Comparative Life Cycle Assessment of Clinker Production with Conventional and Alternative Fuels Usage in Turkey

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***Abstract*—Recently, a considerable increase has been occurred in cement manufacturing, which is a highly intensive energy and resource consuming and carbon emission industry, in parallel with industrialization and urbanization. Turkey is the fourth largest cement producer in the world. Therefore, assessing the life cycle of clinker that is the main material of cement, defining the most important environmental impacts arising from clinker production and practicing the best available production techniques is vital for environmental sustainability. In this study, life cycle assessment of clinker production with conventional fuels was carried out in Turkey (which was named as scenario 1). Additionally, alternative scenarios using alternative fuels (refused derived fuel and dried sludge) were developed and comparative life cycle assessment (LCA) study was performed. As a result of the study, the most environmentally-friendly scenario was determined as Scenario 6 using dried sludge to produce one tone clinker.**

***Index Terms*—Alternative fuel, clinker, environmental impact, life cycle assessment.**

I. Introduction

Cement industry, which accounts for 5% of global anthropogenic CO_2 emissions, is potential anthropogenic source of air pollution [1], [2]. Turkey is the fourth largest cement producer in the world [3]. There are 54 integrated cement plants in Turkey. Eighteen plants are grinding and packing facilities. Clinker production capacity is 80 million tones and cement production capacity is 132 million tons by 2016 [4].

Clinker production is a significant CO_2 emitter and the most energy-intensive part of the cement production process [5], [6]. About 60% of the CO_2 emissions by cement plants are arising from the calcination process, whereas the rest is from the energy consumed during this process [7]. Overall, for one ton of Portland cement clinker 0.87 kg of CO_2 is released into the atmosphere [8]. The important emissions in a cement kiln are nitrogen oxides (NO_x), small quantities of dust, chlorides, fluorides, sulfur dioxide, carbon monoxide, and still smaller quantities of organic compounds and heavy metals in addition to CO_2 [9]. The amount of CO_2 emitted is significantly dependent on the manufacturing method and the type of fuel usage during production [7]. As significant amounts of GHGs (Greenhouse gases) emissions are resulted from the combustion of fossil fuels (petroleum coke, lignite, fuel oil, natural gas, diesel..etc), the use of alternative fuels has significantly increased recently [10], [11]. The most common alternative fuels used globally in the cement industry sewage sludge, waste plastics, scrap tires, refused derived fuels, biomass wastes and textiles [11], [12]. Lots of studies using alternative fuels in order to produce clinker and discussing the environmental performance of them were conducted by researchers [11], [13]-[15].

In this study, we identified the environmental impacts of clinker production process in Turkey with a life cycle perspective. Current situation and five alternative scenarios (a total of 6 scenarios) were considered and the life cycle assessment was performed comparatively. As a result of the study, the most environmentally-friendly scenario was determined, and process contributions were discussed.

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II. Material and Method

A. Goal, Scope and Functional Unit

The goal of this LCA study is determine the environmental impacts of clinker production. The scope is defined as cradle to gate: raw material acquisition, raw material preparation, raw mill and clinker burning. Extraction and transportation of raw materials are included. Transportation of conventional fuels are included, but not extraction of them. In Turkey, most of coal was imported from Colombia (42.2%) and Russia (33.5%) in 2016. Therefore, the distance of import coal was assumed that 8000 km. The transportation of local coal was neglected because it was too small. Infrastructure and facilities are excluded because their impact is too small. The functional unit is one tone clinker.

B. Life Cycle Inventory and Assumptions

In this study, raw material and fuel amounts to produce clinker were obtained from the Ministry of Development of the Republic of Turkey, The State Planning Organization [16]. Average electricity consumptions in different stages of clinker production and fossil fuel usage rate (%) in Turkey were obtained from Salbaş (2016) [17]. Salbaş (2016) analyzed the 49 integrated cement plants in Turkey and identified the average electricity consumption for each production stage (raw material preparation, raw mill, kiln burning and cement grinding) and average CO_2 emissions per ton clinker arising from cement production. According to this study, the CO_2 emission is 849 kg per ton clinker [17].The heating values of refused derived fuel (RDF) for Turkey were obtained from SimaPro libraries (upper heating value: 13.27 MJ/kg; lower heating value: 11.74 MJ/kg). The average kiln emissions in Turkey were obtained from the project of Directorate General of Environmental Management [18]. The fossil fuel consumption rate for cement industry in Turkey is presented in Fig. 1.

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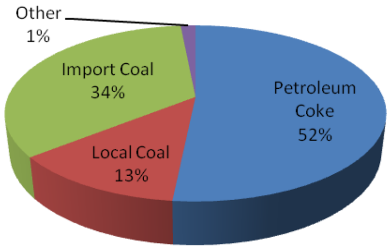

Fig. 1. Fossil fuel consumptions (%) in 2014 (Adapted from [17]).

According to the fossil fuel consumptions in 2014 and the thermal requirements for the production of one ton clinker, we calculated the essential amount of fuel (petroleum coke and coal). The main inputs and outputs for clinker production with conventional fuels are presented in Table I. In this study, iron ore (46% Fe) was also used as raw material to produce clinker in addition to limestone and marl.

TABLE I: LIFE CYCLE INVENTORY OF CLINKER PRODUCTION WITH CONVENTIONAL FUEL USAGE

Parameter	Amount	Unit	Reference
Inputs:			
Raw material:			[16]
Limestone	1.025	ton/clinker	[16]
Marl/clay	0.528		[16]
Other*	0.048		[16]
Energy	110 ±5	kWh/ton.cement	[16]
Fuel	800±50	kcal/kg.clinker	[16]
Petroleum coke**	0.0576	7500 kcal/kg.clinker	Calculated
Import coal**	0.02187	6500 kcal/kg.clinker	Calculated
Local coal**	0.03692	4500 kcal/kg.clinker	Calculated
Water	0.119	kg/ton.clinker	[18]
Outputs:			
Emissions to air:			
NO_2	2.5	kg/ton.clinker	[18]
PM	0.26136	kg/ton.clinker	[18]
CO	2.53	kg/ton.clinker	[18]
CO_2, fossil**	849	kg/ton.clinker	[17]
VOC	0.07015	kg/ton.clinker	[18]
HF	1.1605	g/ton.clinker	[18]
HCl	23.023	g/ton.clinker	[18]
PCDD/F	313.5138	ng/ton.clinker	[18]
Products:			
Clinker	1	ton	-

(*) Bauxite, iron ore, pyrite ash, sand, alternative raw materials etc.
(**) The amount of fuels and CO_2 fossil fuel were calculated for all scenarios.

SimaPro 8.0.4 was used in order to assess the environmental impacts of clinker production for different scenarios. The inventory data for raw material acquisition (limestone and marl mining), electricity country mix were obtained from SimaPro libraries (Ecoinvent). The scenarios are as follows:

Scenario 1 (Current scenario): Thermal requirements to produce 1 ton clinker are supplied with 54% petro coke, 30% import coal, 12.3% local coal and 3.7% RDF (refused derived fuel).

Scenario 2 (Alternative scenario): Thermal requirement to produce 1 ton clinker are supplied with 10% RDF, 50% petro coke, 20% import coal, 20% local coal.

Scenario 3 (Alternative scenario): Thermal requirement to produce 1 ton clinker are supplied with 20% RDF, 30% petro coke, 10% import coal, 40% local coal.

Scenario 4 (Alternative scenario): Thermal requirement to produce 1 ton clinker are supplied with 20% RDF, 30% petro coke, 10% import coal, 35% local coal, 5% natural gas.

Scenario 5 (Alternative scenario): Thermal requirement to produce 1 ton clinker are supplied with 30% RDF, 30% petro coke, 10% import coal, 30% local coal.

Scenario 6 (Alternative scenario): Thermal requirement to produce 1 ton clinker are supplied with 30% SS (sewage sludge), 30% petro coke, 10% import coal, 30% local coal. It is assumed that the sewage sludge is thermally-dried before incineration in clinker kiln and its calorific value is 2500 kcal/kg.

C. Life Cycle Impact Assessment

Life cycle impact assessment was carried out with IMPACT 2002+ method, which is a combination of four methods: IMPACT 2002, Eco-indicator 99, CML and IPCC. The mid-point impact categories considered in IMPACT 2002+ are carcinogens, non-carcinogens, respiratory inorganics, ionizing radiation, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutri, land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy and mineral extraction. The end-point impacts are human health, ecosystem quality, climate change and resources.

III. RESULT AND DISCUSSIONS

A. Characterization and Process Contribution Analysis

The characterization results of life cycle impact assessment (mid-point and end-point effects) for alternative scenarios are summarized in Table II. When the Scenario 1 (current situation) was taken into account, it was determined that imported lignite has high contribution to non-carcinogens, ionizing radiation, land occupation, aquatic eutrophication, and non-renewable energy. Kiln burning process is the highest contributor on global warming, aquatic acidification and terrestrial acid/nutri. Aquatic ecotoxicity, terrestrial ecotoxicity and mineral extraction are mostly affected from the raw mill production including raw material extraction, crushing and homogenization. According to the Table II, all impact categories decreased for alternative scenarios, except from aquatic eutrophication. Aquatic eutrophication impact increased for all scenarios (except from Scenario 6). Especially in Scenario 3, aquatic eutrophication has the highest impact (25%). In this study, the main reason of the high aquatic eutrophication is usage of high amount of local coal (40%), which has a low calorific value (about 4500 kcal/kg.clinker), in order to produce one tone clinker. When the inventory was examined, it has been determined that the highest contributor to aquatic eutrophication effect is phosphate.

The process contribution analysis of Scenario 6 was presented in Fig. 2. The main reason of reduction in aquatic eutrophication is raw sewage sludge for Scenario 6 as can be seen from the Fig. 2.

While the significant reduction has been determined in non-carcinogens; the important increment has been defined in respiratory organics (from 0.085 kg C_2H_4eq to 0.48 kg C_2H_4eq) for Scenario 6 because of the sewage sludge usage. The most important contributor to reduction of non-carcinogens is dioxins in based on dried sludge usage.

But, dried sludge usage can affect the respiratory organics adversely. The increment in respiratory organics arises from NMVOC (Non-methane volatile organic compounds) substantially. When the damage assessment was taken into account, we identified the 4% of reduction in human health impact category with using dried sludge for alternative fuel in clinker production.

TABLE II: THE LIFE CYCLE IMPACT ASSESSMENT RESULTS BY DIFFERENT SCENARIOS

Impact category	Unit	scenario 6	scenario 5	scenario 4	scenario 3	scenario 2	scenario 1
Mid-point impact:							
Carcinogens	kg C2H3Cl eq	1.1E+00	1.8E+00	1.9E+00	1.8E+00	2.0E+00	2.2E+00
Non-carcinogens	kg C2H3Cl eq	-3.1E+00	5.2E-01	5.5E-01	5.3E-01	6.6E-01	7.8E-01
Respiratory inorg.	kg PM2.5 eq	7.9E-01	7.7E-01	7.8E-01	7.7E-01	7.9E-01	8.0E-01
Ionizing radiation	Bq C-14 eq	2.1E+02	2.8E+02	3.0E+02	2.8E+02	4.1E+02	4.9E+02
Respiratory organics	kg C2H4 eq	4.8E-01	6.1E-02	6.5E-02	6.1E-02	7.5E-02	8.5E-02
Aquatic ecotoxicity	kg TEG water	1.1E+04	1.1E+04	1.2E+04	1.1E+04	1.2E+04	1.3E+04
Terrestrial ecotox.	kg TEG soil	3.0E+03	3.3E+03	3.3E+03	3.3E+03	3.7E+03	4.2E+03
Terrestrial acid/nut.	kg SO2 eq	1.5E+01	1.6E+01	1.6E+01	1.6E+01	1.6E+01	1.6E+01
Land occupation	m2org.arable	9.4E-01	1.6E+00	1.6E+00	1.6E+00	2.4E+00	3.2E+00
Aquatic acid.	kg SO2 eq	2.2E+00	2.2E+00	2.3E+00	2.2E+00	2.3E+00	2.4E+00
Aquatic eutrop.	kg PO4 P-lim	5.8E-02	6.5E-02	7.2E-02	7.8E-02	6.2E-02	6.2E-02
Global warming	kg CO2 eq	8.9E+02	9.1E+02	9.0E+02	9.1E+02	9.2E+02	9.5E+02
Non-renewable en.	MJ primary	1.9E+03	1.9E+03	2.2E+03	2.1E+03	2.2E+03	2.4E+03
Mineral extraction	MJ surplus	2.0E+00	2.6E+00	2.7E+00	2.6E+00	3.0E+00	3.5E+00
End-point impact:							
Human health	DALY	0.000545	0.000548	0.000552	0.000548	0.000558	0.000567
Ecosystem quality	PDF*m2*yr	40.96042	44.65901	45.09949	44.70147	49.61359	54.13713
Climate change	kg CO2 eq	892.8601	905.2404	898.4188	911.5195	924.1752	945.2027
Resources	MJ primary	1891.344	1893.867	2217.24	2073.99	2215.142	2422.118

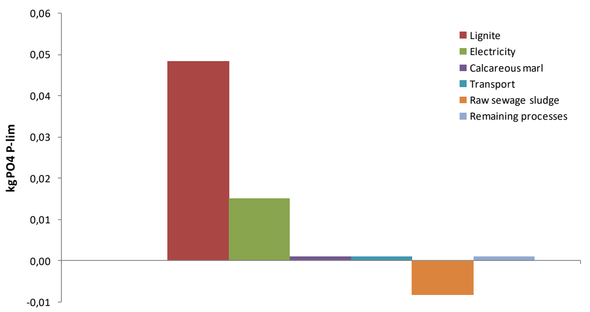

Fig. 2. The process contribution of aquatic eutrophication for Scenario 6.

Recently studies focusing on the determination of the potential human health risks of cement plants using sewage sludge as alternative fuels indicate that the option of using sewage sludge as alternative fuel represent an environmental improvement without additional health risk for the population [6], [19], [20]. Abuşoğlu *et al.* (2017) performed a comparative life cycle assessment (LCA) of a sewage sludge incineration for heat and power production with two scenarios: sewage sludge incineration plant based on a fluidized bed combustor (FBC) and a hypothetical cement kiln (CK) facility using sludge as a secondary fuel. The results of their study, in the human health category, the scores of the CK scenario preceded the scores of FBC for human health category [21]. Aranda-Uson *et al.* (2012) evaluated the environmental performance of clinker production using sewage sludge as alternative fuel with life cycle perspective for different scenarios. According to their study, three midpoint categories indicated an increment in the impacts with the addition of the sludge. It was clarified with the high content of heavy metals of the studied sewage sludge [22].

Considerable decrease has also seen in land occupation impact category. This impact category is impressed by transportation (road network, rail network…etc), mineral extraction site, arable, industrial area, dump site…etc. This result can be explained with the usage of different amount of import lignite, petroleum coke and natural gas (Fig. 3). Because the import lignite usage was decreased, land

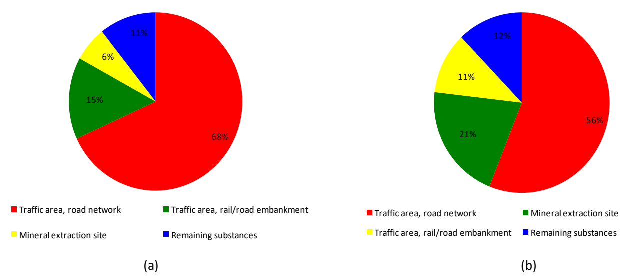

Fig. 3. Inventory of land occupation for Scenario 1 (a) and Scenario 6 (b).

A. Normalization

In addition to characterization results, normalization and weighting was also performed in order to determine the remarkable impacts arising from clinker production.

According to the normalization results, climate change and human health are the most critical impacts arising from clinker production (Fig. 4). Approximately 50% of total environmental impact results from climate change; 41% from human health.

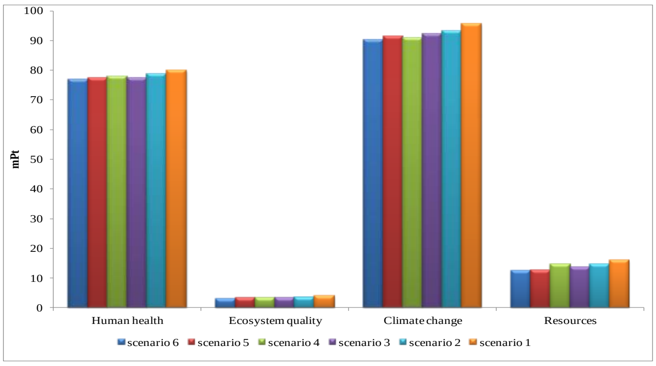

Fig. 4. Normalization results of different scenarios.

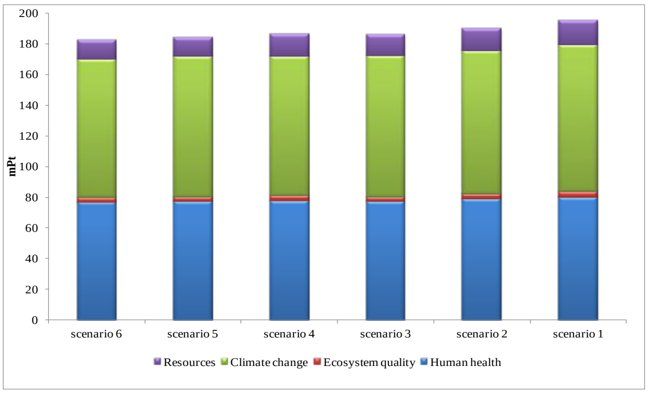

Fig. 5. The single score results of different scenarios.

Carbon dioxide is the main greenhouse gas arising from the cement [23] and the main contributor to climate change. Energy efficiency, the fuel mix which used to provide the required heat, and the amount of carbonate materials which used in clinker production are the main factors that determine CO_2 emissions in cement production in addition to the clinker content of cement [5]. In this study we determined GWP is 945 kg CO_2eq/ton.clinker for Scenario 1, 924 kg CO_2eq/ton.clinker for scenario 2, 912 kg CO_2eq/ton.clinker for scenario 3, 898 kg CO_2eq/ton.clinker for scenario 4, 905 kg CO_2eq/ton.clinker for scenario 5 and 892 kg CO_2eq/ton.clinker for scenario 6. Dried sludge usage reduced global warming impact significantly. Approximately 90% of CO_2 emissions results from kiln burning and 4% from electricity according to the contribution analysis. These values are compatible with other results obtained in literature. Valderrama *et al*. (2013) carried out a life cycle assessment study of clinker production using urban sewage sludge as alternative fuel or raw material in order to evaluate the environmental impact of urban sewage sludge usage in clinker production. As a result of the study, 898 g and 906 g CO_2-eq per kg of clinker produced were obtained for the fuel substitution and without substitution, respectively (about 1% reduction) [6]. In our study, from 2% to 6% reduction occurred in accordance with the proportion of alternative fuel usage. When the human health impact category was analyzed, it was determined that the highest contributor to human health is respiratory inorganics. According to the result of damage assessment, the most important contributor is respiratory inorganics (99%) which includes the $PM_{2.5}$(45%) and nitrogen dioxide (41%).

When the scenarios were taken into account separately (Fig. 5), it is conspicuous that Scenario 6 is the most environmentally-friendly choice. As a result of the impact assessment, the single scores were identified 195 mPt, 190 mPt, 186 mPt, 184mPt, and 182mPt for scenario 1, scenario 2, scenario 3 and scenario 4, scenario 5 and scenario 6; respectively.

IV. Conclusions

In this study, we assessed the life cycle assessment of one ton clinker production for 6 scenarios in Turkey. Dried sewage sludge and refused derived fuel as an alternative fuel instead of conventional fuels for clinker production were evaluated. The results indicate that alternative fuel substitution has significant reductions on ecosystem quality (from 8% to 25%), resources (from 8% to 22%), climate change (from 2% to 6%) and human health (from 2% to 4%). It can be concluded that alternative fuel usage in clinker production not only reduces the global warming potential impact, but also reduces carcinogens, non-carcinogens, land occupation, ionize radiation, acidification, eutrophication, ecotoxicity, energy and mineral extraction. When the 6 scenarios were taken into consideration separately, the most environmentally-friendly option was determined as Scenario 6.

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