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Full Paper

Development of a Guideline to Assess Industrial Boiler Fuels for Sustainable Boiler Operations

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Abstract

Industrial boilers play a significant role as a primary source of energy utilization in the industrial environment. In line with Sri Lanka's Nationally Determined Contributions (NDCs) to reduce carbon emissions, significant actions include converting boiler energy sources to biomass and implementing guidelines to support the transition of industries into sustainable eco-industrial parks. Therefore, as energy sources, the selection of boiler fuel is significant to industries that consider sustainability and NDC actions. In the present study, sets of criteria were identified, and a guideline was formulated to assess industrial boiler fuels before starting the boiler operations for sustainable boiler practices in the Sri Lankan context associated with Seethawaka Export Processing Zone (SEPZ) using primary and secondary data sources. The resulting guideline consists of major boiler fuels, including biomass, coal, oil (diesel, heavy furnace oil and kerosene), processed waste (fabric) and electricity as an energy source. The guideline covers criteria related to fuel quality, maintenance practices, environmental regulations, issues related to fuels, fuel handling requirements, and environmental protection practices for each fuel relating to environmental, economic, and social sustainability. The guideline's practical application was evaluated through a survey of industries at SEPZ. The survey results indicate that SEPZ industries meet the requirements of prepared guidelines by adhering to safety practices, holding necessary permits, and complying with environmental regulations, thus contributing to social sustainability. The SEPZ industries have achieved environmental sustainability by utilizing biomass as boiler fuel (49%), ensuring proper fuel storage, safe ash disposal, and dust arresting systems while maintaining compliance with environmental regulations. Additionally, economic sustainability has been attained through effective boiler maintenance, safety practices, and the widespread use of biomass. Also, awareness related to proper biomass is lower among industries. Thus, the guideline will lead to an increase in the awareness of boiler fuel usage in the industrial environment management sector.

Keywords: Boiler fuels; Industrial boilers; NDCs; SEPZ; Sustainability

Introduction

Sustainability has become a crucial global consideration, leading to the United Nations establishing 17 Sustainable Development Goals (SDGs) that address environmental and socio-economic issues [1]. The world's unsustainable behavior has contributed to environmental deterioration, climate change-related disasters, and socioeconomic injustices, which can be mitigated by implementing these goals [2]. The

energy sector, particularly in industries, plays a key role in sustainability, with industrial processes consuming about 37% of the world's energy, mainly for heating, cooling, and ventilation [3]. Through this energy utilization, boilers use a large amount of the energy consumed worldwide. They are essential for industrial heating and electricity generation. Fossil fuels, including coal, oil, and natural gas, account for around 80% of the energy boilers consume, while biomass contributes 9–14% in developed nations and 1–3% in developing countries [4]. However, sustainable approaches should be driven through the energy sector considering the environmental preservation, improve energy security and the depletion of fossil fuel supplies. In addition to the fluctuation of crude oil prices, combustion of boiler fuels additionally causing emissions including greenhouse gas (GHG) contributing to the climate change and global warming [3]. Those are the major concerns in the energy sector. Due to these concerns, sustainability can be achieved in the industrial sector through boiler fuel to ensure economic, social and environmental health benefits by using the proper boiler fuel [5].

Considering the local context, Sri Lanka, as a developing region, is highly aware of climate change effects and signed the Paris Agreement in 2016 to mitigate these impacts [6]. The country aims for carbon neutrality by 2050 and plans to have 70% of its energy demands met by renewable sources by 2030 while phasing out fossil fuels [7]. The Nationally Determined Contributions (NDCs) outline sectoral actions to achieve these goals, particularly in the industrial sector. Key actions include, under industrial sector 4.4.3, there are particular actions such as continue fuel switching to sustainable biomass energy and improve use friendly in selected industrial sub-sectors (NDC1), establishing eco-industrial parks and village (NDC3) and introduce policy and regulatory regime, including guidelines to ensure all new industrial parks will be set up as eco-industrial parks (NDC3.2) [8]. Industries must shift to sustainable practices, a complex and costly process. Large-scale industries in Sri Lanka, particularly those in export processing zones, focus on improving boiler operations to reduce energy consumption. However, the lack of standardized sustainability guidelines for boiler fuels presents challenges, leading to environmental degradation, resource inefficiency, and increased operational costs. Without clear guidelines, investors face difficulties in decision-making and may incur high costs or halt operations.

Several regulations, guidelines, and policy recommendations have been implemented worldwide and locally, focusing on energy efficiency and sustainable boiler operations. However, those guidelines and policy recommendations do not specifically provide guidance for separate boiler fuel handling. They only focus on boiler operations, as per Table 1.

Table 1. International and local policies / guidelines on boiler fuel operations

International and local bodies	Covered Aspects	Source
International Energy Agency (IEA)	IEA provides guidelines and policy recommendations on efficient energy use in industrial processes Example: • Regulations on Industrial Energy Efficiency (Circular 02/2014 / TT-BCT) on Viet Nam defines economical and efficient energy use in combustion processes	[9]

	• Renewable Heat Act in Austria • Luxembourg's Integrated Energy and Climate Plan - Fossil Fuels Boilers • Germany's 2nd Amendment to the Building Energy Act (GEG) - phase-out of fossil fuels	
World Health Organization (WHO)	The World Health Organization has developed ambient air quality regulations related to the emission of boiler fuels to control these emissions, including maximum average annual levels of 20 μg/m^3 for PM_{10} (particulate matter < 10 μm).	[10]
United States Environmental Protection Agency	The Environment Protection Agency have published guidelines related to the emission factor database addressing emission factors for boilers burning coal, natural gas, fuel oil, wood, and wood residues.	[11]
International Organization for Standardization	ISO 5001 Energy Management System defines the requirement of addressing energy related impacts, conserving resources and efficient energy management system in industries.	[12]
International Finance Corporation (IFC)- World Bank	IFC has developed the environmental, health, and safety Guidelines for industries which define the energy conservation, air quality management, occupational health and safety of industries.	[13]
Central Environmental Authority of Sri Lanka	According to the National Environmental Act of Sri Lanka, all industries must follow regulations related to boiler emissions from each boiler fuel, as mentioned in the national stationary emissions control regulations. That is the only regulation related to boiler fuels in Sri Lanka with the purpose of air quality management. In there, the boiler fuel mainly biomass, coal and oil-related emission limits have been given.	[14]
Department of Labor, Sri Lanka	The labor safety defines according the factory ordinance (No 45 of 1942).	[15]

Establishing standardized criteria for boiler fuel selection is essential to supporting sustainable industrial practices. This study was carried out to develop a guideline to assess industrial boiler fuels for sustainable boiler operations as a requirement of the industrial environment management sector. It also aims to facilitate and educate the industrial sector and contribute to Sri Lanka's NDCs.

Materials and Methods

2.1 Research Design

This study mainly provides a documentary guideline through principles and methodologies relevant to current boiler fuels in Sri Lanka. The research design encompassed mainly qualitative methods to gather details to feed the guideline through primary and secondary data sources. Hence, this is only a guideline, less quantitative data was obtained through secondary data sources to feed some of the sections of the prepared guideline.

2.2 Primary Data Collection

The first phase of the research involved surveying within an industrial setting to collect relevant data regarding boiler fuels. The survey was designed to capture and examine current fuel usage patterns, efficiency levels, environmental impacts, stakeholders' perspectives on sustainability measures, and safety precautions. The questionnaire was prepared to gather the details related to boiler fuels and research the primary setting of the industries with boiler fuels. It included eight sections with the following objectives as Table 2. The industries of SEPZ were visited to get the idea related to boilers, boiler fuels and related practices before preparing the questionnaire as a foundation for questions. And the questions were built up by referring the environmental protection license documents and recommendations of the Environment Management Department of BOI experts as per Text S1. The Environment Management Department of BOI also reviewed the prepared questionnaire to ensure the correctness and ethical considerations. An approved survey questionnaire was sent to industries through the Environment Management Department of the Board of Investment using the Microsoft Forms application. The survey was also conducted physically in SEPZ. During the physical survey, data were collected by visiting boiler operations on-site and conducting interviews with key personnel responsible for boiler operations and fuel procurement. The interviewees included energy conservation engineers, boiler operational managers, Environment Health and Safety team leaders, senior executive engineers, and quality assurance officers.

Table 1. Sections of the prepared questionnaire

Sections of the questionnaire	Objective
Section 01	To identify the industrial categories within the zone
Section 02	To identify the boiler fuel usage within the industries and the current pattern
Section 03	To identify the boiler fuel usage within the industries and its purposes
Section 04	To identify the fuel consumption of each boiler and its cost
Section 05	To identify the operational practices related to biomass boilers
Section 06	To identify the fuel storage conditions, environmental safety practices and compliance regulations
Section 07	To identify the environmental, cost, purchasing issues and mitigatory actions related to boiler fuels
Section 08	To identify maintenance practices related to boiler fuels

2.3 Development of the Guideline

The findings from the survey served as the foundation for developing comprehensive guidelines for assessing industrial boiler fuels for sustainable boiler operations. The findings were categorized into environmental, social, and economic sustainability areas. Environmental sustainability was identified through environmental practices considered when using boiler fuels and environmental regulations. Social sustainability was identified through health and safety practices related to boiler fuels and environmental

regulations. As well as economical sustainability, was identified through fuel handling practices, boiler maintenance practices and selection of fuel types. The different types of boiler fuels were selected through the survey as industrial use fuels, mainly biomass, coal and oil. As well as additionally processed waste and electricity were selected through a literature survey and consultations with the Environment Management Department's expertise. Evaluation criteria were built up for selected boiler fuels using a literature survey and survey findings. The following criteria included fuel qualities, environment regulations, fuel issues, fuel handling requirements and environment protection practices.

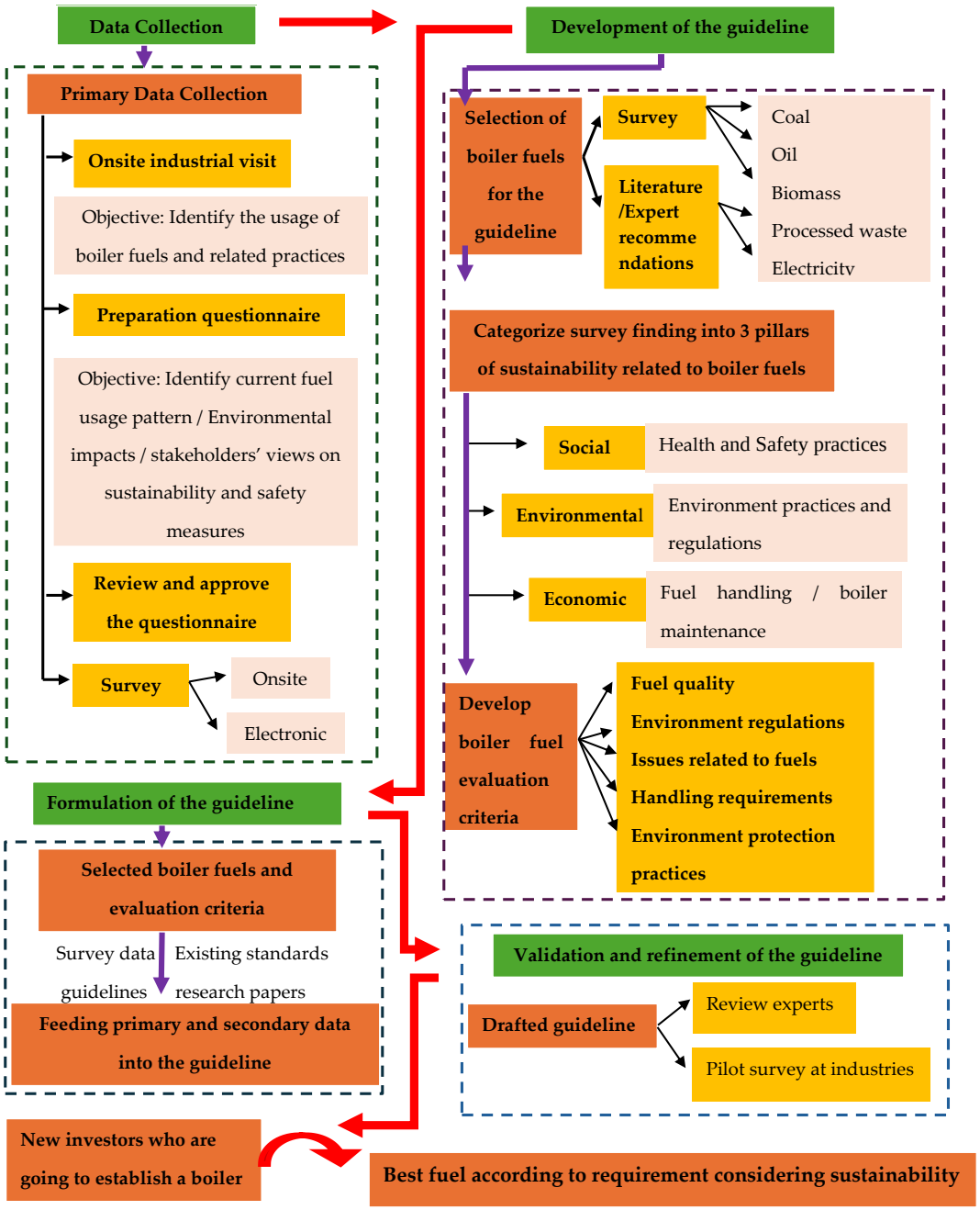

Figure 1. Methodology of the research

2.4 Formulation of the Guideline

The guideline included 18 sections and fed the data using reviewed survey data, research papers, industry standards, regulations, and best practices in sustainable fuel management.

2.5 Validation and Refinement of the Guideline

The draft guideline was reviewed by the subject experts of the Environment Management Department of the Board of Investment, and the practical scenario of the guideline was checked against the findings of the initial survey to draft the recommendations.

Results and Discussion

3.1 Selection of the Boiler Fuel Category to Formulate the Guideline

According to the Nationality Determined Contributions of Sri Lanka in 4.4.3 NDCs, it requires the introduction of policies and regulatory regimes, including guidelines, to ensure all industrial parks settle up as eco-industrial parks [8]. All industrial operations, including wastewater management, air pollution mitigation, and solid waste management sectors, should be considered in setting up the environment management process. Sector by sector, industries have to implement environmentally friendly and sustainable concepts. Industrial boilers are one such operation which can be seen in the industries. In the industrial environment management sector, boiler operations and related air quality management are done by issuing environmental protection licenses as a management of air pollution reduction. As well as the goal of Sri Lanka's NDCs' is the conversion of boiler fuel into sustainable biomass energy. Due to those reasons, selecting the right boiler fuel for industrial boilers is a pivotal step towards sustainable boiler operations. Those are the reasons for selecting the boiler fuel category to formulate the guideline, considering both technical and sustainability criteria.

3.2 Foundations for the Guideline Preparation

This guideline is intended for new investors, looking to implement new boiler operations by choosing a boiler fuel. It is important to understand the existing management practices and issues associated with boiler fuel before selecting the criteria for boiler fuel selection. This information should be provided to the investor or boiler management sector before beginning the operation to avoid any problems associated with their boiler fuel. To achieve this objective and focus on Sri Lankan boiler operations, an online survey and physical survey were conducted. In addition, secondary data from existing literature was used to formulate the guidelines because of insufficient information from the surveys.

3.3 Categorization of the Survey Findings into Pillars of Sustainability

The survey findings have been used to create a guideline for sustainability. To develop this guideline, the findings have been categorized into three pillars of sustainability. These pillars are social, environmental, and economic categories. By using these categories, the guideline has been formulated to ensure that

sustainable practices are followed in all aspects of the organization. The following aspects were taken into consideration for environmental sustainability including selection of boiler fuel types, source of feedstock, fuel storage conditions, ash disposal, availability of dust arresting systems, availability of permits to operate a boiler, environmental issues, mitigation actions, and boiler maintenance. By following these aspects, the damage to the environment can be reduced. For social sustainability practices, safety practices related to boiler fuels and the availability of permits to operate a boiler were considered. By following these aspects, the damages that can arise from the boiler fuels to the community can be minimized. In terms of economic sustainability, continued maintenance of the boiler and fuels, safety practices, and mitigatory actions to reduce environmental damage were considered.

3.4 Selection of the Boiler Fuel to the Guidelines

Careful consideration of the various available types of boiler fuels is essential to ensure social, economic, and environmental sustainability. This study examines five different energy sources for boilers, all of which are relevant within the context of Sri Lanka. By reading and comparing the information presented, readers can gain a better understanding of the pros and cons of each energy source. Based on the results of a survey as Figure , biomass, coal, and oil were identified as the preferred energy sources for industrial boilers in Sri Lanka. In addition to coal, biomass, diesel, and heavy furnace oil, other energy sources such as processed waste (fabric), electricity, and kerosene were selected as industrial boiler fuels based on the literature and expert reviews during the research process. Finally, guidelines were established for Sri Lanka to provide direction on fuel types. The selection of fuel types can be made by referring to the guidance related to various fuels.

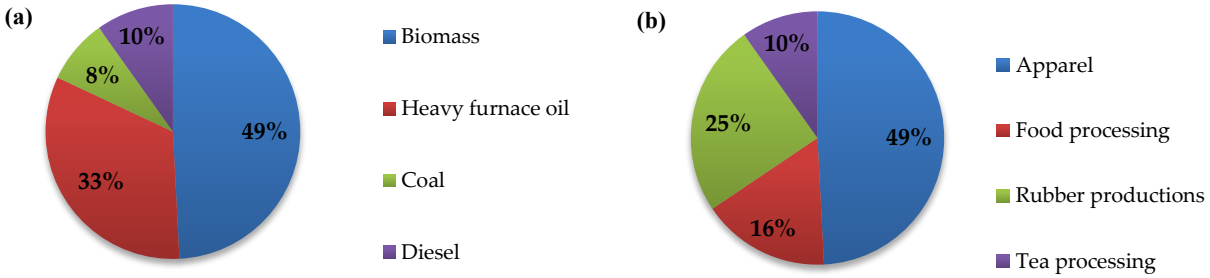

Figure 2. Usage of boiler fuels by industries at SEPZ (a) Boiler usage of industries at SEPZ (b)

3.5 Building Up the Boiler Fuel Evaluation Criteria

Evaluation criteria were developed to select the appropriate boiler fuel based on the sustainability categorization of the survey findings. The following categories are taken relevant to each fuel, including fuel qualities, maintenance practices, environmental regulations, fuel issues, fuel handling requirements, and environmental protection practices. Investors can use these criteria to evaluate different fuels according to the categories mentioned above. These criteria were identified through survey findings and existing literature.

3.6 Sections of the Finalized Guideline

The finalized guideline consisted of 18 sections, including the sustainable guidelines for biomass, coal, oil, processed waste (fabric) and electricity as boiler energy sources. Each section was prepared with information extracted from surveys and literature also provides detailed information regarding the fuel's properties, handling, and performance, enabling users to compare various fuels across predefined categories such as efficiency, cost, environmental impact, and storage requirements. Investors can gain a comprehensive understanding of each boiler fuel. By consolidating all relevant information into one comprehensive document, the guideline ensures that users have convenient access to essential data about fuel handling, eliminating the need to consult multiple external sources. Additionally, the guideline includes specific references to regulations and policies related to boiler fuels, allowing users to address compliance requirements before beginning fuel operations. This centralized resource not only simplifies decision-making but also promotes safe, efficient, and compliant fuel management for boiler systems, as per Table 3.

Table 3. Content of the draft guideline

Section of the guideline	Content of the guideline
Section 01	Introduction (scope and purpose of the guideline)
Section 02	Types of fuels used for boilers
Section 03	Selection of boiler fuel for the industry
Section 04	Selection of a fuel type according to the industrial capacity
Section 05	The calorific value of fuel sources
Section 06	Cost of fuels
Section 07	Contribution to carbon footprint by fuels
Section 08	Biomass fuel 8.1 Wood species 8.2 Waste biomass 8.3 Biomass feeding methods 8.4 Moisture content of biomass 8.5 Biomass Supply Chain 8.6 Issues of biomass fuel
Section 09	Coal as a boiler fuel 9.1 Qualities of coal 9.2 Selection of a coal supplier 9.3 Coal transportation 9.4 Storage of coal 9.5 Preprocessing of coal 9.6 Issues related to coal as a boiler fuel
Section 10	Oil as a boiler fuel 10.1 Qualities of oil 10.2 Storage of oil 10.3 Preprocessing of oil 10.4 Problems related to oil as a boiler fuel

Section 11	Processed waste (fabric) as a boiler fuel 11.1 Why fabric waste is a good option for boiler fuels 11.2 Supply chain of fabric waste 11.3 Special considerations when using fabric waste as a fuel 11.4 Issues of using fabric waste as a boiler fuel
Section 12	Electricity as a boiler energy source 12.1 Why electric boilers should be used 12.2 Issues of electric boilers
Section 13	Ash handling and disposal
Section 14	Air pollution control devices
Section 15	Environmental regulations related to boiler fuels
Section 16	Boiler maintenance according to boiler fuels 16.1 Solid fuels 16.2 Oil-fired boilers 16.3 Electric boilers
Section 17	Health and safety practices related to the boiler fuel
Section 18	Record keeping

3.6.1 Section 1 and 2 of the guidelines

The importance of fuel selection before starting boiler operations is emphasized in these sections. Additionally, basic information about the major purposes and scope of the guideline is included. The purpose of the guideline is to provide a guide on boiler fuels that can be used in Sri Lankan boilers. This is achieved by promoting the use of cleaner and more sustainable fuel options. The guideline also directs the reader towards more detailed information on each boiler fuel and its consequences related to its use before starting boiler operations. Finally, the guideline aims to provide a basic understanding of boiler fuel selection criteria based on sustainable operations.

3.6.2 Section 3 – Selection of a boiler fuel for your industry

In this section, a summary of the selection criteria for boilers is provided to help readers to understand the selected fuels. Readers can compare various boiler fuels based on these criteria. Moreover, each criterion is described to provide a comprehensive understanding. The basic criteria include boiler efficiency, calorific value, fuel cost, availability and supply chain, full diversification, processing requirements and costs, special permission requirements, contribution to carbon footprints, by-product issues, ash content, the requirement of air pollution control systems, fuel storage facilities, health issues for laborers from ash, workplace safety issues, environmental issues, supply chain issues, environmental sustainability, and maintenance requirements. Moreover, readers can understand the life cycle perspective criteria for each fuel.

3.6.3 Section 4 – Selecting a fuel type according to the industry capacity

This section focuses on how the fuel selection for boilers varies with industrial capacity, considering small, medium, and large-scale industries. The following criteria have been introduced to help in the selection process including total heat required for production per day or month, required fuel quantity according to heat requirement, ease of access to the fuel, cost of fuel, heating requirement, fuel flexibility, availability of fuel options, and assessment of boiler capacity.

3.6.4 Section 5 – Calorific value of fuel sources

In this section, the concept of calorific value is given for fuel sources. Calorific value is a standard metric that measures the total energy content produced as heat when a substance is completely combusted with air or oxygen [16]. It is essential to consider the calorific value of fuel sources, as it helps in determining the required heat quantity and the availability of the fuel. Before selecting a boiler fuel, it is crucial to consider the required heat quantity for production by considering the calorific value of the fuel sources.

3.6.5 Section 6 – Cost of fuels

This section provides information on the current cost of fuel. The cost of fuel can change due to several reasons, such as the availability and quality of the fuel, as well as the economic conditions of the country. Through this section, the reader will gain a better understanding of the different costs associated with imported fuels and locally available fuels.

3.6.6 Section 7 - Contribution to carbon footprint by fuels

This section provides information on emission data of each fuel, mainly CO_2 emissions. The amount of CO_2 emissions by burning unit mass of fuel have included using the literature. The reader can understand about how the fuels are contributing to carbon footprint by analyzing emissions. The major environmental impact of fuels is contributing to increase the greenhouse gases in the atmosphere currently.

3.6.7 Section 8 – Biomass fuel

This section provides information on biomass fuels. It includes details on biomass fuel diversification, including section 8.1 of the guideline. The Wood Species section provides information on locally available types of wood species that can be used as boiler fuel in Sri Lanka. Section 8.2 describes another type of biomass diversification, including waste biomass. This gives the reader the ability to select biomass from a product category. Section 8.3 gives details on biomass feeding methods for boilers. Feeding methods, such as wood logs and wood chips, are described, and their limitations are given to select the required feeding method for the boiler. Section 8.4 considers the quality characteristics of wood, such as moisture content. Moisture content is important for efficient combustion. If the user intends to use biomass as a boiler fuel, they should know the moisture content of the biomass. This ensures high-quality biomass fuel. It is essential

to maintain a low moisture content, as combustion of a moist fuel in a biomass boiler results in low boiler efficiency. This is because a large amount of thermal energy released from fuel combustion is required for the evaporation of moisture in the fuel [17]**.** Moisture tests, optimal biomass storage, and biomass preprocessing are suggested in this section. Section 8.5 of the guideline discusses the biomass supply chain. When selecting a supply chain for biomass, it should be sustainable. The guideline provides five criteria, including yearly availability, cost of biomass, reduction in damage to the ecosystem, contribution to the reduction of carbon footprint, and supplier selection. Section 8.6 highlights issues related to biomass fuels, such as health and safety issues, environmental issues, supply chain issues, and storage issues. The reader can gain a broad understanding of these issues and think about preventive measures.

3.6.8 Section 9 - Coal as a boiler fuel

In this section, if the user is required to use coal, a comprehensive guideline is given. Section 9.1.1 highlights the essential quality parameters of coal, which include heating value, volatile matter, ash content, moisture content, and sulfur content. These values are important to ensure efficient combustion and minimize environmental damage by analyzing the coal quality before importing it into the country [18]. In Section 9.1.2, the reader can find a description of coal classification. The different types of coal and their varying moisture content determine the quality of coal. These characteristics may vary depending on the location of the mining site [18]. By reading through this section, the reader can learn to identify these differences, which highlight the importance of quality checks when importing coal.

Section 9.2 of the guideline discusses the coal supply chain. When coal is not available locally and must be imported from another country, selecting the right coal supplier becomes crucial to ensure the efficient functioning of industrial boilers. The choice of coal supplier is related to the stable and sustainable development of the industry, and product quality should be the major consideration in the coal supply chain to ensure sustainability [19]. Coal can contain impurities, including mercury and other heavy metals, which can harm boiler practices and lead to unsustainable environmental practices [20-22]. Section 9.3 of the guideline describes transporting coal. This step is critical as it can cause environmental, health, and safety issues, such as the risk of fires and the loss of imported coal [23]. Special considerations need to be taken when transporting coal from the port to the industrial premises using trucks, and when loading the coal at the premises were included by referring to existing literature. The section 9.4 discusses the importance of proper coal storage practices. Improper storage can lead to exposure to the atmosphere and cause the coal to become wet, leading to issues with feeding and combustion. This results in high levels of ash and carbon and boiler efficiency losses because of the need for high excess air levels to complete combustion. Additionally, storing coal for long periods or at the bottom of a coal pile can cause it to lose some of its volatile content, leading to minor issues with delayed ignition [24].

Section 9.5 describes the requirement for pre-processing of coal. It suggests sizing and conditioning, according to the literature. These steps are significant in achieving good combustion. Large and irregular lumps of coal can cause several problems, such as poor combustion conditions, inadequate furnace temperature, higher excess air resulting in higher stack loss, an increase in the unburnt ash, and low thermal

efficiency [18]. Therefore, proper pre-processing of coal is necessary to avoid these issues. Section 9.6 highlights various issues related to coal, including health and safety, environmental concerns, storage problems, and supply chain issues.

3.6.9 Section 10 – Oil as a boiler fuel

In Section 10 of the guidelines, information is provided about the types of oil that can be used as boiler fuel. Furnace oil, kerosene, and diesel are the primary fuels discussed in this section. Section 10.1 describes the qualities of oil, such as density, specific gravity, viscosity, flash point, pour point, calorific value, sulfur content, ash content, carbon content, and moisture percentage. The average values of these qualities are taken from existing literature to provide an overall understanding of each oil and its significance. For example, the viscosity of the fuel can help to determine whether preheating is required for proper atomization. Poor atomization can lead to the formation of carbon deposits, and preheating requires additional energy [25]. By understanding the qualities of fuel oils, users can make informed decisions. Section 10.2 covers the proper storage of oil to avoid economic, environmental, and safety issues. The guidelines focus on storage tanks, the location of oil storage, requirements for secondary storage tanks, maintenance and protective measures, and ways to avoid fire hazards. In Section 10.3, the pre-treatment of oil is discussed. If oil is used as a boiler fuel, it must be pre-treated to remove contaminants and preheat it [18]. Section 10.4 emphasizes the environmental, health, and safety challenges associated with oil usage. It also covers operation challenges related to oil usage.

3.6.10 Section 11- Processed waste as a boiler fuel

This section highlights the use of fabric waste as a source of fuel for boilers. The rapid growth of the Sri Lankan apparel manufacturing sector over the past 30 years has resulted in a significant amount of solid waste. This waste has become a major environmental and financial burden on the sector. As a solution, some apparel manufacturers have started using cotton apparel waste for biomass boilers. Since the apparel sector is one of the biggest consumers of thermal energy, they see this as a solution not only for the apparel waste disposal issue but also for the challenge of obtaining a continuous supply of firewood for the boilers. The use of fabric waste for boilers can be a solution for energy and waste management, especially in industrial areas [7]. The information in this guideline is based on existing literature and provides details about the supply chain of fabric waste, including its qualities, such as calorific value, moisture content, ash content, particle sizes, nitrogen/chlorine/heavy metal contents, and their significance. This information is meant to provide users with a basic understanding of fabric waste. Before using fabric waste as fuel for boilers, prior approval should be obtained from the Central Environmental Authority. This is because there are no specific air quality regulations for fabric waste in the gazette of the National Environmental Stationary Emission Control Regulations. It should be noted that sufficient details related to fabric waste were not available in the literature. The guidelines only provide a basic path to use fabric waste following the proper mixtures, including biomass and fabric waste, quality testing, air emission testing, ash testing and taking the proper approvals. As well as health and safety issues, environmental issues related to the use of fabric waste as a boiler fuel are emphasized in this guideline.

3.6.11 Section 12 – Electricity as a boiler energy source

This section emphasizes the use of electric boilers as a source of energy for boilers. Small-scale enterprises with a need for heat can benefit greatly from equipping an industrial electric heating boiler, as it can save a significant amount of cost, including labor and boiler costs, while fully meeting the production needs. One way to ensure sustainability in industrial settings is to use the on-site power supply for electric boilers, considering cost as mentioned in the cost section, as well as environmental sustainability [26]**.** However, due to the lack of specific details in the literature, users can only get a basic idea about electric boilers from this prepared guideline.

3.6.12 Section 13 – Ash handling and disposal

The following section discusses ash handling methods, which are generated as a waste product when burning wood and coal. It is important to collect and dispose of these ash quantities properly to minimize any negative impact on the environment, health, and safety. To achieve this, it is recommended to use safe disposal methods, such as agricultural and engineering activities [27] after obtaining proper approval from the Central Environmental Authority.

3.6.13 Section 14 - Air pollution control devices

The following section emphasizes the usage of air pollution control devices because the emissions like fly ash, particulate matter, dust are occurring when burning solid fuels. The available dust arresting devices and particulate matter removal efficiencies have been given to get the reader to select a proper system for the industry as well to increase the awareness on the requirement of a dust arresting system if they use or select solid fuels as boiler energy sources.

3.6.14 Section 15 – Environmental regulations related to boiler fuels

In this section, the special regulations from the central environmental authority are provided according to the National Environmental Stationary Emission Control Regulations of Sri Lanka as gazetted.

3.6.15 Section 16 – Boiler maintenance

This section aims to provide an understanding of maintenance practices related to different types of fuels. Solid fuels, including biomass, coal, and processed waste, have been considered in one account due to their similar properties and outputs, such as ash generation. The maintenance tasks are outlined in the available literature and cover fuel transportation, storage, pre-processing, feeding, regular cleaning, and checks, as well as the control of emissions and byproducts. The maintenance practices for oil-fired boilers were taken into account, considering the output, including particulate matter and soot. The survey details were the source of information. For electric boilers, all maintenance tasks are less significant as they do not produce

ash, soot, or particulate matter [26]. The maintenance procedures for electric boilers are outlined in this guideline, as available in the literature.

3.6.16 Section 17 – Health and safety practices related to boiler fuels

Based on survey findings, health, and safety practices are suggested for laborers and workplaces, taking into consideration conditions such as the risk of exposure to particulate matter, ash and dust, burning issues, the risk of spillage and contamination of the body, fire risk, and physical injuries such as contact with moving parts during fuel handling. The survey findings were used to develop common health and safety practices for laborers and workplaces.

3.6.17 Section 18 – Record keeping

This section emphasizes the fuel user's requirement of record-keeping for fuel operations. Since the beginning of fuel operations, it is important to keep records of the full procurement process to monitor the progress of fuel suppliers. Additionally, environmental test reports should be recorded to make informed decisions on fuel and supplier selection, as well as to identify any maintenance issues that may arise.

3.7 Practical Incidence of the Prepared Guideline

The prepared guidelines mainly focus on the operations of newly installed boilers. Some guidelines were tested through a survey to ensure that the literature findings are applicable in an industrial setting. According to the survey conducted at Seethawaka Export Processing Zone, 33 out of the 12 industries in the zone use boilers for various operations. The apparel, food processing, rubber production, and tea processing industrial categories were included in this study as boiler usage industries at SEPZ as **Error! Reference source not found.**. This is the particular reason for selecting SEPZ to carry out this study because the requirement for a boiler varies based on the industrial category. In various industries of SEPZ, different types of boiler fuels have been used as Figure . In the apparel sector, coal, heavy furnace oil, diesel, and biomass have been commonly used. The tea and rubber processing industries exclusively have used biomass, while the food processing industries have used heavy furnace oil. The apparel industry requires a large amount of heat for various operations such as dyeing, washing, and fabric chemical reactions [28]. Because of the high heat requirements, more than one boiler and fuel have been used in the industry, such as furnace oil/biomass or coal/biomass. Therefore, variations in fuel usage could be observed in the apparel industry.

When analyzing the biomass fuel used by industries, it was found that 50% of them use rubber as their primary source of boiler fuel. In response to a survey conducted among industrial stakeholders, 37% reported using mixed wood, but they were not fully aware of the specific wood species used in their boilers. Additionally, 13% of respondents reported using *Azadirachta indica*, *Mangifera indica,* and *Tectona grandis* as their received wood species. As well as they have also revealed that the usage of the unknown mix of wood has been caused by receiving low heat outputs from their boilers. The different types of wood mixtures can

be the reason for their problem because wood species to wood species calorific value is changed [28] and they have not tested their wood mixtures which feed to the boiler.

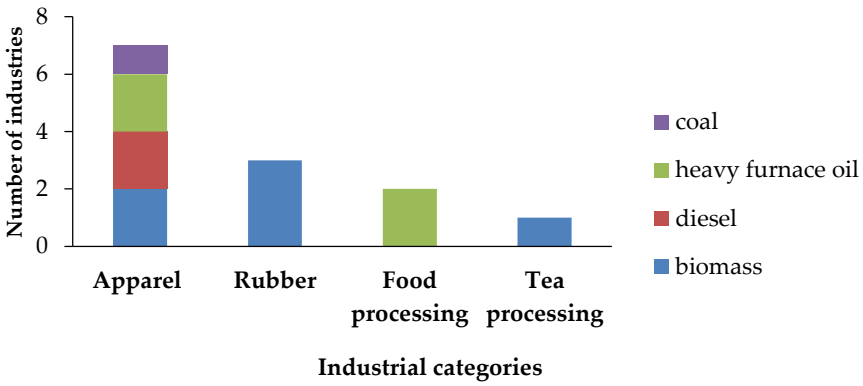

Figure 3. Variation of boiler fuel usage by industries at SEPZ

According to their fuel-feeding methods, biomass has been fed as chips and wood logs respectively 67% and 33% of industries. In there, would chip-used industries have higher capacities of boilers as well as they have used more than one boiler**.** Wood chips are efficient for them because to usage of wood chips has advantages such as having higher surface area and controllability, making combustion more efficient. Also, wood chips are continuously fed and then automated mechanisms compared to conventional wood logs feeding for high-capacity boilers [29]**.** But considering log wood used industries, they had one boiler with a small capacity. Then it is easy to feed the logs manually to small-capacity boilers according to the industrial activities. Also, all industries have maintained biomass storage yards to avoid wetting losses and have used chipping machines as a preprocessing step for their biomass fuel handling practices.

In the biomass supply chain, private suppliers and own plantations have been used as the source of supply. Out of three rubber industries, two of them have utilized rubber woods from their plantations as the energy source. This approach can be considered as sustainable as they continuously maintain their plantations for their production needs. Other industries that use biomass have already made agreements with private suppliers. The major issues related to boiler fuels include contamination of biomass with metals, low calorific values due to the use of mixtures of biomass, and the release of CO and CO_2 due to incomplete burning of the biomass. Only three responses were received related to the issues of using biomass as boiler fuel.

The prepared guideline was followed to evaluate the usage of oil as a fuel for industrial boilers and the fuel storage conditions and potential issues associated with oil as a boiler fuel. Also, it was gathered a few inputs from the industries relevant to oil. Based on their Environmental Protection Guidelines, they have stored oil fuels (Heavy furnace oil -HFO) in a primary tank and implemented secondary containment measures to prevent spills and other related issues. They have also mentioned some concerns regarding oil emissions, such as receiving black smoke, as well as the price escalation of the country. Only a single industry has relied on coal-used boilers. According to the guideline criteria, they check the quality of coal before purchasing the coal to avoid environmental issues. However, their main challenge is fluctuating calorific

values due to variations in imported coal lots. As a pre-processing step, they practiced the sizing of coal to ensure efficient combustion, with a size of 3-4 mm being optimal.

According to the survey, the industries that use biomass boilers dispose of their ashes by sending them to registered fertilizer producers approved by the Central Environmental Authority. The ashes produced by coal are also safely disposed of. Fly ash is used for compost production, and bottom ash is sent to the INSEE Eco Cycle under scheduled waste management. Also under the air pollution control mechanisms of the guideline, in the SEPZ, industries have used various mechanisms to control air pollution, such as cyclones, wet scrubbers, and multi-cyclones. They have also obtained environmental protection licenses indicating their compliance with air quality regulations and tested air emissions. For health and safety practices, industries are responsible for maintaining health and safety through various measures. This has been done by properly maintaining health and safety practices and regularly monitoring and maintaining their boilers. To ensure proper record-keeping, industries have maintained records related to air quality testing and boiler maintenance practices. These records have been managed by the industry's management.

Conclusion

In this study, the prepared guideline consisted of major boiler fuels including biomass, coal, oil as diesel, kerosene, heavy furnace oil, processed waste as fabric waste, and electricity as a boiler energy source. Hence, by referring to the guidelines, the investors can have a basic understanding of each boiler fuel and can select the required boiler fuel considering sustainable approaches, including environmental, social, and economic aspects. As well as this guideline also helps to raise awareness related to each boiler fuel by implementing the management guideline in the industrial environment management sector due to the guideline covers the major criteria including fuel quality, maintenance practices, environmental regulations, issues related to fuels, fuel handling requirements, and environmental protection practices.

According to the survey implemented at SEPZ to check the practical incidence of the guideline, as an industrial zone, industries of SEPZ meet the requirements of the prepared guidelines by contributing to social sustainability through safety practices, availability of permits, and compliance with environmental regulations. Also, they have achieved environmental sustainability by contributing to 49% of industries using biomass as boiler fuels, proper fuel storage conditions, complying with environmental regulations, safe ash disposal, using dust arresting systems, and boiler maintenance. They have attained economic sustainability through these actions including boiler maintenance, safety practices, planned actions to mitigate environmental issues using dust arresting systems, complying with environmental regulations, and usage of biomass by most industries.

Overall, this study emphasized biomass as a sustainable source for industrial zones relating to the maintenance of a sustainable supply chain as own plantations, and usage of proper biomass mixtures incorporating the prepared guideline. By increasing awareness and encouraging the adoption of the developed guidelines, industries can continue to improve their environmental, social, and economic performance. Ultimately, the development of this guideline provides a crucial step toward achieving long-term sustainability in the industrial environment management sector.

Recommendations

It is recommended that the use of biomass as a sustainable source for industrial zones by maintaining a sustainable supply chain as own plantations, usage of proper biomass mixtures including other sustainable practices as per the prepared guideline.

Conflicts of Interest

There is no conflict of interest regarding the publication of this article.

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