Twenty Years of the Polyvinyl Chloride Sustainability Challenges

Mark Everard

Department of Geography and Environmental Management, University of the West of England (UWE), Coldharbour Lane, Frenchay Campus, Bristol, BS16 1QY, UK

Intense campaigning pressure on the UK polyvinyl chloride (PVC) sector up to the late 1990s forced strategic engagement with sustainable development. Simplified outcomes from a detailed, consensus-based analysis by science-based NGO The Natural Step (TNS) took the form of five TNS sustainability challenges for PVC published in 2000. UK manufacturing companies initially used these challenges to direct strategic progress. The challenges have since been progressively taken up across European PVC value chains. The VinylPlus® program uses an updated version of the five challenges as a basis for voluntary commitments and transparent auditing of progress against published targets. Initial framing of the five TNS sustainability challenges for PVC was drafted consciously for generic relevance to other materials. Assessing the sustainability performance of some alternative materials to PVC against the five sustainability challenges reveals different sustainability performance in a range of potential applications. This highlights the danger inherent in automatic selection or deselection of materials in the absence of assessment of options on a "level playing field" of sustainability principles. The five TNS sustainability challenges for PVC remain valid today and into the longer-term future as a basis for making stepwise, profitable progress toward the goal of sustainability for PVC and other materials. J. VINYL ADDIT. TECHNOL., 2019. © 2019 The Author. *Journal of Vinyl and Additive Technology* published by Wiley Periodicals, Inc. on behalf of Society of Plastics Engineers.

INTRODUCTION

Polyvinyl Chloride (PVC) may be one of the world's most highly scrutinized materials due to interconnected NGO, media, and regulatory pressures, with additional demands from retailers that had become the focus of NGO activism relating to sale of PVC-containing products [1]. A positive outcome of these pressures is that it forced the PVC industry to engage strategically with sustainable development from the late 1990s onward, well ahead of other plastics and many other material industries. In order to address intense NGO and media pressure in relation principally to aspects of environmental performance, a *PVC Coordination Group* was established in the United Kingdom in 1998 including the two UK PVC manufacturing companies at the time (Hydro Polymers and EVC), the Environment Agency, the NGO Greenpeace, and a range of retailers including Tesco, Asda, Waitrose, the Cooperative Society, and the Body Shop (a retailer with "green" credentials). The Group was chaired by Jonathon Porritt (Co-founder and Executive Director of the sustainable development charity *Forum for the Future*). Shortly after its inception, Greenpeace and The Body Shop elected to leave the *PVC Coordination Group*.

Recognizing that proactive exploration of sustainable development was highly germane to addressing problems and perceptions of PVC, the Chairman of the Group approached sustainable development NGO The Natural Step (TNS). TNS was consequently commissioned to undertake a sustainable development assessment based on its science-based principles of sustainability (known as the framework for strategic sustainable development or FSSD) and associated tools. The brief was to assess the current performance and trajectory of PVC manufacture and use by society, and the steps that would be necessary were it possible for the material to be envisaged as part of a sustainable future; in other words, a gap analysis of what it would take to make PVC truly sustainable. Key among the TNS tool set is a science-based definition of necessary conditions for sustainability (the four TNS "System Conditions"), assessment of current sustainability performance based on System Conditions, visioning of the goal of full sustainability also based on compliance with System Conditions, and a backcasting approach to identify strategic steps toward the vision of a fully sustainable end point. In 2000, TNS published a sustainability assessment of PVC [2], developed through a consensus-building process facilitated by TNS and supported by the Environment Agency in England and Wales. Summarizing the outcomes of this TNS-based analysis in tractable terms was a series of five TNS sustainability challenges for PVC (see Table 1).

Recognizing both the business opportunities of innovations pre-empting future negative sustainability impacts

Correspondence to: M. Everard; e-mail: mark.everard@uwe.ac.uk
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TABLE 1. The five TNS sustainability challenges for PVC and examples of early progress by Hydro Polymers.

The TNS sustainability challenges for PVC [2]	Examples of early progress by Hydro Polymers (documented in [3])
1. The industry should commit itself long term to becoming carbon-neutral	Innovation of an adiabatic cracker, implementation of a heat exchanger on a slurry stripper, modification stores lighting, updating the road transport fleet, and installing larger silos on sites to accept bigger loads (easing scheduling and off-loading which increasing vehicle payloads). Many of these innovations had payback periods of less than 1 year.
2. The industry should commit itself long term to a controlled-loop system of PVC waste	Promotion of recovery and recycling on PVC post-manufacturing and post-consumer to create new "greener" PVC compound. Undertaking research to ascertain retention and functionality of additives in recyclate including, as examples, calcium carbonate and titanium dioxide [4]. Innovation of a recycled EcoVin® product with enhanced manufacturing and life cycle environmental credentials.
3. The industry should commit itself long term to ensuring that releases of persistent organic compounds from the whole life cycle do not result in systemic increases in concentration in nature	Innovation of novel seal material in reactors to avert formation of dioxins during PVC production, as well as substantial progress towards elimination of fugitive emissions.
4. The industry should review the use of all additives consistent with attaining full sustainability, and especially commit to phasing out long-term substances that can accumulate in nature or where there is reasonable doubt regarding toxic effects	Under the Vinyl2010 voluntary commitment, the European PVC industry committed to phase out lead from PVC compounds by 2015. Hydro Polymers had already taken a unilateral decision to do so by the end of 2007. Recycling experiments carried out by Hydro Polymers, window manufacturers, and universities (e.g., [4]) demonstrated that calcium carbonate is retained in an adequately functional state in PVC compound recycled through multiple thermal cycles.
5. The industry should commit to the raising of awareness about sustainable development across the industry and the inclusion of all participants in its achievement	The *PVC for Tomorrow* program involved about 140 of the 1,400 total employees of Hydro Polymers in TNS-based education, also instituting a competition across Hydro Polymers sites to present their best ideas concerning addressing the five TNS Sustainability Challenges for PVC. Hydro Polymers set out to bring its strategic additive suppliers into the quest for sustainability for PVC, including through annual sustainability conferences, as well as strategic dialogue with some customers.
Synergies across the five TNS sustainability challenges for PVC	All five TNS sustainability challenges for PVC are systemically interconnected. Therefore, as a minimum, progress with one challenge must not inhibit progress with others. However, in practice, innovations can contribute positively to multiple challenges. For example, selection of additives that are inherently recyclable can promote progress with controlled loop management, with reduced energy usage, retention of embodied energy and associated carbon emissions, with little or no potential for problematic fugitive emissions. This helps other players along PVC value chains appreciate the benefits of proactive engagement with sustainable development.

and the risks of business failure were PVC to be substantially deselected, Hydro Polymers subsequently embedded the five challenges into its business under the *PVC for Tomorrow* program. This program encompassed education and innovation across the company, enabling it to identify strategic and beneficial innovations to make progress with the five TNS sustainability challenges for PVC (see examples in Table 1). For detailed accounts of the history of engagement with sustainable development by the PVC industry, see Ref. [1]), and for the history and development of the TNS Sustainability Challenges for PVC and early progress with their implementation see Everard [3].

2020 sees the 20th anniversary of the five TNS sustainability challenges for PVC. In this article, we overview some relevant societal changes that have happened over the succeeding two decades, assess progress with and the continued relevance of the TNS sustainability challenges for both PVC and selected alternative materials, and consider what the next 20 years may hold.

METHODS

Relevant trends are addressed through evaluation of peer-reviewed, corporate, trade association, regulator, and other forms of literature, as well as expert input solicited from players in the PVC industry. Inevitably, given the diversity and magnitude of changes over the past 20 years, this has to be a selective review of major trends.

Changes in the PVC industry and value chain are initially considered. Subsequently, to ensure comprehensive coverage of issues in the wider societal context, the social, technological, ecological, economic, political (STEEP) framework is applied. STEEP was adapted from a range of allied classification schemes by Morris and Wilson [5], primarily for analysis of an organization's operating environment and preparing for organizational transitions ([6]). However, the framework has subsequently been applied to analyze interconnections between domains of human activity with regard to meeting the goal of sustainability [7]. STEEP has been applied as a systems framework addressing systemic interdependences between its five constituent elements to evaluate water systems and associated ecosystem services in Europe [8], South Africa [9], and India [10].

These 20-year trends are then considered in the context of the five TNS sustainability challenges for PVC. PVC materials are considered but also other materials selected on the basis of those commonly serving as alternatives in widespread applications, including timber/forest-based products (window profiles); ductile iron (water pipes); and polyolefins (pipes and cables).

RESULTS

Changes in the PVC Industry and Value Chain

Following publication of the five TNS sustainability challenges for PVC, Hydro Polymers began to address them as corporate priorities from 2001 (see example applications in Table 1). In the same year, the chemical company INEOS had acquired the ICI Chlor chemical business while also acquiring a majority shareholding in EVC, taking on full ownership of EVC in 2005 to form INEOS Vinyls. Hydro Polymers was subsequently purchased by INEOS in 2008. The PVC manufacturing entity after EVC and Hydro Polymers acquisitions was known as Kerling Group. INEOS Chlor Vinyls then in 2011 purchased the Tessenderlo Group (LVM operations) headquartered in Belgium. In 2015, INEOS Chlor Vinyls formed INOVYN as a jointly owned partnership with SolVin, INEOS subsequently buying Solvay's stake of INOVYN group in 2016 such that it became a wholly owned unit within the INEOS group. As part of this process, much of what had formerly been Tessenderlo Group operations had to be sold, as INOVYN was seen by the European Commission as being too large; this divested unit forming the European PVC and chlor-alkali company Vynova that operates production sites in five countries. The corporate name and grouping of the PVC production unit within INEOS group at the time of writing is INOVYN (For a full history of the INEOS acquisitions, see Ref. [11]).

Sustainable development awareness and commitment in the PVC industry was, of course, far from unique to the United Kingdom. Regionally uneven media and NGO pressure was also being exerted particularly across Europe and the USA. Key steps in the progressive uptake of sustainable development in the European PVC industry are summarized in Table 2. However, PVC is a global industry, and PVC products have global value chains and supply chains, necessitating increasing influence of the sustainable development agenda beyond Europe.

TABLE 2. Uptake of sustainable development thinking across the European PVC industry.

Timeline	Development
1995	The European Council of Vinyl Manufacturers (ECVMs) established the "ECVM Charter," initially developed for S-PVC (suspension PVC). ECVM charter was and continues to be focused on ensuring low emissions (below regulatory limits) of organochlorines from manufacturing and processing.
2000	Vinyl2010 was formed between European vinyl-based businesses to agree voluntary commitments relating to sustainable development, with 10-year targets to 2010.
2000	The five TNS sustainability challenges for PVC are published
2001	The ECVM Charter was further extended to include E-PVC (emulsion PVC).
2011	VinylPlus® formed as a successor to Vinyl2010, with the five modified TNS Sustainability Challenges for PVC framing its voluntary commitments with an associated set of targets to 2020 including transparent reporting of progress against them.
2020	A new version of the ECVM Charter is anticipated.
2020	A refresh of VinylPlus® goals and targets is anticipated.

Wider Societal Changes

The following paragraphs highlight selected major global trends pertinent to the PVC value chain across the five constituent parameters of the STEEP framework, noting the high systemic interdependency between the five parameters.

Selected Social Changes over 20 Years. One of the social megatrends over the past 20 years has been the 25+ % growth in the global human population, from 6.1 billion in 2000 with a density of 41 people per km^2 escalating to 7.7 billion in 2019 at a density of 52 people per km^2 (https://www.worldometers.info/world-population/world-population-by-year/). More people making growing demands upon resources as part of a wider "footprint" of pressures imposed on a declining natural resource base inevitably intensifies the need for embarking on a more sustainable form of development. This is part of a wider societal shift in attitude, taking increasing account of impacts on the natural world and across society. It manifests in the commercial sphere as changing customer expectations and demands and linked political/governance pressures.

Selected Relevant Technological Changes over 20 Years. Any overview of the rapid and far-reaching technological changes that have occurred over the past two decades is by its nature partial. Computing power, pervasion, connection, geographic positioning, embedding in day-to-day products and lifestyles, and digital communications including smartphones mean that we have never had so much data and potentially knowledge about the sourcing, consumer life cycles, and fate of materials in use by society. Remote sensing means that there are fewer "blind spots" in understanding these material flows along value chains, with chain of custody more transparent through ubiquitous access to the internet including via social media.

Manufacturing of physical products has also benefited from technological advances enabling substantial reductions in emissions, at least in well-scrutinized and regulated regions of the world. However, easier access to markets means that materials and products produced without such rigor and responsibility can still enter developed world value chains.

Selected Relevant Environmental Changes over 20 Years. Taking account of "long-term" trends in England (defined as greater than a decade, with no assessment made where data are not available), the government's *England Natural Environment Indicators* report [12] identified declines in four out of eight groups of organisms in the wider countryside (with only two groups improving), increasing marine litter, declining "priority" conservation species, with insufficient data available to address metrics such as the ecological status of water bodies, value of woodland ecosystem services, percentage of companies using an Environmental Management Scheme or with environmental requirements in their supply chains, and various air pollution metrics. Overall, 35% of the 29 measures selected by government show long-term declines. On a wider global scale, an unprecedented dangerous decline in global biodiversity was observed in 2019 with approximately 75% of the land-based environment and 66% of the marine environment "severely altered" by human actions, and with an accelerating rate of species extinction, roughly tens to hundreds of times greater than natural extinction rates, putting at risk about 1 million among the estimated 8 million species on Earth [13]. At the same time, 32 countries worldwide are experiencing water stress of between 25% and 70%, with 22 countries considered to be seriously stressed and 15 with water withdrawals exceeding, some of them very substantially, total renewable water resources [14]. There is also recognition that six ecosystem-related factors—extreme weather events, failure of climate change mitigation and adaptation, major natural disasters, man-made environmental damage, major biodiversity loss and ecosystem collapse, and water crises—are amongst the top 10 global risks by likelihood over the next 10 years [15]. These and many other environmental metrics are far from irrelevant to the PVC industry, highlighting declining environmental capacity for supply of raw materials, potential dissipation and re-assimilation of wastes, and potential escalating competition for remaining resources and regulation of pressures.

Two trends of particular relevance to the PVC and wider plastics industries are climate change and build-up of marine litter. Rising climate-active emissions, particularly of carbon dioxide, are destabilizing global climate, NOAA data recorded for atmospheric CO_2 concentration rising from 370.60 ppm in March 2000 to 411.97 ppm in March 2019 [16]. Increasing marine litter is an issue of major and rising global concern in terms of environmental, potential human health, and other concerns [17]. Much of it comprises persistent plastics, as well as other materials, although the dominant market share for PVC is in long-life applications that are often now recovered for recycling, rather than the short-life, single-use products most commonly accounting for the majority of litter.

Selected Relevant Economic Changes over 20 Years. One of the economic shifts pertinent to PVC consumption and life cycle management has been not only the rising human population but also the escalating middle class as a proportion of global population. Kharas [18] found that about 3.2 billion people globally were defined as in the middle class by the end of 2016, with a projected tipping point in 2018/2019 when, for the first time ever, a majority of the world's population would live in middle-class or rich households, the overwhelming majority of new entrants living in Asia. While the development prognosis is in many ways welcome, there is an associated growth in *per capita* material consumption and use. Minx et al. [19] found that the carbon footprint of a middle-class household in the United Kingdom is 50% higher than that of a borderline poor household, indicative of a wider accelerating "footprint" of environmental pressures driven by economic uplift.

Further economic trends are a shift in management accounting from pure up-front costs towards a lifetime "total cost of ownership" (TCO) approach that accounts for the life cycle of ownership. A substantial amount of publications around the complexity of electric vehicle ownership address TCO (e.g., [20]) as capital versus operational cost profiles differ radically from conventionally fueled vehicles. Further economic pressures promoting life cycle thinking include the increasing cost of waste handling and disposal. European Union policy leading to reform of waste management systems promotes waste separation, sharp increases in landfill taxation and other measures to maximize the recovery and recycling of secondary raw materials (total recycling rates in EU Member States are supposed to reach 50% by 2020), compounded by falling prices of secondary raw materials mainly due to China significantly limiting their import [21]. Europe is among more than 40 governments worldwide that has adopted some sort of price on carbon, either through direct taxes on fossil fuels or through cap-and-trade programs, as a spur to stimulate reductions in carbon emissions, though the type of pricing program is a major determinant of the scale and proportionality of reduction measures that are actually implemented [22]. Prices on carbon emissions are just one of a range of pressures contributing to rising costs of transport as well as raw material sourcing and conversion. All of these increasing costs at both upstream and downstream ends are inevitably shared along whole product life cycles, focusing the entire value chain on reducing related environmental pressures in the PVC sector and more widely for all societal material use.

Selected Relevant Political/Governance Changes over 20 Years. From formal government, there have been substantial changes in legislation over the past 20 years relevant to PVC value chains. In Europe, the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) framework, adopted by the EU in 2006, has become a particularly influential chemical regulatory mechanism focused on hazard reduction or elimination intended to secure environmental and human health [23]. Twin European Commission strategies—*Towards a non-toxic environment strategy* [24] and the Commission's *Circular Economy: Implementation of the Circular Economy Action Plan* [25]—have also significantly shaped thinking about chemical use, albeit that there are inherent tensions between resource recovery and the re-entry of "problem" constituents of end-of-life products entering recycling streams [26]. Additional "downstream" pressures on material use and management, including beyond end-of-life,

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emanate from polices and legislation such as the EU's packaging legislation ([27] as amended) and environmental liability regulations [28]. Measures such as the 1999 "Gothenburg Protocol" (the *Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*, also known as the "Multi-effect Protocol") have been implemented and subsequently much amended as a multi-pollutant protocol designed to reduce acidification, eutrophication, and ground-level ozone by setting emissions ceilings for sulfur dioxide, nitrogen oxides, volatile organic compounds, and ammonia [29].

Advances in informal governance pertaining directly to PVC have also been significant. Shortly preceding publication of the five TNS Sustainability Challenges for PVC, two charters commissioned by the *PVC Coordination Group* were published in the United Kingdom in 1999: (1) an *Environmental Charter for UK PVC Manufacturers* [30] and (2) an *Eco-efficiency Code of Practice for the Manufacture of PVC* [31]. These two charters were agreed during 1999 by the *PVC Coordination Group*, including by the two UK PVC manufacturing companies, driving real progress albeit largely relating to eco-efficiency improvements during manufacturing rather than wider life cycle sustainability contexts. A further, particularly significant development for PVC was uptake of the TNS Sustainability Challenges for PVC initially in part by the Vinyl2010 program but, from 2011, by its successor VinylPlus®. VinylPlus® spans the EU-28 Member States plus Switzerland and Norway (also including the UK as it leaves the EU), updating the five Challenges within a voluntary commitment with an associated set of targets up to 2020 (http://www.vinylplus.eu/, accessed September 6, 2019). Table 3 documents the original five TNS Sustainability Challenges for PVC presented by Everard et al. [2], mapped to their adaptation under the VinylPlus® voluntary commitment including relevant VinylPlus® targets to 2020.

Relationships between formal and informal governance as aspects of the political/policy sphere are direct. VinylPlus® and trade associations in the PVC value chain influence formal government policy to avert unhelpful or misinformed legislation, to drive additional regulations to secure a "level playing field" against imported products produced with lesser commitments to sustainability, and to demonstrate the benefits of leadership by example. A pertinent case study here is the explicit citing of VinylPlus® as an exemplar of voluntary and strategic progress contributing to the circular economy and other sustainable development aspirations in the UK Government's 2018 *Our waste, our resources: a strategy for England* [33].

The Interdependence of Changes over 20 Years

The five elements of the STEEP framework are systemically connected. Population rises drive increasing environmental pressures due to demands and emissions, with economic uplift amplifying demands but natural resource limitations increasing costs, all affected by technology choice and innovation within formal and informal governance systems. Evolution in sustainability awareness affecting decisions also has a profound impact on the interconnected elements of the system.

One particular evolving aspect of awareness germane to PVC articles is that, while persistence in chemistry can have negative consequences (e.g., bioaccumulation of substances released into the biosphere), there is a substantially positive contribution in terms of the durability of finished products. For example, while former use of lead in stabilizers (now phased out voluntarily in Europe) can be problematic were the heavy metal to be liberated into the environment, the role of lead and replacement substances in stabilization of PVC means that finished plastic articles are durable with a substantially extended service life, little

TABLE 3. The five TNS and VinylPlus® sustainable development challenges for PVC.

PVC Evaluation using The Natural Step Framework [2]	VinylPlus® Voluntary Commitment [32] (challenges re-numbered by stakeholder priority within the VinylPlus® roadmap) and associated targets to 2020
1. The industry should commit itself long term to becoming carbon-neutral	Challenge 4. Sustainable energy and climate stability—*We will help minimize climate impacts through reducing energy and raw material use, potentially endeavoring to switch to renewable sources and promoting sustainable innovation.*
2. The industry should commit itself long term to a controlled-loop system of PVC waste	Challenge 1. Controlled loop management—*We will work towards the more efficient use and control of PVC throughout its life cycle.*
3. The industry should commit itself long term to ensuring that releases of persistent organic compounds from the whole life cycle do not result in systemic increases in concentration in nature	Challenge 2. Organochlorine emissions—*We will help to ensure that persistent organic compounds do not accumulate in nature and that other emissions are reduced.*
4. The industry should review the use of all additives consistent with attaining full sustainability and especially commit to phasing out long-term substances that can accumulate in nature or where there is reasonable doubt regarding toxic effects	Challenge 3. Sustainable use of additives—*We will review the use of PVC additives and move toward more sustainable additives systems.*
5. The industry should commit to the raising of awareness about sustainable development across the industry and the inclusion of all participants in its achievement	Challenge 5. Sustainability awareness—*We will continue to build sustainability awareness across the value chain—including stakeholders inside and outside the industry—to accelerate progress towards resolving our sustainability challenges.*

TABLE 4. Targets by the five challenges are their attainment

Target	Attainment as of VSF2019
1. Controlled loop management	
Recycling 800,000 t of PVC waste per year by 2020	In 2018, 739,525 t of PVC waste was recycled within the VinylPlus® framework, a 15.6% increase compared to the previous year.
2. Organochlorine emissions	
The Industry Charters for suspension (VCM and S-PVC Charter) and emulsion (E-PVC Charter) PVC are aimed at reducing environmental impact in the production phase. The PVC resin industry is committed to achieving 100% compliance by the end of 2020	Zero emissions from transport accidents were reported in 2018.
3. Sustainable use of additives	
We will review the use of PVC additives and move towards more sustainable additive systems	Complete elective phase-out of lead (2015) and cadmium (2003) stabilizers under VinylPlus® commitments. Development of the Additive Sustainability Footprint (ASF) tool for assessment of the sustainable use of PVC additives throughout article/product life [35].
4. Sustainable use of energy and raw materials	
PVC resin producers are committed to diminishing their energy consumption for the production of EDC, VCM, and PVC, targeting a 20% reduction by 2020.	In 2018, IFEU [36] completed a new verification of ECVM members' energy consumption data for 2015–2016. The energy needed to produce 1 t of PVC decreased by an average of 9.5% compared to the baseline period 2007–2008.
5. Sustainability awareness	
We will continue to build sustainability awareness across the value chain—including stakeholders inside and outside the industry—to accelerate resolving our sustainability challenges	VinylPlus® continues to promote frank and open dialogue with a diversity of stakeholders, third parties, institutions, and organizations, including running annual Vinyl Sustainability Forum events and contributing to other conferences and publications

or no maintenance inputs over life, complete immobilization of the metal throughout that life cycle, and inherent recyclability beyond end-of-life. In addition to this are often-significant sustainability benefits arising from substantially less frequent product replacement, with its associated material inputs, waste arising, disruption, and costs. Durability as a property thereby confers significant sustainability benefits in terms of extended service life in meeting a variety of human needs per chemical unit, reduced maintenance inputs, economic benefits in terms of life cycle costs, reduced environmental footprint when service benefits are equated with a limited pool of constituent molecules, and inherent recoverability and recyclability extending these benefits still further.

Changes in the Context of the Five TNS Sustainability Challenges for PVC

These 20-year trends are then considered in the context of the five TNS sustainability challenges for PVC, both for PVC materials and for selected other substances. Successes for PVC are summarized as progress reported by VinylPlus® [34] with the five (modified) TNS sustainability challenges in Table 4.

Comparator Materials and the Five Sustainability Challenges

Timber/forest-based products are a commonly used alternative to PVC in the European window profile market. A Greenpeace report *Look Out – Your choice of window could seriously harm the planet* (reported in [37]) argued that "*As long as timber is sourced from properly managed forests and care is taken in the choice of preservatives, paints and stains, timber windows are by far the best environmental choice*." In common with the PVC industry, the wood sector has also embarked on voluntary commitments particularly with respect to sourcing. Most prominent amongst these is Forest Stewardship Council (FSC), an independently audited global certification scheme around a published series of ecological and social standards for forest products along entire value chains from wood extraction and forest management to final applications such as plank, paper, carton, newspaper, and other printed matter [38]. FSC covers the two components of Forest Management and Chain of Custody certification. These allow consumers to identify, purchase, and use wood, paper, and other forest products with an audited chain of custody from well-managed forests and/or recycled materials. The supply chains of two ostensibly identical pieces of wood or paper, one FSC-certified and one less responsibly sourced, can have substantially different impacts on environmental and human wellbeing. The FSC was set up in 1994 by a consortium of interests that, at the time, seemed highly improbable ranging from environmental NGOs (WWF, Friends of the Earth, Greenpeace), indigenous forest dwellers, professional forestry interests, and major retailers such as Sweden's IKEA and the UK's Kingfisher Group (notably owning the DIY chain B&Q). All shared a desire for a workable and transparent system that would promote responsible forest management practices and create a clear market for them. This bold, ground-breaking leadership created a scheme that was not only well in advance of what national government or intergovernmental groups had

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achieved, but seemingly also what they could at the time conceive. The business drive was essential to make the FSC scheme workable. As of December 20181,606 FSC forest certificates had been issued in forests in 85 countries spanning 200,963,183 ha (over twice the land area of Portugal), with 35,772 "chain of custody" certificates issued in 123 countries [39]. Beyond market penetration of sustainable sourcing, use of "*preservatives, paints and stains, timber windows*" but also the necessity of their routine reapplication throughout the life of a window profile can have a significant "environmental footprint" as well as time demands for maintenance activities to maintain window functionality. Considering the life cycle of alterative window profile materials, a WWF report [40] concluded of PVC that "*Opinions on its environmental impact and safety are polarised between the chemicals industry and environmental organisations*." In practice, reviews of a range of LCA studies start from different assumptions about the recyclability of PVC (particularly assumptions that PVC is not recycled in some reports) and the impacts of repeated preservative additions to wood profiles (many of them overlooked). Many studies also omit to consider the longevity of different materials and hence their service life per unit molecule and management inputs, and also the potential recyclability/value recovery of preservative-impregnated and/or degraded wood profiles at end-of-life. This means that little consensus can be derived from the range of published comparative LCA studies. (aluminum also has high market penetration in the European window profile market and would be a useful additional comparator, although space limits enforce its omission.)

Cast (ductile) iron is recommended as one alternative to PVC water pipes [41] and was formerly in common use in the United Kingdom. Iron manufacturing is another energy-intensive industry largely founded on raw materials mined from the Earth's crust, although scrap iron from sources such as used car parts, construction waste, and foundry returns now constitutes a significant element of contemporary iron and steel production ([42]). Ductile iron has many applications in the construction industry, both structural and as pipes. Allowing for wastage from corrosion, cast iron can be recycled indefinitely without any decline in mechanical properties. As iron is the fourth most common element in the Earth's crust, residual releases into nature are unlikely to result in significant systematic accumulation in concentration other than at very local scales, and so is unlikely to give rise to unforeseen problems. Mother Earth Living [41] advocates ductile iron as a PVC alternative is it is inert and "*fairly benign*" and is also quiet as it buffers the noise of passing water, but also noting that the weight of the material makes it expensive to install and that it is best "*only used in waste lines*." It is questionable how "*fairly benign*" iron is in terms of its tendency to corrode and so can become unreliable over time, also necessitating replacement with associated expense and disruption. Life expectancy of unprotected ductile iron pipes depends on soil corrosiveness, tending to be shorter where soil is highly corrosive [43]. A lifespan in excess of 100 years has been estimated for ductile iron pipelines installed using "evolved laying practices" including use of properly installed LPS (polyethylene encasement) [44,45], although additional polymer layering does not make a fair comparison between ductile iron and PVC water pipes.

Other plastics, particularly polyolefins, are commonly also used in pipes and cables. In cable and many other applications, PVC is naturally fire-quenching owing to its chlorine content, so comparator polyolefin materials require the addition of fire-retardant chemicals. Mother Earth Living [41] also recommends plastics such as high-density polyethylene (HDPE) and acrylonitrile-butadiene-styrene (ABS) as PVC alternatives for water pipes as they are cheap, light, strong, and flexible and tend not to corrode, also noting negative aspects including that they are "*made with fossil fuels*," that their manufacture is energy-intensive and that they are expandable; in practice, these cited benefits are common to PVC and the negative attributes are common to all alternative materials. Progress has been made in Europe with recycling of polyolefins. Plastics Recyclers Europe [46] noted that recycling capacity for rigid postconsumer and postindustrial polyolefins, in particular HDPE and PP, in Europe totaled 1.7 million tonnes. However, this is a relatively small figure (almost 7%) relative to the approximately 25 million tonnes of polyolefins (polypropylene, low-density polyethylene, and high-density polyethylene) produced in Europe each year [47]. By comparison, VinylPlus® recycles 740,000 t in 2018 relative to the 2.1–2.4 million tonnes of waste PVC collected in Europe per year (31–35% recycled), reflecting the generally long-lived nature of PVC products, investments in recycling and the high value of PVC recyclate and recycled products compared to many other materials.

DISCUSSION

PVC may be one of the most heavily scrutinized of all materials in common use by society [1]. But though it has suffered specific issues and has also been singled out by pressure groups and subsequently by regulatory institutions, it is one among many materials deployed for beneficial uses in a range of societal applications. All materials should ideally be assessed in common terms within specific applications.

A significant factor in the author's thinking in framing the five TNS-based sustainability challenges for PVC was not only that this summation of key issues would make practical understanding and engagement with sustainable development more tractable for the PVC sector, but that the challenges should also be relevant across all materials. After all, if the sustainability analysis and agenda for action related only to PVC, they would reinforce a perception that PVC was a material distinct from all others. Yet the reality is that the sustainability challenges facing all materials used by society relate to common factors, as evidenced, for example, by social, technological, environmental, economic, and political changes over the past 20 years. At the level of wider sustainability principles, the commonality of challenges for all materials used by society is exposed by the scientific principles underpinning the TNS model and definition of sustainability. Leadership within the PVC sector on proactively addressing the five TNS sustainability challenges was undoubtedly stimulated by the substantial pressure to which the PVC industry was subject [1]. However, this has put the sector in a leadership position, recognized by UK Government [33], with respect to voluntary, transparent commitments, and progress with sustainable development challenges. Although sustainable development awareness and pressure have informed initiatives by other materials sectors, progress by the PVC sector has been substantially accelerated.

This progress has, in the long term, proved beneficial in terms of responding electively and proactively to changing societal perceptions and requirements that otherwise would have to be managed reactively as awareness and concerns manifested. On publication in 2000, the five TNS sustainability challenges for PVC were viewed as hugely ambitious with the relevance of some not widely grasped. For example, the first of the TNS Sustainability Challenges ("1. The industry should commit itself long term to becoming carbon-neutral"), reframed today as VinylPlus® Challenge No. 4 (Sustainable use of energy and raw materials), was seen as a major challenge for a polymer with a high embedded carbon content and intensive (mainly fossil carbon based) energy inputs, regarding an issue for which there were at the time no significant statutory drivers. (PVC does start from a lower climate-active "footprint" compared with other polymers as the organic component of the molecule—mostly oil-based—is 43% with chlorine atoms comprising 57% by polymer mass.) However, since 2000, there has been mounting consensus, regulatory response, and financial gains (rising energy and other costs as well as fiscal measures) for addressing carbon emissions. There has also been innovation across the PVC sector that, in the light of emerging financial, legal, and perception drivers, have been cost beneficial. This carbon/energy-related challenge, as for the other four TNS Sustainability Challenges for PVC, is germane to all materials.

Recognition of potential problems through backcasting from science-based sustainability principles, inherent in The Natural Step approach, is thereby more strategic and beneficial than reaction to issues once they manifest in public, NGO, and government consciousness and response. This reveals one of the key strengths of the TNS approach, based on a science-based set of sustainability principles rather than simply focused on eco-efficiency (lightening current impacts) and responding to currently known concerns. By basing itself on the potential for impacts that may arise from systematically increasing environmental concentrations of substances derived from the Earth's crust or synthesized by society, as well as processes physically degrading natural systems and/or preventing sectors of society meeting their needs, unforeseen issues and concerns likely to happen later are pre-empted. This is ultimately far more advantageous that reactivity, particularly where vested interests have become established around maintaining a status quo when problems manifest. It also inherently addresses life-cycle risks and innovations to manage them, rather than simple hazard assessment.

Recognizing the commonalities of sustainability problems for all material used by society, Table 5 summarizes some aspects of selected materials assessed against the five TNS Sustainability Challenges for PVC.

The purpose of this article is not to suggest that PVC is more sustainable than other materials. Nor is it to dismiss nor denigrate progress with sustainable development by interests in other materials, all of which are welcomed and commended. Rather, it is to ground consideration of all materials on a "level playing field" of common interconnected sustainability principles. The largely illustrative "traffic lights" scoring in Table 5 highlights context-specific issues for differing materials across the five sustainability challenges. The use of the TNS model (or in this case the summary five sustainability challenges) rather than, for example, simplistic chemical hazard criteria, addresses an integrated range of social as well as environmental issues in the context of whole product life cycles. This posits longer-term progress with sustainability criteria at least as important as immediate cost and technical performance in product use and design, taking account of potential emergent issues in a changing world. The rising demands of a growing and increasingly affluent human population subsisting on a declining natural resource base informs us that sustainability pressures will increasingly inform supply chain security and potential liabilities, regulations, economic considerations, and consequently decision-making. Founding these decisions proactively on science-based sustainability criteria therefore makes strategic sense and by implication sound business judgment.

On the basis of this "level playing field" and systemically connected assessment, it is, for example, possible to explore how a lack of commitment to the second TNS sustainability challenge ("*2. The industry should commit itself long term to a controlled-loop system of PVC waste*") for any material can compromise progress with other dimensions of sustainable development. Referring to the TNS rather than the VinylPlus® reframing of these five sustainability challenges, lack of recycling and associated infrastructure and markets would mean that carbon neutrality (Challenge 1), potential release of persistent organic compounds (Challenge 2) particularly through incautious disposal, the sustainable use of additives (Challenge 4) that are not eventually recovered, and raising of awareness about sustainable development across the industry (Challenge 5) critically including the value chain beyond the manufacturing sector would be practically impossible. Equally, we have to recognize that some products, such as food wrappers or ice cream scoops, will not only inevitably enter general, mixed waste streams but will also be contaminated. For these purposes, PVC and many other durable materials may be a poor choice if sustainability challenges and TNS System Conditions cannot practically be met, creating problems and associated liabilities into the future. For these shortlife, mixed waste applications, materials that are compostable or otherwise benignly

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TABLE 5. Coarse comparison of alternative materials by the five original TNS sustainability challenges for PVC. [Color table can be viewed at wileyonlinelibrary.com]

TNS sustainability challenges	PVC	Forest-based products (in window profiles)	Ductile iron (in water pipes)	Polyolefins in cable insulation)
1. The industry should commit itself long term to becoming carbon neutral	• Progress with reducing carbon intensity per unit PVC is reported annually by VinylPlus® GREEN	• Forests naturally recycle carbon, though timber harvesting and processing entail carbon inputs • Lack of recoverability at end-of-life means that some of this benefit is lost AMBER	• Ductile iron manufacturing is energy-intensive, though recycling captures embedded energy • The weight of pipes also adds to carbon emissions in transport GREEN	• Polyolefins are carbon-intensive in terms of manufacturing energy, but also embodied carbon (which is far higher than PVC which significantly comprises chlorine atoms) • Some recycling occurs though at a low rate compared to production AMBER
2. The industry should commit itself long term to a controlled-loop system of PVC waste	• Under VinylPlus®, substantial investments have substantially increased the rate of physical and chemical recycling of PVC across Europe, with associated market expansion or recyclate • Some PVC materials are not yet substantially recovered, for example in packaging though this is a small part of the European PVC market GREEN	• For timber window profiles, often degraded and impregnated with preservative, there is no current recycling model after end-of-life • [Note that contaminated food packaging waste can be composted, where collected, potentially compling with this Challenge but this is not the case for window profiles RED	• Considerable recovery and re-melting, with some shrinkage from degradation GREEN	• Polyolefins comprise a significant proportion of contemporary visible marine litter, consequent from prevalent uses in short-life applications and lack of effective recovery at end-of-life • Some recycling occurs though at a low rate compared to production RED
3. The industry should commit itself long term to ensuring that releases of persistent organic compounds from the whole life cycle do not result in systemic increases in concentration in nature	• Substantial innovations in manufacturing and transport have virtually eliminated fugitive or accidental releases of harmful compounds from manufacturing phases GREEN • VinylPlus® openly reports on this Sustainability Challenge • Investment in the controlled loop also prevents incautious disposal of PVC in ways that may generate problem substances at end-of-life GREEN	• While timber production is generally cleaner than heavy chemical manufacture, regular additions of preservatives are required in wood profiles to prolong service life • The Minamata Protocol Gothennburg Protocol are examples among a range of regulatory and consensual agreements limiting use of hazardous chemicals in preservatives AMBER	• Few if any persistent substances (other than iron itself that is common in the Earth's crust) are entailed in ductile iron pipes beyond manufacturing phases GREEN	• Lower additive additions to polyolefins relative to PVC reduce this risk, though lack of recovery means that the risk of persistent organic compound generation throughout societal life cycle, particularly on disposal, is far from minimal AMBER
4. The industry should review the use of all additives consistent with attaining full sustainability, and especially commit to phasing out long term substances that can accumulate in nature or where there is reasonable doubt regarding toxic effects	• The European PVC industry electively phased out cadmium by 2003 and lead by 2015 under VinylPlus® commitments • In 2019, initial development was completed on the Additive Sustainability Footprint (ASF) tool for assessment of the sustainable use	• Preservatives, including paints and other coatings, integrated into timber during product manufacture and during product life are generally overlooked in terms of their potential sustainability implications RED	• Low relevance as ductile iron has little additive use other than in production • Many water pipe applications today of ductile iron use a polymer coating to prolong life, though this is not directly comparable to PVC pipes and is not considered here AMBER	• Polyolefins generally contain fewer additives in water pipe applications, though owing to the flammability of polyolefin molecules, many polyolefin applications (cables, pipes and others) require the incorporation of flame-suppressant additives RED

(Continues)

Table 5. Continued [Color table can be viewed at wileyonlinelibrary.com]

TNS sustainability challenges	PVC	Forest-based products (in window profiles)	Ductile iron (in water pipes)	Polyolefins in cable insulation)
	of PVC additives throughout article/ product life [35]. • Other potentially problematic additives have also been phased out, such as DEHP plasticizers • Investment in recycling of end-of-life PVC also recovers embedded additives, preventing their dispersal into waste streams and ecosystems GREEN			
5. The industry should commit to the raising of awareness about sustainable development across the industry, and the inclusion of all participants in its achievement	• Beyond the initial TNS study and Challenges, Initiatives by Hydro Polymers, various Charters and Vinyl2010, VinylPlus® has since 2011 devoted a great deal of resources to connections across the value chain including, as example, a range of transparent publications, annual Vinyl Sustainability Forum events, liaison with product group trade associations, interactions and influence with regulators, and investment in recycling and markets for recycled PVC GREEN	• The FSC scheme, noted in the body of this text, has created substantial and global markets for timber and other forest products spanning whole value chains from production to consumer products • However, once forest-based products reach end-of-life, there is no further control on their fate, including that of preservative-impregnated or degraded timber that is not readily reused or recycled other than by energy recovery or other forms of disposal AMBER	• Consortia such as the International Council on Mining & Metals promote sustainable development through 10 principles [48], and ductile iron manufacturing industries are subject to continuous improvement and more stringent regulation • However, there is no evidence of full value chain stewardship of ductile iron beyond product manufacture AMBER	• In January 2018, the polyolefin circular economy platform [49] of PlasticsEurope published a Voluntary Commitment to 2030. This forms part of the wider PlasticsEurope target to increase circularity and resource efficiency, comprising targets and initiatives focused on increasing re-use and recycling, preventing plastics leakage into the environment, and accelerating resource efficiency • This initiative is very welcome, albeit starting from a later baseline than PVC voluntary commitments GREEN

The "'traffic lights'" color coding denotes: Green = material progress; Amber = mixed progress; and Red = no substantive progress against each challenge.

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manageable may be the most sustainable choice when assessed on TNS criteria including the five summary sustainability challenges. This contrast, for example, with durable products like window profiles, pipes, and wiring insulation where long life, low inputs for maintenance, recoverability, and recyclability are not only possible but are increasingly well developed. Shorter lifetime materials and those needing repeated addition of preservatives or other management interventions, though potentially more sustainably sourced, may over the full product life cycle be less sustainable including the difficulties inherent in their recovery at end-of-life. The importance of accounting for sustainability across full product life cycles is increasingly acknowledged (e.g., by the [50]). Material selection is therefore not a simplistic judgment of what is sustainable and what is not, but must necessarily be context-specific, taking account of inherent properties, specific applications, and the societal infrastructure enabling management throughout their full life cycles.

From this brief analysis, it would appear that the five TNS sustainability challenges for PVC remain entirely relevant 20 years after their initial publication and have stimulated quantifiable innovation and progress with sustainable development. Issues emerging within the last 20 years, such as concerns about marine accumulation of plastic litter and also of environmental microplastics, relate directly to lack of product recovery. This is as relevant to plastics as other materials, albeit that the persistence of plastics makes their accumulation in the environment more obvious compared to, for example, preservative-contaminated wood fragments or degraded rust particles. Not only are the five challenges still relevant to PVC, but they are also relevant to other materials. Also, in a globalized and increasingly globalizing industry, they necessarily need to inform whole international value chains such that retailer or public sector specifiers, for example, do not profess commitment to sustainable development yet buy overwhelmingly on price resulting in purchasing from PVC or other material and product producers in less rigorously controlled global regions. Challenge 5—raising of awareness about sustainable development across the industry (in both the TNS and VinylPlus® articulations)—therefore relates to players in the complete societal life cycle of PVC products, with international context in Europe and world-wide integral to assessment and influence. System innovation is essential to achieve fundamental changes in both social dimensions and technical dimensions and, importantly, the relations between them, noting that realization of sustainable chemistry "…*requires the transformation of value chains as well as institutional and financial structures*…" ([51], p. 98).

That the PVC sector has taken an acknowledged leadership role over the past two decades was, as people in the industry will admit, substantially driven by the pressure to which the industry was exposed. This momentum includes a strong drive in innovation of material use including additives, processing, recovery and recycling, processes, and scrutiny of the whole societal life cycle of PVC, increasing research and development stimulating more human benefits per unit of chemical use. Demonstrable benefits to the industry have resulted from innovation against commitments to sustainable development. Sustainability challenges are relevant to all material choices, so extension of relevant and informative principles more widely across industry and society is a necessity. Further research is necessary to add substance to the rudimentary comparative analysis of alternative materials against the five TNS sustainability challenges for PVC and to work with other industry sectors to help adapt these sustainability challenges to aid with progress with sustainable development for business and wider societal benefit. Further research can help sectors of society beyond manufacturing companies—specifiers, waste and recycling, regulators, and so on—adapt this learning to progress and accelerate their practical engagement with sustainable development, including assisting them in avoiding future potential problems. It can also help connect international supply and value chains on the basis of common sustainable development perceptions and principles directed towards profitable and beneficial long-term goals.

CONCLUSIONS

- PVC may be one of the world's most scrutinized materials driven substantially by a history of interconnected NGO, media, and regulatory pressures.
- These pressures have combined to drive the PVC sector, initially in the United Kingdom but spreading Europe-wide and latterly global, to engage strategically with sustainable development.
- Outcomes from The Natural Step approach of backcasting from science-based principles of sustainability applied to PVC were summarized in practical terms into the five TNS sustainability challenges for PVC, published in 2000. The challenges initially assisted UK manufacturing companies with identifying strategic areas of progress and shaping innovation and have subsequently been progressively taken up across European PVC value chains.
- The VinylPlus® program is today centered on voluntary commitments to sustainable development by the European PVC industry, adapting the five TNS sustainability challenges for PVC against which investments and innovations are made and progress is transparently audited.
- As PVC value chains are global, the five TNS sustainability challenges for PVC are influencing innovation and improvements in social and environmental performance with global reach.
- The initial framing of the five TNS sustainability challenges for PVC were drafted consciously for more generic relevance to other materials. Assessing the sustainability performance of a number of other materials used as alternatives to PVC against the five challenges reveals different sustainability performance in a range of potential applications. This highlights the danger inherent in automatic selection or deselection of materials in the absence of assessment of options on a "level playing field" of sustainability principles.
- The five TNS sustainability challenges for PVC remain valid today and into the longer-term future as a basis for making stepwise, profitable progress toward the eventual goal of full sustainability for PVC as well as for other materials.

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