



# Sustainable Building and Living, Focus on Plastics

Workstream Report





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## ISC<sub>3</sub>: Who are we and what are our objectives?

The International Sustainable Chemistry Collaborative Centre (ISC<sub>3</sub>) is a globally acting institution and a multi-stakeholder platform operating on behalf of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the German Environment Agency (UBA). ISC<sub>3</sub> aims to shape the transformation of the chemical sector towards sustainable chemistry, thus contributing to the preservation of the environment and the establishment of a circular economy in order to meet the UN Sustainable Development Goals (SDGs).

ISC<sub>3</sub> consists of three partner institutions: GIZ, DECHEMA and LEUPHANA.

### ISC<sub>3</sub> Head Office (HO):

The Head Office is hosted by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in Bonn.

GIZ is a German agency for international cooperation working in over 120 countries worldwide, with a focus on developing countries and emerging economies.

The head office coordinates the centre's work, provides an operational framework and infrastructure and is responsible for the areas of collaboration, information, communication, policy, thematic workstreams and focus topics as well as stakeholder involvement.

### ISC<sub>3</sub> Innovation Hub (IH):

The Innovation Hub is hosted by DECHEMA in Frankfurt. DECHEMA is a non-profit society for engineering and biotechnology. IH initiates and supports innovation in the field of sustainable chemistry and fosters entrepreneurs worldwide in order to help solve pressing societal challenges. IH works directly with start-ups, assisting them in the development of new sustainable ideas and business models.

### ISC<sub>3</sub> Research & Education Hub (REH):

The Research & Education Hub is hosted by the Institute of Sustainable and Environmental Chemistry at the Faculty of Sustainability of the Leuphana University of Lüneburg. REH carries out academic trend scouting as well as developing and running study programmes and training courses (e.g. master's programme 'MSc in Sustainable Chemistry', thematic summer schools, etc.). REH is active in the scientific world and lays theoretical groundwork for sustainable chemistry.

To summarise the action fields of the three partners: ISC<sub>3</sub> has established itself as an international institution that promotes and develops sustainable chemistry solutions worldwide. ISC<sub>3</sub> is building up a knowledge platform and a network of experts. It offers support and training, especially for developing countries, and carries out scouting activities for innovations in the field in order to establish new technologies and business models.



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## Abbreviations

AABMTs	Alternative and appropriate building materials and technologies	ISC <sub>3</sub>	International Sustainable Chemistry Collaborative Centre
ABS	Acrylonitrile butadiene styrene	IEA	International Energy Agency
ACC	American Chemistry Council	IRENA	International Renewable Energy Agency
AI	Artificial intelligence	ITO	Indium tin oxide
AMF	Artificial mineral fibres	KNBS	Kenya National Bureau of Statistics
APEG	Allyl alcohol polyethylene glycol ether	LCA	Life cycle assessment
ASEP	Acid esters with phenol	LDPE	Low density polyethylene
BBP	Benzyl butyl phthalate	LSO	Linseed oil
BPA	Bisphenol A	MAH	Monocyclic aromatic hydrocarbons
CAS	Chemical Abstracts Service	MLS	Modified lignosulphonate
CCU	Carbon capture and utilisation	MPEG	Methoxy polyethylene glycol
Cd	Cadmium	NBPA	Non-BPA
CE	CE labelling	NCA	National Construction Authority
CER	Certified Emissions Reduction (of carbon)	NHC	National Housing Corporation
CHB	Concrete hollow blocks	NIPU	Non-isocyanate PUR
ChP	Chemicals in products	NMA	Nadic methyl anhydride
CO <sub>2</sub>	Carbon dioxide	NRP, NFRP	Natural fibre-reinforced polymer
COMGHA	Acetylated monoglycerides of fully hydrogenated castor oil	NTI	2-[(5-nitro-1,3-thiazol-2-yl)carbamoyl] phenyl acetate
CRP, CFRP	Carbon-reinforced plastic, carbon fibre reinforced polymer	OSB	Oriented strand board
CSF	Composite solid fibre	OSC	Organic solar cell
DBP	Dibutyl phthalate	PA	Polyamide
DDT	Dichlorodiphenyltrichloroethane	PAH	Polycyclic aromatic hydrocarbons
DEHP	Bis(2-ethylhexyl) phthalate	PBT	Polybutylene terephthalate
DGEBA-NMA	Diglycidyl ether bisphenol A-nadic methyl anhydride	PC	Polycarbonate
DGNB	German Sustainable Building Council	PCB	Polychlorinated biphenyl
DIBP	Diisobutyl phthalate	PCE	Polycarboxylate ether
DSSC	Dye-sensitised solar cells	PCM	Phase change material
E-plastic	Embracing plastic	PDO	1,3-propanediol
ECHA	European Chemicals Agency	PE	Polyethylene
ECPI	European Council for Plasticisers and Intermediates	PE-HD	→ HDPE
EPD	Environmental product declarations	PE-LD	→ LDPE
EPO	European Patent Office	PEN	Polyethylene naphthalate
EPS	Expanded polystyrene	PES	Polyarylether sulphone
ETFE	Ethylene tetrafluoroethylene copolymer	PET	Polyethylene terephthalate
EVA	Ethylene-vinyl acetate	PIR	Polyisocyanurate
EXP	Expanded	PHF	Phenolic foam
FED	Fractional effective dose	PMDI	Polymeric diphenylmethane diisocyanate
FRP	Fibre-reinforced polymer	PMMA	Polymethyl metacrylate
GDP	Gross domestic product	PNF	Polymeric nanofibres
GHG	Greenhouse gas	PNP	Polymeric nanoparticles
GRP, GFRP	Glass-reinforced plastic, glass fibre-reinforced polymer	PP	Polypropylene
HAP	Household air pollution	PPS	Polyphenylene sulphide
HBCD	Hexabromocyclododecane	PS	Polystyrene
HCFC	Hydrochlorofluorocarbon	PTFE	Polytetrafluoroethylene
HDPE	High density polyethylene	PUR	Polyurethane
		PV	Photovoltaic
		PVC	Polyvinyl chloride
		PVDF	Polyvinylidene fluoride
		PVOH	Polyvinyl alcohol
		Q-NMA	Quercetin-nadic methyl anhydride

<b>R&amp;D</b>	Research and development	<b>SEC</b>	Securities and Exchange Commission
<b>RDF</b>	Refuse derived fuel	<b>SMF</b>	Sulphonated melamine formaldehydes
<b>REACH</b>	Registration, Evaluation, Authorisation and Restriction of Chemicals	<b>SNF</b>	Sulphonated naphthalene formaldehydes
<b>REFB</b>	Reinforced eco-fire brick	<b>SVOC</b>	Semivolatile organic compounds
<b>RSA</b>	Republic of South Africa	<b>TBBPA</b>	Tetrabromobisphenol A
<b>SAICM</b>	Strategic Approach to International Chemicals Management	<b>TMBPF</b>	Tetramethyl bisphenol F
<b>SCCP</b>	Short-chain chlorinated paraffins	<b>UNEP</b>	United Nations Environment Programme
<b>SCIP</b>	Substances of Concern In articles as such or in complex objects (Products)	<b>USGBC</b>	U.S. Green Building Council
<b>SDG</b>	Sustainable Development Goal	<b>VOC</b>	Volatile organic compounds
<b>SEAC</b>	Committee for Socio-Economic Analysis	<b>WRAP</b>	Waste & Resources Action Programme
		<b>XPS</b>	Extruded polystyrene

## Editorial

Construction plastics is a growth industry today, with manufacturing capacities particularly in emerging markets having overtaken the roughly equally strong regions of Europe and North/South America in recent years. In developing and emerging countries, plastics are rapidly advancing as an indispensable building material. The ‘polymer age’ in the building materials sector began in the mid-1930s with the first pipes made of hard polyvinyl chloride.

But how sustainable are these plastics really in comparison to other materials used in construction? This question is not easy to answer, as many aspects play a role. Ultimately, the entire life cycle of such products must be considered, their special properties during use and the effects on people and the environment. At the end of their useful life, the method of disposal is an important factor. How recyclable are the plastics used? Different authors from various fields have addressed these complex questions in this paper. ISC<sub>3</sub> – International Sustainable Chemistry Collaborative Centre – has succeeded in attracting experts from science, public authorities and companies to debate these questions. **Chapter 5** includes recommendations on how to deal with plastics in construction, together with comments on how sustainable their use is and how recyclable they are from today’s point of view. Of course, not all questions can be answered, but this work can be the starting point for a discussion that has to take place at UN level.

The topic of the workstream Plastics in Sustainable Building & Living is based on the SDGs and the global

megatrends according to the Global Chemicals Outlook, but its focus is on sustainable chemistry. The workstream initiated a dialogue with various stakeholders worldwide. This report has been prepared on the basis of international thematic workshops, interviews, online surveys and contributions by experts. The chosen approach involved three steps: preliminary study, qualitative stakeholder dialogue and final report. The selected topics were explored and discussed in thematic workshops at the conferences in China, Kenya, Austria and the USA. Four online surveys were compiled, one for each workshop topic. During the conference Resilient Cities, interviews with international guests were conducted at the interactive stand of ISC<sub>3</sub>.

The expert workshops were attended by 58 international experts from various sectors: chemical producers, associations, recycling companies, ministries, agencies (construction, environment), financial sector, NGOs and major international organisations.

The report expresses the position of ISC<sub>3</sub> and, as a guide, addresses current issues in the field of plastics in construction. It discusses a possible route to sustainable solutions in terms of the SDGs. Questions regarding relevant innovative fields and potentials for sustainable chemistry are raised, using the start-ups mentioned in the report as examples.

I hope that you enjoy reading this report. Please feel free to contact the authors and send us your ideas.

With best regards,  
Dr Beate Kummer



**FIGURE 1**  
Workstream: Method

Source: ISC<sub>3</sub>

## Foreword by ISC<sub>3</sub>

Products manufactured by the chemical and allied industries contribute to high living standards and quality of life. These include plastics, which – have a wide range of applications and properties that can be adjusted to various functional requirements. One field where they are greatly in demand is the construction sector. Despite their broad and manifold applications, plastics are often not visible in buildings and therefore not perceived as important materials. In this sector, which includes architecture and design, there is often no understanding about the present and future legacies they cause. The use of plastics in the building sector is profoundly influenced by the current megatrends: climate pollution, demography and urbanisation, need for resilience, health as well as affordable housing with its regional contours.

Environmental and health issues as well as the social and economic challenges along the life cycle of building plastics are the main impacts. Unsound management of chemicals in construction has accompanied negative trade-offs until today and will continue to do so in the coming decades, since circularity has not been a guiding principle until now. Initiatives such as the Strategic Approach to International Chemicals Management (SAICM) are developing strategies for a safe use of chemicals. Nevertheless, guidance is needed on how the construction and building industry, including the related economic sectors, has to transform in order to become more sustainable, i.e. respect the **precautionary principle**, **embrace systems thinking** and follow a holistic approach to go beyond **green chemistry** and contribute to the SDGs in a sustainable manner.

For this report, we involved a wide range of stakeholders from academia, industry, international organisations and NGOs, who considered aspects of ethics and social responsibility alongside the technical issues.

The report aims essentially to show **the potentials for sustainable chemistry** in the construction sector and to answer the following questions: How can plastics be used in a sustainable way in buildings? What obstacles are there and how can they be overcome? Which steps need to follow, under consideration of regional differences? In the **last chapter**, we have derived recommendations for the areas of research, sustainable innovation, capacity building and policy, based on the contributions by our authors and the expert workshops.

In this respect, we hope that this study will be well received by readers and support all stakeholders to contribute to a more sustainable use of plastics and other materials in the building and construction sector.

Bonn, Frankfurt, Lüneburg  
December 2020

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left to right:  
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# 1. Introduction

Professor Henning Friege



## 1.1 Current use of polymers in building and living – policy background



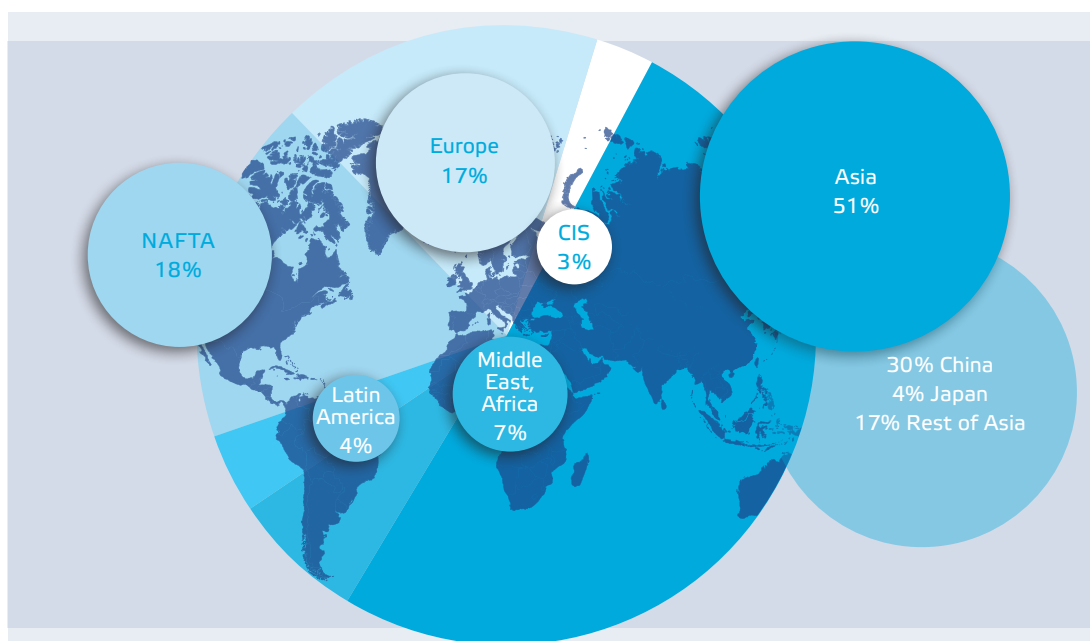
### ONLINE SURVEYS WITH EXPERTS (see Annex A, B, figure B):

Price is the leading factor for the choice of materials (97%) followed by health (78%) and availability (76%). Sustainability was rated as least important by 55% or even not important at all by 24% of survey respondents. Plastics score with their performance (40%), handling and low price (each 23%).

ISC<sub>3</sub> on the one hand works on key issues that are crucial to reaching the SDGs and on the other hand investigates the contribution made by the concept of sustainable chemistry.

Due to the enormous scale of this field and the variety of application areas of chemicals in all sectors of modern life, it is necessary to choose special areas of in-

terest when defining the concept of sustainable chemistry, which are mentioned in the 2030 Agenda (UN, 2015). After the identification of this specific issue, ISC<sub>3</sub> started a workstream for collaboration with external partners over a period of two years. This work was linked to other strategic tasks, namely innovation and research as well as education. In 2019, the main focus was on the construction and building sector, especially



**FIGURE 2**  
Distribution of global plastics production

In 2018, China was responsible for 30% of global plastics production.

Global plastics\* production: 359 million tonnes

\*Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP fibers. Not included: PET fibers, PA fibers and polyacryl fibers.

Source: PlasticsEurope Market Research Group (PEMRG) and Conversio Market & Strategy GmbH

highlighting the development of plastic materials and their use in buildings. Plastics production is increasing rapidly. In 2018, 359 million tonnes of plastic materials were produced worldwide. In that year, Asia was the largest producer and consumer of polymers, with 51% of total global production, followed by NAFTA (18%) and Europe (17%). 30% of plastics worldwide are manufactured in China (PlasticsEurope, 2019).

The political importance of the building and construction sector for global development is illustrated, for example, by the 2030 Agenda. Sustainable cities and settlements are the aim of SDG 11 (see overview of SDG 11 targets in **Infobox 1**). More than half the world's population now lives in urban areas. By 2050 that figure will have risen to 6.5 billion people. Sustainable development cannot be achieved without significantly transforming the way of building and managing urban spaces. Enormous investment in new buildings and the renovation of existing buildings is therefore necessary in order to achieve 'adequate and affordable housing' (SDG 11.1). Enormous resources are needed for the construction and maintenance of buildings in order to ensure adequate housing for an increasing number of people. This trend is triggered not only by a growing population, especially in developing countries, but also by a rural exodus that accelerates urbanisation. Due to the enormous amount of resources and energy, which are needed not only in the construction phase but also for heating, cooling and many other functions, as well as for maintenance and renovation, SDG 11 is linked to other SDGs:

- 'Clean water and sanitation' (SDG 6) mean 'safe and affordable drinking water' (SDG 6.1) and 'access to adequate and equitable sanitation and hygiene' (SDG 6.2), i.e. durable, safe and clean pipes for water and waste water in buildings.

- 'Good health and well-being' (SDG 3) also mean the reduction of 'the number of deaths and illnesses from hazardous chemicals'. Moreover, SDG 12.4 aims at 'the environmentally sound management of chemicals and all wastes throughout their life cycle', i.e. safe handling of chemicals by construction workers and craftsmen and also healthy indoor air that is not affected by chemicals released from building materials over time.
- The intention is to double 'the global rate of improvement in energy efficiency' by 2030 (SDG 7.3). This is in line with SDG 13.2, which targets the integration of climate change measures into national policies, strategies and planning. Energy consumption in the building sector is rising continuously due to population growth, more time spent indoors, increased demand for building functions and indoor environmental quality, and more air conditioning systems as a result of climate change. 'Building energy use currently accounts for over 40% of total primary energy consumption in the U.S. and E.U.' (Xiadong et al., 2016). For the construction sector, efficient heating and cooling systems for houses, including far better insulation of walls and roofs, are urgently needed.
- SDG 12.2 calls for 'sustainable management and efficient use of natural resources' and presents two groups of indicators, namely material footprint and domestic material consumption. Resources for the construction of buildings include traditional materials (e.g. bricks, wood), but in particular an increasing amount of concrete. In most countries, construction and building are the source for the largest material streams.

#### **Target 11.1: Safe and affordable housing**

UN definition: By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.

#### **Target 11.2: Affordable and sustainable transport systems**

UN definition: By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons.

#### **Target 11.3: Inclusive and sustainable urbanisation**

UN definition: By 2030, enhance inclusive and sustainable urbanisation and capacity for participatory, integrated and sustainable human settlement planning and management in all countries.

#### **INFOBOX 1:**

In what areas do the targets of SDG 11 aim to transform our world?

**Target 11.4: Protect the world's cultural and natural heritage**

UN definition: Strengthen efforts to protect and safeguard the world's cultural and natural heritage.

**Target 11.5: Reduce the adverse effects of natural disasters**

UN definition: By 2030, significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.

**Target 11.6: Reduce the environmental impacts of cities**

UN definition: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.

**Target 11.7: Provide access to safe and inclusive green and public spaces**

UN definition: By 2030, provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities.

**Target 11.A: Strong national and regional development planning**

UN definition: Support positive economic, social and environmental links between urban, peri-urban and rural areas by strengthening national and regional development planning.

**Target 11.B: Implement policies for inclusion, resource efficiency and disaster risk reduction**

UN definition: By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015–2030, holistic disaster risk management at all levels.

**Target 11.C: Support least developed countries in sustainable and resilient building**

UN definition: Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilising local materials.

## 1.2 Main megatrends in construction

Rapid urbanisation is a major challenge with respect to SDG 11.1: 'By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.' This also means the need for infrastructure (SDG 9.1) and supply of clean water, availability of drainage and waste management. Today, about 3.5 billion people live in cities, and 5 billion people are projected to live in cities by 2030. 95% of urban expansion in the next decades will take place in developing countries. The proportion of the global urban population living in slums has fallen from 46 to 23% since 1990, but today about 880 million people still live in slum areas (UN, 2016). Urbanisation, population growth especially in Africa and Asia as well as rising demand for living space in wealthy countries are leading to an enormous consumption of building materials. Concrete is already the second most used material after water. In some areas of the world, sand is running short, and the over-

exploitation of sand on riverbanks damages nature severely (Bendixen et al., 2019). The production especially of cement, but also of other building materials such as bricks, steel and aluminium, is energy-intensive. Global greenhouse gas emissions from cement production amount to about 500 million tonnes per year. Urbanisation therefore also poses a resource and a climate problem and thus also affects SDG 12.2 and 13.

The construction of resilient houses should be affordable, but this also applies to the costs during the use phase of the building, and this period should be as long as possible. Sustainable building materials should therefore be durable and require as little energy as possible during production. Buildings should consume as little energy as possible for heating and cooling during the use phase. Of course, the materials used in construction should not endanger the health of construc-

tion workers or residents, thus taking SDG 12.4 into account. Occupational health problems and health hazards for residents caused by construction chemicals are classified as an 'emerging policy issue' by SAICM (Strategic Approach to International Chemicals Management). Moreover, the amount of waste on the one hand and the proportion of recycled materials used for a new construction project on the other are of interest in terms of resource conservation and waste minimisation, i.e. SDG 12.5. If the selection of building materials is to contribute to sustainable living and working, the following criteria must therefore be considered: functionality, affordability, resource conservation, energy consumption, GHG (greenhouse gas) emissions, longevity, health issues, waste minimisation and recycling.

Although buildings are mainly mineral-based, the use of plastic materials for specific components and purposes has increased rapidly over about the last 50 years. The consumption of concrete in Western Europe (2010)

amounts to 530 million tonnes compared to 9.5 million tonnes of polymers (Diogo, 2015). The term 'plastics' covers polymers such as PE, PP, PVC, PUR, EPS and also some more expensive materials such as PMMA. Because the properties of polymers can be adapted to the respective application by means of additives or compounds with other polymers, a vast range of materials is available on the market. In this paper, we aim to lead the reader through all the considerations that need to be taken when using polymers in building and living. We therefore look at the aspects of health, environment, resource management, resilience, affordability, etc. This should empower readers to decide under which circumstances polymers are considered sustainable building materials and which products can by no means be described as sustainable. Since the availability of resources for building materials varies from region to region, these recommendations cannot be uniform, but instead are differentiated according to the prevailing circumstances.

GlobalABC stakeholders have the common goal of achieving low-carbon, energy-efficient and resilient buildings: countries, communities and industries commit to net zero carbon buildings. Three specific roadmaps for Africa, Asia and Latin America have been published with the aim of supporting national strategies and policies, such as NDCs<sup>1</sup>. Eight activity fields were defined: urban planning, new buildings, existing buildings, building operations, appliances and systems, materials, resilience and clean energy, for each of which key actions, policies, technologies and targets up until 2050 are proposed (see Figure A in Annex B).

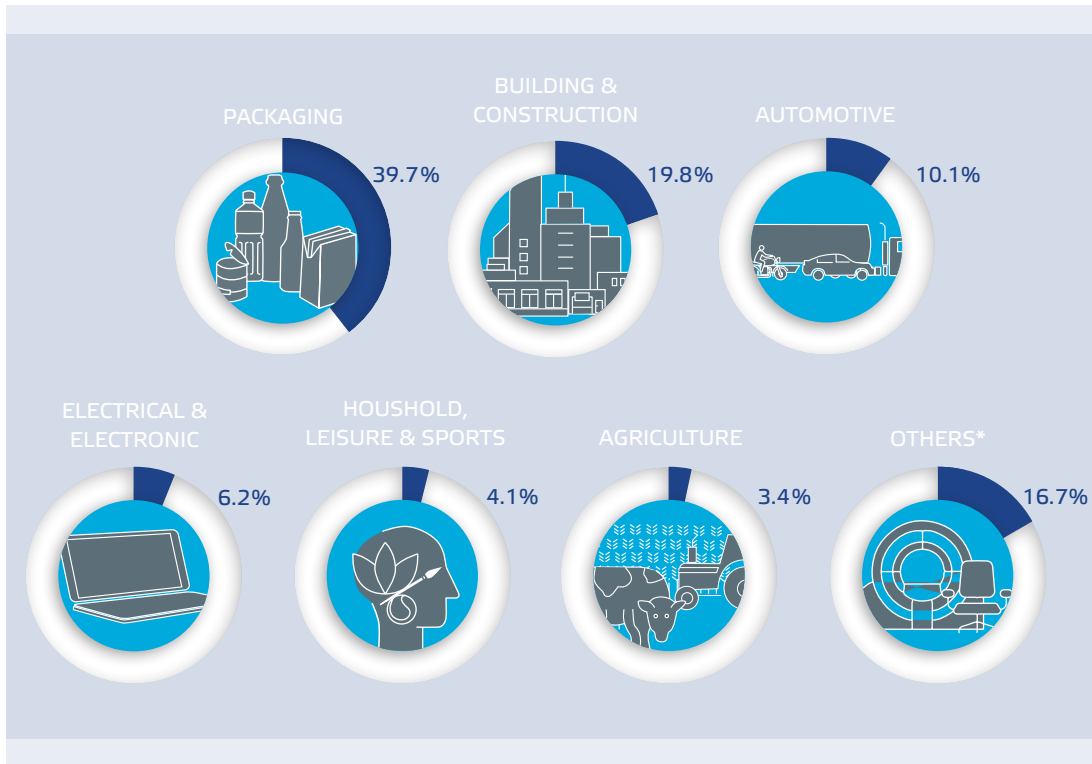
**INFOBOX 2:**  
Global Alliance  
for Buildings and  
Construction  
(GlobalABC)

## 1.3 Share of plastics in buildings

As outlined above, polymers can solve many technical problems in the construction sector. With the exception of waste from the construction phase, products remain in the building normally as long as the building exists. Polymers are persistent, but many plastic products age under the influence of higher temperatures, sunlight, high humidity, etc., leading to embrittlement or fading and also to loss of functionality. This is especially true for soft plastic products. It may therefore be necessary to replace plastic products after a certain period of time, e.g. carpets, sealers, façade elements – this has to be taken into account in life cycle calculations.

The current 'plastics issue' is largely influenced by the problems with plastic waste in the environment, especially rivers and oceans. Soils are also a very important sink for plastic particles – something which is probably underestimated at present. These plastic particles mostly stem from packaging, single-use products in general, fishing equipment and tyre abrasion. At this moment in time, the significance of plastic waste from the construction sector for such pollution appears to be limited. The amount of plastic waste from buildings will increase steeply in future as can be seen in European statistics (Figure 3). Europe uses almost 52 million tonnes of plastic per year, of which 19.8% for the construction sector. There are similar figures for the US market, where about 16% of all polymers produced are used for construction (ACC, 2019). In Europe, 26 million tonnes of plastic waste currently have to be managed, of which about 5% are from construction and demo-

<sup>1</sup> Nationally Determined Contributions



**FIGURE 3**  
Distribution of European (EU28+NO/CH) plastic converter by segment in 2017 (in Mt)

Total converter demand 51.2 Mt

Use of plastics in different areas and percentage of plastic waste from these applications.

\* medical equipment, plastic furniture and furniture equipment, technical parts used for mechanical engineering or machine-building, etc..

Source: Graphics compiled from PlasticsEurope, 2018

lition (PlasticsEurope, 2012; European Commission, 2018). The difference can be found in durable products that are still in use in buildings. Obviously, all these materials will become waste, maybe in 10, 20 or 40 years. But we must be prepared.

In **Table 1**, figures from several countries are presented, which give an impression of the importance of the use of plastic materials in the construction sector. The data indicate that the quantity of plastic materials used in the construction sector correlates approximately with GDP (Gross Domestic Product). The proportion of

plastic consumption in the construction industry in relation to overall plastic consumption does not vary significantly. However, it can be assumed that these data do not include the indoor use of plastics, e.g. for furniture, wallpaper, etc. **Table 2** shows the main plastic fractions used in various building and housing materials.

According to fairly early studies by Dietz et al. (1955), plastics have a very wide range of physical properties that is comparable to the physical property range of metals and exceeds that of timber and concrete. Thus, through new formulations and by adopting innova-

Country	Inhabitants	Plastics consumption [kt]	Plastics consumption overall/for construction [kg/inh x yr]		Consumption in the construction industry
France	64.275m	4,180	65.0	12.8	19.70%
Saudi Arabia	31.386m	2,942	93.7	18.1	19.30%
Tunisia	11.110m	0,287	25.8	4.6	18.00%
Kenya	44.226m	0,362	6.2	1.3	21.10%
USA	321.601m	30,162	93.8	17.4	18.50%
Colombia	48.203m	1,144	23.7	4.8	20.10%
Brazil	204.451m	6,314	30.9	6.0	19.40%
Japan	126.926m	8,348	65.8	11.3	17.20%
China	1,374.620m	79,595	57.9	13.3	23.00%
Malaysia	30.996m	2,327	75.1	12.8	17.10%
Indonesia	255.462m	4,377	17.1	2.8	16.10%
Vietnam	91.678m	3,237	35.3	6.6	18.60%

**TABLE 1:**  
Use of plastic materials in the construction sector in several countries in 2015  
Source: EUROMAP, 2016

tions, plastics' potential can be improved and enhance the economic performance, efficiency and life span of conventional building materials and facilitate affordable housing. When using plastic building materials, the chemical composition and structure of polymer materials are exposed to a multitude of changes due to the combination of heat, oxygen, water, light, microorganisms, chemical media and other environmental factors. Physical properties will become correspondingly poor, e.g. hard, sticky, brittle, discoloured or loss of strength. These changes and phenomena are called aging. For example, the aging life of ABS plastic products in indoor applications can be ten years, outdoors it can be five years at most.

The following innovations are needed in order to save energy and master the consequences of urbanisation and climate change, but they must also be compatible with health:

- Decreasing energy consumption in the life cycle, i.e. construction, use phase and demolition
- Reduction of overall material demand, use of regional building materials preferred
- Longevity of the building construction, higher stability against natural disasters
- Flexibility in the use phase, i.e. potential for different types of use

- Affordable housing especially for low-income groups and substitution of slum dwellings
- Ensuring the potential of dismantling and recycling at the end of the building's use phase

	Material	Kilotonnes	Total
Tubing/conduits	PVC	1.329	1.922
	HDPE	0.341	
	PP	0.121	
	LDPE	0.088	
	ABS	0.013	
Insulation	PU	0.464	1.044
	EPS	0.440	
	XPS	0.140	
Floors/walls	PVC	0.343	0.343
Window and door frames, windows	PVC	0.600	0.600
	Profiles	PVC	
Carpets, rugs	PE	0.156	0.266
	PVC	0.110	
Furniture	PS	0,156	0.425
	UP	0.085	
	PC	0.075	
	PMMA	0.070	
	Amino	0.020	
	PA	0.025	
	POM	0.004	
Total			4.890

**TABLE 2:** Main uses of plastic materials in the European building and construction sector  
Source: Diogo, 2014

In order to gain an impression of the development and potential of plastic materials in the construction sector, we can look at cities or buildings that are considered particularly innovative. Masdar City in Abu Dhabi (home to the headquarters of the International Renewable Energy Agency (IRENA)) was designed to be pedestrian and bicycle-friendly. 'The temperature in the streets is generally 15 to 20°C cooler than the surrounding desert. The temperature difference is due to Masdar's unique construction. A 45-metre-high wind tower sucks air from above and pushes a cooling breeze through Masdar's streets. The site is raised above the surrounding land to create a slight cooling effect. Buildings are clustered close together to create streets and walkways shielded from the sun.' (Wikipedia). The city of Masdar, is 'pioneering the future of sustainability' with a focus on green energy, green buildings, etc. 'Buildings in Masdar are eco-building prototypes, combining energy efficiency and construction economy with leading-edge design adapted for a subtropical climate. The aim is to develop new solutions in the field of optimised-energy-consumption buildings through, for example, the use of plastics. Smart, giant parasols, 'corridors' running through the city for natural ventilation; laboratories and offices of concrete covered with large plastic cushions (ETFE – ethylene tetrafluoroethylene copolymer) which reflect the sun's rays and lessen their effects; roofs of plastic and photovoltaic panels... Among other materials, polystyrene foam is used for optimum thermal insulation of buildings. Polyurethane, for example, makes it possible to insulate cool air intakes, ensuring maximum efficiency, while microscopic plastic capsules filled with wax are incorporated into the plaster or concrete, absorbing excess internal heat through phase-change processes.' (PlasticsEurope, 2012). It remains open which of these innovations point in the direction of sustainability.

**INFOBOX 3:** What are the drivers for innovations such as sustainable materials?



At present, innovations in construction focus mainly on:

- Decreasing energy consumption either by suitable construction or better insulation
- Energy production integrated in the building (e.g. solar energy, functional walls)
- Lightweight buildings to reduce overall material demand
- Higher convenience with respect to living temperature, ventilation, heating, cooling, etc.
- Efficient transport of residents and goods as well as collection of waste within large buildings
- Cutting costs

These driving forces are in part consistent with the above objectives resulting from the SDGs, but there are also some contradictory developments, which will be discussed in the next chapters.

Innovations are very often based on modifications of classical resources for construction and on newly developed materials. Plastic materials with their enormous variety of tailor-made properties are increasingly important for meeting new demands:

- Modification of macromolecules within their molecular structure in order to achieve higher flexibility, rigidity, durability, etc. (see Table 3)
- Addition of certain chemicals to support specific functions (heat-resistant, flame-retardant, insulating)
- Combination with other materials (e.g. wood) or other plastics (e.g. polyester fibres) to produce composites

In this report, a number of examples of plastics applications are presented which contribute to one or more of the drivers described above.

Additive/Filter/Reinforcement	Common materials	Effects on polymer properties
Reinforcing fibers	Baron, carbon, fibrous minerals, glass, <i>Kevlar</i>	<ul style="list-style-type: none"> <li>■ Increases tensile strength;</li> <li>■ Increases flexural modulus;</li> <li>■ Increases heat-deflection temperature (HDT);</li> <li>■ Resists shrinkage and warpage;</li> </ul>
Conductives fillers	Aluminium powders, carbon fiber, graphite	<ul style="list-style-type: none"> <li>■ Improves electrical and thermal conductivity;</li> </ul>
Coupling agents	Silanes, titanates	<ul style="list-style-type: none"> <li>■ Improves interface bonding between polymer matrix and the fibers;</li> </ul>
Flame retardants	Chlorine, bromine, phosphorous, metallic salts	<ul style="list-style-type: none"> <li>■ Reduces the occurrence and spread of combustion;</li> </ul>
Extender fillers	Calcium carbonate, silica, clay	<ul style="list-style-type: none"> <li>■ Reduces materials cost;</li> </ul>
Plastisizers	Monomeric liquids, low-molecular-weight materials	<ul style="list-style-type: none"> <li>■ Improves melt flow properties;</li> <li>■ Enhances flexibility;</li> </ul>
Colorants (pigments and dyes)	Metal oxides chromates, carbon blacks	<ul style="list-style-type: none"> <li>■ Provides colorfastness;</li> <li>■ Protects from thermal and UV degradation (with carbon blacks);</li> </ul>
Blowing agents	Gas, azo compounds, hydrazine derivatives	<ul style="list-style-type: none"> <li>■ Generates a cellular form to obtain a low-density material.</li> </ul>

**TABLE 3:** Additives in plastics to improve properties, performance and durability  
Source: Santa Clara University, 2020

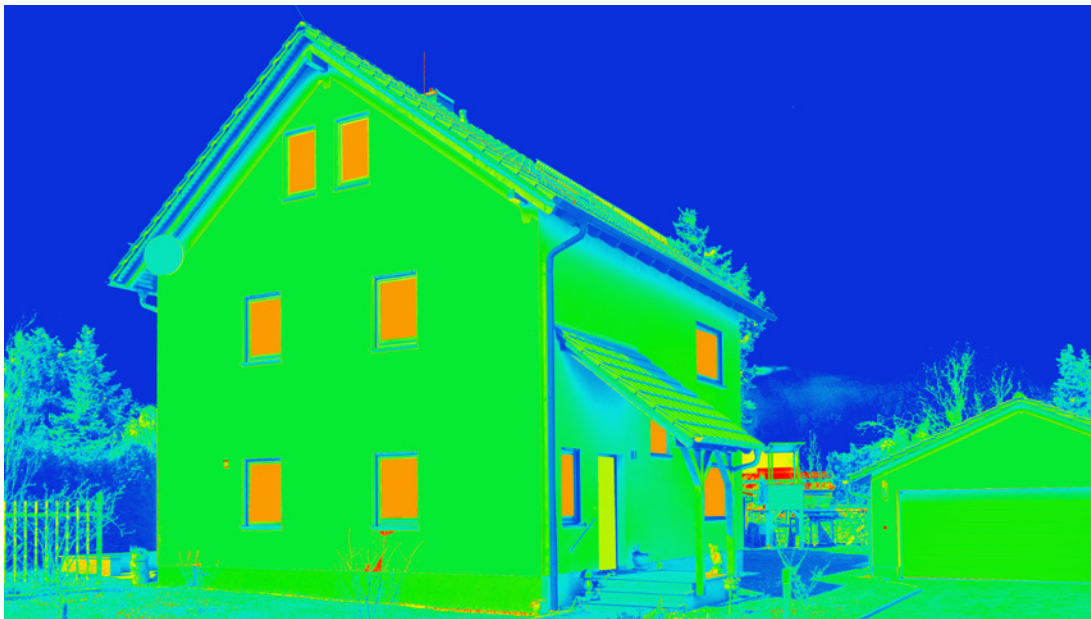
## 1.4 Can plastics decrease energy consumption in buildings?

In Europe (EU-27 and the United Kingdom), 25.4% of the final energy demand can be attributed to heating, cooling and power supply for households (EuroStat, 2018). According to the International Energy Agency (IEA, 2020), residential and service-sector buildings ac-

counted worldwide for 21% and 8% of final energy consumption, respectively. These few figures underline the enormous influence of the building sector on energy consumption and climate. Renovation of building stock and minimisation of the energy consumption of new buildings are an enormous challenge. Plastics are often used for the insulation of walls, roofs and ceilings, normally in the form of foam (EPS, XPS) or sprayed in place (PUR). In the case of concrete walls, rigid boards made of XPS, EPS or PUR are often additionally installed. EPS and XPS have very low specific weights and can be easily processed on site. Due to their high flammability, they must contain flame retardants as additives, many of which lead to health problems, **see Chapter 3** (European Commission, 2018). Some figures are presented in **Table 4**.

Material	Thickness [cm]	Heat transition [W/m <sup>2</sup> x K]
Concrete	25	3.3
Building bricks	24	1.5
Solid timber	20.5	0.5
Polystyrene foam	10	0.35
Aerated concrete blocks	36.5	0.18 – 0.23
Building bricks + PUR	17.5 + 12.5	0.32

**TABLE 4:** Heat transition of various building materials; solutions based on plastic materials are marked. Data taken from <https://de.wikipedia.org/wiki/Wärmedurchgangskoeffizient>



Thermographic image showing heat leakages in a building.

Photovoltaic (PV) modules are normally placed on roofs. There is considerable interest in integrating PV cells in walls (e.g. of skyscrapers) to make more surface area available. Modules should be as light as possible in order to avoid massive structures. With respect to the module's frame, shifting from metal (mostly aluminium) to plastic decreases the weight and thus the cost for the required static load capacity. Dye-sensitised solar cells (DSSC) and organic solar cells (OSC) are low-cost alternatives to silicon solar cells with lower energy efficiency, but far lighter due to the use of thin films of plastic electrodes coated with photosensitive material. Phase change materials (PCM) are used to store energy in walls. The energy is retained/released during melting/solidification of the PCM. PCM are based on inorganic salts with large hydrate shells or on paraffin wax. Easy-to-handle PCM is microencapsulated in an acrylic polymer resin (Micronal® PCM). These developments will prove difficult regarding the demand for dismantlability and recyclability.

**INFOBOX 4:** Which materials are innovative in buildings?

## 1.5 Issues and questions

In this study, we focus on important sustainability drivers in the building and housing sector (with respect to the SDGs described above) and identify typical plastic products that are needed for such approaches (e.g. **Infobox 18** and the start-up initiatives introduced). In particular, this means products that have been introduced or further developed in the last ten years or are known as innovations in research or pilot studies. The tasks of ISC<sub>3</sub> are to:

- Act as a think tank and a central knowledge hub for sustainable chemistry and substitution of critical chemicals
- Link sustainable chemistry and SDGs
- Support emerging and developing countries in questions concerned with the safe handling of chemicals (Friege et al., 2017).

The links between different SDGs and more or less sustainable technical solutions in the building sector, the role of potentially hazardous chemicals and their substitution and the transfer of good practice from industrialised to developing countries are of special interest. Due to time restrictions, only a limited number of (potentially not always representative) examples are included in the study. From the evaluation of the information and data collected, we then pose some key questions and recommend strategic pathways which could help ISC<sub>3</sub> to define sustainable chemistry practice for the building sector, thus enabling it, alongside international organisations (e.g. UNEP) and national governmental bodies, to integrate the SDGs in a holistic approach with respect to chemicals as ingredients of materials for building and construction. The use of polymers in construction and buildings offers opportunities with respect to the SDGs but also risks. The following questions will be addressed in these guidelines:

- How can sustainable chemistry contribute to making buildings sustainable? (**see examples in Infobox 4**)
- How can we drive construction products towards sustainability in the sense of the SDGs? (**Chapter 4.1 – 4.3**)
- What are the most relevant innovations and potentials for sustainable chemistry in the area of building, living and plastics? (**Chapter 3.6, 4.4, 4.6 and Annex A**)
- What hidden costs are there in building's life cycle? (**Chapter 2.3**)
- How can energy be saved and greenhouse gas emissions avoided? (**Chapter 4.1 and 4.2**)
- What does recycling mean for buildings? How can the consumption of resources in the building industry be reduced? (**Chapter 4.4 and 4.5**)
- What about hazardous additives? How can these substances be substituted? How can we ensure that exposures and releases are kept as low as possible? (**Chapter 3.2, 3.3, Infobox 15 and 16**)
- How can we address the growing demand for energy-efficient houses, e.g. better insulation materials, but also new solutions, e.g. 'cool roof', 'phase change walls'? (**Chapter 4.4 and 4.5**)
- How can sustainable solutions in developing countries be created that are based on 'resilient buildings utilising local materials'? (**Chapter 2.3 and 2.4**)

Sustainable chemistry contributes to a long-term positive development in society, environment and economy. Through new approaches and technologies, it develops value-creating products and services for the needs of civil society. Sustainable chemistry increasingly uses substances, materials and processes with the least possible adverse effects. Moreover, substitutes, alternative processes and recycling concepts are used and natural resources preserved. Damage and impairments to humans, ecosystems and resources are thus avoided. Sustainable chemistry is based on a holistic approach, setting measurable objectives for a continuous process of change. Scientific research and education for sustainable development in schools and vocational training serve as an important basis for this (Blum et al., 2017).

**INFOBOX 5:**  
What is sustainable chemistry?





# 2. Urbanisation, Affordable Housing & Resilience

Professor Andreas Gerdes

Amy Jones

Joern Meyer

Esther Moltie

Ruth Onkangi

Xiaodong Rong

Pourya Salehi

## 2.1 Megatrends (Joern Meyer, Esther Moltie)



### ONLINE SURVEYS WITH EXPERTS (see Annex A):

Plastics score with their performance (40%), handling and low price (each 23%) but are criticised for pollution and recycling issues (60%).

In 2050, almost ten billion people are expected to inhabit the globe. More than two thirds of them will live in urban areas. This surge in urbanisation is taking place almost exclusively in Africa and Asia. What has developed in Europe over centuries is taking place on these continents within a few decades. Rapid urban growth also means that by 2030 there will be more than 40 megacities with over ten million inhabitants. However, urbanisation will be most drastic in small and medium-sized cities (population under 500,000), where already half the urban population currently lives. However, these cities in particular lack the resources and qualified personnel needed to use the existing potential for shaping the future on the one hand and to master the major challenges and meet the enormous financing requirements on the other. In global terms, about half of urban growth will result from population growth, while the other half will be due to migration from rural areas.

With its own goal (SDG 11) within the 2030 Agenda of inclusive, safe, resilient and sustainable cities and settlements, the international community has recognised the importance of cities and local actors. They are key to sustainable development. However, cities also play a central role beyond SDG 11: two thirds of all Sustainable Development Goals can only be achieved in and

with cities. Urban development encompasses practically all areas of life, and urbanisation unleashes considerable transformational power. Interactions between the various sectors can be better identified and addressed in urban space. However, cities are important not only for human development but also for successful climate protection. On the one hand, cities are responsible for 75% of global energy-related greenhouse gas emissions. On the other hand, they are particularly vulnerable to the effects of climate change and its negative impacts.

Cities therefore need to improve their resilience, i.e. their ability to adapt and resist the effects of climate change and other natural disasters in a poverty-oriented and inclusive way. To this end, the infrastructure for basic services such as water supply and energy, transport and housing must be adapted to the challenges of climate change. Social security systems and new financing instruments, such as climate risk insurance, also contribute to the resilience of a city. It is important that particularly vulnerable population groups are involved in decision-making and planning processes for the implementation of resilience strategies. Measures to increase resilience, such as the construction of dams, must not be at the expense of the poorest, e.g. in the form of forced resettlement.



## Are there any links between urbanisation, sustainable construction and building materials?

Rapid urbanisation results in massive demand and an increase in formal and informal building activities. In a nutshell, we will have to build as much in the next 30 years as in the 3,000 years of human history before. In Africa alone, where 500 million additional urban dwellers will live by 2050, around 130 cities the size of Berlin will have to be built within 30 years. Today, the building and construction sector already accounts for nearly 40% percent of total energy-related emissions and 36% of final energy use worldwide. Population growth as well as a rapid increase in purchasing power in emerging economies and developing countries mean that energy demand in buildings could increase by 50% by 2060.

However, the complete life cycle of buildings and especially the question of using more sustainable construction materials are often not addressed. After 50 years

of usage, the emissions produced before a building is completed is about double the amount compared to emissions caused by the actual running of the building. The global use of concrete has multiplied 25 times since 1950. At the same time, locally available, traditional or renewable materials, such as clay, stones, fire bricks, bamboo or wood, have been largely replaced by concrete, aluminium and steel. Conventional building materials in cities are responsible for as much as three quarters of the CO<sub>2</sub> budget for the 1.5°C goal (European Commission, 2015).

Using more sustainable materials in the construction industry is therefore essential for the future reduction of greenhouse gas emissions. Only by addressing the sustainability aspects of all available materials – conventional and renewables – as well as recycling building materials, can the global climate goals be realised.

## 2.2 Status quo of plastics in construction (Xiaodong Rong)

Use of polymers is popular because of their light specific weight compared to conventional materials such as bricks or concrete. This enables the architect to design and build lighter structures, partially with improved performance. Due to their easy deformability (moulding and shaping) by heating at relatively low temperatures (between 50 and 250 °C), energy consumption is also lower compared to the processing of metals or ceramics.

The overall consumption of plastics in Europe in 2017 was more than 50 million tonnes per year (EU-28 + Norway and Switzerland) (see Figure 3). About 20% of all plastics are used in the building and construction sector. In Germany, 22.7% of plastics demand is connected to building and construction (Consultic, 2016). In this sector, PVC (window frames, pipes) is the most important polymer followed by PE-HD and PP (pipes, miscellaneous), PS and PUR (insulation, furniture). Plastic materials are mainly used for window and door frames, window blinds, gas, water and sewage systems, insulating material for electrical cables, bathroom and sanitary equipment, thermal insulation, skylights, flooring or coatings for flooring, impermeable coatings and covers for swimming pools, roofs, etc. More ad-

vanced plastic materials have only a small market share by mass but are of increasing importance. 'Engineering plastics' are materials that exhibit improved properties, such as mechanical strength, heat resistance, chemical stability and dimensional stability, compared to commodity plastics. These include polybutylene tere-



In 2018, over 7 million tonnes of polyvinyl chloride (PVC) were used worldwide for the production of sewage pipes.



phthalate (PBT), aliphatic polyamides (PA), polymethyl methacrylate (PMMA), polyurethane (PUR) and polytetrafluoroethylene (PTFE, Teflon), among others.

Plastic building materials are also a 'rising star' in the building materials industry worldwide. With the rapid growth of the global real estate sector and increasing investments in infrastructure, the plastic building materials industry has become the second pillar in the plastics industry after packaging. The plastic building materials industry has accelerated the pace of research and development and encouraged applications, the scale of production in the industry continues to expand, the level of technology has steadily improved, and especially plastic profiles and pipes are experiencing mature and stable growth.

Plastic building materials are becoming more and more widespread as building materials, following the ones currently most used, i.e. steel, wood and cement. At present, global construction plastic production exceeds 15 million tonnes per year, accounting for more than 35% of total plastic production. The proportion of PVC

applications worldwide is roughly as follows: construction plastic products (mainly used for water pipes, drainage pipes, etc.) accounted for 65%, packaging 8%, electrical and electronic 7%, furniture and decoration 5%, general consumption 4%, other 1.1%.

Construction plastics are also widely used in waterproof materials, such as thin film materials, coatings and seam materials, adhesive materials, insulation materials such as insulation sandwich components and sandwich plates. Construction materials are composite foam splints, lightweight materials such as plastic bricks, floors, roofs and other large-scale components. In construction projects, plastic products continue to replace metal products, mainly for pipes, roofing materials, doors and windows as well as outside decoration. Production of and demand for waterproof insulation materials are increasing. The wide application of building plastics can reduce the weight of the structure, facilitate the use of modern construction methods, improve the quality and durability of the building. It can be said that plastics have become important building materials alongside concrete, steel, wood, etc.

A new UK study shows that waste plastic can replace sand in concrete. Research from the University of Bath has demonstrated that some of the sand used in concrete can be substituted with waste plastic. The study, conducted in cooperation with Goa Engineering College, India, was prompted by India's booming construction sector, which is leading to a continuing sand shortage in the country as a result. It is estimated that over 20 billion tons of concrete are produced worldwide each year, making it the world's second most used substance after fresh water. Sand typically makes up 30% of any concrete mixture. By replacing 10% of that sand with finely ground plastic particles, the Bath team estimates that over 800 million tons of sand could be saved (Thorneycroft et al., 2018).

**INFOBOX 6:**  
Could plastics (from waste) replace sand as a rare material?

## The special situation in China

Plastic building materials can not only replace steel and wood and therefore preserve these resources but also have the advantages of saving energy, protecting the ecological environment, improving building function and quality, reducing building weight, etc. Plastic building materials are used very widely in construction, municipal engineering and industrial construction. Their energy-saving properties are good. Construction plastic products need only 20% of the energy consumption of steel and 10% of that of aluminium. In addition, energy consumption in the production of hard PVC products is only 30 to 50% of that of cast iron and steel pipes and PVC can be recycled several times.

Compared with metal pipes, plastic water supply and drainage pipes can improve water supply capacity by

about 20%, and construction efficiency can be increased to 60%. PVC water supply and drainage pipes have been laid in more than 20 provinces and autonomous regions in China. Plastic slot line pipes have also been widely used in residential areas, high-density PE gas pipes and indoor water supply pipes are also being used on a pilot scale. There are also many examples of applications of plastic pipes in agricultural irrigation and drainage, chemical plants, mining construction and other projects. Plastic doors and windows have excellent sealing properties and are resistant to corrosion, making them particularly suitable for buildings and industrial plants in cold regions and coastal areas, since they require little or no maintenance and can thus save costs.

Thermoplastic elastomers are plastics which behave at room temperature in a similar way to classic elastomers but can be deformed when heat is applied and thus exhibit thermoplastic behaviour. Thermoplastics can be moulded at high temperatures and are elastic at room temperature. Thermoplastic elastomers are polymeric materials with similar mechanical and use properties as rubber and can be processed and recycled like thermoplastics. Thermoplastic elastomers replace the vulcanisation process of traditional rubber, can be used in the same way as plastic injection pressure, extrusion, blow moulding, and other methods of processing. The advantages are: relatively simple process operation, high production efficiency, short moulding cycle, cost savings, possibility to reuse processing additives and side materials, conduciveness to environmental protection with specific properties such as light weight and high product size accuracy.

**INFOBOX 7:**  
What are the characteristics of thermoplastic elastomers?

## 2.3 Affordability and sustainability of plastics – an African perspective (Ruth Onkangi)



### ONLINE SURVEYS WITH EXPERTS (see Annex A):

For low-income groups, natural (59%) and waste-sourced (48%) materials are rated as affordable and resilient. Plastics, especially compounds, remained far behind and met with a mixed opinion in the survey.

There are numerous mega innovations poised to disrupt the construction industry, these being artificial intelligence (AI), robotics, digital construction, 3D printing and drones. Many of these are gaining traction in the Global North but currently not within reach for many emerging economies due to affordability as well as an absence of policies, building codes and standards to guide their adoption and use. Developing countries have development goals and targets that include five to six-digit figures for building miles of infrastructure and high numbers of affordable houses. The realisation of these goals, coupled with population explosion, brings about an expanding urban fabric and an enormous ecological footprint. Rapid, uncontrolled development consequently leaves developing countries grappling with two problems: providing more affordable and quality housing and infrastructure for citizens and battling environmental degradation. Poor solid waste management (more so plastic waste) and poor waste water management is a shared problem. Nonetheless, here lies a solution hidden in plain sight.

In the coming decades, 90% of urbanisation will be in developing and emerging countries, especially in Africa and Asia. The number of African cities will triple by 2050 due to demographic development and urbanisation. Affordable housing is among the key factors for sustainable development. In line with SDG 11 of the 2030 Agenda, 'affordable housing' is defined in SDG 11.1., 11.5. and 11.c. (see Infobox 1).

In addition, SDG 11 lists public transport, open spaces, resilience, resource consumption, etc. Besides the serious lack of adequate living space, there is a lack of reliable infrastructure. SDG 6 should therefore be included, which focuses on access to safe and affordable drinking water and safely managed sanitation services for all. As outlined above, the enormous energy consumption and mass flows in construction and housing drive climate change.

## The special situation in Kenya

Infrastructure advancement is a key economic growth driver, indicator and priority area for both the national and county governments in Kenya. Construction is intricately linked to various sectors of the economy and social wellness, thus greatly fostering the country's prosperity and development. The 2019 Economic Survey by the Kenya National Bureau of Statistics (KNBS) reports that the construction sector recorded a slower growth of 6.6% in 2018 compared to 8.5% growth in 2017. Cement consumption increased by 1.6% in 2018. The length of paved road as of June 2018 was 18,655 km compared to 17,033.9 km in June 2017. Loans and advances to the sector increased by 1.8% to KSh 114.0 billion (USD 1.06 billion) in 2018 (KNBS, 2019).

Kenya's per capita income is also improving, with the country earning itself a low middle income status in the recent past. With better livelihood come a corresponding increase in consumption and accordingly the demand for better quality infrastructure. The quality of infrastructure (future and retrofitted) should therefore be in line with contemporary standards in order to offer world-class service, while decoupling environmental degradation from economic growth. This can be achieved by using technologies that enhance performance and efficiency in the construction and maintenance of buildings and infrastructure. These technologies are being constantly improved and introduced into the market at better rates than before. Kenya depends to 40% on its natural capital. More development without responsible consumption and production means rapid depletion of natural resources, more solid and liquid waste and slower economic growth. There is a need to embrace the use of suitable plastic construction materials as a sustainable, win-win solution.

Plastics have been used for a long time in Kenya in low-volume applications, such as piping, cladding, films, panels, adhesives, foams, exterior and interior coverings in building and construction (see Chapter 1, Table 1). Steel and concrete are reserved for the structure/building envelope, although bamboo (Ghavami, 2005) is making inroads globally – albeit minimal – and its strength is still less trusted despite thorough testing. The façades of many post-1990 buildings in Kenya are now mostly glass. Use of plastics in building and construction in Kenya is minimal. This is mainly due to negative perceptions and the immense faith placed in the 'knock test' for any building component (it is common practice in Kenya to knock hard on a building component to establish its strength). Plastics are not seen to pass this test. Building partitions are hence mostly made from mortar and stone, or in rare cases wood and metal. Use of wood, plastic and even metals (most-



ly iron sheets known locally as 'mabati') in partitions is seen by many as a sign of poverty.

Plastics are gradually being used in the interiors of buildings and less sophisticated plastic resins made from recycled material with sand are being used as roofing, fencing and paving materials, although uptake is very low. Some plastic building components were used in a few projects in Nairobi and proved a disappointment due to their low quality. As a result, many developers and building professionals have shied away from the use of plastics on a wide scale. Standards – such as the European CEN norms – for these components as alternative building materials and technologies are yet to be developed and adopted in Kenya. This has also influenced their low uptake. The current building code and county bylaws do not support the use of alternative materials such as stabilised soil blocks, clay bricks, interlocking bricks (in use countrywide) and plastics. Besides negative perception, quality, missing policy and standards, low awareness of plastics in construction has also contributed to the inertia in the wide-scale use of plastics in construction in Kenya.

Yet with a greater use of plastic, it would be possible to improve the efficiency, economic performance and life of conventional building materials. Jalaluddin (2017) established that 'by using plastic waste as modifier, we can reduce the quantity of cement and sand by their weight, hence decreasing the overall cost of construction'. Furthermore, at 5% optimum modifier content, the strength of modified concrete was seen to be greater than that of plain cement concrete (Jalaluddin, 2017). According to Kumar and Baskar (2017): 'The effect of adding the E-plastic (embracing plastic) in concrete reduced the dry density of the concrete and showed the high deformability behavior before failure.

Kibera, a neighbourhood of Nairobi, Kenya, is the biggest urban slum in Africa, with an estimated one million inhabitants.

The lesser dry density may be having advantage in self-weight reduction in structural elements which leads to lesser attraction of pseudo inertia forces in the seismic prone area.'

Perhaps 'embracing plastic' (adopting plastic use and deliberately using plastic as a material of choice) in construction will greatly support dematerialisation in an industry that has a large and unparalleled appetite for materials. This has yet to be proven by studies.

According to UNEP, 66% of infrastructure in developing countries is yet to be built. With national budgets having competing needs, such as healthcare provision or addressing food and water insecurity, governments can explore alternative, safe, affordable and ubiquitous materials. Plastic materials, especially recycled plastics, can play an even more important role in construction if they substitute energy-consuming alternatives and if they are recycled after use to avoid further contamination of the environment.

## How are the costs for plastics as building materials?

Compared to other basic materials for buildings, polymers are not cheap:

- Ready-mix concrete: about € 80 to 110/m<sup>3</sup> (~ 2.3 tons) or USD 95–130
- Construction timber: about € 200/m<sup>3</sup> (~ 0.75 tons) or USD 237
- Polyethylene (HDPE): about € 900/ton (granulate) or USD 1,065
- Polyvinylchloride (PVC): about € 500/ton (ground material) or USD 590

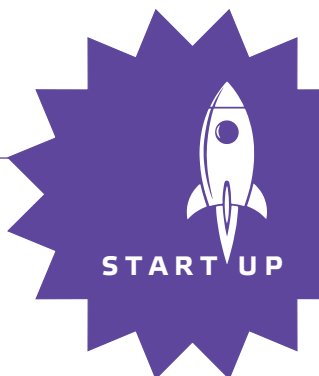
When plastics replace much heavier materials, the static requirements on the building and thus overall material demand are reduced. Using PP pipes for drainage instead of concrete or stoneware saves about 80–90% of the weight. Cable conduits made from PVC can substitute those made from metals. By means of additives,

mechanical strength and other properties of plastic materials can be varied relatively easily. With respect to the production and use phase, long-life plastic products can save money and resources, e.g. energy in the production phase. According to Kenya's National Construction Authority, tubes and conduits are the most important construction products made from plastics.

Normally, plastic materials cannot substitute materials which are important for a structure's static, such as concrete or bricks. Especially for low-budget houses or buildings, which are erected to serve as temporary homes for victims of earthquakes, etc., 'polymer concrete' is available. This is produced from sand or other granulated minerals, glass fibres and unsaturated polyester, which serves as a binder for the inorganic material after the curing process. In addition to the German factory, there is one plant in Namibia – the roll-out process is in progress (see company information in **Infobox 7**).

**Polycare produces polymer concrete components from desert sand and a special polyester resin as a binder made to 40% from recycled PET bottles. The components are designed like LEGO blocks. Polycare causes 60% less emissions.**

**PRO:** The blocks can be used by untrained personnel and substitute conventional polymer concrete, thus also serving as a recycling opportunity for PET waste. The product is inert and does not react with the environment, hence erodibility of plastic is mitigated. **CONTRA:** PET bottles can normally be recycled (bottle to bottle), but other types of PET waste should be tested. The technology produces building blocks only. It is not clear how low the embodied energy is. **RECOMMENDATION:** In comparison to conventional polymer concrete, it is a simple and more sustainable alternative which is especially suitable for low-income countries. It is affordable and has a wide range of alternative components to desert sand.



## INFOBOX 8: What is affordability vs. real costs?

Affordable housing must be seen from a human rights' perspective and the three pillars of sustainability. There is a need to define affordability in relation to housing projects and the point where such a project is considered affordable. Affordability should not be limited to upfront project costs but also include both quantifiable and non-quantifiable latent costs. Limiting affordability to upfront project costs is acute short-termism. This leads to more severe consequences that are eventually borne by all (rich and poor) in society. Latent costs include the operating costs of the house, which are often omitted if affordable housing projects only focus on upfront costs. Operating costs for utilities throughout the project's life cycle are quantifiable. Upfront project costs are NOT the real costs. The costs associated with 'sick buildings', such as poor indoor environmental quality, poor thermal comfort, poor indoor air quality, poor solid and liquid waste management, water and energy inefficiencies, environmental degradation, poor human settlement planning, flooding, water insecurity and food insecurity, are unquantifiable and enormous. There is therefore a need to formulate a definition for affordable housing that is precise and comprehensive. This will also help define the roles of various stakeholders and counter short-termism. Affordable housing means low life cycle costs for housing. i.e. construction, operation and demolition.

If plastic replaces wood, e.g. as a floor covering, this has no static effect. Any cost savings depend on the regional raw material prices (timber vs. plastics) and labour costs. The labour-saving use of plastic products instead of traditional materials is an economic driver when labour costs are high, e.g. by using PUR foams for window installation. Use of recycled polymers for the production of construction materials can considerably decrease costs. In Europe, secondary polymers are not much cheaper – some polymers are even more expensive – than primary polymers, especially in the case of post-consumer waste due to the enormous effort required for sorting, cleaning and re-granulating. In countries with low labour costs, sorting specific plastic materials out of waste is cheap. Some construction products available on the market in developing countries therefore utilise large amounts of recycled plastic from other sectors, e.g. HDPE plastic bottles for use in plastic pipes. The sustainability of these attempts is discussed below.

To make the construction of dwellings as cost-effective as possible, UN-Habitat favours the use of domestic raw materials. Since the raw materials available differ from region to region and prices also vary, a comparison with the use of plastics can only be made at regional level. It is necessary to compare the costs of alternative choices fairly with regard to purchase price, repair susceptibility and durability.

Apart from in the Maghreb countries and South Africa (RSA), polymer production does not play any role at all in Africa. Raw materials are imported to African countries as well as most products made from plastics. The per capita consumption in Africa is about 16 kg per year (Babayemi, 2019, **see also Table 1**). By comparison, German consumption per inhabitant is about 140 kg including industrial products (Conversio, 2017). Consumption of plastic products is likely to be mainly

related to packaging, while the use of plastics in the construction sector will develop later, as has been experienced in other countries (Geyer et al., 2017). It can therefore be assumed that the consumption of plastic products in the construction sector in Africa is still below 20% of total consumption, i.e. below 3 kg per capita per year. If plastic products are used instead of very heavy materials (e.g. in the case of drinking water PE/PP pipes instead of cast iron, copper, stainless steel; in the case of waste water PVC or PP pipes instead of cast iron, stoneware, concrete), especially overall material demand but also costs can be reduced.

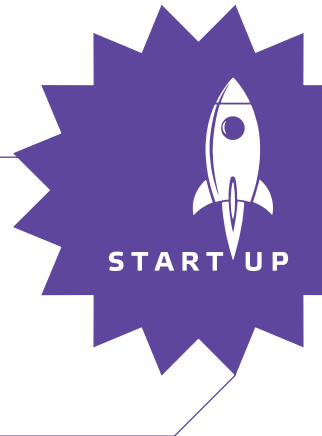
Some plastics could be possible for alternative building technologies in developing countries. In Kenya, they could be useful in 'leapfrogging', that is, for surpassing or overtaking barriers and risks in order to achieve and sustain high economic growth. They are affordable, ubiquitous and suitable to the climate in Kenya. Compared to existing alternatives such as interlocking bricks, stabilised soil blocks and clay bricks, plastics fair better because they last longer and do not disrupt topsoils or compete with food security. In addition, with only minimal adjustments, existing manufacturing apparatus can deliver plastic building materials and create more jobs. Clay bricks are made in Kenya by numerous entities, over 90% of which are informal. Sometimes the bricks are made on site or within the project locality. They are widely used in Kenya for construction because they are outside the current building code. Plastics are better, as they last longer, do not involve disrupting the topsoil and do not compete with food security. In addition, with only minimal adjustments, existing manufacturing equipment can produce plastic building materials and create more employment. The downside of plastics: at present, plastics from packaging, etc. are endangering the marine environment, rivers and perhaps also soils. If plastics could be recycled before entering the environment, this would be real progress.

An example of one important plastic construction product used in high volumes in Kenya is EPS panels (expanded polystyrene) for insulation. Pipes and conduits are made from PVC. EPS bonds well with concrete and mortar, plastering is also easier with EPS. EPS, as a type of foamed plastic, is being used increasingly in Kenya and manufactured at the National Housing Cor-

poration (NHC) factory in Mlolongo, Machakos County. NHC is a government agency. Recent fieldwork on alternative building materials and technologies in Kenya by the National Construction Authority (NCA) revealed the growing use of EPS in construction, mostly in the South Rift, lower Eastern and Central Kenya.

**GREEN PAVERS uses waste plastic, which has low or limited use, and recycles it to produce resin roofing tiles, manhole covers, plastic lumber planks and fence posts.**

The plastic is collected and delivered to special centres, where it is mechanically processed before being recycled.  
**PRO:** The company uses waste plastics as a resource thus providing workplaces for informal recyclers.  
**CONTRA:** The stability and recyclability of the tiles produced is not clear. **RECOMMENDATION:** GREEN PAVERS provide an interesting interim solution for plastic waste in developing countries.



## 2.4 Demands on building resilience (Andreas Gerdes, Amy Jones, Pourya Salehi)

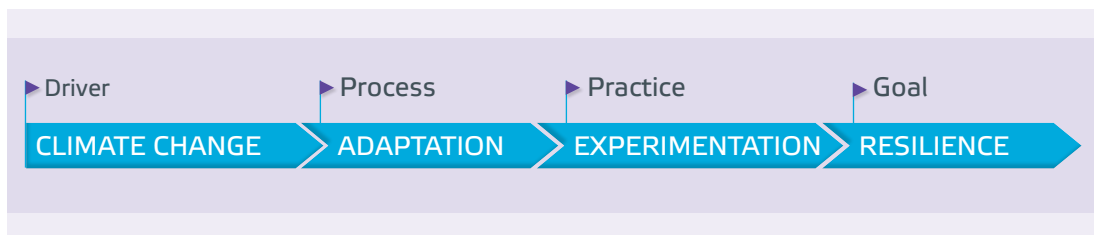


### ONLINE SURVEYS WITH EXPERTS (see Annex A , B, figure C):

Experts disagree on the resilience of plastics: 33% rated plastics resilient vs. 39% not resilient.

Resilience is fundamental for sustainability and has become a guiding principle for a framework of development and disaster risk reduction (Davoudi et al., 2012). The concept originates from the natural sciences, having evolved from ecology in the 1970s (Alexander, 2013), although it is important to note that a variety of disciplines now share this concept (Chelleri et al., 2015). Making cities more resilient to climate change is important because it will help them to recover from a

disaster swiftly and encounter less monetary loss from it as well as reduce risk and vulnerability and allow higher dependability on infrastructure and services (TERI, 2016). It is the role of policymakers, corporate entities, researchers and communities to experiment in order to find alternative solutions to the problems that climate change and other natural, technological and manmade hazards are causing for human settlements (see Figure 4).



**Figure 4:** Illustration of the connection between resilience, adaptation and experimentation



Examples of different types of resilience include seismic, engineering and ecological resilience. Seismic resilience can be defined as ‘the ability of a system to reduce the chances of a shock, to absorb such a shock if it occurs (abrupt reduction of performance), and to recover quickly after a shock (re-establish normal performance)’ (Bruneau and Reinhorn, 2017). Engineering resilience is results-driven, static and refers to a system bouncing back to its original condition (Rus et al., 2017). Ecological resilience can be defined as the ability

of systems to function, regardless of the stability of the population it supports. Socio-ecological resilience has developed from this definition because of the strong link between ecological systems and human influence on climate change (Adger, 2005). The term socio-ecological resilience was coined by Berkes and Folke (1998) and defines resilience as a process whereby a system will bounce back from a disruption while also adapting to new challenges (Rus et al., 2017).

Hazards fall into three categories: natural, technological and human-influenced natural hazards exacerbated by human activities. Natural hazards are caused by natural phenomena including e.g. geophysical events, such as earthquakes and volcanic eruptions, or hydrological events, such as flooding (IFRC, 2020). Technological hazards, on the other hand, are manmade and include e.g. conflict and war, displaced populations and also natural hazards exacerbated by human activities, such as deforestation, or maladaptive practices, such as building with materials which amplify the risk of landslides or fires.

**INFOBOX 9:**  
What are the types of hazards?

## What do we need to know about building resilience?

It is important that building regulations and frameworks consider resilience, since the cost of inaction is higher than the cost of action when adapting to the effects of climate change (EOD, 2016). Resilient urbanism has become a dominant discourse for governments, international organisations and researchers. In practice, this takes the form of technocratic solutions (Davoudi, 2016). Frameworks and building codes are top-down tools for building urban resilience and aim to increase the recovery time of buildings (Joerin et al., 2012). This links to the concept of the robust city, which refers to

the part of resilience that focuses on a city’s ability to recover its infrastructure and capital after a shock (Meriläinen, 2019). The concept of robust cities is found in the Resilient Framework by the Rockefeller Foundation, which argues that building codes and standards facilitate the long-term robustness of cities. This should include buildings being well designed and built to withstand the known hazards in the area in order to prevent disasters from occurring (ARIP, 2015).

After 25–30 years, most buildings require extensive repairs, which mean extensive technological, ecological and economic burdens. In the case of a bridge pier, for example, the negative ecological effects and the costs are up to three times higher compared to the environmental impact of the initial building construction. This makes it all the more thought-provoking that 80% of the structures repaired in this way suffer damage again after only six years.

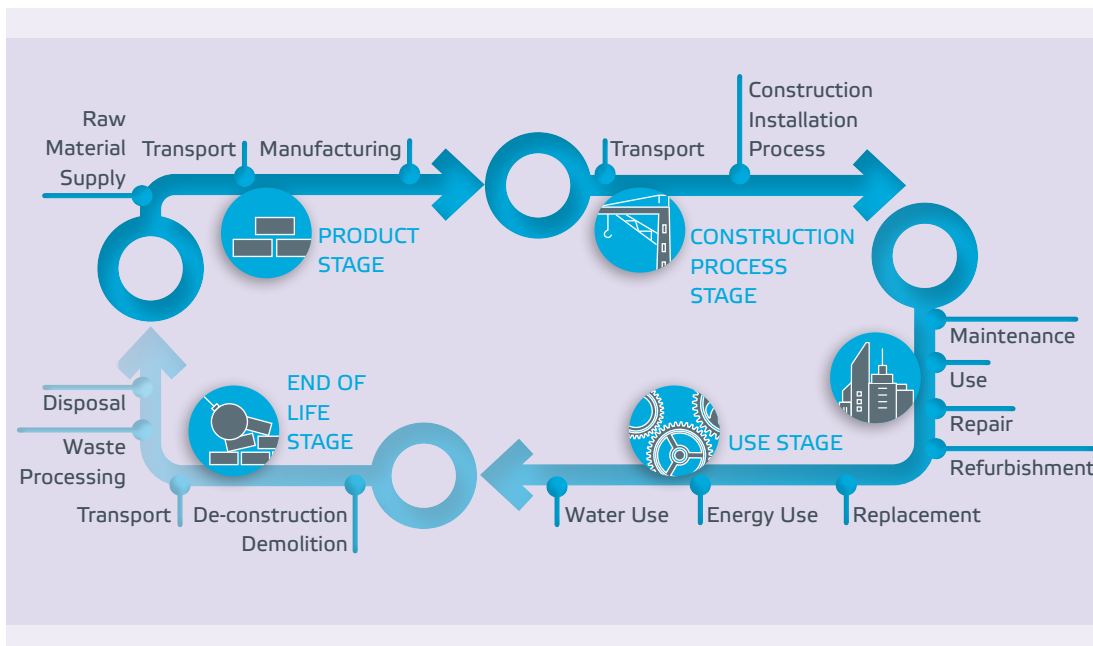
Changing climate conditions lead to a reduction in the service life of building materials, components and structures. Polymer-based joint sealants, originally developed for a service life of 20–25 years, fail after only 7–10 years.

There are thus new challenges in the area of mitigation and adaptation. We must compensate for the avoidable release of greenhouse gases as a result of early material failure by improving the durability of climate-adapted materials. According to the current state of science, however, this can only be achieved by using organic-based additives, such as polymers or surfactants.

**INFOBOX 10:**  
Polymer resilience and climate change – the case of polymer-based sealants (Andreas Gerdes)

The New Urban Agenda (UN, 2017) is designed to contribute towards achieving the SDGs. Point 51 of the implementation plan states that the UN is committed to promoting the development of urban spatial frameworks which will impact on urban planning and encourage sustainable land and resource use. Point 75 of the plan highlights the importance of energy-efficient buildings and encourages the use of construction models which facilitate energy efficiency. Point 76 states that local, non-toxic and recycled materials with paints and coatings free of lead additives should be used to construct sustainable, resource-efficient buildings, in addition to maximising the efficiency of concrete, metals, wood, minerals and land. Point 101 states that the UN aims to practise disaster risk reduction and climate change adaptation and mitigation via construction processes for buildings. Point 121 states the importance of public buildings and industrial buildings being built to be energy-efficient and use sustainable renewable energy as well as retrofitting existing buildings to ensure they are also energy-efficient. To achieve this, building performance codes, standards and energy efficiency targets should be implemented. Point 144 indicates the potential for cities to collaborate with insurance and re-insurance institutions to invest in urban buildings which will be resilient to climate and disaster risks.

**Figure 5** shows the stages of the building process and the many opportunities for sustainable practices in line with assessment frameworks. Sustainability is a multi-dimensional issue, and this should therefore be reflected in building frameworks. It is important to note that there is no blueprint solution that can be applied to all cities, so it is important that frameworks allow cities to be flexible and make decisions based on their climate and the local materials available (Zolfani and Zavadskas, 2013). It is important to use local materials because there is often a greater supply of these materials, lower transport costs and their use will support local businesses (Tobias, 2020). As shown in **Figure 5**, this is critical at the product stage. At the construction stage, it is important to use low-energy methods and, at the use stage, buildings should be energy-efficient, which can be achieved by using measures such as triple glazing, solar heating, natural and LED lighting and natural ventilation (Tobias, 2020). Climatic conditions should also be considered during the building process because climate change brings different challenges to different regions. In hot climates, buildings should be resilient to overheating and drought. In cold, coastal climates, buildings must overcome high levels of precipitation and maximise heat retention (Stagrum et al., 2020).



**FIGURE 5**  
Life cycle stages of a building

Source: Philips et al., 2017

## What are the major challenges in the future?

Alawneh et al. (2019) has proposed an index for analysing the extent to which green buildings contribute to achieving the SDGs through energy and water efficiency measures. This in turn contributes to the overall resilience of cities. This methodology aims to bridge the current gap between energy and water efficiency and achieving the SDGs. This index can be used in combination with third-party rating frameworks. Greening solutions such as green roofs have the potential to increase thermal comfort and decrease energy and water consumption. A study in Paris showed that greening generated a cooling effect between 0.5 and 2°C during a heatwave. A similar study was carried out in London, which showed that green roofs would be an effective solution for reducing temperatures within buildings and facilitating annual energy savings in the projected climate scenario for 2050 (Stagrum et al., 2020).

The Living Building Challenge is popular within resilience building and has been designed to complement the US Green Building Council's LEED green building rating system. A living building must generate more energy than it consumes, which means it helps to negate negative impacts and fossil fuels emitted from traditional building projects (International Living Future Institute, 2020). A

study by Welsh-Huggins et al. (2020) has revealed that an alternative concrete cement diluted with fly ash can decrease the environmental impacts of building with concrete. Buildings constructed from fly ash concrete are not able to withstand earthquakes more effectively than buildings constructed with conventional concrete, but the environmental impacts associated with the life cycle of buildings in areas prone to earthquakes are lower because the production process emits less CO<sub>2</sub>. Fly ash concrete could therefore be considered as an alternative building material for cities at risk of being affected by earthquakes, as producing fly ash concrete for building repairs emits less CO<sub>2</sub>. The COVID-19 pandemic has highlighted opportunities for increasing the resilience of buildings in relation to disease. In order to limit the transmission of disease within buildings, factors such as ventilation, indoor air quality, humidity, lighting, choice of surface materials and size of communal areas are important (Pinheiro and Luis, 2020).

Porosity and pore size distribution are important material properties for the performance and durability of cement-based materials. Concrete has a porosity of approx. 10–15%. After production, this pore space is initially filled with water that was added for concrete production. When exposed to the environment at corresponding temperatures and low values for relative air humidity, young concrete dries out and shrinks. This volume contraction causes mechanical stresses which, if sufficiently large, lead to fine cracks, called shrinkage cracks.

This behaviour is inherent in the system, but due to the consequences of climate change the importance of this damage mechanism is rapidly increasing. In the event of pronounced shrinkage, not only cracks appear but also delamination can occur, often leading to the complete failure of concrete elements. The repair of damaged concrete structures involves both high costs and high environmental impacts, which in total make a significant contribution to climate change.

A technical measure to avoid cracks and delamination is the addition of polymer fibres based on polypropylene or polyethylene, which are mixed in small quantities (0–2 mass %, based on the cement weight) during the production of cement-based materials. The polymer fibres take over the function of a unidirectional reinforcement, which countervails mechanical stresses occurring during the shrinkage process. This prevents shrinkage cracks and delamination, thus avoiding negative effects on and through the structure.

**INFOBOX 11:**  
Polymer and concrete  
resilience – the case  
of repair mortars  
(Andreas Gerdes)





# 3. Protecting Human Health and the Environment

Professor T. Richard Hull

Dr Barbara Zeschmar-Lahl

Professor Anna A. Stec

Jim Vallette

### 3.1 Megatrends (Jim Vallette)



#### ONLINE SURVEYS WITH EXPERTS (see Annex A, B, figure D):

According to the survey, the critical stages for health and environment are: Recycling (79%), fire situations (77%), production (69%) and demolition (57%). Uncritical: Construction site (55%), transportation (53%) and use phase (43%).

The building and construction industry is a major driver of global economic activity. Erecting buildings generates societal and ecological benefits, from providing shelter to supporting bio-based and circular economies. It can also harm human health and the environment through the sourcing of unsustainable products, using toxic substances, releasing chemicals with high global warming potential, and consuming and wasting vast resources during product manufacture, building construction and demolition. Each week, new construction equivalent to the square metres of buildings in Paris, France, is added to the planet (UN, 2017). One of the major sources of household air pollution (HAP), especially in developing countries, where broad parts of the population live in ill-ventilated and ill-lit houses, is smoke (Apte and Salvi, 2016). Incomplete combustion of solid fuels (e.g. wood, coal, dung) or kerosene for cooking, heating and lighting leads to the emission of several pollutants (particulate matter, black carbon, polycyclic aromatic hydrocarbons (PAH) and carbon monoxide) that are associated with serious health risks. The same applies to the smoking of tobacco products.

Especially in the developing and rural world, insecticides and repellents are used widely to combat communicable and infectious diseases, usually borne by vectors such as mosquitoes and other insects (e.g. malaria, dengue, yellow fever), and ticks (Lyme disease). The use of standard mosquito coils can lead to levels of PM<sub>2.5</sub> and CO in the indoor air that are 2,200 and 10

times the limits permissible by the WHO, respectively, when the mosquito coil is burnt with doors and windows closed (Apte and Salvi, 2016).

The 2030 Agenda for Sustainable Development, adopted by the United Nations in 2015, recognises the scale of this industry's demands and impacts. It raises current challenges and provides a framework for minimising harm and maximising benefits. Member states committed to (UN, 2015):

- 'Ensure access for all to adequate, safe and affordable housing' (SDG 11.1)
- 'Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilising local materials' (SDG 11.c)
- 'Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination' (SDG 3.9)
- 'Significantly reduce' the generation and release of toxic chemical pollution (SDG 12.4) and 'minimise their adverse impacts on human health and the environment' (SDG 12.5)
- 'Double the global rate of improvement in energy efficiency' (SDG 7.3).

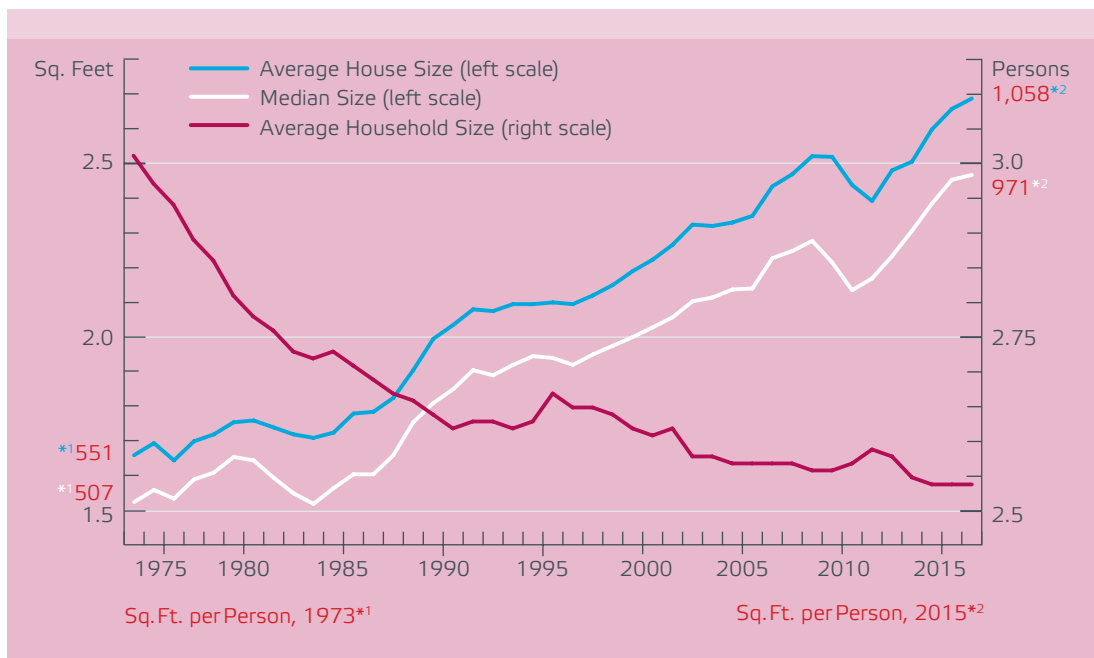


Achieving these goals worldwide by 2030 necessitates fundamental changes in the building and construction industry (BMU, 2017). It requires a full understanding of the life cycle implications of product formulations. It also demands an understanding that some materials that solve one goal can conflict with other goals, such as the use of polyvinyl chloride (PVC) plastic pipes to supply drinking water or plastic foam insulation to make buildings more energy-efficient (EPA, 2020)

Some of the growth in resource consumption per capita reflects global economic progress, and the good news is that more people are living in adequate housing. But a good portion of this growth is due to homeowners and other building owners who are spreading out, creating more space per occupant. In the United States, this area nearly doubled between 1973 and 2015 to over 100 square metres per person (Figure 6, American Enterprise Institute, 2016). By comparison, in 1979, 100% of people in Africa and Latin America and 75% of people in Asia and Oceania lived on less than 20 square metres of floor space per person (UN, 2015).

More space per person means more materials and resource consumption. Green building standards do not reward limits on space per person. Indeed, these programmes measure their success by total square metre (World Green Building Council, 2016). Limits on sprawl in post-industrial countries are, however, essential if the planet is to meet the SDGs.

Most new construction often relies on petrochemical-based plastic interior finishes, such as flooring and wall coverings, and exterior façades, such as PVC siding and polyurethane foam insulation. China helped sustain the global polyvinyl chloride industry in the 2000s and 2010s with its surging demand for building and construction projects. India, with its massive and growing middle class, and a goal of building tens of millions of new affordable houses by the year 2022, may do the same (Bundhun, 2020), see also Table 1.<sup>2</sup>



**FIGURE 6**  
Average and median square feet for new single-family US houses (1973 – 2015)

Diagram from the American Enterprise Institute

Source: Philips, et al., 2017

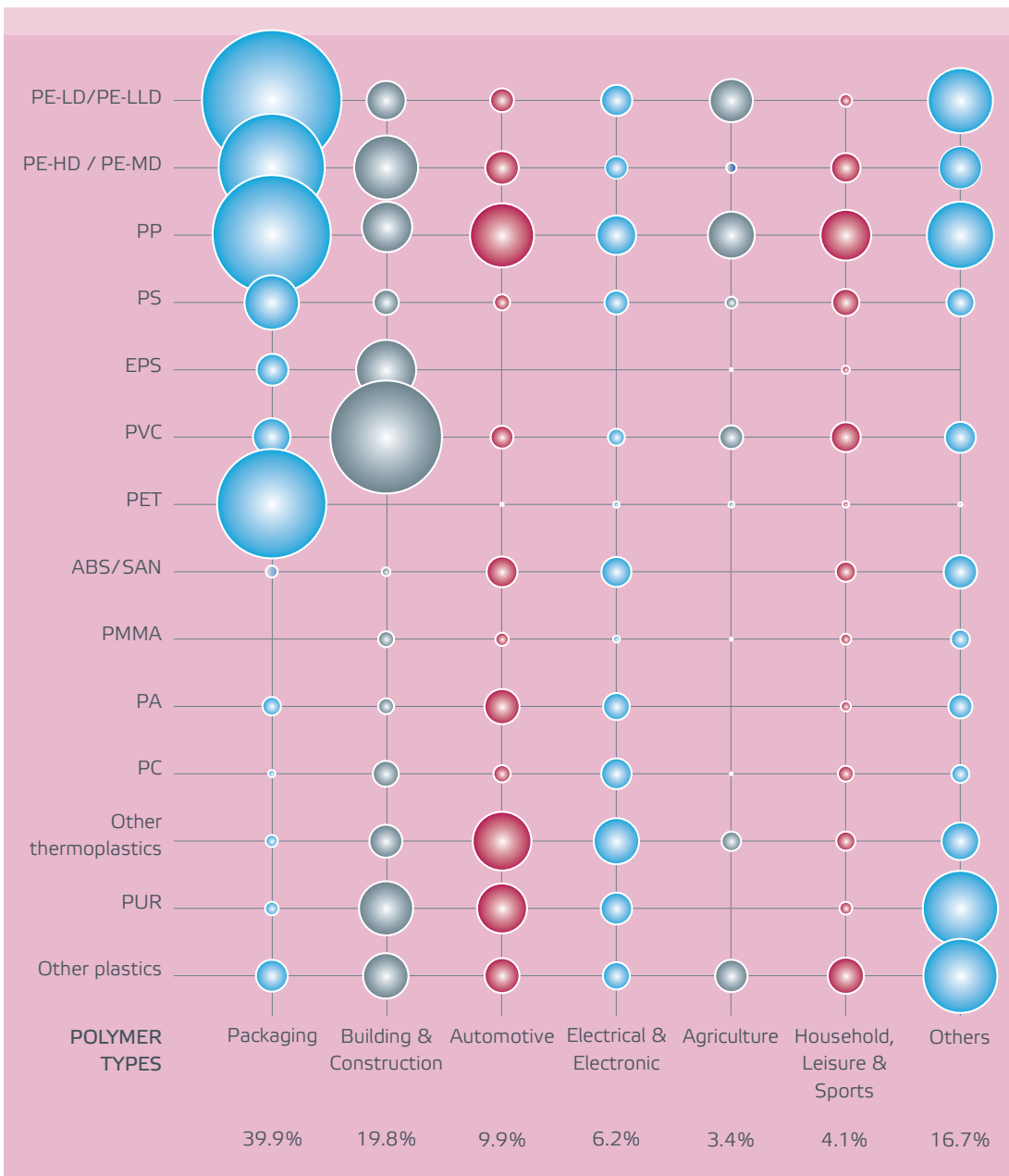
2 <https://www.thenational.ae/business/economy/affordable-homes-push-for-india-s-poor-is-slowly-delivering-results-1.979338>

### 3.2 Status quo of known health and environmental issues

(Jim Vallette, Barbara Zeschmar-Lahl)

The ability of regulators to curtail the industry’s worst impacts varies from country to country. In much of the world, the content of building materials is largely unregulated. Some parts of society adhere to volun-

tary green building standards. An increasing number of these standards seek to eliminate substances of concern, most of which are petrochemicals and plastic components. The dominant type of plastic building ma-



**FIGURE 7**  
Plastics demand by segments and polymer types in 2018  
Total 51.2 Mt

Data for EU28+NO/CH

Source: PlasticsEurope, 2019

**INFOBOX 12:**  
What are the new demands for life cycle assessment?

Life cycle assessments of plastics typically do not include ethane crackers and chlor-alkali plants (production processes) within their scope. This skews perceptions of the relative impacts of plastics versus other materials. The process of turning brine into caustic soda and chlorine requires massive amounts of electricity. China is the world's leading PVC producer and worldwide source of PVC flooring. Much of China's PVC resin comes from chlor-alkali plants located in the far western XUAR province, including the world's largest PVC plant, Xinjiang Zhongtai in Urumqi, which has a PVC production capacity of 1.5 million tonnes per year. These plants are located in the heart of China's coal belt and have on-site, coal-fired plants, including a 900-megawatt plant at Xinjiang Zhongtai. In addition to using large quantities of coal, these plants rely on the use of mercury to produce feedstock for PVC. This process uses acetylene (created by reacting coke with mercury) instead of ethylene to react with chlorine and create vinyl chloride monomer.

terial is polyvinyl chloride (PVC). Building and construction consumes about 70% of all PVC worldwide (Geyer et al., 2017). Other plastics used in buildings include, in descending order of volume, polyethylene, polystyrene, polyurethane, polypropylene, nylon (PA) and acrylic (PMMA). The building industry is, by far, the leading consumer of two types of plastics, PVC and expanded polystyrene (see Figure 7, PlasticsEurope 2015).

The life cycle impacts from making, using and disposing of these plastic building materials undermine the 2030 Agenda. This is the status quo, with the force of decades of investment in linear, toxic, wasteful production. Along each step, careless practices pollute the air, water and land, and can harm living beings. Impacts reach as far as Earth's stratosphere, where blowing agents released from plastic foam insulation damage the ozone layer. Impacts begin at wellheads where oil and gas – the key ingredients of plastic building materials – are extracted.

Environmental and human health impacts continue when these petrochemical plastics are processed into building materials, installed and used in buildings, dismantled from those buildings, disposed of in incinerators or landfills, or recycled into new products. Almost all plastics used in buildings can be considered single-use plastics, albeit used over years. Most efforts to boost recycling rates of plastics including PVC have been symbolic and/or not economically viable due to the low price of virgin plastics. Plastic products often contain toxic additives, such as ortho-phthalate plasticisers and flame retardants. When plastics are recycled, these substances are usually not separated or destroyed but carried over into products made from recycled materials and thus remain in circulation. While regulations have phased out the intentional use of some of these additives, plastic scrap contains these legacy chemicals.

In developed countries with a temperate climate, people spend up to 90% of their time indoors. The quality of indoor air can therefore have a significant impact on people's health. One of the main sources of poor indoor air quality is behavioural and can therefore be easily avoided: tobacco smoke. The situation is different with hazardous substances contained in consumer products and building materials. Wall construction materials, insulation, sealants, doors, windows and interior decoration materials, such as floor coverings, wall and ceiling cladding or furniture, contain chemicals that can leach, migrate, abrade or off-gas, resulting in human exposure (Mitro et al., 2016). Ventilation only provides a temporary improvement here. Examples are:

- PCB: Since the 1950s and until their ban in 1978, PCB were used among others as plasticisers, stabilisers or flame retardants in many building materials, such as caulking and elastic sealants, paints, mastics and other adhesives. Today, PCB in building materials are still a problem of inherited burden. PCB are considered to be reprotoxic (i.e. they can impair fertility and damage unborn life) and are potentially carcinogenic.
- Formaldehyde: This substance belongs to the group of volatile organic compounds (VOC). It is widely used as a binder in chipboard, blockboard and plywood for furniture and interior design. The main source of indoor pollution from formaldehyde is chipboard, but other wood-based materials glued with urea-formaldehyde or melamine-urea-formaldehyde resins also contribute. Formaldehyde emission of these products decreases noticeably, especially at the beginning, but can occasionally remain at an increased level for years. If very poor qualities are used, formaldehyde emission is still high even after decades. Urea-formaldehyde foams (UF foams) can also cause greatly increased concentrations of formaldehyde in the indoor air over long periods of time. Formaldehyde is irritating to mucous mem-

branes, can cause allergies and is classified under EU law as a probable human carcinogen (ECHA, 2020).

- Volatile organic compounds (VOC): VOC consist of thousands of individual substances and are found indoors in widely varying concentrations. Sources are, on the one hand, paints, paint strippers, adhesives and other household products containing organic solvents. VOC are mainly emitted during application of these products. On the other hand, VOC are also emitted by construction materials. Once installed in a building, these materials can emit VOC over a long period of time and thus contribute to the long-term pollution of indoor air. Products concerned are chipboard and UF foams (see formaldehyde) or interior decoration materials, such as carpets. VOC can have different health effects, ranging from irritation of the respiratory tract and eyes to acute and chronic toxicity (neurotoxic, allergenic, carcinogenic, mutagenic, reprotoxic).
- Semivolatile organic compounds (SVOC): Analyses show that house dust often contains high concentrations of semivolatile organic compounds, such as phthalates. DEHP and other phthalates often served as plasticisers in floor coverings, profiles, cables and films made of plastic, especially flexible PVC. Some phthalates, flame retardants and phenol were consistently found in at least 90% of dust samples across multiple studies, indicating ubiquitous presence in indoor environments. 'Exposure to one or more of these chemical classes has been associated with adverse health effects including reproductive toxicity, endocrine disruption, cognitive and behavioral impairment in children, cancer, asthma, immune dysfunction, and chronic disease.' (Mitro et al., 2016).



Although the hazard potential for the individual substances or groups of substances causing household air pollution can be described, there are no reliable data on the illnesses and deaths they cause. Nevertheless, many countries have banned or strictly regulated the use of problematic substances in building materials. For example, the emission class E1 (0.1 ppm formaldehyde for boards) already became obligatory for wood-based panels in Austria, Denmark, Germany, Sweden and other European countries in the 1980s. The phthalates DEHP, DBP, BBP and DIBP are included in the restricted substance list of REACH<sup>3</sup> (Annex XVII). They may not

Plastic pollution from packaging, textiles and building materials is a serious problem for animals worldwide. Birds and fish ingest small pieces of plastic or fibres including polyester, polypropylene and nylon.

3 REACH regulation: REACH stands for Registration, Evaluation, Authorisation and Restriction of Chemicals. It entered into force on 1 June 2007.

Isocyanates are associated with the production of PUR but also present in foams, coatings, paints, wire insulation, adhesives, rubbers and fibres. The ones most frequently used are diisocyanates, such as toluene diisocyanate, methylene diphenyl diisocyanate and hexamethylene diisocyanate (Hamilton 2013). Germany's Federal Institute for Occupational Safety and Health (BAUA) connects isocyanate exposure to dermatitis, irritation of the mucous membranes, eyes, nose and throat, gastrointestinal irritation, chemical bronchitis and pneumonitis. Especially continued exposure can lead to asthma, which is officially recognised as a professional disease connected to them in Germany (BMGS 2004).

#### **Bhopal and isocyanates**

The broad spectrum of health damages caused by exposure to methyl-isocyanate was observed after the catastrophic incident in 1984 in Bhopal, India, which led to about 10,000 dead and some 100,000 injured. The effects varied from acute breathlessness to serious, long-term chronic lung diseases years and decades after exposure (Ganguly et al., 2017).

#### **INFOBOX 13: Isocyanates**

#### INFOBOX 14: REACH

The REACH regulation (**R**egistration, **E**valuation, **A**uthorisation and **R**estriction of **C**hemicals) is a European regulative framework for chemicals. There are three categories for the registration of chemicals, depending on annual production volume. For large volumes (from 10 t/y), chemical safety reports (CSR) are compulsory. There are also lists of substances of very high concern that require specific authorisation procedures. Polymers, however, are not included in the registration process.

REACH is an advanced regulative policy, nevertheless, it has some gaps: it is aimed mostly at emerging substances on the market. The European chemicals' market consists of about 100,000 substances, of which 30,000 are covered by REACH (Gundert-Remy, 2007). Detailed information and risk tests are compulsory only for 100 t/y and more. Of the substances covered by the regulation, about 2/3 are in the category of less than 10 tonnes a year, for which only basic information is required. There are various exceptions and circuitous routes for producers to market substances of high concern. There are the terms 'controlled risk' for substances of concern and 'socio-economic benefits', which can outweigh environmental or health considerations (Lahl/Hawxwell, 2006).

Nonetheless, after the regulation came in force in 2007, it has become an example for a successful chemical policy worldwide. Internationally, REACH shows the most progressive approach to the management of chemicals and possible impacts on health and the environment.

be placed on the market after 7 July 2020 in articles, individually or in any combination, in a concentration equal to or greater than 0.1% (w/w) of the plasticised material in the article. Other 'substances of very high concern' (SVHC) found in carpets (Anthesis Consulting Group, 2018), such as the halogenated flame retardants decaBDE and TCEP, are included in the REACH Candidate List. Companies supplying products that contain substances listed herein are obliged to submit information on these products to the SCIP database (ECHA, 2020) – ECHA's database on **S**ubstances of **C**oncern **I**n articles as such or in complex objects (**P**roducts) – as from 5 January 2021.

Today, modern buildings have to meet high standards in terms of energy consumption, reduction of greenhouse gas emissions and noise, and fire protection. The demand for air conditioning/ventilation systems, energy control systems and information and communication technology is increasing. One of the characteristics of the three-litre house is the abundant use of polymeric materials (Diogo, 2014): polystyrene in high-performance thermal insulation foams, polypropylene in ventilation systems, energy control system, thermal insulation foam and solar panels, polyurethane in the form of foams, polyvinyl chloride in ventilation and energy control systems, in window frames and

#### INFOBOX 15: What has been done to restrict toxic sub- stances in buildings?

Instruments such as bans, mandatory authorisation, strict regulations concerning use or product quality, information obligations such as REACH and eco-labelling trigger the phase out of use and stimulate the substitution of hazardous substances in building materials (and others). For example, conventional adhesives with reduced formaldehyde emissions today dominate the wood-based panel industries, and even formaldehyde-free adhesives are available, such as PMDI (polymeric diphenylmethane diisocyanate). PMDI is mainly used in oriented strand board (OSB). Phthalate-free plasticisers, such as alkylsulphonic acid esters with phenol (ASEP), have good compatibility with a large number of polymers, including acrylates, polyurethane, polyvinyl chloride, and rubbers, and are not classified as hazardous (European Plasticisers, 2020). The Healthy Building Network found acetylated monoglycerides of fully hydrogenated castor oil (COMGHA) and isosorbide diesters – both bio-based products – to be the least toxic and therefore preferable over the other plasticisers studied in its assessment (HBN, 2014). Other phthalate-free, non-VOC and bio-based plasticisers based on dioctyl succinate/bis(2-ethylhexyl)succinate or acetyl tributyl citrate, respectively, have been available for some years (OXEA, 2014). Meanwhile, PVC and plasticiser-free synthetic floor coverings are also available (e.g. GREENVINYL). Such innovations will contribute to reducing household air pollution problems.





**FIGURE 8**  
Exposure to  
substances in  
buildings

Source: U.S. Green Building Council – USGBC, Better Building Materials Guide, 2020

solar panels, polyethylene in ventilation system and floor heating, polybutylene in floor heating, engineering thermoplastics in ventilation system, fuel cells, energy control system and solar panels. This increasing demand will probably foster the development and use of advanced polymers. However, the high quality of indoor air must always be guaranteed, particularly with regard to vulnerable subpopulations such as pregnant women and children.

and use (e.g. isocyanates, epoxy resins), and end-of-life issues (Friege et al., 2019) have to be assessed for all innovations too. A simple way of achieving energy efficiency, avoiding toxic chemicals and preventing fires is to use natural cork or fibreglass insulation, which are inherently flame-retardant. Better yet, cork insulation supports bio-based economies, and fibreglass insulation, if it uses recycled glass cullet, boosts the circular economy.

However, indoor air quality is only one aspect of sustainable building and living. Use of resources (Wang et al., 2020), occupational safety and health in production

**Epoxy resins and polycarbonates without BPA:** Epoxy adhesive resins are normally formed by combining bisphenol A, an endocrine disruptor, and epichlorohydrin, a carcinogenic toxicant. Such epoxy resins are recognised asthmagens (<https://healthybuilding.net/uploads/files/eliminating-toxics-in-carpet-lessons-for-the-future-of-recycling.pdf>). German company RS Office Products makes BPA-free floor mats made of PET (<http://www.rs-office.com>). Covestro produces polycarbonate resins with less than 0.1% w/w or residual BPA (<https://www.covestro.com>).

**Halogen-free flame retardants for polystyrene and PUR:** EXP and XPS are widely used insulation materials and need to be fireproof. Polybrominated aromatic molecules and diphenyl ethers HBCD and TBBPA have been used as flame retardants for polystyrene and polyurethane materials for decades. They were rated as high-persistent, bioaccumulative and toxic by REACH. EPS can be flame-retarded by water-based coating with nanoparticles of boehmite and PVOH as char former (Hamdani-Devarenesab et al., 2016).

**INFOBOX 16:**  
What has been  
done to replace toxic  
substances in plastics  
(a few examples from  
industry)?

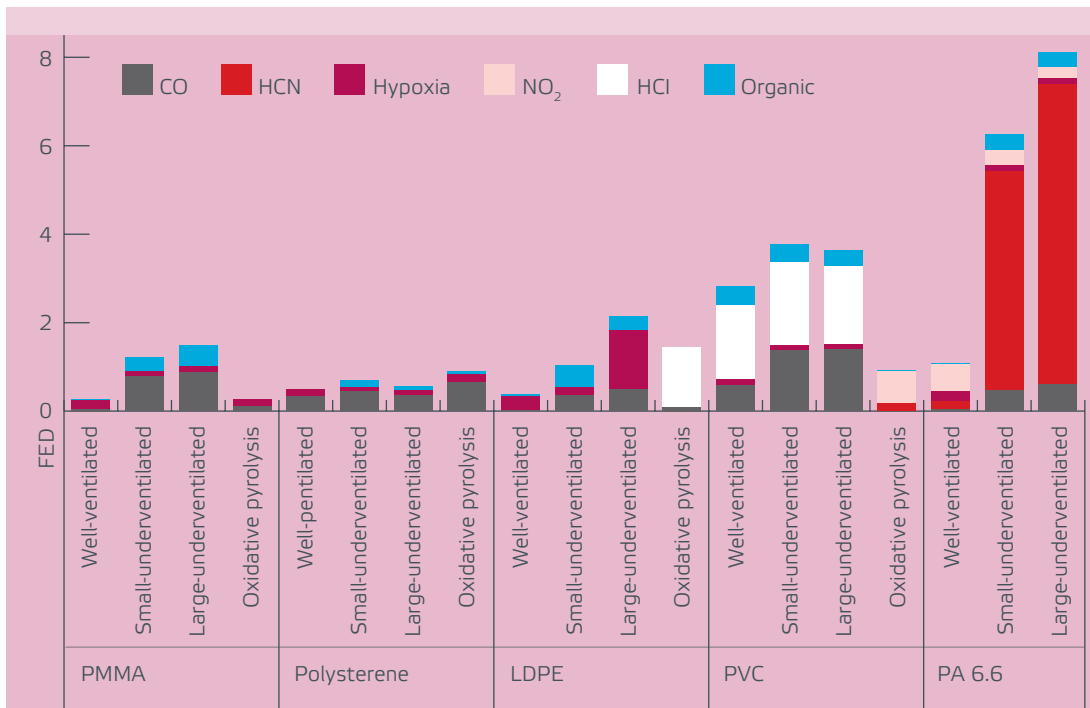
### 3.3 Fire toxicity (Anna Stec, Richard Hull)

The apparent conflict between sustainability, particularly minimising carbon emissions, and protection of human health and the environment, and particularly fire safety, demands more detailed comprehension and direction from regulators. The construction industry consumes 20% of plastics in Europe, providing cheaper products with many advantages, such as better thermal insulation, better resistance to wear and decay, sophisticated off-site manufacture, and improved hygiene and greater comfort. However, compared to the materials they replace, many of these plastics involve problematic end-of-life processing, while plastics derived from oil are combustible and often highly flammable. They can reduce fire safety, fuelling fires and generating large quantities of toxic fumes and residues. Worse, in order to allow the cheapest plastics to pass regulatory tests, for use in high fire-risk applications such as construction products fire retardants are added, many of which are toxic, and released into the environment during the lifetime of the product (potentially causing harm without providing adequate fire protection) and they increase the toxicity of the smoke.

Three factors drive smoke toxicity, approximately in order of importance.

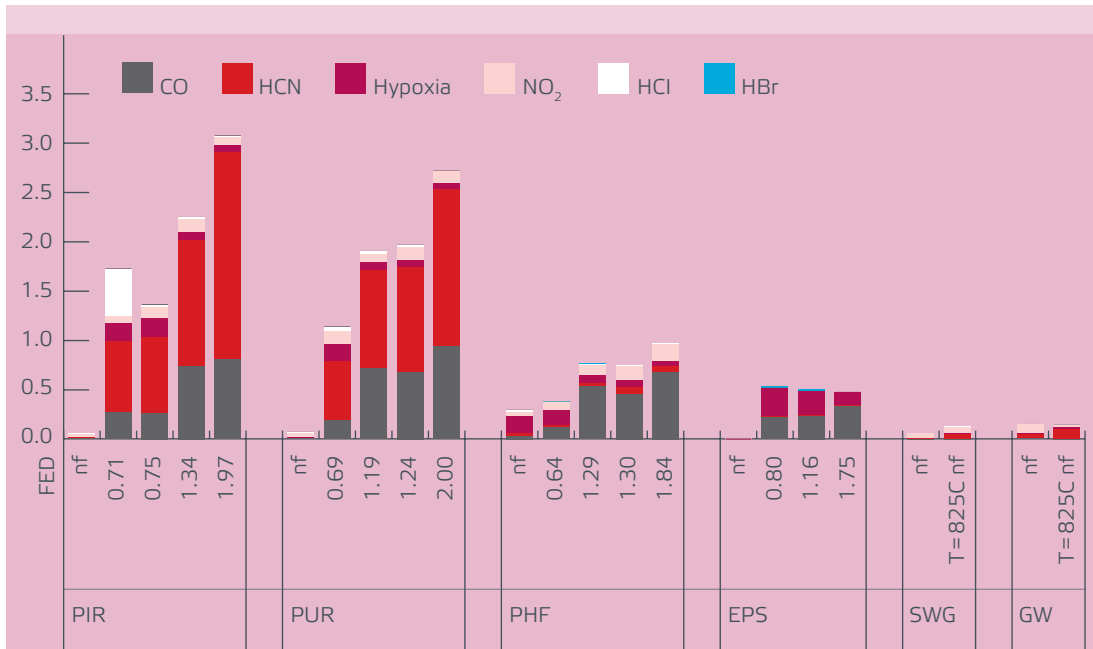
- **The presence of a flame.** When a flame is present, the combustion reaction is much faster, but the products are initially less toxic until the fire grows.
- **The ventilation conditions.** A small well-ventilated (w-v) fire will have very low toxicity, but if there is sufficient fuel, it will quickly grow to become under-ventilated (u-v) when the toxicity can increase by a factor of 20 or more.
- **The presence of other chemical elements,** such as nitrogen, chlorine or bromine. These can form more toxic substances, such as hydrogen cyanide (HCN), or enhance the formation of other toxicants such as carbon monoxide (CO).

To illustrate the factors driving smoke toxicity, **Figure 9** shows how it varies for five common plastics under different fire conditions. In all cases, the transition from well-ventilated to under-ventilated flaming results in a significant increase in toxicity (FED – fractional effective dose – increases). This effect is greatest when elements such as chlorine (e.g. for PVC, when HCl is released) or nitrogen (e.g. for PA 6.6, when the plastic contains nitrogen most of the toxicity



**FIGURE 9**  
Smoke toxicity of common polymers under different fire conditions

Source: Stec et al., 2019



**FIGURE 10**  
Smoke toxicity of six commercial thermal insulation products

Source: Hull et al., 2008

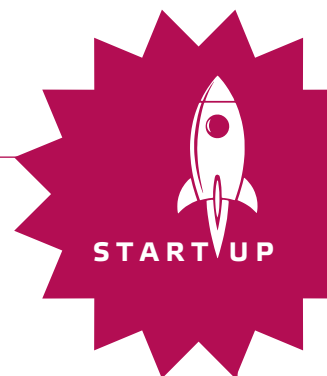
in under-ventilated conditions comes from the HCN) are present.

Insulation products are very widely used in construction but vary from non-combustible, stone wool (SW) or glass wool (GW) to combustible, polyisocyanurate (PIR), polyurethane (PUR), phenolic (PHF) and expanded polystyrene (EPS) foams. **Figure 10** shows the large differences in the toxicity of these products when burning. In particular, PIR (which was used extensively on Grenfell Tower, London, where 72 deaths occurred) and PUR have much higher toxicity because of their nitrogen content than other combustible insulation, such as PHF and EPS, while non-combustible insulation products show low toxicity, as their organic binders burn. It is important to understand that combustible foams will support the spread of a fire, releasing enough heat to ignite the next section, whereas non-combustible products will not support flame spread.

What are the main findings and conclusions for fire toxicity of plastics? Smoke toxicity is the biggest threat to humans and the environment in the event of a fire. Its lack of regulation has left manufacturers without any incentive to minimise the smoke toxicity of their products. While upholstered furniture drives the greatest loss of life from fire, combustible construction products fuel major fire disasters, such as Grenfell Tower in the United Kingdom or the Düsseldorf Airport fire. As a society, we cannot regulate what people put in their homes, but we must insist that their homes are built safely. Despite the clear and well-documented evidence, neither the European Commission nor any of its member states have so far attempted to regulate the smoke toxicity of construction products or furniture. Certain industry sectors, notably manufacturers of PVC and rigid foam insulation, have lobbied very hard and successfully to prevent such regulation (Reuters, 2017).

**INDRESMAT produces window frames from bio-based polyurethane which is recyclable and a low carbon footprint material that improves energy efficiency in buildings.**

**PRO:** Replacing PVC frames is advantageous where no take-back schemes for PVC exist. Bio-based sources provide an alternative to fossil sources. The design with few component materials allows for easier separation after use. **CONTRA:** The isocyanates used are not yet bio-based and recyclable, the problem of flammability and smoke toxicity is not yet solved. **RECOMMENDATION:** Provide third-party verified transparency of ingredients and LCA compared to conventional materials.



### 3.4 Policy and regulations – a US perspective (Jim Vallette)

The composition of building materials varies from country to country. Factors include costs, availability, local building design culture, marketplace awareness and, perhaps most importantly, government regulations. In China, where the government controls the entire supply chain, from raw material extraction to final product manufacturing, regulations are not much of a concern for producers of vinyl flooring, for example. Massive volumes of carbon dioxide and mercury catalyst waste are released in the process. The European Union, through REACH, prohibits the use of a wide range of toxic chemicals from use in building materials.

The chemical industry too has succeeded in preventing the leading green building standard in the United States, the U.S. Green Building Council's LEED rating system, from adopting restrictions on certain substances. In the early 2010s, when the American Chemistry Council (ACC) moved to credit projects that avoided the use of PVC, it started lobbying states and the federal government to prohibit the use of the LEED rating system. A pivotal moment in the green building movement occurred in 2014 when the USGBC issued a joint press release announcing an agreement to cooperate with the chemical industry (USGBC, 2014). This cooperation is further reflected in a 2016 statement from

the USGBC's chief operating officer, Mahesh Ramanujam, stating (USGBC, 2016): 'The products and materials that ACC's member companies offer in the market directly contribute to more sustainable outcomes for the building and construction industry. These products consistently raise the bar on how our buildings perform, especially from an energy efficiency standpoint, and help the building and construction industry to meet their sustainability goals.'

A lot of policy discussion in green building standards now evolves around transparency and the adoption of disclosure tools such as Health Product Declarations (HPD) and Environmental Product Declarations (EPD). However, transparency is just a first step towards sustainability. Far more important is what is done with that information. Many well-disclosed products are now listed in various directories of green building products, and yet they contain toxic substances that harm building occupants, workers and the planet. Even products certified by the Living Building Challenge and Cradle to Cradle contain toxic chemicals such as isocyanates. This can only confuse consumers. The influence of the chemical industry has overwhelmed the green building community (Healthy Building Network, 2017).

### 3.5 Necessary steps towards sustainability of plastics (Jim Vallette)

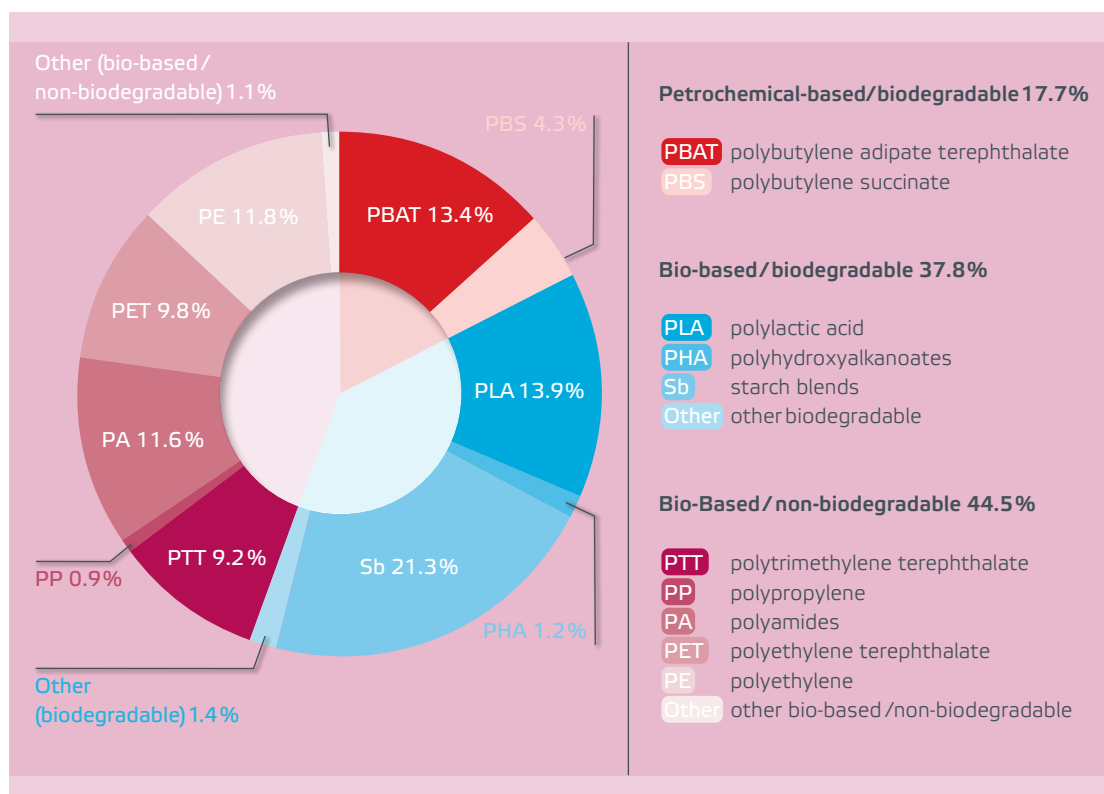
Green building advocacy centred for a while on the 'precautionary principle,' to first do no harm. Today, it uses narrow life cycle assessments that ignore the unsustainability of plastic production. It focuses on rewarding marginal improvements in the form of opaque transparency. Building product certification bodies list products with contents that are only partially disclosed by manufacturers. Some systems list products simply for participating in industry-wide 'Environmental Product Declarations' that aggregate and average data from multiple manufacturers and thus mask important product-by-product differences between manufacturing practices. Another practice that is rewarded by the certification industry is the use of bio-based materials in plastics, even when most of the product is comprised of toxic petrochemicals. Some spray foam insulation,

for example, is marketed as being 'bio-based.' This is due to the replacement of petroleum-based polyols – a small portion, typically no more than 10%, of the formulation that is reacted to make this product – with soy-based polyols (HBN, 2010).

Plastics will only be sustainable when they are no longer derived from fossil but rather from renewable carbon sources or from carbon capture and utilisation. CCU refers to the capture of carbon dioxide (CO<sub>2</sub>), especially from combustion exhaust gases, and its subsequent use in other chemical processes, e.g. bio-based plastics, typically made from soybean oil, are already used in products such as corner guards and wall coverings (Covestro, 2020; Alparach, 2020; Carnegie, 2019). Ocean algae-based plastics offer more prom-

**INFOBOX 17:**  
Bio-based and bio-degradable plastics

Bio-derived polymers based on molecules extracted from biological material, e.g. plants, are not necessarily biologically degradable (White Paper 2020). About half of bio-based plastics are not biologically degradable. And vice versa some biodegradable plastics such as PBS and PBAT are largely based on petrochemicals. About one third of bioplastics are both bio-based and biodegradable (European Bioplastics, 2019).



**FIGURE 11**  
Global production of biodegradable and bio-based plastics

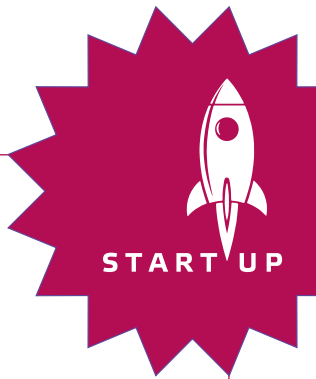
Source: A white paper from the 8th Chemical Sciences and Society Summit (CS3), June 2020

ise of sustainability, as they do not rely on fertilisers or pesticides that can harm people and the planet (Heikkinen, 2015). Many sustainable solutions are ready for adoption in green building practices, with the primary hurdle being market acceptance. Affordable solutions are at hand for many categories of building materials. Simple bio-based replacements are available, such as wood siding and linoleum floors. Other alternatives are yet to be fully realised, such as algae-based plastics.

manufacturers. It promises to organise disparate efforts, find substitutes for hazardous substances that are energy and material-efficient and develop inherently safe consumer products (Friege, 2017).

Global policies also offer some promise of a wide application of sustainable solutions. Multilateral environmental agreements are developing a Strategic Approach to International Chemicals Management (SAICM). This approach has started to collect information on chemicals in building products and advocates for more disclosure of these ingredients by product





**TGSeed produces high-tech wood made of various natural fibrous raw materials mixed with plastic waste. It aims to compensate timber consumption and deforestation.**

**PRO:** Interim solution for emerging and developing economies. Combination of bio-based waste and plastic waste shows how to give waste a value, potentially reducing deforestation. **CONTRA:** Source of waste: not every type of plastic is suitable (toxic additives). Flammability of polymers. Recyclability is questionable. **RECOMMENDATION:** Value creation should be established in a way that lets local production in Kenya benefit and hinders deforestation. The source waste materials should be screened for toxic substances.

### 3.6 Existing solutions and necessary innovations – a US perspective (Jim Vallette)



#### ONLINE SURVEYS WITH EXPERTS (see Annex A, B, figure E):

Asked for necessary innovations, respondents proposed removal of and more sustainable additives, bio-based and biodegradable polymers, design for recycling.

The last chapter has focused largely on a wide view of product sustainability, from the extraction of raw materials to the end of a product's use. At that aperture, progress can appear hard to see, but there is quite a lot to celebrate. In the past 20 years, a combination of marketplace and regulatory pressures has removed some very harmful materials from the built environment. Formaldehyde is no longer used in fibre-glass insulation. Ortho-phthalate plasticisers are largely phased out of vinyl flooring. Alkylphenol ethoxylates – including nonylphenol and oxyphenol ethoxylates, which are highly toxic to fish and suspected of being endocrine disruptors – have been phased out in much of the world from use in standard paint. These changes reveal a very fluid but malleable marketplace.

Scientific understanding of the industry's impact on health has also increased. As building product ingredients became better known, so too has an understanding that they are released into people's homes, workplaces and food chain and not – contrary to earlier beliefs – 'bound in a matrix' as industry has asserted for decades. The market has also become more familiar with the built environment's connections to chronic diseases such as asthma (e.g. isocyanates) and diabetes (endocrine-disrupting chemicals).

Ten years ago, manufacturers disclosed very little about what was in their building products. Today, the marketplace expects full transparency. Now, through open access databases such as the Healthy Building Network's Pharos Project (HBN, 2020), consumers can discover what kinds of hazards are associated with the disclosed ingredients. The SAICM's focus on chemicals in building products is yet another indicator of progress toward finding alternatives to the most problematic materials.

**Polyamide:** Bio-based polyamide grades have been available on the market since a couple of years. PA 6.10 and PA 10.10 are made by polycondensing hexamethylenediamine and sebacic acid (produced, for example, by DuPont, BASF, Evonik), which is extracted from the seeds of the castor oil plant. Both grades exhibit high strength, heat resistance, chemical resistance and overall durability. PA 6.10 absorbs far less moisture than the common PA 6 and PA 6.6. PA 6.10 is therefore a good engineering material for applications that require high dimensional stability (Akro-Plastic, 2018). Dowels are normally made of polyamide ('nylon'). The dowel is therefore an interesting application. It is marketed by Fischer (Germany) as a 'Green-line' product, German name 'Biodübel' (Federal Ministry of Education and Research, 2014).

**Epoxy resins** (without BPA) can be based on a renewable resource such as polyphenols. 'Quercetin (Q-NMA) was functionalized and cross-linked to afford a robust epoxy network. The thermal and mechanical properties of this naturally derived network were compared to those of a conventional diglycidyl ether bisphenol A-derived counterpart (DGEBA-NMA). Q-NMA had similar thermal properties... and comparable mechanical properties to that of DGEBA-NMA.' Development of Q-NMA can lead to an interesting substitute for bisphenol A-based epoxies in various specialised engineering applications (Kristufek et al., 2016).

**PUR** based on renewable compounds without isocyanates ('non-isocyanate polyurethane – NIPU): there is a long tradition in the synthesis of non-isocyanate urethane polymers of using the reaction of cyclic carbonate with an amine, starting with a US patent in 1954. The main actors and patent applicants in the last decade are BASF, Dow Global Technologies and Polymate/NTI.

**Polyethylene (PE):** 'Green ethylene' is produced by dehydration of ethanol (Braskem, Brazil), which stems from sugarcane. Brazil has a long tradition in using sugarcane to produce ethanol for fuel. Polymerisation of 'green ethylene' does not differ from fossil-based ethylene. Quite clearly, there is a massive reduction of CO<sub>2</sub> emissions, since sugarcane ethanol requires only a small amount of fossil fuels for its production. On the other hand, future large-scale ethanol production from sugarcane might lead to the destruction or damage of biodiversity and further deforestation.

**INFOBOX 18:**  
What kind of plastics can be produced from renewable raw materials (examples of a few company solutions)?



# 4. Resource Demand and Recycling

Oleg Ditkovskiy

Professor Henning Frieger

Professor Kay Künzel

Professor Bernhard Möglinger

Swetlana Wagner

## 4.1 Building plastics and aspects of sustainability

(Bernhard Möglinger)



### ONLINE SURVEYS WITH EXPERTS (see Annex A, B, figure F):

While the experts estimate the potential for energy saving in plastic insulation as very high (65%), they recognise that energy demand during production, recycling and general resource demand for disposal are very high as well (> 50%).

Polymeric materials (thermoplastics, rubbers and thermosets) play an important role in civil engineering and the construction of buildings. Whereas the core of a building is usually made of stone or concrete, polymers are mainly used in a wide variety of applications for infrastructure purposes (pipes for water and gas supply, floor heating, waste water, cable insulation and housings, window frames), surface protection (water proofing, wall paints), thermal insulation (polymer foams, vapour diffusion barriers, etc.). Over the last 30 years, typically 25% of global polymer production found its way into building applications each year, meaning an increase from 25 tonnes in 1990 to 75 tonnes in 2020. This fact underlines the necessity to introduce life cycle assessment (LCA) considerations already in the design and planning phase of buildings as well as the use of environmentally friendly plastic materials that do not contain more than a minimum of 'unhealthy' additives.

In the past, the main aim of sustainability considerations in civil engineering was to minimise the energy consumption of buildings. Still even today, there is often the problem that construction costs are paid from a different budget than maintenance costs. This is often an obstacle to a more sustainable construction of buildings due to imagined budget savings. However, in the future a holistic view of constructing buildings is necessary if aims such as the following are to be achieved:

- Affordable homes for the growing world population with at least minimum comfort and basic hygiene facilities
- Provision of a certain level of comfort with minimal resource consumption
- Transformation of the current economy towards a circular economy. In this context, the use of polymers is crucial to achieving these goals as well as satisfying the human desire for comfort because of their unique materials and processing properties.

Buildings are the human mass products that have the longest life expectancies, and they are absorbing huge amounts of materials. In the past, it was not necessary to take into account end-of-life scenarios of buildings, as their waste consisted of minerals and corroding metals that did not cause severe problems on landfills. Often stones, bricks and wooden beams were directly recycled in new buildings. At the latest since the beginning of the new millennium, the situation has changed significantly, as waste from buildings has shifted to an increasingly complex materials mix that consists of minerals, metals, different kinds of polymers and electronic components containing a lot of additives and composite materials. In the environment of a landfill, many chemical reactions become possible that can endanger human health, drinking water resources and the natural environment and can poison food, e.g. through

the release of hazardous substances or microplastics. This partly already happens during the use phase of buildings. Paints can be considered as one of the major sources of global microplastics. The International Union for Conservation of Nature reports that the contribution to microplastics of marine coatings is 4 %, road markings 7 % and city dust, consisting to a certain part of wall paints, 24 % (International Union for Conservation of Nature, 2017). This example shows already that depositing construction waste on landfills is no longer an option for the future.

It can be observed in public discussions that many people consider plastics as a single kind of material because they consist of macromolecular chains. However, the problem-solving capabilities of polymeric materials stem from the fact that these macromolecular chains differ significantly with respect to chemical composition and chain conformation. LCA (life cycle assessment) data show that the synthesis of polymers is an optimised process that is linked to an energy input of around 60 and 80 MJ/kg and greenhouse gas (GHG) emissions of typically 1.5 to 3.5 kg CO<sub>2</sub> equivalents. Significant improvements in the environmental impact cannot be expected in the synthesis (although the use of renewably produced monomers contributes to a remarkable reduction of GHG emissions) but in the recycling field, as the large impacts due to production are then distributed across the number of recycling cycles.

The use of recycled polymers does not require the synthesis step itself. However, different synthesis processes might be required that ease recycling afterwards. In order to meet currently valid requirements and guidelines for materials in civil engineering, a lot of additives have to be used in polymer compounding, e.g. flame retardants, stabilisers, softeners, etc. Of course, these additives do a good job with respect to the primary intention, but they might sometimes generate side effects that are more harmful than the primary damage. Furthermore, many requirements are old and stem from times when conditions in house building and style of living were very different from today. From a sustainability point of view, they can often be considered counterproductive.

More sustainability in the area of polymers in building applications and their chemistry requires firstly the admission that most buildings – especially their technical interior installations – are not made for eternity, and secondly a review of all corresponding standards and guidelines in order to address and include end of life and thus to facilitate the recycling of polymer prod-

ucts used by the construction industry and their reuse. These efforts will lead to polymeric materials having a simpler but still well-performing composition with better recycling capabilities. In this context, it would be important to create a database in which polymer compounds for buildings with approved additives are defined together with possible recycling routes. To design these recycling routes efficiently, homogeneous polymer collection is needed, which can be done, for example, by means of harmless tracer substances or colouring.

Furthermore, many polymer products for buildings are composites with either a multi-layer or a sandwich structure. The proper recycling of such materials is only possible if the separation of multi-layers or composites to homogeneous material fractions is already taken into account in the design phase, supplemented by adequate and efficient reprocessing technologies. The consequences of a holistic view of constructing buildings are:

- Generation of greater awareness of these long-term aspects in the training of architects, civil engineers, manufacturers of building components and construction companies
- The reformulation of legislation to address a really sustainable construction of buildings

Currently, these two aspects have not yet come to the attention of technically highly developed societies and their public opinions but are only addressed by non-governmental organisations such as the 'Deutsche Gesellschaft für nachhaltiges Bauen – DGNB' (German Sustainable Building Council). The DGNB provides detailed information, partly in the form of flow charts, which guide, for example, towards the sustainable use of polymeric materials and parts in building construction. If we want to solve and overcome these current challenges in particular in relation to the use of polymeric materials and parts in building construction, a large-scale, ongoing, global and concerted effort will be necessary in order to introduce sustainable chemistry into the value chain of polymer production and shift people's thinking towards sustainability. In that respect, this report is a first step in the right direction.



Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB) is a German Sustainable Building Council. The DGNB lists contacts and provides extensive information on all aspects of sustainable construction and renovation of buildings on the website <https://www.dgnb.de/en/>. An example is a checklist on how to construct new buildings or redesign old buildings in a sustainable and deconstruction-friendly manner which can be downloaded from [https://static.dgnb.de/fileadmin/dgnb-ev/en/topics/circular-economy/DGNB\\_Toolbox\\_CE\\_checklist\\_deconstruction.pdf?m=1568806725&](https://static.dgnb.de/fileadmin/dgnb-ev/en/topics/circular-economy/DGNB_Toolbox_CE_checklist_deconstruction.pdf?m=1568806725&)

## INFOBOX 19: DGNB Toolbox

## 4.2 Building insulation: LCA and alternative materials

(Oleg Ditkovskiy)

In the four surveys undertaken by ISC<sub>3</sub>, the experts in the field of construction interviewed about plastics and sustainability stated that plastic materials have low maintenance and investment costs and are easy to use and maintain but difficult to recycle (Survey, Q6). Nevertheless, the respondents gave plastics' performance as their main advantage, especially in conjunction with their low price (Survey, Q5).

There was no uniform opinion among the experts on the aspect of energy efficiency. About 40% considered plastics to be more energy-efficient in comparison to other materials and another 40% found the exact opposite (Survey, Q8). This has to do with two aspects of construction polymers. While experts estimate the potential for energy saving for plastic insulation as very high (65%), they at the same time recognise that energy demand during production, recycling and the general resource demand for disposal are very high as well (53% – 60%) (Survey, Q3).

A research study by ifeu on different insulation materials published in 2019 (Reinhardt et al., 2019) compared insulation made of renewables, minerals and synthetic materials. The research is based on life cycle assessment and concludes that, taking into account today's building and recycling practice, renewable raw materials are the most sustainable from an LCA perspective, e.g. wood-fibre, blown-in insulation as well as hemp and jute mats. The reason for this is their environment-friendly production and low pollution rates in the disposal phase.

In second place, according to the study, are cellulose, blown-in insulation, new, non-HBCD EPS and wood-fibre mats. In third place are most other insulation materials in board or mat form (PU, XPS boards, dry-produced, wood-fibre boards, rockwool boards, glass wool mats, mineral foam boards). The worst performers in this comparison are wet-produced, wood-fibre insulation boards and foam glass boards because of the high energy demand for manufacturing.

The comparison was based solely on the LCA data in accordance with the EN 15804 norm and the 50:50 approach and did not take into account toxic substances and environmental pollution, e.g. through microplastics, or material properties such as flammability, moisture resistance or load-bearing capacity.

Following this methodology, hemp and jute products received a good rating as long as they are made from residual biomass or secondary raw materials, such as used cocoa sacks.

The study forecasts that the life cycle assessment of insulation materials will improve in the future due to new recycling processes. For bonded insulation boards (e.g. EIFS), renewable raw materials are almost on a par with HBCD-free EPS at the current level of waste incineration. EPS boards will gain an advantage as soon as circular economy is achieved. A prerequisite for this is that EPS is recycled and fed back into production. However, material recycling is only possible with virgin and non-HBCD material. Unfortunately, most future waste will be EPS used in earlier decades that is contaminated with HBCD. These materials could be separated and recycled with the CreaSolV® process developed by the Fraunhofer Institute for Process Engineering and Packaging IVV. However, this technology (described in **Chapter 4.6**) is currently only used in a demonstration plant on a small scale.



Wood-fibre, blown-in insulation as well as hemp and jute mats showed the best LCA results in the 2019 study by IFEU.

The most sustainable solution with which to make insulation materials reduce their ecological imprint is a circular economy that should be implemented in the future.

While today old insulation materials are mainly disposed in waste incineration or cement production plants, the study shows the specific advantages of material recycling: old processed masses from old insulation materials can be further processed into other products or fed back into their original production as raw material. This reduces resource consumption and significantly improves their ecological balance. A prerequisite for such material recycling is that the construction and building materials are suitable, meaning that insulated building

components must not consist of mixed materials and inseparable composites. In addition, efficient material recycling methods are required.

The study by ifeu concludes that certain insulating materials made from renewable raw materials are ahead in terms of life cycle assessment but cannot be used for all areas of application. Insulation materials made from mineral or synthetic raw materials have a broader range of applications. In order to achieve a good ecological balance, they will need recycling on a much larger scale in the future in order to enter into a circular economy and thus lessen their considerable ecological footprint.

## 4.3 Demands on building materials – an architect’s perspective

(Kay Künzel)

Anyone working as an architect needs to have a certain degree of resilience. After all, they have to deal with topics that are both complex and diverse. From drawing, constructional details, standards and codes, divergent building materials, right down to overseeing work on the construction site – nuanced questions require competent and fast solutions. Sustainable building also requires detailed expertise in structural physics as well as extensive knowledge of the core topics of ecology and sustainability.

Unlike many other modern professions, an architect’s work is geared towards creating something that will endure. An architect creates a structure that will last for decades, something that is functional, aesthetic and should provide a healthy environment for its occupants throughout the life of the building. The question we need to address is this: what kind of expertise can the architect provide in order to cover all aspects of this undertaking, from design to mathematics, from physics to chemistry? Against the backdrop of global challenges in terms of ecology and sustainability, how can we ensure future-proof construction?

As far as ecological and sustainable construction is concerned, the architect faces the task of dealing with issues in the area of building chemistry. The decades-old question of how vapours from chemical building materials affect building occupants and indoor air quality has so far remained unanswered, especially since the adverse interactions between the materials used have largely been unexplored. The disposal of building materials from the 1970s is also still an important issue, and often dismantling is made more difficult by problemat-



ic building materials that were previously used widely, such as asbestos or polystyrene.

As the situation currently stands, architects and consumers simply have to trust what manufacturers tell them about their products. However, this trust has already been abused many times, for example, in the case of polycyclic aromatic hydrocarbons (PAH), asbestos, pentachlorophenol or lindane, DDT (dichlorodiphenyltrichloroethane), paints contaminated with tetrachloroethylene, formaldehyde-containing building panels, and insulation materials laden with flame retardants such as HCB. All the same, this has led to at least one debate currently taking place about recyclability – for instance, about building materials that decompose over the long term, such as mineral fibres.

The debate marks an important step, given that construction requires long-term, future-oriented thinking and planning. However, the problem of the health effects that chemical substances have on the human body and indoor air quality should not be neglected. To put it succinctly, almost all building materials, including furniture and interior fittings, and even the people

A truly sustainable building requires proper design for the whole life cycle of materials already in the planning phase.

themselves have the potential to off-gas chemical substances. In various EU directives and regulations, all emitted vapours are considered in blanket terms, that is, all volatile organic compounds (VOC) are placed in one category.

However, simply lumping everything together is not productive. For example, the vapours emitted from plants may be viewed as active ingredients rather than

pollutants, such as the well-known soporific and anti-bacterial effect of Swiss pine. Here, the concentration makes all the difference as to whether the substances are beneficial or harmful. Yet, in the latter case, this is usually a temporary problem, as herbal essential oils and their constituents are significantly more unstable than comparable chemically manufactured products. It is well known that SVOC (Semivolatile Organic Compounds) emit substances slowly and continuously over

decades, although the consequences for the human body are not known.

The volatile hydrocarbons in construction products based on petroleum, which pollute the air in the room, are particularly problematic. It would be essential to know which building materials emit which substances, how their constituents disperse, and which chemicals release unstable compounds. Additionally, we need to consider and examine interdependencies and reciprocal effects of the materials so that they can be taken into account in architectural planning.

On a positive note, in part because of the current coronavirus pandemic, the topic of indoor air quality has never been more acknowledged. Bacteria can attach themselves to dust particles, for example. The current debate on viruses is also bringing the topics of indoor air quality, electrostatics, dry air and dust into focus.

## What does this mean from an architect's point of view?

The architect cannot afford to assess the effect of building materials, how they interact with each other and how they affect human health. An evaluation of this would have to be included in the scope of services provided by the (specialist) planner and accounted for in the remuneration arrangement. However, monitoring of structural environmental protection is explicitly required in state building regulations. If the regulated limit values for indoor air pollution are exceeded and hygiene tests are negative, the architect is jointly and severally liable.

A full disclosure, both for chemical and natural building materials, is extremely important (see Chapter 4.1, DGNB standards). Regulations that govern toxicity in other industries (e.g. for cosmetics) should also be possible in the construction sector. The current documentation with supposedly ecological seals is not really meaningful and frequently misleading, especially for consumers. The predominant test methods relate too little to the installed state under real conditions.

The term 'sustainability', originally from forestry, tends to be 'run into the ground' in the construction industry to use a simple carbon footprint assessment for building materials. This simplifies considerations, since the rather than providing more clarity. The calculation methods for assessing environmental impacts are complicated, confusing and not comparable. As part of today's requirements, building materials must be evaluated over their entire life cycle, i.e. from the 'cradle to the grave'.

How is the architect supposed to manage this assessment without the support of the industry? Transparency

can only be guaranteed by means of a full declaration of building materials and therefore more detailed than the DGNB standards (see Chapter 4.1). An evaluation system is needed that makes it possible, for example, to use a simple carbon footprint assessment for building materials. This simplifies considerations, since the connections between CO<sub>2</sub> pollution and human health are known and have long been regulated. It is also possible to consider further environmental pollution.

According to the KISS principle (Keep It Simple, Stupid), we need a simple and clear declaration for building materials in the form of a traffic light. The "greener" the declaration, the more CO<sub>2</sub>-improving the substance is. There should also be a bonus system for particularly "green" building materials. That is more motivating than a regulation based on penalties.

The use of building materials that are as sustainable as possible should be part of any calls for tender as a matter of course. Natural, mineral substances should be given priority over fossil-based substances. The origin of the raw materials plays an important role from a global ecological point of view. The difference between whether carbon is obtained from crude oil or from plants is significant.

Architects must be able to have confidence in the products, including the ingredients, which they use in their projects. Ultimately, this is also what clients and users of the buildings expect; they are becoming increasingly aware of this set of issues and demanding transparency as a result.

## 4.4 How to achieve sustainability in buildings (Henning Friege)



### ONLINE SURVEYS WITH EXPERTS (see Annex A):

Requirements for better use of plastics in future: reduced complexity of materials (50%), upcycling technology/better or same quality for recyclates (50%).

To achieve sustainability in buildings, there are several important aspects, such as substitution of hazardous substances (e.g. additives in plastics), use of lightweight materials, and energy efficiency. Firstly, various toxic additives, such as some phthalates or flame retardants, were used in the past and some of them are already restricted or banned in Europe (e.g. bisphenol A, plasticisers such as DEHP, flame retardant HBCD) by the REACH regulation. Since the first restrictions by REACH in 2007, many new products and additives have been developed. Phthalate alternatives are in demand, e.g. in the area of PVC bonding agents. To date, isocyanates dissolved in phthalates have frequently been used to ensure optimal bonding of PVC plastisols to technical fabrics made, for example, from polyester fibres. DBP has mostly been used for this. LANXESS states: In the course of the discussion on phthalates, they created a new bonding agent that uses the same isocyanate previously deployed in the former one with phthalates. The new bonding agent 'is dissolved in a phthalate-free plasticizer' (LANXESS, 2018). In the case of flame retardants, there are also some positive developments. Expanded polystyrene (EPS) foam has been success

fully flame-retarded by a water-based coating containing nanoparticles of boehmite and poly(vinyl alcohol) (PVOH) as char former (Hamdani-Devarennasab, 2016).

Secondly, materials for lightweight construction play an important role for buildings, transport, etc. With regard to construction and buildings, there is special interest in lightweight concrete, where many recipes are already available. Developments in lightweight concrete go as far as Ultra High Performance Concrete, 'where nano-silicic acid is used, which through better nucleation during setting results in a concrete far lighter than conventional types of concrete with the same strength, rigidity and load-bearing capacity. Precise control of setting, amongst others with the objective of faster hardening with as high a level of homogeneity as possible, in



turn leads to a demand for special chemicals.' (Bazzanella et al., 2017). Aerated concrete exhibiting good insulation properties and low specific weight has been known for decades and is very popular in European countries. Up to now, this material cannot be properly recovered; recycling processes are now under development (Federal Ministry of Education and Research, 2020). Organic materials, i.e. polymers with a considerably smaller GHG footprint compared to concrete, normally cannot substitute concrete or steel for static loads. They are, however, used for reinforcement. The reinforcement of construction materials with fibres is a technique with a long tradition. Combinations of fibres with polymers have been produced on an industrial scale since about 30 years (Hänninen, 2010). FRP (fibre-reinforced plastics) are composite materials based on thermoplastics and thermosets. Bio-based polymers have not been very important up to now. Thermosetting plastics are used widely in vehicles, aircraft and ships but seldom in buildings, with the exception of special construction purposes, e.g. wind power plants. For special construction purposes, such as sealants or materials exposed to fluctuating ambient temperatures, FRP with 'self-healing' properties are of interest (see below).

The shift from fossil-based to renewable resources is one step towards sustainability in construction.

Thirdly, there is a huge demand for energy efficiency in housing. About 40% of energy consumption in Germany (heating, cooling and power supply) is generated by buildings (85% for residential houses and 15% for buildings used commercially). As mentioned at the beginning, in Europe (EU-28, 2016), 25.4% of the final energy demand can be attributed to heating, cooling and power supply for households (Eurostat, 2018). According to the International Energy Agency (IEA, 2020), residential and service-sector buildings account world wide for 21% and 8% of final energy consumption respectively (figures from 2018), exceeding final energy use in industry (38%) and transportation (29%). These few figures underline the enormous influence of the building sector on energy consumption and climate. Many innovations in construction and buildings therefore focus on reducing energy demand and/or on solutions that enable the production of energy by installing integrated PV modules. Although major research efforts are underway that focus on new buildings, the main problem is with building stock: 'As a matter of fact, about 70 % of buildings in the EU have been built after the Second World War (1960s to 1990s) and well before the entry into force of regulatory measures on energy consumption reduction.' (Ferrante, 2018).

Here are some examples of materials that improve energy efficiency in buildings:

**Walls** are often insulated with polystyrene or polyurethane. These materials are normally used in the form of foam (polystyrene) or sprayed in place (polyurethane and polyisocyanurate, see above). In the case of thick concrete walls, rigid boards made of polystyrene or polyurethane are also used.

**Fenestration** (windows and doors) provides thermal comfort and optimum illumination levels in a building. Glazing technologies, including solar control glass, insulating glass units, low emissivity coatings, evacuated glazing, aerogels and gas cavity fills, have been developed either for use as an additive function to commercial windowpanes or as part of 'smart windows'.

**Green façades and vertical gardens:** Horizontal and vertical greenery on buildings has an important impact

on a house's thermal performance and also benefits the urban environment. Plants function as a solar filter; they decrease heat absorption by the construction materials. Green façades have the potential to cool the building envelope, which is very important during summer periods in warmer climates.

**Sun protection, cooling and heating:** In regions with a very hot climate, more and more roofs (made from tiles, concrete, etc.) are being capped with solar reflective coatings (elastomers), white PVC membranes or other materials to enhance reflectivity and thus decrease the roof's surface temperature.

**Photovoltaic modules on roof and walls:** Photovoltaic (PV) modules are normally placed on roofs or located in the landscape just above ground level. There is considerable interest in integrating PV cells in walls (e.g. of skyscrapers) to make more surface area available. In the case of buildings, modules should be as light as possible in order to avoid massive structures. With respect to the module's frame, shifting junction boxes and other components from metal (mostly aluminium) to plastic decreases the weight and thus the cost for the required static load capacity.

**'Smart interior' – functional furnishing:** Plastic products used indoors are based on the same basic building materials as those used in the construction sector. However, other requirements apply, e.g. with regard to indoor air. They are therefore described separately. The topic of 'functional furniture' or 'transformer furniture' was researched. However, articles in literature focus on functionality and hardly any information is available about the materials used. Consumer demand for 'non-toxic' or 'organic' interiors is triggering numerous developments in the furniture industry. By way of example, the German Classen Group is marketing its natural design floor covering 'Neo by Classen': 'This hi-tech design floor covering, which was created using a new mix of materials and innovative production technologies, is based on wood-based biological materials without PVC and free of harmful chemicals, e.g. chlorine or phthalates.'

**Hifa produces biomaterials from waste rice, husks, sawdust or stubble to replace plastics. This waste is mixed with an edible fungus that previously grew on a substrate.**

**PRO:** Bio-based materials + agro-industrial waste + biodegradability is attractive. **CONTRA:** The exact products and material properties are inexplicit. **RECOMMENDATION:** The products made from these materials should meet the needs for biodegradability. The products have to show a better eco-balance in comparison to conventional materials.





## 4.5 Circular economy for polymers in construction? (Henning Frieger)



### ONLINE SURVEYS WITH EXPERTS (see Annex A):

The survey identifies recycling issues: Not profitable due to low quality of recyclates; missing technology, missing legislation/regulation. Composites are non-recyclable. Chemical recycling is not seen as a working solution (<10%).

The amount of waste plastics from construction and buildings will increase rapidly in the next decades due to the fact that plastic has been used in large quantities in buildings for about 50 years, of which more and more are now reaching the end of their useful life. In the European Union, waste and recycling regulations are more stringent in comparison to most other countries. Even in Europe, the recovery of plastics from the construction sector is rather poor, as can be seen from **Table 5**. The figures also include waste from construction sites, e.g. cutting waste and other residues (PlasticsEurope, 2017).

In the table, recovery is divided into 'mechanical recycling', which means 'recycling' or 'material recycling', and 'energy recovery'. With respect to the European waste hierarchy (Waste Framework Directive, Art. 4), recovery steps are prioritised: recycling of materials is preferable to energy recovery. Although chemical recycling is not mentioned in the directive, this might be

placed in between with respect to the conservation of a basic molecular structure. Disposal of plastics in landfills or incineration without energy recovery are not useful alternatives and should be avoided. In some European countries, landfilling of plastics is already banned, thus forcing the producers of waste to recover material or energy.

Plastic materials can be found in nearly every building, including very old ones (>50 years) due to renovation or refurbishment. This means that millions of tonnes of very different polymers are used in construction and can be recovered at the end of life of buildings. In order to recover material from dilapidated houses, it is necessary to dismantle them instead of pulling them down ('deconstruction'). The first problem to overcome is: What is known about the products used in the building or infrastructure at the end of life? Before deconstruction, it is necessary to consult the building plans (if available) or identify the most important components

Type of plastic	Total waste generation		Recovery					Disposal			
	In kt	In %	Total in kt	Thereof mechanical recycling		Thereof energy recovery		Total in kt	In %	Thereof landfill	Thereof incineration without energy recovery
				In kt	In %	In kt	In %			In kt	
PE-LD	40	2.7%	31	11	27.5%	20	50.0%	9	22.5%	8	1
PE-HD	120	8.2%	85	27	22.5%	58	48.3%	35	29.2%	33	2
PP	60	4.1%	42	11	18.3%	31	51.7%	18	30.0%	17	1
PS	15	1.0%	10	1	6.7%	9	60.0%	5	33.3%	5	0
EPS	135	9.3%	85	9	6.7%	76	56.3%	50	37.0%	47	3
PVC	840	57.6%	520	270	32.1%	250	29.8%	320	38.1%	310	10
Others	248	17.0%	197	17	6.9%	180	72.6%	51	20.6%	46	5
<b>Total</b>	<b>1458</b>	<b>100.0%</b>	<b>970</b>	<b>346</b>	<b>23.7%</b>	<b>624</b>	<b>42.8%</b>	<b>488</b>	<b>33.5%</b>	<b>466</b>	<b>22</b>

**TABLE 5:** Post-consumer building and construction waste generation 2014  
Source: Europe EU 28+ NO/CH

**INFOBOX 20:**  
**'Seven stumbling blocks' for recycling**

- **The entropy dilemma.** It is impossible to close recycling loops completely. It is very difficult to recover valuable materials encased in products, and energy is needed for their separation. In simple terms: The greater the number of materials in a product or the number of components in a material, the more energy is needed to decompose it after use.
- **Dissipative use:** This is a special form of the entropy problem – consumption of goods means a dissipative dispersion of products. If goods are distributed in millions of households, there is little chance of recovering them completely after use.
- **Dual character of waste and resource:** This is either a resource or a peril. The more the material or product in question is mixed up with potentially hazardous substances, the more difficult the recovery of valuables is. (Bilitewski et al., 2012).
- **Lack of enforcement:** The composition of waste is often not known; waste characterisation is difficult. This facilitates the fraudulent handling of waste and hampers the enforcement of legal standards.
- **Wasting of resources:** Booming economic systems rely on more and more primary materials from nature without considering the possibilities of further use after their application.
- **Socio-economic framework:** From an economic point of view, waste is a good with a negative price, i.e. for waste disposal, a price has to be paid depending on the quality and the amount of waste. If waste contains valuable components, the waste owner might decide to keep this waste fraction separate in order to decrease the price to be paid for the residual waste. High income disparities as well as low labour costs in relation to the market price of virgin materials are an incentive for formal as well as informal collection activities (Rodic et al., 2010; Steuer et al., 2017).
- **Role of time:** Time is a crucial challenge for waste management for several reasons. Firstly, consumption habits change with time and thus lead to unforeseen changes in the volume and/or the composition of waste. Secondly, valuable resources cannot be substituted with secondary raw materials as long as they are in use. Thirdly, chemicals banned for use in new products are present in the waste and thus disrupt recycling processes.

and possible pollutants by analysing the building. Core drillings can help. The second problem to overcome is: Is there a market for used or recovered materials? Only in the case of deconstruction can some parts of the building be separated and offered to recycling companies. Careful separation of the different components of a construction allows the recycling of the individual materials, e.g. masonry, concrete, steel, gypsum boards, cables and plastic parts.

However, even careful disassembly has its limits due to labour costs and the size of the building parts. This means that only large items made from plastics can be separated, such as window frames, shutters, insulation

boards, water and drainage pipes. Re-extrusion of separated plastic materials is only possible in the case of thermoplastics, such as PE, PP, PVC, but not with thermosets, such as PUR, silicones, epoxy resins. The latter can only be used for energy recovery or 'downcycled' to basic chemicals (see below). In contrast to most inorganic construction materials, the composition of many plastic products is complicated and varies with time. Additives, which give plastic materials special technical properties, impede the recovery of the pure polymers (see Chapter 1), either due to new technical demands or because one of the additives is now classified as hazardous. Two examples:

EU/305/2011 of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC – Construction Products Regulation, Annex I, No. 7: Sustainable use of natural resources. 'The construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following: (a) reuse or recyclability of the construction works, their materials and parts after demolition; (b) durability of the construction works; (c) use of environmentally compatible raw and secondary materials in the construction works.' However, this requirement laid down in the European Construction Products Regulation has not yet been implemented in any product standard.

**INFOBOX 21:**  
**Legal background – Construction Products Regulation**

- 40 years ago, PVC window frames contained cadmium (Cd) stabilisers to aid resistance against heat and UV radiation. These compounds have been banned in many countries because of the toxicity of cadmium (in Europe since 2001). According to REACH Annex XVII, Cd concentration in plastic materials should not exceed 100 mg/kg (0.01% w/w) with the exception of recovered PVC waste mixtures and items, which may contain up to 1,000 mg/kg (0.1% w/w). More highly contaminated materials can only be used for special building applications, such as profiles, rigid sheets, windows, shutters, cable ducts, etc. These products must be visibly, legibly and indelibly marked as follows: 'Contains recovered PVC' or with a pictogram. The Cd concentration in old windows is about 0.3%. As this additive cannot be separated from the polymer, old PVC frames can only be used as inner parts of new frames (Friege et al., 2018).
- Due to the worldwide ban of a very common flame retardant (HBCD was added to the Stockholm Convention) for EPS and XPS, which are the dominant insulation materials on the European market, mechanical recycling of used polystyrene from buildings is no longer possible. In Germany in particular, the amount of EPS and XPS waste from construction will increase from 36,000 tonnes in 2015 to 76,000 tonnes in 2035. This is a tremendous incentive to create chemical solutions because incineration of the enormous volume of foam is difficult. In the Netherlands, a pilot plant financed by an industrial consortium is under construction, which will separate the flame retardant by means of a special mixture of solvents, leaving the polystyrene

unchanged. The flame retardant will be incinerated and yield hydrogen bromide (CreaSolv, 2016, **see Infobox 23 and Chapter 4.6**).

These examples clearly demonstrate suitable alternatives: There is a need to separate hazardous compounds from plastics to be recycled or to dispose of the plastic stream in question completely if hazardous ingredients cannot be separated.

Mixed plastics – also from construction – are widely used as substitutes for coal or oil in cement kilns or for energy production in special power stations (refuse derived fuel – RDF plants), which are designed for waste with high calorific values. In this case too, pre-sorting of plastic waste is necessary in order to meet the standards of the cement kilns or the power plants. Contamination of the environment is otherwise inevitable because cement kilns have only limited exhaust air treatment. Plastic waste mixed up with other residual waste, residues from sorting, etc. can be safely incinerated in municipal waste incinerators, providing steam for industrial plants, district heating and cooling and/or grid power.

Recovery of plastic residues from construction sites is far easier than that of plastics from deconstruction because this material is mostly not contaminated with other waste and can be mixed with virgin material due to its identical composition. However, in this case too, thorough separation of waste fractions on site is necessary. Moreover, the producer must be able to take back the residues without considerable logistical effort. The example of a German company is presented in **Infobox 23**.

## Mechanical recycling of plastics in buildings?

In general, we have to differentiate between 'monofractions', i.e. PE or PVC or another polymer without relevant shares of other polymers or other waste, and 'mixed fractions', i.e. mixed plastics. In the first case, new polymers of sufficient quality can be recovered after thorough cleaning. In the latter case, a dark-coloured

material with certain physical properties (e.g. defined softening temperature, static strength after extrusion) is obtained, which can be used for simple plastic applications in infrastructure, e.g. draining pipes or fences. Even in the case of homogenous monofractions, the technical requirements for certain plastic products are

- Careful dismantling of the respective building
- Selection of the components suitable for possible recycling
- Separation of the various waste fractions
- Introduction of suitable processing methods in the recycling industry, including separation and disposal of hazardous residues
- A market for secondary plastics

**INFOBOX 22:**  
The main pillars of material recovery of plastic parts from buildings requires:

**INFOBOX 23:**  
**Example of EPS recycling**  
(Reinhard Pfaller,  
Rygol Dämmstoffe)

Rygol is located in Bavaria and Saxony and is a manufacturer of EPS boards of all kinds for roof, cellar, floor and wall applications. EPS is a lightweight insulation material with a thermal conductivity of between 0.031 W/mK and 0.045 W/mK. Due to the extremely low density of the material, it saves considerable fossil energy resources. Used as wall insulation, for example, the primary energy needed to produce the EPS boards, including production of the pellets, can be amortised in just a few months. German legislation prescribes that such products must be 'hardly flammable' for many applications, which is why the material contains a flame retardant. Changes in legislation and REACH made it necessary to substitute this flame retardant. A newly developed and very environmentally friendly flame retardant (FR) has been used since then. This is called PolyFR. This material has no bioavailability. The main costs of production are the raw material and transportation to the construction site. These represent over 70% of the production costs for the product. All kinds of production wastes are shredded directly at the machine and reused for the production of new EPS blocks. This kind of recycling has been practised since 1990. None of the production waste has ever been burned or deposited. If the material is cut at the construction site, the cuttings have to be collected in a sack, which is either picked up by the EPS manufacturer himself or a recycling company. They regrind even lightly dirty material. This product is used as lightweight aggregate for equalising screeds, for example. In the case of the dismantling of old buildings with material containing HBCD, special treatment is required. One way to destroy HBCD is incineration. However, in contrast to regenerative materials, this is not an option for the EPS industry.

To be able to recycle material containing HBCD, the sector needed a process which is able to isolate the brominated flame retardant and allow the reuse of the polystyrene in the solvent. The Fraunhofer Institute has developed a method to dissolve EPS and separate the bromine. This solution feeds the cleaned polystyrene into a new life cycle as clean and virgin raw material. The process closes the life cycle loop of EPS, even for polluted material from the construction site. To prove its performance on an industrial scale, a demonstration plant for EPS recycling is being built in Terneuzen in the Netherlands. A cooperative called PolystyreneLoop is in charge of this project, which was completed at the end of 2020 with a factory designed to dissolve 3,000 t of EPS and feed it back into a new life cycle in construction, with at least the same technical properties as the original product. As the bromine is removed from the material, it is an upcycling process that leads to a new and modern version of EPS raw material.



not met by secondary plastics due to high concentrations of interfering additives. In many processes, recycling steps mean downgrading of quality. Repeated extrusion, i.e. thermal reprocessing, may adversely affect the plastic material's properties. Recycled polymers – not only from construction but also from packaging and other areas of application – are therefore frequently used for the production of 'simple items', such as floor tiles, carpets or damp-proofing membranes (see, for example, the British Waste and Resources Action Programme – WRAP, 2020).

Pipes made from PE, PP or PVC are already collected separately where market conditions are favourable, e.g. by PIPA (Plastics Industry Pipe Association of Australia, 2020) or KRV (Kunststoffrohrverband, 2020). Only clean waste fractions (no other waste, not mixed up with other plastic waste) are accepted by the recycling industry (Tönsmeier, 2020). ROOFCOLLECT® in the UK recycles roof membranes made from PVC. Old roofs must be cleaned with a broom and cut up before deconstruction (ROOFCOLLECT, 2020). There has been considerable pressure on PVC recycling in

Europe for many years. This is partially due to the fact that rubble with a high PVC concentration is rejected by waste-to-energy plants because of the formation of hydrochloric acid, which damages the boiler. Window frames, doors, shutters, pipes and other PVC products are collected by a network called VinylPlus®<sup>4</sup> founded by the manufacturers of PVC-containing products. Window frames and doors represent the most important part of this waste stream, which amounts to about 740,000 tonnes Europe-wide (VinylPlus, 2019).

Ground plastic waste (preferably monofractions) can be used as a substitute for sand in concrete. Such experiments were first carried out twenty years ago

4 VinylPlus® is the voluntary commitment to sustainable development of the European PVC industry. The programme establishes a long-term framework for the sustainable development of the PVC industry by tackling a number of critical challenges in EU-28, Norway and Switzerland ([www.vinylplus.eu](http://www.vinylplus.eu)).

(Thorneycroft et al., 2018). Nowadays, over-dredging of sand is a problem in India and many other countries due to rapid urbanisation (see above). For this purpose, the durability of the products and their mechanical strength must be proven. Recipes are sought where the mechanical and chemical properties of the cement are not impaired by the addition of plastic instead of sand (Al-Tayeb et al., 2017; Hama, et al., 2017).

Separated polymers from waste (e.g. plastic bags) with low concentrations of other types of plastics can be crushed and moulded to produce simple products such as tiles, poles, etc., thus substituting stoneware, concrete or timber (GREEN PAVERS, 2019). Plastic waste can also be mixed with natural fibres (agricultural residues), producing a solid material that can be used instead of wood (Smart Wood, 2020). Products made from these materials can be used outdoors (e.g. fences), but mostly indoors (e.g. furniture, doors, partition walls). Outdoor deck material (planks, boards) made approximately of 40–50% thermoplastics and 50–60% wood fibres is very common in the USA and sold worldwide.

According to the producer, plastic is 'obtained primarily from reclaimed/recycled grocery bags and stretch film. Wood fiber is typically obtained from furniture makers and/or waste pallets' (TREX, 2018).

What does that mean overall? Products made of mixed plastics and inorganic components solve the waste problem for a certain time, but the products are not recyclable again because of the mixing of the materials. These products might become mainstream in countries faced with an enormous amount of plastic waste until plastics-to-plastics recycling is introduced. Legislators, producers and interest groups should be aware of the waste streams that occur with the end of use of these products: open incineration of these materials – as is common for timber products – will lead to health risks. Dumped plastic waste endangers rivers and oceans. Only controlled waste-to-energy plants could serve as a solution.

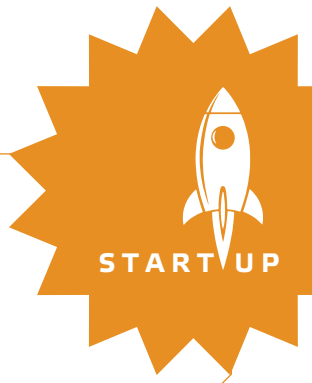
**PVC (polyvinylchloride)** can contain the softeners DEHP, DBP, BBP and DIBP. These are already regulated and restricted. Most (72%) PVC containing DEHP is incinerated. It can be assumed that DEHP is destroyed in the process. The remaining part is partly reused as material. Since grinding steps are also used in this process, emissions during recycling cannot be excluded (Polcher et al., 2020). PVC windows can contain heavy metals such as lead and cadmium. Approx. 70% (in Europe) are collected separately, with subsequent material recycling. No evidence could be found that this results in Cd emissions. PVC window frames made from recycled PVC usually consist of a PVC 'sandwich', where recycled PVC is used for the profile core and the outer cover layer is made of virgin PVC. This measure is intended to prevent possible exposure to pollutants of the environment and humans. Nevertheless, the pollutants remain in the cycle. Even in the case of energy recovery, lead and cadmium are not destroyed and remain in the ashes, slag and dust (Polcher et al., 2020). Bisphenol A (BPA) is a SVHC substance. Most PVC is disposed of in an energetic way. BPA is destroyed in the process.

**PE (polyethylene) and PP (polypropylene)** can contain chromium in pigments and arsenic as biostabilisers, as well as organic pollutants which have mainly been used as flame retardants. These are mainly POP substances (SCCP, HBCDD) and tetrabromobisphenol A. The combustion of halogenated flame retardants can lead to the formation of further pollutants (polyhalogenated dioxins and furans). Due to their physicochemical and ecotoxicological properties, short-chain chlorinated paraffins (SCCP) are identified as SVHC substances under REACH. At sites where recycling of plastics containing SCCP takes place, which may include processes such as crushing and grinding, SCCP can be released.

**EPS (expanded polystyrene)** – if produced before 2015 – can contain hexabromocyclododecane (HBCDD). HBCDD has long been the main flame retardant used in EPS and extruded polystyrene (XPS). HBCDD is persistent, which means it hardly degrades in the environment and is bioaccumulative. In 2008, HBCDD was included in the list of substances of very high concern (SVHC under REACH). At the end of its service life, an EPS product still contains about 99.99% of the original HBCDD from its manufacture. Possible emissions during product lifetime are therefore negligible. However, emissions from the demolition of buildings could be a future scenario, as many buildings with HBCDD-containing insulation material will be demolished in the future. HBCDD is destroyed in incineration processes.

**INFOBOX 24:**  
Possible emissions from plastics during recycling and incineration  
(Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU))





**RESHA Technologies is working to develop a recovery technology for end-of-life PV modules. It extracts glass, aluminum, silver, silicon, copper and polymers.**

**PRO:** Avoidance of future waste problems by providing appropriate recycling methods, taking renewable energy and end of life into account. **CONTRA:** While approach and idea are important, the techniques used still remain unclear. **RECOMMENDATION:** A set of construction guidelines for PV should be created that allow disassembling while maintaining functionality during usage.

## Chemical recycling of plastics in buildings?

Chemical or feedstock recycling is another alternative especially for thermosets (which cannot be thermally reprocessed, see above), plastics with hazardous additives or mixed plastics. To date, chemical recycling plays only a niche role and takes place exclusively in pilot plants. Products from feedstock recycling are basic molecules. In comparison to virgin products from refineries, the process is rather costly. The amount of plastic waste converted into basic molecules by chemical recycling is estimated to be less than 100,000 tonnes, compared to 25.1 million tonnes of plastic waste in Europe (PlasticsEurope, 2019).

There are also many attempts to convert plastic into a sort of oil or fuel through gasification or pyrolysis. So far, these attempts have failed due to technical problems and/or high costs. Newcomers in this business often underestimate the problems that arise with inevitable by-products such as tars (including toxic polyaromatic hydrocarbons). Due to ambitious recycling targets, which were introduced with the amendment of the European Waste Framework Directive, the importance of chemical recycling will increase. It remains to be seen whether other countries will follow this example.

The project, which was funded by Germany's Federal Ministry of Education and Research and supported by a broad consortium of research partners and representatives of industry and associations in the plastics value chain, was concerned with developing a concept for the sustainable recycling of plastic waste from the construction industry, with a special focus on chemical recycling. The various stakeholders in the value chain were included in the analysis, as was a comprehensive ecological and economic evaluation. Especially the value chain itself was examined, starting with the installation or use of plastics in buildings, through dismantling after the end of the use phase and the corresponding logistics required, to the processing and recycling of construction plastics. For this purpose, the KUBA project first analysed the plastics used in the construction industry and compiled a product and material register. This register shows the current quantities of plastics used in building construction and civil engineering in Germany, their utilisation and disposal periods, and statements on the dynamics of change for these material groups. Subsequently, a sample analysis of the waste streams currently generated by new construction, conversion and deconstruction measures was conducted, with a focus on the plastic components contained in them. With regard to collection and logistics, systems of different technological maturity for various material fractions and applications were examined. The project ran until the end of 2020 and the results will be published by DECHEMA – Gesellschaft für Chemische Technik und Biotechnologie e.V., Frankfurt, at the beginning of 2021.

**INFOBOX 25:**  
Pilot project 'KUBA – Sustainable Plastics Value Chain'

## 4.6 New recycling solutions (Swetlana Wagner)

While most global plastic waste still ends up in landfills (Ellen MacArthur Foundation, 2019), incineration and recycling constitute safer options for the environment. Nevertheless, not every type of plastic waste is recyclable, e.g. those that contain legacy additives. Legacy additives are substances that were added to the plastics at the manufacturing stage in order to improve their properties (e.g. fire protection, heat resistance, flexibility) (Zweifel et al., 2009). At the time of production, such substances were harmless, but from today's perspective some of them are now declared as harmful for human life and the environment (Hahladakis et al., 2018). The only safe destruction method is controlled incineration, but this leads to a waste of valuable resources. A more environmentally friendly solution includes safe destruction of harmful substances and the recovery of the polymer. The CreaSolv® Process represents such an approach, a solvent-based recycling process developed by the Fraunhofer Institute for Process Engineering and Packaging IVV and CreaCycle GmbH. In the CreaSolv® Process, thermoplastics are dissolved in what are known as 'green' solvent formulations, which are specific for the target polymer. Through this process, not only undesired impurities (e.g. non-polymers, other polymers) can be removed but also harmful substances.

To reduce energy consumption in buildings, thermal insulation is attached to walls. One example is thermal insulation systems made of EPS. To meet national fire regulations, EPS for insulation has to contain flame retardants. In the past, especially hexabromocyclododecane (HBCD) was used. After a service life of up to 50 years, buildings are demolished, and the EPS insulation becomes waste. There are three main challenges at the disposal stage of EPS:

- Because of their high volume and low mass (98% of EPS is air) transport is very inefficient, resulting in high costs and CO<sub>2</sub> contribution.
- HBCD is declared as a persistent organic pollutant (POP) according to the Stockholm Convention.
- Conventional recycling of EPS containing HBCD (e.g. re-melting) is not possible.

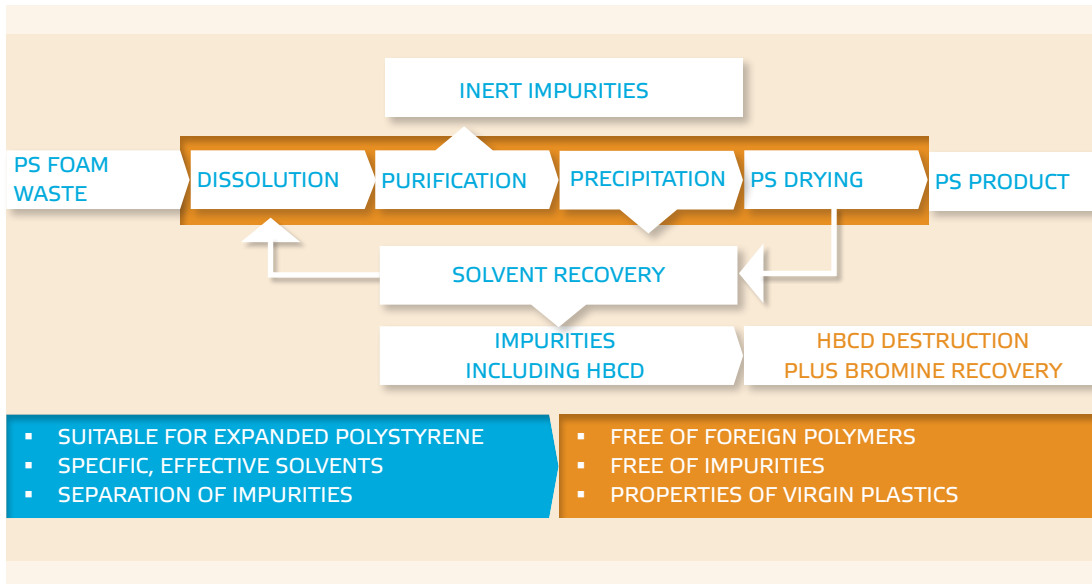
A promising approach to solve the challenges described is the solvent-based CreaSolv® Process. This physical recycling process enables the separation of polystyrene from impurities and the removal of legislated additives such as HBCD. Feasibility has been shown on a small

technical scale at technology readiness level 5 (Schlummer et al., 2017). The PolyStyreneLoop cooperative is a non-profit organisation, consisting of members from the entire polystyrene foam value chain. PolyStyreneLoop is currently building a closed-loop demonstration plant in Terneuzen, the Netherlands, for the recycling of EPS thermal insulation boards, based on the CreaSolv® Process.

This project is funded under EU Life<sup>5</sup> and contributing to the establishment of a circular economy in the European Union. Besides these activities, a working group is dealing with the integration of XPS boards containing (H)CFCs (hydrochlorofluorocarbons) into this recycling process. The XPS working group is supported by the Province of Zeeland and the Ministry of Agriculture, Nature and Food Quality of the Netherlands. In the CreaSolv® Process, the polymer is selectively dissolved using a specific proprietary solvent formulation. This dissolution is a physical separation process. It is a pre-treatment technology, which has the potential to recover plastic molecules from thermoplastics and separate them from legislated additives (such as HBCD).

The separation of different building materials and layers is the basic rule for successful recycling. Composites made of various polymers, mixed with minerals and other additives, are not suitable for recycling.





**FIGURE 12:**  
The PSLoop  
CreaSolv®  
Process

Solvent-based material recovery for polystyrene with HBCD elimination from thermal insulation boards

\*Includes thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants and PP-fibers. Not included: PET fibers, PA fibers and Polyacryl fibers.

Source: PolyStyreneLoop B.V

Today, these legislated additives must be destroyed in order to meet regulatory requirements<sup>6</sup>. The process consists of three steps. Steps 1 and 2 are pre-treatment for step 3 (see Figure 12).

- **First**, the PS foam waste is dissolved in a tank containing a PS-specific liquid. The solid impurities (dirt, cement, etc.) are separated by means of filtration and then incinerated or landfilled.
- **Next**, another liquid is added, which transforms the PS into a gel, while the additive (HBCD) stays in the remaining liquid. The PS gel is then separated from the process liquids. Once cleaned, this gel is converted into granulated polymer and the liquid, together with the additive, is distilled and reused in a closed loop; the additives remain as sludge.

This process is followed by the destruction of the HBCD additive within the sludge in high-temperature waste incineration, complementing PolyStyreneLoop at the ICL Bromine Recovery Unit. During the last step, the elemental bromine, used in modern flame retardants, is recovered and can be reused to produce new products, such as modern flame retardants in the same application (XPS or X-EPS), thereby closing the loop.

6 COMMISSION REGULATION (EU) 2016/293 of 1 March 2016





# 5. Summary, Outlook & Recommendations

Dr Claudio Cinquemani

Oleg Ditkovskiy

Professor Henning Frieger

Professor Sean Smith





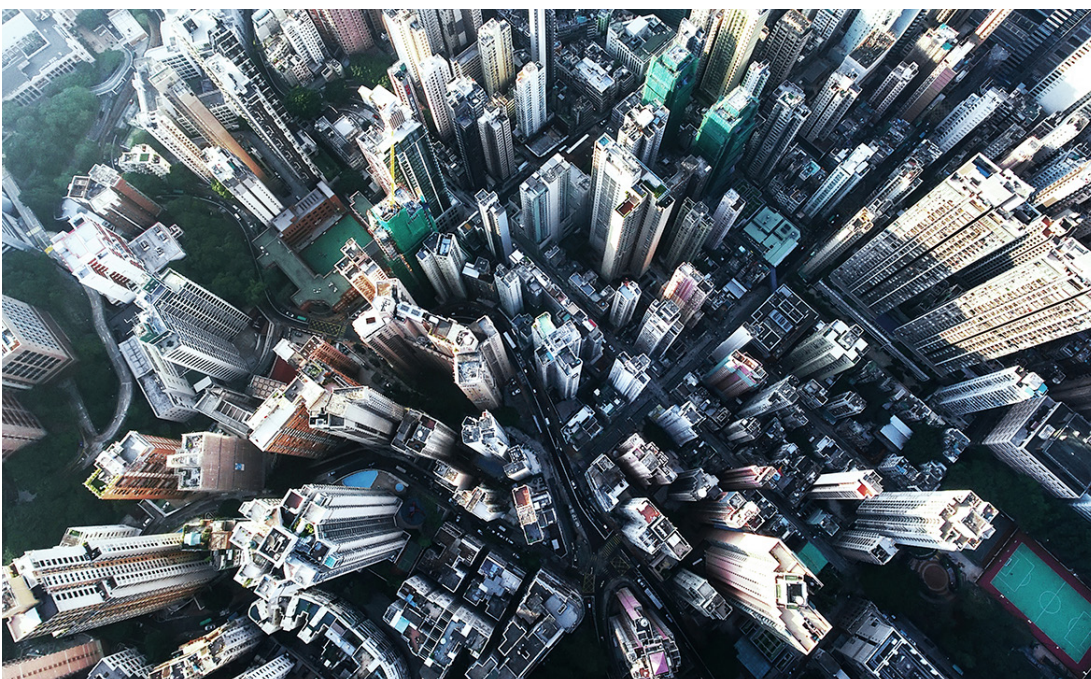
## 5.1 Urbanisation, affordable housing and resilience (Oleg Ditkovskiy)

According to Prof. Smith (2020) the world will have to build over two billion homes over the next 80 years in order to meet the 40% increase in global population, 2/3 of which will live in cities. What is more important, 2/3 of these cities will be situated in Asia and Africa. Vulnerable social groups in emerging economies and developing countries should be involved in planning processes, since the informal building sector will be a massive part of the urbanisation process, and the rapid development in construction should not be allowed to happen at the expense of those groups.

Plastics, both new and recycled from waste, can play a major role here as a relatively affordable material if well managed and depending on the local situation in terms of the availability of materials. However, affordable housing is not only a matter of the upfront costs for

the construction phase but also includes the costs of 'sick building', for example, and other mismanagement throughout the whole life cycle.

The enormous energy demand for the construction, residential use and maintenance of buildings will hinder global plans to reduce CO<sub>2</sub>, thus influencing climate change and, at the bottom line, the resilience of cities. To contribute to the better resilience of cities - energy and water efficiency of the buildings should be drastically improved. Resilience is fundamental for sustainability – and climate change itself is a driver for the (innovation) process of adaptation through experimentation with the goal of resilience. The question is: In which applications can suitable plastic products contribute to resilience?



Two thirds of the world's population will live in cities in Asia and Africa by 2100.



## 5.2 Plastics vs. alternatives – what is more sustainable?

(Oleg Ditkovskiy, Sean Smith)

For a variety of reasons, plastics have been a key choice for building systems and products. Compared with other materials, handling, price, functional properties and integration within mass production have proven to be attractive. The many functionalities are achieved through a large number of additives, which on the other hand massively hamper recycling.

Over the last 15 years, there has been a move to use greener products and systems. In addition, more countries have formulated sustainable development objectives, regulations and planning approaches, also for the building sector. This has often involved bringing together a mosaic of different construction materials, including plastics, and embedding them within construction and building standards so that they are more compatible with the SDGs. Many approaches are focused on one specific aspect, e.g. the reduction of CO<sub>2</sub> emissions, where plastic insulation plays a major role. In actual fact, these approaches lack holistic systems thinking.

There is no 'one-size-fits-all' material with respect to construction purposes. Depending on climate and regionally available raw materials, sustainable solutions are not uniform. There is therefore no simple answer to the question of if and when the use of plastic materials should be preferred or avoided. As we have to meet various demands that are often interdependent, such as energy consumption (see **Infobox 20**), climate change and its influence on building resilience (see **Chapter 2.4**), resource depletion (see **Chapter 2.3 and**

**3.1**), waste recycling (see **Chapter 4.2. and 4.5**) and indoor air quality (see **Chapter 3.2**), the choice of material for a specific application in construction is difficult and should be made transparent.

Plastic materials can be a rational choice if

- the weight of the product is far less than that of alternative materials, thus decreasing static load,
- energy consumption (within the life of the product) is significantly lower in comparison to alternative materials,
- the specific functionality of the product is essential for the building but cannot be provided by other material.

Plastic materials should be avoided if

- their use leads to indoor air problems as a result of the additives used (see also **Chapter 5.4**),
- hazardous materials (e.g. PUR foam made on site) cannot be processed safely by the workers,
- alternative products, especially from renewable sources, are available,
- reuse or recycling after use is not possible (see also **Chapter 5.3**).

With respect to recycling and reuse, separation of plastics from mineral waste at source is an indispensable prerequisite for recycling. This means deconstruction instead of demolition. If material recovery is not possible, incineration (state-of-the-art waste-to-energy plants) of plastic waste from construction, refurbishment or deconstruction is an option, especially in the case of polymers with hazardous additives.

Plastic building materials are attractive because of their specific properties, such as light weight, easy handling on site and relatively low price.



Plastics differ in many ways. With respect to the criteria mentioned above, lightweight products without hazardous ingredients which can be separated and recycled from buildings (e.g. PP pipes) appear to be a sustainable alternative in comparison to pipes made from concrete or cast iron. On the other hand, PVC flooring tiles slowly emitting plasticisers are clearly inferior to natural materials such as wood in the ecological competition.

## 5.3 Influence of plastics in buildings on resources and health

(Oleg Ditkovskiy)

Plastic building materials can contribute to reaching important SDGs, such as reduction of the energy consumption of buildings, yet at the same time conflict with health protection. Health issues in buildings are often also connected to the indoor air, which is influenced by chemicals in walls, ventilation, insulation, sealants and furniture. Because of hazardous additives, certain plastic materials emit volatile compounds that can have serious health consequences of an endocrine, reproductive, carcinogenic, cognitive and immune nature. Some of the substances have been banned from the market for decades in many countries but can be still found in old constructions and are still causing harm. Even if banned globally (e.g. by the Stockholm Convention), they can still be purchased on the internet. Since

plastic materials in buildings contain flame retardants, the danger posed by fire is underestimated. Burning polymers release toxic fumes and residues and those which are flame-retarded increase smoke toxicity due to the hazardous chemical additives. There is still a lack of regulations for smoke toxicity in many countries.

Plastics intended for use in buildings must be free of toxic by-products that can be emitted during their lifetime. There is a need to regulate emission standards for plastics as well as the smoke toxicity of construction products or furniture at best on a global level. These standards can build on preliminary work, such as national standards or regulations, and on the quality standards of leading manufacturers.



Plastic pollution has many dimensions: floating islands of garbage in the oceans, emissions of toxic additives, almost invisible microparticles, which re mixed up with plankton and thus enter the entire food chain from fish to human.

## 5.4 Outlook – circular economy and energy demand

(Henning Frieger)

Current and recent policy approaches to decrease GHG emissions will place greater pressure on energy usage.

At the same time, the inclusion of material feedstock and additional factors, such as design for manufacture and future disassembly, material recovery and embodied carbon, must be embedded in international standards. Factors such as type of raw materials, their origins, production and, in the first instance, energy saving on the one hand and recovery of materials from buildings on the other are therefore very important in what we build new or retrofit into our existing building stock.

The plastics industry has a responsibility to develop or standardise approaches to assist in future disassembly and recovery for reuse of materials. However, solutions for the deconstruction of buildings at the present time are also needed, even if the plastics produced in former decades are not based on 'design for recycling'. This means separate collection of plastic materials from refurbishment and deconstruction, aiming at the use of secondary raw materials for new products.

Plastic waste from packaging can also be a source of new building materials, but this requires homogenous waste fractions. In this case, new plastic products can be manufactured by extrusion of secondary raw material. Due to the enormous demand for cheap building products, tiles or bricks made from a mixture of minerals and plastic waste as a substitute for sand have been introduced in many African and Asian countries. Even if no other cheap alternatives have been identified so far, construction companies as well as authorities should have the end of life of these buildings in mind. Currently, the after-use phase of these materials is unclear. Additionally, tiles and bricks made entirely of waste plastics (sometimes recommended as 'eco bricks') are life-threatening products in the event of fire.

The demand for circular economy solutions is communicated to all producers of building materials and not only the plastics industry on a global level by the scientific

community, reports such as GCO II and instruments such as the 2030 Agenda. Future growth in the construction sector and innovations that reduce waste can help it to achieve sustainable solutions, which can be designed for easier deconstruction and reuse in the future. However, further guidelines for sustainable development are required in order to achieve any real improvement.

We have summarised the main issues of using plastics in building, considering the megatrends urbanisation, resilience and affordable housing. Environment and human health can be endangered by the (improper) use

Circular economy is based on well-functioning recycling: collection of plastics materials from refurbishment and deconstruction and their use as secondary raw materials for new products.



of plastics. New emerging issues in this area involve energy and recycling and depend, in the first instance, on the quality of the original feedstock. In order to deal with this complex setting, we would like to highlight various approaches under different regional conditions in the **next chapter** and point toward some action fields in **Chapter 5.6**.



## 5.5 Different approaches in industrialised, developing and emerging economies (Oleg Ditkovskiy)

Sustainable use of plastics in construction as well as sustainable development in general follow common global principles such as:

- The shift from fossil-based to renewable resources whenever possible and feasible
- Consideration of life cycle assessment already in the design and planning phase
- Restriction and substitution of hazardous additives.

However, overall socio-economic, technical, regulative conditions and resources can vary tremendously in each country and region. Indeed, there is no 'one-size-fits-all' solution with which to make the construction and housing industry sustainable in one go.

Regional conditions, e.g. temperature, humidity, flooding, thunderstorms, economy, culture, availability of resources, need for new housing, etc., play an important role in the choice of sound building materials. Renewable materials of sufficient quality should in any case be used as far as possible in order to avoid GHG emissions. This greatly depends on the regional availability of resources, raw materials, manufacturing capabilities, know-how and legislation. Regional conditions are a significant factor, for example in cases where bio-resources such as wood or plants could be used as a natural source for organic polymers. To date, most countries use fossil resources as raw material for organic polymers.

Other regional conditions are of a social and cultural nature, for instance, growing individual living space and, in conjunction with this, the increasing need for material resources per capita, e.g. in the USA and Switzerland. At the same time, there is a lack of housing altogether for a rapidly growing population in Asian and African countries. For developing economies, rapid, uncontrolled growth very often results in two problems: lack of affordable and healthy housing and infrastructure on the one hand and environmental degradation and poor waste management on the other. These economies should strive to decouple environmental degradation from economic growth. Many different challenges thus have to be tackled in a short space of time.



Bringing sustainability to the building and construction sector means challenges at many levels of urban planning. Cities need to improve their resilience: their ability to adapt and resist the effects of climate change and other natural catastrophes, especially in a poverty-oriented and inclusive way. Plastics can and should foster the resilience of buildings, e.g. against earthquakes and other catastrophes.

The question of what is sustainable in the area of building polymers varies depending on the region and the timeframe. On the one hand, recycled waste polymers used in composite materials in highly polluted regions bring a number of advantages: cleaning of land and water from plastic waste, their relative affordability and easy use on site. In countries experiencing a building boom, such as India, the substitution of sand for concrete with polymers can save enormous amounts of sand, thus reducing the scarcity of this natural material as well as the weight of the concrete, meaning improved performance.

On the other hand, the use of such composites will bring new problems after their use phase at the end of their life in some decades, since it will not be possible to separate these materials and recycle them again –

Most recycled building materials cannot achieve a level of quality comparable to their virgin counterparts (with some exceptions). Market incentives for recycled products are required.

or only with high energy input and waste output. The ingredients in the initial plastic often include toxic additives that remain in the cycle and with high probability are released to humans during the use phase (sick building); toxic substances in the waste will also become a problem for landfill or open incineration after the end of the life cycle. The only solution might be found in controlled waste-to-energy plants.

While products from recovered plastics in industrialised countries are usually regulated by binding standards, such standards are often lacking in emerging markets. Standards and quality inspection of materials are needed in order to guarantee the technical performance for the application in question. The availability of large amounts of plastic waste together with higher prices for virgin plastics stimulate the production of composite materials in Africa, Asia and Latin America; and vice versa low prices and stricter regulations for waste in industrialised countries make the recycling of building plastics and their further use unattractive. Industrialised countries should therefore stop their current common practice of exporting waste to developing and emerging economies that can be only processed in low-quality construction products and indisputably lead to environmental and health problems for the next generations.

Most African, Asian and Latin American countries are facing pressing social issues in conjunction with affordable housing. Health, environment or sustainability are expensive and not ranked as a top priority. A bottom-up approach should be adopted in these regions. This means that in order to encourage sustainability, the informal sector, i.e. self-builders, should be helped, and regulations, financial and social programmes, and training introduced.

In China, the top-down approach to sustainability prevails, since the government drives most innovations and developments along the whole supply chain. The two biggest issues in China at present are the lack of proper recycling technologies as well as a lack of awareness towards cost-benefit analysis in the building materials sector.

In the USA, a general awareness towards sustainability is missing, as are regulations for dealing with hazardous substances in the building sector. Lobbying of the chemical and construction industry in the USA is so powerful that in recent decades there have been many obstacles to the realisation of sustainable and environmentally friendly proposals. It is therefore necessary to develop a public strategy in the USA that is able to support the environment through a set of regulations.

Alongside region-specific regulations, consumption and waste handling culture also influences industry. After hazardous HBCD was included in the Stockholm Convention and the REACH Annex as SVHC, it became impossible in Europe to continue using recycled polystyrene from old insulation panels. During the coming decade, many buildings containing such panels will come to their end of life, but there will be no market for such recyclates unless HBCD is removed from them. As mentioned above, such technology is under development, but so far they exist only as an experimental process. It is therefore crucial to focus on sustainability already in the planning and design phase in order to prevent situations like that with HBCD. For example, the substitution of toxic additives and designs for the separation of various materials and their further recycling are essential.

As described in **Chapter 2**, the demand for material resources will also be significant. Current global shortages, such as river sand for concrete, illustrate the type of pressure on future material supplies and the need to embed circular economy approaches in all countries as soon as possible. It is essential on the one hand that conventional and renewable materials are used and on the other that recycling technologies and take-back schemes are implemented and widespread. Due to their unique properties, plastics can also play an important role in new applications and technologies in order to solve, for example, weight and performance problems as well as to save energy and reduce GHG emissions during the use phase.



## 5.6 Most relevant action fields and potentials for sustainable solutions (Claudio Cinquemani)



Traditional building materials can be a sustainable alternative for plastics, but in some cases cannot be used for all building applications.

To motivate stakeholders to embrace sustainable construction and buildings, with or without plastics, we have derived recommendations from Chapters 1–4 in the areas of research, innovation, capacity building as well as policy and stakeholder dialogue.

### General points:

- Decisions have to be knowledge-based in order to facilitate both incremental and disruptive innovation and systems thinking aimed at avoiding rebound effects and the substitution of hazardous materials by other materials containing other hazardous chemicals (regrettable substitution) in the present or the future.
- The framework conditions for innovations need to be understood from the very beginning, as design, for example, is often a deciding factor in the subsequent choice of materials.
- To foster a more sustainable development of the construction sector, developers and manufacturers need a proper innovation framework.

- Awareness raising among the stakeholders involved and proper training for staff are key to the adoption of innovations.
- Structured stakeholder dialogue is needed, including discussion of the development and enforcement of political and legal frameworks on various levels (local, national, regional, global).

### Research needs to foster knowledge-based decisions:

- The SDGs have to be seen in the context of megatrends that drive construction and choice of materials: Sustainable development can only be achieved by transforming the way of building and managing urban spaces, since that is where growth happens. Knowledge of regional aspects related to demography, regional affordability and special needs for resilience have to be considered in the planning and construction process.
- A better understanding of the entire life cycle of materials, particularly plastics, is needed, from source-

ing, production, building, use phase to deconstruction. It is also necessary to compare conventional materials with plastics(-based) materials. This must include considerations such as health aspects, functionality, affordability, resource conservation, energy consumption, GHG emissions, longevity, waste minimisation and recycling, among others, i.e. all possible impacts along the whole life cycle of materials and their application in construction in general and broken down into specific cases (type and function of building, region etc.).

- Risks should preferably be avoided already in the design phase of a building. Additionally, monitoring of ambient hazardous agents might be necessary in existing buildings. While many countries have banned problematic substances in plastics, some countries have no reliable data on illnesses and deaths caused by these materials (particularly for vulnerable subpopulations) and on the true extent of environmental pollution.
- Plastics from renewable sources should be favoured over those of fossil origin. Several products have already been launched onto the building market, including renewable-sourced polyamide, epoxy resins, non-isocyanate polyurethane and sugarcane-based PE. While CO<sub>2</sub> emissions can be reduced, large-scale production of sugarcane might lead to the destruction or damage of biodiversity and further deforestation. Biodegradable polymers, on the other hand, are not designed for a circular economy. Functionality and end-of-use requirements therefore need to be considered.
- An understanding is needed of how materials, products and applications can be designed for recycling and proven to be recyclable. Starting with raw materials, their design should make provisions for the economic and environmental aspects of production and transportation as well as possible social impacts in the target regions, proper and safe usage, easy separation and infrastructure for recycling or reuse, including technologies, and a market. This means that extended producer responsibility should be introduced in the building products' market.

- Traditional building materials, such as clay, stone and wood, have been largely replaced by plastics in several applications. The use of traditional and thus locally available materials as well as recycled materials needs to be explored in greater depth – taking other sustainability aspects such as material scarcity and health impacts into consideration at the same time.
- Hazardous substances in plastics need to be clearly identified and research is needed on non-regrettable substitution for these substances.
- New, unconventional technologies such as polymer-based photovoltaic façades, lightweight constructions and self-healing materials need to be monitored and both their possible contribution to sustainability as well as possible adverse effects better understood. Their use needs to be more sustainable than alternatives.
- The recycling and health aspects of using plastic (e.g. from post-industrial or consumer waste) as an alternative binder to replace sand in concrete in order to facilitate the use of local raw material are not yet understood. Besides suitability in a particular region, above all health issues and recycling possibilities should be investigated.

Research into the substitution of hazardous substances requires a careful approach in order to avoid rebound effects.



## Innovation framework:

- To achieve the SDGs, sustainable transformation in and with cities is essential. At the same time, cities have less access to natural building materials and are particularly vulnerable to the effects of climate change – this needs to be taken into account by planners.
- Prototypes need to be tested under real-life conditions: For example, urban experiments with eco-pilot buildings and new concepts that consider pedestrians and cyclists, thus showcasing alternative approaches to all interested stakeholders.
- -Due to lack of affordability, mega innovations that could disrupt the construction industry (such as AI, robotics, 3D printing) are outside the reach of many emerging economies. As this cannot be solved instantly, it needs to be kept in mind.
- While some regional and international standards exist, starting with how to design with plastics up to how to take back and recycle them, we need to acknowledge that there is no blueprint solution and countries/regions/cities need to be flexible and make decisions tailored to their needs.
- Many polymer products have to be replaced during the lifespan of a building – materials need to be developed and/or used that meet that lifespan. Plastics which do not meet the lifespan must be accessible and replaceable.
- Plastics are seen as affordable innovations in comparison to conventional materials. However, upfront project costs are not real costs. There is therefore a need to adopt a definition of affordable housing that includes health and environmental issues. Enormous investments are needed for adequate and affordable housing – conventional financing instruments cannot deliver this, and new financing instruments, such as climate risk insurance, are needed.
- An index that analyses the contribution of a building and its materials – including plastics – to the SDGs could help, and a third-party rating framework would add credibility. As long as indices of this type are not introduced on a global level, existing and reliable assessment tools should be used.
- Life cycle assessment for plastic building materials and alternatives needs to address the social dimension as well as upstream processes, including the sourcing of raw materials.



- All costs along the life cycle, including environmental, health and social costs, have to be considered when it comes to pricing (internalisation of external costs/true full costs of a product and its application). This would foster innovations.
- Building costs are paid from different budgets and by different stakeholders than maintenance and recycling costs. These costs have to be internalised. The use of more sustainable alternatives (even more expensive ones) pays back over the entire life span.
- The increased use of polymers with their additives has led to major health threats through smoke in the event of fire. Improved regulating of these additives is needed and will incentivise industry to develop and implement non-hazardous or less hazardous alternatives.
- Fostering the organisation of cooperatives that embrace members from the entire value chain and the complete life cycle can help to build a recycling loop that creates materials and products for which there is a demand on the market.

New technologies, such as 3D printing and artificial intelligence (AI), are being explored as ways to support sustainable development in the construction sector too.



## Capacity building: awareness raising, education and training:

- In particular cities as well as many regions lack resources and a qualified workforce – especially for the use of non-traditional materials. Training in the construction of sustainable buildings under regional conditions is key to a sustainable future of these cities.
- Awareness of the use of plastics in construction needs to be established, especially in fast-growing economies, alongside know-how on the healthy use and recycling of these materials.
- Information on the materials used in a building needs to be available, processed in an understandable way and made accessible for all stakeholders. Especially the most vulnerable population groups need to be involved and should have an opportunity to acquire the know-how already needed for the planning phase.
- Residents need to understand that with more floor space per person the negative implications also increase – even green building standards do not reward limits on space per person. Additionally, residents are often unaware that contributing to one goal can conflict with another.
- Industry needs to understand – also through training for its decision-makers and operative staff – that offering more sustainable products provides an opportunity to improve market entry or even access new markets, thus additionally de-risking their business model.
- Independent non-governmental organisations should support awareness raising, education for architects, civil engineers and manufacturers as well as a redefinition of legislation in order to address the sustainable construction of buildings, while avoiding green washing and sustainability washing.

## Policy and stakeholder dialogue:

- Bans, mandatory authorisation and strict regulations are instruments to foster the development of substitutes for toxic substances. Information, obligations such as those under REACH or eco-labelling are less imposing measures and might therefore be a route to more rapid progress.
- Framework and building codes are top-down tools that have to be in place for resilient buildings and comply with the New Urban Agenda, which also



takes into account energy-efficient buildings, local, non-toxic and recycled/recyclable materials. Such instruments, however, need to be implemented with greater consistency.

- In many economies, standards, such as CEN norms, are yet to be developed for plastics for use in construction. These must take into consideration the available country-specific recycling opportunities and routes as well as the markets and demand for such products.
- Appropriate documentation of all the ingredients in a product and the entire building needs to be ensured. Transparency would be greatly enhanced through a 'pass' for building and other infrastructure materials. Next generations have to learn how to deal with a building after its life cycle through training in how to read and interpret such documentation in order to solve dismantling and recycling issues. Compiling such documentation is easily done in today's era of digital information and web 4.0, but training is also required.
- A combination of market pressure and regulatory pressure has already removed some harmful substances. In order to keep all data accessible, transparent and understandable for everyone, aggregating and averaging data should be avoided. At the same time, a simple and clear declaration could help to avoid confusion. Considering both aspects is clearly a challenge for legislation.
- Producers must make their products traceable, retrievable and recyclable to other players on the market too – and also avoid hazardous ingredients that would only allow downcycling or energetic recycling.

Staff training and awareness raising among all stakeholders are crucial for the adoption of innovations.



Stakeholder dialogue on different levels includes legal, financial and social aspects.

- Existing standards and guidelines have to be reviewed in order to include end of life and recycling – alongside a database of reliable recycling routes.

Viewed overall, implementing most of these recommendations is essential if the vision – a more sustainable construction sector – is to be achieved. For some recommendations, an international solution will prove successful, for some a regional approach and in some cases a local solution has to be found. It seems that for a coherent programme a top-down approach is needed – again, this largely depends on the circumstances

and the environment where the measures are to be implemented, and sometimes a bottom-up approach or a combination of both may be more appropriate. This has to be better understood: in a wealthy, highly industrialised setting with recycling technology and take-back schemes in place, other solutions will work than in an environment that calls solely for affordable housing – a largely informal building sector is more likely to accept bottom-up approaches. These differences in industrialised countries as opposed to emerging markets are a clear challenge. Still, however, elementary requirements have to be met by all.



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## Annex A: Online surveys

ISC<sub>3</sub> conducted four online surveys dedicated to the corresponding topics of the workshops. Each survey contained up to 16 questions. 103 experts took part. Some figures from the surveys are depicted in **Annex B**.

### 1. Background, Participants, Geographical Focus

Three main groups were represented in this survey: 40% are scientists and researchers, 15% engineers and architects and 14% have a background in legislation and policy. The participants work mostly in production of materials (15%), NGOs (14%), ministries (14%), recycling (12%) and construction (9%). Their geographical focus is Europe (35%), Asia (28%) including East Asia and the Middle East, South and North America (20%), Africa (11%) and the Pacific region including Australia and New Zealand (5%).

### 2. Choice of Materials, Cost Benefits, Advantages and Attitude to Plastics

From the arguments supporting the choice of building materials, price was selected first and almost unanimously by 97% of respondents followed by health (78%) and availability (76%). Convenience and durability were next with 71% and 68% respectively. Sustainability was at the bottom of the list with only 55% of the answers, with 24% of respondents specifying explicitly that sustainability is not important at all. The participants were asked to name the main products that drive the use of plastics. Piping and thermal insulation were the ones specified most (24% each), followed by façades (14%) and flooring (10%). Most respondents found that plastic materials involve low maintenance costs (73%) and also low investment costs (59%), are easy to use in construction (68%) and also easy to maintain (55%). At the same time, more than half the respondents (53%) found that plastics are difficult to recycle and rate their durability as low (48%). There was no uniform opinion concerning disposal costs, which were rated by 47% as high and by 33% as low. Most participants regarded

plastics' performance as their main positive feature (40%), followed by easy handling and low price (each 23%). The main negative aspects connected to plastics were pollution and recycling problems, which were stated by 60% of experts, followed by performance issues (19%) and use of fossil-based raw material (11%).

### 3. Energy Efficiency, Resilience and Affordability of Plastics

There is a clear and united opinion on two aspects of plastic building materials (health and affordability): Most respondents (62%) did not agree with the statement that plastic building materials are healthier, while 52% agreed that they are more affordable. At the same time, there was no uniform opinion on two aspects: resilience and energy efficiency. Opposite opinions were represented with almost the same share of answers: 39% of respondents disagreed that plastic is more resilient but 33% found that it is. In a similar way, 42% agreed that it is more energy-efficient but 38% disagreed.

### 4. Resilience and Affordability for Low-income Populations

The respondents were asked to name resilient materials that are affordable for low-income populations. Both natural (59%) and waste-sourced (48%) materials were seen as the most affordable and resilient materials. Metals and compounds were evaluated negatively in the sense of the question (=not affordable and resilient). For concrete, there was no clear tendency (with 52% a neutral answer). The evaluation for plastics was again mixed and spread equally – about one third of respondents in each category rated plastics as poor, neutral and good in terms of resilience and affordability.

### 5. Sustainability and Plastics Use

The participants were asked how plastics support or hinder sustainability. According to a third of the respondents, plastics contribute to sustainability because of their longevity and recyclability, specific properties, energy-saving and insulation potential (28% each), their socio-economic benefits (12%) and the fact that they help to preserve other natural resources such as trees (12%). On the other hand, plastics hinder sustainability because of issues with recycling (50%) and health and environment (19%).

### 6. Life Cycle Expectancy

The respondents expressed a clear opinion on materials: metals (82%) and concrete (71%) have the highest life cycle expectations, followed by plastics (61%). Natural materials are in the middle with 44% positive expectations (high) and 33% average expectations. Compounds and waste-sourced materials were rated as having an average expectation by about half the respondents.

## 7. Recycling

When asked about the main issues for the recycling of plastics in construction materials, the experts reported that no recycling is taking place because it is not profitable, the recycled products are of low quality and technologies as well as legislation and regulations are missing. Chemical recycling is not seen as a working solution (< 10%). Nearly 50% of participants regarded recycling and disposal as the dominant problems; about 30% saw a need for new policy and information for capacity building as a solution. The only material group that can be recycled for certain according to most of the experts is metals (66%). Especially composites are seen as non-recyclable, 74% said that they are disposed of together with plastics and concrete (both 46%). Minerals are rated equally for either disposal, recovery or recycling (1/3 of respondents each).

## 8. Life Cycle Stages and Health/Environment

Within the life cycle of plastic building materials, respondents rated the following stages as critical for health and environment: Recycling (79%), fire incidents (77%), production (69%) and demolition (57%). The following phases were rated uncritical: Construction site (55%), transportation (53%) and use phase (43%).

## 9. Emissions during Life Cycle

The respondents were asked about problems related to waste status and emissions in the life cycle. During construction packaging was the predominant answer (40%). In the use phase, the answers for the most concerns were spread between PVC, VOC, piping and plastics containing MAH and PAH (25% each). The following were named by 20% as the second most important concerns during the use phase: Composites, façades, emissions and plastics with toxic additives (such as brominated FR). In the demolition phase, compounds were mentioned by half the respondents. Plastics with flame retardants, e.g. PVC and EXP/XPS, aroused concerns among about 38% of the respondents. Plastics used as binders for AMF (artificial mineral fibres) were also mentioned by individual respondents.

## 10. Recycling (Technologies)

The respondents were asked about technologies for reusing or recycling construction plastics. More than half (56%) specified chemical recycling. Mechanical recycling of pure fractions, e.g. PVC windows frames, and take-back systems gathered 27% of answers, landfill as the only solution was mentioned in 9% of answers. 9% also replied that reuse and recycling of plastics are easy if they are toxic-free. Half the respondents would like to see a reduction in the complexity of plastic materials. An-

other half would welcome an upcycling technology or at least like to see that quality stays the same after recycling.

## 11. Energy and Emissions Savings

The experts were asked how energy could be saved and high emissions avoided by using plastic materials in buildings. A third of the respondents mentioned recycling, specific design and sustainable production (30% each), followed by using insulation (24%) and alternatives together with the avoidance of plastics in general (21%).

## 12. Risks, Health and Environment

38% of respondents named emissions, climate and environment as the main risk in building and living, followed by impacts on human health and biodiversity (19%) and social and political issues (18%) at second place. Materials and resource scarcity was mentioned by 14%, followed by waste and recycling problems (11%).

## 13. Health

The respondents were asked to rate different materials regarding human health. With over 70%, only natural materials received a positive response, followed by metals with 54%. Compounds (50%) and waste-sourced materials (42%) have the most negative image. Concrete received a 47% neutral and a 35% negative response. Opinion of plastics is ambivalent: the general attitude of the respondents was reflected in three relatively similar groups: impact on health was evaluated as good (38%), neutral (28%) and poor (33%).

## 14. Innovations to Avoid Health and Environment Issues

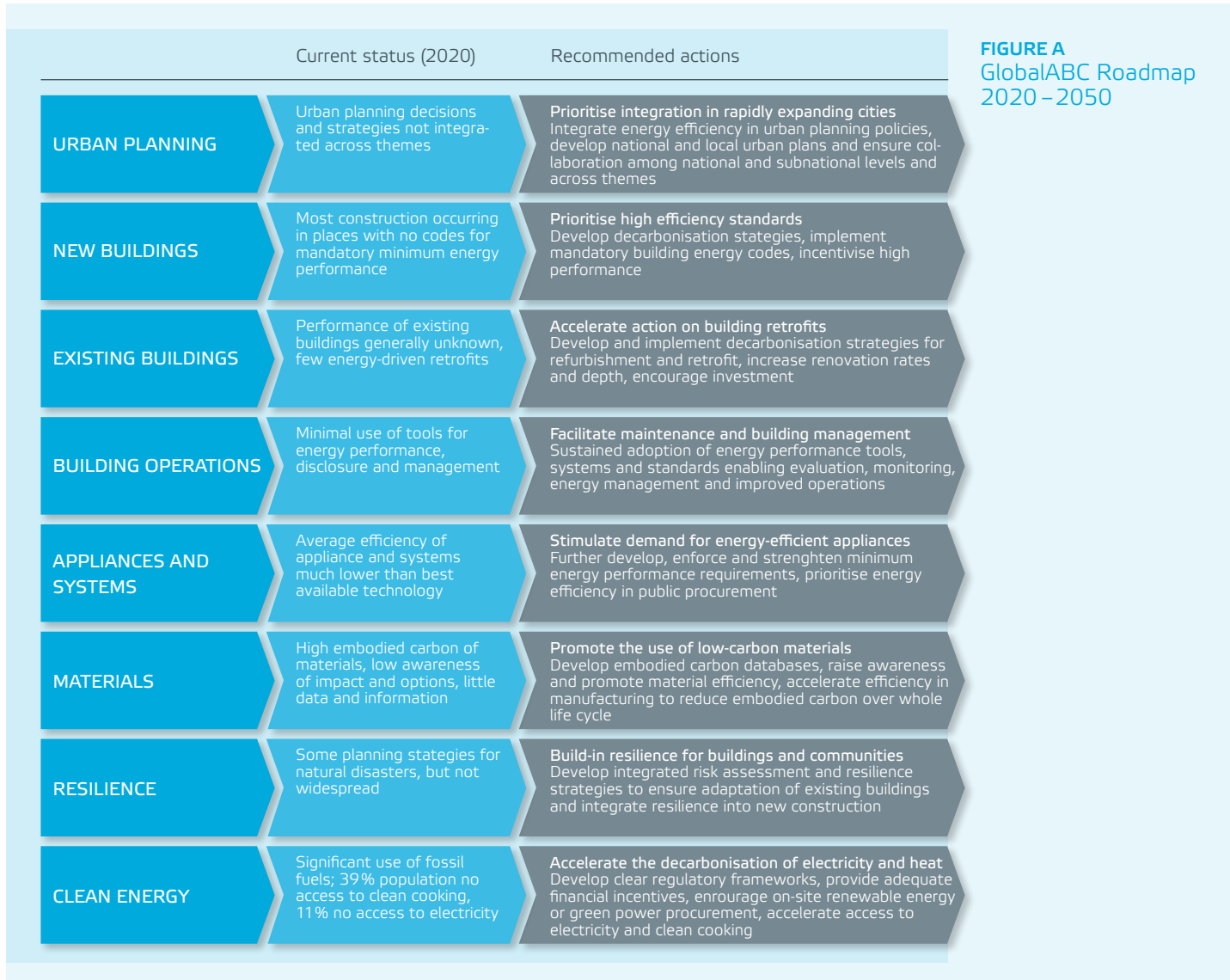
The respondents in Asia were asked whether they were familiar with any polymer-based innovations to avoid health and environmental issues. 35% could not give any clear answer. The other 65% made the following propositions: removal of additives, bio-based and biodegradable polymers, design for recycling, high-performance insulation, more sustainable plasticisers, sterility, sealants, food packaging, long-lasting and healthy pipes, more sustainable blowing agents and renewable feedstocks.

## 15. Restrictions for Plastics Usage

Policy and a ban on plastics (e.g. because of emissions) were seen by 31% of the respondents as the most important way to restrict plastics. Rising prices were considered to be the second most important issue (15%). Other given examples, such as supply shortage and technologies, were not mentioned at al

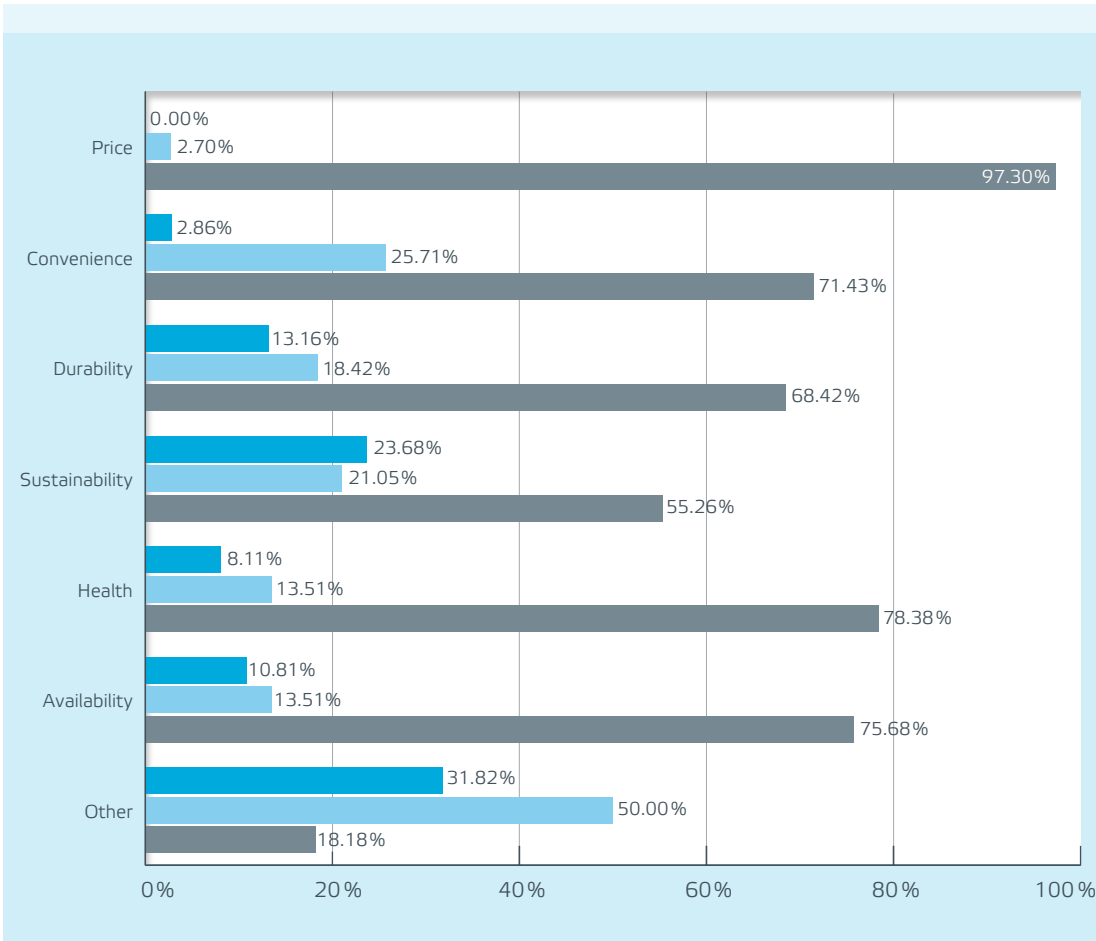


## Annex B: Figures



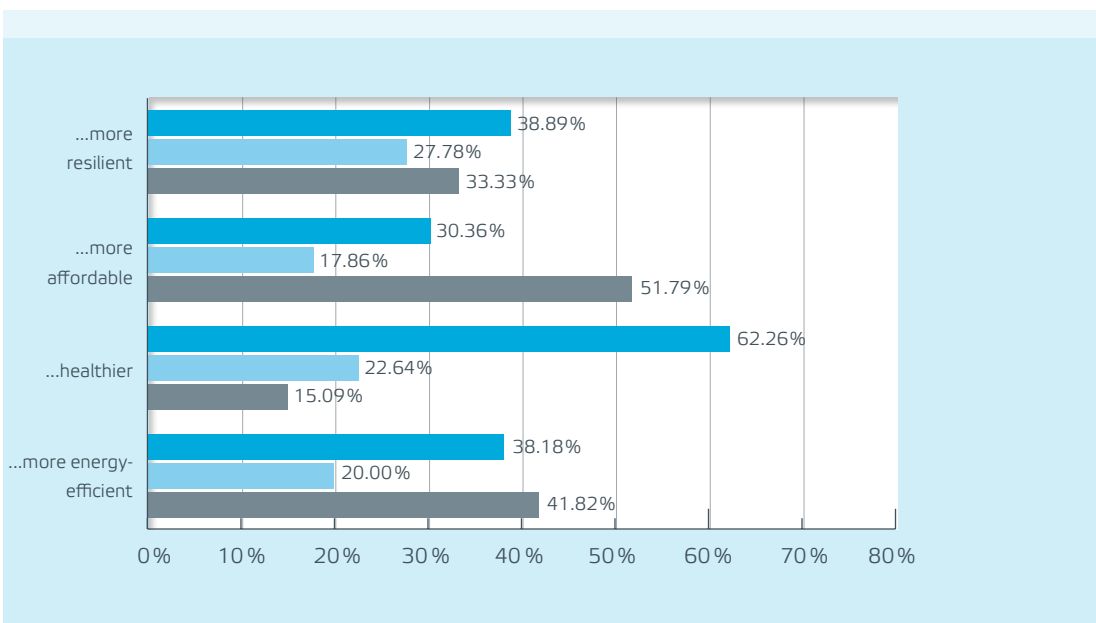
**FIGURE A**  
GlobalABC Roadmap  
2020 – 2050

Source: GlobalABC Roadmap for Buildings and Construction 2020–2050, Towards a zero-emission, efficient and resilient buildings and construction sector, 2020



**FIGURE B**  
Which argument is most important for the choice of materials?

■ Unimportant  
■ Neutral  
■ Important

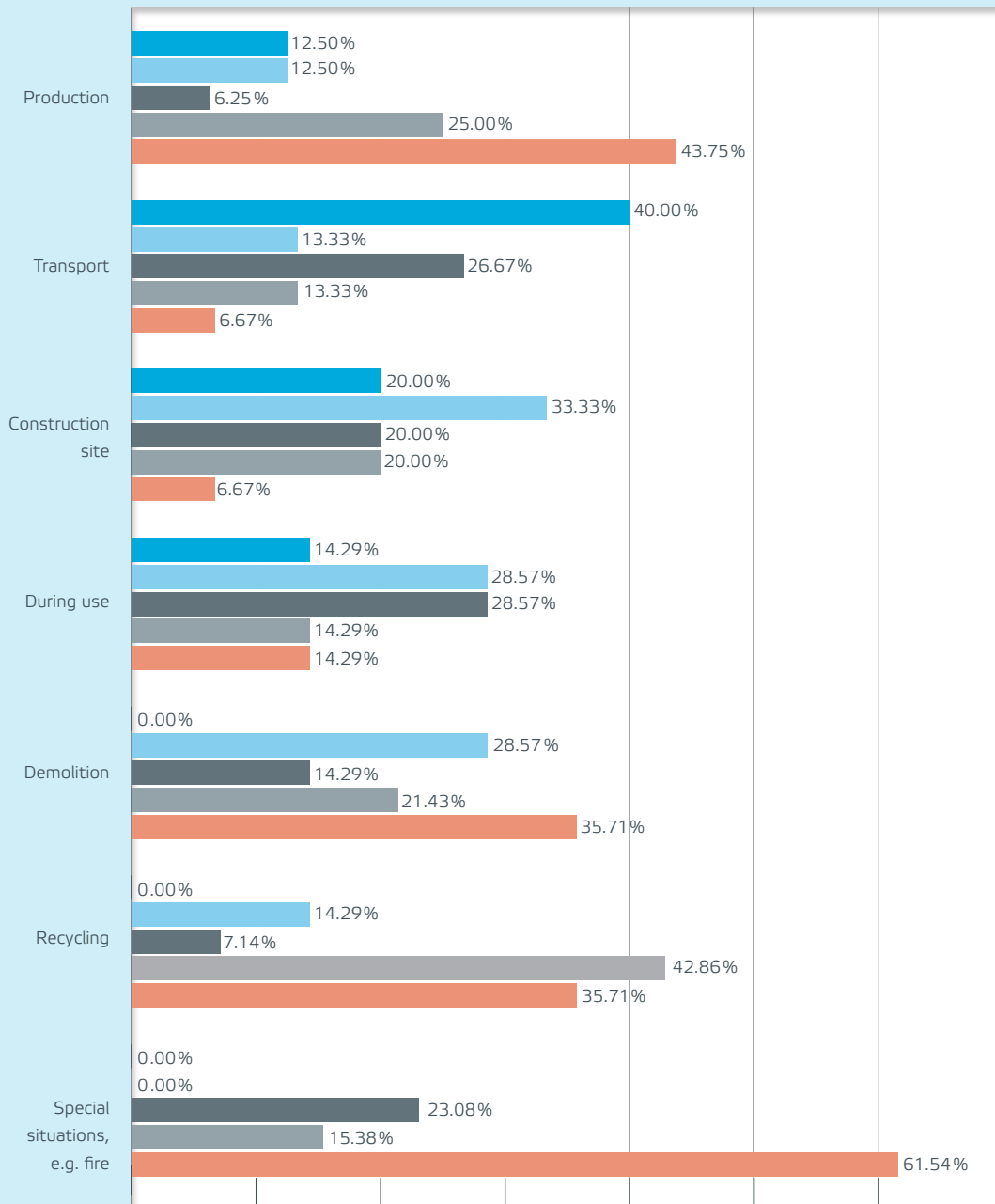


**FIGURE C**  
Aspects of construction plastics

Will plastics support the following aspects in building constructions:

■ Disagree  
■ Neither agree nor disagree  
■ Agree

Source figures: ISC<sub>3</sub> Online Survey, 2019



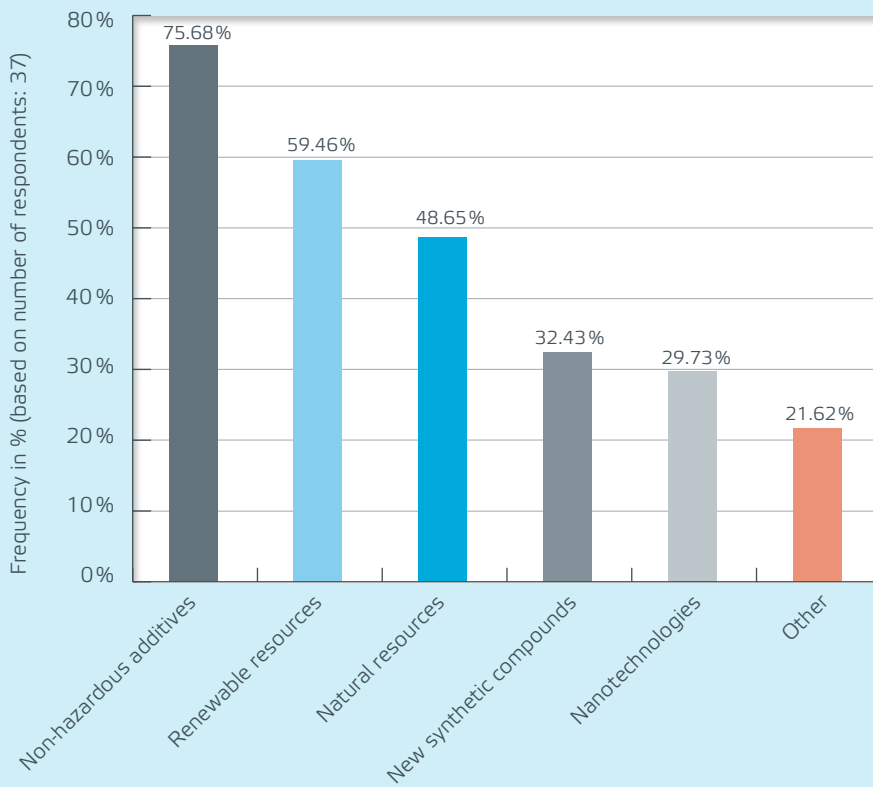
**FIGURE D**  
Critical stages in the life cycle of construction plastics

At what stage of their life cycle are plastics critical to health or environment?

i

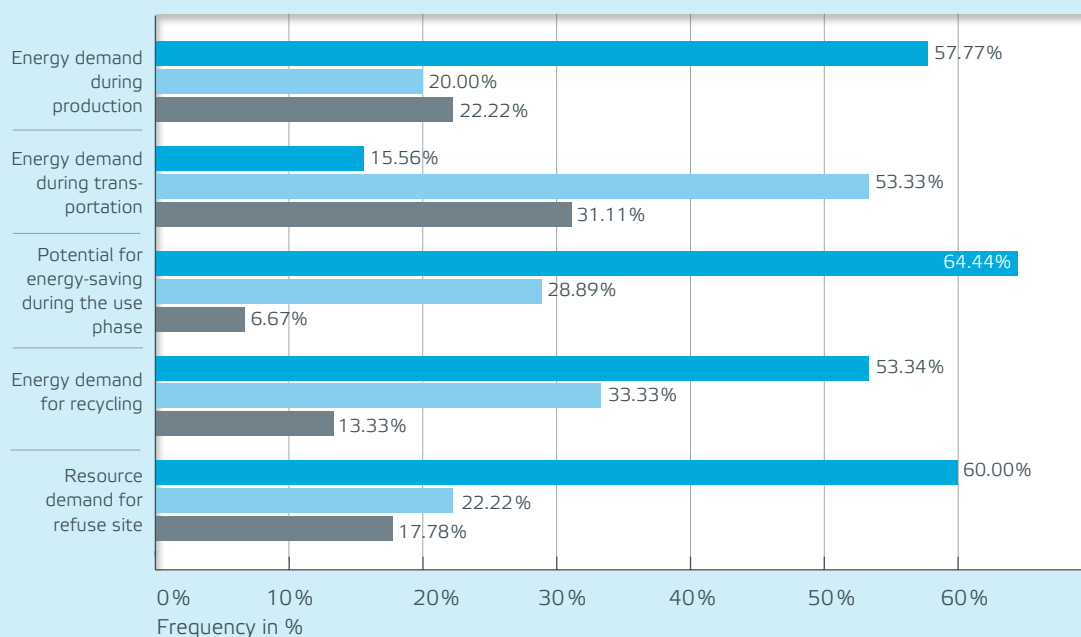


Source: ISC<sub>3</sub> Online Survey, 2019



**FIGURE E**  
How to substitute SHC?

Which trends and technologies can substitute substances of high concern in polymers in buildings?



**FIGURE F**  
Resource demand

How do you estimate resource demand for plastic insulation materials compared to their alternatives?

■ High  
■ Average  
■ Low

## Annex C: Authors' contact details



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Dr Claudio Cinquemani studied environmental engineering and holds a PhD in chemistry. Academic research in green solvents led to a position in industry, where he optimised polymer use for technical applications. Fostering innovative and sustainable solutions in chemistry is his daily business as director for Science & Innovation at ISC<sub>3</sub>.



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Oleg Ditkovskiy studied political sciences with a focus on European chemical policy and worked on projects at BASF, ECCO and GIZ in Chemicals Management on building materials, pesticides and international conventions. As a workstream manager, he is responsible for the workstreams and focus topics of ISC<sub>3</sub>.



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Professor Henning Friege studied chemistry and then worked for more than ten years in the analysis of environmental pollutants, the remediation of contaminated sites and assessment of chemicals. Later on, he was elected as commissioner for environmental protection and other areas by Düsseldorf City Council. Between 1998 and 2013, he worked as managing director of waste management companies. He is the founder of N<sup>3</sup> Thinking Ahead and lecturer at TU Dresden and Leuphana University.



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Richard Hull is a Professor of Chemistry and Fire Science at the University of Central Lancashire in the UK. He has worked on fire and flammability since his PhD in the 1980s. Part of the last 25 years have been focused on smoke toxicity, while most of his work in the last 3½ years has addressed the fallout following the tragic fire at Grenfell Tower in London in 2017.



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Kay Künzel, architect and engineer, is the influential mind behind the architectural office >>raum für architektur<<, recognised specialists in energy-efficient, sustainable, healthy and ecological construction.  
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Dr Beate Kummer, consultant, since 2005 managing director of her own consulting company Kummer umwelt:kommunikation GmbH with offices in Germany and Malta, has around 25 years' experience in sustainability issues, waste management and occupational health and safety. She also has extensive experience in science, consulting, lobbying, stakeholder management, education, communication and political affairs. After completing her studies in Freiburg and Los Angeles in 1994 with degrees in chemistry and toxicology, she joined bvse – Bundesverband Sekundärrohstoffe und Entsorgung e.V. in Bonn, first as consultant, later she became managing director. As managing director of environmental consultants Haase & Naundorf Umweltconsulting GmbH in Bad Honnef between 2002 and 2005, she was responsible for key account clients. She is also working as a lecturer at the University of Leipzig.



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Professor Bernhard Möglinger studied physics with a focus on polymer physics and wrote his PhD on 'Effects of processing on deformation behavior of PBT'. In 1999, he became a professor of polymer testing. He fosters polymer engineering with a holistic approach by implementing sustainability tools such as LCA already in the early development phase of plastic products.



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Esther Moltie holds a MPhil in urban infrastructure, design and management from the African Centre for Cities in Cape Town, South Africa. She has more than 10 years' experience in the urban development field, focusing on the Global South. Currently she is working as an urban policy advisor within the GIZ sector programme 'Cities', where she is responsible for the topic of sustainable buildings and construction. Esther is especially interested in the interface between affordable housing and low-carbon construction materials.



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Ruth Onkangi studied chemistry at Moi University in Kenya and holds a Master of Science degree in environmental chemistry from the University of Nairobi. Her environmental research work focuses on responsible resource consumption and production and policy in the built environment. She has contributed to various national policy documents on environmental sustainability. She is currently a research officer with the National Construction Authority Kenya and head of the Advocacy Committee at the Kenya Green Building Society. There is nothing about sustainable construction that she does not like.



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Reinhard Pfaller is CEO of Rygol Dämmstoffe GmbH. He has a Master (CCI) Professional of Technical Management and Bachelor (CCI) Professional of Metal Production and Management. Reinhard Pfaller has been responsible for the Technical Sales and Application Technology Department since 2007. He has over 20 years' experience in the insulation market.

Executive director at RYGOL Dämmstoffe and executive board member of the national EPS association (IVH) responsible for environmental issues and product security since January 2018.

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Xiaodong Rong, former chairman of the board of Southeast Province Shanxi Subsidiary Co. Ltd, whose mother company is China Chemical Engineering Second Construction Corporation. He has contributed to promoting sustainable chemical construction throughout his career, especially the use of green and environmentally compatible construction materials.



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Pourya Salehi is an urban planner, and sustainability, resilience, and innovation expert who graduated with a Master of Science from the Technical University of Munich (TUM).

With a decade of professional experience, Pourya is currently the Research Officer at the ICLEI World Secretariat where he manages and coordinates ICLEI's Global Research Strategy across all ICLEI offices. He also manages, coordinates, and contributes to a number of research and innovation projects for ICLEI.



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Professor Sean Smith is Chair of Future Construction and Director of the Centre for Future Infrastructure at the Edinburgh Futures Institute, University of Edinburgh. He has worked extensively with the construction product sector over the past 25 years involving sustainable construction products and system solutions which have also incorporated polymer-based products. His applied research and projects have supported over 200 low-carbon products and systems to market.



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Anna Stec is a Professor of Fire Chemistry and Toxicity at the University of Central Lancashire. Her work has focused on the acute and chronic toxicity of fire effluents. She is an expert witness to the Grenfell Tower Inquiry and is leading a project with the Fire Brigades Union investigating the unusually high levels of cancer amongst UK firefighters.



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Jim Vallette is a lifelong researcher of industries that impact human health and the environment around the world. He is co-founder and president of Material Research, L3C, a low-profit, mission-driven company based in Maine, USA. Jim Vallette was previously the lead researcher for the Healthy Building Network for over a decade, where he led efforts to understand the composition of building materials including polymers, and helped to develop the Pharos database.



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Swetlana Wagner studied biotechnology/bioengineering. She is a senior scientist and group leader at Fraunhofer IVV in Freising. Her research focus is the removal of restricted and harmful substances in plastics with solvent-based recycling processes.

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Dr Barbara Zeschmar-Lahl studied biology and earned her PhD on a waste management topic. In 1994, she founded BZL Kommunikation und Projektsteuerung GmbH. Barbara has been working for many years on various aspects of (sustainable) chemistry, from chemical policy and international chemicals management to resource efficiency in the chemical industry.

## Annex D: Information sources

### Information sources: Sustainable use of chemicals in the building sector

P. Fullana, P. Frankl, J. Kreissig: Communication of Life Cycle Information in the Building and Energy Sectors (Ed.: UNEP DTIE), Paris 2008. This booklet includes a list of 'Green Building' regulations and rating systems.

K. Kobeticova, R. Cerný: Ecotoxicology of building materials: A critical review of recent studies. *Journal of Cleaner Production* 165 (2017) 500–508.

B. Huang, K. Xing, St. Pullen: Energy and carbon performance evaluation for buildings and urban precincts: review and a new modelling concept. *Journal of Cleaner Production* 163 (2017) 24–35.

Y. He, Th. Kvan, M. Liu, B. Li: How green building rating systems affect designing green. *Building and Environment* 133 (2018) 19–31.

### German sources:

ÖKOBAUDAT: [www.oekobaudat.de](http://www.oekobaudat.de)

BMF project 'Nachhaltige Wertschöpfungsketten im Baubereich' (Contact: Dr Sartorius (VCI), Katja Wendler (DECHEMA))

WECOBIS: <http://www.wecobis.de/>

GISBAU: Available in 16 languages, [www.gisbau.de](http://www.gisbau.de)

### Collaboration partners:

Science Campus, K'19, Düsseldorf (most important trade fair worldwide for plastic materials), offers the possibility to present results from research.

Please contact Robert Nicolic (Messe Düsseldorf, [nicolicR@messe-duesseldorf.de](mailto:nicolicR@messe-duesseldorf.de)).

BauHow5 is an alliance of five leading, research-intensive universities in architecture and the built environment (TU Munich (lead), Chalmers University of Technology, ETH Zurich, ...), which concentrates on circular solutions, also with regard to modern materials: <http://www.bauhow5.eu/>. One of the focuses at TU Delft BK Bouwkunde is construction and circularity, e.g. Engineering Design for a Circular Economy by Ester van der Voet, David Peck et al. <https://www.edx.org/course/product-design-for-a-circular-economy>



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#### Published by

International Sustainable Chemistry Collaborative Centre (ISC<sub>3</sub>)  
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ISBN 978-3-9823669-0-6



#### Design

now [nau], kommunikative & visuelle gestaltung, Frankfurt am Main

#### Photography

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We thank the authors for their provided portraits.

December 2020

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