

‘THE SUSTAINABLE WINDOW’: THE IMPACT OF INNOVATION IN PVC WINDOW MANUFACTURING AND FUTURE IMPLICATIONS

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Abstract

Polyvinyl chloride (PVC) is a versatile thermoplastic, that since rapid industrialisation in the 1930's has become one of the world's most commonly produced plastics. Its durability, versatility and relative low cost, has resulted in widespread adoption throughout industries such as construction, healthcare and consumer goods, with global production of PVC resin exceeding 40 million tons per year (British Plastics Federation, n.d.). This upward trend in demand shows no sign of slowing. In 2021 the industry generated a revenue worth around US\$78.90 billion, with approximately US\$101.45 billion projected by 2028 (Zion market research, 2022). Despite a rise in popularity throughout industry over the last century, PVC's history and current reputation remains tainted with controversy and debate, surrounding sustainability and significant environmental and health concerns. A historic lack of infrastructure and legislation to manage the disposal of post-consumer and industrial PVC waste, resulted in decades of waste to landfill, combined with toxic additives that posed serious risks to health and the environment.

In 2000 the European PVC industry united, launching Vinyl 2010, a voluntary initiative that aimed to clean up the image of PVC by creating a more responsible, circular manufacturing sector. Collaborating with government, the initiative laid out a 10-year strategy, which set ambitious goals. This has helped shape the more sustainable industry witnessed today. The initiative sparked widespread innovation, regulatory change and a shift in attitude from industry, government and the consumer and kickstarted a journey toward sustainability.

This dissertation explores the building and construction sector, one of the biggest consumers of PVC products, specifically focusing on the PVC window manufacturing industry. Using a traditional literature review methodology, the history of PVC as a manufacturing material was examined to help the reader understand how the rapid soar in demand significantly affected health and the environment and prompted change. The research found that in 2000, landfilling was the most common waste route for PVC throughout European member states, with 2.9Mt of PVC waste to landfill annually (European Commission, 2000). This alarming statistic was further amplified with toxic and carcinogenic additives found amongst early PVC compounds, which posed considerable risk of leaching into ground soil and contaminating watercourses. The lack of material recycling and the rise in demand for PVC products, created the need for vast quantities of virgin PVC. Dependence on non-renewables, both as a raw material source and to fuel an energy intensive manufacturing process, also proved a significant contributor to carbon emissions. Case studies examined three key innovations that not only helped improve the sustainability of the polymer but increase profitability and competitiveness within the industry.

A review of the state of the industry today, examined how innovation impacted sustainability in modern window manufacturing. Findings highlight how the phasing out of harmful heavy metals based stabilisers, such as lead and cadmium, removed significant toxicity hazards in PVC products. The commitment of an industry to improve its image, combined with changes to legislation, has unquestionably resulted in a dramatic reduction of waste to landfill. This reduction was also initiated by the advancements in waste handling, sorting and manufacturing technologies, which helped reduce waste and provided the opportunity to procure and process high quality recycled material as an alternative to virgin plastics.

Finally, an analysis of how emerging technologies, changes regulation and shifts in consumer behaviours, provided an insight toward 'the sustainable window' of tomorrow.

1. Opening

1.1 Introduction

In an era of increasing environmental awareness, the pressure and expectation for businesses in the construction sector to deliver modern, sustainable building material solutions is ever growing. As the global population rapidly increases, the demand for products and services places ever more strain on natural resources, with manufacturing practices, materials and lifecycle impacts coming under increasing scrutiny.

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020 (Lee, Romero and The Core Writing Team, 2023). The release of CO₂ into the earth's atmosphere, caused by the burning of fossil fuels for energy and transportation, harmful gas release from industrial processes and the mismanagement of waste such as landfilling, are some of the major contributors to global temperature rise. Leading scientists continue to deliver stark warnings that the international community must come together and accelerate efforts to limit global temperatures to 1.5°C above pre-industrial levels (Harvey, 2023). Many argue that a failure to act would result in an increased risk of rising sea levels, loss of habitat and ecosystems, as well as severe weather events.

Over the last century PVC windows have emerged as a pioneering alternative to traditional wood and metal window systems, combining durability, cost-effectiveness and versatility. Despite the widespread success of the polymer as a construction material, the journey of PVC window development since inception is steeped in controversy and debate surrounding hazardous, unsustainable production and disposal methods. This dissertation seeks to understand the challenges faced by the industry in balancing sustainability with growing global demand over the last century.

Research will be undertaken following a traditional literature review methodology. As a mature industry which has endured significant challenges and change over the last century, there has been extensive research and reporting conducted and published, surrounding the sustainability of PVC. The traditional literature review synthesizes primary findings from existing research and provides newcomers to the topic with a thorough overview of the state of relevant knowledge surrounding the subject matter (Rozas and Klein, 2010).

At the heart of this exploration lies an analysis of early history and a surge in demand for PVC products. It examines the environmental and health concerns regarding carbon emissions, mismanagement of waste and the use of harmful substances in stabilisers and plasticisers, seeking to understand the factors that prompted industry and government to initiate change. It explores how these widespread deep-rooted issues, sparked disruptive and continuous innovations in manufacturing processes, recycling, material development and legislation and assesses how they helped dramatically shape sustainability in window manufacturing today.

Moreover, the study examines the current landscape throughout the industry. It assesses the changing forces driving sustainability and acknowledges the challenges and complexities still faced, looking at modern day practices and the development of circular economies.

Looking forward, the dissertation explores emerging technology, changing regulatory landscapes and market shifts that could impact future sustainability efforts. Using a survey and interviews, directed at key stakeholders within the PVC window manufacturing industry, the research will collect and analyse feedback direct from industry and understand how innovation and future changes are impacting PVC window manufacturing today and helping create “The Sustainable window” of tomorrow.

It is hoped that this work will contribute to a deeper understanding of the scale of the challenge still faced throughout the industry, highlight the consequences of innovation not keeping pace with demand and assesses how industry is adapting toward circular practices. Finally, by drawing upon and analysing past, present and future innovations, the work provides a reference and encouragement for manufacturers looking to develop a more sustainable future for their businesses and for PVC.

1.2 Aims and objectives.

The aim of this dissertation is to:

- Examine historic challenges and issues regarding sustainability within the PVC industry, and better understand the factors that prompted change.
- Evaluate the past innovation that helped shape modern practices.
- Examine the sustainability landscape within window manufacturing today, to identify current challenges and barriers that may inhibit progression.
- Explore emerging technologies and potential change. Evaluate the influence they had in other industries and assess the impact they may have to securing the future of PVC as a material choice for window systems.
- Create a body of work bringing together past, present and future innovation, to assess the future impact toward sustainability within the PVC window manufacturing industry.
- Collect feedback direct from industry to assess how emerging technology and potential changes are being prioritised in future business models.
- Provide a reference for manufacturers looking to develop circular business practices and contribute to the future sustainability of PVC windows.

The specific objectives of this dissertation are:

- Analyse PVC’s material properties, understand the advantages and disadvantages of PVC as a material choice for manufacturers.

- Analyse PVC's early history, explore reasoning for rise in global demand, identify the factors that contributed to an unsustainable future.
- Evaluate the historic health hazards throughout production, processing and disposal of waste PVC.
- Explore historic innovations in additive manufacture, recycling and processing through interview and case studies. Evaluate their influence on the current state of the industry.
- Identify current challenges regarding material availability, waste preparation, infrastructure and processing and how they inhibit development in the industry today.
- Explore emerging technologies, future changes to regulatory framework and changes in consumer behaviour. Analyse their impact in other applications or sectors. Assess how they may impact the future of PVC windows.
- Analyse secondary data in the form of a literature review. Collect and analyse qualitative primary data in the form of survey feedback and interviews.

1.3 Justification

Over exploitation of fossil fuels, severe plastic contamination of land and oceans and increasing carbon emissions, are the harsh realities and consequence of rapid industrialisation and present a true reflection of the world in which we live today. Unless significant efforts are accelerated to curb the damage human activity imposes on the planet, the risk of dramatic climate change, impact to health, loss of habitat and extinction of a species, will reach irreversible levels. An astonishing statistic published in 2017, suggested that between 1950-2015, 60% (4900 Mt) of all plastics ever produced were discarded and accumulated in landfills or the natural environment (Geyer, Jambeck and Law, 2017). This grim statement highlights the damage already inflicted by the plastics industry and acts as a stark reminder that the lessons of yesterday must serve as the motivation for change today.

Although the sustainability of PVC is a topic which has been well researched and reported on, literature that provides a reader with an overview of historical and current challenges, disruptive and continuous innovation success and guidance for the future are less available. This dissertation aims to bridge that gap, acknowledging the past, but looking toward emerging technologies and other industries for future solutions. For larger, well-established organisations, where investment, access to markets and supply chains and expertise are more available, such literature may be less required. However, for small and medium enterprises (SME), this holistic viewpoint could provide better understanding and guidance in decision making and managing the incremental changes that are viable within their business. Research will provide the reader with an insight of emerging technology and potential changes that may impact the industry, while feedback direct from key stakeholders will offer a snapshot of how businesses are organising themselves to prepare for the future.

It is vitally important that industry as a whole, is pushing toward a circular future for PVC windows. Maximum awareness and encouragement is crucial, particularly amongst SME, to ensure it is not only

larger companies who contribute towards sustainability. This will help manufacturers create security and future opportunity for both their business and the entire sector.

1.4 Methodology

1.4.1 Literature review

As this dissertation isn't specifically defined by one question and serves as a holistic viewpoint assessment covering multiple factors within a wider topic, a traditional or narrative literature review methodology will be employed. This approach will provide a flexible but comprehensive review of existing research literature. The research will not be bound to any specific search or analysis protocols, and references will be detailed throughout the full body of work.

1.4.2 Secondary data collection

- Research will focus on credible sources of literature extracted from peer reviewed journals, reports, books and articles and also reliable websites and newspapers.
- Literature will be sourced from credible databases such as ScienceDirect, PubMed, ProQuest and Google Scholar.
- The citation software MyBib will be used to collect all references of works used throughout the dissertation. The software will also be used to assess credibility of works.

1.4.3 Primary data collection - survey

A Likert scale survey was sent to key stakeholders within the sector. Using the likert approach provided a user-friendly format, offering multiple options to encourage participation amongst respondents. The industries targeted within the sector were PVC resin manufacturers, additive manufacturers, recycling, converters, fabricators and installers to give a holistic viewpoint from industry. The survey was split into three categories, covering fourteen questions. Categories focussed on:

1. Current/ future challenges for sustainable PVC Windows (Q2-4)
2. Drivers of sustainability and circular economies in PVC window manufacture (Q5-8)
3. Emerging technologies and innovation opportunities in PVC window manufacture (Q9-13)

Details of categories and question shown in table 1.

Category	Question Number	Question
	1	Job title and industry
Current/ future challenges for sustainable PVC Windows.	2	Market competition for recycled material limits the feasibility of implementing sustainable innovations.
	3	The integration of recycled materials into new products is a significant challenge for my organisation.
	4	The cost of transitioning to circular practices is prohibiting future sustainability within my organisation.
	5	Consumer awareness is driving my organisation to help develop more sustainable window solutions.
Drivers of sustainability and circular economies in PVC window manufacture.	6	Regulatory pressure is a critical driver for adapting circular economy principles within my organisation.
	7	I perceive technological advancements in the PVC industry, as a major factor in driving sustainability within my organisation.
	8	The cost of recycled material over virgin material is a major driver in adopting circular practices.
	9	Are you familiar with industry 4 and advanced recycling technologies?
Emerging Technologies and innovation Opportunities in PVC window manufacture.	10	My organisation has employed industry 4 technologies as part of its future sustainability strategy.
	11	My organisation is exploring advanced recycling technologies as part of its future sustainability strategy.
	12	I believe bioplastics and bio-additives could significantly impact the future of window manufacturing.
	13	I am confident there is sufficient skill and expertise within the PVC window industry, to implement sustainable technological advancements?
Comments and personal opinions.	14	If you have any additional comments, feedback, or personal insights about any of the topics discussed in this survey, please share them with me in the text box. Your perspectives are invaluable to my research and analysis.

Table 1. Details the 14-point Likert style questionnaire sent to industry (actual survey monkey questionnaire sample is found in Annex C)

1.4.4 Survey data collection

Surveys were sent using Mail Chimp web service. Questions gave the respondent the option to answer each question using a 5-point Likert scale, as illustrated in Fig 1.

2. Market competition for recycled material, limits the feasibility of implementing sustainable innovations.	
	Rating
Strongly agree	☐
Agree	☐
Neutral	☐
Disagree	☐
Strongly disagree	☐

Fig 1, Example of the question layout from survey

Survey feedback provided primary qualitative data. The respondent was given the option of anonymity to encourage participation, however they were asked to enter their job title and industry. To give respondents the opportunity to add personal opinions and information an optional comments box was added at the end of the survey form.

1.4.5 Survey data analysis

Data from survey will be analysed using the following processes:

- Number of survey invitations versus number of completed returned surveys.
- Number of respondents in relation to specific industry.
- Individual question ratings.
- Individual feedback comments from respondents.

1.4.6 Primary data collection – interview and case studies

Interviews with key individuals in the industry, gave an insight into historic innovations and provided primary data for case studies. Interviews were carried out in person and via Microsoft teams.

1.4.7 Limitations

Sustainability of plastics and its effect on the environment is controversial in both public and political domains. This may prompt certain biases in survey results, such as central bias where the respondent may avoid extreme view points and offer a more neutral option (Crosetto et al., 2020), other than their own, or social desirability bias where the respondent may offer a more socially acceptable answer as opposed to their actual opinion. In this case, future research capturing a wider number of respondents would help dilute bias results into the overall findings.

2. PVC through the ages

Section 2 of this paper aims to provide an overview of the early history of PVC, to help understand how the polymer gained popularity as a manufacturing material and highlights the driving forces behind a rapid rise in demand.

2.1 Early history of PVC

Manufactured from 57% salt and typically 43% hydrocarbon oil, Polyvinyl chloride (PVC) or $(\text{H}_2\text{C}-\text{CHCl})_n$ is a synthetic resin made from vinyl chloride (VC) and is one of the earliest produced polymers in the large group, broadly referred to as “vinyls” (Takeoka, 2015).

PVC’s history began in 1835, when German Chemist Justus von Liebig and his French research student Henri Victor, reported the discovery of a highly flammable gas known today as VC (Braun, 2001). Forty-three years later, German chemist Eugen Baumann first observed light polymerisation of VC and is today commonly credited as the inventor of PVC (Takeoka, 2015). The early 1900’s saw significant industrial developments in PVC manufacture, following chemist Friedrich Klatte successfully initiating the polymerisation of VC, adding hydrochloric acid (HCl) to acetylenyl (C_2H_2) and later with organic peroxides (Braun, 2001). Klatte also demonstrated the polymer could be processed by means of heating and pressurisation, which sparked interest in PVC throughout Europe, however PVC failed to maintain sufficient industrial interest, which ultimately led to the expiration of Griesheim's patent (Braun, 2001). This was the catalyst for wide scale industrial innovation and commercial production, driving new PVC products into the consumer market. Toward the end of the 1930’s demand significantly escalated, partially driven by WW2, where PVC was used to coat and protect electrical wires in military hardware (Patrick and Rapra Technology Limited, 2005).

Despite these significant developments, early PVC producers faced significant manufacturing challenges, due to poor thermal stability of the material and degradation over time in the presence of light (Braun, 2001). When Processing PVC above a temperature of 150°C , early converters found that hydrogen chloride (HCl) split off from polymer chains. This caused defects that rapidly accelerated forming carbon=carbon($\text{C}=\text{C}$) double bonds in a process known as ‘zipping’ and triggered discoloration and yellow staining (Fröhlich, 2013). To prevent and counteract formation of hydrochloride, additives known as stabilisers were developed, which helped improve thermal stability. From around 1937 lead, barium, cadmium calcium and zinc were commonly used to stabilise PVC formulators (Braun, 2001).

2.2 The rise of PVC

The advancements in processing capability and improved thermal stability, combined with a growing use case, resulted in rapid surge in demand for PVC products. From 1939 to 2000, global PVC consumption soared from 0.011Mt to 25.7Mt (Braun, 2001) as the polymer became entrenched in society with PVC products found in fashion, leisure, medical and construction. PVC’s widespread varied use case can be largely attributed to its excellent compatibility with different additives. Modern PVC formulations are combined with a number of functional additives that alter material properties to suit the desired product application. Functional additives used in PVC materials include heat stabilisers, lubricants and, in flexible PVC, plasticisers, with optional additives, including impact and thermal modifiers, UV stabilisers, flame retardants, fillers, pigments and biocides (British Plastics

Federation, 2010). When plasticisers are added, the resultant products are known as "flexible" or "plasticised" PVC (p-PVC or PVC-P). Alternatively, manufacturing PVC without plasticisers yields "rigid" or "unplasticised" PVC (u-PVC or PVC-U) products (Schiller, 2022, p.3).

The way PVC material properties can be modified to meet the requirements of specific applications, offered an excellent material choice for window and door frame manufacture. PVC-U systems made their way from Germany to the UK between the late 1970s and early 1980s, rapidly rising in popularity (British Plastics Federation, n.d.), with innovative window systems that offered less maintenance, better insulation and greater durability, compared to wood and metal frames (Sathish, 2010). Advancements in manufacturing and extrusion technologies combined with the introduction of double glazing, reduced cost and created an attractive product for the energy conscious consumer, further increasing demand in the market.

3. Environmental and health concerns

Section 3 explores some of the environmental and health concerns that overshadowed the success of PVC as a manufacturing material, prompting action by industry and governments, opening the door for innovation.

As the industry boomed throughout the 1980's and 1990's, partially driven by the surge in demand for u-PVC windows and doors, so did alarming volumes of waste. In the two decades leading into the 21st century almost 100Mt of PVC waste was produced (Geyer, Jambeck and Law, 2017) and by 2010 global PVC production rose to over 26Mt (OECD, cited in Our world data, 2023). In stark contrast to the celebrated success of the polymer as a superior material choice for manufacturers, PVC received intense scrutiny from media and NGO's, with campaigns provoking concern amongst consumers regarding toxic additives and emissions and unsustainable manufacturing and end of life waste management.

3.1 Waste to landfill

In 2000 a report published by the Commission of the European Communities stated landfilling was the most common waste management route for PVC waste, estimating around 2.9Mt of PVC waste to landfill annually (European Commission, 2000). The Commission also stated 82% of all PVC waste produced in EU-15 countries, was disposed of to landfill (Brown et al., 2000). The construction industry produced 1132Kt of PVC waste and was recognised as the largest contributing sector, with almost all non-masonry waste landfilled (Brown et al., 2000). Compared to other methods such as recycling and incineration, landfill proved the cheapest form of PVC waste disposal, with both post-industrial and post-construction waste generally discharged with municipal solid waste (MSW). During early PVC industrialisation, a lack of push factors combined with weak market demand for sustainable products, provided little incentive or competitive advantage for businesses to develop sustainable end of life solutions.

The excessive volumes of waste were further amplified by the mechanical properties of PVC as a waste material. Due to its durability, PVC waste could lay in landfills without degradation for hundreds of years posing a substantial challenge regarding the consumption of landfill capacity (Thornton, 2002). Although PVC resin is considered inert in landfill conditions, highly toxic additives such as phthalate

plasticisers and lead and cadmium stabilisers were not chemically bonded with the polymer and could react with surrounding materials (Thornton, 2002). This posed a risk of leaching, run-off and contamination of terrestrial and aquatic ecosystems, particularly in unmanaged waste sites (Brown et al., 2000).

3.2 Incineration

Incineration was primarily used as a pre-treatment option for waste disposal, namely waste stabilisation and bulk reduction. However, by the early 1900s, advancements in incineration technology provided waste disposers a means of offsetting disposal cost against energy recovery (as heat or energy) (Brown et al., 2000). Regarding its association with PVC waste disposal, the method became heavily criticised for the release of persistent environmental pollutants (POPs) into the environment. In his paper evaluating the environmental impacts of PVC building materials, Thornton (2002) stated 'in every inventory of dioxin sources in the world, trash incinerators and other combustion sources account for the majority of identified dioxin releases into the environment and PVC is the predominant source of dioxin-generating chlorine in these facilities'.

Throughout the 1970's and 1980's, catastrophic accidents such as the 1976 Icmesa chemical company disaster in Seveso, resulted in greater awareness and concern regarding the health risks attributed to incineration and the release of highly toxic dioxins and furans. The explosion released a cloud of highly toxic 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD), causing considerable health issues amongst the local population (Health and Safety Executive, 2015). The event prompted new directives from the EU Commission, shining a spotlight on many industrial processes, including PVC incineration (De Marchi, Funtowicz and Ravetz, n.d.).

Factors such as low or uncontrolled incineration temperatures and incomplete chemical reactions are documented as major contributing factors in the formation of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (The European Commission, 2022). These conditions were not only attributed to early industrial incineration processes, but also to PVC landfill fires. With an absence of flue gas cleaning, potential presence of catalysts such as lead, zinc and cadmium and poor combustion conditions, PVC landfill fires were recognised as significant contributors to the release of dioxin emissions (Zhang et al., 2015), posing considerable risk to health and the environment. Thornton (2002) suggests "PVC is the major chlorine source in the majority of the combustion facilities that dominate inventories of dioxin sources. The production and use of PVC also contributes to dioxin pollution. It therefore appears that PVC is responsible for more dioxin generation than any other single product".

3.3 Carbon emissions

Early on, carbon emissions generated throughout the PVC lifecycle was a subject of environmental concern, with fossil fuels used as both raw materials and energy sources. The high demand for the PVC products combined with considerably low recycling rates, resulted in a dependence of greater volumes of non-renewable raw materials for use in the manufacture of virgin plastics.

This issue was further exacerbated by carbon emitted in the energy intensive manufacturing process of vinyl chloride (VC) and PVC resin. The production of chlorine by means of electrolysis, required

enormous consumptions of electricity and was one of the world's most energy-intensive industrial processes, consuming about 1 percent of the world's total electricity output (SRI International, cited in Thornton, 2002). Moreover, chlorine produced for the PVC market, consumed an estimated 47 billion kilowatt-hours per year (equivalent to the annual total output of eight medium-sized nuclear power plants) (SRI International, cited in Thornton, 2002). Chlorine production was also regarded as a contributor to mercury release, air pollution, as well as SO₂ emissions, resulting in a high Global Warming Potential (GWP) and Acidification Potential (AP) (Baitz et al., 2004).

During PVC conversion, methods such as extrusion, film calendaring, injection and blow molding also required considerable amounts of heat and electricity to provide efficient mixing flowability and homogenization. A report produced for the European Commission, also published concerns regarding CO₂ emissions during waste disposal, concluding 'incinerating emissions of fossil CO₂ were about five or six times higher for PVC than MSW and when accounting for CO₂ emitted during the manufacture of alkali (required to abate acid gas emissions), the total CO₂ emitted from incinerating PVC increased to almost 8 times that for MSW' (Brown et al., 2000).

3.4 Heavy metal based stabilisers

Heavy metal-based stabilisers were used as an additive in PVC formulation to prevent thermal and UV degradation, during the converting and use stage. Praised for their cost-effectiveness and high performance, lead and cadmium were two of the most widely used stabilisers (Fröhlich and Robinson, 2022). Despite their popularity and widespread adoption, heavy metal stabilisers came under significant scrutiny due to their considerable environmental and health risks, leading to widespread condemnation.

In the late 1990's lead was the most common stabiliser used throughout Europe, representing around 70% of all stabilizer consumption (EVCN, cited in European Commission, 2000). Lead is classified by the European chemical agency (ECHA) as potentially damaging to fertility or unborn children, damaging to organs through prolonged or repeated exposure, Carcinogenic, harmful to breast-fed children and very toxic to aquatic life (European chemicals agency, 2023b). Cadmium and its compounds shared a similar classification, with additional warnings of acute toxicity and risk of birth defects amongst humans (European chemicals agency, 2023a).

Although humans were exposed to lead and cadmium compounds during the manufacture and converting stages of stabilisers, the majority of concern was centered around use stage, end of life and disposal. During use stage, there was much debate surrounding the actual level of risk PVC products exposed to humans and the environment, however many studies warned of the longer-term threats posed by lead and cadmium stabilizers. In an example from the pipe industry, a report by the European chemical agency in 2016 stated 'that although diffusion rates from PVC pipes were low, there was sufficient extensive evidence that indicated long term leaching of lead into drinking water does occur' (Brink and van der Jagt, 1998; Hameter and Hanause, 1995; Al-Malack, 2001; Wong et al, 1998; Zhang and Lin, 2015, cited in European Chemicals Agency, 2016).

Disposal of heavy metal sources used in PVC posed one of the biggest environmental and health challenges. ECHA (2016) stated, greater than 95% of the total lead releases from PVC articles were

associated with end-of-life activities. As lead could not be destroyed by incineration, the compound would be emitted into the environment via stack emission, fly-ash, scrubber effluent, or waste water sludges (Thornton, 2002). This was also the case with cadmium. Both lead and cadmium suspended in ash and effluent wastes, were classed as hazardous wastes and were required to be disposed of in hazardous waste landfill (European Commission, 2000). Although specialist sites with robust liners were used, incinerator fly-ash was acknowledged to be heavily contaminated, particularly with unstable heavy metals that could be readily released from the fly-ash matrix through leaching (European Chemicals Agency, 2016). Although there is mixed opinions regarding the level of risk, leachate entering soil and water courses could potentially increase the risk of human exposure through drinking water and food.

3.5 Plasticisers

Phthalates are a type of plasticiser additive commonly used in PVC formulation, primarily to increase flowability in processing. In 2000, a reported 900,000 tons of phthalates were produced for use in PVC, making up around 93% of all PVC plasticisers (European Commission, 2000). Bis-2-ethylhexyl phthalate (DEHP), diisodecyl phthalate (DIDP) and diisononyl phthalate (DINP) were the most commonly used phthalates with DEHP arguably the most controversial. Serious concerns arose amongst consumers, when numerous studies indicated the considerable risk of phthalate leaching from PVC products such as children's toys, teethingers, pacifiers and medical devices.

In all stages of the phthalate lifecycle, reports such as European Union Risk Assessment Report BIS(2-ETHYLHEXYL) PHTHALATE (DEHP) (2008), warned of concerns regarding risk to aquatic and terrestrial ecosystems near production facilities, also hazards to human health through inhalation, dermal, oral and intravenous exposure. In laboratory tests, DEHP was found to be highly carcinogenic in rodents (Shea, 1982) and exposure to humans was linked with concerns regarding testicular effects, fertility, and toxicity to kidneys amongst children (European Chemicals Bureau, 2008).

3.6 A call for change

In 2000, following decades of negative publicity, the European PVC industry came together in an effort to improve the image of the polymer, launching the Vinyl 2010 initiative. The project served as a collaborative, voluntary initiative lead by the sector, that set out specific targets to stay ahead of regulation and proactively transform the sustainability of PVC throughout its lifecycle.

The vinyl 2010 centered around four main commitments highlighted in Table 2

Commitment	Aim
Responsible manufacturing	Minimising or removing harmful additives from PVC compounds, promoting more sustainable solutions.
Resource efficiency	Reducing reliance and more efficient use of non-renewable materials.
Recovery	Minimising waste to landfill, increasing mechanical and feedstock recycling capabilities and pollution-controlled energy recovery through innovation and investment in technology and infrastructure.
Create a “responsible care” culture	Create measurable goals based on commitments, engage and consult with stakeholders, create and follow targets and goals within an agreed audited framework. Improve communications and transparency to the public and stakeholders (at local, National and European levels).

Table 2, Main commitments of the vinyl 2010 initiative table adapted from (European Council of Vinyl Manufacturers et al., n.d.)

4. Case studies of innovational impacts on sustainability.

Section 4 examines three of the many important innovations that emerged following the drive to improve the sustainability of PVC. Using three case studies, based upon interviews conducted with key figures within the industry, the section explores the drivers of sustainability, examining the relationship between manufacturing costs and health and the environment.

4.1 Case study 1. Baerlocher, the switch from lead to calcium-based stabilisers.

One of the of the most significant changes following the coming together of industry through the vinyl 2010 initiative, was the phasing out of lead based stabalisers. Describing the change Fröhlich (2022) commented “The prime goal of this initiative is to give PVC the rightful positive image it can have. It's a lobbying organisation but lobbying alone is not enough. The additive manufacturers, had to commit to have a more sustainable, less toxic solution”. In addition to Vinyl 2010, the threat of regulation from the European Union, concerning Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH), also proved a primary driver in developing new compounds to replace traditional heavy metal-based stabilisers.

With an increased awareness in chemical safety and heightened controversy surrounding lead use in consumer products, Baerlocher chose to act before REACH regulation came into force, committing to phasing out lead-based stabilisers by 2015. The initial push factors came from additive manufacturers, not from converters, who were content with lead additives’ high performance and were reluctant to change. From a technical standpoint, lead was well established throughout the industry and was trusted and relied on for its excellent properties, processibility and responsible pricing. Baerlocher faced the considerable challenge of developing a new product that would not only match the performance and cost of legacy stabilisers, but also win the trust and confidence of stakeholders. After much research, development and collaboration with industry and government, Baerlocher introduced

their calcium-zinc based stabilizer compound to the PVC community, as a non-toxic alternative to heavy metal stabilisers that did not compromise on quality or performance.

Early on, Baerlocher faced significant barriers while integrating this disruptive innovation into their existing systems, such as establishing new supply chains, process changes and trialing and optimising the new product with converters. Challenges were not only limited to the manufacturing process. Baerlocher faced issues with weak demand from fabricators and the end customer, as Fröhlich (2022) described “On the one hand the customer wanted toxic-free, environmentally safe product, but on the other hand, once the window was fitted, the customer could not tell the difference between the two. The idea was not easy to transport to the end customer, so they would ask specifically for a calcium-based window. We also initially had difficulty selling the product to the extruders, who were happy with the existing product”. Despite these barriers in the period between 2000- 2007, industry started to embrace the changes, lead stabilisers (in EU-15) decreased by 43,014 tons (-33.82%), and calcium organic stabilisers (in EU-15 plus Norway, Switzerland and Turkey) increased by 38,243 tons (Programme, 2008)

The voluntary approach of industry acted as main pull factor, with Baerlocher slowly integrating the new product into a reluctant and cautious market. This changed around 2006 to 2007 where two major push factors accelerated the switch. During this period a global commodities boom saw the price of lead soar from \$558 per tonne to \$3415 per tonne (tradingeconomics, 2022), severely impacting manufacturing costs for companies still using legacy stabiliser. This prompted Baerlocher to optimise their formula, reducing costs to gain a competitive advantage over lead-based products. Additionally, in June 2007 the European Union launched REACH, radical new legislation adopted to improve the protection of human health and the environment from the risks posed by chemicals (European Chemicals Agency, 2018) imposing mandatory actions such as hazardous material labelling. This helped change the sentiment of installers and customers, which accelerated the switch to lead free compounds. In a bold move, Baerlocher completely phased out lead stabilisers in their UK plant in Bury, becoming the first in Europe to fully convert (Baerlocher switches to Ca-based stabilizers at UK plant, restores Italian production, 2011)

4.2 Case study 2. Duraflex, Implementing recycling technologies.

Industry recognised the need to scale up existing plastic recycling technologies and continuously innovate, to achieve the ambitious recycling targets of the Vinyl 2010 initiative. The growing awareness and controversy surrounding the use of fossil fuels in the manufacture of new plastic, combined with condemnation of common waste disposal methods, prompted converters to commit 200,000 tonnes of post-consumer PVC waste by the end of 2010 (Vinyl 2010, 2011). An excellent example of how recycling technologies not only created opportunities for circular economies to develop, but improved profitability and competitiveness was the implementation of recycling technologies at Duraflex.

Originally based in Toddington in Gloucester, Duraflex were once one of the largest extruders of PVC-u window profile in the UK. In the early 2000's, owners MASCO planned to scale up their operations with a move to a purpose-built factory in Tewkesbury. With the European outlook on PVC sustainability changing and a volatile oil market, Duraflex realised they needed to change their

business model to adapt to future changes in technology, attitudes and regulation. Former operations director at Duraflex Barry McCarthy, spearheaded the new factory build and recalled “When we built the new site, it was obvious that things were going to change regarding recycling, but we didn't know how. Nobody really knew. There was talk about recycling, but if I was being brutally honest, in the window industry, nobody knew what it meant for us. Nobody really knew whether post-consumer waste was going to happen. It was a complete blank sheet. So, when we built the new factory, we built in as much flexibility as we could afford”.

At the company's old factory at Toddington, the recycling capacity was merely one granulator, capable of recycling a small portion of scrap profile the business produced. This material was then reused through two dedicated extruders, for non-window profile such as sill and cavity closures. This left the business extremely restricted with limited options to how they could reprocess the recycled material. For excess scrap that could not be internally recycled, three options were available. Either sell to recycling companies, subcontract out recycling and transport back, or landfill for disposal. Duraflex opted to sell this excess scrap on the open market.

The business direction changed in 2004, when the firm commenced operations in a 275,000 sq/ft state of the art, purpose-built facility in Tewkesbury, making them the largest single site extruder of hollow PVC-u profile in the UK (Duraflex, no date). Duraflex designed the new site to incorporate a mixing plant, so that dry blends compounding could be carried out internally. Additionally, an automated recycling plant was also commissioned, consisting of multiple granulators, a pulveriser and materials conveying equipment. This machinery allowed internal post-industrial scrap to be recycled on site, producing a fine micronised powder that could be added to dry blends in the compounding process, or fed directly into extruders. Moreover, there were no restrictions regarding which window profile the recycled material could be used in, resulting in greater profit margins across the product offering. Later the business invested optical colour sorting equipment, which dramatically improved colour sorting capabilities and removed the need to subcontract materials outside the business. This strategic move also proved extremely lucrative, returning investment within a year and delivered an estimated saving of around £800,000 a year.

Interestingly, Duraflex had originally adapted operations because of the anticipated changes in sustainability within the industry, however when questioned around the main drivers that accelerated change within the business, McCarthy (2024) commented “In the 2000's round about the start of the recession, there was a massive spike in polymer price. And very quickly, that is what if you like, accelerated the industry to look at recycling. It was absolutely not environmental”.

Describing the positive impact recycling innovation had on the business McCarthy (2024) commented “ We actually got to the point ,where the scrap that we made on day one. was recycled on day two, put in the mixing plant on day three and extruded. So there was no stockpile of scrap. We actually got it slick enough so it was going around in circles. So huge benefits. Space was saved, materials handling was saved, 1.5 thousand tons of virgin was saved (annually). The savings were colossal”

4.3 Case study 3. Duraflex, Co-extrusion technology, frugal innovation

It became clear that if the window industry could successfully overcome significant challenges in collection, sorting and recycling then it would unlock an untapped supply of low-cost post-consumer and post-industrial waste material. However, converters were also faced with the additional problem of how to reintroduce and process r-PVC back into new window profiles.

Toward the end of the 20th century, co-extrusion technology became increasingly popular as a means of layering different materials, to amalgamate specific properties and improve product performance. During the process of co-extrusion, dissimilar materials are pushed through two extruders, as opposed to the traditional single method of extrusion. Melt streams from each extruder are forced through a complex die construction, in which separate melt path manifolds are arranged to merge at a point close to the die exit (Drobny, 2020). In Europe, converters such as Veka and Kommerling used co-extrusion to produce window profile with pigmented layers, while other converters developed the method to combine PVC with Polymethyl methacrylate (PMMA) to improve impact resistance and slow heating (Rafał Karaś, 2021).

As large-scale automated recycling facilities emerged throughout Europe creating an abundance of r-PVC, converters continued to innovate production methods, turning their attention to co-extrusion as a means to reintroduce r-PVC back into new window profile. Using the co-extrusion process, converters developed techniques of extruding recycled PVC through the core of a window profile, while using a second extruder to produce a layer of virgin PVC to encapsulate it. For Duraflex, co-extrusion technology was something they had seen used in Europe. The company had scaled up their recycling capability, however their internal recycled material supply was limited to the volume of scrap they produced, which was also impacted by business key performance objectives to reduce scrap to increase production efficiencies.

Duraflex faced a significant supply challenge. Their recycled internal scrap was fed directly into the dry blend, meaning it could be used in any profile on any surface, however if the business wanted to increase the amount of recycled material they could use and exceed their internal capacity, they needed to source material externally. External scrap and post-consumer waste presented other challenges regarding window specification, McCarthy (2024) explained “if you take other window companies scrap, from different types of windows, that was all mixed or post-consumer waste, the minute you've got no history and you don't know exactly what it is, it could only be used in the core of a profile not a visible surface. So that was the driver for Core- technology”.

A lack of capital investment required to employ co-extrusion technology became the next hurdle for Duraflex. Co-extrusion technology, consisting of two extruders, mounted one on top of the other was expensive and unaffordable for the business. Pushing the boundaries of conventional thinking, Duraflex worked closely with the die manufacturer to create a custom-made die, then adapted frugal methods of innovating their existing extrusion processes, McCarthy (2024) described the development “Our problem was we couldn't afford it. So we bought a second hand refurbished CMT (extruder) from Cincinnati, we took one out of line, we coupled them together at right angles. So, we could use conventional extruders and they gave us the in. And from there, we had the capability to use post-industrial or post-consumer waste of any sort in the core.... Co-extrusion!”.

This frugal method of innovation resulted in two dedicated ‘core-lines’, processing window profile with a r-PVC core and virgin outer layer. Co-extrusion allowed the business to expand the volumes of r-PVC they processed, by purchasing external recyclate from recyclers, in turn decreasing dependence on virgin PVC. In creating new circular supply chains, in 2021 the business recorded in excess of £1.3 million in savings against the cost of virgin material.

5. A view of today’s PVC window industry

Section 5 provides an overview of the PVC window industry today, following over two decades of change. This section also examines how stakeholders are interconnected and their relationship with waste and creating circular supply chains.

5.1 General market overview

Today, PVC is the world’s third most commonly produced plastic, dominating sectors such as construction, medical and health care and automotive. In 2021 the EU Polyvinyl chloride market was estimated at approximately \$6.6B, with an expected compounded annual growth rate (CAGR) of 3.8% between 2022 and 2030 (Jaganmohan, 2024)

In 2022, PVC made up 9.1% of the 58.7 million tons of plastic produced in EU27⁺³, with total combined plastic consumption reaching 53.6 million tons (Plastic Europe, 2023). The building and construction sector demanding the largest volumes from PVC converters, for use in applications such as piping, window frames, roofing, cladding, and flooring. Additionally, packaging, leisure, agriculture, electrical and electronics industries are also among other large consumers of converted PVC (Plastics Europe, 2022).

Despite advancements in recycling technology and shifts in industry and consumer behaviour over the last two decades, in 2022 post-industrial and post-consumer PVC waste, contributed to just 16% of the estimated 5 million tons of PVC produced (Schulz, 2022) (VinylPlus, 2023). The building and construction sector is responsible for generating over 44% of all PVC post-consumer waste. Recycled window profiles contributed the largest volume of rPVC back to converters, with 169,770 tons of post-industrial and 238,381 tons of post-consumer waste recycled (VinylPlus, 2023).

Although there is a lack of reliable data regarding PVC waste disposal routes in the EU27 (Plus UK, Switzerland and Norway), reports suggest around 35% of PVC waste is recycled, with 46% incinerated for energy recovery and 19% landfilled or incinerated without energy recovery (Conversio Market & Strategy GmbH, cited in The European Commission, 2022).

5.2 Current structure and description of the PVC window industry

The PVC window industry is placed amongst the wider construction materials sectors and relies on a well-established supply chain, from material supply to installation and waste management. Fig.... illustrates a general overview of the industry structure.

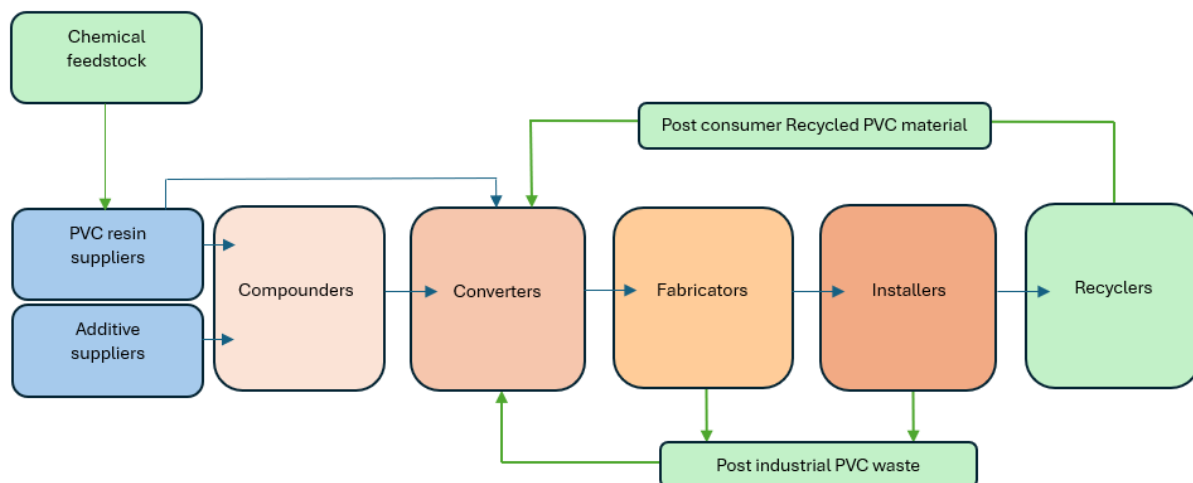


Fig 2. An overview of the PVC window industry structure

5.2.1 Raw materials suppliers

PVC resin and additive suppliers are the foundation of the PVC window industry. In PVC resin manufacture, sophisticated chemical processes are used to produce ethylene and chlorine which are thermally cracked to produce VCM. VCM synthesis is then followed by the polymerization process, where VCM undergoes exothermic reactions in which long polymer chains are created forming PVC resin. PVC resin is typically delivered to converters or compounders in powder form, using tankers, travelling by road networks. Tankers discharge powder deliveries to bulk material holding silos at converter facilities. Cite

Additive manufacturers produce materials to enhance processing capability and PVC performance. Compounders and converters maintain close working relationships with additive producers, modifying formulation recipes to meet cost and application requirements. Additives supplied include heat and UV stabilisers, impact modifiers, lubricants, fillers and pigments and are delivered to compounders or directly to converters (with blending capabilities) using tanker, traveling by road network.

5.2.2 Compounders

Compounders play an integral role in the PVC supply chain, acting as a link between resin and additive manufacturers, converters and recyclers. Compounding companies take PVC resin and additives and mix using weighing, batching, mixing and cooling machinery, to produce a powder referred to as 'dry blends'. Dry blends are delivered directly to converters in powder form or can be extruded into pellets, dependent on customer preference. Compounders work closely with converters to tailor recipes to meet specific cost, performance and application requirements. Many larger and medium sized converting businesses, are equipped to carry out compounding within their own facility, however for smaller organisations without the necessary infrastructure, compounding companies prove vital to their operations.

5.2.3 Converters

Converters use PVC compounds to produce physical products such as window profile. Some converters may have separate PVC resin and additive supply chains, then compound within their own facilities, however businesses without necessary infrastructure, may choose to purchase ready-made blends for processing (European council of vinyl manufacturers, n.d.). Converters use extrusion as a method for producing window profile. In a typical extrusion process, dry blend compounds are gravity fed into a screw and barrel section which is individually heated and cooled, dependant on process parameters (Kent, 1998, p.4). Melting, shearing and homogenization take place, as the material is screw conveyed and forced down a barrel before entering a die. Each die is intricately designed to create the desired profile shape. A calibrator located in front of the die zone helps shape, size and cool the profile before it enters a water-cooling tank. Once cooled, profile is guided into a saw section or guillotine for cutting to the required length. Converters produce a wide range of profile types for fabricators within their own organisation, or sell to other window manufacturers.

5.2.3. Fabricators

The fabrication process involves the assembly of profile, glass and furniture, creating a complete window system. Fabricators maintain close working relationships with converters in the design of products, specification and quality control and waste management. During the fabrication process, profile is precisely cut to the required angles and lengths for joining. The finished profiles are then clamped in position where the edges are heated and pressed together, forming a strong welded bond as the material cools. Welded edges are then trimmed before the frame assembly is cleaned. Assembly of furniture and fixings such as hinges, handles, brackets, and locks are fitted before the window is sealed and glazed. Fabricators may supply installers within their own organisation or supply customers such as builder's merchants, the government, construction companies or other window and door retailers.

5.2.4. Installers

The primary role of the installer is to install and remove PVCu windows. Their knowledge and experience of window systems enables them to advise customers of style, functionality, efficiency and suitability in specific applications. Installation companies are supplied directly from manufacturers, distributors and merchants or by fabricators within their organisation. They may operate by working on large scale developments with architects and developers, work directly or subcontract for construction companies, or by direct selling to homeowners. Installers play a pivotal role in the management of post-consumer waste and advancement of circular economies. Their direct role in both the sale and disposal of PVCu windows not only advocates products containing recycled material in the sale of new windows, but helps advise on disposal, collection and sorting old windows for recycling and reuse.

5.2.5. Recyclers

Recyclers play a crucial role in the management of both post-consumer and post-industrial waste, providing high quality recycled material, feeding circular economies. For converters without recycling capabilities, recycling companies provide a supply chain for high quality recycled material. PVCu waste recycling can be classified by two main categories, mechanical recycling and chemical recycling. Mechanical recycling is the most common form of recycling. Mechanical recycling for window grade material is fed from two waste streams, post-industrial waste (production scrap, off cuts and rejects) and post-consumer waste from disposal of old windows. Material can be supplied to converters or compounders in micronised powder, pellet or re-grind form. Chemical or feedstock recycling is a less common but growing industry. Unlike in mechanical recycling, where waste material is broken down into smaller reusable pieces, chemical recycling breaks down polymers into monomer form using chemical reactions, allowing them to be reused to virgin quality standard.

5.3 Waste Routes

5.3.1 Mechanical recycled waste

Post-industrial waste

Throughout Europe, PVC is almost completely recycled via mechanical recycling processes (The European Commission, 2022). The waste supply source for post-industrial mechanical recycling, is generated from the production waste of final and intermediate PVC products, along with installation waste from of PVC products (Baitz et al., 2004). Post-industrial waste can be directly recycled 'in house' by converters with recycling capabilities or transported to recycling companies for those without. First, waste is collected, manually sorted, segregated by profile colour then fed into granulators which break the waste down into smaller fragments known as 're-chip' or 're-grind'. Electrostatic metal separators filtration systems remove metal contaminates and fine dust from the material. Clean Re-grind material can be fed directly back into special co-extruders or can be further ground to a fine micronised powder using pulverisers. Micronised power can be blended with compound formulars or also be fed directly in co-extruders, often offering smoother processing compared to re-grind material.

Post-consumer waste

Mechanical recycling of post-consumer waste is a larger, more complex operation. This waste stream originates from the removal of old installations and demolition waste. Segregated sorting and collection can prove a considerable first stage task and often the main challenge in post-consumer recycling for any material (not just PVC), not in the recycling technology itself, but rather the setup of a cost-effective collection and sorting scheme (Baitz et al., 2004). Hammer mills, often located in satellite locations, break down frames into smaller pieces, displacing glass, metal furniture and fixings, creating a more manageable load to transport. Waste is then fed into shredders fitted with magnets, which further breaks down material, removing metal contamination. To enable the supply of high-

quality material required for use in the window manufacturing industry, shredded material is washed, before optical colour sorting equipment separates coloured material, rubber and non-metal fragments. As with post-industrial waste, at this stage the material is granulated and pulverised, however post-industrial waste requires an additional level of purification known as melt filtration, which removes any remaining contaminants. Finally, material is extruded into thin strands and cut into pellets ready for delivery to converters.

Incineration

Although incineration is primarily a method used to reduce waste volume and decrease waste to landfill, technological advancements in recent decades have transformed the process into a means of generating energy sources such as heat, fuel or electricity. PVC waste is regarded as a favourable material for energy recovery. With a high calorific value of approximately 19 megajoules per kilogram (MJ/kg), PVC waste can be compared to brown coal and can produce a higher heat value than municipal waste (11 MJ/kg) used to generate electricity (VinylPlus, 2017). The process begins with waste sorting and segregation, removing non-combustibles and recyclable materials. To further prepare waste, mechanical equipment such as shredders and grinders may be used to reduce bulky material and reduce particle size. Waste is then dried to remove moisture to stabilise combustion during incineration. PVC waste is often homogenised with municipal waste prior to incineration, to ensure consistent burning and efficient energy output. The heat generated can be used to produce high pressure steam, that can power turbines which generate electricity.

Landfilling

Despite a decline in use over the last twenty years, landfilling still remains a disposal route for PVC windows and a considerable method for building and construction waste. Although disposal is advised as a last resort in the waste hierarchy (Department for environment and rural affairs, 2011), between 1960 and 2012, around 10 million tons of PVC waste was directed to landfill, with more recent statistics reporting around 23% of PVC in construction waste (0.25 million tons) routed through disposal routes (The European Commission, 2022).

Modern landfill sites are designed to manage leachate and gas capture, to limit the risk of contamination of soil and water courses and greenhouse gas emissions, although these risks still remain present. Challenges with some PVC waste, such as legacy additives, waste that is difficult to separate or incineration waste may result a diversion toward disposal. Typically, PVC waste is directed to non-hazardous waste landfill, however PVC fly ash and bottom ash waste, produced during incineration, is typically directed to hazardous facilities.

Chemical recycling

Chemical or feedstock recycling, utilises thermal and chemical methods such as gasification and pyrolysis to break down mixed plastic waste into its basic components. Chemical recycling is more suitable for unsorted plastic mixtures and waste streams containing composite materials (VinylPlus, 2017). Unlike traditional incineration, which converts carbon into CO₂, these processes aim to recover

carbon in the form of smaller, low molecular weight compounds (The European Commission, 2022). The products derived from chemical recycling serve as raw materials in the creation of fuel sources, polymers and other chemical entities. Chemical recycling is still in early development stages and is currently not operating on an industrial scale, with just 1,000 tons of PVC chemically recycled in the EU in 2020 (Conversio Market & Strategy GmbH, cited in The European Commission, 2022). A more detailed description on chemical recycling is presented in section 7 of the paper, where methods will be analysed as potential emerging technology.

5.4 Factors affecting r-PVC availability.

5.4.1 Economic factors

As with most materials, PVC cost can be heavily impacted by economic factors, such as conflict, inflation and commodities prices. Market demand for PVC is largely driven by the building and construction sector (Ciacci, Passarini and Vassura, 2017), due to the large volumes of PVC materials consumed each year. In periods of economic downturns or when construction slows, the demand for PVC declines, resulting in surplus stock or overproduction, driving down prices. This was evident in March 2023 when the European PVC market saw a drop of 12%, due to weak demand from the construction sector due to a falling housing market (Jayavikraman, 2023). With less demand for PVC products, the call for r-PVC also declines, which in turn lowers recycled material costs. In addition to a decrease in building and construction activities, shifts in consumer spending, such as the cost-of-living crisis, may also impact PVC and r-PVC demand. A lack of consumer spending may also reduce recyclate availability, as households replace less older items. The window manufacturing industry is a good example of an industry that would be particularly impacted in this scenario.

5.4.2 Quality

PVC prices are also governed by material quality, with different industries and applications requiring different levels of material specification. This is particularly prominent in r-PVC material where factors such as colour, particle size and waste type, may affect the price paid by converters. One example would be mixed colour PVC recyclate referred to in the industry as 'jazz' which can be difficult to separate (Veka, n.d., cited in Miliute-Plepiene, Fr  ne and Almasi, 2021)

Mixed colour recyclate may be suitable for products such as pipes or products that will be hidden during use phase (Mccarthy, 2024), this type of r-PVC would require minimal sorting and separating activity and would be reflected in lower resale prices. The sale price of jazz rechip would typically range from £350-£400 per/tonne (Mccarthy, 2024). Recyclate destined for the window industry, however requires a more stringent and intensive sorting process to produce the high quality clean r-PVC demanded by the industry. Many industries may also be more selective with which recyclate waste streams meet their product specification, which may limit material availability, driving up costs. This is apparent in the window industry, where r-PVC produced is derived entirely for old windows. Window converters sourcing clean micronized recyclate from external recyclers could typically pay around £750 per/ tonne, almost double the cost of mixing colour rechip (Mccarthy, 2024).

5.4.3 Commodities

The cost of raw materials naturally fluctuates however dramatic swings in commodities markets could positively or negatively affect PVC and r-PVC sales prices. Prices of virgin PVC tend to fluctuate cyclically due to changes in supply, demand, and the cost of the material itself. Consequently, with the increasing scarcity of oil, it is logical to anticipate a rise in PVC prices (Thompson, 2005). Recent events, such as the global energy crisis, saw energy intensive industries such as PVC manufacturing suffer, as higher electricity prices raised chlorine production costs and higher gas prices impacted PVC resin production across Europe (Vitiello, May and Rajendra, 2022). Energy prices would also impact other areas of the sector that also consume large amounts of energy, such as recycling and conversion which would in turn drive up r-PVC and converted product prices. Global events, tension and conflict may also significantly impact material costs. Recent unprecedented events such as the Covid-19 pandemic or conflicts such as the Russia, Ukraine war may also disrupt supply chains, which would negatively affect material costs.

5.5 Linear to Circular: Transitioning Economic models.

As with many industries, since conception the PVC industry has traditionally followed a linear economy model. Linear economies can be best described as “take, make and waste” (Ellen MacArthur Foundation, 2023) style operations that since early industrialisation are thought to have significantly contributed to the global pollution and climate change challenges of today. Over the last forty years the idea of a circular economy has challenged cradle to grave models, as a solution to create sustainable and responsible practices which create a cradle-to-cradle concept. Circular economies are described as “a system where materials never become waste and nature is regenerated. In a circular economy, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting” (Ellen MacArthur Foundation, 2022). Today’s PVC industry has made significant progress in its journey towards a circular economy with the European Trade Association of PVC Window System Suppliers (EPPA) (n.d.) suggesting, as a result of considerable investment “The PVC profile industry is the only sector (compared to other window materials) which keeps the material in a controlled (window to construction applications) or even closed loop (window to window) system.

6. Current challenges in creating circular economies.

Section 6 explores some of the many barriers and challenges of adopting circular economies in today’s PVC window industry. This section also pays particular attention to the impact faced by SMEs in comparison to larger organisations.

6.1 Material availability

With the vast quantities of u-PVC windows created each year and the mountains of end-of-life windows seen in the PR releases of large multinational converters, it would be easy to imagine an endless supply of recyclate available for any company to access. Indeed, the largest fraction of recycled PVC waste is window profiles (Miliute-Plepiene, Frâne and Almasi, 2021) However, material

availability is complex and presents particular challenges in creating circular economies in the PVC window industry. To date, the amounts of post-consumer recyclate available from rigid PVC currently is not sufficient to include recyclate into all new window profiles (EPPA profiles 2018).

The supply of post-consumer recyclate is closely tied to specific sectors like building and construction, making it challenging to boost the inflow volumes. These industries are also susceptible to changes in economic conditions, which can slow or speed up building, demolition and renovation, impacting demand for new windows and reducing the availability of waste. Another challenge for the industry is what has been described in the construction sector as 'controlled loop' recycling (European Trade Association of PVC Window System Suppliers, n.d.). Slightly differing from traditional 'closed loop' recycling, recyclate is not only recycled back into its original product but can be repurposed into other construction materials. It is common practice to use PVC window profile recyclate for PVC pipes, mainly due to the fact that PVC pipe waste is lacking in quantity, thus reducing material availability for window production (McCarthy, 2024). Repurposing recyclate for some pipe profiles, where a lower specification is acceptable, requires less effort, machinery and cost for small recycling businesses, which could also result recyclate diverted away for the window industry (McCarthy, 2024).

SMEs in the converting and recycling industry, face the more complex challenge of competing with the multi-national giants of the industry such as Veka, Eurocell and Rehau for recyclate material. With vast, state of the art recycling facilities these companies have established wide spanning sorting and collection networks consuming majority shares of post-consumer waste. Miliute-Plepiene, Frâne and Almasi (2021), suggest "The biggest challenge for the rigid PVC recycling sector is to obtain PVC waste". The struggle of smaller business in obtaining material while competing with larger firms is highlighted by McCarthy (2024) who comments "they are really struggling because the big, big multinational players have got to get as much windows and scrap and everything else as they can get their hands on, to feed these colossal extrusion plants", he also added "it can be very difficult to compete where people have made the heavy investment and you haven't. Because they then sucked out that recycled raw material source".

6.2 Infrastructure requirements

For SME converters planning to invest in post-industrial recycling operations, capital investment, knowledge and infrastructure required could be described as more feasible and easier to backward integrate into existing processes, compared to post-consumer recycling. There is a healthy market for pre-used, refurbished granulators and pulverisers and alternatively many recyclers willing to recycle pre-consumer waste on behalf on converters.

Post-consumer recycling however, is a complex, expensive operation comprising of vast logistical networks and large recycling facilities with specialist sorting, cleaning and extrusion equipment (Lewandowski and Skórczewska, 2022). For many SME a lack technologies, knowledge and information may inhibit adoption of circular practices (Tura et al., 2019). Many of the successful converters of window profile operating in the UK today such as Profine, Veka and Eurocell, have already adapted their business models, investing early recycling businesses alongside their converters. Describing the situation, McCarthy (2024) commented "All the major companies are heavily into recycling. Now, what's interesting is the commitment and investment that those other companies have made is

colossal". An example of the sheer size of these operations is the 6-acre recycling facility in Wellingborough, Northamptonshire, owned by Veka, costing around £15 million and capable of recycling 35,000 tons of PVC windows annually (Veka, n.d.). The implementation and management of circular economies, requires of high level of investment in technology and training of human resource (Pathak and Endayilalu, 2019). As with the example of Veka, these investments are well published as success stories in the media, however these high costs could not only price smaller businesses out of post-consumer recycling, but also impact their ability to remain competitive.

6.3 Waste sorting, collection and preparation

A significant portion of the expenses associated with recycling rigid PVC consists of fixed costs stemming from the collection, sorting, and segregation processes. Regarding post-consumer waste, the logistical task of segregating window profile from mixed construction waste, storing, reducing the bulk of window frames into denser more manageable pieces, then arranging transport to collect and deliver waste, is costly and labour intensive. Lewandowski (2022) describes organising waste collection that guarantees raw material availability and quality as a strategic task.

For many SME these additional fixed costs, resource and infrastructure requirements would undoubtedly drive up the total cost of post-consumer recyclate to prices which would question the feasibility of using r-PVC over virgin material. Furthermore, an economic obstacle to separate collection includes the regional aggregation of individually small quantities of waste. In an interview with McCarthy (2022), he described the challenges of a SME, balancing transport costs with the collection of external post-industrial offcuts, on return journeys of customer deliveries, stating "if we had a customer that could supply us with 5 tons of offcuts a week and four customers with 1 tonne a week, we would have to turn the 4 customers down, saving space for the larger offering. To make collections work, there could be any additional cost involved"

6.4 Processing

The processing or converting of r-PVC introduces specific challenges, barriers and limitations of creating true circular economies. The tight specification associated with window profile extrusion based on European standard EN12608 permits that all visible surfaces of a window must be covered by virgin material, meaning r-PVC is mainly extruded through the core on the profile (The European PVC Window Profile and Related Building Products Association, 2018). Conforming with this standard, results in an average of around 50% recyclate is used in new profile extrusion, with the remaining depending on virgin materials (The European PVC Window Profile and Related Building Products Association, 2018).

Co-extrusion technology presents converters with opportunities to extrude both mixed post-industrial and post-consumer waste into the core of window profile, however this technology requires significant investment to purchase machinery and a robust supply chain to ensure consistent inflow of recyclate to return investment. Both present challenge for SME's. Additionally, the quality of post-consumer waste and lack of experience in processing it, may also affect efficiency, producing excess scrap and downtime, especially during early stages of introduction into new businesses. McCarthy

(2024) describes these challenges “. We'd have a great run of a day, two days, three days, and then we'd have a run of absolute disaster, where we literally made scrap, maybe another couple of days, then it would come good. If you talk about efficiency losses and everything else while processing post-consumer waste, it's very high capital, it's a huge amount of money. McCarthy also added “I genuinely don't know from a cost perspective whether it's cheaper to use post -consumer waste or virgin for smaller businesses”. Low quality r-PVC cannot be used in the production of new windows, which also reduces material availability (The European Commission, 2022), therefore if high quality r-PVC is achieved, then both environmental and financial revenues are possible (Faraca, Martinez-Sanchez and Astrup, 2019).

Another limiting factor influencing a circular economy is the number of recycling cycles that a PVC recyclate can undergo before losing its necessary properties, as repeated life cycles can influence the concentration of a specific substance in a product (dilution or accumulation) depending on the recycling processes and resulting products (Blaeij et al. 2019, cited in The European Commission, 2022). Although reports vary from between 4 and 10, VinylPlus suggest PVC can be recycled 7 times without effecting quality, however tracking these cycles over time could be challenging presenting a risk of poor processing or defected products a risk.

6.5 Legacy additives in recyclate

Although the European PVC industry successfully phased out cadmium and lead stabilizers from use in new PVC window profile, the issue surrounding legacy stabilisers present in recyclate still remains a challenge unsolved. With an average window lifetime of 30-40 years, it is assumed that concentrations of lead in PVC waste windows will decrease after 2035 (VinylPlus 2021, cited in The European Commission, 2022), with the share from windows containing cadmium will decrease by 2050 (The Swedish Chemicals Agency, 2020). This is problematic for an industry trying to maintain a toxic free persona, as conforming to European standard EN12608, recyclate containing legacy stabilisers is encapsulated in a layer of virgin material during co extrusion. Although it could be argued that co-extrusion encases legacy additives in the profile core, this process in effect mixes toxic additives with clean virgin material and releases them when the profile next enters a mechanical recycling phase. The European Commission (2022) states ‘With regard to legacy additives in a Circular Economy, the practice of co-/tri-extrusion requires explicit consideration. Tri-/co-extrusion increases the resource efficiency of recycled PVC but can be seen critically in the context of a toxic-free environment as the use of PVC recyclate containing legacy substances postpones the final disposal to a later stage’.

6.6 Driving forces for circular economies

Fluctuations in raw materials markets, will inevitably affect polymer and additives cost, however they also interfere with circular economies influencing procurement decisions of virgin materials over recyclate. This factor is particularly evident in all three case studies presented in this paper. Proactive efforts by industry to offer more sustainable or toxic free products, driven by ecological and health

concerns, were met with challenges from some customers interested in cost over sustainability (Fröhlich and Robinson, 2022) (McCarthy, 2024). The issue of cost over conscience, is also demonstrated by McCarthy (2024) who describes how a drop in virgin polymer prices saw converters quickly switch back from using recyclate to purchase lower cost virgin material, leaving one recycler with an abundance of r-PVC he couldn't sell. Other examples include a commodities boom which spiked the price of lead, proving the accelerating factor in the switch to non-toxic stabilisers (Fröhlich and Robinson, 2022). These actions sit far from the principles of circular economies and poses the question what is really driving circularity within the industry?

From a consumer level, The European Plastic Pipe and Fittings Association (TEPPFA) suggest in today's markets, the demand for recycled PVC is not only driven by price fluctuations but also by sustainability factors, with customers requesting recycled content in the products (TEPPFA, 2021, cited in The European Commission, 2022). Hina et al (2022) cites Edbring et al, (2016) work on exploring consumer attitudes, suggesting some customers may associate circular economies with higher costs, with a reluctance to change their traditional consumption patterns, or to purchase alternative products in the absence of tangible benefits. Currently with no heavy penalty from governing bodies for producing 100% virgin PVC windows profile and no significant concern or loss of sales from the consumer, this presents a barrier to sustainable efforts. There is an obvious challenge in balancing manufacturing costs and the willingness to improve health and the environment, particularly with SME trying to remain competitive in the market.

7. Emerging technology and future impacts.

Section 7 explores key emerging technologies and their potential future impact on the future of sustainability in the PVC window industry.

7.1 Bioplastics

The bioplastic timeline began in 1862 where Alexander Parkes created the first man-made plastic from Cellulose (Barrett, 2018). Over time, development of more sustainable forms of plastic has gained traction, resulting in breakthrough and disruptive innovations such as Bakelite and cellophane (Barrett, 2018). The progress and acceleration of bioplastic development has often faltered due to global events, in which an abundance cheap oil supply is released into the market (Barrett, 2018). In recent years, extensive research and development (R&D) has positioned bioplastics as an attractive substitute to replace some traditional non-renewables. A report conducted by nova-Institute (2018) found that Europe ranks top in R&D of bioplastics acting as a major hub for bioplastics production and consumption.

European Bioplastics suggests (2016) defines 'a plastic material as a bioplastic if it is either biobased, biodegradable, or features both properties'. For use as construction materials, there are some obvious challenges with choosing bioplastics over conventional plastics, including many inferior mechanical properties, including brittleness, low mechanical strength, high water permeability and low thermal stability (Kong, Rawi and Tay, 2023). To counteract these attributes, reinforcing materials can be added to improve bioplastic properties. Natural reinforcing includes natural resources and biomass

materials, such as cellulose fibre, protein, chitosan, clay and Lignocellulosic fibre (Kong, Rawi and Tay, 2023).

Plastic category	Plastic classification	Plastic type example	Use case
Biobased, non-biodegradable	Biobased or partly biobased, non-biodegradable polyolefines	Bio-PE, Bio-PP, Bio-PVC, biobased PET	Used in rigid containers, bottles, and caps. Favoured for good mechanical properties like flexibility, strength, and moisture and chemical resistance.
	Biobased, non-biodegradable technical/performance polymers	Polyamides (PA), polyesters (e.g. PTT, PBT), polyurethanes (PUR) and polyepoxides.	Diverse use case, including textile fibres, automotive applications like foams for seating, casings, cables, hoses, and covers.
Biobased, biodegradable plastics	Plastics that are both biobased and biodegradable	Polylactic acid (PLA) or polyhydroxyalkanoate (PHA)	Primarily used for short-lived products such as packaging. Has end of life recycling potential.
Biodegradable, fossil-based plastics	Plastics that are based on fossil resources and are biodegradable.	Polybutylene adipate terephthalate (PBAT)	Mainly used in combination with starch or other bioplastics because they improve the application-specific performance.

Table 3. Classification of biobased and biodegradable plastic, type and brief use case description – table (European Bioplastics, 2016)

Focusing on future materials for window frame manufacture, lignocellulosic fibre-reinforced bioplastics offer advantages of elasticity, biodegradability, and strong mechanical properties (Kong, Rawi and Tay, 2023) and have been reported to be commonly used in construction products including windows (Verma, et al 2021, cited in Kong, Rawi and Tay, 2023). In 2017 German based Fraunhofer WKL, launched a resource-conserving, Bioprofile project, which aimed to extrude and produce natural-fiber composite facades and windows, using natural fibers and natural-fiber flours, including wood and other vegetable sources (Fraunhofer Institute for Wood Research, 2017).

Perhaps going a step further in confirming bio solutions as having future innovational impact in PVC windows, is the production and installation of 113 bio-attributed windows by German firm Kömmerling. This radical innovation uses pine oil-based raw material instead of crude oil in the production of ethylene, with the business claiming up to a 90% reduction of CO₂ compared to conventional PVC (Kömmerling, 2023).

7.2 Advanced recycling technologies

Chemical recycled waste

Chemical recycling is a less common method compared to traditional mechanical recycling, especially regarding window frame waste. This method of PVC recycling consists of breaking down polymers by means of chemical reaction, returning waste back to its original monomer (Vasudeo et al., 2016). As with mechanical waste recycling, the process typically begins with collection segregation and sorting of waste. Also reflecting the mechanical process, chemical waste supply is often broken down into more manageable pieces using mills, shredders and granulators.

Chemical recycling is acknowledged for its ability to handle mixed or contaminated waste, or material that may be classed as unrecyclable under normal mechanical methods. Chemical recycling is conducted using a variety of different methods including hydrothermal treatment, gasification,

catalytic cracking and reforming, hydrogenation and chemical depolymerization (Vasudeo et al., 2016). Techniques such as pyrolysis, and solvolysis breakdown PVC waste to its fundamental components, producing VCM which can be reintroduced in the production of virgin plastics. Syngas, another useful commodity produced by solvolysis and gasification, can be used as an alternative solution to natural gas and can be combusted in gas turbines to generate electricity (Kanwal et al., 2022).

Chemical recycling aligns with sustainability principles (Jiang et al., 2022), recovering valuable materials from PVC waste sources, which can be reintroduced in the production of virgin plastics, reducing dependence of new non-renewable raw materials, therefore closing the loop in the PVC lifecycle (Zouhair Ait-Touchente et al., 2023). Chemical recycling is currently viewed as an emerging technology under development and, aside from pilot and research projects, it has yet to be implemented on a significant industrial scale within the EU (The European Commission, 2022).

For the window manufacturing industry, R&D projects partnered by vinylPlus are helping push the chemical recycling narrative within the industry. Projects such as ChemRecPolymer, which aims to develop scalable chemical pyrolysis recycling, RecoSalt a chloring recovery venture and RecoChlor, a chloring recovery project to produce hydrochloric acid for waste to energy treatment plants, could provide future sustainability for PVC windows. Despite widespread commendation, chemical recycling should not be regarded as a silver bullet. The disadvantages of chemical recycling, such as high energy costs and complex chemistry (Jiang et al., 2022), should not be overlooked and could potentially inhibit interest, particularly with well-regarded mechanical recycling infrastructure already established in the window industry. However advanced recycling technology will undoubtedly produce further innovation and with further advancements, chemical recycling technology holds the potential to play a significant role in the sustainable management of PVC wastes and help contribute to a more circular PVC industry (Zouhair Ait-Touchente et al., 2023).

7.3 Industry 4.0 technologies

Industry 4.0 (I4.0) represents the era of the 4th industrial revolution. Described by IBM (2022) as ‘the realisation of the digital transformation of the field, delivering real-time decision making, enhanced productivity, flexibility and agility to revolutionize the way companies manufacture, improve and distribute their products’. I4.0 includes a wide range of technologies including big data analytics, autonomous robots, cloud computing, blockchain, additive manufacturing, the internet of things (IoT), cyber-physical systems (CPS), artificial intelligence (AI) and augmented reality. These technologies provide an opportunity to combine digital integration with sustainability to enhance circular economies.

In circular economies and in particular plastics economies, complex logistical operations are carried out daily across a wide network to ensure the locating, segregation, sorting and delivery of waste material and r-PVC is accurately executed. Using I4.0 technologies, such as global positioning systems (GPS) and radio frequency identification (RFID), block chain and cloud-based servers, materials can be located, identified, tracked and recorded on a secure, transparent digital ledger. This could be particularly useful in traceability of end-of-life material, materials containing legacy additives or to track the recycle count of window profiles. An example of I4.0 technology adoption in complex

logistical industries is DHL who have recently integrated blockchain technology into their operations, describing how 'blockchain can achieve cost savings by powering leaner, more automated and error-free processes as well as adding visibility and predictability to logistics operations, it can accelerate the physical flow of goods' (DHL Customer Solutions & Innovation, 2018).

Fluctuations regarding micro and macroeconomics such as volatility in the commodities market affecting consumer behaviour, which has been described in various accounts throughout this paper, could also be positively impacted by the introduction of AI and big data analytics. The use of big data analytics within businesses, can significantly contribute in advancing digital transformation efforts and the interpretation of data insights crucial for enhancing the performance of the circular economy (Awan, Sroufe and Shahbaz, 2021) through data collection and algorithms. This could enhance data driven decision making amongst business leaders.

Regarding the converting industries, IoT advancements in extrusion technologies, such as the Digi.Line Extrusion 4.0, a fully automated extrusion line fitted with a networked controller that digitally connect all line components and centrally controls the whole extrusion process. With automated weigh, flow and temperature control, as well as dimensional scanning, the machine can automatically adjust profile weight and dimensions, reducing material loss and scrap (Exelliq, 2019). In the development of innovative new products, additive manufacturing or 3D printing and simulation may also offer significant advantages, especially in the development of bioplastic. Regarding prototyping of new products, additive manufacturing displays clear advantages compared to traditional manufacturing methods, in terms of environmental impact with reduced wastage of material and resource efficiency (Pereira, Kennedy and Potgieter, 2019).

8. Potential impacting factors beyond technological innovation

8.1 Changes to regulatory framework

Often the intentions of industry are not enough to sufficiently impact circular economies, the involvement of government regulatory bodies as either a support function or an enforcer is inevitable. As the UK government presses on with its ambition to achieving net Zero by 2050 (GOV.UK, 2023), changes in policy, regulations and action plans could help stimulate innovation and create circular economies.

In 2018 the UK government CITE published A Green Future, setting out a 25-year plan to improve the environment (UK Government, 2018). Key takeaways from the paper, with the potential to impact the PVC window industry include:

- Minimise waste, reuse materials and manage materials at the end of their life to minimise the impact on the environment.
- Working toward a target of eliminating avoidable plastic waste by end of 2042.
- Developing ambitious new future landfill, reuse and recycling targets and milestones.
- An Industrial Strategy promoting the move towards a regenerative, circular economy.

- Support for processes such as industrial symbiosis –where two or more industrial facilities or companies join up and the wastes or by-products of one become the raw materials of another.
- Development of business models that challenge inefficient production practice by working with industry to explore options for making waste tracking data universally digitised.
- Plans for a Bioeconomy Strategy which will build on the UK's strengths to ensure we can develop a world-class bio-based economy by removing our dependence on finite fossil resources.

Additionally in 2022, the European Commission put forward new regulation for establishing a framework for setting ecodesign requirements for sustainable products, that may also impact the PVC window manufacture. Key takeaways include –

- New ecodesign requirements to improve product durability, reusability, reparability, refurbishment and maintenance. Increase energy and resource efficiency, reduce their expected generation of waste materials and increase recycled content in products. Enabling remanufacturing and high-quality recycling, reducing carbon and environmental footprints.
- Creation of 'product passports' for enhanced tracking.
- Mandatory requirements on recycled plastic content and plastic waste reduction measures for key products such as packaging and construction materials.
- Policy framework for bio-based plastics and biodegradable or compostable plastics.
- EU-wide harmonised model for separate collection of waste and labelling to facilitate separate collection.
- Methodologies to track and minimise the presence of substances of concern in recycled materials and articles made thereof.
- Harmonised information systems for the presence of substances of concern.
- Supporting the circular economy transition through the skills Agenda, the forthcoming Action Plan for Social Economy, the Pact for Skills and the European Social Fund Plus.
- Supporting the circular economy transition through Cohesion policy funds, the Just Transition Mechanism and urban initiatives

The strategic focus regarding regenerative, circular economies, industrial symbiosis, combined with new ambitious target for waste managements could see additional funding and support for new infrastructure, training and research and development. Frameworks will ensure that industry remains clear on the intent of the government in the transition from linear to circular economies. This will give business leaders confidence in decision making, helping to plan future objectives and capital investments. Additionally, the intent to create product passports, digitalised production and material

tracking, could open the door to advancements in I4.0 technologies, while the focus on biobased industries helps drive sustainable material innovation.

8.2 Market shift and social trends

As with all industries, the success of products and services are susceptible to changes in social trends and behaviours, with some businesses seeing increased profits and others losing market share. Some key examples of how changes in consumer behaviour can impact sustainability efforts, can be found in industries such as the textile industry, where a rise in popularity for upcycling, vintage clothing, repair, and reuse, has seen businesses such as Vinted, Ebay and Patagonia prosper in recent years. Another example includes the farming sector, which has seen a decline in the sale of meat products, caused by large shifts to plant-based diets (The Meat Free Monday Foundation, n.d.).

Additionally, as history proves, the plastics sector can be influenced by global, micro and macroeconomics which can either drive or slow circular development. Forbes suggests climate change decisions affecting politics and slow economic growth, which could affect net zero targets, are among the major global trends that will define 2024 (Marr, 2023). Conflicts such as the recent war in Ukraine can cause spikes in commodities prices, which could drive businesses to look for cheaper or more easily accessible materials, an example of this is the 1973 oil and energy crisis, caused by the embargo of Arab oil producing countries, reported as a major driver for bioplastic development (Barrett, 2018). Alternatively, a drop in commodities prices can stall innovation such as the slow in bioplastic development due to the overproduction of oil, following the 1979 Iran War, or the end to soy-based plastics in car parts by Henry Ford due to an abundance of oil following WW2 (Barrett, 2018).

9. Research Findings

Survey completion rate

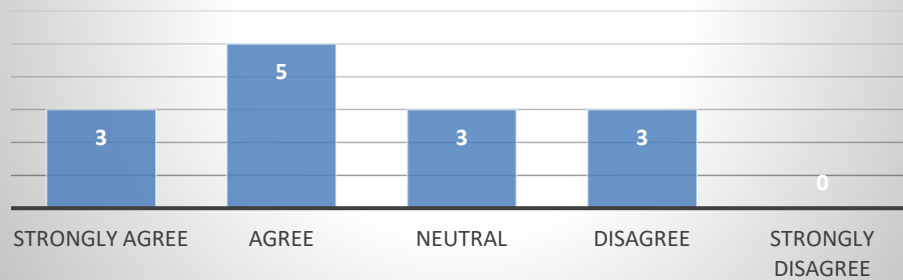
Invitations were sent to 30 key stakeholders within the industry. Using the website Survey Monkey, a likert style survey was sent via weblink, using Outlook and LinkedIn messenger. The survey sample is shown in Annex C. The number of respondents that completed the survey was 14. The number of respondents from each industry is shown in table 4. Although the completed survey total was under 50%, there was a well-balanced mix of key individuals from across the industry. PVC manufacturing was the only industry in which invitations failed to receive a response.

Q1. Job Title	Q1. Industry
Managing Director - PVC Stabiliser producer	Additives manufacture
Global Business Director of PVC stabiliser manufacturer	Additives manufacture
Mixing Plant and Materials Manager	Compounding
Technical, PVCu extrusion/ fabrication	Converting /extrusion
Operations Director. PVC Window Extrusion	Converting /extrusion
Technical Engineer, PVC profile extrusion	Converting /extrusion
Production Manager PVCu extrusion	Converting /extrusion
Engineering and facilities manager, Extrusion	Converting /extrusion
Operations Manager PVCu Extrusion	Converting /extrusion
Engineering manager Window manufacturing	Fabrication
Head of Engineering UKWDG	Fabrication
Managing Director UPVC specialist re-processor	Recycling
Principal Consultant - sustainable consulting	Recycling
EHS Manager UPVC Manufacturing	Recycling

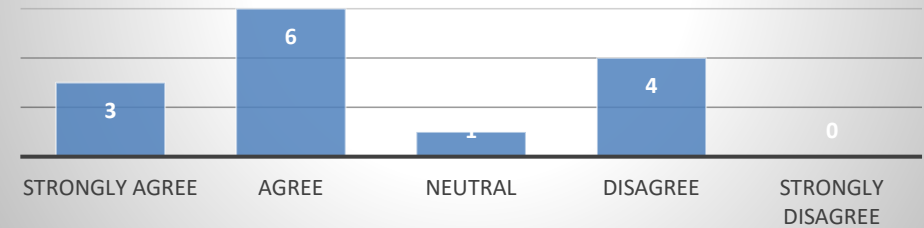
Table 4. Q1. From the survey detailing respondents job title and industry

Current/ future challenges for sustainable PVC Windows. Q2-4

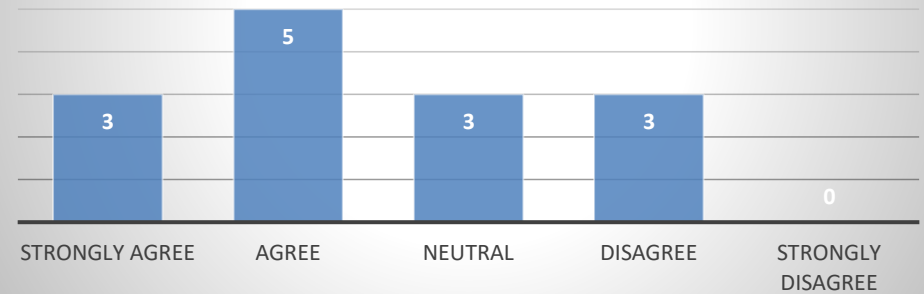
Q2. Market competition for recycled material, limits the feasibility of implementing sustainable innovations.



Q3. The integration of recycled materials into new products, is a significant challenge for my organisation.



Q4. The cost of transitioning to circular practices, is prohibiting future sustainability within my organisation.



Section 1. Current/ future challenges for sustainable PVC Windows. Q2-3

Questions 2-4 aimed to understand the current and anticipated future challenges of the sustainability within the industry.

Question 2. Assessed market competition and how this impacts innovation. Findings revealed that around 57% of respondents either agreed or strongly agreed, that competition impacted the implementation of sustainable innovation within their business. 21% strongly disagreeing and 21% responding with a neutral opinion.

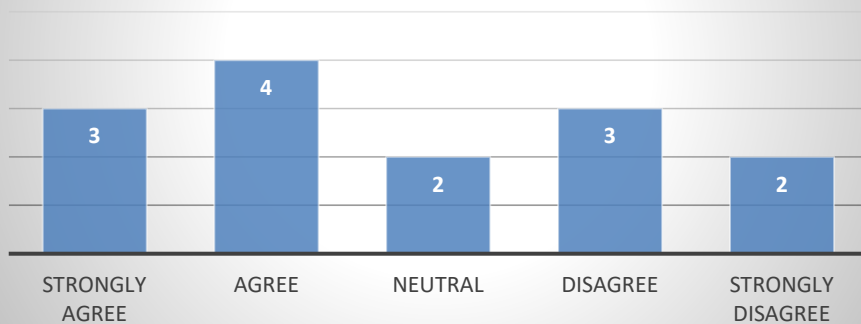
Question 3. Aimed to gather feedback on the integration of recycled material into products. Of the 14 respondents, 64% agreed or strongly agreed that it was a significant challenge to integrate recycled material into new products. Only 29% disagreed, with 7% of a neutral opinion.

Question 4. Respondents were asked to consider how cost impacted the transition toward circular economies within their organisation. 57% of respondents agreed or strongly agreed that the cost of transitioning prohibited future sustainability efforts within their organisation. 21% felt this was not the case and 21% responding neutrally.

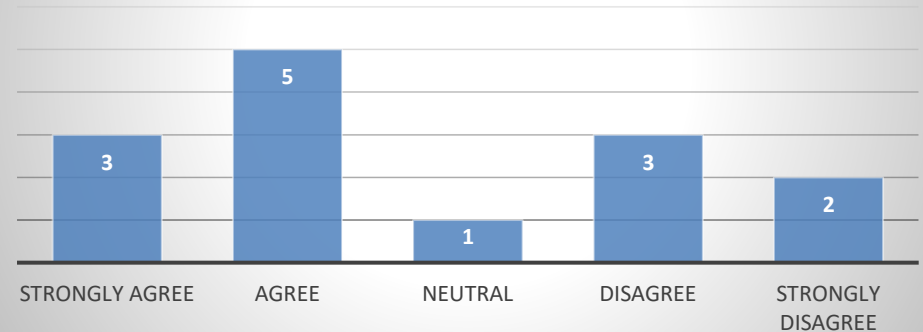
Findings for this category indicate that in each question, the majority share of respondents agreed or strongly agreed that competition for recycled material, the challenge of integrating recycled material and the cost of transitioning toward circular economies, posed current and future challenges within their organisation. Of the three questions posed, the integration of recycled material into new products appeared to pose the biggest challenge.

Drivers of sustainability and circular economies in PVC window manufacture.

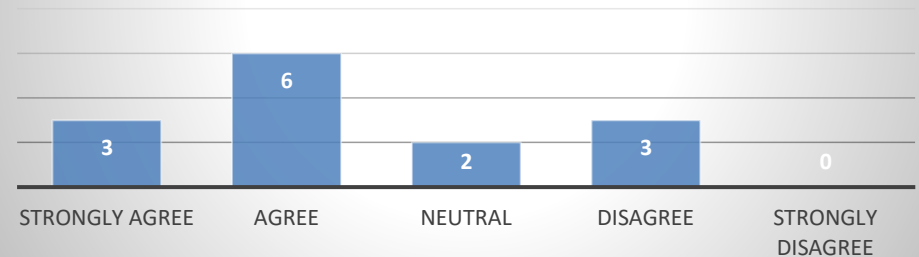
Q5. Consumer awareness is driving my organisation to help develop more sustainable window solutions.



Q6. Regulatory pressure is a critical driver for adapting circular economy principles within my organisation.



Q7. I perceive technological advancements in the PVC industry, as a major factor in driving sustainability within my organisation.



Section 2. Drivers of sustainability and circular economies in PVC window manufacture.

Questions 5 -8 aimed to understand what industry perceives as the drivers of circular economies within the PVC window industry.

Question 5 resulted in a mixed response regarding customer awareness as a driver for sustainable development, with 57% either agreeing or strongly agreeing, 35% disagreeing or strongly disagreeing and 14% remaining neutral.

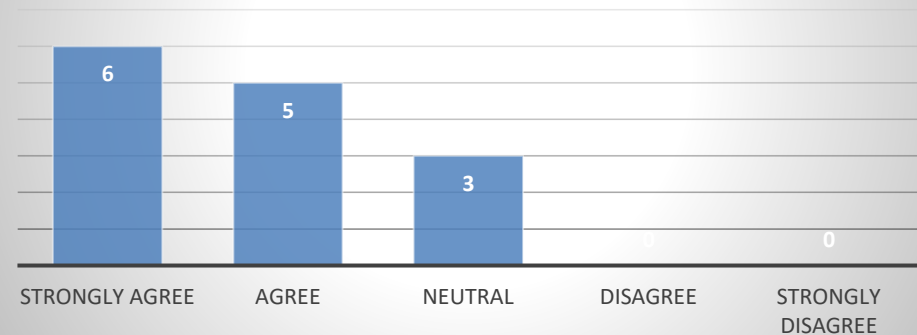
Regarding regulatory pressure, question 6 revealed that 57% of respondents agreed or strongly agreed that regulation acted as a critical driver for circular economies within their organisation. 36% either disagreed or strongly disagreed with the statement, with 7% sharing neutral opinions.

Question 7 found respondents largely perceiving technological advancements as a major driver of sustainability within their organisation, with around 64% agreeing or strongly agreeing. Just 21% of respondents disagreed, with 3 remaining neutral.

Question 8 showed just under half of the respondents strongly agreed that the cost of recycling was a major driver for adopting circular practices, with around 36% also agreeing. Interestingly none of the respondents disagreed or strongly disagreed, with 3 respondents sharing neutral views.

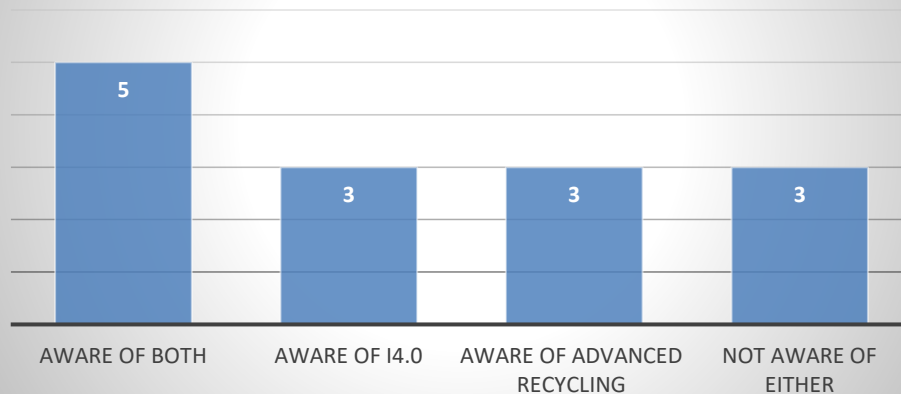
Interestingly, in comparison with section one, the cost of material also features significantly in the results found in section two. With 79% of respondents indicating that the cost of recycled material was a major driver in circular economies, cost was perceived as the most prominent driver, with none of the respondents disagreeing or strongly disagreeing. Technological advancements and regulatory pressure also featured highly as considerable drivers, with customer awareness receiving more balanced feedback.

Q8. The cost of recycled material over virgin material, is a major driver in adopting circular practices.

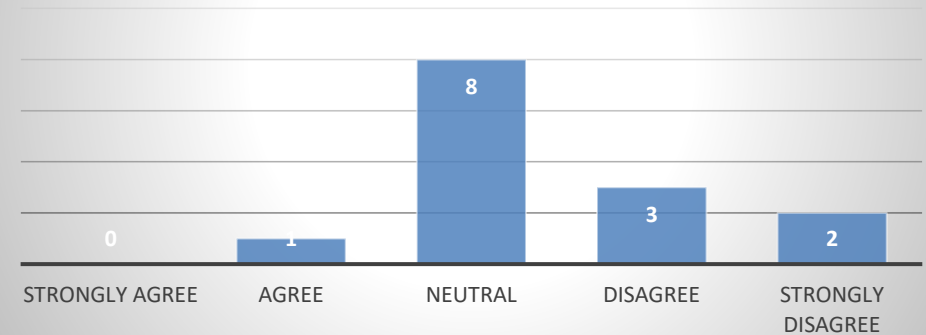


Emerging technologies and innovation opportunities in PVC window manufacturing.

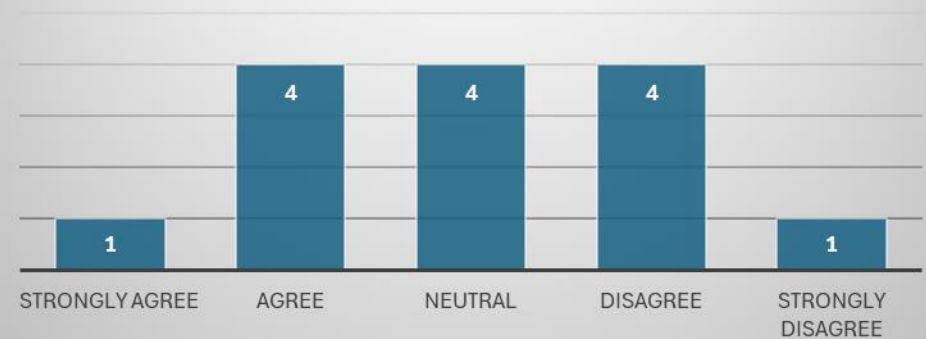
Q9. Are you familiar with industry 4 and advanced recycling technologies ?



Q10. My organisation has employed industry 4 technologies as part of its future sustainability strategy.



Q11. My organisation is exploring advanced recycling technologies as part of its future sustainability strategy.



Emerging technologies and innovation opportunities in PVC window manufacturing.

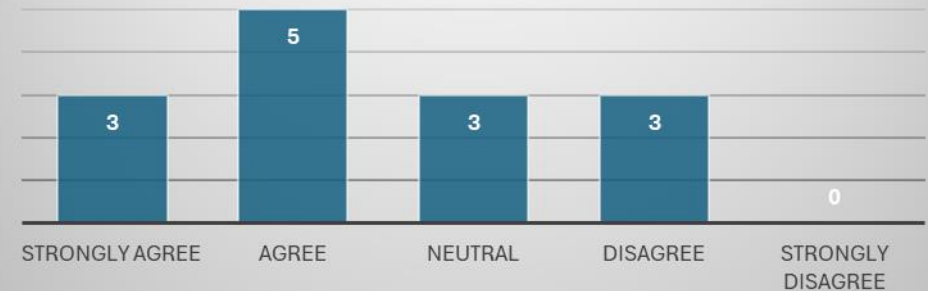
Questions 9-13 aimed to understand the awareness of industry regarding emerging technology and tries to establish how these businesses are planning and adapting for future change.

I4.0 and advanced recycling technologies are two areas of emerging technology that could significantly impact circular economies. Question 9 attempts to understand the level of awareness regarding these technologies throughout the industry today. Findings highlight around 36% of respondents were aware of both emerging technologies, with 21% only aware of I4.0, 21% were only aware of advanced recycling technologies and 21% not aware of either. When considering the respondents who knew about both, the total awareness for I4.0 and advanced recycling totaled 57% for each.

Despite over half of respondents aware of I4.0, question 10 revealed that only 1 person agreed that their organisation had employed the technology, with around 36% either disagreeing or strongly disagreeing. The largest portion of answers, 57%, indicated neutral views, which could imply unfamiliarity with what actually falls within the I4.0 technology umbrella. These findings also imply that this technology has not yet made a significant impact in the industry, with findings indicating respondents' limited exposure.

Question 11 found a more balanced response regarding the exploration of advanced recycling technology in future business strategies, with around 37% of respondents agreeing or strongly agreeing. This percentage was mirrored for respondents that disagreed or strongly disagreed. 29% remained neutral. Unlike question 10, with higher percentages either side of the neutral option and a lower neutral response,

Q12. I believe bioplastics and bio-additives could significantly impact the future of window manufacturing.



Q13. I am confident there is sufficient skill and expertise within the PVCu window industry, to implement sustainable technological...



this may imply businesses are more aware of what is categorised as advanced recycling technologies.

Question 12 indicated 57% of respondents believed bioplastic and bio-additives could significantly impact the future of PVC, with only around 21% disagreeing and 21% holding neutral views. With the majority share of respondents in agreement, this could indicate this technology has already gained the confidence of the industry, with findings suggesting a strong awareness.

Question 13 revealed that there is mixed confidence regarding the sufficient skill and expertise to implement circular economies. Around 43% felt there is sufficient experience within the industry and 35% either disagreed or strongly disagreed. Around 21% remained neutral.

Section 3 revealed somewhat clouded findings. Question 9 indicated over half of respondents were aware of I4.0 technologies, however feedback in question 10 seemed to contradict the previous question. With 8 out of 14 with neutral views on implementation of the technology within their organisation, this may indicate a limited understanding of the technology. With round 37% in agreement and 37% in disagreement, question 11 indicates that advanced recycling appears somewhat lower in organisations' plans for the future. Regarding bioplastics, the majority of respondents felt this technology could significantly impact future sustainability efforts, with only 21% disagreeing. Finally, respondents appear divided over the skill level currently in the industry, capable of implementing sustainable technology. This may also relate to the lack of awareness highlighted in questions 9, 10 and 11.

Q14. Additional comment feedback

Table Details the optional feedback comments from respondents, segregated into industries categories.

Q1. Industry	Q1. Job Title	Comments
Additives manufacture	Managing Director - PVC Stabiliser producer	As a supplier backward in the PVC Window production supply chain to many window profile production companies. I view the move towards recycle addition primarily as a hybrid between cost & marketing goals. Largely (but by no means completely) interaction with legislative bodies Vinyl Plus etc. is left to upstream suppliers (polymer / additive etc.) it is more and more essential that the industry becomes more involved at every level to ensure its long term sustainability especially since Brexit to ensure we do not blindly adopt EU legislation which could harm rather than help circularity.
	Global Business Director of PVC stabiliser manufacturer	The presence of legacy additives and the scientific mid regulation surrounding their use is the most critical impact on the circular PVC window industry. The UK SH oh Id not follow the EU approach
Compounding	Mixing Plant and Materials Manager	No Comment.
Converting /extrusion	Technical, PVCu extrusion/ fabrication	Bio plastics etc, the industry moves with the time. Significant research would be required to understand the characteristics of the material and how it could be used
	Operations Director. PVC Window Extrusion	Virgin price volatility has direct impact on recycled material usage. The technology required to produce high volumes of consistent recycled material is both costly and is relatively new. Windows demand a far higher grade of recycled material (colour in particular) than pipe industry hence lower volume usage. Major window extruders are still struggling with material consistency. UK Market driven more by cost than environmental considerations
	Technical Engineer, PVC profile extrusion	No Comment.
	Production Manager PVCu extrusion	No Comment.
	Engineering and facilities manager, Extrusion	The completion for high quality post consumer, recycled materials is challenging. The lack of consistent post consumer recycled material supply, limits the feasibility of buying equipment such as co-extrusion technology in turn decreasing our businesses competitiveness against larger organisations. Implementing circular practices is extremely challenging.
	Operations Manager PVCu Extrusion	The cost of implementing technological advances can be prohibitive in many companies
Fabrication	Engineering manager Window manufacturing	No Comment.
	Head of Engineering UKWDG	No Comment.
Recycling	Managing Director UPVC specialist re-processor	No Comment.
	Principal Consultant - sustainable consulting	Consumer demand is not yet the leading factor behind the need for recycled content. Customers are yet to demand and expect recycled content
	EHS Manager UPVC Manufacturing	No Comment.

Table 5. Details the optional feedback comments from respondents, segregated into industries categories.

10. Closing

10.2 Conclusion

Over the last two decades the PVC industry has been on a journey of transformation in a bid to clean up its image and promote PVC as a sustainable building material of the future. The three primary aims of this dissertation are to provide the reader with an insight into the turbulent history of the industry, assess the challenges still faced today and also to explore opportunities for a sustainable future.

The coming together of industry through the Vinyl 2010 initiative, saw business leaders commit to bring about change before regulation came into force. Ambitious targets to phase out toxic chemicals, reduce waste and reduce consumption of virgin materials through mechanical recycling, acted as the catalyst to reshape the industry. With change came opportunity, with many European converters choosing to invest heavily in mechanical recycling infrastructure. Significant developments in recycling and co-extrusion technologies, opened vast supply chains of recycled material for use in new window profiles.

In today's industry, converters such as Veka, Eurocell and Profine have scaled up recycling operations on a colossal scale. The impressive development of these larger organisations is widely seen as a success story within the industry, however the research in this dissertation highlights the detrimental effect this has on SMEs, regarding the availability of pre and post-consumer waste. Additionally, for smaller businesses the requirement for vast capital investments to adopt circular principles, is often unfeasible, limiting their ability to remain competitive.

Another common finding throughout the dissertation was how cost often outweighed sustainability, with new products struggling to win over the consumers, converters switching to virgin materials when markets fluctuate and cost becoming the driving factor in the adoption of circular practices. This was evident in both survey findings and case studies documented in this paper.

Looking forward, developments in emerging technologies such as bioplastics, I4.0 and advanced recycling have the potential to change the future of PVC, although it is clear that there is a lack of awareness and adoption throughout the industry today. Governing bodies must continue to fund and support circular development, to help integrate these technologies into industry. Directives such as the European Commission's Ecodesign and the UK Government's 25-year plan will help foster and develop circular economies throughout the PVC industry, helping create the sustainable window of tomorrow.

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12. Appendix

Annex A- details the sorting of responses from Survey monkey. Selected Excel as a method due to analysis on the survey monkey website being extremely poor.

		Current/ future challenges for sustainable			Drivers of sustainability and circular economies in PVC window				Emerging Technologies and innovation Opportunities PVC window manufacture				
Q1. Job Title	Q1. Industry	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13
Managing Director - PVC Stabiliser producer	Additives manufacture	DA	A	N	SA	A	A	N	RT	DA	A	A	SDA
Global Business Director of PVC stabiliser manufacturer	Additives manufacture	N	DA	A	SDA	SA	SA	N	B	A	A	DA	N
Mixing Plant and Materials Manager	Compounding	N	N	N	A	A	A	A	NB	N	A	A	A
Technical, PVCu extrusion/ fabrication	Converting /extrusion	A	DA	DA	SA	N	SA	A	I4	N	SA	SA	A
Operations Director. PVC Window Extrusion	Converting /extrusion	A	SA	SA	N	DA	N	SA	NB	DA	DA	SA	SDA
Technical Engineer, PVC profile extrusion	Converting /extrusion	DA	DA	N	DA	DA	A	SA	B	N	DA	N	A
Production Manager PVCu extrusion	Converting /extrusion	SA	A	DA	A	A	N	SA	RT	N	A	DA	DA
Engineering and facilities manager, Extrusion	Converting /extrusion	SA	A	SA	DA	SA	DA	SA	B	SDA	SDA	N	N
Operations Manager PVCu Extrusion	Converting /extrusion	A	A	A	N	A	DA	A	I4	SDA	DA	A	A
Engineering manager Window manufacturing	Fabrication	N	DA	DA	SDA	SA	A	N	I4	N	N	DA	DA
Head of Engineering UKWDG	Fabrication	SA	A	A	A	SA	SA	SA	B	DA	DA	SA	DA
Managing Director UPVC specialist re-processor	Recycling	A	SA	SA	SA	DA	DA	A	NB	N	N	N	SA
Principal Consultant - sustainable consulting	Recycling	DA	A	A	A	A	A	A	B	N	N	A	N
EHS Manager UPVC Manufacturing	Recycling	A	SA	A	DA	SA	A	SA	RT	N	N	A	SA

Annex B- Details web responses.

Total Responses 14		Response Notifications Manage Notifications ?		
NICKNAME	STATUS	RESPONSES	DATE MODIFIED	
Web Link 1 https://www.surveymonkey.com/r/VYY82... QR Code Copy URL Created 2/10/2024	OPEN	13	2/21/2024	...
Email Invitation 1 Created 2/10/2024	OPEN	1	2/10/2024	...

Annex C - Illustrates a question sample from the survey.

Assessing circular economies and sustainability opportunities, in PVCu window manufacturing.

1. Job Title and industry

2. Market competition for recycled material, limits the feasibility of implementing sustainable innovations.

	Rating
Strongly agree	☐
Agree	☐
Neutral	☐
Disagree	☐
Strongly disagree	☐