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A systematic LCA-enhanced KPI evaluation towards sustainable manufacturing in industrial decision-making processes. A case study in glass and ceramic frits production.

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Abstract

Technologies are difficult to assess in an early stage of development. A comparison between innovative and conventional technologies is often complex due to differences in scale (large-scale with several 100 t/d vs. demonstrator-scale with less than 100 kg/d) and subsequent efficiency. A methodology is implemented using Key Performance Indicators (KPIs) enhanced by Life Cycle Assessment (LCA) aspects and incorporating industrial principles for technology assessment. The methodology is applied to identify the trade-off between direct and indirect emissions and to evaluate scale dependency with focus on energy and broader sustainability. The applicability is illustrated for glass and ceramic frits production and supported by experimental data for conventionally and innovatively heated processes.

Keywords: Key Performance Indicator; technology assessment; Life Cycle Assessment; sustainable manufacturing; case study; microwave; glass production

1. Introduction

Diminishing resources and increasing energy prices are key drivers for industrial producers to develop sustainable and innovative manufacturing processes. Investments in innovative production processes may appear to be less beneficial in an early stage of development than investments in state-of-the-art technologies. This is mainly connected to the size differences between innovative demonstrator-scale technologies (kg/d output) and conventional (CONV) large-scale technologies (t/d output). These differences have to be taken into account in a technology assessment concerning effectiveness and efficiency. The development and implementation of performance measurement methods using Key Performance Indicators (KPIs) support producers by quantifying processes, highlighting potential vulnerabilities and evaluating and benchmarking them [1]. These quantifiable and strategic measures are essential for understanding and improving manufacturing performances, both from the perspective of eliminating waste as well as achieving strategic goals which are most critical for current and future success [2-3]. Based on industrial principles for technology assessment, KPIs support the comparison of different processes and their results within a branch of manufacturing industry, but are limited in regard to different production scales and methodologies. Therefore, this paper presents a contribution on new types of KPIs with focus on energy and broader sustainability. In existing literature [4-5] the indirect emissions are exclusively assigned to the generation of electricity.

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The present work introduces KPIs which incorporate additional sources of indirect CO_2 and NO_X emissions for the first time, such as production and transportation of raw materials and fuels used (natural gas in particular). Combined KPI and Life Cycle Assessment (LCA) methodologies were only recently introduced for technology assessment and decision making processes [6-7]. This paper illustrates further development of a combined KPI and LCA technology assessment under consideration of scale effects due to production rates and/or plant sizes using the example of glass and ceramic frits melting. Implementing a LCA approach is considered necessary in order to properly understand the trade-off of emissions being "reallocated" from a "gate-to-gate" boundary to upstream "cradle-to-gate" processes, like presented in the case study examined.

2. The role of technology assessment in glass and ceramic frits production

Conventional glass processing comprises of raw material preparation, melting, fining and forming, whereby temperatures above 1500°C are necessary. The goal is the production of various glass products of specified shape, colour and quality. Ceramic frits are produced by melting raw materials at 1200°C, usually prepared in a powdery state, and quenching the molten material in water, obtaining a vitreous, insoluble material.

The intensive energy demand, that characterizes the industrial processes of these materials, is mainly linked to limited thermal efficiency of conventional furnaces involved in running plants. Different manufacturing processes exist and play an important role for technology assessment since every production process has its specific behaviour. This has to be taken into account for starting a KPI evaluation. Therefore, the substitution of CONV with innovative furnaces is investigated for the innovative microwave (MW) technology. The application of MW heating has already proven advantageous in lab scale trials for glass and ceramic frits production. A scaled-up version (demonstrator-scale) of a developed MW lab-scale prototype from [7] was used for this study, comprising of a 915 MHz magnetron with an usable output of 30 kW. The demonstrator was used to melt glass and ceramic frits. Energy consumption of the magnetron was measured directly by a power meter at power supply.

3. Methodological approach

3.1. Description of overall methodology

Life-Cycle-Assessment is a methodology that estimates the environmental impact of processes and products during their entire life cycle. The conventional LCA approach [8-10] is divided into four steps (see Figure 1; white boxes). The main differences between the conventional LCA and the methodology proposed are related to the second (2) and the third (3) step of the LCA. These are the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA), which are extended by KPI aspects (see Figure 1; grey boxes).

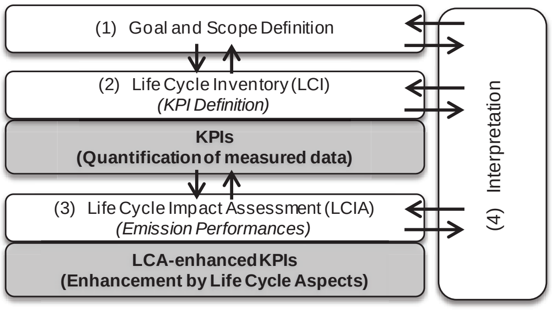

Figure 1: Methodological approach for LCA-enhanced KPI study

In a first step (1), the LCA-enhanced KPIs focus on the evaluation of the entire manufacturing process of glass and ceramic frits materials, based on both CONV and MW heating systems (Goal and Scope Definition). The second step (2) of the methodology concerns the collection of all necessary information about consumption (inputs) and outputs of the manufacturing processes (LCI). A comprehensive process understanding is significant within this step to define and identify relevant KPIs in terms of energy consumption and emissions for the assessment of the processes investigated. Moreover, the KPIs can be quantified directly by the measurement of material flows. Within the third step (3), the evaluation of the emission performance of the quantified KPIs enhances the study by life cycle aspects (LCIA). Indeed, the LCA results are not presented through common environmental indicators, such as Global Warming Potential, Acidification and Eutrophication [17] but focus on CO_2 and NO_X emissions per ton of material.

The main purposes of the LCA-enhanced KPI study are the assessment and comparison of environmental impacts of different production processes. The applied methodology provides several benefits for decision makers, although it is obvious that KPIs can only be measured and applied after a new technology has already been implemented. Benefits are the identification of opportunities to improve environmental performance of products and technologies, the adoption of new technologies and the easy interpretation by the end-users due to quantitative results.

3.2. LCA for glass and ceramic frits production

The LCA is a considerable basis for the identification of KPIs as those parameters which are of special importance for the assessment of a process. In particular, the LCA focuses on the evaluation of the entire manufacturing process, based on high temperature heating systems. Different materials, energy consumption and energy efficiency have been taken into account in terms of KPIs associated with the proposed solutions over the "cradle-to-gate" life cycle of the products. Since the main difference between the CONV and MW system boundary is the melting step (main process), the LCA system boundaries are applied for this phase to generate a functional unit of 1 t of glass and ceramic frits as a final product. Other life cycle phases, e.g. use and end of life, are excluded from the analysis, since they represent phases common to all alternatives and contribute the same environmental impacts. Natural gas is