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Sustainable manufacturing of consumer appliances: Reducing life cycle environmental impacts and costs of domestic ovens

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ABSTRACT

Electric ovens are among the least energy efficient appliances, with the efficiency of only 10%–12%. With new policy instruments in Europe requiring energy reduction, manufactures are seeking to develop more efficient domestic appliances. The aim of this paper is to aid sustainable manufacturing of an innovative, highly-efficient oven (HEO) by evaluating its life cycle environmental impacts and costs in comparison to conventional ovens. The results suggest that the HEO has 9%–62% lower environmental impacts than conventional ovens with the equivalent savings in the life cycle costs ranging from 25% to 61%. Replacement of conventional ovens by HEO in Europe (EU28) would save 0.5–5.2 Mt of CO_2 eq. and the life cycle costs would be lower by €0.5–1.96 billion (10^9) per year. At the household level, energy consumption would be reduced by up to 30% and consumer costs by 25%–50%. These results suggest that policy measures should be put in place to encourage the uptake of energy efficient ovens by consumers.

Keywords: Life cycle assessment; Life cycle costs; Domestic ovens; Sustainable manufacturing

1. Introduction

It is estimated that there were 185.3 million cooking appliance units globally in 2015 (Global Industry Analyst, 2011) with the market value expected to reach $231 bn by 2018 (Data Monitor Research, 2014). In Europe, around 12 million electric ovens are sold each year (Eurostat, 2009). Electric ovens are among the least energy efficient appliances, with the efficiency of only 10%–12%. Given that they consume 100–300 kWh per year (Fonseca et al., 2009) and that 61% of 213.8 million households in the European Union (EU28) have electric ovens (Bertoldi et al., 2001), this amounts to around 26 TWh of electricity per year. If their efficiency increased by only 20%, that would mean a saving of around 5 TWh of electricity annually. In an attempt to stimulate reduction of energy use by domestic appliances and particularly ovens, the EU has adopted several policy instruments, including the Energy Labelling Directive (EC, 2013a). The Directive, which for ovens came into force in January 2015, classifies ovens into seven categories, from A+++ to D, based on the energy efficiency of the oven cavity. The Directive requires manufacturers and retailers to display on a label the energy consumption by the oven (expressed in kWh per cycle) based on a standard load.

In anticipation of the Directive, manufactures have been seeking to develop more efficient appliances. This paper considers sustainable manufacturing of a new highly-efficient oven (HEO), being developed by Whirlpool, one of the largest oven manufacturers in the world. The primary aim of developing the HEO is to increase the energy efficiency of domestic ovens during use by around 30% relative to

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conventional ovens. A further aim is to improve energy efficiency of oven manufacturing. These improvements are also expected to reduce the costs to consumers and the manufacturer as well as to lead to substantial savings in environmental impacts. To quantify these potential benefits, HEO is compared here to conventional ovens using life cycle assessment (LCA) and life cycle costing (LCC). To our knowledge, this is the first study of its kind for domestic ovens. The following section details the methodology, followed by the discussion of the results in Section 3 and conclusions in Section 4.

2. Methodology

The LCA methodology follows the guidelines in ISO 14040/44 (ISO, 2006a,b) and 14044 (ISO, 2013). The environmental impacts have been estimated as follows (Azapagic et al., 2007):

$$B_j = \sum_{i=1}^{I} b_{j,i} x_i \quad j = 1, 2, \ldots, J \tag{1}$$

$$E_k = \sum_{j=1}^{J} ec_{k,j} B_j \quad k = 1, 2, \ldots, K \tag{2}$$

where:

$b_{j,i}$ environmental burden j per unit activity i, with burdens representing raw materials and energy used in the system and emissions to air, water and land

x_i mass or energy flow associated with unit activity i

$e_{k,j}$ relative contribution of the total burden B_j to impact E_k as defined by the CML 2001 method (Guinée et al., 2001).

The focus of the study is on the global warming potential (GWP) but the following impacts are also considered to ensure that greenhouse gas emissions are not reduced at the expense of other aspects: acidification, eutrophication, ozone layer depletion, photochemical smog and human toxicity. The eco-toxicity categories are not considered due to a lack of data and the associated uncertainty.

The LCC methodology is congruent with LCA and follows the approach developed by UNEP and SETAC (UNEP and SETAC, 2009) and Swarr et al. (2011) The life cycle costs have been estimated according to:

$$LCC = C_{RM} + C_M + C_U + C_W \tag{3}$$

where:

LCC total life cycle costs over the lifetime of the oven

C_{RM} costs of raw materials

C_M costs of manufacturing

C_U costs of use of ovens over the lifetime, including electricity and cleaning agents

C_W costs of end-of-life waste disposal.

The CCaLC v3.1 software (CCaLC, 2013) has been used to model the system and estimate both the environmental impacts and life cycle costs. The following sections detail the goal of the study, system boundaries, data and assumptions.

2.1. Goal and scope of the study

The main goal of the study is to assess the life cycle environmental impacts and life cycle costs of the HEO and quantify the environmental and economic benefits relative to conventional ovens. As described further below, the only difference in the design of the two oven types is the cavity, so that the study considers only this part of the oven. As illustrated in Fig. 1, the system boundary includes production of the raw materials used to manufacture the cavity, the manufacturing process, use of the oven and end-of-life waste management. Transport is excluded as it contributes less than 0.1% to the impacts and costs.

Both ovens have the same volume of the cavity (73 litres) but they are made from different materials: low-carbon steel and enamel are used for the conventional oven, while the HEO cavity is made using stainless steel and sol–gel (Fig. 2). Stainless steel is used for the HEO because of its high reflectivity (Fig. 3) and ease of cleaning, while the sol–gel coating prevents loss of reflectivity owing to metal oxidation which occurs at high temperatures, a common problem in conventional enamel-based oven cavities. The manufacturing process for both ovens is the same except for the enamelling process for the conventional oven and application of sol–gel for the HEO. Therefore, only the enamelling and application of sol–gel are considered, respectively, in the manufacturing stage.

The substrate material for the enamel layer in the conventional oven is a low-carbon enamelling grade steel formed into a cavity. The stainless steel substrate for the HEO cavity is produced at supplier in the form of coil. A protective film is then applied to the coil, which is then rolled and shipped to the in-house post-coating line. The coil is unwound and cut into appropriate panel dimensions after which the protective film is removed and the panels degreased. The first sol–gel coating is applied in a liquid-spray coating stage, dried, cured and allowed to cool down. Subsequently, the second sol–gel layer is applied again in another liquid-spray coating stage, dried, cured and allowed to cool down. The coated panels are then sent to the manufacturing line after application of a protective film.

The use stage includes electricity consumed and oven cleaning over its lifetime. The conventional oven can be cleaned either by using chemicals (aerosol oven cleaners or traditional dish-washing detergents) or a built-in pyrolytic self-cleaning cycle in which the oven is heated to over 400 °C to reduce any deposits to a thin layer of ash, which can then be cleaned away easily. The HEO, on the other hand, can be cleaned using traditional dish-washing detergents.

The unit of analysis (functional unit) of the study is defined as the 'manufacture of 1 domestic electric oven cavity and its use over a lifetime of 19 years'. This lifetime is based on the average lifetime of ovens estimated by Mudgal et al. (2011); however, a shorter lifetime is considered as part of a sensitivity analysis. The oven is manufactured in Italy and assumed to be used in the EU28 region.

2.2. Data and assumptions

Tables 1–3 summarise the data used in the study and their sources. As indicated in the tables, primary production data have been sourced from Whirlpool Europe while the secondary data have been obtained from LCA databases and the literature.

For the use stage, 110 use cycles are assumed annually over 19 years for both types of oven. The conventional oven consumes 0.69 kWh of electricity per cycle as measured by the manufacturer in accordance with the standards CSA