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Energy Procedia 72 (2015) 127 – 134

Energy Procedia

International Scientific Conference "Environmental and Climate Technologies – CONECT 2014"

Life cycle assessment of renewable energy alternatives for replacement of natural gas in building material industry

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Abstract

Due to environmental and geopolitical reasons, the need for substitution of fossil fuels with renewable alternatives in industry is augmenting. The main objective was to assess environmental impacts of "cradle-to-gate" brick production stages and to evaluate the effect of fuel substitution and variation of electricity mix on the impact. Scenarios with natural gas, bio-methane, first and second generation bio-fuels used as the fuels in industrial furnace were studied. Scenarios were analyzed using "*ReCiPe*" and "*EcoIndicator'99*" impact assessment methods. Results show that environmental impact can be reduced by circa 50 % when natural gas is substituted with bio-methane or second generation bio-fuel.

Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment

Keywords: Bio-methane; Brick production; Building industry; Cradle-to-gate; Eco-design; Life cycle assessment; Renewable energy; Sustainable construction; System innovation

1. Introduction

Production sector of ceramic construction materials is energy-intensive due to operation of high-temperature kilns for long periods [1, 2]. Due to the energy consumption of machinery, the manufacturing stage of these materials contributes significantly to global warming by emissions of greenhouse gases (GHG). The construction sector consumes approximately 40 % of raw materials used globally every year [3] and bricks are among the major materials used for building construction [4]. Substantial amounts of energy are needed to fire bricks and tiles as well

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Peer-review under responsibility of Riga Technical University, Institute of Energy Systems and Environment
doi:10.1016/j.egypro.2015.06.018

as melt, shape, and harden ceramics. Although the production phase of construction materials has large environmental impact, the materials have a long life-time and reduce energy consumption of buildings. Therefore, life cycle assessment data are needed for comparison of various alternatives for selection of construction materials.

Various studies have been conducted to optimize kilns and plants [5–7], to study the effects of additives on fuel consumption and on mechanical-physical properties of bricks [8–10], to develop sustainable construction materials via waste recycling [11, 12], and to assess life cycle of buildings or building construction systems [13, 14]. Notwithstanding, less attention seems to be paid to the evaluation of environmental impact caused by the production of certain types of construction materials, or to rate changes of environmental impact caused by the substitution of fuel.

As to the first, only a few studies are published which show evaluation of the environmental impact of ceramic building materials. The study of environmental assessment of brick production in Greece [4] used the method *EcoIndicator'95* to quantify impact. This method is a predecessor of the *EcoIndicator'99* method. But currently even more recently developed methods such as the *ReCiPe* [15], which is used to evaluate environmental aspects of brick production in Latvia in the present study, are available.

There are studies related to energy efficiency improvements or use of renewable energy sources [16, 17] for reduction of GHG emissions per unit of production. However, it is expected that the energy "embodied" in the construction materials will become more critical in the future as the energy efficiency of buildings will increase. In the Reference Document on best available technologies (BAT) in the Ceramic Manufacturing Industry (issued by the European Commission) it is mentioned that mostly natural gas, liquefied petroleum gas and extra light fuel oil are used for brick firing at the present time. Other energy sources, e.g. liquefied natural gas, biogas, biomass, electricity, heavy fuel oil and solid fuels (e.g. coal, petroleum coke) are used in burners of furnaces [1]. In the Reference Document it is declared that environmental benefits could be achieved by switching from heavy fuel oils or solid fuels to natural gas (also liquefied petroleum gas and liquefied natural gas). It is also noted that renewable energy sources could play a role as energy sources for burners, but information gaps still exist– lack of emission and consumption data [1].

Studies based on life cycle inventory data [18, 19] show that if bio-methane is substituted for natural gas, GHG emissions can be reduced by nearly 80 %. It can be claimed that substitution of fuels in this type of industry can give more substantial environmental benefits than gradual improvements of equipment efficiencies. Recently Ellersdorfer and Weiβ have described integration of biogas plants in the cement industry from the energy and economic point of view [17]. However, a more detailed study based on life cycle assessment and considering other alternatives, e.g. bio-fuels is needed. Therefore, in this research three different renewable energy sources, i.e. bio-methane, as well as 1st and 2nd generation bio-fuels, for use in the Latvian ceramic brick industry are compared on the basis of environmental impact.

The research questions for this study are the following: how large are environmental impacts created by processes of brick production in Latvia and how these impacts change if energy sources used for the production, i.e. fuel for heat supply and electricity mix, are varied? The main goal of this study was to characterize environmental impacts of brick production stages ("cradle-to-gate") at midpoint and endpoint impact category level (1), to evaluate the effect of fuel substitution and variation of electricity mix on the environmental impact (2). The results were primarily targeted for the purpose of ecodesign applied to the building sector as well as to reduce the environmental impact of the brick production industry. Results of the study are important for building design and construction material industry as well as for planning future energy supply systems. Bricks manufactured in Latvia are exported to many countries and therefore the results are relevant for a wider region. This study continues the previous research [18–20] where the environmental impact of building materials for the purpose of ecodesign were characterized, environmental aspects of substitution of the natural gas by bio-synthetic natural gas were analyzed, and life cycle assessment of biomethane supply system was carried out, by considering more fuel alternatives for brick firing and using LCA methodology with two impact assessment methods.

2. Materials and methods

Life cycle assessment (LCA) methodology was used to characterize the “cradle-to-gate” environmental impact of bricks produced in Latvia. LCA is one of the most important tools for ecodesign, and it covers a multitude of environmental aspects [21–23]. LCA in this study is made following the procedures set by ISO standards 14 040 and 14 044 [24, 25].

The study aims to assess the changes of the environmental impacts when natural gas which is currently used in the brick firing furnace, is replaced by bio-methane and liquid bio-fuels. The influence of electricity supply mix on environmental impacts was studied as well.

2.1. Functional unit and system boundary

One ton of brick was chosen as a functional unit and the reference flow for the purpose of the study. The system investigated, including the main inputs and outputs, is shown in Fig. 1. Construction of the plant was not evaluated in the study.

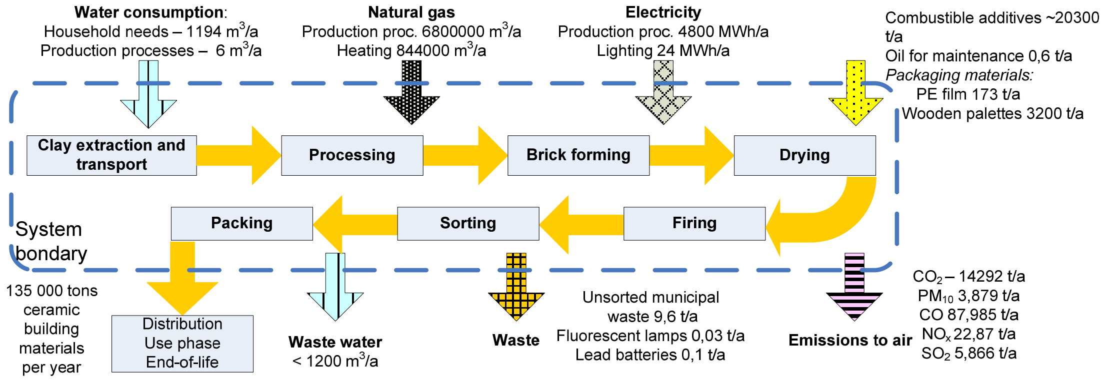

Fig. 1. Schematic presentation of the system boundary and the main inputs and outputs Life cycle impact assessment methodology and types of impacts

The LCA software “*SimaPro 8.0.0*” [26] was used to model and analyze environmental impacts caused during a product’s life-cycle. EcoInvent (v2.2), European Life Cycle Database (ELCD v2.0) and U.S. Life Cycle Inventory (USLCI) database were used. Only system processes from the databases were selected for this study.

Environmental characterization of “cradle-to-gate” brick production was done both at midpoint impact category level and by calculating the single score indicator. To make the study results comparable with recent studies performed worldwide and applicable for ecodesign purpose in cases where Latvian produced ceramic materials are involved, the following two impact assessment methodologies were used:

- *ReCiPe* which is the most recent and harmonized indicator approach available in life cycle impact assessment and is an improvement on *CML 2000* and *EcoIndicator'99*. *ReCiPe* comprises harmonized category indicators at the midpoint and endpoint level;
- *EcoIndicator'99* is one of the most widely used impact assessment methods in LCA and the first endpoint impact assessment method, which allowed the environmental load of a product to be expressed in a single score. *EcoIndicator'99* method was used in this study since during recent years many other studies were based on this method and therefore the results of this study can be compared with the results of other researchers.

Both methods have been created for three different cultural perspectives: Egalitarian, Hierarchist and Individualist to consider the potential damage from a particular substance [26]. Only the Hierarchist perspective is selected for the study. Hierarchist perspective is described [27–29] as the one which takes a long-term look at all substances if there is consensus regarding their effect. Hierarchist perspective coincides with the view that the time perspective is balanced and impacts can be avoided with proper management. Hierarchist is often considered to be the default model and was also chosen for this study. Therefore, for the study *ReCiPe* Endpoint (Europe ReCiPe H/A) [29] and *EcoIndicator'99* (Europe EI 99 H/A) methodologies [30] were selected. "H" refers to the weighting set belonging to the hierarchist perspective. "A" refers to the average weighting set and is recommended by the developers of both methods.

Only those impact categories which had at least 5 % of the total environmental impact were chosen for further analysis and are shown in the results. Hence, the following six impact categories of the *ReCiPe* method were considered: (1) fossil depletion, (2&3) climate change (human health and ecosystem), (4) particulate matter formation, (5) agricultural land occupation and (6) terrestrial ecotoxicity. Similarly five impact categories were considered for *EcoIndicator'99* method: (1) fossil fuels, (2) respiratory inorganics, (3) climate change, (4) carcinogens and (5) land use. "Cradle-to-gate" LCA was performed and the system boundary include clay extraction and processing, shaping, drying and firing of bricks, and packaging. *The aim of the study was not to compare results obtained by ReCiPe and EcoIndicator'99 methods but to obtain results which, despite the differences and sensitivity in the methods, allow to arrive at similar conclusions regarding the choice of scenarios.*

2.2. Types and source of data

The study was based on one year operational data obtained from site visits to a brick factory and data reported in the polluting activities permit issued to the company [31]. The main inventory results are presented in Fig.1.

Life cycle impact of production depends on electricity sources which in turn depend on power market conditions. Therefore, the assessment was started by setting up two electricity supply mixes which are referred to as "A" and "B" in order to find out the influence of electricity market conditions on environmental impact of the brick production. If during winter ethe lectricity prices in "NordPool Spot" market are relatively high, domestic natural gas-fired cogeneration plants are competitive and produce circa 40 % of gross annual power consumption (scenario "A"). Another 40 % of the gross annual power consumption is supplied by local hydropower plants and the remaining 20 % are imported. However, if the market electricity prices are low, district heat is produced by heat-only boilers and the share of cogeneration plants reduces to 20 % while the share of imported electricity increases to 30 % (scenario "B"). The remaining electricity is supplied by hydropower plants.

Since a large share of imported electricity in Latvia is supplied from Estonia, it was assumed that 90 % of the electricity import comes from Estonia and 10 % from the Nordic countries. Oil shale is the main fuel for power production in Estonia and around 90 % of the electricity is produced in oil shale - fired Narva condensing power plants [32]. For the purpose of the life cycle impact assessment, lignite was used instead of oil shale and hydropower was used as the electricity production source in the Nordic countries. It is reasonable to assume that for conditions of low electricity market price (scenario "B") a large share of the gross annual power consumption is supplied by hydropower since the low power price is characteristic for the periods with increased hydropower production.

In order to analyze life cycle impact of production depending on fuel, four different fuel scenarios, referred to as "N", "M", "F1" and "F2", were established. Scenario "N" refers to the existing situation where natural gas is used for firing furnaces. Scenario "M" refers to using bio-methane instead of natural gas. Life cycle impact when 1st generation and 2nd generation bio-fuels are used for the production was assessed in scenarios "F1" and "F2", respectively. Construction of the bio-fuel plants was not included in the study.

Bio-methane as a renewable substitute for natural gas was selected for the study. Bio-methane can be produced locally by the anaerobic digestion of organic waste (such as plant material, animal manure, sewage, organic waste, etc.). Bio-methane is considered as one of the most viable renewable substitutes for natural gas [33] since after removal of contaminants, bio-methane can be used as the natural gas utilizing advantages of the well-developed natural gas infrastructure. Biogas, due to sufficiently high average heating value (21 MJ/m^3 with 60 % methane), can also be directly used as a fuel in burning processes [17] but, because biogas cannot be injected into the natural gas grid, it cannot be considered as a direct substitute for natural gas if not upgraded to the quality of the natural gas.

Rape methyl ester was chosen as the 1st generation bio-fuel for scenario “F1” and vegetable oil from waste cooking oil was chosen as the 2nd generation bio-fuel for scenario “F2”. Data for life cycle impact assessment of these fuels were taken from the *SimaPro* database. Lower heating value for both bio-fuels was assumed to be 37.27 MJ/kg for calculations of the necessary amount of fuels.

Natural gas is used mainly in the firing stage and circa 11 % are used for heating needs. Hence, all natural gas consumption as well as emissions to air are limited to this stage only. The clay processing stage has the largest electricity consumption therefore it is assumed that 40 % of all electrical energy is used during this stage. 25 % of electricity is consumed in both drying and firing stages, but 5 % of the electricity is used in the forming and packing stages.

3. Results and discussion

Results of environmental impact of the electricity mix obtained with *ReCiPe* method for scenarios “A” and “B” are 13.8 mPt/MJ and 13 mPt/MJ respectively. Study with *Ecoindicator’99* method gave larger difference, i.e. 12.4 mPt/MJ and 10 mPt/MJ respectively. Result of scenario “A” and the result available in ELCD database [26] for Latvian medium voltage electricity mix correspond very well. When electricity scenario “B” is used instead of “A”, the environmental impact per functional unit, expressed as a single score, reduces by only 0.6 % for *ReCiPe* (or by 2.2 % for the *Ecoindicator’99* method). Since variation of the electricity mix does not significantly impact the resulting total impact, only the electricity mix of scenario “A” was used for further analysis.

Assessment of environmental impacts of the production of 1 ton of ceramic building materials with *ReCiPe* method shows that the largest share of environmental impact for all scenarios is associated with the consumption of firing fuel and electricity. Impacts created by clay extraction, added sawdust (combustible additive) and packaging materials (polyethylene film and wooden pallets) have minor and similar impact (Table 1: the results obtained with the EcoIndicator’99 method are indicated in brackets).

Table 1. Environmental impacts related to the production processes per functional unit obtained with *ReCiPe* method*

Scenario	N	M	F1	F2
Fuel (%)	81 (76)	64 (52)	90 (94)	57 (63)
Electricity (%)	11 (12)	20 (24)	6 (3)	24 (18)
Clay extraction (%)	2 (4)	4 (8)	1 (1)	5 (6)
Additives (%)	2 (3)	4 (5)	1 (1)	5 (5)
Packaging (%)	4 (5)	8 (11)	2 (1)	9 (8)

*Results obtained with the EcoIndicator’99 method are indicated in brackets

When natural gas is replaced with bio-methane (scenario “M”), total environmental impact is reduced by 46 % by the *ReCiPe* method (Fig. 2a) and by 51 % if the *EcoIndicator’99* method is used for assessment (Fig. 2b). If 2nd generation bio-fuel is used instead of natural gas (scenario “F2”), impact is reduced by 55 % and 35 % respectively. In contrast, the use of the 1st generation bio-fuel (scenario “F1”) would greatly increase environmental impact for both methods, i.e. by 93 % and 321 % respectively. The increase of environmental impact may be associated mainly with cultivation of rapeseeds requiring use of land and fertilizers.

Comparing results for scenario “N” with the total environmental impact calculated for brick production process from the EcoInvent (v2.2) database, it can be concluded that ceramic building material production in Latvia, using natural gas as a firing fuel, causes ~18 % less environmental impact when the *ReCiPe* method is used, and ~10 % less if the *EcoIndicator’99* method is used. This difference may arise due to discrepancies in fuel consumption input. As we know bricks, suitable for different purposes, differ in their composition and the quality of the raw materials used, weight and size of the bricks, and other factors. Thus, the duration of the firing and temperature, and fuel consumption may vary.

Due to use of natural gas most affected impact categories for the scenario "N" are fossil depletion and climate change when *ReCiPe* method is used (Fig. 2a) and fossil fuel category with *EcoIndicator'99* method (Fig. 2b). For scenario "M", the greatest impact is in the same categories as for scenario "N", i.e. fossil depletion and climate change for *ReCiPe* and in the categories fossil fuel and respiratory inorganics if *EcoIndicator'99* method is used. These impacts are associated mainly with the usage of fossil fuel for biogas production and purification.

Results of scenario "F1" differ from the results of the two preceding scenarios in that the major impact occurs in categories related to agricultural land occupation and terrestrial ecotoxicity (31 % and 23 % of the total impact respectively) with *ReCiPe* (Fig. 2a) and land use (67 % of the total impact) with *Ecoindicator'99* (Fig. 2b). These impact categories can be related to the soil cultivation, sowing, weed control, fertilization, pest and pathogen control, harvest and drying of the grains necessary for the production of 1st generation bio-fuel.

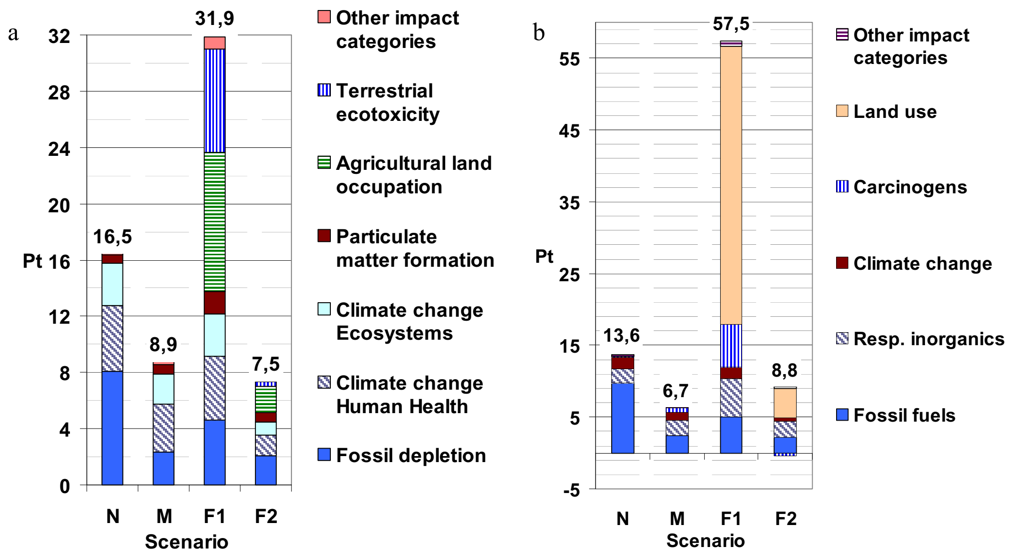

Fig. 2. Cumulated single score results of environmental impact per functional unit obtained using (a) ReCiPe and (b) EcoIndicator'99 impact assessment method for the considered alternatives of the firing fuel. "N" – natural gas; "M" – bio-methane; "F1" – 1st generation bio-fuel; "F2" – 2nd generation bio-fuel

In scenario "F2" the greatest impact occurs in two categories – fossil depletion and agricultural land occupation (27 % and 25 % of the total impact) with *ReCiPe* (Fig. 2a) and similarly as in scenario "F1" in land use category (46 % of the total impact) with *Ecoindicator'99* (Fig. 2b). Environmental impact in those categories could arise from the consumption of fossil fuel for the esterification process of the vegetable oil to methyl ester and glycerin, as well as for farming processes to obtain grains necessary for the production of vegetable oil.

Koroneos and Dompros using *EcoIndicator'95* method calculated that the impact indicator of 1 ton of brick production in Greece is 0.35 Pt if pet-coke is used for firing [4]. When *EcoIndicator'95* method was used in this study for the purpose of comparison of the results, the obtained cumulated single score indicator for 1 ton of bricks was 0.15 Pt if natural gas or 2nd generation bio-fuel is used; 0.29 Pt if bio-methane is used; and 0.54 Pt if the 1st generation bio-fuel is used.

4. Conclusions

The total single score results indicate that the most substantial decrease of environmental impact of brick production may be achieved if natural gas is substituted by bio-methane for firing of the bricks. It is important to consider that this option would not require technical changes of furnace burners. The second best alternative from the environmental point of view would be use of the 2nd generation bio-fuel. However, technical adjustments for firing of the fuel may be required. Use of the 1st generation bio-fuel would have the greatest impact on the environment by far exceeding the scenario where natural gas is used as the firing fuel. The vast impact in this case may be related to land use, all of the agricultural activities, including also fertilization. Variation of electricity mix due to power market conditions does not have a significant effect on the total environmental impact for the studied electricity supply system: environmental impact per functional unit reduces by only 0.6 % if the *ReCiPe* (or by 2.2 % if *Ecoindicator'99*) method is used.

Supply of bio-methane to industry could be done via the existing natural gas supply infrastructure. Technical, environmental and economic criteria of alternatives for development of bio-methane supply system which is based on the natural gas grid need to be studied to find out optimal solutions.

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