Resources, Conservation and Recycling 71 (2013) 40–47

Contents lists available at SciVerse ScienceDirect

Resources, Conservation and Recycling

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

Life cycle assessment of recycling PVC window frames

Heinz Stichnothe[a,b], Adisa Azapagic[a,*]

[a] School of Chemical Engineering and Analytical Science, The Mill, Sackville Street, The University of Manchester, Manchester M13 9PL, UK
[b] Johann Heinrich von Thünen Institut (vTI), Institut für Agrartechnologie und Biosystemtechnik, Bundesallee 50, 38116 Braunschweig, Germany

ARTICLE INFO

Article history:
Received 18 August 2012
Received in revised form 20 October 2012
Accepted 11 December 2012

Keywords:
Environmental impacts
LCA
Metals recycling
PVC recycling
PVC windows

ABSTRACT

This paper presents the life cycle impacts of recycling PVC window frames. Both post-industrial and post-consumer waste are considered to produce white and non-white chips and powder. The results suggest that significant savings of environmental impacts can be achieved by using PVC from recycled waste frames compared to virgin PVC resin. Recycling post-consumer waste leads to higher savings than post-industrial waste due to the credits for metals recycling. For example, replacing virgin by PVC from post-consumer waste saves around 2 t of CO_2 eq./t of PVC while PVC from post-industrial waste saves 1.8 t. The results are sensitive to transport distances and truck payloads. For instance, the global warming potential (GWP) of non-white PVC chips increases 1.7 times when the transport distance increases from 100 to 500 km and the payload factor decreases from 0.7 to 0.2. Credits for metals recycling influence the environmental savings: crediting the system for virgin aluminium saves 54 times more CO_2 eq./t of recycled PVC compared to the credits for recycled aluminium.

1. Introduction

Polyvinyl chloride (PVC) is by market share the third largest thermoplastics in the world, with the annual production of around 36 million tonnes in 2011 (Leadbitter, 2012) of which around 5.5 million is consumed in Europe (Plastics Europe, 2011). PVC can be combined with a number of additives to yield a wide range of end-use properties, from rigid plastics to flexible material. Its mechanical strength and chemical resistance make it suitable for the construction sector so that PVC is mainly used for window frames, pipes, cable insulation and floor covering (Plastics Europe, 2011). However, the environmental and health impacts of PVC have been under intense scrutiny over the years, largely due to the use of heavy metals and phthalates in the manufacturing process and emissions of dioxins from incineration of PVC waste (Leadbitter, 2002; Everard, 2008; Azapagic, 2011). As a results, over 60 life cycle assessment (LCA) studies of PVC have been conducted globally since the 1990s (VCA, 2012) to assess the environmental and health impacts of different PVC products. More recent examples include LCA studies by Paulsen (2003), EC (2004), Baitz et al. (2005), USGBC (2007), Bidoki and Wittlinger (2010), Plastics Europe (2010), Carolin et al. (2011) and CCaLC (2011).

This paper focuses on PVC window frames and considers the life cycle environmental impacts of recycled window profiles[1]. Global annual consumption of PVC for window frames is estimated at around 3 million tonnes, or around 8% of the global PVC production (Leadbitter, 2012). Together with the estimated 400 million tonnes of PVC consumed since the 1960s, of which half is still in use in products such as window frames (Sadat-Shojai and Bakhshandeh, 2011), this means that large volumes of waste PVC could be available for recycling, potentially leading to a significant reduction in environmental impacts of PVC window frames. This potential is also confirmed by the European PVC industry, which in 2011 recycled around 100 kt of post-consumer window frames (VinylPlus, 2012). In the UK, 42,730 tonnes of used PVC construction waste, including windows, were recycled in 2008 (Defra, 2010). Until 2011 recycling of window frames (and other unregulated PVC waste) in Europe was subsidised by Recovinyl, an initiative of the PVC industry, which paid financial incentives to companies to collect and recycle PVC waste (Recovinyl, undated). From 2012, Recovinyl shifted the focus from recycling and started to stimulate the re-use of recycled PVC with the aim of creating the 'market pull' and growing the demand for recycled PVC.

There have been several LCA studies of PVC window frames, mainly aimed at comparisons of PVC with aluminium and wood (e.g. Spindler and Engelmann, 1999; Citherlet et al., 2000; Asif, 2002; Asif et al., 2002; EC, 2004). However, no LCA studies have

* Corresponding author.
E-mail address: adisa.azapagic@manchester.ac.uk (A. Azapagic).

[1] The term "profiles" is more accurate and is used by the industry but the term "frames" is more widely known and is therefore used in this paper throughout.

0921-3449/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.resconrec.2012.12.005

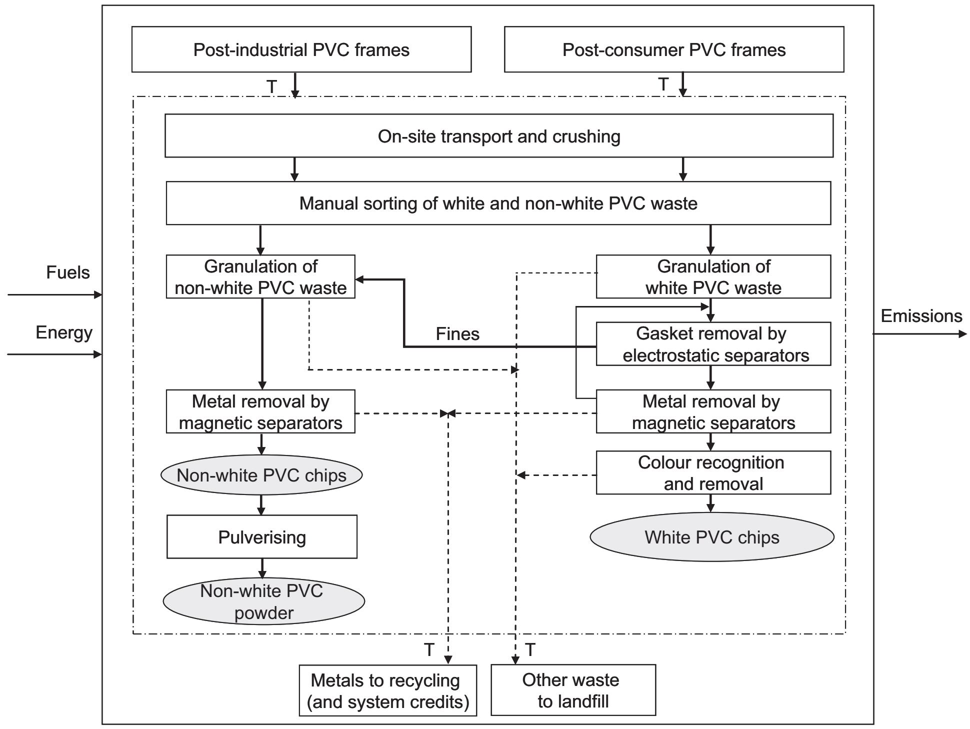

Fig. 1. The life cycle of recycling of post-industrial and post-consumer PVC window frames. (-·-·-) Recycling process (—) Product flows and (----) Waste flows.

been found in literature on recycling of PVC frames. This is the focus of the current study which considers the life cycle environmental impacts of recycling of both post-industrial and post-consumer PVC frames; as far as the authors are aware, this is the first study of its kind.

2. Overview of the process for recycling of PVC window frames

This section describes the recycling process for post-industrial and post-consumer PVC window frames considered in this study. Post-industrial waste comprises off-cuts and rejects from the manufacturing process, while post-consumer waste represents used frames recovered at the end of their useful lifetime. Both types of waste are processed in the same recycling facility.

The recycling process considered here is outlined in Fig. 1. After being transported to the recycling facility, post-consumer frames are first crashed using hammer mills to break up the frames and liberate aluminium and ferrous metals contained within; the metals are separated and sent for recycling. Larger pieces of post-industrial waste also need to be cut (some pieces can be up to 6 m long). The waste is then sorted manually into white and non-white PVC. The subsequent processing of the former involves:

- granulation of PVC into chips;
- gasket (rubber) separation by electrostatic separators;
- removal of metals by magnetic separators; and
- removal of any remaining coloured particles using an image recognition system.

The waste from the metals-separation process is partly returned to the electrostatic separation units to increase process efficiency and the rest is landfilled. The fines from the electrostatic separators can be used in the recycling of non-white PVC. The process for non-white PVC is less complex and involves only granulation of waste and removal of metals (see Fig. 1).

The produced PVC chips can be converted into powders with a desired particle size using a pulveriser. This allows blending with other grades of PVC or in a form that suits certain types of extruders thus broadening the range of applications of recycled PVC. Although both white and non-white chips can be converted into powder, the latter is more common and is considered in this study. Owing to a high-quality specification, white chips can be used for window applications and can be recycled several times without the loss of properties (Leadbitter and Bradley, 1997). The lower grade non-white material can be used for pipes or non-visible parts of window frames.

3. Methodology, data and assumptions

LCA has been used as a tool to estimate the environmental impacts of window frames recycling following the ISO 14040/44 methodology (ISO, 2006a,b). The goal of the study is to estimate the environmental impacts of recycled PVC from post-industrial and post-consumer window frames. The functional unit is defined as ‘production of 1 tonne of recycled PVC from waste window frames’. The following types of recycled PVC are considered:

- white chips, non-white chips[2] and non-white powder produced by recycling post-industrial waste frames; and
- white chips produced by recycling post-consumer waste frames.

The life cycle of the system considered is shown in Fig. 1. As can be seen, the system boundary is from ‘cradle to gate’, comprising collection and transport of waste to the recycling facility and processing of waste frames to produce PVC chips and powder. The glass from the window frames is removed elsewhere (for health and safety reasons) and is therefore not included within the system boundary.

[2] Non-white chips is also referred to as “jazz” in the PVC industry.

Table 1
Data for the PVC frames recycling process.

Recycled PVC from:	Post-industrial window frames			Post-consumer window frames
	White chips	Non-white chips	Non-white powder	White chips
Process inputs				
Waste PVC frames (kg/t)	1070	1020	985	1430
Fines from ESP [a] (kg/t)	–	–	54	–
Diesel [b] (kg/t)	2.3	2.2	2.1	3.0
Electricity (MJ/t)	380	260	420	1100[c]
Process outputs				
White chips (kg/t)	1000	–	–	1000
Non-white chips (kg/t)	–	1000	–	–
Non-white powder (kg/t)	–	–	1000	–
Ferrous metals (kg/t)	–	–	–	270
Aluminium (kg/t)	–	–	–	40
Process waste (kg/t)	70	20	39	120

[a] Electrostatic precipitator (see Fig. 1).
[b] Used for on-site transport and machinery.
[c] Hammer mills are used to crush post-consumer waste. Crushing of post-industrial waste is not considered.

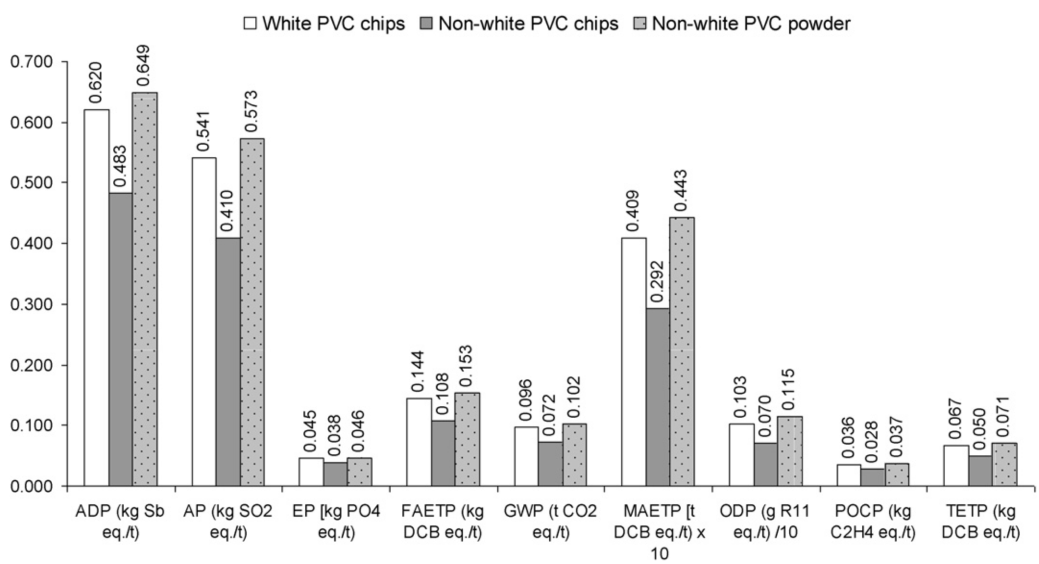

Fig. 2. Environmental impacts of recycling post-industrial PVC waste window frames to produce white and non-white chips and non-white powder (All impacts expressed per tonne of recycled PVC frames. ADP: abiotic resource depletion; AP: acidification potential; EP: eutrophication potential; FAETP: fresh water aquatic eco-toxicity potential; GWP: global warming potential; MAETP: marine aquatic eco-toxicity potential; ODP: ozone layer depletion potential, POCP: photochemical ozone creation potential; TETP: terrestrial eco-toxicity potential).

The study is based on a recycling facility situated in the UK, with a capacity to process 50,000 tonnes of waste PVC frames per year. However, as the mechanical recycling process considered here is similar to that used for waste PVC frames elsewhere (Recovinyl, undated), the findings and conclusions of this research are applicable more generally.

The data used for the study are summarised in Table 1. They have been sourced directly from a recycling company. For the transport of waste PVC to the recycling facility, an average distance of 160 km by a 22 t truck with a payload factor of 0.3[3] is assumed. All waste from the recycling process is assumed to be landfilled except for the metals recovered from the post-consumer waste which are recycled (for further assumptions on metals recycling and system credits, see Section 4.2). A distance of 20 km is assumed for the transport of process waste to a landfill.

[3] The load factor is the ratio of the average load to the total truck freight capacity. The load factor in the transport of waste window frames is limited by volume rather than mass due to a bulky waste, hence a relatively low load factor is assumed.

The LCA modelling has been carried out using the CCaLC (2011) tool. The background data have been sourced from the CCaLC (2011) and Ecoinvent (2009) databases. The CML 2001 method has been used for estimating the environmental impacts (Guinée et al., 2001). The CCaLC model with the data and example case studies related to the recycling of post-consumer PVC frames considered here is available at http://www.ccalc.org.uk/pvcsustainability.php.

4. Results and discussion

This section first presents the results for recycling the post-industrial PVC waste, followed by the post-consumer waste. The final section compares the recycled with virgin PVC.

4.1. PVC from post-industrial waste

The environmental impacts from post-industrial waste recycling are shown in Fig. 2 for three different PVC products: white chips, non-white chips and non-white powder. The results correlate directly to the energy used in the process so that the production of non-white chips has the lowest and the powder

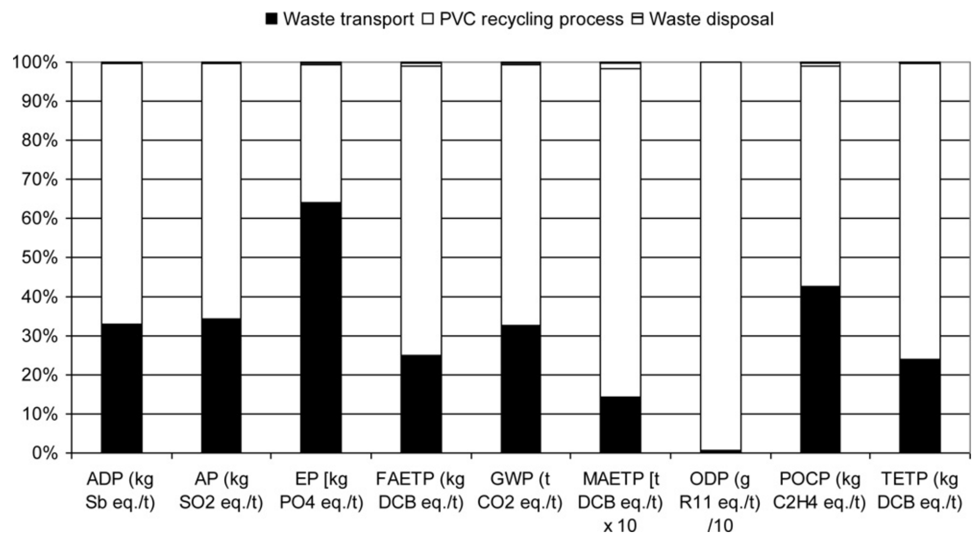

Fig. 3. Contribution of different life cycle stages to the total impacts of non-white chips from post-industrial waste (All impacts expressed per tonne of recycled PVC frames. For the full names of impact categories, see Fig. 2).

the highest environmental impacts across all the categories – on average, the impacts from the powder are around 30% higher than from the non-white chips. This is largely due to the additional electricity used for pulverising the chips. The impacts of white chips are only slightly lower than the impacts of the powder (on average by 6%): although the production of white chips does not require pulverising, the recycling process is more complex than for the non-white chips (see Fig. 1) used for the production of powder.

The main contributor to the impacts are the recycling process and transport of waste to the recycling facility; waste disposal contributes little to the total. As an example, the contribution analysis is shown for the non-white chips in Fig. 3 which indicates that the recycling process contributes on average 67% to the impacts, transport 32% and waste disposal less than 1%. An exception to this is eutrophication for which the waste transport is the main contributor (64%, due to the NO_x emissions), followed by the recycling process (35%). Another exception to the trend is ozone layer depletion which is mainly caused by recycling (99%) due to the life cycle of electricity used in the process. Similar trends are found for the other two types of PVC product.

Given the significant contribution of transport, it is important to explore how the impacts change with the distance and truck payload. Two representative impacts are considered for these purposes: global warming (GWP) and eutrophication (EP) potentials, the former because it is close to the average contribution of transport to the total impacts (∼33%) and the latter because the contribution of transport is highest for this impact. The case of non-white chips is considered again as an example.

As shown in Fig. 4, the GWP of non-white PVC chips increases 1.7 times (from 64 to 107 kg CO_2 eq./t) for the distance increase from 100 to 500 km while the EP triples (from 40 to 120 kg PO_4 eq./t). Therefore, the results are quite sensitive to transport distances so that optimising collection logistics is a critical factor for minimising the impacts from PVC recycling.

Furthermore, as waste can be bulky it can significantly influence the payload factor of a truck and hence the amount of waste that can be transported (the truck capacity is constrained by the volume of waste rather than its mass). Equally, if the waste can be broken and cut to smaller pieces prior to transport, higher payloads could be achieved.

The influence of this parameter for different payload factors ranging from 0.1 to 0.7 is indicated in Fig. 5 for the GWP and EP of non-white chips. As can be seen, reducing the payload factor from 0.3 to 0.1 doubles the EP and increases the GWP by 1.5 times. The payload factor of 0.2 would increase GWP (and most other impacts) by 10% while EP would go up by 20% compared to the payload factor of 0.3. On the other hand, increasing the payload from 0.3 to 0.7, would reduce the GWP by 1.4 times and EP by 1.8 times. A similar effect is also found for most of the other environmental categories (not shown).

Therefore, as demonstrated by these analyses, the combined effect of long transport distances and low payloads could result in a significant increase in the impacts from PVC recycling. Although only the example of the post-industrial waste is considered here, the same applies for the post-consumer waste. However, as discussed further below, even in the worst case, the impacts are still significantly lower than from the virgin PVC resin. Prior to that, the results for the recycled post-consumer waste window frames are presented next.

4.2. Post-consumer waste

The environmental impacts of white PVC chips from post-consumer waste are shown in Fig. 6. Following the ISO 14040/44 standard (2006a,b), the system has been credited for metals recycling using the avoided burdens approach by subtracting from the system the impacts of virgin or secondary metals (for an explanation of the avoided burdens approach, see e.g. Azapagic and Clift, 1999). As almost 100% of the steel from the construction sector is recycled or reused in the UK (Sansom, 2001), the system has been credited using the secondary (100% recycled) steel. Around 75% of aluminium is recycled in the UK (Dahlstrom and Ekins, 2007) so that the system has been credited using the average aluminium mix of 75% secondary and 25% primary (virgin) aluminium.

As indicated in Fig. 6, all environmental impacts of white chips from post-consumer waste are negative (apart from ozone layer depletion), representing a saving in both abiotic resources and environmental impacts. For example, recycling PVC from post-consumer windows saves 1.18 kg Sb eq. of abiotic resources (ADP), 146 kg CO_2 eq. of GWP and 344 t DCB eq. of marine eco-toxicity (MAETP) per tonne of PVC recycled. These savings are largely due to the credits for metals recycling and do not take into account the savings from displacing the virgin PVC, which is discussed in the next section. Unlike for the post-industrial waste, transport plays a minor role in post-consumer waste recycling because of the comparatively higher energy consumption in the recycling

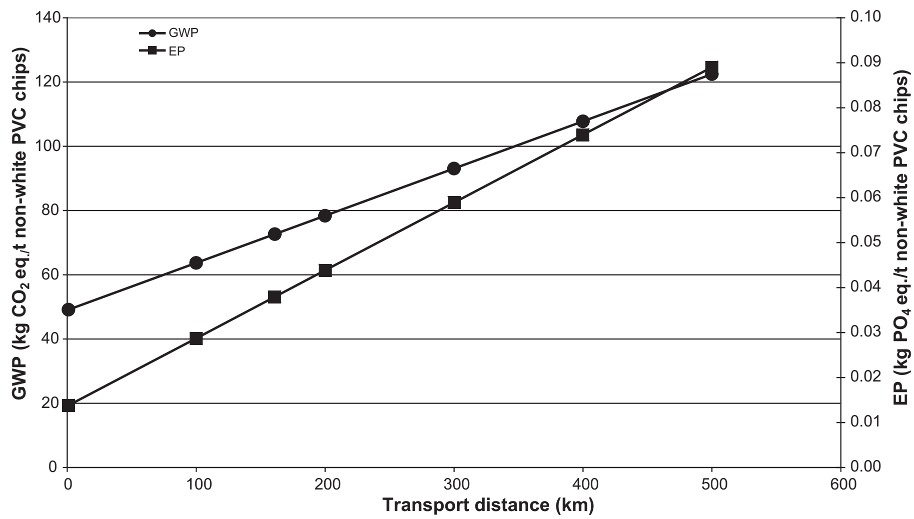

Fig. 4. Influence of transport distance on the GWP and EP of non-white PVC chips from post-industrial waste (Both impacts expressed per tonne of recycled PVC frames. Truck payload factor: 0.3. For reference, the originally assumed distance in the study is 160 km, for which the results are also shown in this figure as well as in Fig. 2).

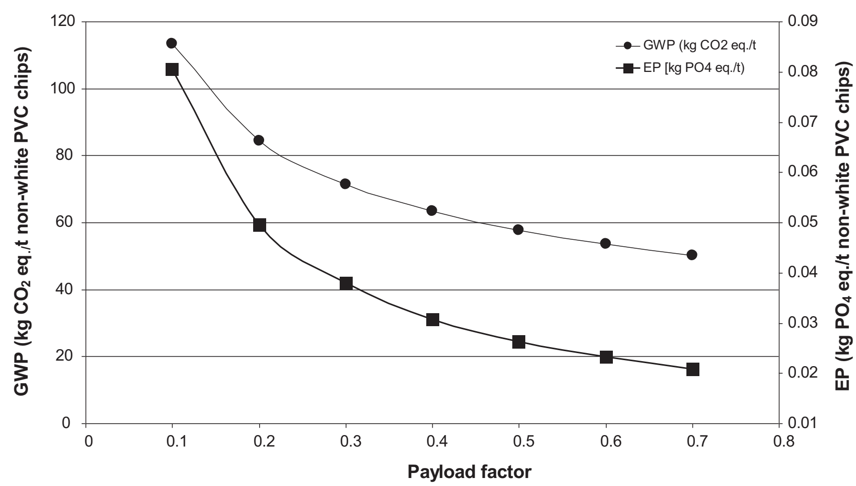

Fig. 5. Influence of truck payload factors on the GWP and EP of non-white PVC chips from post-industrial waste (Both impacts expressed per tonne of recycled PVC frames. Transport distance: 160 km. For reference, the originally assumed value in the study for payload is 0.3 for which the results are also shown in this figure as well as in Fig. 2).

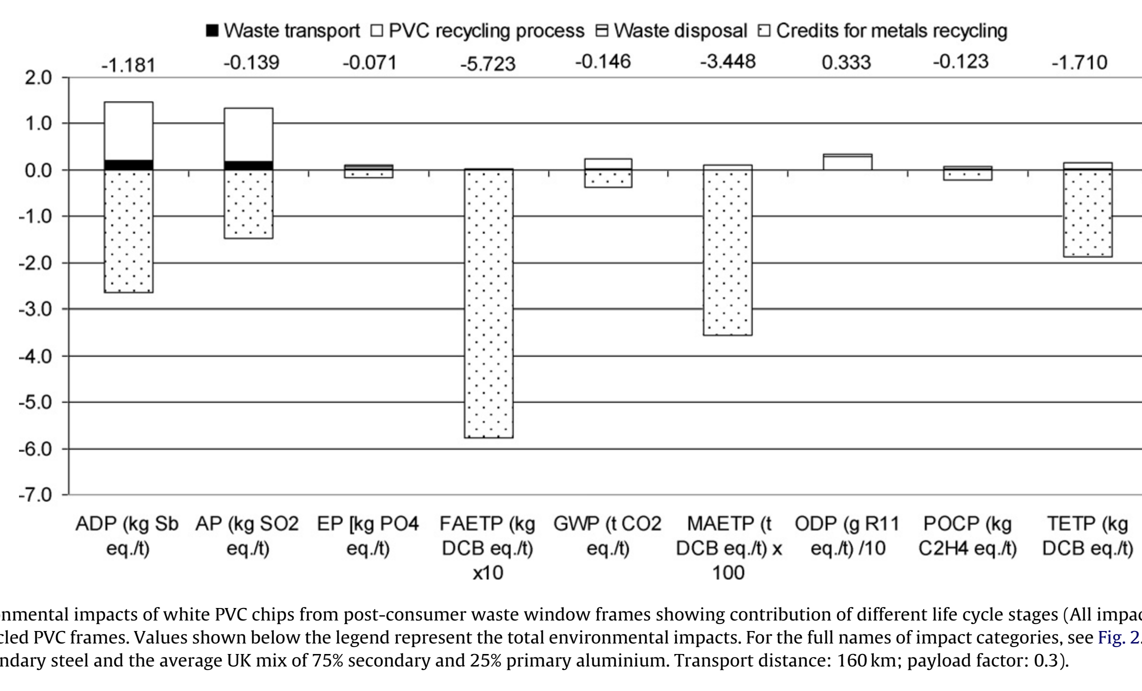

Fig. 6. Environmental impacts of white PVC chips from post-consumer waste window frames showing contribution of different life cycle stages (All impacts expressed per tonne of recycled PVC frames. Values shown below the legend represent the total environmental impacts. For the full names of impact categories, see Fig. 2. System credited for 100% secondary steel and the average UK mix of 75% secondary and 25% primary aluminium. Transport distance: 160 km; payload factor: 0.3).

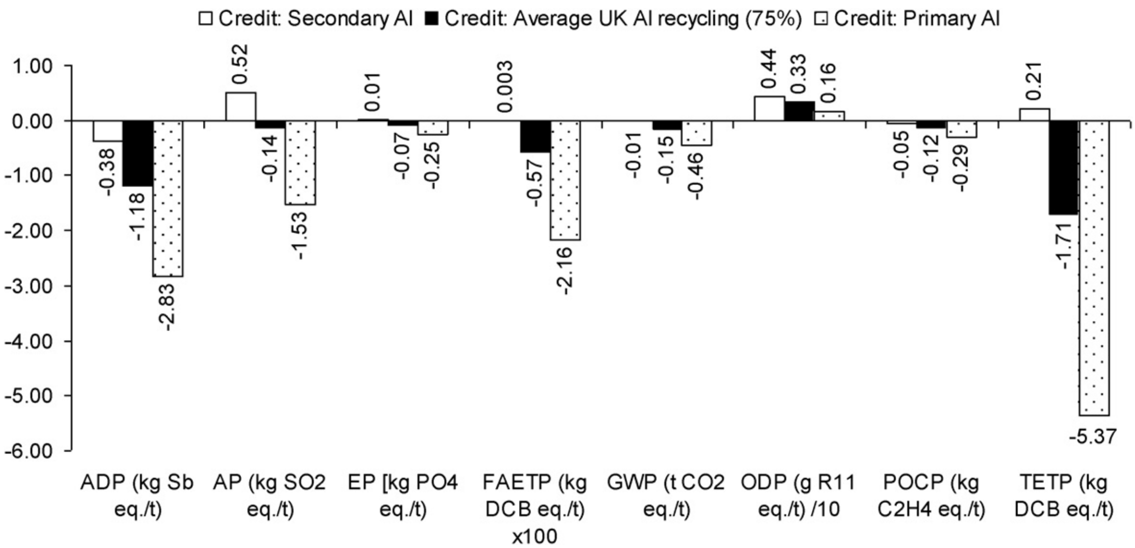

Fig. 7. Influence on the impacts of different credits for aluminium recycling from post-consumer PVC frames (All impacts expressed per tonne of recycled PVC frames. For the full names of impact categories, see Fig. 2. Transport distance: 160 km; payload factor: 0.3).

process, largely for crushing the frames by hammer mills (see Table 1).

To examine the influence of the recycling credits on the environmental impacts, two further options for aluminium are considered: credits for 100% primary and for 100% secondary aluminium. The actual type of aluminium – virgin or recycled – that the aluminium from this (or any other system) would be replacing will depend on the market conditions at the time, including the supply, demand and price. No further options for steel credits are considered due to the near-100% recycling rate of steel. The results are shown in Fig. 7 indicating that, irrespective of the credits, all the impacts are still negative (apart from ozone depletion, as previously). Not surprisingly, the greatest savings are achieved when the system is credited for the primary aluminium and the lowest for the secondary aluminium. For example, the former saves 54 times more CO_2 eq. and 800 times more DCB eq. (for MAETP) compared to the latter.

4.3. Comparison of recycled and virgin PVC

The environmental impacts of recycled PVC white chips estimated in this study are compared to the impacts of virgin PVC resin in Fig. 8. The data for the virgin PVC are sourced from Plastics Europe (2010). Recycled white chips are chosen for comparison with virgin PVC due to their high-quality specification which is close to the virgin PVC resin.

As indicated in the figure, recycled PVC saves a significant amount of abiotic resources and environmental impacts compared to virgin PVC. For example, PVC from post-industrial waste has on average 85 times lower impacts than the virgin resin, with the greatest reductions achieved for eco-toxicity, ranging from 56 times for marine (MAETP) to 465 times for freshwater toxicity (FAETP). Depletion of abiotic resources (ADP) is reduced by 36 times (from 22.5 to 0.62 kg Sb eq./t) and GWP by 20 times (from 1910 to 100 kg CO_2 eq./t PVC).

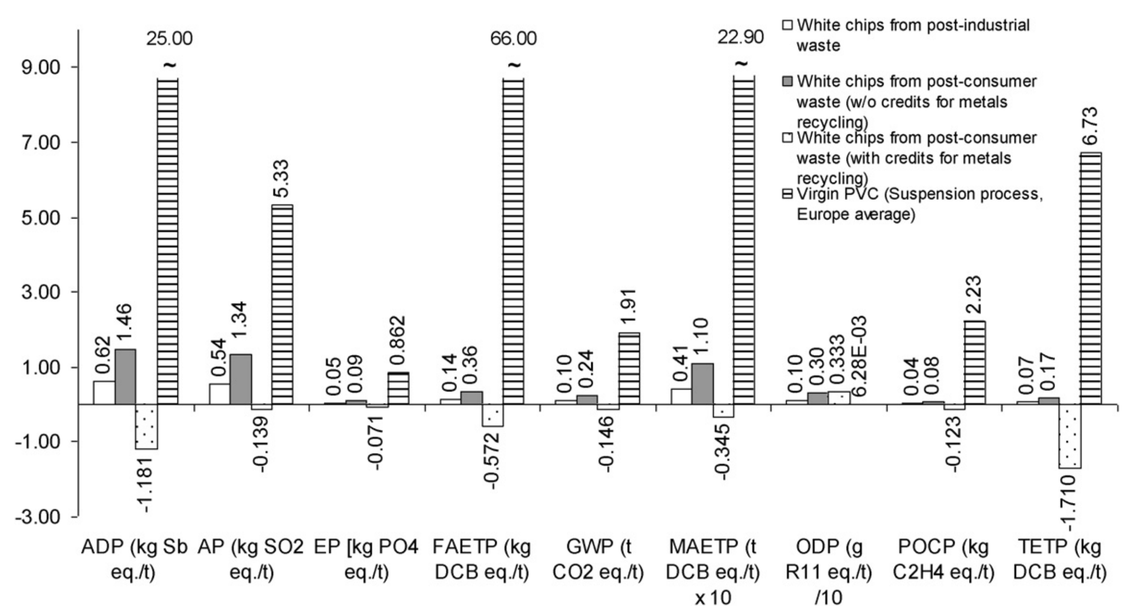

Fig. 8. Comparison of environmental impacts of different types of recycled and virgin PVC (All impacts expressed per tonne of PVC. For the full names of impact categories, see Fig. 2. Transport distance: 160 km; payload factor: 0.3. Data for virgin PVC from Plastics Europe (2010)).

For the post-consumer waste, if the system is not credited for the recycled metals, the reduction in the impacts is on average 34 times. The greatest savings are again for eco-toxicity. With the system credits, the savings are much greater than for the post-industrial waste as all the impacts become negative. For example, the GWP is reduced from 1910 kg to −146 kg CO_2 eq./t PVC, thus saving in total 2056 kg of CO_2 eq. per tonne of PVC. At the European level, based on the current recycling rate of waste PVC frames of 100 kt/yr (VinylPlus, 2012), this would be equivalent to a saving of around 200 kt of CO_2 eq./yr (assuming the displacement of virgin by the recycled PVC).

PVC from the post-consumer waste is a better option than the post-industrial waste largely due to the credits for metals recycling; without metals recycling and the related credits, PVC chips from post-industrial waste would be a better option due to lower process energy requirements.

However, it should be noted that these comparison between the virgin and recycled PVC are not exactly on a like-for-like basis. This is due to two reasons:

i) The recycled PVC has some additives while the virgin resin is additive-free; this means that the impacts of virgin PVC would increase if the same additives were to be added as contained in the recycled PVC. Due to a lack of data, this aspect is not considered in this study.
ii) The results for the recycled PVC are based on the UK background data while the virgin PVC resin refers to the average European data (Plastics Europe, 2010) whereby the former generally leads to higher impacts compared to the latter due to the higher impacts from the energy mix. This data mismatch is evident with ozone layer depletion (ODP) which is lower for the virgin than for the recycled PVC. This could mean that if the same background data were used for comparisons, the savings in the impacts from the recycled PVC would be higher still than discussed here.

5. Conclusions

The results of this study suggest that significant savings of environmental impacts can be achieved by using recycled instead of virgin PVC for window frames. The greatest savings are achieved from recycled post-consumer waste due to the credits for metals recycling. For example, displacing virgin PVC resin by PVC from post-consumer waste saves 2056 kg of CO_2 eq. per tonne of PVC. With an estimated global annual consumption of PVC for window frames of around 3 Mt and possibly 200 Mt of frames in use, the potential savings of GHG emissions and other impacts are considerable. Based on the result obtained in this study, recycling of 100 kt/yr of waste frames in Europe has a potential to save around 200 kt of CO_2 eq./yr Furthermore, PVC recycling reduces the amount of waste that has to be landfilled and/or incinerated. The latter is particularly controversial due to the health concerns related to potential dioxin formation in the incineration process.

Among the products made from post-industrial waste considered here, non-white chips have the lowest and the non-white powder the highest environmental impacts. The impacts of white chips are only slightly lower than the impacts of the non-white powder.

The results are sensitive to the transport distances and truck payload factors. For example, the GWP of non-white PVC chips from post-industrial waste increases 1.7 times (from 64 to 107 kg CO_2 eq./t) when the distance increases from 100 to 500 km. Similarly, reducing the payload factor from 0.3 to 0.1 increases the GWP by 1.5 times. On the other hand, increasing the payload from 0.3 to 0.7 can reduce the GWP by 1.4 times. Therefore, optimising collection logistics and payloads is critical for minimising the impacts from PVC recycling.

The results are also sensitive to system credits for metals recycling for post-consumer waste. Three different credit options have been examined for aluminium recycling, assuming credits for primary, secondary and the UK average mix of both. In all cases, the environmental impacts of recycled white chips become negative with the greatest reduction achieved when the system is credited for the primary aluminium and the lowest for the secondary aluminium. For example, the former saves 54 times more CO_2 eq. per tonne of PVC recycled compared to the latter.

Recycling of PVC windows is currently in its infancy and different market and policy mechanisms will be needed to foster its growth to benefit from the environmental savings that it offers. One particular area that needs to be looked at is legislation related to waste recycling. An example are heavy metals such as lead and cadmium which were used as PVC additives in the past (but have been largely phased out by the industry). Given that they are banned for most applications, this may hamper the wider recycling and use of PVC. The influence of legislation and market conditions has not be investigated in this study although they might be crucial for the future of PVC recycling.

Acknowledgements

This research has been funded by the UK Engineering and Physical Sciences Research Council (EPSRC) within the projects "Carbon Calculation over the Life Cycle of Industrial Activities (CCaLC)" (grant no. EP/F003501/1) and "Improving Sustainability of PVC through Novel Materials, Processes and Life Cycle Methodologies" (EP/D505372/2). This funding is gratefully acknowledged. The authors are also grateful to the two (anonymous) reviewers for their constructive comments for improvements of the paper.

References

Asif M. Life cycle assessment of aluminium-clad timber windows. PhD Thesis, Napier University; 2002. http://researchrepository.napier.ac.uk/2505
Asif M, Davidson A, Muneer T. Life cycle analysis of window materials – a comparative assessment. In: CIBSE National Technical Conference; 2002. http://www.cfsgs.com/uploads/3/6/0/1/3601225/71.pdf
Azapagic. Sustainable process design: the case of vinyl chloride monomer, (VCM). In: Azapagic A, Perdan S, editors. Sustainable development in practice: case studies for engineers and scientists. 2nd ed. Chichester: John Wiley & Sons; 2011 [chapter 13].
Azapagic A, Clift R. Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production 1999;7(2):101–19.
Baitz M, Kreissig J, Makishi C. Life cycle assessment of PVC in product optimisation and green procurement – fact-based decisions towards sustainable solutions. Plastics, Rubbers and Composites 2005;34(3):95–8 http://www.pe-international.com/fileadmin/user_upload/news/2006/downloads/PRC2171_pub_ba.pdf
Bidoki SM, Wittlinger R. Environmental and economical acceptance of polyvinyl chloride (PVC) coating agents. Journal of Cleaner Production 2010;18(3):219–25.
Carolin S, Vanderreydt I, Vercalsteren A, Boonen K. Life cycle assessment of a PVC-U solid wall sewer pipe system (according to EN 1401); 2011 http://www.teppfa.com/pdf/EPD/PVC-solidWallSewer-ThirdPartyReport-June2011.pdf
CCaLC. CCaLC database and software tool; 2011 http://www.ccalc.org.uk
Citherlet S, Di Guglielmo F, Gay J-B. Window and advanced glazing systems life cycle assessment. Energy and Buildings 2000;32:225–34.
Dahlstrom K, Ekins P. Combining economic and environmental dimensions: value chain analysis of UK aluminium flows. Resources, Conservation and Recycling 2007;51(3):541–60.
Defra. Windows Sustainability Action Plan. Report 00IA. UK: Defra; 2010 http://www.defra.gov.uk/publications/files/pb13438-windows-101019.pdf
EC. Life cycle assessment of PVC and competing materials, report commissioned by the European Commission; 2004 http://ec.europa.eu/enterprise/sectors/chemicals/files/sust dev/pvc-executive_summary_lca_en.pdf
Ecoinvent. Ecoinvent Database Version 2.1. In: Ecoinvent; 2009 http://www.ecoinvent.org/database
Everard M. PVC: reaching for sustainability. London: BPF; 2008, 269.
Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning. A life cycle assessment: an operational guide to the ISO standards; Part 2a. Leiden: CML; 2001

http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html
ISO 14040: environmental management – life cycle assessment – principles and framework. Geneva: ISO; 2006a.
ISO: 14044 environmental management – life cycle assessment – requirements and guidelines. Geneva: ISO; 2006b.
Leadbitter J. PVC and sustainability. Progress in Polymer Science 2002;27:2197–226.
Leadbitter J. Personal communication; 2012.
Leadbitter J, Bradley J. Closed loop recycling opportunities for PVC. Institute of Polymer Technology and Materials Engineering, Loughborough University; 1997 http://www.bpfwindowsgroup.com/recycling.cfm
Paulsen JH. The maintenance of linoleum and PVC floor coverings in Sweden – the significance of the usage phase in an LCA. International Journal of Life Cycle Assessment 2003;8(6):357–64.
Plastics Europe. PVC ecoprofiles; 2010 http://www.plasticseurope.org/plastics-sustainability/eco-profiles/browse-by-flowchart.aspx?LCAID=r43
Plastics Europe. Plastics – the facts 2011. An analysis of European plastics production. In: Demand and Recovery for 2010; 2011 http://www.plasticseurope.org/documents/document/20111107101127-final_pe_factsfigures_uk2011_lr_041111.pdf
Recovinyl. Recycling rigid and flexible PVC. Recovinyl, Brussels. www.recovinyl.com/docs/english/sortingguide.pdf; undated.
Sadat-Shojai M, Bakhshandeh G-R. Recycling of PVC wastes. Polymer Degradation and Stability 2011;96:404–15.
Sansom M. Construction steel reuse and recycling rates approach 100%; 2001 http://www.steelconstruction.org
Spindler E-J, Engelmann M. Dioxins and other carcinogenic substances in life-cycle work (assessment of relative risk potential). Organohalogen Compounds 1999;44:499–504.
VinylPlus. Progress report 2012. VinylPlus; 2012 http://www.vinylplus.eu/uploads/Progress_Report_2012/VinylPlus_ProgressReport_2012.pdf
USGBC. Assessment of the basis for a PVC related credit for LEED. United States Green Building Council; 2007 http://www.usgbc.org/Docs/LEED_tsac/USGBC
VCA. Life cycle assessment. Vinyl Council of Australia; 2012 http://www.vinyl.org.au/LifeCycleAssessments