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Project Report

Alternative Fuels Substitution in Cement Industries for Improved Energy Efficiency and Sustainability

Essossinam Beguedou [1,*], Satyanarayana Narra [1], Ekua Afrakoma Armoo [1], Komi Agboka [2] and Mani Kongnine Damgou [3]

[1] Department of Waste and Resource Management, University of Rostock, 18059 Rostock, Germany
[2] West African Service Center for Climate Change and Adaptive Land Use (WASCAL), University of Lomé, Lomé 01BP1515, Togo
[3] Department of Physics, University of Lomé, Lomé 01BP1515, Togo
* Correspondence: essossinam.beguedou85@gmail.com or essossinam.beguedou@uni-rostock.de; Tel.: +228-99582652

Abstract: The conventional energy source in cement industries is fossil fuels, mainly coal, which has a high environmental footprint. On average, energy expenditures account for 40% of the overall production costs per ton of cement. Reducing both the environmental impact and economic expenditure involves incorporating alternative energy sources (fuels) such as biomass, solid-derived fuel (SDF), refuse-derived fuel (RDF) etc. However, within cement plants, the substitution of conventional fossil fuels with alternative fuels poses several challenges due to the difficulty in incorporating additional fuel-saving techniques. Typically, an additional 3000 MJ of electricity per ton of clinker is required. One of the most effective solutions to this is thermal optimization through co-processing and pre-processing, which makes it possible to implement additional fossil-fuel-saving techniques. In developing nations such as Togo, waste-management systems rely on co-processing in cement factories through a waste-to-energy relationship. Also, there are some old cement plants with low-efficiency, multi-stage preheaters without pre-calciners, reciprocating huge coolers, low-efficiency motors etc., which still operate and need to be made environmentally sustainable. However, compared to modern kilns which can have up to 95% of energy recovery from waste, an old suspension preheater kiln can recover only up to 60% of its heat energy depending on the cooler type, and due to the lack of a bypass and combustion chamber (pre-calciner). This research paper evaluated the performance of a cement plant incorporating AF and presents the procedures and recommendations to optimize AF substitution in cement plants. To achieve this, a comparative performance study was carried out by assessing the alternative fuel characteristics and the equipment performance before and after the incorporation of the alternative fuel. Data were collected on the optimum substitution ratio, pre-processing and co-processing performance, raw-meal design and economic analysis. Results indicated that the cost to be covered per ton of waste input is €10.9 for solid-derived fuel (SDF), €15 for refuse-derived fuel (RDF), and that the co-processing cost optimization for the cement plant could have a cost saving of up to 7.81€/GJ. In conclusion, it is recommended that appropriate kiln and alternative-fuel models be created for forecasting production based on various AF.

Keywords: alternative fuel; refuse-derived fuel; tire-derived fuel; solid-derived fuel; Togo; cement plant; waste to energy; energy substitution; sustainability; cement kiln

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1. Introduction

In cement manufacturing, the conventional clinker burning process involves a four-stage suspension preheater system. However, such systems have a relatively poor thermal efficiency of about 50%. The enthalpy of the kiln's exhaust gases is the biggest loss accounting for more than 50% of all thermal losses. Both thermal efficiency (heat transfer from the burning process in a rotary kiln and pre-calciner to the raw material) and dedusting effectiveness (effectiveness of the separation of particles with gas) are largely dependent on the design and quantity of cyclones located in the preheater tower [1]. Such systems can be effectively modernized by incorporating improved designs rather than discarding and installing entirely new systems. The common ways of modernizing involves incorporating a decarbonizing system (pre-calciner) or additional stage(s) or both. By modernizing the suspension preheater with pre-calciner and including more stages, the thermal efficiency of the burning process is increased [2].

Incorporating additional stages, for instance, requires extra cyclone stages which in turn has a lower hydraulic resistance and higher raw meal dedusting effectiveness and ultimately, a higher fuel efficiency [2,3]. Typically, adding a fifth stage requires an innovative cyclone design which results in a pressure drop in the suspension preheater from 6.45 kPa to 6.1 kPa, reduction in heat consumption by around 200 kJ/kg kl, a 6% increase in electrical energy demand and 0.06 kWh/ton reduction in energy use [2]. The Austrian A-TEC Company's Hurricane technology is a prime illustration of this [4]. Also, increasing the number of stages from four to six results in an average heat consumption reduction of roughly 200 kJ/kg kl, which equals a one-leap level of energy consumption of 2930 kJ/kg kl [2,5].

Another modernization method is the substitution of conventional fossil fuels (such as furnace oil, coal, and petcock) with alternative fuels (AF); mainly biomass or processed waste materials such as sewage sludge, MSW (municipal solid waste), refuse-derived fuels (RDF), tire-derived fuel (TDF), plastic-derived fuel (PDF), biomass-derived fuel. Rising energy costs and environmental regulations have increased the interest of cement producers all over the world to assess the feasibility of AF substitution [6]. The primary advantages of using AF in cement kilns include improved energy recovery and conservation of non-renewable fossil fuels, which in turn, translates into an immediate reduction in greenhouse gas emissions related to not only the mining and utilization of conventional fuels but also helps the cement industry to dispel its reputation as one of the most polluting and CO_2-emitting industries. A decrease in cement manufacturing costs is anticipated [7]. Also, an added advantage is that the cement kiln's high temperature of >1500 °C, extended residence durations of up to 10 s, and extreme turbulence, guarantees that all organic components in the waste materials are destroyed [8].

However, system optimization during substitution is of great importance. An understanding of the energy efficiency response of the system to a particular AF or the substitution ratio is required to optimize the system. Also, due to the complexity of the Alkali-Sulphur ratio circumstances within the suspension preheater and many physical and chemical processes, it is required to individually examine each case or utilize a variety of approaches, followed by a verification of the characterization results of AF [9]. More recent studies on fuel substitution focus on improving the flow and heat transfer problems [10]. Increasing access to ever-more-efficient computational hardware and software is increasing the substitution optimization of AF.

To substitute fossil fuel with AF, the AF must first undergo pre-processing which involves reducing moisture and the particle size to increase the Lower Heating Value (LHV) during firing. An efficient pre-processing result in an improved co-processing. This is because during the clinker manufacturing process, there is constant heat exchange between the hot gases and the raw material at each stage inside the cyclone of the preheater. It is therefore possible to balance heat transmission relationship between the gas and raw material. A similar relationship occurs between pre-processing and co-processing of AF.

The EU Waste Incineration Directive in particular sets minimum standards for AF using industrial operations [11]. For instance, to ensure proper combustion, the recommended minimum process temperature and time at the start of co-processing with AF must be greater than 850 °C; at a time greater than two seconds which positions the injection point within the zone of calcination in the preheater. The process specification also determines most appropriate particle size of the AF. For instance, the calciner's design and retention period may permit coarser material than the main burner requires. Generally, large particles work best in the calciner burner whereas small particles work best in the main burner. In relation to the gas velocity and the surface of the AF, there is a force elevating the AF within the calciner on one side and a force allowing it to descend through the calciner to the intake chamber on the other. Due to this, smaller, heavier AF fragments fall into the inlet chamber while larger, lighter fragments follow the gas [12]. The detrimental effect of AF substitution on clinker production often increases as the moisture content of AF increases. An Induced Draft (ID) fan and pre-heater must be used to move the water vapor volume. The ID fan's capacity is frequently a constraint. In addition, high moisture content in the AF will cause the flame temperature to decrease. Each fuel also has a unique requirement for combustion air or oxygen [13].

Another major challenge of AF substitution is the wide variation in characteristics of the fuel, even from the same vendor. AF is frequently given by several vendors, and even when all the terms of the contracts are fulfilled and consistent controls are in place, the characteristics vary greatly, and the material is not uniform. To compensate the differences in the AF dosing, standard fossil fuels or a steady stream of other AF, such as waste oil or solvents, can be employed as fine-tuning fuel [14].

Previous studies have assessed the factors that contribute to low interest of co-processing in cement plants, as well as national and regional legislation, economic viability, industry perspective, and business models [15]. For instance, in Algeria, one of the strategies identified to properly manage MSW with subsequent environmental and general public health protection is the conversion to RDF. The RDF can then be utilized as an substitute fuel, saving 4347.7 tons of natural gas and 0.3 Mt of CO_2 emissions, with a net gas cost savings of 65 USD [16].

For the co-processing of AF, systematic frameworks, and best practices must be devised to reduce investment risks and guarantee maximum operational dependability. One of the pioneers in the co-processing of AF, "DI MATTEO" established a strong foundation for practically every application scenario and particular bulk material [17]. The subject of development of more efficient new technologies that save and recover energy while also increasing productivity, reliability, and efficiency has increased because of the recent scarcity of energy supplies.

The goal of this study is to present the major issues to consider when a plant is planning to undertake AF substitution. Also, the study presents preliminary results on a case study of AF-fuel substitution in a cement kiln in Togo focusing on plant performance and economic analysis. As with other developing countries, Togo has gained a range of experiences with co-processing during the past years, the majority of which have been advantageous. The corporate and policy communities have already largely embraced this Waste to Energy technology in the cement industry. Even though its application is presently primarily focused on specialized municipal solid waste and agricultural waste, there are a few successful examples of its use for the non-recyclable fraction of municipal solid waste.

Although cement kiln technologies do not change significantly across geographical contexts, the nature, and characteristics (source) of AF varies with geographical context thus its impact on system efficiency and performance is expected to change. The study is expected to have impact on the cement manufacturing process across Africa and most of the developing world where AF characteristics may be similar. Also, globally, this review and case study provides a clear direction on the various technical considerations to make during AF substitution to achieve high system optimization.

2. Technical Considerations for AF Substitution in Cement Plants

Cement manufacture demands advanced equipment, a full knowledge of the operational principles of the plant, comprehensive approach, and other factors. This section, which is based on other research studies, will describe key technical considerations including handling, sourcing, pre-processing, co-processing and cost saving estimation.

2.1. Procurement and Supply of AF

To ensure that good quality AF is supplied and available for use, it is necessary to carefully design a robust supply chain from source of production to the cement plant.

2.1.1. Supply Management

The supply chain cannot exist without transportation, which plays a crucial element in the distribution of goods. When the ratio of "the cost of transportation" to "the value of commodities", such as cement manufacturing, is substantial, this role is underlined. In recent years, green cement industries have emerged as one of the world's major cement production hubs. However, due to the inadequate structure of the transportation fleet and its independent activity, transportation presents the biggest barrier in the distribution and reception of cement composed products [18]. The following are recommended: Organization of traffic on site, avoidance of mixing with other logistics, such as cement, coal and maintenance work on site and provide parking area for trucks [19]. This action allocates weekly requests to the transportation fleet while considering the relationship between the number of active vehicles and the cement company. Additionally, it improves the effectiveness of the transportation fleet and works to reduce response times. The two other condition-based actions, "no limits on distinct routes of trucks" and "single-route model for trucks", are compared to this [20].

2.1.2. Storage

Two approaches can be used: No storage and short storage [10]. Prolonged storage must be avoided due to the possibility of decomposition of organic based AF with high moisture content causing unsightly conditions with odours, disease transmitting insects and rodents [20].

i. No storage approach—This is the most preferred option because it is less costly requiring less storage facilities. AF is delivered just in time, based on a specific demand of the plant. However, some storage space may be made available on-site or by the supplier for periods of planned/unplanned plant shut down.
ii. Short Storage—This approach requires delivery five days a week during daytime and storage during the weekend (two days with an additional one day for contingency).

AF supply requires a highly efficient and organized system to avoid shortages. The following precautionary measures are important [12]:

- Supply contracts must specify time slots for various suppliers where more than one supplier is used, to avoid long waiting times
- Communication with suppliers is important and appropriate lines of communication must be established
- AF stocks must be maintained at required levels. Predictions must be based on the plant's demand pattern
- Contingency storage spaces must be planned together with the supplier for planned shut downs such as maintenance or unplanned breakdowns for repair.

All vehicles must pass through the weighing bridge.

The storage size depends on the safety margin you need between your supplies and your consumption. Storage can be created under ground floor or above ground floor. There is a preference for storage halls if the amount to be stored is getting too big. For example, Table 1; represents 90% substitution for 3 days storage capacity which equals 6.885 m^3. The density of RDF is 0.1, the kiln capacity 3000 t/day with specific heat consumption of 3.4 Gj/tclker. The AF-Fuel demand is 16 h per day with trucks number of 2 trucks per hours. The needed crane capacity 6.4 t/week for handle amount of 1.2 to 3.1 t/week, the operation time 80 h/week of receiving material. Kiln fuels are all fuels used in and for the clinker production process, The kiln specific fuel consumption (GJ/tClinker) is the energies need to process one ton of clinker which is 3.4 in project design. The total heat demand (GJ/day or GJ/h) is the amount of heat energy that would need to be added to maintain the temperature in an acceptable range for clinker production in pyro-system. The alternative fuel demand (AF-demand) is capacity of alternative fuel can be available in the plant (GJ/hAF or t/hAF). The volume not compacted is storage spaces of material with low density, from 0.1 to 0.2, the unit of AF-Density not compacted is t/m^3.

The design principles and optimizations of the storage and query engine created as part of the Advanced Knowledge Technologies project, enables the effective management of enormous alternative fuel knowledge bases [21].

Table 1. RDF storage conception.

No.	Item	Unit	Starter Kit	Starter Kit	Mid-Size	Mid-Size	Crane Hall	Crane Hall
			1 Docking Station	**2 Docking Station**	**2 Boxes**	**4 Boxes**	**Without Possibility of Direct Feed**	**Without Possibility of Direct Feed**
1	Basic data							
2	AF-Material		RDF	RDF	RDF	RDF	RDF	RDF
3	AF-Density	t/m^3	0.1	0.1	0.1	0.1	0.1	0.1
4	AF-Heat value	GJ/t AF	20	20	20	20	20	20
5	AF-Substitution Rate	%	90	90	90	90	90	90
6	Kiln Capacity	t/day	3000	3000	3000	3000	3000	3000
7	kiln specific fuel consumption	GJ/clinker	3.4	3.4	3.4	3.4	3.4	3.4
8	kiln total Heat demand	GJ/day	10,200	10,200	10,200	10,200	10,200	10,200
9	kiln total Heat demand	GJ/h	425	425	425	425	425	425
10	AF-demand	GJ/h AF	383	383	383	383	383	383
11	AF-demand	t/h AF	19.1	19.1	19.1	19.1	19.1	19.1
12	Logistic							
13	Truck size	m^3	100	100	100	100	100	100
	AF-Density, not compacted	t/m^3	0.2	0.2	0.2	0.2	0.2	0.2
14	AF-Material per truck	t	20	20	20	20	20	20
15	AF-delivery days/week	days	5	5	5	5	5	5
16	AF-delivery hours/day	h/days	16	16	16	16	16	16
17	AF-demand per week	h/week	3.213	3.213	3.213	3.213	3.213	3.213
18	Amount of trucks	trucks/h	2.01	2.01	2.01	2.01	2.01	2.01
19	Storage size							
20	Volume	m^3	100	200	1000	2000	5000	5000
21	Volume, not compacted	t	10	20	100	200	500	500
22	Storage size/truck size		1	2	10	20	50	50
23	Storage size	h	0.5	1	5.2	10.5	26.1	26.1
24	Storage demand for weekend	days	3	3	3	3	3	3
25	Storage demand size	t	1.377	1.378	1.379	1.380	1.381	1.382
26	Storage demand size, compacteg	m^3	6.885	6.886	6.887	6.888	6.889	6.890
	Crane capacity							
28	Receiving material time	h/week					80	80
29	AF-diret feed to kiln	day/week					0	4
30	AF-diret feed to kiln	h/week					0	64
31	AF-diret feed to kiln	h/week					0	1.224
32	AF-amount transported to storage	t/week					3.213	1.989
33	AF-amount back from storage	t/week					3.213	1.989
34	AF-total amount handled by crane	t/week					3.2 f13	1.989
35	cran capacity	t/week					6.426	3.978
36	AF-delivery days/week	t/hAF					38.3	23.7

The first type of storage is the overhead crane hall. This type of storage is suitable for large capacities. An automatic crane in a storage hall can take-in the material from a pit. The capacity of the pit shall be big enough to receive minimum one truck, including the dead edges. A clamp shell grab is therefore the preferred solution compared to an orange-peel type of grab. During unloading of the truck, the crane may not move above the pit for safety reasons. The capacity of the crane shall be enough to complete the following activities in relation to the materials: intake, storing, extraction to the dosing unit and the possibility of mixing different materials stored in hall areas. The automatic crane should be able to feed directly from the truck unloading point to the inn in case of a crane failure or maintenance, and the crane software should be designed to limit the self-heating or ignition effect of AF [22].

The second type is the top loader re-claimer system. This type of storage is suitable for medium storage capacities and has an open drag chain, supported by winches, to cover the whole height of the box. It is "first-in, last-out" and gives the opportunity to mix and homogenize the input of up to 10 trucks and to empty and clear the boxes completely. Conveying to dosing unit is with screw conveyors, drag chains or belt conveyors. A minimum two boxes are required to have a constant feed, and different boxes can have different alternatives fuels which adds more mixing possibilities. With increased storage heights the risk of not detecting a fire in time also rises. There is the need to check the local country safety rules for the maximum possible storage height [23].

Another type is the live bottom system. This system is suitable for small storage capacities or for material reception. The sliding frame is installed on a floor. There can be a washing-out-effect of the concrete floor below the live bottom. The frame is split in several sections depending on the width of the floor. Each section can move independently. The drive is hydraulic. As a reception from a truck the frame can be installed in a pit, which involves high civil costs [24]. The sliding floor pit can serve as storage depending on the required storage volume. If the requested volume is high, one can use the sliding floor in a pit as reception hopper and convey the material to the main storage above ground level. The height on top of the sliding frame shall be limited to about 2 to 3 times the width. The hydraulic cylinders are in the room next to the sliding frames. A good seal is required between the two rooms. A hydraulic drive is preferred and oil reservoir above ground level in a separate building to limit the risk of fire. If a walking floor is used there could be some material leakage to the level below [25].

A further option is the storage of AF in silos and extraction via a rotating screw conveyor. It must be considered that silos can have extraction problems, bridging, blockages and wrapping up of foils or tapes around the screw. Therefore, the selection of this solution must be done very carefully, and material tests and extraction calculations must be done [26].

One of the major issues to consider during storage is ventilation. AF materials have some fines and dust, which can lead to low visibility in the storage hall and disposal of fine dust on floors, structures, equipment etc. In addition, the water content can, combined with higher temperature, lead to water vaporing in the hall. The fine dust gets sticky. The equipment and steel structures start corroding. Be aware that this sticky dust can as well cover fire detection devices and cameras. The smell can be a problem if the plant is in an urban environment but as well for the employees [27]. To overcome these problems, it is proposed to extract the vapor including the fine dust from the top of the storage and to convey the gas to the suction of the clinker cooler fan, in case of satellite coolers to the clinker drop out cover of the satellite cooler [28]. The air flow rate and the required extraction fan capacity shall be adapted to the individual situation. Duct work can be made from light, galvanized steel plates, e.g., for air-conditioning proposes. The gas speed to be high enough to avoid dust settlement in the duct [29].

De-dusting a complete hall e.g., is not feasible. In case the AF have a high number of fine particles, de-dusting can be installed at places where there is a high dust concentration, e.g., at transfer points, screens, or material reception stations. Filter bags with PTFE (polytetrafluoroethylene) coating are preferred [30]. Inserted filters, having vertical walls, can be installed on top of the dust source. The captured dust material will then be returned in the material flow after the dust extraction point to avoid dust cycles. The air speed shall be low which is achievable with short filter bags. The distance between the filter bags shall be large enough, to avoid blockages. Short bags will also reduce the need for (expensive) tall buildings. Since the dust concentration in the filter is high, dust explosion risks shall be considered [31]. Therefore, the design should be done shock resistant or with pressure relief e.g., by installing burst discs. The outlet of the burst discs shall be outside the building. Classical de-dusting, with pipework to several de-dusting points and a dust receiving hopper under the filter shall be avoided. Blockages are likely to happen [32].

2.1.3. Conveying

Generally, for conveying AF, several kinds of mechanical transport systems are possible. The loads are relatively low, and the wear rate is moderate, if the input of impurities is under control [33]. There are various types of conveyors:

Screw conveyor: They can be classical from the design. Intermediate bearings are not allowed. Double screws in parallel will give reliable results against blockages. One screw turns clockwise and the other counterclockwise. At the point of discharge, the cross section of the screw must be reduced to the shaft size, to give space for the AF to drop out of the casing. A Screw conveyor without center tube is possible, but the wear on the bottom of the screw housing will be too high for 24 h/day operations and is thus not recommended. Advantage is a closed conveying without spillage. There is a certain risk that AF can include long foils or tapes wraps around the screw [34].

Drag chain conveyors: Classical drag chains can convey the AF materials in a closed way without spillage and are feasible even for high inclined transportation. Noise could be an issue if the chain conveyor is empty, and the chain is sliding above the chain conveyor bottom, or the chain tensioning system is not properly adjusted. Forged chains and roller chains are in use. There is a risk of wear of the chains and conveyor bottom, and the energy demand is higher than belt conveyors [34].

Open belt conveyor: In principle open conveying is possible, but due to the low weight of the AF, spillage is likely to happen. A simple cover cannot prevent the impact of wind on the AF [34]. In general, it is not recommended to open transport because of the environmental impact. The only advantage is the low cost for investment, but there are high costs for site-cleaning efforts (CAPEX vs. OPEX) [35].

Enclosed belt conveyor: This type of belt known as SICON conveyor or Pipe conveyor is suitable in case the AF must be transported over a long distance, which is too long and therefore economically not possible with a drag chain. There is a particle-size limitation of the AF to be transported at the feeding point as the conveyor is fully closed. As a rule of thumb, the conveyor diameter should be a minimum of three times the maximum size of the AF's material [23]. Damage (cut in the length) to the enclosed belt conveyor leads to a very costly breakdown of the entire installation. Another disadvantage can be that a curved pipe conveyor can start rolling between the supporting rollers and the opening can come to the bottom [34].

2.2. AF Characterisation

In cement plants, material characterization is a major activity. It is necessary to determine the physical and chemical properties of raw materials, fuels (including AF) and cement and the clinker ratio values to enhance process optimization and product quality assessment.

2.2.1. Physical Properties of the Material

The fibrous-flaky particle shape of AF has a negative effect on the flow properties if large forces, and therefore internal stresses, are impacting on the material. This means that high stresses and local stress concentration must be avoided when conveying the AF. Due to its nature, AF is difficult to extract from hoppers and silos. The walls of hoppers and chutes must be vertical and in the best case made of stainless steel. When the hopper extraction is from below, the storage height must not be more than one to two times the width whiles when the hopper extraction is from above the storage height must not be more than three times the width [36].

The particle sizes of AF on the market are sometimes larger than 60 mm. If using coarser AF materials, combustion chambers can be beneficial and should be considered during kiln-modernization projects or new kiln lines [12].

2.2.2. Chemical Properties

The presence of oxides in AF (municipal solid waste and agriculture waste) is a very critical quality parameter because it negatively affects co-processing and determines the quality of the AF itself. Analysis of the AF oxides (ZnO, Na_2O, K_2O SO_3 etc.) is done by sorting, crushing, pressing of the AF, and sintering to pellets) [37]. Various examples of the use of physical mixing and the application of co-precipitation to reduce the concentration of oxides was presented by [20]. Laboratory analyses must be carried out according to international standards (ISO 17025) or the internal guidance paper of the company [38,39].

2.2.3. Sampling

A study outlined processes to guarantee the quality of the finished products, including the quality control of the finished products, the in-process materials at all steps of the production and the various incoming materials. It also describes how to improve the sampling and testing plan by a systematic and regular review of its content [40].

Quality audits and experience have shown that numerous quality incidents are linked to a lack of control of laboratories' workloads or if the sampling and testing plan are driven by the currently available resources rather than the manufacturing needs, and also if there is a lack of control of incoming materials. An effective sampling and testing plan is critical to ensure that finished products meet customer needs, to reduce re-processing, lower production costs, and improve plant performance [12]. An effective sampling and testing plan focuses on control at early stages of the manufacturing process, including incoming materials and in-process materials. It is driven by manufacturing needs and not by existing resources or equipment. The lack of resources must not lead to reducing the scope of the sampling and testing plan [37].

Moreover, audits of plants have shown that there is no unique model or standard template of a sampling and testing plan, which must be implemented [20]. It is highly recommended to consider the testing of competitors' products for benchmarking. Collecting those samples must be organized by the local sales departments. As the sampling and testing plans are integral parts of the quality-management system, they must comply with the instructions in place and must bear batch number and effective date. The sampling and testing plan must include the following aspects and any additional information: material to be sampled and tested, sampling location or point, sample type, grab or composite, sampling frequency, defined time interval or material throughput, tests to be conducted or parameters to be determined.

It is advisable to complete the sampling and testing plan where needed, e.g., with additional indications such as: sample taker (operator if manually, or automatic sampler), quantity of each sample, test procedure or reference to the standard operation procedure (SOP), test operator (lab automation, lab technician, or e.g., mortar lab, chemical lab, external lab), testing frequency (if different from sampling frequency, e.g., monthly on average sample) and data collection and documentation [20]. Storage conditions of retained samples were also found in examples of sampling and testing plans collected in different plants, countries, and areas. Detailed plans provided by some plants, which are designated as quality-control plans rather than just sampling and testing plans, even included quality targets [37].

It must be emphasized that the sampling and testing plan is specific for each plant and must reflect the local situation, such as: fluctuation of all materials sampled and tested, plant equipment, process-control parameters and standards, permits, directives and laws. For instance, for EU countries, participation in the European Union's emission trading scheme obligates cement plants to monitor their carbon dioxide (CO_2) emissions and to disclose them in an annual emission report. Therefore, a specific sampling and testing plan for that purpose is required. Updates and reviews of the sampling and testing plan are carried out using the following recommended guideline headings [40]:

- For updates—new incoming material, new source, new finished product, new or modification of shop, new method, new or revised external standard and export of a product to a new country;
- For formal review at least once a year—inconsistency in analysis results, data analysis versus process targets, control-chart analysis and control-chart effectiveness.

Sampling methods can be manual or automatic and are generally used depending on the sampling location, the material and amount to be sampled, the assurance of sample representativeness, the local situation, the available budget, etc. The safety of manual sampling procedures must be ensured in all circumstances [37]. Sampling frequencies are partially regulated by standards like EN 196-7 (Methods of taking and preparing samples of cement), ASTM C183 (Standard Practice for Sampling) etc. They can also be fixed in local regulations and permits, or in specific agreements with customers. Sampling and testing are strongly influenced by limitations in laboratory resources or the availability of laboratory automation, which must be checked on a case-by-case basis in each plant [41]. Sampling bias is by far greater than analysis bias. Pierre GY, the world-renowned sampling specialist, stated: "On the primary sampling, bias can be up to 1.0% and up to 50% on the secondary sampling (when required), whereas they never exceed 0.1 to 1% in analysis" [42]. As a rule of thumb, sampling error, error in sample preparation and error in measurements/instruments must be approximately 80%, 15% and 5%, respectively [20].

Poor sampling can lead to substandard batches of material being accepted or sorted out, invalid decisions being made about raw materials, and potential impacts on public health and productivity [43]. In order to obtain a representative sample, the objective of the sampling must first be defined and whether it is used for process control or product-quality control. For instance, in some situations, grain fine size may give enough information for process control, while the chemical and mineralogical results may deviate from a representative sample of the real grain-size distribution. A good example regarding the minimum mass to be taken for each primary sample is given in the ISO Standard 8656 "Refractory products—Sampling of raw materials and unshaped products" [20].

Grab samples must be taken and mixed to form a composite sample, which can be stored as a retained sample or reduced to a laboratory sample [44]. The reduction of mass is obtained by succession of fragmentation and split techniques. For large particle size AF products, the mass of the elementary sample can be decreased if the particle size is reduced. For example, while sampling AF up to 50 mm granule size, the mass of the elementary sample can be reduced from 5 kg to 200 g after crushing the clinker down to 5 mm (Table 2). The described procedure applies also to representative sampling from continuous material flow, for example, at the discharge of a belt conveyor, in a vertical chute or in an air slide. The mass of each elementary sample must be determined as well as the number of elementary samples to be taken over a defined period. In the case of powders, if the total mass of samples collected is too high, it can be reduced after homogenization by division. In the case of a coarse material, it can be reduced after particle-size reduction and then homogenization and division [45].

Table 2. Representative Sampling of AF.

Minimum Particle Size (95%)	Minimum Mass of Each Elementary Sample
>100 mm	30 kg
100 mm	15 kg
50 mm	5 kg
20 mm	2 kg
10 mm	500 g
5 mm	200 g
1 mm	50 g

As a general rule, the more uniform the production, the lower the standard deviation and the lower the number of necessary samples [40]. An adequate frequency of sampling is required for effective product quality and process control. Sampling at a too-large interval might lead to non-representative sampling or undetected deviation of quality. Sampling at a short interval is unnecessary during normal or stable operations, but a temporary higher frequency is justified in the case of quality deviation to re-establish normal operation as quickly as possible. The frequency can be fixed as a time interval, e.g., hourly, or in defined material throughput, e.g., each 5 to 10 tons of alternative production or consumption. The frequency must be adjusted, taking into consideration the following [46]: homogeneity/heterogeneity of the material is less frequent with increasing homogeneity, mass flow is less frequent with decreasing mass flow and dead time and response time of controllers (Ziegler-Nichols tuning rules).

The sampling location or point must be chosen appropriately to obtain the most representative sample of the full material stream, including any dust return from dust extraction systems. The locations of sampling points are to be selected in such a way to ensure easy and safe accessibility for manual sampling as well as for maintenance of automatic samplers [47]. The essential sampling locations refer to raw meal, kiln feed, clinker, AF, and cement. Typical sampling points include: raw materials, the raw mix of fuels, before stockpiling, before the raw mill and kiln as well as the sampling at reception. Other points include supplied materials and AF for raw mix preparation, supplied constituents for cement production and fuels for the burning process [46].

Sampling at the bulk clinker, alternative fuel silo, and cement dispatch points (silo outlets) or of bagged cement is often regulated by the cement and alternative fuel standards. Sampling at loading and during shipping of larger amounts of cement (batches) might also be conducted in agreement with customers. Sampling from a material flow or transport must be preferably carried out while cutting the complete flow of product for sample representativeness: at the discharge of a belt conveyor and also in a vertical chute [45]. Manual sampling from a belt may only be carried out on a stopped belt [48].

2.2.4. Dosing

Since every method has advantages and disadvantages, choosing the appropriate dosage apparatus is not an easy process. It is strongly advised to choose the appropriate equipment for each individual scenario after conducting thorough feasibility studies and considering lessons discovered from other research facilities. A crucial technical step for developing efficient and economical material feeding or mixing plants is the integration of efficient and accurate gravimetric dosing devices into conveyor lines for bulk material transportation. The bulk material transportation in the cement industry has up until now been metered using various dosing equipment [49]. However, since AF-dosing performance frequently suffers from volatile bulk material properties, a stable mechanical framework and an advanced controller architecture integration are required for the implementation process of an accurate gravimetric dosing device for transporting AF in cement plants (e.g., varying bulk density and humidity) [50].

Dosing equipment should be installed as close as is feasible to the burner (suspension preheater feeding point, calciner intake or main burner) to improve process control. This is especially necessary if the AF serve as the primary fuel for the formation of clinker. Due to the high levels of ambient air at these locations, melting of plastic in the conveying equipment must be prevented as this may produce obstructions [51]. A common dosing device can be added at the end of the conveying line to improve control precision.

Extraction from the dosing hopper can be done with either a live bottom towards a double screw, or a hopper with extraction screws over the full width and length of the floor or samson feeder. Special attention must be given if the AF are noticeably light and tends to bridge and does not flow out of the hopper. Solutions can be divergent walls and agitators in the hopper. The dosing can be done with weigh belt feeders, controlling the hopper extraction speed.

The dosing belt can be equipped with two weighing sections. The first should be located at the dosing-belt loading point. The signal gives the load on the belt. This signal can control the speed of the hopper extraction. The second load cell is located on the straight section after the first load cell. The signal gives the real load on the belt and will control the speed of the belt to have a correct gravimetric dosing. The dosing belt has some covers but cannot be considered as an enclosed dosing system (spillage problem). The dosing system is low cost and is suitable for a small AF feed [52]. The dosing belt e.g., can be installed directly after the AF walking floor receiving hopper. After the dosing belt, a mechanical or pneumatic transport system can be foreseen to the suspension preheater, calciner or main burner.

The hopper is equipped with an apron over the full width from 1500 mm up to 3000 mm. The apron is in an inclined position. The extraction layer thickness is controlled through the back rolling of material using a paddle drum that is spinning. Long foils have a propensity to encircle the paddle drum as it rotates. The whole thing is mounted on load cells. The load signal can be used as a control signal to deliver AF to the unit and for calibration. Make sure there is no mechanical connection between the building and the Doseahorse. Gravimetric dosing is ensured via an incorporated weighing part at the top of the machine. The Doseahorse, which performs both the hopper extraction and the weighing mechanism, is a drawback of this method. Additionally, there is a buildup of spillage inside the machine's casing beneath the belt conveyor [53].

A screw conveyor mounted on load cells is a recent innovation by Di Matteo. The screw conveyor section's casing is supported by load cells. The difference in load between the weight of the housing when it is empty and the weight of the housing when it is in use is measured. The screw's progress is measured in millimeters per second (m/s). The gravimetric dosing rate is calculated by multiplying both values. Low building height and no leakage are necessary. A tiny extraction hopper and discharge chute must be included with the unit [53].

Rotor weigh feeder (Pfister TRW-S/D): A calibration hopper is included with the dosing device of the DRW type. The entire apparatus is mounted on load cells. Before the material drops into the rotor, the open spiral in the pre-hopper moves the AF along the wall upward. Despite the heavy rotor, the mechanism achieves its precision. A hopper or silo must be used to feed the dosing unit [54].

Screw weigh feeder: On a single frame, the screw and hopper are mounted. Installed on load cells are the frame. Both calibration and a control signal for supplying AF to the dosage unit can be done using the signal. Load cells are contained on the screw conveyor. It is possible to measure the weight of the AF in the screw conveyor. Gravimetric dosing is accomplished by measuring the screw conveyor's speed. If the loose screw (new design) used in the Schenck MultiFlex for AF is fully filled, it offers good linear accuracy. A pressure-proof design is also available in some AF sustainable plants [55].

Burner suppliers having experience with combustion of AF include: Pillard Rotaflam, Unitherm. M.A.S., Greco, FLS Duoflex, KHD Pyrojet, FCT, Rockteq, TKIS, Dynamis [56,57].

(a) General requirement for AF burning at the kiln:

The injection must be in the center or a jacket tube parallel to the center;

The pneumatic supply line in front of the burner must be straight and the dosing system installed as close as possible to the burner to prevent risk of frequent blockages;

Mechanical transport up to the burner platform is recommended;

In general, the conveying line velocity is typically between 25–40 m/s whiles load should be kept <4 kg fuel/kg air to prevent pulsations or even blockages;

The conveying air should be kept as low as possible, as it has a negative impact on the heat consumption.

(b) Preheater feeding requirement for:

Pneumatic feed.

- The conveying line velocities requirements are similar as for main burner but there should be larger margins for fuel load depending on distance between dosing system and injection point. The injection speed should be low e.g., 15 m/s to 20 m/s;
- There is no need to install a specific burner with primary air for flame shaping but conveying line connection to calciner must be made of high temperature resistant steel;
- In case of emergency, the fuel supply must be stopped immediately where as the blower still runs for a few seconds more, just to clean the pipe.

Gravity feed.

- Dosing system should be installed as close as possible to the feeding location at the calciner to increase reaction speed for fuel adjustments;
- A closed metal conveyor e.g., a screw or drag chain should be used to convey material to the feeding point which should allow for minimizing air leakages.

Air leakages.

- As the result of operating the calciner with under-pressure, it is expected that a certain amount of fresh air will enter the calciner;
- This air should be minimized as much as possible with a closed transport system. The connection to calciner should include a protective layer with refractory;
- Too much fresh air entering the calciner will reduce the thermal efficiency of the kiln process (it has a negative impact on the heat consumption).

Air sealing.

- A normal rotary air lock can be used if the particle size is < 40 mm. The number of compartments between and along the wall, should be at least 3 to achieve enough sealing;
- Double sliding gates are not suitable. This makes the leakage around the gate is too high. In an open position, the blade cools down which results in blade deformations;
- A double-pendulum valve is suitable for sealing (metal to metal contact). The flaps are in constant temperature and no leakage to the outside;
- Depending on the AF feed rate the design can be a flap 90° or two flaps under 45° with the advantage that the weight per flap is only the half and more cycles per minute are possible.

Over pressure in calciner (in an emergency case).

- Temperature and pressure sensors should be installed on the duct connecting to the calciner to detect and prevent hot-gas back flow;
- Pneumatic cylinders can close the double flap at any time if a compressed air buffer at a local pressure vessel is installed;
- A fan can start on emergency power to provide sealing air between the flaps. No heat can ignite any AF in the feeding line;
- Raw meal can be injected in the screw conveyor and seal off the feed.

The sulfur-alkalis ratio in clinker should be within 0.8–1.2 (ideally 0.9–1.1). The same ranges are applicable if the alkalis-sulfur ratio is calculated from [58].

$$\frac{S}{A} = 100 * \left(\frac{\frac{SO3}{80}}{\left(\frac{K2O}{94}\right) + \left(\frac{Na2o}{62}\right) - \left(\frac{Cl}{71}\right)} \right) \quad (1)$$

Equation (1): Sulfur and alkalis calculation formula.

A kiln's heat variation can provide a wealth of information on the system's thermal performance. Based on the straightforward axiom that input equals output, heat variation indicates where or how fuel heat is utilized. Unnecessary energy losses are simple to identify, and the concept of heat variation is simple to apply to other systems including preheaters, coolers, and drying systems. As a result, the application of this study to systems other than cement kilns is possible [59]. Tables 3 and 4 are examples of calculations for one- and two-fuel feeds.

Table 3. Heat input variation calculation for one-fuel feed.

Fuel Name:	Unit	Average	Min	Max	St-Dev	Coeff. of Variance
Fuel 1	kg/h	1700	1680	1732	20.0	1.18%
Fuel 1	GJ/t	28.5	27.86	29.12	0.5	1.75%
Heat input variation	GJ/h	48.45			1.18 × 1.75 =	2.06%

Table 4. Heat input variation calculation for two-fuel feed.

Fuel Name:	Unit	Average	Min	Max	St-Dev	Coeff. of Variance
Fuel 2	kg/h	4300	4237	4375	70.0	1.63%
Fuel 2	GJ/t	21.5	20.42	23.2	1.3	6.05%
Heat input variation	GJ/h	92.45			1.63 × 6.05 =	9.84%
Overall heat input variation	(48.45 × 2.06 + 92.45 × 9.84)/(48.45 + 92.45) =					7.17%

2.2.5. Characterization Equipment

For on-site cement and fuel quality analysis in cement plants, one of the most important pieces of equipment is a laboratory laser-induced breakdown spectroscopy (LIBS) apparatus that primarily consists of a sealed optical module and an analysis chamber [60]. The LIBS apparatus, the sealed optical path, the temperature-controlled spectrometer, the sample holder, the appropriate calibration model built for minimizing the matrix effects, and a correction approach suggested for getting around the "drift" problem must all be given special attention [61]. The laboratory measurement results from the LIBS approach and those from the conventional method have been shown to be in good agreement. The stated absolute measurement errors for oxides analysis can vary from 0.5% to 0.2%, while those for ratio values can range from 0.04 to 0.05. The LIBS apparatus is ideal for use in cement factories since it can perform a reliable and precise composition and proximate analysis of AF and cement [62].

To set up an appropriate laboratory setup, the following sample preparation, physical and chemical analysis equipment and their uses are recommended (Table 5) [63]:

Table 5. Appropriate laboratory equipment and usage.

Equipment	Use
Sample Preparation	
Cutting Mill	cutting big size and wet materials for general analysis
Ultra-Centrifugal Mill	Cutting small size and dry materials for Carbon (C), Hydrogen (H) Azote (N) analysis
Pellet Press	Pelleting for Xray determinations
Pelleting press	Pelleting for calorific value determination
Microwave Digestion System	Sample decomposition for ICP OES spectroscopy determinations
Physical Analysis	
Halogen Moisture Analyzer and drying oven	Moisture content
Flash Point tester	Flash point
Bomb calorimeter	Calorific value
Mufle furnace	Ash and volatiles content
Chemical Analysis	
CHNS O Analyzer	Elemental Analysis C, H, N, S and O Energy Dispersive X Ray Fluorescence.
Spectrometer	ED-XRF Heavy Metals
High Performance Liquid Chromatograph	Ion-Chromatografy Anions: Cl^-, F^-, SO_4
Gas chromatograph	Gas Cromatography
Laboratory pH meter	Ph
ICP OES spectrometer	Heavy metals

There are various types of manual and auto-samplers available from different manufacturers. Even "home-made" samplers might be a reliable, cost-efficient, and economical solution, provided that the mandatory safety precautions are strictly followed Safety Procedures and Precautions. Choosing the correct sampling technique and the correct sampling point is essential to get a representative sample [64]. Most common samplers include screw sampler, spoon and scoop sampler, piston sampler, air slide slot sampler, different types of rotary samplers, e.g., Vezin sampler, linear crosscut sampler, beam sampler, hammer cross belt sampler [46]. The installation and the good working order of auto-samplers regarding self-cleaning to get a representative sample are crucial. Also, the expenditure for maintenance must be considered as a non-negligible point. The investment costs will highly depend on the configuration, with or without automatic transport of the sample to the laboratory. As previously mentioned, sampling frequencies are partially regulated by standards like regarding final products EN 196-7, ASTM C183, etc. They can also be fixed in local regulations and permits, e.g., for the use of AF, or in specific agreements with customers [45].

2.3. AF Co-Processing Installations and Feeding Point for Suspension Preheater Kiln

In cement plants, switching from conventional fossil fuels not only reduces CO_2 emissions but also enables the use of leftover materials such as municipal solid waste (MSW), which would otherwise need to be disposed of in some manner or another. Cement companies has recently begun testing the usage of refuse-derived Fuel (RDF), tire-derived fuel (TDF) made from MSW in place of fossil fuel [65]. A functional test must be gradually started with different feeding positions with different types of AF, by obtaining a maximum partial replacement of 60% of the needed energy with suspension kiln and up to 90% for a modern kiln with a low quality of AF. Monitoring surveys carried out before and after the AF deployment help to analyze the effects of the new process [66].

Due to its compliance with the current EU environmental rules, which include the reduction of CO_2 emissions and the energy valorization of municipal solid waste (MSW) and agricultural waste, refuse-derived Fuel (RDF), tire-derived fuel (TDF) and biofuels may prove to be an effective alternative to traditional fossil fuels. However, additional long-term environmental, social, and economic studies are required to confirm AF safety regarding dangers to human health and macro-economy development in communities [19].To ensure regulated combustion, co-processing requires reasonably homogeneous waste streams with set characteristics. Waste can be converted into refuse-derived fuel (RDF) by various pre-treatment procedures; the abbreviations AFR (alternative fuel and raw materials) and SRF (solid-recovery fuel) are also used. As an illustration of how municipal solid waste can be pre-processed to RDF, Table 4 shows the cost estimation of a mechanical biological treatment (MBT) facility in Togo [67].

The careful selection of feeding locations in the kiln system through operational control in accordance with unique waste characteristics and quantities are necessary for safe and responsible waste management. Smooth continuous kiln operation, product quality, or the site's environmental performance should not be adversely affected by its use (Figures 1 and 2) Therefore, it is necessary to provide stable waste quality and feed rates [68].

For the pre-processing of waste or the generation of RDF, TDF, SRF and biomass, Table 6 presents the investment costs needed for installation and the waste sourcing to the MBT plant. From this data it can be seen that TDF and biomass CAPEX are higher than the others. This is due to the sourcing cost of the tires (15.26 Euro/t) and biomass crops (12.52 Euro/t) from the communities, as delivery controls must be frequently performed in ordinary operations [69].

A strong focus on operational health and safety is required, as are regular communications with environmental regulators, the municipality, surrounding communities, and other stakeholders. Cement factories frequently belong to international organizations that can offer detailed information and subject-matter specialists for plant operations. It is advised to utilize refuse-derived fuel (RDF) that has the properties and composition that are clearly determined for co-processing pyro-system plants [70].

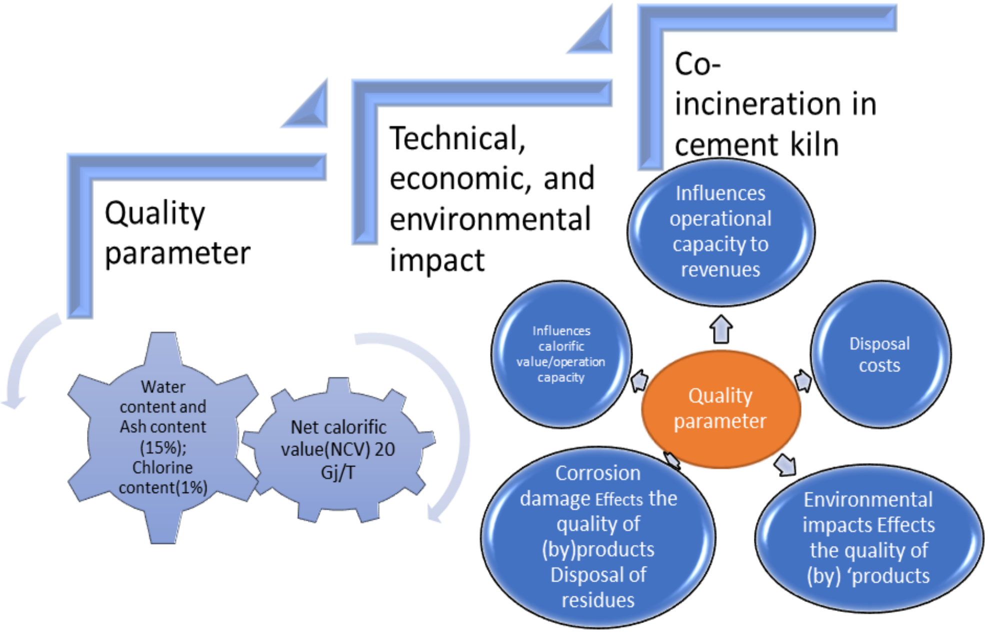

Figure 1. Refused derived fuel (RDF) characterizations for modern kiln.

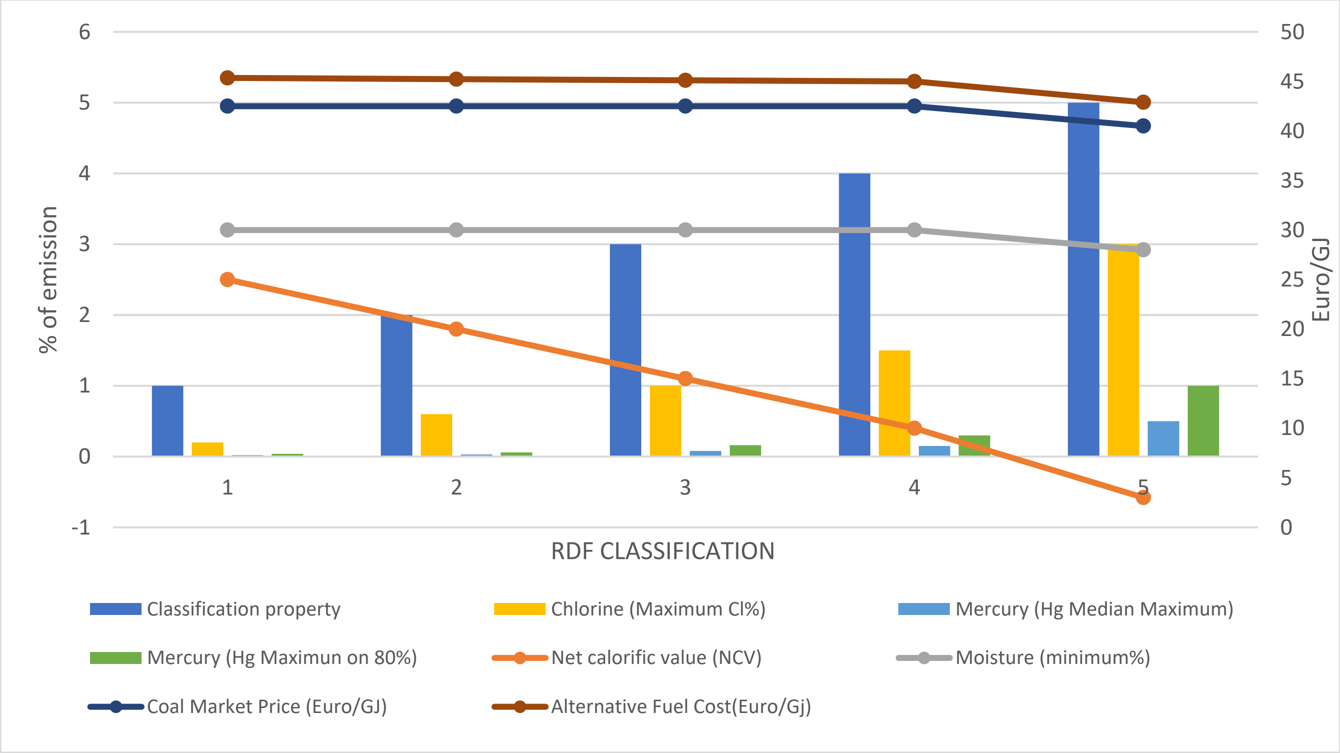

Figure 2. Solid-derived fuel characterizations for a modern kiln.

Table 6. Cost estimate of MBT with cement plant pre- and co-processing in Togo.

MBT and Co-Processing Capacity: t/a	Initial Investment (Million EUR)	Capital Costs per Ton of Waste Input (EUR/t)	O and M Costs per Ton (EUR/t)	Total Cost per Ton (EUR/t)	Revenues from Energy Sales per Ton EUR/t (Electricity/RDF)	Cost to Be Covered per Ton Waste Input (EUR/t)	Capacity kt/a
SRF pre- and co-processing estimation cost in emerging countries, output capacity: 120 kt/a	6.7	55.9	15	70.9	60	10.9	120
RDF pre- and co-processing estimation cost in emerging countries, output capacity: 150 kt/a	6	40	5	45	30	15	150
TDF pre- and co-processing estimation cost in emerging countries, output capacity: 50 kt/a	7.5	150	10	160	100	60	50
Biomass pre- and co-processing estimation cost in emerging countries, output capacity: 90 kt/a	7	78	12	90	50	40	90

The major reason a cement plant owner would invest in co-processing is to lower the cost of fuel and raw materials. This means that the choice to invest depends on the erratic market-pricing for raw materials such as coal, pet coke, natural gas, and metals, as well as other financial incentives. Such an investment will be more alluring the more expensive basic fuels or raw materials are [71]. The following factors have an impact on pre-processing, AF production, and co-processing costs: project planning and permit costs; installation capacity for handling waste, preparing the waste for dosing, and feeding the waste into the cement kiln; operational health and safety measures and emissions control; plant utilization rates; spare parts, maintenance, and auxiliary materials; capital expenditures, taxes, and insurance;; laboratory analysis to ascertain the composition of waste and RDF; administration, personnel, and salaries [72].

Pre-processing to create a homogenous mixed RDF, SRF, TDF etc., the addition of conveyer belts and additional technical functions to enable AF input to the combustion process, as well as storage rooms and safety precautions to decrease the risk of fire, are the main initial investments. If newer cement facilities were built with the co-processing of waste in mind, adjustments may not be as necessary. If up to 500,000 metric tons of various kinds of waste are used annually and around 25% of the primary energy input is substituted, a co-processing project example in the cement sector under the Clean Development Mechanism (CDM) or Mechanical Biological Treatment (MBT) predicts investment costs [73].

The qualities of the waste and the industry in which it is used determine whether it is suitable for co-processing. Typically, the common knowledge of AF, is related to the separated, high-calorie portion of MSW, and commercial- or industrial-process wastes [74]. Problems with operations or the environment can result from waste that contains a lot of chlorine or mercury. As a result, leftovers made of PVC-plastic, for instance, are inappropriate for co-processing. AF′ properties, such as its concentration of trace metals, chlorine, and sulfur, are defined by quality standards. AF should have a calorific value of between 10 and 15 MJ/kg to operate economically [75].

2.3.1. Operation Parameters

In order to minimize the risk of build-ups and ring formation, a proper balance of sulfur and alkalis must be maintained; chlorides must be properly controlled and tower cleaning tools must be well maintained.

It is crucial to have alkalis and sulfur that are appropriately balanced. Alkali/sulfur material corrections must be used to achieve a balanced system. Bear in mind that in case a bypass is operated, part of the alkalis is removed, which can lead to an imbalance. Bypass dust-handling should be considered during the evaluation or measurement of volatiles and mass-balance creation together with inputs via raw materials and fuels. An excess of alkalis or sulfur leads to the undesirable formation of preheater build-ups or, alternatively, kiln rings. The balance of volatiles must be calculated as a starting point to eliminate formation of build-ups and rings during kiln operation. Ideally, the SO_3 content in the clinker must be below 1.5% to avoid a dusty clinker which can reduce a recuperation efficiency of the clinker cooler. Sulfur volatility should be monitored and should always be below 70% [76].

With a higher substitution of high-chloride AF, it is unavoidable to install and operate a chloride bypass. It is recommended to use it if the total input of chloride is higher than 0.3–0.4 kg of Cl/t of clinker. Nevertheless, the exact number depends on other factors; especially the sulfur volatility, the tower-cleaning tools and quality of their use, and in some cases chloride inputs without the operation of a bypass can be even higher [77]. In case there is no other source of chlorides 0.3–0.4 kg of Cl/t of clinker corresponds to approximately 50% of the AF with the average content of 0.5% of chloride and a net heat value (NHV) of 22–23 GJ/t [6]. In general, preheater kilns and calciner kilns can be operated safely (without kiln stoppage due to frequent cyclone blockages) by controlling chloride in a hot meal below 1.0% and by controlling SO_3 in a hot meal below 5.0%. SO_3 + 2Cl in hot meal should be calculated and monitored. The risk of cyclone blockage will be increased when the percentage is higher than 3.5. Maintaining high oxygen at the kiln inlet to decrease SO_3 in hot meal can minimize the risk of kiln stoppage due to cyclone blockage as well [77].

Proper and well-maintained tower-cleaning tools are essential for the fast action of pilot valves, fast pressure release, tightness without air leakages, and good quality of compressed air. Periodic operational checks of air cannons are required [78], as are air cannons with flexible control systems; grouping, adjustments of time sequences, and time delays specific for certain areas. The Cardox system employs high-pressure CO_2 (700–1200 pressures), is quick and very efficient, and can clean large areas and remove large lumps of coating with the requirement that all staff receive safety training. As it is the most perilous, medium- to high-pressure water cleaning requires regular training and the use of specialized safety equipment (high-temperature-resistant cloths) [79].

In order to input moisture at the main burner, the fuel mix's moisture levels must be kept low. Total moisture for a main burner should preferably be less than 20-kg H_2O/ton of clinker (for example, clinker with 40 kg H_2O/ton has a 400 °C lower flame temperature). If there are no other ways to prevent high water input via the main burner fuels, an AF drier must be installed to prevent excessive specific water content at the main burner. Other issues for consideration include AF quality selection, alternative supplies, low-quality penalties for non-standard deliveries etc., [78]. For ash input at the main burner, excessive fuel-mix ash must be avoided. The total ash for a main burner should ideally be below 30 kg ash/ton of a clinker [80].

"Booster fuel" can also be used, ideally alternatives such as: waste oils/solvents, or alternatively, fossil fuels e.g., natural gas, heavy oil. Properly atomized liquid fuel spread into the main burner with net heat value minimum of 27–28 GJ/t in the amount >4–5% and can help to intensify and stabilize the flame (flame-shortening) and help to further increase the total AF substitution. In such a case it is feasible to achieve even very high solid-fuel replacement rates (>80%) [81]. For the fuel mix package at the main burner, a stable fuel-mix package must be maintained, and the complexity of fuel mix package should be avoided to prevent huge amount of fuel transport air at main burner. Also, combustion can be improved under the oxygen-enriched primary air, typically used in the amount of 7–10 kg O_2/MW. In this case, the flame and fuel burnout must be shortened to have a positive impact on sulfur volatilization, and at least partially eliminate reducing conditions. Fuel-cost evaluation is also necessary in this case [81].

Stability should be a standard for any kind of process; and for high use of AF it is even more essential. Process must be kept much more stable to allow feed of lower quality AF in comparison with fossil fuel combustion. The process itself needs more attention, cross checks, control of instrumentation to prevent its failure [82]. Stability can be obtained by paying close attention to the feeding and weighing, clinker chemistry and heat input. For stability during feeding and weighing, the maximum allowable limits for fluctuations of kiln-feed dosing and traditional fuel is 1.0% for 10 min test while the coefficients of variation for R90 micron of kiln feed and traditional fuel must be a maximum of 5.0%. Also, for a stable clinker chemistry, maximum limits for the short-term standard deviation of LSF is 1.2 (daily basis), for aluminum and silica ratios it is 0.04 while the long-term standard deviation of LSF ≤ 1.0 (monthly basis). The maximum limit standard deviation of free lime in a clinker is 0, while for P_2O_5 it is 0.5.

A low heat-input fluctuation is essential, especially for the main burner fuel mix. The fluctuation of calciner fuels is absorbed by proper control of the bottom stage inlet/outlet temperature. The overall stability of the heat flow is given by a combination of feeding accuracy and stability of the fuel mix average net heat value (NHV). The coefficient of variation for each part can be determined with following formulas [83]:

1. Coefficient of variation (NHV) = standard deviation (NHV)/average (NHV) × 100%
2. Coefficient of variation (weight) = standard deviation (fuel feeding)/average (fuel feed) × 100%

The variations in fuel weight should not be higher than 1.5%, while the variation of the fuel net heat value (NHV fluctuation) should ideally be below 3%. The overall variation of heat input should be a multiplication of both numbers and should be less than 5%. In cases where there are more fuels fed into the kiln, each fuel should be analyzed separately and, as well, overall heat input variation. The overall heat input variation should be weighed averaged. High variation of one fuel input should not have high influence while its share in the heat input is much smaller than those with higher stability. Below example shows calculation for 2 fuels but the same method should be applied to multifuel input.

In case the coefficient of variation for total heat input can be kept below the number as mentioned above, extra excess air level in the kiln and calciner will not be required and less negative impact on specific heat consumption and clinker production after maximizing

AF can be observed. To achieve this, a proper fuel weighing must be done via proper maintenance, appropriate weighing equipment and proper weight-device setting. Also, proper fuel mixing must be done through fuel proportioning and improved control of the fuel recipe [80]. Finally, the use of new instrumentation tools must be evaluated to predict/supply the information about incoming quality to the burner

The NHV data set for fuels must include at least 24 results (on an hourly basis) per day to calculate the coefficient of variation (NHV). Many cement plants use alternate fuel at the main burner without having a complete understanding of how heat input varies. This is one of the variables that prevents the use of alternative fuels in the main burner from being maximized [9].

Combustion efficiency of conventional/AF at the main burner can be improved by using an infrared camera. Flame shape and pulsation at the main burner can be observed clearly when using this technique. With this information, the proper adjustment of all "airs" amounts (transport, axial, radial, central) to obtain an optimum flame propagation will be easily achieved. There are some cases where infrared cameras can detect solid AF flowing out of the flame due to low-swirl air pressure. It is recommended to use this technique for both the main and, if any, satellite burners especially with a complex fuel mix package [84].

The use of AF in the kiln burner must be preferably done via the main burner. Satellite burning cannot be considered to be a proven idea when compared to the main burner based on the most recent information in cement technology. AF delivery through a satellite burner carries the danger of improper combustion, and some of the solid particles it delivers may fall into the clinker bed and affect the clinker's quality [85]. The excessive burning zone-specific heat input will be brought on by improper burning via the satellite burner and/or main burner. This finding is based on a new kiln line in the Schelklingen facility, where firing solid alternative fuel via a satellite burner with incorrect POLFLAME burner combustion resulted in a more than 50% increase in heat input. AF must therefore be injected through the main burner; satellite burners are merely an "option" [86].

As a controlled parameter, NO_x can be used at the kiln inlet to reduce the possibility of meal flushing. Heat input via the main burner and the kiln ID-fan must be adjusted appropriately when NO_x is being observed at the kiln intake beneath the target. When compared to kiln main drive current, employing NO_x at the kiln entrance has the advantage of quicker control over kiln operation. A standard indicator for any kiln should be the main driving indication (amps, kW, etc.). Due to the short material retention time inside this type of kiln, NO_x control as an early indicator is especially advised for calciner kilns [83].

In terms of the particle size of AF, proper fineness is necessary; finer means better. Light particles (e.g., foils, papers, thin 1D or 2D pieces) must be less than 40 mm, medium 2D weight particles (e.g., harder plastics) must be less than 15 mm but preferably less than10 mm and heavy or 3D particles (e.g., rubber chips, hard plastics) must be maximum of 10 mm but preferably less than 5 mm [80].

Too-low average net heat values at the main burner should be avoided. Ranges should be at least 21 GJ/t for AF replacement rate substitution (0–65%) and at least 23 GJ/t for an AF replacement rate of 65–90%. Its borderline depends on fuel type when finer high volatile fuels are allowed to operate with lower overall net heat value (animal meal/sewage sludge, liquid waste) while bigger moist particles demand a higher burner average net heat value [87].

As opposed to calciner kilns, the degree of calcination (DoC) of preheater kilns is less stable. Fuel quality, including moisture content, net heat value, ash content, fineness, volatile content, and the stability of heat input from fuels, can have a big impact on how well a kiln works. In comparison to calciner kilns, maintaining a constant temperature profile in a preheater system's back and front ends is more difficult [88].

The maximum specific heat load allowed in the kiln-burning zone is 6 MW/m^2 (5.17 $Gcal/h/m^2$ or 21.62 $GJ/h/m^2$). Refractories' lifespans can be decreased by an excessively high specific heat load in the burning zone of a kiln, especially if several types of AF are being burned through the main burner. This occurs because of the burning-zone coating becoming significantly less stable. It might be a bottleneck for further AF-rate growth. An aid could be a fuel split between the primary burner and the back of the kiln [87]. Additionally, altering the refractory arrangement in crucial locations and covering unstable ones can help the problem. The use of pure alumina spinel bricks can help to tolerate greater surface temperatures by preventing material washing/melting and reducing corrosion brought on by the liquid phase. These bricks also have low iron content and porosity.

It is advised to separate the fuel feed to the kiln-inlet area when it reaches 6 MW/m^2. The specific heat load of a preheating kiln with tire-feeding at the kiln entrance will be reduced. The kiln burning zone's maximum specific heat-load restriction must be considered on a case-by-case basis. There are instances where the refractory lifespan is adequate even with 6.5–7.0 MW/m^2 [88]. The improvement of the clinker cooler is a crucial step in boosting the use of AF. The increased AF rate is feasible for secondary air temperatures higher than 1000 °C. If high-quality fuels are not readily available, the rate will be limited by the satellites' clinker cooler [89]. The pneumatic portion of the transport line from the AFs to the main burner needs to be as short as possible (ideally, from the main burner platform), and a straight transport line without any bends to the main burner is highly advised to reduce the amount of transport air and pulsation issues [9].

Preheater kilns can reach an AF replacement rate (excluding liquid fuel and tires) at 60%. By feeding tires into the kiln inlet and employing a booster fuel at the main burner, a higher AF replacement rate of up to 90% is also feasible. The most important equipment to increase combustion efficiency for the highest AF replacement rates is the main burner and clinker cooler [84]. Tolerances (also called operating range) and the permitted margin of tolerances (also called action range) as well as the tolerances admitted and normative limits [87] should be considered. It must be noted however that, practice has shown that it is crucial to foresee a contingency plan in the case of failure of automated samplers, lab automation and automated analyzers [87].

2.3.2. Solid Recovered Fuel (SRF)

Solid recovered fuel (SRF), also known as refuse-derived fuel (RDF), is a fuel product with a market value that is increasingly produced using MBT. SRF is becoming important for obtaining energy from trash, mostly in Europe. After adequate mechanical processing, bio drying the waste reduces excess moisture and increases its potential for heat recovery. Potential inclusion of the biogenic component of the initial waste stream, a carbon dioxide (CO2) neutral and alternative energy source, into the fuel is one of the main advantages of SRF. Because it is possible that higher concentrations of chlorine could make ash deposition in a boilers' convective parts worse, the concentration of chlorine in SRF is crucial to fuel quality [90].

Quality assurance is a component of quality management that aims to provide customers confidence that quality requirements will be met, according to DIN EN ISO 9000 (2005). This means that for RDF/SRF, quality parameters and requirements must be established while considering the individual preferences of RDF/SRF users, and they must also be guaranteed. RDF/SRF quality requirements can be broken down into [91]: parameters, describing the incineration properties (e.g., calorific value, particle size), heavy metal content and halogen/sulphur content.

Multistage mechanical processing plant is used by various suppliers for the production of SRF at different quality ranges: low, medium and premium quality. The higher the SRF quality, the more pre-treatment and processing procedures for the waste are required. Good quality SRF should have higher LHV but lower particle size (d95) and impurity content. The quality of SRF manufactured is primarily dependent on the input waste materials as well as the type and extent of processing steps applied in the multistage (mechanical/physical) SRF processing plants. The properties of three different manufactured SRF types are presented below [89].

- SRF low quality: having $d^{95} \leq 120$ [mm] and $3 \leq \text{LHV} \leq 12$ [MJ kgOS^{-1}] and is used for energy recovery in stationary fluidized bed incinerator;

- SRF medium quality: having $d^{95} \leq 80$ (for Hotdisc: $d^{95} \leq 300$ mm) and $12 \leq \text{LHV} \leq 18$ (MJ kgOS^{-1}) and is used for energy recovery in secondary firing systems of cement kiln and/or in special pre-combustion chambers like Hotdisc;
- SRF premium quality: having $d^{95} \leq 30$ (up to 35 mm) and $18 \leq \text{LHV} \leq 25$ (MJ kgOS^{-1}) and is used for energy recovery in primary firing system of cement kiln.

The total amount of municipal solid waste collected still appears to be quite limited, about 1600 t/day; with a collection efficiency of 40%, the municipal solid waste consists mainly of (wet) organic waste, plastics, and mineral residues, together contributing about 85% of the collected waste [84].

Waste-to-energy technology is already widely accepted by the business community and decision-makers. There are a few successful examples of its usage for the non-recyclable portion of municipal solid trash, even though its application is now concentrated on specialized high-caloric industrial and hazardous waste. The transfer of waste from towns to the cement factory is also a restricting constraint [89].

3. Methodology

A preliminary case study is presented on the substitution of coal with AF in a cement production plant in Togo. Two major types of AF were sourced from local suppliers: Agricultural waste/biomass; specifically, palm-kernel shell (PKS) and SRF. The study was carried out over a three-month period. AF was assessed for both pre-processing and co-processing. The AF was first characterized by laboratory analysis for key parameters on-site. In terms of co-processing, the energy efficiency and performance of the plant was evaluated as compared to the conventional single energy source (coal). The methodology for the case study is presented in Figure 3 and is like that described in [14]. The following steps elaborate the various activities carried out as part of the case study.

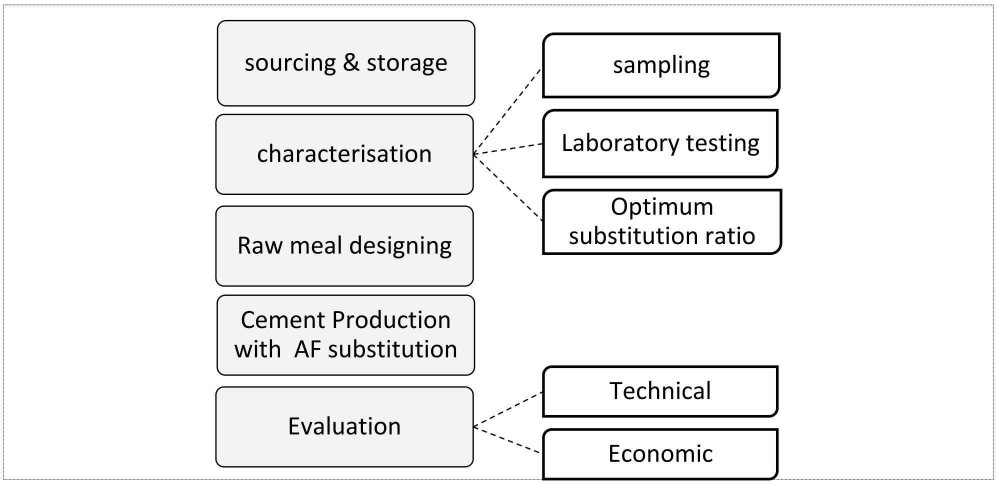

Figure 3. Methodology for the case study.

3.1. AF Souricng and Storage

The material considered in this paper was sourced from a supplier site (Mechanical Biological Treatment (MBT) of GRL-Togo) where AF (RDF, SRF TDF, pelleted biomass) where AF is produced from municipal solid waste, agriculture and forest waste and crop biomass. The exact tolerable specifications of AF were communicated to the supplier within the contract to ensure that a high quality was always supplied; beyond which the AF may be rejected. Upon arrival at the plant site, the truck passed through the weighing bridge to determine the exact quantity of AF received. The average quantity received per day was 95 tons. The plant is in operation all year round, except on scheduled maintenance or emergency breakdowns, thus during the period of the case study, there was no recorded incidence of prolonged plant shutdowns beyond 5 h. Due to this, the supplier was requested to supply for five weekdays with an additional two days before the weekend. Adequate storage space was made available for weekend storage. An extra one-day storage was always kept as backup for unforeseen delays from the supplier. This arrangement ensured that there was always an adequate supply of AF to feed the plant in the required quantities.

3.2. Characterisation of the SRF and Biomass

The AF were sampled to perform laboratory investigations on them. In the laboratory, the following parameters were investigated: LHV, moisture content, and density. Also, an analysis of the optimum substitution ratio (between AF and coal) was carried out to determine the optimum ratio at which the specific AF from this particular supplier would provide maximum plant performance and energy efficiency. This was done by the measurement of O_2 and CO% at the kiln inlet.

3.3. Change of the Raw Meal Design

The raw meal was redesigned to accommodate the new co-processing system. In the new design, the lime saturation factor was increased to fit with the ash content in the AF.

3.4. Operation and Technical Performance

The plant has accumulated several years of data on its performance using 100% conventional fuels (mainly coal). To assess the technical viability of the co-processing with a percentage of new fuel, a direct comparison of the plant's performance before and after substitution was carried out based on the kiln-inlet oxygen level. The pyro-system gas was analyzed to determine internal conditions of the pyro system and the following were analyzed: the pre-calciner gas analysis (P Gaz Anal) of dioxygen (O_2) and carbon monoxide (CO). The kiln-inlet gas analyses (Kiln Gaz Anal) of dioxygen included carbon monoxide and kiln-motor ampere (Am). The induced draft fan (ID Fan) opening was presented in percentages (%) and pressure drop was presented in (Mba).

3.5. Economic Evaluation

The economic evaluation is based on cost savings from either the sourcing of the fuel and/or the energy savings as compared to that of coal. The energy cost as landed is the cost of energy with a free moisture charge whiles the energy cost at the pyro-system is the main power fee added to the energy cost as landed which represents the real expenses of the plant by using fuels.

4. Results and Discussion

Table 7 shows the laboratory results and the economic comparison.

Table 7. Cement plant Fuels data.

Items	Moisture	Density	Q (Net)	Purchase Price	Energy Cost as Landed	Energy Cost at Pyro-System
	%	T/m^3	[GJ/t]	Euro/t	Euro/GJ/m^3	Euro/GJ/m^3
Biomass	15.65	0.62	12.087	27.10	4.56	5.77
SRF	3.25	0.72	21.41	67.87	4.55	5.76
Coal	8	1.1	25.14	229.2	8.87	9.02

Tables 7 and 8 show the operation record parameter during the operation. The substitution rate was tested with 35.78%, 44.22%, 50.02%, and 57.16%. The raw-meal feed in the pyro system for clinker production was between 203 T/h and 278 T/h, while the lime saturation factor (LSF) was between 103.2 and 117.1; the silica module (SM) was between 2.36 and 2.47, the iron module (IM) ranged from 1.43 to 1.7 and the raw meal varied from 10.2 on 90 µm to 11.7 on 90 µm. The pyro system alternative fuel (AF) varied from 10.2 T/h minimal to 14.5 T/h; the coal feeding in the main burner (c-mb) varied from 8.37 T/h to 10.2 T/h, and the coal feeding at the pre-calciner varied from 16.4 T/h to 20.6 T/h.

Table 8. Pyro system technical performance record at various AF: coal substitution ratios.

Sub%	**RAW MILL**					**AF**	**c-mb**	**c-prc**	**P Gas Anal**		**Kiln Gas Analysis**				**ID Fan**	
	T/h	**LSF**	**SM**	**IM**	**90 µm**	**T/h**	**Feeding**		**O2**	**CO**	**O_2**	**CO**	**Mba**	**Am**	**%**	**Mba**
35.78%	224	113.6	2.42	1.7	10.7	10.5	9.66	20.6	9.73	0.02	3.42	0.01	−3.6	488	79.9	−4.1
	206	113.6	2.42	1.5	11.7	10.7	10.2	20	9.73	0.02	3.29	0.02	−3.6	420	79.9	−4.2
44.22%	203	110.3	2.36	1.5	10.2	12.4	9.54	18.5	7.19	0.03	4.12	0.01	−4.7	414	80.5	−4.3
	265	110.3	2.36	1.5	10.5	12.3	9.99	18.6	7.19	0.04	2.8	0.01	−4.3	539	80.6	−4.2
	278	103.2	2.47	1.49	11.2	12.3	9.4	18.9	7.04	0.03	2.46	0.01	−5.3	480	80.8	−4.4
50.02%	274	113.6	2.42	1.5	10.7	13.2	9.4	17.3	6.96	0.05	2.36	0.01	−4.7	465	80.9	−4.4
	265	110.3	2.36	1.5	10.8	13.3	9.4	17.3	6.29	0.05	2.44	0.01	−4.3	573	81.2	−4.8
	269	116.5	2.38	1.53	10.2	13.2	9.4	17.3	6.33	0.06	2.86	0.01	−5.1	549	80.9	−4.6
57.16%	254	1103	2.36	1.5	10.7	14.5	8.45	16.8	4.91	0.5	1.72	0.04	−4.7	470	83	−5.2
	271.1	110.3	2.36	1.5	10.6	14.2	8.37	17.9	4.6	0.03	1.22	0.06	−4.3	433	82	−5.7
	254.2	117.1	2.41	1.43	10.3	14.4	8.63	16.4	4.6	0.09	3.07	0.09	−5.1	452	82.4	−5.4

Sub% = the percentage of coal substituted with AF, LSF = lime saturation factor, SM = Silicate module, IM = iron module. The finesse is 90 µm for raw meal, the coal injected at main burner(c-mb) = 9 t/h, coal injected at the pre-calciner(c-prc) = 17.3 t/h, the pre-calciner gas analyses (P Gas anal) and kiln Gas analysis (oxygen and monoxide of carbon).

Supplying over 200 miles makes the entire process unappealing from a financial and environmental standpoint. Due to the instability of fossil-fuel prices as well as the low earnings from waste-disposal fees in most municipalities in developing and emerging nations, the economic attractiveness of AF is another limiting factor.

Co-processing has the potential to help minimize the total environmental effects of cement manufacturing, which requires a lot of resources and emits several airborne pollutants that must be monitored and brought down to legally permitted levels using the right methods (Figure 4. Dust, nitrogen oxides (NO_x), sulfur dioxide (SO_2), dioxins and furans, carbon oxides (CO, CO_2), volatile organic compounds, hydrogen chloride (HCI), hydrogen fluoride (HF), and heavy metals are all possible emissions from cement kilns.

Operators of cement plants must follow guidelines, such as those provided by the Basel Convention, to ensure environmentally sound co-processing of RDF in cement kilns. The emissions must be the same as, or less than, when RDF is not used. Modern methods and technologies, such as injecting RDF directly into the kiln's high-temperature zones, are required for this purpose. Modern cement facilities frequently already adhere to international standards when it comes to design. The requirements to update emission control for co-processing are minimal if this is guaranteed [92].

It is possible to estimate a net reduction of expenses of fossil-fuel consumption. For 1.5 million GJ of waste-to-energy which can be substituted in the cement plant by 50%, the accompanying economic assessment resulting from the cost savings would be 12.1 million euros. In turn, it was estimated that between 20% of biomass and 80% of SRF, which are 50% coal substitution at the suspension preheater kiln, CO_2 emissions were reduced by 160,000 tons [93]. The global savings, assuming a cost of 163.86 euros per ton alternative fuel as illustrated in Table 9 and Figure 4. Co-processing necessitates a sizable capital investment and needs to be backed by long-term financial planning as well as the resources to ensure ongoing equipment operation and maintenance (Figure 5). Initial investment money may be available in developing nations, but frequently, financial resources for the operating phase are appropriately considered. Initial investment expenditures and anticipated operational costs must be annualized to compare and evaluate the entire financial sustainability of alternative fuel co-processing [94].

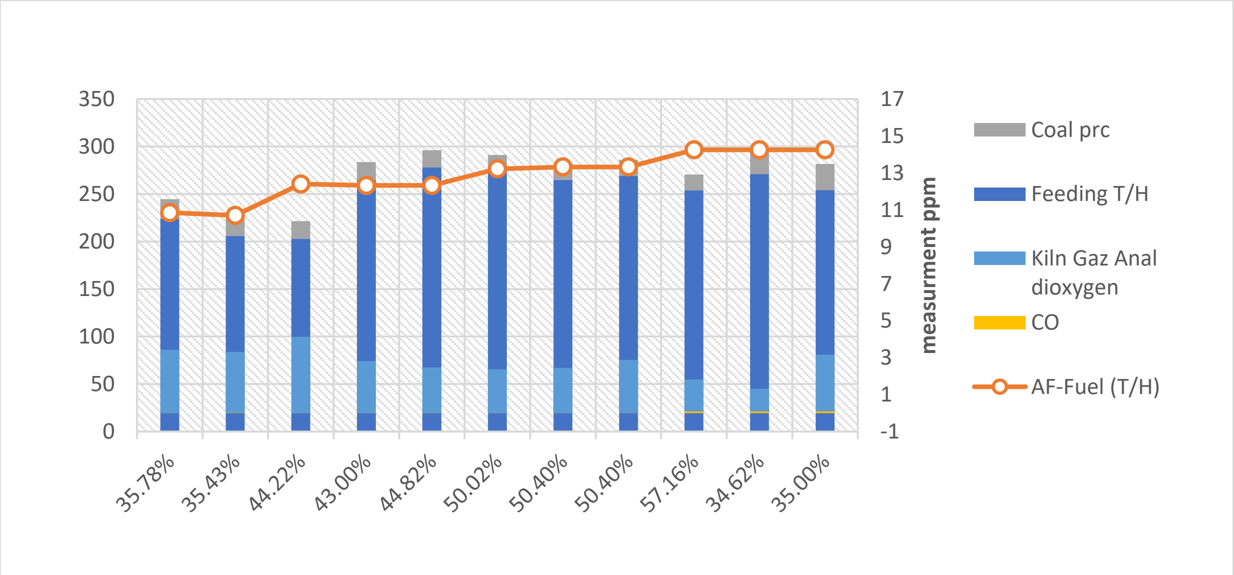

Figure 4. AF substitution operation analyses.

Table 9. Cost saving for 50% substitution for suspension preheater kiln.

Data			**SRF (80%) and Biomass (20%), Saving from 4.1 Gj/tclk of 2500 TPD Cement Plant**			
SRF LHV	21.7	GJ/T		Total SRF	57,142.9	Tons
Biomass LHV	18.5	GJ/T	Annual capital expenses		121,840,404.0	CFA
Coal LHV	23.50	GJ/T	Additional costs		10,512,000.0	CFA
SRF cost	25.000	CFA/ton	Annual operational costs		23,660,000.0	CFA
Biomass cost	22.000	CFA/ton				
Coal Cost	150.000	CFA/ton		Total Biomass	16,756.8	Tons
Power cost	80.00	CFA/Kwh	Annual capital expenses		121,840,404.0	CFA
Coal Mill SPC	28.00	kWh/ton	Additional costs		10,512,000.0	CFA
Annuel operational costs					23,660,000.0	CFA
Total Energy from SRF				1,240,000.06	GJ	
Total Energy from Biomass				310,000.06	GJ	
			Total	1,550,000.12	GJ	
Total Coal Subs by SRF				52,762.30	Tons	
Total Coal Subs by Biomass				13,190.58	Tons	
			Total.	65,952.87	Tons	
Total cost of Coal Subs by AF				10,040,665,627.56	CFA	
			Total Cost of AF	2,109,245,028.00	CFA	
			Savings	7,931,420,599.56	CFA	
				12,109,039.08	Euro	

A significant obstacle to the development of MBT projects in developing nations is typically high initial investment costs. Efforts are being made to market MBT projects with lower costs and a basic technical standard for low-income nations, but there has been little experience with these solutions, and it is still unknown whether these plants will be able to successfully meet the required technical and emissions standards over the long haul [95].

Annual capital expenses are estimated using the initial investments, the required interest rate (for example, 9.45% annually), and the anticipated lifespan of the equipment (e.g., 10–15 years). Due to economies of scale, large equipment requires greater absolute initial investments than smaller facilities but has lower specific yearly costs per ton of AF co-processing. This cost growth does not correspond linearly to the volume of waste that is processed. It is estimated that 35% more money is invested for big equipment compared to small equipment [85].

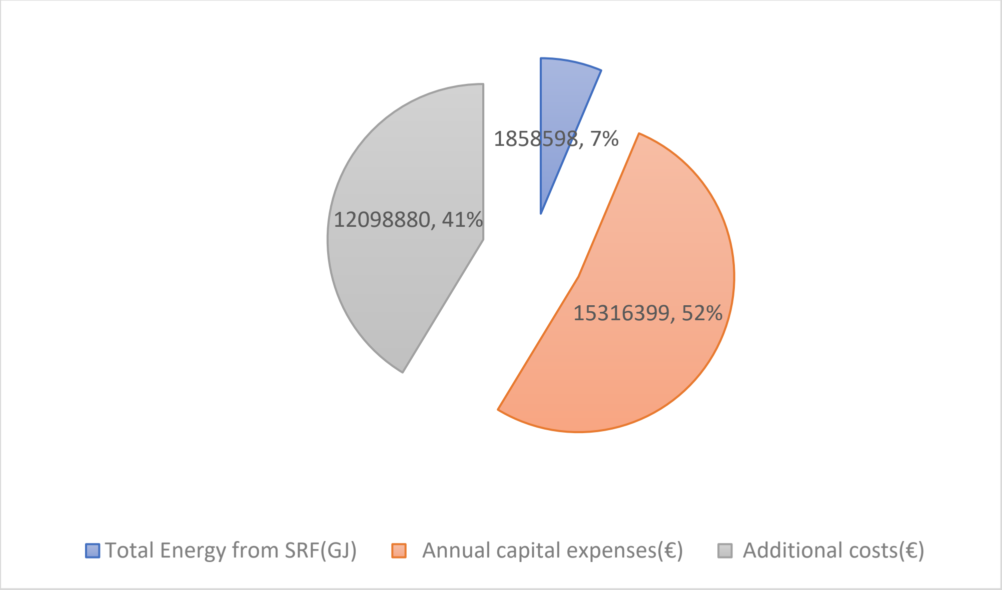

Figure 5. Energy and cost saving analyses.

Annual operational costs: personnel costs, auxiliary materials (such as chemicals for flue-gas treatment), spare parts and maintenance, insurance and taxes, and power are the key components of our operational costs. The potential expense of processing more AF should also be considered. As the plant's processing capacity and utilization rate rise, so do the specific investment and operating expenses per ton of alternative fuel.

Recommendations for Subsequent Implementation Based on Case Study

- From a financial and environmental perspective, the sourcing of AF is not appealing beyond 200 km from the fuel source;
- Due to the instability of fossil-fuel costs and the low income from waste-disposal fees in many developing nations, the economic attractiveness of AF is another constraining factor;
- It is essential to keep the clinker quality within the desired ranges with regard to free lime, mineral content, crystal size, liter weight, grinding capacity, etc.;
- The kiln needs to be sturdy enough to prevent both over- and under-burning. For the best clinker quality and operational safety, excessive sulfur volatilization AF must be avoided and good kiln oxidizing conditions are required;
- Because of the alkaline environment, high temperatures, and prolonged residence times seen in cement plants, a range of AF can be considered.

5. Conclusions

This project report presented the various considerations that need to be made to during AF substitution and analyzed and discussed various relevant research publications as well as recent developments in the use of AF in the cement industry. Studies on ways to reduce environmental pollution during AF substitution were included in this research article. The present situation of AF, how they are used in the cement business, and their environmental benefits were also discussed. The case study presented results on preliminary studies showing substantial economic benefits from AF substitution, which makes it an attractive alternative to more environmentally polluting conventional fuels such as coal.

The pre-processing of AF provides better co-processing with good cost savings. It is expected that the plant will have fewer kiln breakdowns due to alkalis clocking in the cyclone. The kiln breakdowns have an impact on plant cost-savings.

Finally, it is recommended that cement businesses embrace and incorporate the usage of AF where applicable. Further thermographic investigations of alternate fuel behaviors on the pyro-system are also needed.

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