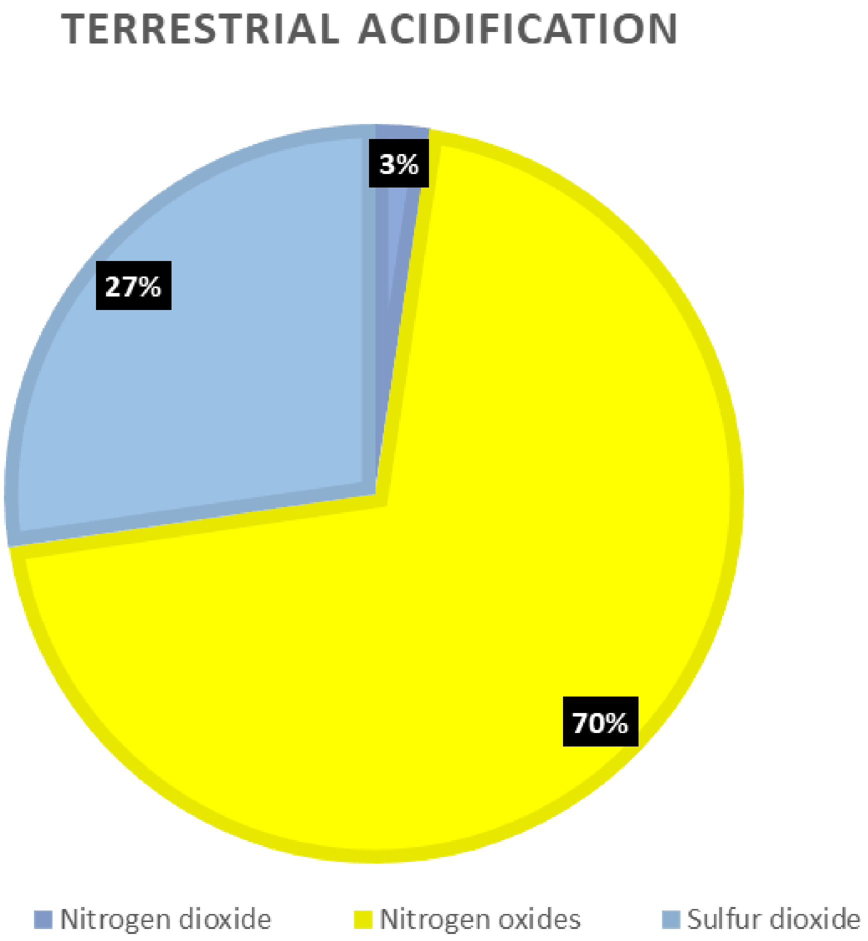
Figure 8: Contribution of flows for terrestrial acidification



4.CONCLUSIONS AND RECOMMENDATIONS

4.1Recommendations

The installation of emission management structures, together with selective catalytic reduction (SCR) for NOx removal, Bag filtration or ESP model for particulate matter, and activated carbon injection for dioxin and furan removal, is recommended to mitigate the damaging impacts on human fitness and ecosystems. Conduct a complete evaluation of the boiler's combustion system to become aware of opportunities for boosting efficiency. This may involve adjusting air-gas ratios, imposing superior combustion manipulation systems, and exploring alternative fuel mixes to reduce emissions while preserving strength output. Investigate the capacity of incorporating other biomass or waste-derived gasoline assets that have lower emissions profiles or better power densities. This should encompass agricultural residues, municipal solid waste, or commercial by-use products, ensuring a balanced approach that considers both environmental and monetary factors.

Implement a sturdy tracking program to continuously monitor stack emissions, electricity efficiency, and other operational parameters. These records will allow knowledgeable selection-making, facilitate compliance with environmental policies, and assist in identifying regions for additional development. Ensure ordinary boiler devices and associated tools are preserved, adhering to manufacturer suggestions and first-rate practices. Additionally, comprehensive education on green operation, maintenance, and emergency response strategies should be provided to operators to reduce the risk of incidents and optimize performance. Foster collaboration with industry companions, studies establishments, and regulatory bodies to share pleasant practices, explore progressive answers, and align with emerging sustainable technologies and regulations inside the WtE quarter. Engage with nearby groups, environmental corporations, and the overall public to raise recognition approximately the WtE initiative and promote transparency concerning the environmental impact assessment and mitigation techniques.

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Figure 9: SCR catalyst for NOx removal

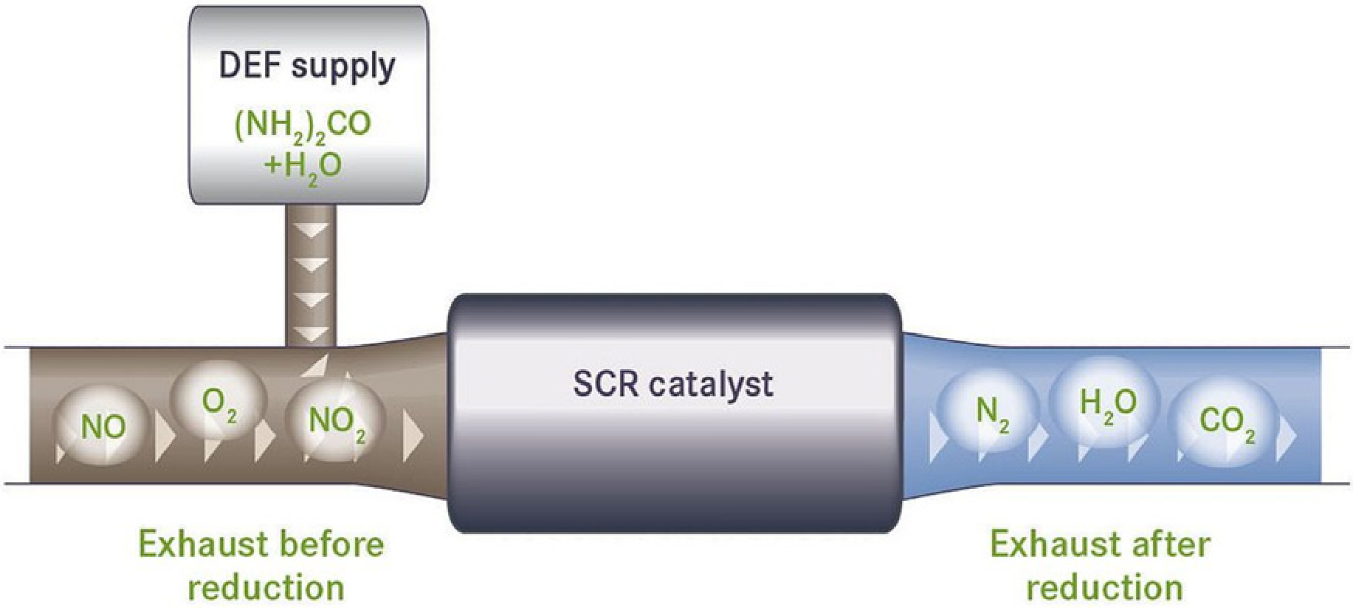
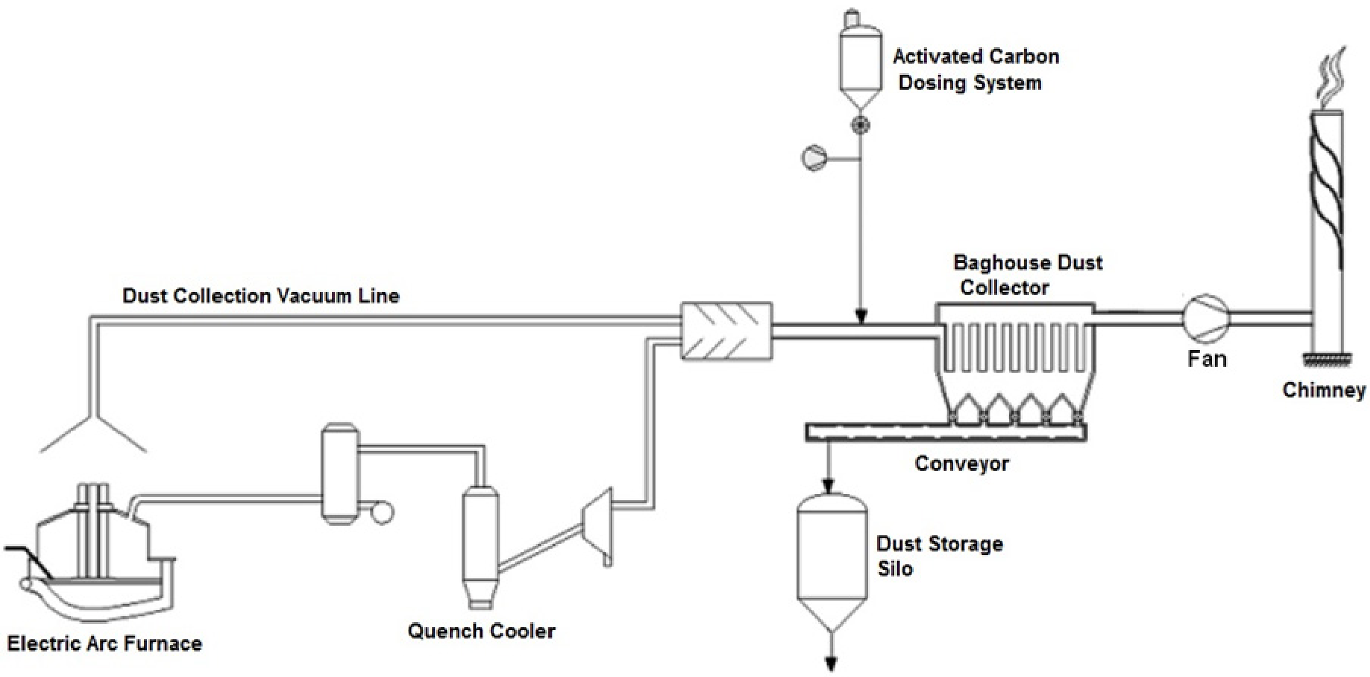


Figure 10: Activated carbon injection for dioxin and furan removal



CONCLUSION

This life cycle evaluation has a look at evaluating the environmental effects related to a waste-to-energy boiler at the KIP. The analysis found numerous regions of concern that need to be addressed to enhance the sustainability of the boiler operations. The effect assessment highlighted human carcinogenic toxicity, ecotoxicity, and worldwide warming potential as the most tremendous environmental issues. Emissions consisting of dioxins, furans, carbon monoxide, particulate matter, heavy metals, sulfur dioxide, and nitrogen oxides contribute to these effects, posing dangers to human fitness and ecosystems.

While the WtE method aligns with round economy concepts utilizing business waste streams as fuel sources, the emissions from the combustion manner require mitigation strategies to reduce the environmental footprint. Optimizing combustion efficiency, enforcing advanced emission control technologies, and exploring opportunity gas mixes ought to potentially mitigate these effects. It is critical to strike a balance between the financial blessings of business symbiosis and environmental sustainability. The examination underscores the significance of adopting a holistic technique that considers not most proficient power recuperation but also the associated environmental implications for the duration of the life cycle.

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