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Reducing the environmental impacts of vitreous optical fiber production – A Life Cycle Impact Assessment

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ABSTRACT

Optical fibers have become the backbone of long distance telecommunications, thus, reducing the environmental impacts of its production process poses as a crucial step towards its sustainable deployment worldwide. This paper presents and discusses the Life Cycle Impact Assessment of the Modified Chemical Vapor Deposition (MCVD) vitreous optical fiber production process. The environmental impacts of 18 production scenarios were analyzed and compared using the Umberto NXT modeling software, generating cradle-to-gate results in accordance to the criteria of two Project Oriented Environmental Management indicators: IPCC 2007 Global Warming Potential and ReCiPe Hierarchical Average Environmental Impact. Two main results were achieved: (a) the carbon footprint of the MCVD production process (8.02 kgCO_2eq per kilometer of optical fiber, business as usual) – which represents a novel contribution to this field of scientific research –, and (b) less environmentally impactful production alternatives – namely metallic, ceramic and chalcogenic raw material combinations, renewable energies and a different catalyst. Secondary results and analyses of the production process were also discussed in order to highlight the importance of decision-making in raw material and energy sourcing strategies as drivers to reduce the environmental impacts of vitreous optical fiber production.

1. Introduction

Optical fibers were designed to surpass the current generation of copper- and aluminum-based communication technologies that permeate human relations (Schramm, 1988; Agrawal, 2003). They are already a key component in cloud computing, self-correcting networks, mobile data telephony and non-satellite wireless infrastructure (Artundo et al., 2011; CITEL, 2015).

According to the International Telecommunications Union (ITU), optical fibers' participation in overall telecommunications networks has grown significantly since 2013, especially in Europe (21.5%) and the Americas (14.2%) (ITU, 2010, 2015). Nevertheless, it is natural that all countries will seek the same reality of countries such as Japan and Korea, where optical connections have already exceeded 60% of the total (OECD, 2011; Hwang and Choi, 2012).

To ensure that optical communication systems are increasingly efficient, several experts and scientists are dedicated to the improvement of optical fibers' production processes, however, its environmental aspects are not yet thoroughly discussed (Bartnikas and Srivastava, 2003; Haykin, 2001).

There is an increasing number of laws, standards and certifications addressing environmental impacts in several areas – including telecommunications –, but few address optical fibers directly (Haykin, 2001; Mendez and Morse, 2007). Therefore, there is a gap not only in terms of legal and regulatory framework, but also scientific and technical studies regarding the environmental aspects of optical fibers (Deveau, 2001; Bartnikas and Srivastava, 2003).

This paper aims to contribute to the discussions within said gap

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and to suggest environmentally friendlier production arrangements and sourcing strategies. To that end, the physical and chemical data that permeate the environmental aspects of optical fiber production were surveyed, modelled and production scenarios were simulated.

1.1. The production process

Optical fibers weigh, on average, less than 1 g per meter and can be produced with ceramic (Farhi et al., 2009), polymeric (Carvalho, 2010; Ritzhaupt-Kleissl et al., 2006) and vitreous materials (Skorinkarpov et al., 2012; Mrabet et al., 2010), being the latter the most common for long range telecommunication (Bäumer, 2011; Poulain et al., 2003), especially when combined with rare-earth minerals such as erbium, ytterbium, gadolinium, praseodymium, and neodymium (Augustyn et al., 2011; Ballato et al., 2010; Churbanov et al., 2010).

Currently, the most common process to produce vitreous optical fibers is the modified chemical vapor deposition (MCVD) (Mendez and Morse, 2007), which consists of depositing several layers of SiO_2 and GeO_2 inside a glass tube that will undergo a stretching process (Agrawal, 2003; Ferdousi et al., 2012).

Fig. 1 shows the primary stage of the production process, which occurs in a precision lathe equipped with a hydrogen-oxygen transverse mobile blowtorch. The glass tube is placed in the lathe and, while it rotates, oxygen acts as a vehicle to inject $SiCl_4$ and $GeCl_4$ into it (Mendez and Morse, 2007). A gaseous catalyst is also injected to stabilize the temperature, namely phosphoric oxychloride ($POCl_3$, which breaks into P_2O_5) or boron tribromide (BBr_3, which breaks into B_2O_3) (Agrawal, 2003). As these gases are cyclically injected, the blowtorch moves along the tube, raising its temperature to 1500 °C. As a function of the temperature difference between the injected gases and the heated tube – a physical phenomenon known as thermophoresis (Prat et al., 2007) –, there is sequential deposition of thin layers of vapor on the inner walls of the silica tube, forming what will become the fiber's core (Bentzen, 2006; Lin et al., 2008; 2012).

Once all the layers have been deposited inside the silica tube, it goes through a sealing process, in which the torch reaches 2000 °C and runs the length of the tube until the high temperature causes the silica cladding to merge with the films deposited in its interior, configuring a solid cylinder known as preform. Next, the pulling/drawing is responsible for converting the preform into a fiber, a process that takes place in a mechanical system called a pulling/drawing tower, seen in Fig. 2.

The tower's feeding mechanism (V_1) inserts the preform into the center of a precision furnace (V_2), melting the preform at 2000 °C (2273.15 K) (Agrawal, 2003; Mendez and Morse, 2007). Based on the speed with which the preform is inserted into the furnace, its temperature, and the preform's viscosity, its own weight and the action of the force of gravity cause the material to stretch, creating a filament (Cheng and Jaluria, 2005; Lancry et al., 2012). At this temperature, the vitreous silica (SiO_2) rearranges its crystalline molecular angles and distances in order to become α-cristobalite, with a refractive index that can reach 2.34 (Vainshtein et al., 2000; Yang and Jaluria, 2009).

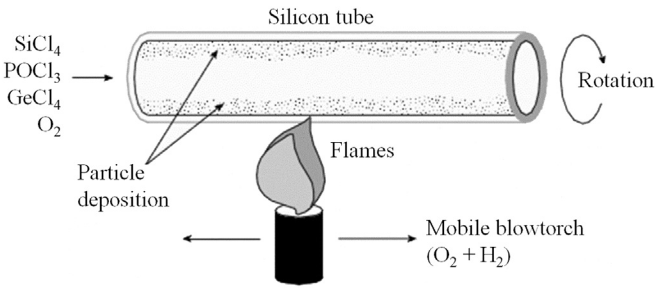

Fig. 1. Preform manufacturing process (adapted from Ribeiro, 2006).

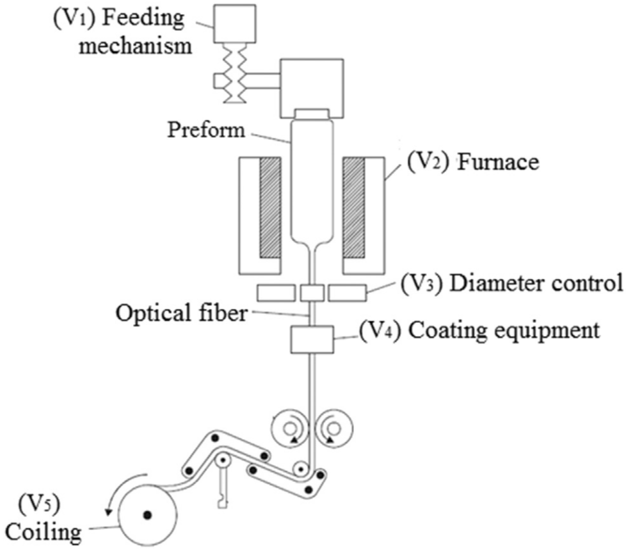

Fig. 2. Pulling/drawing process (adapted from ITU, 2010).

Shortly after leaving the furnace, the diameter of the filament is measured (V_3) and, as the fiber loses heat, it passes through an acrylate or silicone ultraviolet coating mechanism (V_4) (Agrawal, 2003). Finally, as a meter-long preform becomes a kilometers-long fiber, it is spooled onto a reel (V_5) (Ribeiro, 2006). Additional protective layers of coating can be then added to the fiber before it goes through performance and resistance testing (Achenie et al., 2006; Yang and Jaluria, 2009).

1.2. Environmental aspects

Just as any other material or product, optical fibers generate their own carbon footprint and specific environmentally hazardous emissions throughout the entire supply chain (Unger and Gough, 2007; Gutierrez et al., 2011).

According to Azapagic et al. (2004), changing how optical fibers are produced while keeping in mind factors such as transportation and reverse logistics can potentially reduce 30–60% of its current environmental impacts, depending on the end-of-life destination. Nevertheless, most studies about the environmental impacts of optical fibers focus on its operation, stage in which direct and indirect CO_2 emissions are present during installation (14%), use (77%), maintenance (1%) and end-of-life (8%) (Azapagic et al., 2004).

Few studies on optical fibers focus on the mineral extraction impacts of Silicon (Si) and especially of Germanium (Ge), both elements that have similar physical and chemical characteristics but that are distributed in the Earth's crust significantly differently and generate different types of environmental impacts as they are extracted:

Silicon in solid state is mainly surface-mined as silica quartz (SiO_2), and represents about 27–35% of Earth's crust, distributed in continental crusts (60.1%) and oceanic floors (39.9%) (Corathers, 2014; Dolley, 2015). Germanium, in turn, is present in Earth's crust at a rate of 1.5 mg/kg, and found mainly as a byproduct of deep-mining for Argirodite (Ag_8GeS_6) – with germanium content that ranges from 1.8 to 6.9% – and Germanite ($Cu_{13}Fe_2Ge_2S_{16}$) –