Resources, Conservation and Recycling 123 (2017) 108–116

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

The European PVC cycle: In-use stock and flows

L. Ciacci[a,*], F. Passarini[a,b], I. Vassura[a,b]

[a] Interdepartmental Center for Industrial Research “Energy & Environment”, University of Bologna, Rimini, Italy
[b] Department of Industrial Chemistry “Toso Montanari”, University of Bologna, Bologna, Italy

ARTICLE INFO

Article history:
Received 31 March 2016
Received in revised form 3 August 2016
Accepted 8 August 2016
Available online 11 August 2016

Keywords:
Thermoplastic
Industrial ecology
Polymer recycling
Material flow analysis
Building and construction
Urban mining

ABSTRACT

More than any other material, plastic is likely the commodity that has changed and characterized everyday life in the last 60 years. Although fairly young, the petrochemical industry has grown rapidly and moved to a variety of products and applications that has become one of the biggest industries worldwide. Notwithstanding such a presence in the modern society, plastics have been little analyzed from a material flow analysis perspective; low recycling rates and a strong reliance on primary material inputs give plastic greatest potentials for closing material loops. With this aim, polyvinyl chloride (PVC) stocks and flows in Europe are investigated historically to 2012. By volume, PVC is one the major thermoplastics used today and its employment in applications having relative long lifespans such as building and construction implies accumulation in anthropogenic reservoir as future sources of secondary material. The results show that about two thirds of the cumulative apparent consumption of PVC are still in use, reaching about 270 kg/capita at current levels. The remaining one third that came out of use has been mostly landfilled, with only a minor fraction being recycled. Flow analysis shows that significant margins for improving material and energy recovery at end-of-life do exist for PVC if the recycling challenge is timely and properly addressed in the coming years. Design for recycling, ban on plastic landfilling, and recycling targets with a focus on the recycled content in new products are keys for ensuring resource efficiency and the creation of an adequate recycling infrastructure across Europe.

1. Introduction

A growing interest in characterizing the metabolism of modern society has spurred industry and academia to understand how material flows are used within and among economies and dynamics behind the accumulation of product stocks in anthropogenic reservoirs. Ultimately, anthropogenic in-use stock represents a pool of secondary material sources and provides perspectives for investigating long-term demand-supply patterns (Graedel and Lifset, 2016; Liu et al., 2013).

Industrialization, urbanization, and needs for improving human wellbeing have determined an on-going development of technology and progress in material manufacturing such that almost the entire periodic table of elements is used in everyday products and goods (Graedel et al., 2015a). The material voracity of modern society is not limited to metal forms, but extends the demand to other commodities, with petrochemicals from crude oil refining and natural gas processing being an example.

The petrochemical industry is fairly young: it started to grow in the 1940s, but rapidly moved to a variety of forms and uses that became one of the most important industries worldwide. Through cracking and reforming processes, crude oil and natural gas are converted to olefins and aromatics that are key building blocks for commodities as synthetic polymers and rubbers. These major products of petrochemical industry have such an extensive presence in modern society that the XX century was given the name of “plastic age” (Thompson et al., 2009).

The plastic industry in Europe counts more than 60,000 companies including raw material producers, plastics converters and manufacturers (PlasticsEurope, 2015), and with about 60 Mt in 2013 follows only China in the global plastics production rank. Five countries (i.e., Germany, Italy, France, United Kingdom, and Spain) concentrate about two thirds of plastics demand in the region. By polymer type, polyethylene, polypropylene, and polyvinyl chloride (PVC) represent about 60% of total plastic volume in Europe for household goods, medical equipment, leisure products, and other major applications (PlasticsEurope, 2015).

As known, plastics vary in quality and quantity, in morphology, and end-uses. Two major classes of polymers are thermosets and thermoplastics. Respect to other thermoplastics, PVC has unique properties and great versatility that together with a relative low

* Corresponding author.
E-mail address: luca.ciacci5@unibo.it (L. Ciacci).

http://dx.doi.org/10.1016/j.resconrec.2016.08.008
0921-3449/

price boosted its use and diffusion. This resin was first polymerized during the second half of the XIX century and since its mass-produced manufacturing (circa 1920s) (PlasticsEurope, 2016), PVC has constituted a synthetic substitute for natural rubber. During the World War II, PVC production increased strongly thanks to water resistant features and non-flammable electrical properties. Better quality of PVC compared to caoutchouc was also exploited in the music industry for reducing the thickness of vinyl discs (or simply known as vinyls) and allowed the long-playing recording, which decreased the rotation speed from 78 to $33^{1/3}$ revolutions per minute. In fact, PVC is still used today for vinyls with no substitute thanks to high quality for music records and relative low cost. More recently, the range of applications has become wider consequently to novel manufacturing routes that have increased its durability and made PVC an essential material for building and construction. In addition, in light of criticality issues due to potential supply risk and restriction, PVC has been identified has a primary substitute with good performance for replacing copper in plumbing (Graedel et al., 2015b).

Due to its rigidity at normal temperature, PVC cannot be used alone, but it is always mixed with additives including plasticizers, heat stabilizers, fillers, pigments, lubricants, and other agents to enable PVC manufacturing and to improve its physical and mechanical properties. Rigid, unplasticized PVC has a total additives content less than 10% on weight (Fischer et al., 2014), but much higher concentrations can be found in flexible PVC products (Stringer et al., 2000; Whitfield and Associates, 2008). Intrinsic PVC instability is due to its subjection to heat, which causes self-accelerating dehydrochlorination reactions. Inorganic and organic salts of metals as calcium, zinc, lead, and tin have been historically used as stabilizers for heat and UV-light degradation or for preventing oxidation at air. Due to harmful effects related with potential release of toxic metals and their accumulation in the human body, the EU has phased out the use of cadmium stabilizers in PVC manufacturing. A voluntary commitment, named "Vynil 2010", by the European Stabiliser Producers Association and the European Plastics Converters Association aimed at replacing lead stabilizer used in PVC by 2015 (PVCplus, 2012). Bans to toxic metals have increased attention to stabilizers containing calcium and zinc and to novel metal-free systems.

Concerns have been raised also on the use of additives to increase plasticity to PVC products. The most common plasticizers are standard phthalates (i.e., esters of phthalic anhydride with C_8–C_{10} alcohols, representing more than 85% of world plasticizers production), of which 90% is annually used in PVC manufacturing (EVCM, 2016). The greatest concern related to the use of phthalates is due to endocrine modulation and alleged disruption to the human health, particularly to toxic effect to reproduction and fertility. The EU has limited the use of short-chained and low molecular weight phthalates such as bis(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), diisobutyl phthalate (DIBP), and benzyl butyl phthalate (BBP), as substance or as constituents of preparations, at concentrations of greater than 0.1% by mass of the plasticized material and banned their use in toys and baby articles (Directive 2005/84/EC); such a restriction has been recently extended to all electrical and electronic equipment (Commission Delegated Directive (EU) 2015/863). The replacement of DEHP, DBP, DIBP, and BBP with other plasticizers will be likely enhanced by the inclusion of the four phthalates within the REACH regulation as "substances of very high concern" (ECHA, 2016).

High molecular weight and long-chained phthalates (e.g., diisononyl phthalate (DINP), diisodecyl phthalate (DIDP), and di-(*n*-octyl) phthalate (DNOP)) may be used at limited concentrations in toys and baby articles which children do not place in their mouths (Directive 2005/84/EC). The European Chemicals Agency's risk assessment indicated that no unacceptable risk has been characterized for the use of DINP and DIDP in current consumer applications (ECHA, 2010a,b). Consequently to EU regulations and health concerns, plasticizers derived from adipic acid, therephtalates, and phthalate-free additives have increased their economic importance and their employment in new PVC formulation.

Material Flow Analysis (MFA) has been applied extensively to characterize anthropogenic material cycles. Major interest has been oriented to metals due to their wide use in the society and market value. Dynamic and standard MFA studies quantified in-use stock for most base metals, specialty metals, and rare earths with different scope (Chen and Graedel, 2012; Ciacci et al., 2013; Du and Graedel, 2011; Glöser et al., 2013; Izard and Müller, 2010; Kral et al., 2014; Liu et al., 2011; Meylan and Reck, 2016; Pauliuk et al., 2013). Additional studies focused on materials other than metals including construction minerals and biomass (Hashimoto et al., 2007; Krausmann et al., 2009). Notwithstanding their extensive presence in the contemporary society, low recycling rates, and the related environmental implications, plastics, and particularly PVC, have been little investigated from an MFA perspective. Tukker et al. (1996) performed a detailed substance flow analysis for PVC and related emissions in Sweden (Tukker et al., 1996); the results were later employed to estimate outflows of PVC waste as function of delaying mechanism of stock in the same country (Kleijn et al., 2000). Patel et al. (1998) analyzed plastics streams in Germany and estimated resulting long-term production, consumption, and waste generation patterns (Patel et al., 1998); Nakamura et al. (2009) applied input-output tables for characterizing Japanese PVC industry and provided a summary of MFA studies on plastics to 2000 (Nakamura et al., 2009). A dynamic MFA was applied to quantify the U.S. polyethylene terephthalate cycle by (Kuczenski and Geyer, 2010); Zhou et al. (2013) analyzed the Chinese industrial metabolism of PVC and provided insights for future waste generation (Zhou et al., 2013). Bogucka et al. (2008) applied MFA to support multi-resin waste management in Poland and Austria (Bogucka et al., 2008); similarly, Van Eygen et al. (2015) proposed an in-depth analysis of plastics flows and stocks in Austria for 2010 (Van Eygen et al., 2015). Bellstedt (2015) determined PVC stock in civil infrastructure in Amsterdam as case study to support the development of a circular economy (Bellstedt, 2015).

In this work, MFA is applied to quantify European flows and stocks of PVC historically to 2012. We expect the results provide significant insights for the European PVC industry, including estimates of potentials for PVC recycling and performance indicators such as recovery rate, end-of-life recycling rate, and annual additions to stock. On a broader perspective, the results will contribute to the international Industrial Ecology community by enlarging the number of material cycles investigated and increasing the knowledge about the metabolism of modern society.

2. Methodology

MFA applies the mass conservation to balance for inflows and outflows from each stage of a material's life cycle. Similarly to metals, the life cycle of PVC can be divided into four main phases, including production, manufacturing and processing into finished goods, use, and waste management. A major distinction with metals (with the exception of those having anthropogenic origin, e.g., technetium) is that plastics are produced artificially. Thus, system boundaries for the anthropogenic PVC cycle are set to include flows and process dealing with a defined and uniform composition of this material. In other words, system boundaries begin with resin PVC production and end with end-of-life treatment of PVC waste. Material flows to incineration, waste to energy plants, or to landfill are not disaggregated further as PVC undergoes processes that change the chemical structure of the material of interest. The scope