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Regional Case Study

Analysis of Cumulative Energy Demand Potential Using Life Cycle Assessment Approach: A Case Study of XYZ Laboratory

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Abstract

Environmental issues such as ecosystem damage, degradation and climate change require effective environmental management strategy. This study analyzes the cumulative energy demand (CED) potential of the XYZ Laboratory activities using a Life Cycle Assessment (LCA) approach. The LCA methodology, adhering to ISO 14040 and ISO 14044 standards, encompasses goal and scope definition, inventory analysis, impact assesment, and interpretation. Data were collected from XYZ Laboratory's activities during 2023, focusing on four main process units: sample administration, fulfillment of testing laboratory conditions, sample preparation, and instrumentation analysis. The environmental impact of CED was characterized using OpenLCA version 2.0 software with the Ecoinvent database and then calculated using a spreadsheet. The result is XYZ Laboratory have a significant environmental impact. The instrumentation analysis stage and sample preparation stage are the two highest potential impacts of CED with a contribution of 52.559 MJ per analysis service (50.948%) and 35.970 MJ per analysis service (34.867%).The study concludes that significant efforts are required to reduce energy use and environmental impact, suggesting techniques such as good housekeeping, input change, better process control, technology change, on-site reuse and recycling, and production of useful by-products. These strategies aim to enhance energy efficiency of laboratory operations.

Keywords: CED; LCA; XYZ Laboratory; Energy Efficiency; Environmental Impact

1. Introduction

Environmental issues have garnered increasing global attention, emphasizing the urgent need for environmental conservation (Abbass, K et. al 2022). The degradation of ecosystems, climate change, and other environmental damages significantly impact human life, both currently and in the future. The consequences of large energy use, air and water pollution, loss of biodiversity, and extreme weather changes underscore the importance of environmental management systems to ensure human survival and ecosystem balance. Understanding the human dimensions of global environmental change is crucial for developing effective strategies to mitigate and reduce these impacts (United Nations Press., 2022).

The state of environmental management in laboratories, particularly those with advanced instrumentation, is a critical area of focus. A study conducted by Yang et.al (2024) shows that laboratories, especially those using sophisticated equipment, have high energy consumption laboratories such as the XYZ laboratory, which is a non-profit laboratory built by the Indonesian government for monitoring products, require significant amounts of electrical energy to operate sophisticated equipment like High Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), and Liquid Chromatography tandem with Mass Spectrometry (LCMSMS). Studies have shown that laboratories consume three to six times more energy per unit area compared to typical office buildings, primarily due to energy-intensive laboratory equipment (Napolitano, 2021). The excessive use of fossil energy in laboratories leads to environmental damage, including deforestation, soil erosion, and water pollution, which further contribute to greenhouse gas emissions and climate change (Aimin et al., 2024).

Despite the significant environmental impacts associated with laboratory operations, there is a gap in current research regarding the application of LCA in evaluating the cumulative energy demand (CED) of laboratory activities. Most LCA studies have focused on product cycles rather than service-based activities like those in laboratories. This study aims to address this gap by conducting a comprehensive LCA analysis to assess the environmental impacts of energy use in laboratory activities and identify opportunities for reduction.

The primary objective of this study is to analyze the cumulative energy demand potential using the LCA approach as a case study of the XYZ Laboratory. The specific objectives include evaluating the environmental impacts of energy use in laboratory activities, identifying opportunities for reducing energy consumption and minimizing the environmental footprint of laboratory operations, and developing strategies to minimize these impacts, thereby contributing to a more sustainable future for laboratory operations. By understanding the CED and applying LCA methodology, this study aims to provide a comprehensive framework for evaluating the environmental impacts of products and processes throughout their entire life cycle.

2. Methods

The LCA method used refers to the ISO 14040 and ISO 14044 standard which consists of four components: goal and scope definition, inventory analysis, impact assessment, and interpretation, as shown in Figure 1 (ISO 2006., 2024). The obtained data is then processed and analyzed using OpenLCA software version 2.0. The characterization factor (CF) determined use the Cummulative Energy Demand (CED) method using Ecoinvent database and calculated using an excel spreadsheet. Non Renewable nuclear, Renewable biomass, Renewable water, Renewable wind solar geothermal are applied and evaluated in LCIA CED. In this research, LCIA energy calculations are calculated from the accumulation of CED evaluations with the aim of providing a holistic picture of the environmental impacts of various energy sources to make more sustainable decisions based on scientific data.

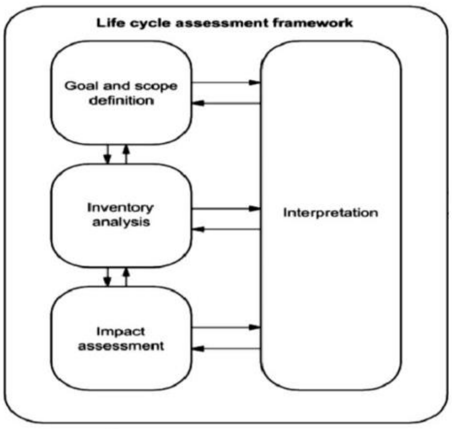

Figure 1. Life Cycle Assessment flow diagram ISO 14040 and ISO 14044 (ISO 14040 and ISO 14044, 2006)

2.1 Goal and Scope

The focus of this research is on the 4 main process units in XYZ Laboratory because the Life Cycle Assessment (LCA) carried out is limited to the "gate to gate" scope. This limitation means that the LCA only reviews the closest activities, which include the flow of testing sample entry from the time the sample arrives through the administration process until the sample is analyzed using instrumentation, declared test complete, liquid waste measurement, and a report on the test results is made. This scope is chosen because it is the shortest LCA, which implies that it focuses on the most immediate and critical steps in the laboratory process, ensuring that the assessment is comprehensive and relevant to the immediate activities within the laboratory.

Table 1. Goal and scope of LCA study at XYZ Laboratory in 2023

Goal / Function Unit	Process Units
Reviewing 1 analysis laboratory service during 2023	1. Sample administration 2. Fulfillment of Testing Laboratory Conditions 3. Sample Preparation 4. Instrumentation Analysis

Sample administration activities involve a series of tasks related to the management and processing of inormation and documents in a laboratory context including receiving samples, preparing for tests, and managing data related to the analyzed samples (Smith, J and Johnson, K, 2020). Sample administration involves several special activities, namely receiving samples from the sampling department or third parties and ensuring that the samples meet the criteria and can be tested according to the test criteria as well as organizing and managing the data obtained from the test results. On the other hand, sample administration includes managing office tasks such as record keeping, archiving documents, and handling internal and external communications. This administrative activity is important in supporting the smooth and efficient operation of the laboratory.

Fulfillment with laboratory environmental conditions is an important aspect that must be considered to ensure correct test performance (Lee, S and Kim, J, 2020). Accommodation conditions and laboratory environments must be conditioned in such a way that they meet the requirements of specifications, procedures or technical provisions. This includes various aspects such as temperature and humidity, lighting quality, air circulation, and electrical induction in the laboratory space. The goal is to enable laboratories to perform testing more efficiently and accurately, which is critical to ensuring data quality and meeting legal and regulatory requirements (Kim, J and Lee, S, 2020).

As highlited by Johnson, K and Smith, J (2020), sample preparation is a sample preparation process which aims to analyze a substance in a material for which a testing method has been determined. This process is very important because it greatly influences the accuracy of the analysis results. The main goal of sample preparation is to separate the analyte from the complex sample matrix, so that the sample is cleaner and ready for testing or analysis. Apart from that, sample preparation also aims to chemically and microbiologically modify the sample in order to improve the analysis process, such as increasing test sensitivity, producing more volatile compounds, or producing thermo-stable compounds.

Instrumentation analysis is a process that involves the use of tools and devices to carry out measurements, control and analysis on samples that have previously been prepared so that they can provide information about a sample through qualitative and quantitative analysis (Brown, M and Davis, T. 2019). The instrumentation in the XYZ laboratory includes the use of instrumentation devices such as HPLC, GCMS-MS, AAS, LCMSMS, ICP OES, UV/Visible Spectrophotometer, and others. Instrumentation technology has experienced rapid development, enabling the measurement of parameters previously thought impossible and achieving greatly increased accuracy, precision and control.

2.2 System Boundary

The limitations of the gate to gate system for implementing LCA in laboratory activities at laboratory XYZ are depicted in Figure 2.

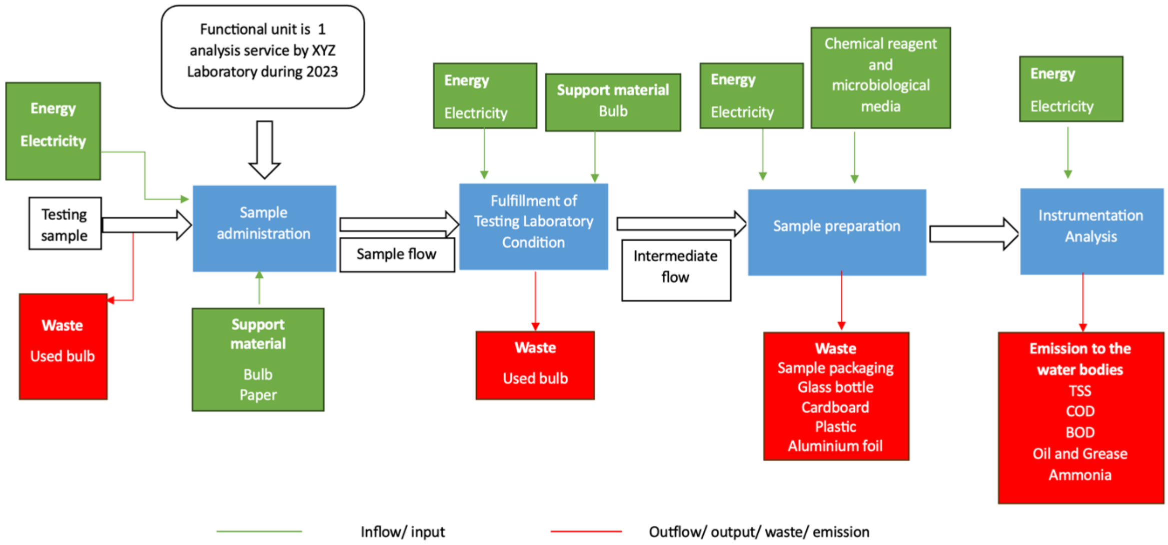

Figure 2. Diagram tree the limitations of the gate to gate system for implementing LCA in laboratory activities at XYZ Laboratory

2.3 Life Cycle Inventory

The input and output data required when choosing an LCA approach is a very important process (Baldini et al, 2017) because the life cycle depends on the data collected from the system. Data was collected follows general guidelines from ISO (ISO, 14040: 2006; ISO, 14044: 2006). Primary and secondary data are collected from XYZ laboratory at certain time intervals throughout 2023. The data used in this research consists of primary data and secondary data. Primary data is data obtained directly at XYZ laboratory. The data obtained are data on electrical power consumption, data on the type and amount of chemical reagent and microbiological media used, data on paper use, data on the production of packaging waste for test samples, results of waste water testing by third parties, as well as other data. Secondary data in this research was obtained from the most extensive database for LCA, namely Ecoinvent OpenLCA, literature in the form of journals, research results and other sources in order to strengthen this research. Data aggregation is carried out both vertically and horizontally. Documentation and justification of aggregation procedures will be stated transparently. Inventory documentation for both input and output will be classified by category.

2.4 Database Compilation using OpenLCA Software

OpenLCA is a widely known freeware and open-source software package that is easy to handle and allows users to calculate all stages related to LCA. One of the advantages of this software is that it offers users the possibility to work with different databases, enabling comprehensive LCA calculations. The Gross Calorific Value (GCV) of various fuels and materials is used to determine the characterization factor (CF). Compiling a database in LCA is a crucial step that involves collecting and making available data related to all inputs, waste, and outputs in the life cycle of a product or process defined at the Life Cycle Inventory (LCI) stage. Each material has a specific value or number that differs according to the chosen impact characterization method (Belyanovskaya, A. I et al, 2020).

The specific values from NR Nuclear, Renewable Biomass, Renewable Water, Renewable Wind, Solar, and Geothermal are accumulated into total energy. The total energy calculated is referred to as the Characterization Factor (CF). This CF value is then used in calculating LCA scoring after being multiplied by the LCI function unit. The CED method includes direct and indirect use of energy but excludes waste used for energy purposes. The ecoinvent database is chosen in openLCA because it provides a highly extensive and detailed dataset, covering almost 300.000 different data sets, thus significantly supporting comprehensive and accurate LCA analysis (OpenLCA, 2024). The Characterization Value (CF) from all the material as input and output in calculation LCA of XYZ laboratory shown in Table 2.

Table 2. Characterisation Factor of LCA Study at XYZ Laboratory in 2023 using Ecoinvent Database Available on Open LCA version 2.0

Material	Characterization Factor (CF) Energy Consumption (Cummulative Energy Demand)					
	NR Nuclear	Renewable Biomass	Renewable Water	Renewable Wind and Solar Geotherm	Energy Total	Source
Electricity	1.850e-04	1.200E-02	1.670E-01	2.770E-01	4.562E-01	Electricity, high voltage {ID} market for | APOS, S
Paper	2.100E+00	1.289E+01	1.250E+00	3.300E-01	1.657E+01	Market for paper, newsprint | paper, newsprint | APOS, S - RoW
Bulb	7.260E+00	1.070E+00	3.570E+00	9.200E-01	1.282E+01	Market for compact fluorescent lamp | compact fluorescent lamp | APOS, S - GLO
Used Bulb	1.300E-01	5.000E-02	6.900E-02	1.700E-02	2.660E-01	Market for used fluorescent lamp | used fluorescent lamp | APOS, S - GLO
Sample Packaging Glass Bottle	3.850E+00	4.600E-01	1.360E+00	5.000E-01	6.170E+00	Market for glass fibre | glass fibre | APOS, S - GLO
Sample Packaging Cardboard	6.709E+01	1.324E+01	8.600E-01	1.500E-01	8.134E+01	Market for folding boxboard carton | folding boxboard carton | APOS, S - RoW
Sample Packaging Plastic	2.700E-01	1.009E-01	2.042E-01	5.027E-02	6.254E-01	Market for aluminium hydroxide | aluminium hydroxide | APOS, S - GLO
Sample Packaging Aluminium Foil	1.380E+00	6.470E-01	4.700E-01	7.900E-02	2.576E+00	Market for aluminium oxide, non-metallurgical | aluminium oxide, non-metallurgical | APOS, S - RoW
Chemical Reagent and Microbiological Media	1.985E+02	3.218E+02	9.211E+01	2.271E+01	6.351E+02	Markets for Reagents, APOS,S-GLO|APOS,S-RoW
TSS	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Suspended solids, unspecified (Elementary flow>emission to water>unspecified)
COD	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	COD, Chemical Oxygen Demand (Elementary flow>emission to water>unspecified)
BOD	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	BOD_5, Biological Oxygen Demand (Elementary flow>emission to water>unspecified)
Oil and Grease	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Sulfur (Elementary flow>emission to water>unspecified)
Ammonia	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00	Ammonia ((Elementary flow>emission to water>unspecified)

2.5 Life Cycle Impact Assesment

Life Cycle Impact Assessment (LCIA) is an assessment method for assessing the overall impact of a product or process itself. To carry out LCIA, what is needed is a data inventory along with the input flow to the output/ reference flow (Mahath et al, 2019). In this research, the data is analyzed of the midpoint impact. The impact of the midpoint studied is Cummulative Energy Demand (CED). CED is created based on the method published by the ecoinvent center. The aim of this method is to measure primary energy use throughout the life cycle of a good or service (Ecoinvent, 2024).

3. Result and Discussion

3.1 Description of Existing Conditions

The description of existing condition stage is a review activity of data sources with the aim of obtaining accurate and relevant data. In this stage, the review is carried out mainly on laboratory activities and sample administration. One of the main tasks of the XYZ Laboratory is to carry out chemical and microbiological tests. In carrying out the test, there are four process units which will later be taken into account in preparing the XYZ Laboratory LCA, namely office administration, compliance with laboratory environmental conditions, sample preparation and instrumentation analysis. The four process units will be taken into consideration in preparing the LCA of XYZ Laboratory. In the existing condition stage, a review will be conducted on relevant data sources to obtain accurate and relevant data about laboratory activities and sample administration. The data collected in this stage will be used as input for the next stage, which is the Life Cycle Inventory (LCI) stage. LCI is a stage that involves collecting data about the input and output of the system being studied, in this case, XYZ Laboratory. Therefore, the existing condition stage is an important initial stage in conducting LCA at XYZ Laboratory, as it will determine the accuracy and relevance of the data used in the subsequent stages.

3.2 Life Cycle Inventory (LCI)

Life Cycle Inventory is a stage in the LCA aimed at inventorying all materials that enter and leave the sample administration process to instrumentation analysis (Baldini, 2017).

After data collection was carried out during 2023, the sample administration activities of the XYZ laboratory tested 5,006 samples using 119,427 kWh of electrical energy. This energy is used to support various administrative activities involving electronic equipment and lighting. This stage also requiring 257 light bulbs, and using 270 kg of paper. The use of 270 kg of paper in administration suggests the potential to reduce paper usage through the digitalization of processes. In addition, during 2023, sample office administration activities produced waste in the form of 257 used light bulbs in its activities.

To support activities to meet laboratory conditions, 274 kWh of electrical power is required to maintain the operational conditions of the laboratory. This includes the use of equipment that ensures the laboratory environment remains up to standard, such as HVAC (Heating, Ventilation, and Air Conditioning) systems. using 835 bulbs, and producing 835 used bulbs as waste during 2023. The number of light bulbs used and discarded as waste indicates a need for efficient lighting and the potential for recycling light bulb waste.

In sample preparation activities, the electrical power required during 2023 is 16,814 kWh. Apart from that, during 2023, many chemical reagents and microbiological media will be used. Calculation of using all reagent and microbiological media during 2023 is 1,417.202 kg. A total of 1,417.202 kg of reagents and media were used, indicating the importance of efficient and safe chemical management. Sample preparation activities for testing involve various stages to prepare samples so they are suitable for testing in the laboratory. This process includes weighing, drying, crushing, mixing, and dividing the sample. During this process, samples are packaged in various types of packaging such as cardboard, glass bottles, aluminum foil, and plastic. Sample packages are then collected per type and weighed, then the average value of how many kg of waste per type per day was found and then calculated as the amount of waste for 2023. From the weighing results it was found that the weight of the glass sample bottle packaging was 1,765.015 kg. The weight of the cardboard sample packaging is 1,914.091 kg, the weight of the plastic sample packaging is 2,396.871 kg and the weight of the aluminum foil sample packaging is 563.741 kg. The total packaging waste amounts to 6,639.718 kg. This highlights the need for effective waste reduction and recycling strategies.

In the instrumentation analysis, 576,759 kWh of electrical power is required. This stage is the most energy-intensive. During this phase, complex and advanced analytical equipment is used to obtain accurate data from the samples. The instrument analysis also produces emissions (liquid waste) with details of 4,929,375.5 kg TSS; 5,578,658.3 kg COD, 2,187,845.8 kg BOD; 2,987,500.0 kg oil and grease, and 94,524.5 kg ammonia during 2023. This indicates a significant environmental impact, requiring strict waste management and advanced waste treatment technologies to reduce the negative effects on the environment. The inventory data for the XYZ Laboratory is shown in Table 3. Inventory data was obtained based on the results of XYZ laboratory data collection during 2023. With this data, laboratory XYZ can identify areas that require improvement in terms of energy efficiency, waste reduction, and emissions management to enhance their operational sustainability.

Table 3. Life Cycle Inventory XYZ Laboratory in 2023

Sample Administration			
	Life Cycle Inventory	Amount	Unit
Input			
Testing sample	Sample during 2023	5,006	sample
Energy	Electricity	119,427	kWh
Support material	Bulb	257	pcs
	Paper	270	kg
Waste			
Support material	Used bulb	257	pcs
Fulfillment of Testing Laboratory Condition			
Input			
Testing sample	Sample during 2023	5,006	sample
Energy	Electricity	274	kWh
Support material	Bulb	835	pcs
Waste			
Support material	Used bulb	835	pcs
Sample Preparation			
Input			
Testing sample	Sample during 2023	5,006	sample
Energy	Electricity	16,814	kWh
Chemical reagent and microbiological media	Calculation of using all reagent and microbiological media during 2023	1,417.202	kg
Waste			
Sample Packaging	Glass bottle	1,765.015	kg
	Cardboard	1,914.091	kg
	Plastic	2,396.871	kg
	Aluminium foil	563.741	kg
Instrumentation Analysis			
Input			
Testing sample	Sample during 2023	5,006	sample
Energy	Electricity	576,759	kWh
Emission to water	TSS	4,929,375	kg
	COD	5,578,658	kg
	BOD	2,187,845	kg
	Oil and grease	2,987,500	kg

Ammonia	94,524	kg

3.3 Life Cycle Inventory Functional Unit

The functional unit in preparing the Life Cycle Inventory (LCI) within LCA plays a crucial role as it serves as the foundation for measuring and comparing the environmental impact of the product, process, or service being analyzed, as outlined in ISO 14040 and ISO 14044 (2006). This functional unit provides a consistent reference point for collecting and evaluating data, enabling objective comparisons between different options or alternatives. By defining functional units, analysts can ensure that all data collected and calculated in the LCI are relevant and comparable, which is essential for producing valid and reliable results in environmental impact assessments.

Functional units are typically defined based on the quantitative characteristics of the product or system under study, such as weight, volume, or other relevant metrics. In the LCA study for the XYZ laboratory, the functional unit used is one laboratory analysis service for the year 2023. This functional unit allows for a fair and equal assessment between different systems or products by controlling other variables that may influence the analysis results.

The LCI value of a functional unit is calculated by dividing the total discharge or demand for raw materials, waste, and emissions for one year (2023) by the number of products or samples tested during that year, which is 5,006 testing samples/ analysis services. For instance, if the paper usage for the year is 270 kg, the LCI value for paper per functional unit is 0.054 kg (270 kg divided by 5,006 analysis services). Calculations revealed that the LCI value for electricity use in sample administration is 23,860 kWh, for bulbs and used bulbs is 0.051 pieces, and for paper is 0.054 kg. Under laboratory environmental conditions, the LCI value for electricity is 0.055 kWh, and for used bulbs and bulbs, it is 0.167 pieces.

In the sample preparation process unit, the LCI value for electrical energy is 3,359 kWh. For packaging materials, the LCI values per functional unit are 0.353 kg for glass bottles, 0.382 kg for cardboard, 0.479 kg for plastic, and 0.113 kg for aluminum foil. In instrumentation analysis, the LCI value for electrical energy is 115.2136 kWh. For emissions to water bodies, the LCI values are 984.693 kg for TSS, 1,114.394 kg for COD, 437.045 kg for BOD, 596.784 kg for oil and grease, and 18.882 kg for ammonia.

These LCI values are used as characterization factor (CF) multipliers for each product or material, forming the basis for calculating the environmental impact of each laboratory analysis service performed. A precise definition of the functional unit is critical in LCA because it ensures the consistency and accuracy of the results. With a clear functional unit, the analysis can be applied to the same context in the future, maintaining the relevance and reliability of the results. Furthermore, the functional unit facilitates fair comparisons between different products or systems, which is essential for making informed environmental decisions. Thus, the functional unit is a key component in LCA, ensuring that the analysis provides valid insights into the environmental impact of the assessed product or service. All LCI Functional Unit details are shown in Supplement 1.

3.4 Life Cycle Impact Assesment

Cumulative Energy Demand (CED) is a methodology used to measure both direct and indirect energy use in Mega Joules (MJ) throughout the life cycle of a process or product. This methodology includes energy consumption during the laboratory testing stages of materials. In the context of LCA, CED is a crucial impact indicator used to estimate the primary energy consumed to produce a specific unit of product. In the study by Frischknecht et al. (2015), CED considers four energy categories: Non-Renewable Nuclear, which is energy derived from non-renewable nuclear sources; Renewable Biomass, which is energy sourced from renewable biomass; Renewable Water, which is energy generated from renewable water sources such as hydroelectric power; and Renewable Wind Solar Geothermal, which is energy derived from renewable wind, solar, and geothermal sources. The impacts of these four categories are accumulated into the total CED.

In LCA calculations for analyzing CED, this value is referred to as the characteristic factor (CF), which is a coefficient indicating the amount of emissions energy produced per unit of activity (Ecoinvent, 2024). The CF values are obtained from the OpenLCA 2.0 software and are used to calculate the LCIA CED value by multiplying them with the relevant quantities. The case study in the XYZ laboratory shows the LCIA CED calculation results shows in Figure 3. Sample administration activities have an LCIA value for electrical energy of 10.883 MJ per analysis service. The use of bulbs is 0.658 MJ, paper is 0.895 MJ, and used bulb waste produces 0.014 MJ per analysis service. Fulfilling laboratory environmental conditions has an LCIA value for electrical energy of 0.025 MJ per analysis service, bulbs 2.138 MJ, and used bulbs 0.021 MJ per analysis service. The sample preparation stage has an LCIA value for electricity use of 1.532 MJ per analysis service, chemicals and microbiological media is 0.572 MJ. Glass bottle sample packaging has an LCIA impact of 2.175 MJ, cardboard 31.101 MJ, plastic 0.299 MJ, and aluminum foil 0.290 MJ per analysis service.

Instrumentation analysis is the largest contributor to CED's potential impact, with electricity use ranking first at 52.559 MJ per analysis service. Waste such as TSS, COD, BOD, ammonia, oil, and grease has an impact of zero MJ per analysis service, indicating that this stage does not significantly impact CED potential (Marendra et.al, 2018). The CED methodology provides a comprehensive view of energy use throughout the product life cycle, allowing for the identification of areas with the greatest energy impact and potential for energy efficiency improvements. The LCIA CED for each input, waste and emissions is presented in Figure 3.

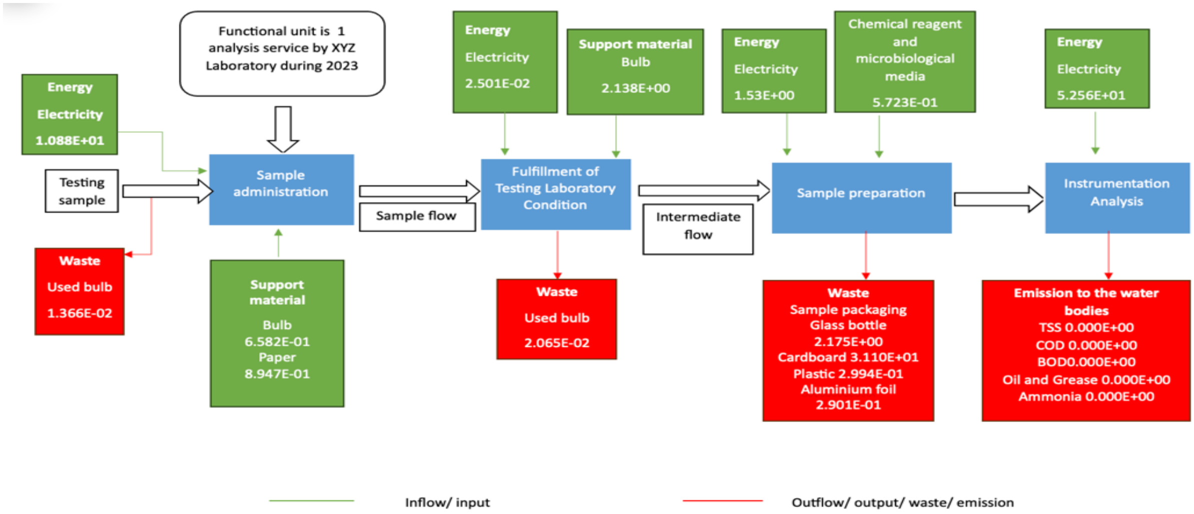

Figure 3. Life Cycle Impact Assesment Cummulative Energy Demand diagram tree

3.5 Life Cycle Interpretation

The interpretation phase in LCA is the final and crucial step for understanding and analyzing the results of the entire LCA process. This phase involves evaluating the outcomes from the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) to provide relevant insights and develop actionable recommendations . In addition, the interpretation stage is also useful in determining the parts of the life cycle that have the greatest environmental impact, which are called hotspots (Hauschild et.al, 2028). In the LCA calculations at the XYZ laboratory, the instrumentation and sample preparation stages were identified as the main hotspots due to high energy consumption. The instrumentation stage ranks first with the highest energy use of 52.559 MJ per analysis service (50.948%) and the sample preparation stage follows in second place with 35.970 MJ per analysis service (34.867%). The highest energy consumption indicating a significant environmental impact. The sample administration stage has a moderate impact because contributes 12.450 MJ per analysis service (12.068%), and the stage of fulfilling laboratory environmental conditions has the lowest energy 2.184 MJ per analysis service (2.117%). A summary of the

LCIA calculation results for each LCA unit is visualized in Figure 4 and Figure 5. Given the high CED values, particularly in the instrumentation and sample preparation stages, these stages are considered to have a significant adverse environmental impact due to their substantial energy consumption. Therefore, serious attention is needed to reduce environmental impacts.

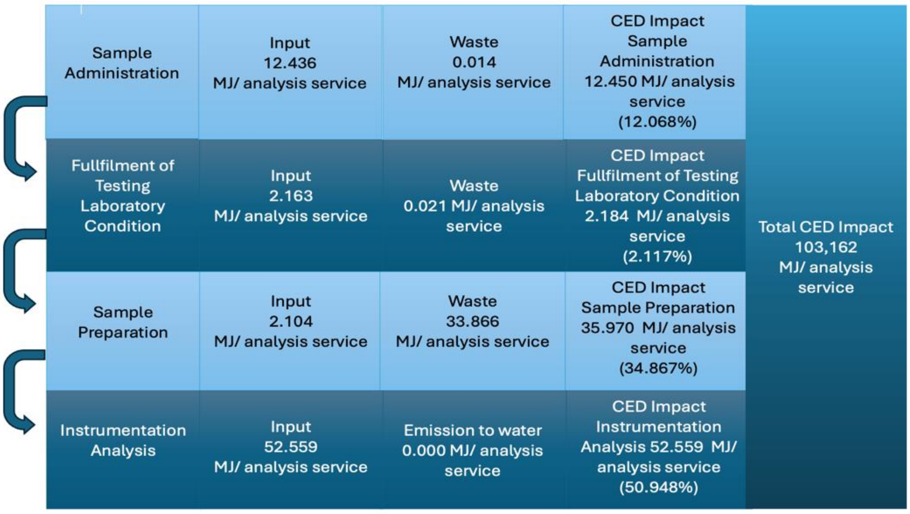

Figure 4. Summary of LCA calculation results for each LCA Process Unit in 2023

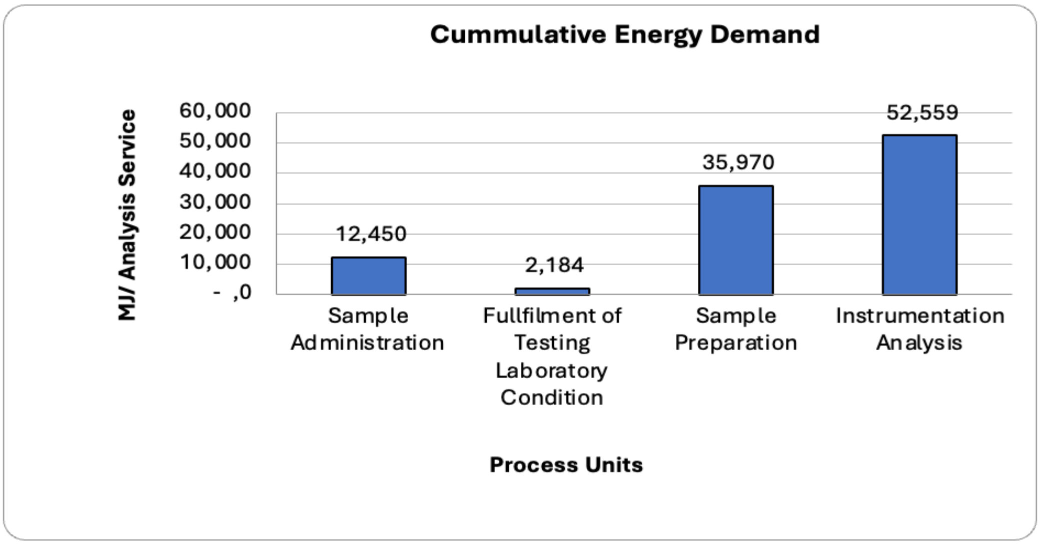

Figure 5. CED potential diagram for the four LCA Process units XYZ Laboratory in 2023

As shown in Figure 5, the main contributors to high electricity consumption are the operation of testing instruments such as High Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), Atomic Absorption Spectroscopy (AAS), Inductively Coupled Plasma Optical Emission Spectrometry (ICP OES), and Liquid Chromatography tandem with Mass Spectrometry (LCMSMS) in XYZ laboratory. That instrumentation require significant electrical energy for their operation. This finding aligns with the study conducted by Yang et al. (2024), which indicates that laboratories, especially those using advanced equipment, have high energy consumption. Additionally, a study by My Green Lab reveals that laboratories use three to six times more energy per unit area compared to regular office buildings, with this energy usage primarily stemming from energy-intensive laboratory equipment (Napolitano, 2021).

The Sample prepatation phase at the XYZ laboratory contributes the second-largest contributor to the total Cumulative Energy Demand (CED) produced. The high Cumulative Energy Demand (CED) values in Life Cycle Impact Assessment (LCIA) for packaging materials such as cardboard, plastic, aluminum foil, and glass bottles can be explained by several factors related to their production, use, and disposal processes. According to Ketkale, H and Simske, S (2023), cardboard production involves the extraction and processing of wood pulp, which requires significant amounts of energy. The pulp cooking process, especially when chemical cooking is used, consumes large amounts of energy. The manufacturing processes for cardboard, including the production of kraftliner and folding box board, require substantial energy inputs for operations such as cooking, drying, and paperboard forming. Although recycling cardboard can reduce the overall environmental impact, the recycling process itself is energy-intensive, involving energy consumption for collecting, transporting, and reprocessing the material.

According to research conducted by Marczak, H (2022), plastic packaging production involves the extraction and refining of petroleum, which requires a lot of energy. Production of resins such as LDPE, HDPE, PP, PVC, PS, and PET requires significant energy input. The conversion of plastic resins into packaging products involves processes such as extrusion, molding, and thermoforming, all of which consume a lot of energy. Disposal and recycling of plastic packaging also contributes to high CED values. Although recycling can reduce some impacts, the energy required for collection, sorting and reprocessing is considerable. Izhar, T. N. T. (2020) states that primary aluminum production is one of the industrial processes that requires the most energy. This involves extracting bauxite ore, refining it into alumina, and then smelting it into aluminum, which requires a lot of electricity. Milling aluminum sheets to produce foil is another energy-intensive step. High energy consumption in the grinding process contributes significantly to the overall CED. Although aluminum is highly recyclable, the recycling process still requires a significant amount of energy, especially for melting and reprocessing the material. Glass bottle production involves melting raw materials such as silica sand at very high temperatures (around 1500°C), which requires a lot of energy. The forming and cooling processes in glass bottle production also require a lot of energy. Maintaining the high temperatures required for this process contributes to high CED values (Aigner, 2022). Overall, the high LCIA CED scores for these packaging materials are primarily due to the energy-intensive nature of their raw material extraction, production, and processing stages, as well as the energy required for recycling and transportation.

Strategies for reducing electrical energy consumption that can be carried out by the XYZ Laboratory include the use of alternative energy. The main sources of potential CED in XYZ laboratory include energy use for buildings, such as electricity for lighting, cooling, and other office equipment. Naimah et al. (2023) state that the building sector absorbs 40% of the world's energy resources. In Indonesia, this sector is responsible for 50% of total energy expenditure and more than 70% of overall electricity consumption. Use of alternative energy such as solar, wind and hydroelectric power can reduce the use of fossil fuels and increase energy use. In addition, increasing energy efficiency in XYZ Laboratory activities can reduce the amount of energy needed for daily activities. Practical examples of what can be done include choosing the most efficient type of lamp and being disciplined in turning off electrical equipment and instruments after use, using energy-saving electrical equipment, and optimizing HVAC systems to reduce energy consumption.

According to research conducted by Dewi (2022), increasing energy productivity can be done by choosing sustainable resources and using energy efficiently. Some of these techniques can be applied at the XYZ Laboratory. Some of these techniques include good housekeeping, input change, better process control, technology change, on-site reuse and recycling, production of useful by-products, and product modification. Good housekeeping techniques involve keeping the environment and workplace in XYZ Laboratory so that they remain organized, clean and productive to reduce waste. Examples of these techniques include minimizing and managing stock, turning off unused equipment and instruments, and keeping the work space clean and organized. This practice not only improves energy efficiency but also improves safety and productivity in the workplace. The input change technique involves selecting inputs that are more efficient and environmentally friendly in the sample testing process in the laboratory. Examples include using renewable energy, sustainable renewable materials, and choosing chemical reagents and microbiological medias from manufacturers who have implemented LCA in their production and product delivery processes. Better process control is carried out by monitoring and controlling every process and equipment so that it runs with high efficiency and reduces energy waste.

XYZ Laboratory can do include following work guidelines or standard operating procedures, as well as controlling process requirements such as pressure, speed and temperature. Efficiency in the use of electrical equipment and instrumentation in the laboratory is also important, including considering the number of samples to be analyzed to avoid wasting energy. A small number of samples but being analyzed using instruments that require large amounts of electrical energy is a waste. It is necessary to regulate the number of samples to be tested for simultaneous analysis for energy efficiency. Technology change is carried out by adopting new technology that is more efficient in energy use. Examples include the use of solar panels and wind turbines, as well as replacing processes with more environmentally friendly ones based on green chemistry principles. On site reuse and recycling techniques involve reusing material, energy or water that was previously wasted or turned into waste for similar or alternative purposes. Examples are product packaging reuse, condensation, and heat energy recovery. Production of useful by products involves the conversion of waste into useful products at another place or station. Examples include using used air conditioner water for external heating or cooling purposes, as well as separating items that can be recycled for external recycling. CED reduction is not only beneficial in reducing operational costs but is also important in climate change mitigation efforts. Efficient energy use contributes to reducing greenhouse gas emissions, which is one of the main goals in global efforts to tackle climate change. By implementing these techniques, XYZ Laboratory can achieve higher energy efficiency and significantly reduce their environmental impact.

Better management of cardboard packaging, glass bottles, plastic and aluminum foil from chemical testing sample packaging and effective microbiological testing helps reduce the impact of CED. Applying the 2R concept (Reuse and Recycle) will result in a reduction in the energy required for recycling, while reducing is somewhat difficult to do because the variety or quantity of samples entering the laboratory cannot be regulated. XYZ Laboratory can seek reuse or use, for example by reusing used liquid reagent bottles and used solid reagent containers. Used liquid reagent bottles and used solid reagent containers are converted into waste solvent/ mobile phase containers for instrumentation tools such as HPLC or with creativity converted into flower vases or other decorations that can add beauty to the office area. Once the items cannot be reused, the final process that can be carried out is recycling. The recycling process can be carried out, for example, by processing sample packaging into new products, for example handing it over to a third party so that it can be processed into recycled paper, art paper, paper mill materials and so on. All efforts must be made as much as possible so that packaging waste does not end up in landfills. However, among the various strategies and techniques implemented to reduce energy consumption, some require high implementation costs, such as the use of alternative energy. Therefore, a Life Cycle Cost (LCC) analysis is needed to calculate the costs comprehensively.

4. Conclusion

The primary objective of this study is to analyze the Cumulative Energy Demand (CED) potential using the LCA approach as a case study of the XYZ Laboratory. From the research results, valuable insights into the environmental impacts of laboratory operations were obtained. The analysis reveals that the instrumentation analysis stage has the highest energy consumption, contributing 52.559% of the total CED, which amounts to 103,162 Mega Joules per analysis service. This significant energy use is attributed to the operation of sophisticated equipment such as High Performance Liquid Chromatography (HPLC), Gas Chromatography (GC), and Liquid Chromatography tandem with Mass Spectrometry (LCMSMS). The substantial electrical energy consumption leads to environmental damage including deforestation, soil erosion, and water pollution, further contributing to greenhouse gas emissions and climate change. For this reason, several strategies are recommended such as good housekeeping, input change, better process control, technology change, on-site reuse and recycling, and production of useful by-products. These strategies aim to enhance energy efficiency and minimize the environmental footprint of laboratory operations. The results highlight the importance of reducing CED to increase energy efficiency and minimize environmental impacts associated with excessive energy use. The study concludes that significant efforts are required to reduce energy use and environmental impact. Future research efforts could conduct in-depth analyzes of other impacts and scope, including more complete data collection, a wider scope, and calculation of the impact on emissions to soil and air on laboratory management systems. Additionally, calculating the Life Cycle Cost Assessment of the strategy described in the paper is necessary to reduce energy use in laboratory management. By understanding the CED and applying LCA methodology, this study aims to provide a comprehensive framework for evaluating the environmental impacts of products and processes throughout their entire life cycle, ultimately contributing to a more sustainable future for laboratory operations.

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