European Climate Foundation

Spring 2014

EUROPE'S LOW-CARBON TRANSITION: UNDERSTANDING THE CHALLENGES AND OPPORTUNITIES FOR THE CHEMICAL SECTOR

PRODUCT DEEP-DIVES

Contents

A Introduction to PVC

Used for construction | Partly used for construction | Other applications

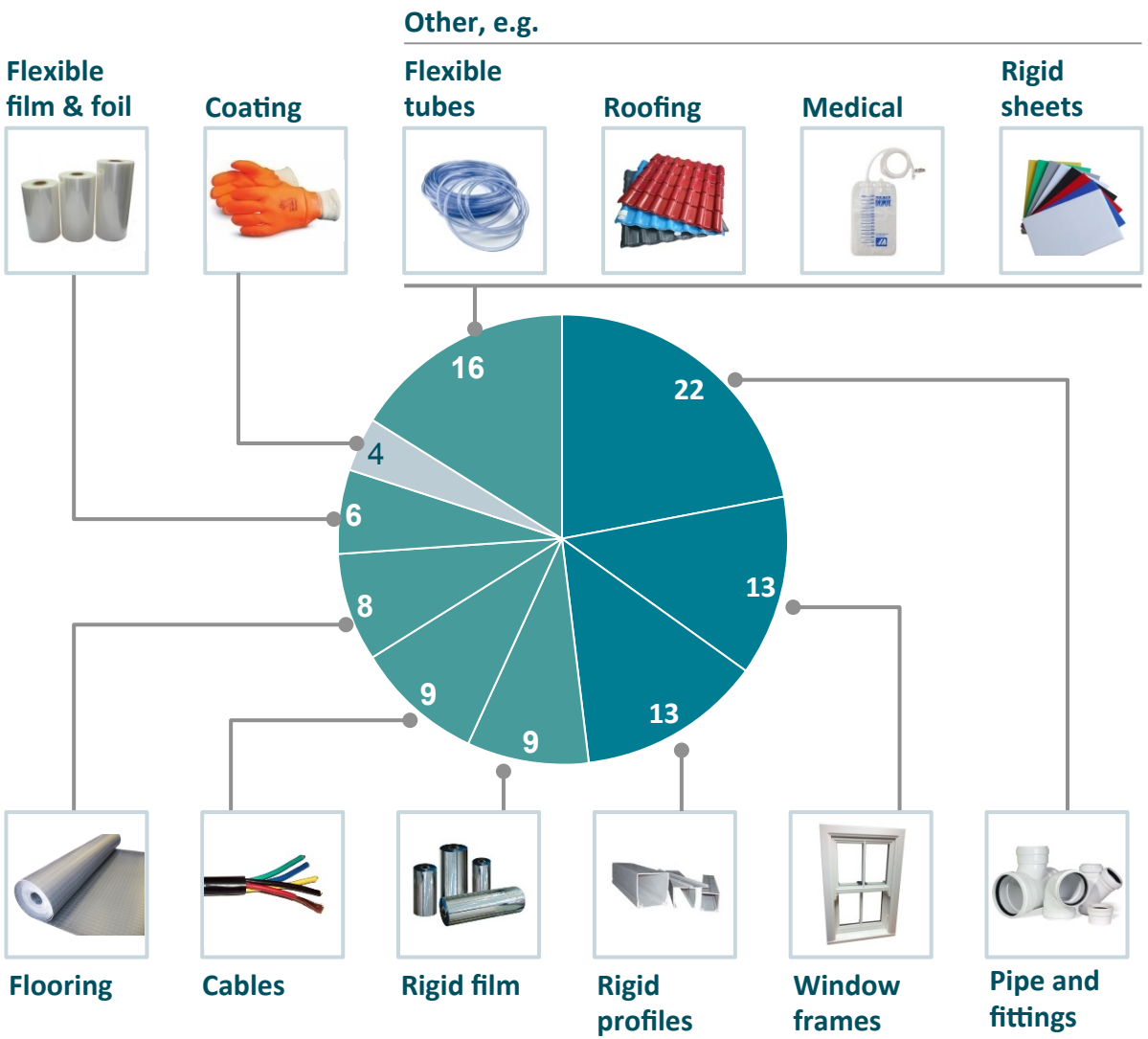
Introduction to PVC

- PVC (polyvinyl chloride) is **the third most common plastic** in the world after polyethylene and polypropylene
- Its strength, durability and flexibility allows for a **broad range of applications,** especially for long-term use in outdoor construction
- **Cost-effective** material compared to, e.g., aluminum and wood
- Mainly produced from **ethylene** and **chlorine**

Key facts

- **EU production of ~6 million metric tons** in 2012
- **~70% consumed by the construction sector**
- Consolidated market where the **top 6 manufacturers produce 75%** of PVC resin in Europe
- **Energy intense production of chlorine** main driver of total PVC emissions of **~12 $MtCO_2e$**
- **~360,000 tons recycled 2012** (of ~2-2.5m tons post-consumer waste)

PVC applications, percent



SOURCE: Analysis based on industry reports and interviews

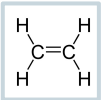
Overview of value chain and associated emissions

Overview of emissions across PVC value chain

Value chain

Feedstock → **Production of PVC** → **Manufacturing** → **End-of-life solutions**

Ethylene
- Gas with high intraregion trade
- In Europe mainly produced from naphtha



Chlorine
- Gas produced from electrolysis of brine
- Short trans-portation range

PVC precursors[1]
- EDC (liquid) and VCM (liquified gas) are intermediates
- EDC and VCM are traded, albeit in smaller volumes today

PVC
- Globally traded

Additives

PVC compound
- Blended with 5-50% additives
- Globally traded
- Can take form of pellets

PVC product
- Processed PVC compound

End-of-life solutions

~2-2.5 million tons of post-consumer waste

Land-filling (majority)

Inciner-ation

Recycling (~260,000 tons,15%)

Emis-sions

End-of-life | Indirect | Direct

Per ton of virgin PVC produced[2], (tCO_2e)

Ethylene	Chlorine	Processes	Additives	End-of-life	Total
0.5-0.6[3]	1.2-1.3[4]	~0.1[5]	<0.1[6]	0-1.4[7]	1.9-3.5
					0-1.4
					1.0-1.1
					0.9-1.0

Total European emissions[8] ($MtCO_2e$)

Ethylene	Chlorine	Processes	Additives	End-of-life	Total
0.5-0.6	5.2-5.8	~0.2	<0.1	0	6.0-6.7
2.3-2.6	1.4-1.6	0.4-0.5	<0.1	~0.4-0.5[9]	4.7-5.1

Total: 10.7-11.8

1 Ethylene dichloride (EDC) and vinyl chloride monomers (VCM); 2 For one ton of PVC resin as amount of additives varies greatly between applications. Transportation emissions included in chain; 3 Emissions from naphtha production/ extraction and from ethylene production through conventional cracking, 0.29 ton ethylene/ ton of PVC; 4 Data for diaphragm cells, similar electricity requirements for diaphragm and membrane according to CEFIC. 0.73 ton chlorine/ ton PVC; 5 Include chlorination to EDC (53% direct chlorination and 47% oxychlorination, only ~60% of emissions accounted for- rest to HCl), EDC cracking to VCM and bulk polymerization to PVC; 6 Assumed additional 5% on weight basis, assumed average emissions from chemical industry (166m tons CO2 emissions from ~400m tons produced). Excludes plasticizers; 7 Shows range from 0 (landfilling) to 1.4 (incineration) tCO2/ ton PVC; 8 Lower range presented in bubbles assuming 15% recycling, upper range assuming no recycling; 9 Assuming 15% of waste incinerated

NOTE: Analysis based on production of 6m tons 2012. Indirect emissions 75-85% lower in France, representing ~13% of EU 27 market

SOURCE: Analysis based on industry reports and interviews

Key abatement levers across the value chain

Use bio-ethylene as feedstock

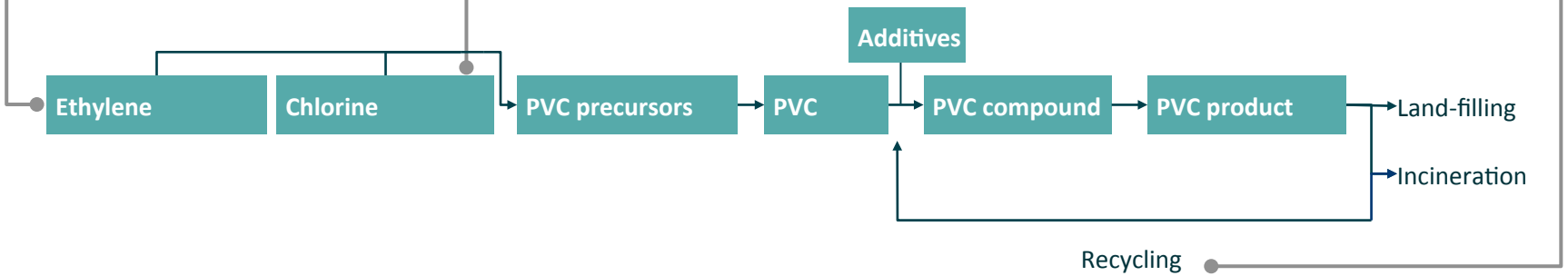
- Can technically substitute petrochemical based ethylene completely
- Bio-ethylene based on ligno-cellolosic biomass required, with uncertain feasibility in near to mid-term horizon
- Breakthrough dependent on local conditions, technology mature and economic viability

Implement new technology in chlorine electrolysis

- Continue shift from mercury cell electrolysis towards more energy efficient membrane cell and ODC electrolysis
- Compared to mercury cell, membrane cell has ~25% lower emissions. In ODC technology emissions are ~40% lower than mercury cell emissions

Increase recycling rates with focus on pipes, fittings and window frames

- Composite structures containing at least 70% of PVC can be recycled using, e.g., the VinyLoop[1] process
- Availability of used PVC a short term barrier given lifetimes of up to 50 years and more
- Large potential from installed base in the coming decades from lead and cadmium free production since the 1980's



Switch to green energy throughout the value chain

- Non-fossil energy share of total electricity production to be increased from today's 46% to ~70%[2], reducing CO_2 emissions from electricity generation by ~50%

Improve process and energy efficiency

- Continuous efficiency improvements in multiple process steps leading to a 25% reduction by 2030 (~2% p.a.)
- Examples may include improved polymerization techniques and decomposition of GHGs

1 Partnership between Solvay and Serge Ferrari; 2 Based on Enerdata Emergence case
SOURCE: Analysis based on industry reports and interviews

Overview of total emission reduction opportunity by 2030

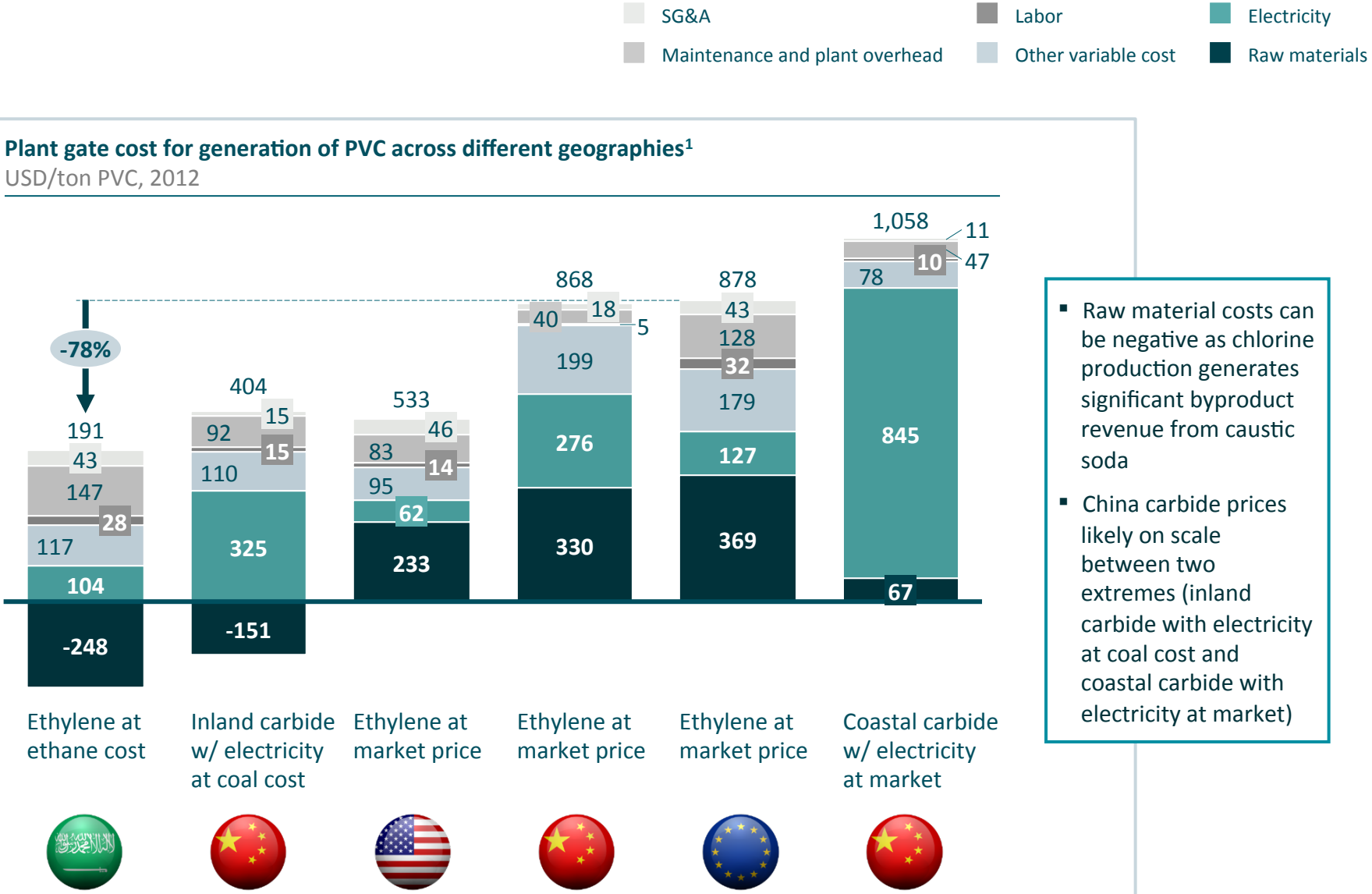
$MtCO_2e$, 2030, assuming levers pursued in parallel[1]

Direct | Indirect

			Assumptions	Emission reduction
			Frozen technology 2030[2]	14
Scope 1 + 2	Shift to renewable feedstock	Use bio-ethylene as feedstock	▪ 50% of ethylene replaced with bio-ethylene by 2030, with 40% emission reduction per ton output ▪ Uncertainty around technology maturity and economic viability, but research ongoing	0.3-0.6
Scope 1 + 2	Process and energy efficiency	Implement new electrolysis technology	▪ Replace mercury cell capacity (20% of European capacity) with membrane cell or ODC technology ▪ Average electricity consumption in membrane cell electrolysis 23% lower than in mercury cells, in ODC 42% lower	0.2-0.4
Scope 1 + 2	Process and energy efficiency	Improve other processes	▪ 1.5-2% process and energy efficiency improvement annually until 2030, potential in electrolysis step assumed be 50% less given amount of electrochemical energy needed ▪ In line with industry's 20% target of reduced energy consumption for resin producers by 2020	1.8-2.4
Scope 1 + 2	Recycling/ re-use	Increased use of recycled PVC in production	▪ Lower limit: 2m tons PVC recycled, conservative pace compared to industry target of 800,000 tons recycled in 2020 ▪ Upper limit: 75% of pipes & fittings, 50% of window frames and on average 25% of other applications produced with recycled PVC	2.2-2.6
Scope 1 + 2	Shift to green energy	Go to more green energy mix	▪ Green energy share of total electricity production to be increased from today's 46% to ~70%, reducing CO_2 emissions from electricity generation by 50%[3]	1.3-1.5
			The full abatement potential is not commercially available **Total emissions, 2030**	6.5-8 ◀ -45-55%
Scope 3	Global emission reductions	Global potential[4]	▪ Likely that others will follow if a breakthrough in bio-ethylene production occur ▪ Potential from exporting electrolysis technologies outside of Europe. Less likely that other, individually less impactful, process efficiency improvements would be spread ▪ Further, large potential from showing that recycling can be successfully implemented	10-25

1 Individual levers have larger potential if pursued alone; 2 Assuming 1.0% production growth from 2012;
3 Potential reduced to account for in-house energy production; 4 PVC scope
SOURCE: Analysis based on industry reports and interviews

PVC regional production cost



- Raw material costs can be negative as chlorine production generates significant byproduct revenue from caustic soda
- China carbide prices likely on scale between two extremes (inland carbide with electricity at coal cost and coastal carbide with electricity at market)

1 250 kta PVC plant integrated with 500 kta chlorine membrane unit, balanced EDC/VCM unit
SOURCE: McKinsey margin models

Contents

Introduction to polycarbonate

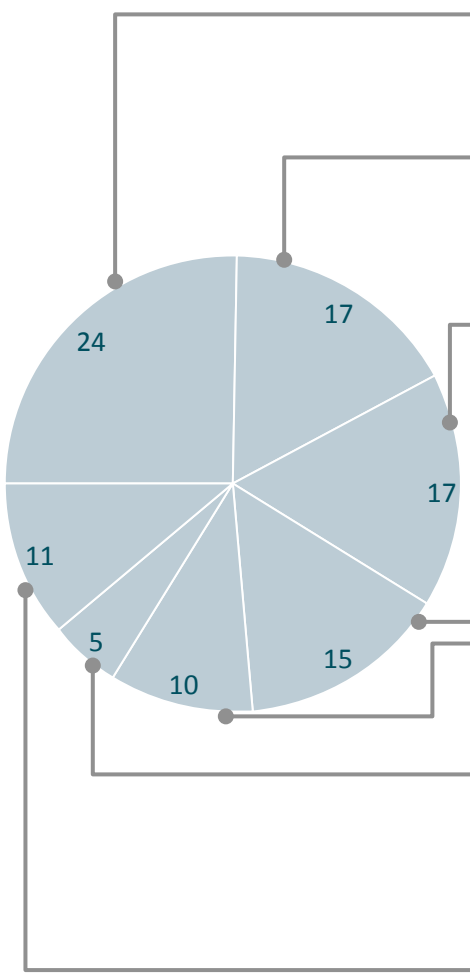
Introduction to PC[1]

- **Easily worked, molded and thermoformed plastic**, making it useful in many applications
- Main advantage over other types of plastics is **great strength combined with light weight**
- Known under trademarked names such as Lexan, Markrolon and Markoclear
- Two largest players, Bayer and SABIC, make up 51% of world capacity and five players make up 76%

Key facts

- **~0.8 million metric tons production in Europe per year** (comprising 21% of global production)
- **Total emissions: 4.4 – 4.5 $MtCO_2e$** (3.8 – 6.3 tCO_2e per ton PC[2])
- Produced by condensation polymerization between bisphenol A and phosgene

Polycarbonate applications, percent



Building & construction
- Sheets and films for signs, security windows and soundwalls

Electronics/electrical
- Computers, laptops, e-book readers, smartphones

Automotive
- Headlights, wheel covers, radiator grills

Domestic appliances
- Coffee makers, hairdryers, microwave oven doors

Optical media
- CDs and DVDs

Consumer/sports
- Motorcycle helmets, glasses

Other
- Packaging, medical appliances

1 Polycarbonate; 2 Upper range assuming no recycling, lower range assuming 5% recycling and reuse
SOURCE: Analysis based on industry reports and interviews

B Overview of value chain and associated emissions

Overview of emissions across PC value chain

Value chain

Basic chemicals

Chlorine
- Energy and emission intensive production
- Very limited trade because of hazardous to transport

Carbon monoxide
- Toxic gas with many applications in chemical industry

Acetone
- Produced simultaneously as phenol in cumene production

Phenol
- Most common production method is oxidation of cumene

Intermediates

Phosgene
- Gas that is almost always produced and consumed within same plant because of toxicity

Bisphenol A
- Common solid plastics chemical, mainly used for production of polycarbonate
- Banned from from certain applications (e.g. baby bottles), due to health effects

Production

Polycarbonate
- Globally traded plastics
- Concentrated industry with 5 large players (76% of production), e.g., Bayer and SABIC

Applications

High tradeability | Low tradeability

New BPA & DPC

Building & construction	25%
Electronic/ electrical	17%
Automotive	17%
Domestic appliances	15%
Optical media	10%
Consumer/ sports	5%
Other	11%

End-of-life solutions

- Recycling more common for high-volume applications (e.g. 5-gallon water bottles)
- Lower recycling rate than plastics in general (assuming 50% energy recovery)

Plastics in general

Recycling	26%
Energy recovery	36%
Landfill disposal	38%

Emis-sions[1]

Per ton of virgin PC produced (tCO_2e)

End-of-life | Indirect | Direct

Basic chemicals	Intermediates	Production	End-of-life	Total
2.6 – 2.8[2]	0.5 – 0.7[3]	0.7 – 0.9[4]	0 – 2.8[5]	3.8 – 6.3[6]
			0 - 2.8	1.6 – 1.8
				2.3 – 2.5[5]

Total European emissions ($MtCO_2e$)

Basic chemicals	Intermediates	Production	End-of-life	Total
0.9 - 1.0[7]	~0.2	0.2	0	~1.4[7]
1.1 - 1.2[7]	~0.3	0.5	1.1[8]	3.0 – 3.1[7]

Total: 4.4 – 4.5[7]

1 Transport emissions account for less than 1% of total emissions and are therefore excluded; 2 Residual from Plastics Europe PC Eco-profile when excluding BPA and phosgene emissions. Split between direct and indirect emissions assumed to be 50:50; 3 BPA data from Eco-profile, phosgene data from input figures in PC Eco-profile; 4 Data from PC Eco-profiles; 5 Depending on end-of-life solution. Energy recovery emissions amount to 2.7-2.8 tCO2e / ton PC; 6 Cradle-to-gate figures based on figures from Plastic Europe eco-profiles. Cradle-to-grave given by adding end-of-life solution; 7 Upper range assuming no recycling, lower range assuming 5% recycling and reuse of today's waste stream (50% of production); 8 Assuming energy recovery is used as disposal method for 50% of all PC

SOURCE: Analysis based on industry reports and interviews

Key abatement levers across the value chain

Implement optimal technology in chlorine electrolysis

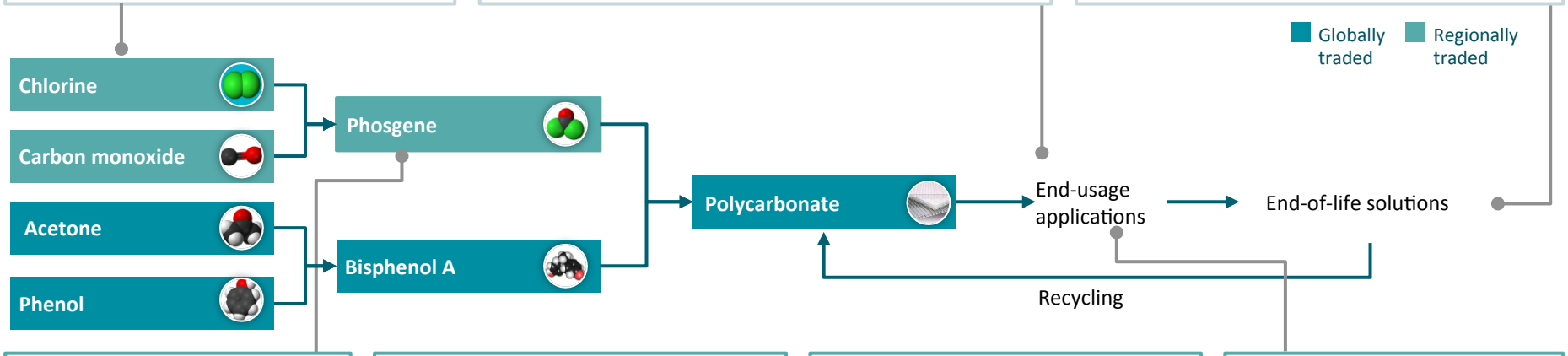
- Continue shift from mercury cell electrolysis towards more energy efficient membrane cell and ODC electrolysis
- Compared to mercury cell, membrane cell has ~25% lower emissions. In ODC technology emissions are ~40% lower than mercury cell emissions

Use as light-weight material in cars

- PC can be used to reduce weight and improve fuel efficiency in vehicles, e.g., by replacing glass or metal parts
- Scratch resistance is still an obstacle, but can to some extent be mitigated by coatings and films
- Extensive research being conducted and more applications possible in the future
- Usages today include FIAT'S 500L and VW XL1 (side windows)

Increase reuse and recycling

- Recycling and reuse rate target of 25%. Chemical reduction turns used PC into new feedstock. Used PC can be grounded up and used in automotive, computer and appliance applications
- Limited additional recycling process and transport emissions
- Collection is challenge since PC is generally not used in bulk quantities



Replace phosgene with CO_2 based feedstock

- Production process uses ethylene oxide (EO), by-produced CO2 and Bisphenol A, reducing CO2 emissions by 0.173 ton per ton PC

Improve process and energy efficiency

- Continuous efficiency improvements in multiple process steps leading to a 25% reduction by 2030 (~2% p.a.)
- Examples include improved process cooling and better catalyst systems

Switch to green energy throughout the value chain

- Non-fossil energy share of total electricity production assumed to increase from today's 46% to ~70%[1], reducing CO2 emissions from electricity generation by ~50%

Replace PC with bio-based plastics

- Bio-polycarbonates are made with isosorbide in place of bisphenol A in a process that avoids the use of phosgene

1 Based on Enerdata Emergence Case

SOURCE: Analysis based on industry reports and interviews

Overview of total emission reduction opportunity by 2030

$MtCO_2e$, 2030, assuming levers pursued in parallel[1]

Indirect | Direct

			Assumptions	Emission reduction
			Frozen technology 2030[2]	6
Scope 1 + 2	Shift to renewable feedstock	Replace phosgene with CO_2 based feedstock	▪ Production process uses ethylene oxide (EO), by-produced CO_2 and Bisphenol A, reducing CO_2 emissions by 0.17 ton per ton PC ▪ Replacement possible in 80% of applications	0.1-0.2
Scope 1 + 2	Process and energy efficiency	Implement optimal electrolysis method	▪ Replace mercury cell capacity (20% of European capacity) with membrane cell or ODC electrolysis technology ▪ Average electricity consumption in membrane cell electrolysis 23% lower than in mercury cells, in ODC 42% lower	<0.1
Scope 1 + 2	Process and energy efficiency	Improve other processes	▪ 1.5-2% process and energy efficiency improvement annually from 2011 to 2030 ▪ Examples include improved process cooling and better catalyst systems	1.2-1.4
Scope 1 + 2	Recycling/ re-use	Increase reuse and recycling	▪ Recycling and reuse rate target of ~25%. Chemical reduction turns used PC into new feedstock. Used PC can be grounded up and used in automotive, computer and appliance applications ▪ Savings reduced by 20-30% by additional transportation and processing emissions	0.6-0.8
Scope 1 + 2	Shift to green energy	Go to more green energy mix	▪ Non-fossil energy share of total electricity production assumed to increase from today's 46% to ~70%[1], reducing CO2 emissions from electricity generation by ~50%	0.8-0.9
Scope 1 + 2	Product/ materials substitution	Replace PC with bio-based plastics	▪ Bio-polycarbonates are made with isosorbide in place of Bisphenol A ▪ Can be used in 40% of all PC applications ▪ Net effect when assuming half of PC is bio-based and other half has implemented levers above	0.2-0.4 ← 55-60%[3]
			Total emissions, 2030	~3[4] ← 50-55%[4]
Scope 3	Enabling downstream and global emission reductions	Use as light-weight material in cars	▪ Additional PC production associated with materials substitution in cars ▪ Assuming other levers have been implemented	~1
Scope 3	Enabling downstream and global emission reductions	Use as light-weight material in cars	▪ Weight reduction of ~20 kg per car, CO_2 emission abatement from lower weight is 8.4 g/100 kg reduction (per km). Assuming PC in ~40% of produced vehicle fleet in 2030 ▪ After implementing emission-reducing levers, the production emissions will be less than 2 tCO_2e higher for PC than glass per ton end-product	4-8
Scope 3	Enabling downstream and global emission reductions	Global potential	▪ Largest global potential comes from replacing glass in cars outside Europe. If European car producers would perform lighter, more fuel efficient cars, this would put pressure on other manufacturers to do the same. European manufactured cars are also exported ▪ Some additional potential from e.g. bio-feedstock, new electrolysis, bio-PC and recycling	10-25

The full abatement potential is not commercially available

1 Individual levers have larger potential if pursued alone;
2 Assuming same carbon footprint as today with 1.3% production growth rate per year (historical growth rate 2000-11);
3 Including shift to bio-based plastics;
4 Excluding shift to bio-based plastics

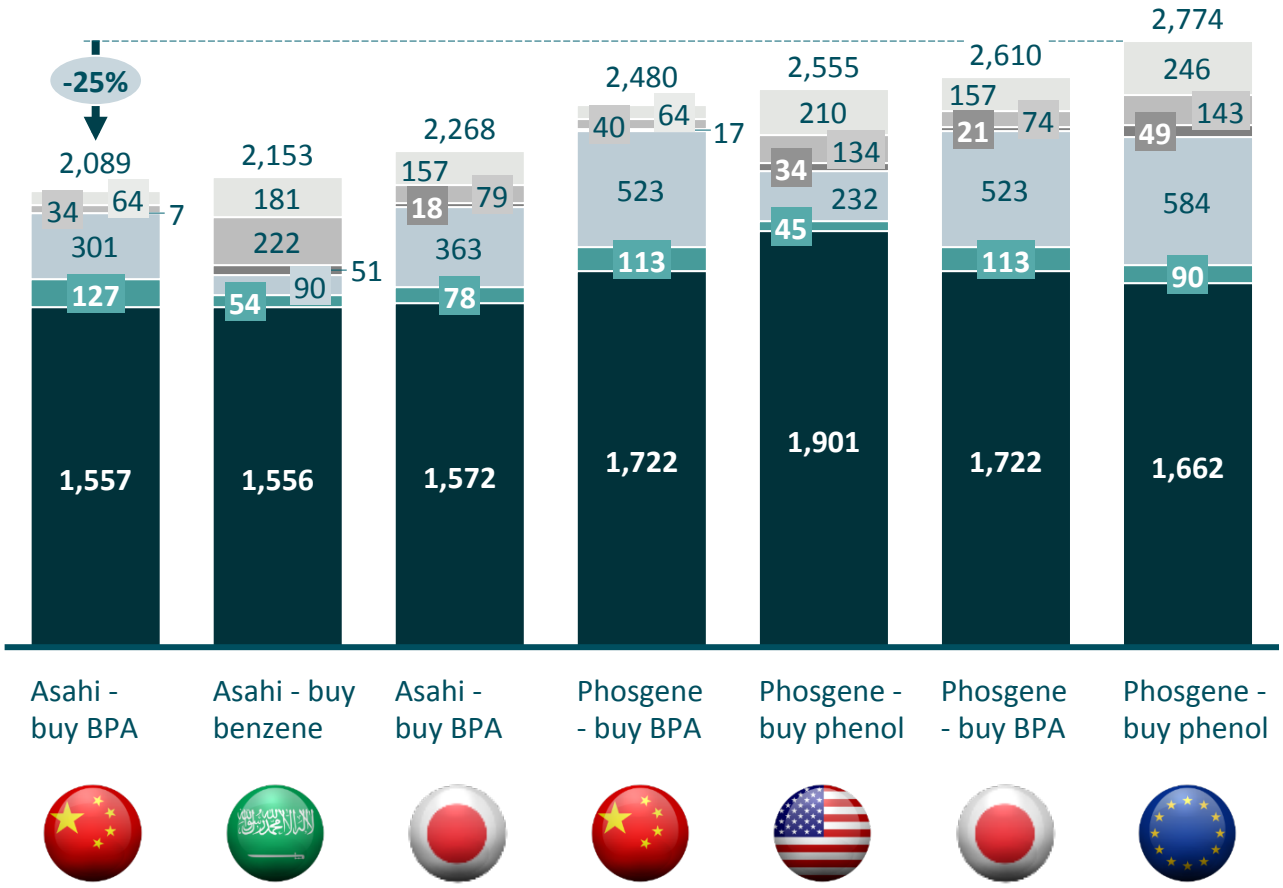
SOURCE: Analysis based on industry reports and interviews

Polycarbonate regional production cost

SG&A | Maintenance and plant overhead | Labor | Other variable cost | Electricity | Raw materials

Plant gate cost for generation of PC across different geographies[1]

USD/ton PC, 2012



- New Asahi technology consistently lower cost than conventional phosgene technology
- US cost advantaged vs. WE due to energy costs, despite raw material disadvantage (higher phenol cost)
- WE highest cost producer, largely due to high fixed costs and old technology
- WE and US producers largely integrated into BPA, Asia producers buy BPA on spot market

1 250 kta conventional PC plant with integrated phosgene production, or 250 kta Asahi PC plant with integrated EO. Saudi plant integrated with BPA/phenol

SOURCE: McKinsey margin models

Contents

Introduction to rigid polyurethane

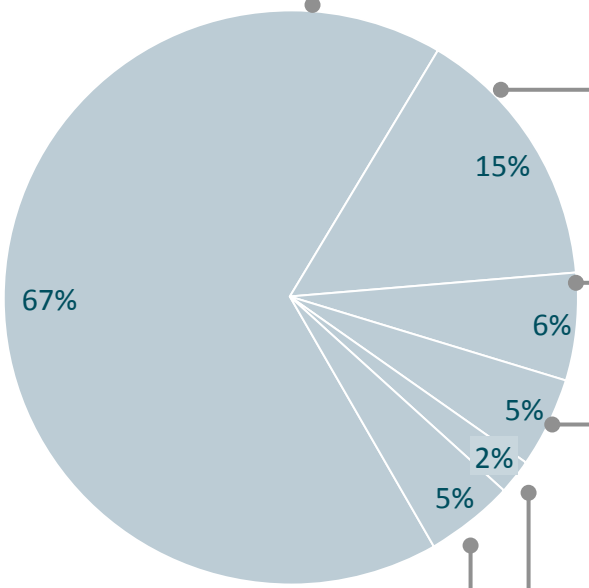
Introduction to rigid PU[1]

- Polymer used as **insulation material**
- One of the **most effective insulation materials** in terms of insulation value
- Comprises **10-15% of total insulation market**
- Regional product since low density makes it **expensive to ship**, however, intermediates and components are traded
- End-user applications include, e.g., **construction and appliances**

Key facts

- **~1.3 million metric tons production in Europe** (comprising ~25% of global production)
- **Total emissions: 6.2 – 6.6 $MtCO_2e$ (4.1 – 5.9** tCO_2e per ton PU)
- Produced by reacting an isocyanate (often MDI) with a polyol

Rigid polyurethane applications, percent



Building industry
- Sandwich panels
- Insulating boards
- Spray-in-place insulation foam

Appliances
- Refrigerators/freezers
- Hot water tanks
- Cold rooms

Industrial thermal insulation
- Storage tanks
- District heating pipes

Packaging
- Pour-in-place packaging for industrial equipment, computers, etc.

Transportation
- Thermal insulation of refrigerated vehicles/ containers

Other applications
- Boat hulls, surfboards, etc.

1 Polyurethane
SOURCE: Analysis based on industry reports and interviews

Overview of value chain and associated emissions

Overview of emissions across PU value chain

Value chain

Basic chemicals → Components → Foam → Applications → End-of-life solutions

Propylene oxide production
- Commodity liquid mainly used for PU and surfactants production

Phosgene (chlorine based)
- Toxic gas always produced and consumed within same plant
- Chlorine production is very energy intensive and large emission contributor

Formaldehyde production
- Toxic liquid that is common building block to more complex compounds and materials

Aniline production
- Liquid mostly used for MDI production (76%)
- Several producers integrated into MDI production

Polyol production
- Commodity alcohol produced by major chemical companies , e.g., Bayer, BASF, Dow

MDI production
- Isocyanate produced by the major chemical manufactures
- Traded extensively

Foam production
- Regional reach because of low density making it expensive to ship
- Thousands of producers, 90% of them SMEs

Applications: Building industry; Domestic appliances; Industrial thermal insulation; Packaging; Transport-ation

End-of-life solutions:
- Reuse (5-10%)
- Refurbishment (e.g. for boards, profiles packaging)
- Chemical recycling
- Energy recovery (50%)
- Landfilling

New polyols

High tradability / Low tradability

Emis-sions[1,2]

Per ton of virgin PU produced (tCO_2e)

End-of-life / Indirect / Direct

Feedstock production	Polyol and MDI production	Foam production	End-of-life	Total emissions
~2.0[3]	~0.3[4]	~2.0[4]	0 – 1.5[5]	4.1 – 5.9[6]
				0 – 1.5
				1.5 – 1.7
				2.5 – 2.7[5]

Total European emissions ($MtCO_e$)

Feedstock production	Polyol and MDI production	Foam production	End-of-life	Total emissions
~1.3	~0.1	~0.7	0	2.0-2-2[7]
~1.3	~0.2	~1.9	~1.0[7]	4.2-4.4[7]

Total: 6.2-6.6[7]

1 Includes transport emissions; 2 No reuse or recycling assumed because of low waste generation today; 3 Residual from Plastics Europe PU Eco-profile when excluding MDI and polyol emissions. Split between direct and indirect emissions assumed to be 50:50; 4 Data from PU, MDI and polyol Eco-profiles; 5 Depending on end-of-life solution. Energy recovery emissions amount to ~1.5 tCO2e / ton PU; 6 Cradle-to-gate figures based on figures from Eco-profiles. Cradle-to-grave given by adding end-of-life solution; 7 Assuming energy recovery is used as disposal method for 50% of all PU

SOURCE: Analysis based on industry reports and interviews

Key abatement levers across the value chain

Use renewable carbon as feedstock in polyol production

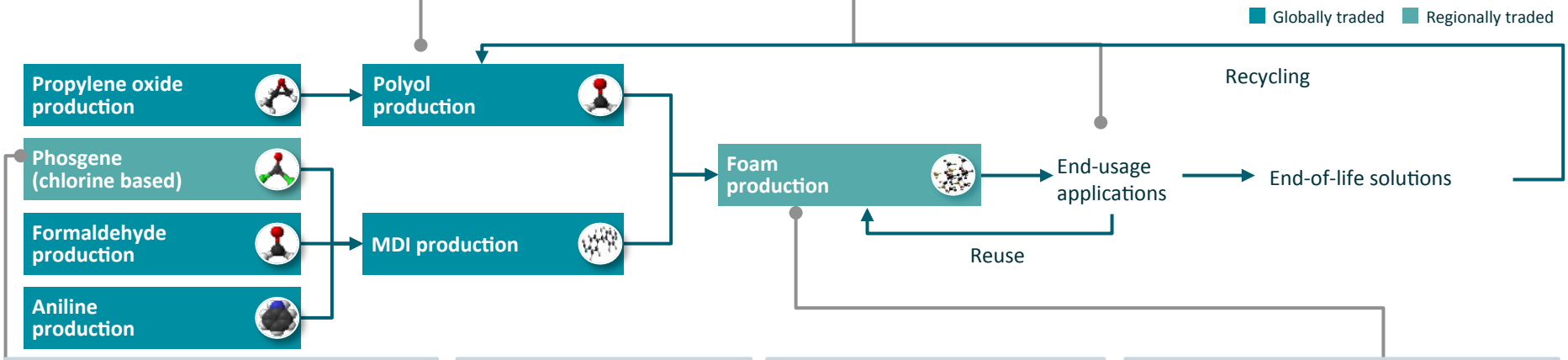
- Switch to renewable carbon as feedstock in polyol production, enabling 80% emission reduction in this production step
- Polyol production accounts for 17% of total production emissions today

Improve house insulation

- Accelerate retrofit house and building insulation to reduce indirect emissions from heating and cooling
- Significant potential for energy savings, amounting to 5-10% of EU total CO2 emissions

Increase reuse and recycling

- Increase chemical conversion, reuse and refurbishing into new products
- Recycling rate assumed to increase to 85-95% in production waste, and up to 5% in construction waste



Implement new technology in chlorine electrolysis

- Continue shift from mercury cell electrolysis towards more energy efficient membrane cell (25% lower emissions) and ODC electrolysis (40% lower emissions)

Improve process and energy efficiency

- Pursue continuous efficiency improvements in multiple process steps leading to a 25% reduction by 2030

Switch to green energy throughout the value chain

- Increase non-fossil energy share of total electricity production from today's 46% to ~70%[1], reducing CO2 emissions from electricity generation by 50%

Use of greener foam blowers

- Complete the transition from use of HFCs towards pentane or CO_2 – can save 90% of emissions on the remaining 15% HFCs used

1 Based on Enerdata Emergence Case
SOURCE: Analysis based on industry reports and interviews

Overview of total emission reduction opportunity by 2030

$MtCO_2e$, 2030, assuming levers pursued in parallel[1]

Indirect | Direct

			Assumptions	Emission reduction
			Frozen technology 20302	16
Scope 1 + 2	Shift to renewable feedstock	Use renewable carbon as feedstock in polyol production	▪ Renewable carbon used as feedstock in polyol production, enabling 80% emission reduction in this production stage. Assuming used in 80% of all PU ▪ Polyol production accounting for 17% of total production emissions	~1
Scope 1 + 2	Process and energy efficiency	Implement optimal electrolysis method	▪ Replace mercury cell capacity (20% of European capacity) with membrane cell or ODC electrolysis technology ▪ Average electricity consumption in membrane cell electrolysis 23% lower than in mercury cells, in ODC 42% lower	<1
Scope 1 + 2	Process and energy efficiency	Use greener foam blowers	▪ Transition from use of fluorochemicals towards pentane or CO_2 as foam blowers can reduce emission at this stage by up to 90%. Assuming complete move away from fluorochemicals ▪ Fluorochemical losses in foaming process account for 75% of foaming process direct emissions	2-3
Scope 1 + 2	Process and energy efficiency	Improve other processes	▪ 1.5-2% process and energy efficiency improvement annually from 2011 to 2030 ▪ Examples include further integration and energy efficiency	2-4
Scope 1 + 2	Recycling/ re-use	Increase reuse and recycling[3]	▪ Chemical conversion, reuse in less demanding construction applications and refurbishing into new products (e.g. boards replacing wood chipboards in construction) are possible alternatives ▪ Recycling rate assumed to increase to 85-95% in production waste and up to 5% in construction waste	<1
Scope 1 + 2	Shift to green energy	Go to more green energy mix	▪ Non-fossil energy share of total electricity production assumed to increase from today's 46% to ~70%, reducing CO2 emissions from electricity generation by ~50%	2-3
			The full abatement potential is not commercially available **Total emissions, 2030**	~7 **55-60%**
Scope 3	Enabling down-stream and global emission reductions	Improve house insulation	▪ Additional PU production associated with improved insulation ▪ Assuming other levers have been implemented	10-20
Scope 3	Enabling down-stream and global emission reductions	Improve house insulation	▪ Energy savings potential of up to 40%, depending on house age and type, by improving insulation in buildings. ▪ PU account for 50% of abatement potential, other insulation materials the rest	50-100
Scope 3	Enabling down-stream and global emission reductions	Global potential	▪ Largest potential in bio based feedstock where technical improvements in Europe will lower the threshold abroad. Additional potential from e.g. recycling and new electrolysis technique ▪ Huge additional potential if chemical industry can replicate insulation improvements and switch to greener foam blowers abroad. Role of Europe unclear in capturing these savings, hence not included	10-20

1 Individual levers have larger potential if pursued alone; 2 Assuming same carbon footprint as today with 5% production growth rate per year; 3 Including additional transportation and process emissions (10% reduction of abatement)

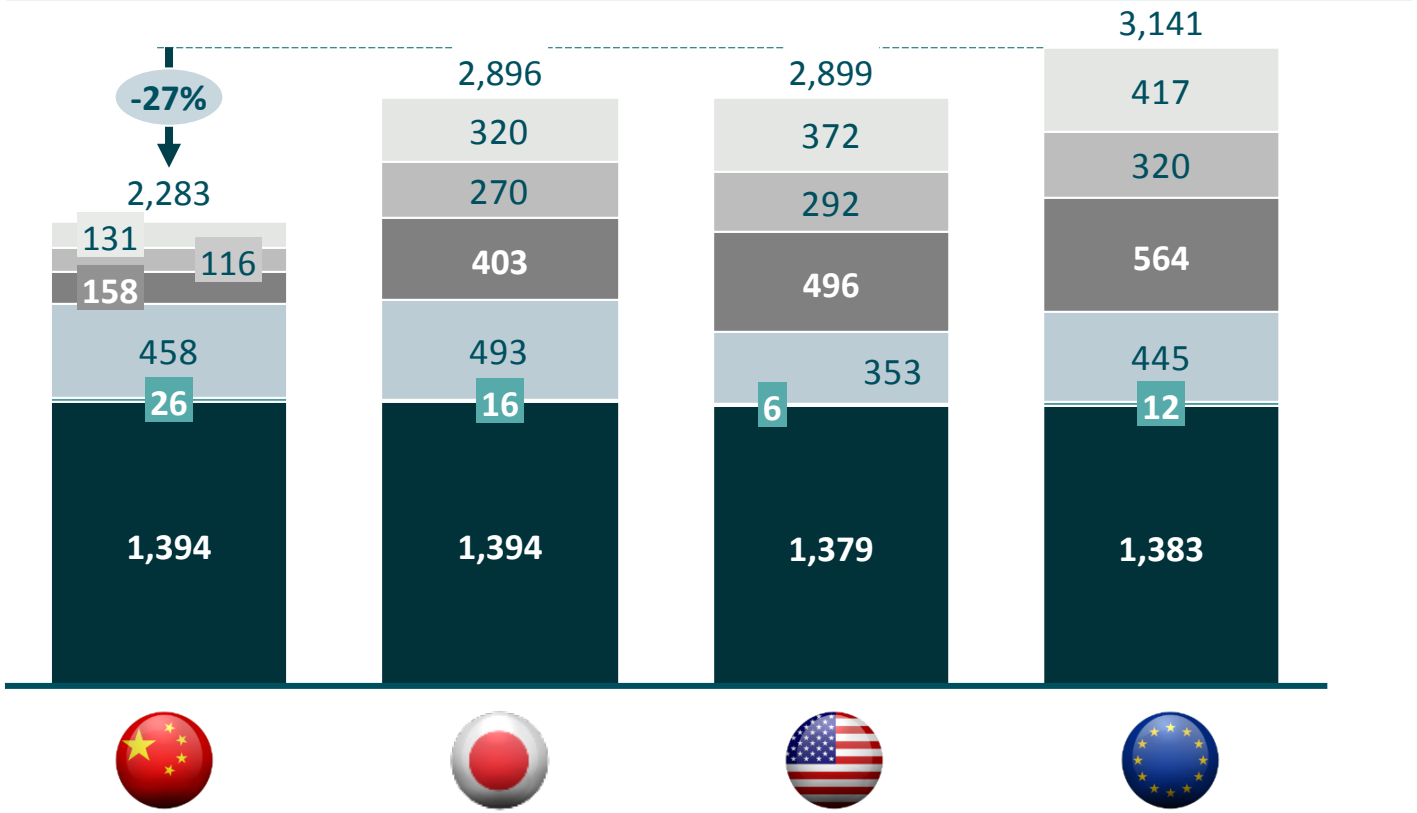
SOURCE: Analysis based on industry reports and interviews

Polyurethane regional production cost

SG&A | Direct labor | Electricity
Maintenance and plant overhead | Other variable cost | Raw materials

Plant gate cost for generation of base PU (without additives[1]) across different geographies[2]

USD/ton PU, 2012



- Raw material and other variable costs are largely similar across regions
- Labor-related costs make a large difference in production costs
  - In WE, almost half the cost of PU is labor, maintenance, overhead and SG&A
  - In China, they only make up ~20%

1 Additives add 30-50% cost to PU
2 5 kta PU plant using purchased TDI, integrated PO and polyether polyols
SOURCE: McKinsey margin models

Contents

Introduction to polyalphaolefins[1]

Introduction to PAO[2]

- **PAOs used mainly as base fluid for lubricating oils**
  - **PAO** as base fluid (Group IV classification) **with ~50% share** in synthetic lubricant base fluid segment
  - **5% share of total lubricant market**
- **High-performance lubricant properties** (e.g., viscosity, low temperature resistance , low pour point)
- **Replaces mineral-oil-based base fluids** (Group I-III) in selected applications due to higher purity/performance and despite its higher costs
- Produced by integrated oil companies or chemical companies, e.g., ExxonMobil and Dow
- Close collaboration, e.g through EOM certification, making it a customer/ service intensive product

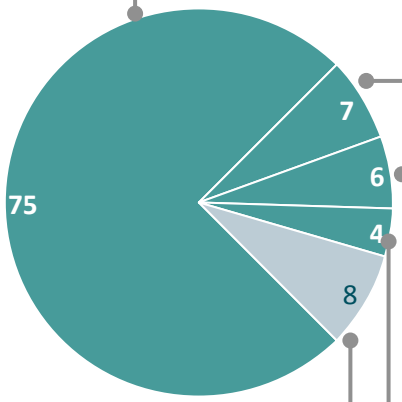
Key facts

- **Total European production: 213 thousand metric tons**
- **Total emissions: 0.8-1.4[3] $MtCO_2e$** (4.5-6.5 tCO_2e per ton PAO)
- Produced through the polymerization of an alpha-olefin

PAO applications, percent

Lubricant applications

Non-lubricant applications



Automotive engine oils

- Component in high-performance engine oils, both for gasoline (largest part) and diesel engines

Automotive gear oils

- Increased gear train operating temperatures and trend towards sealed-for-life gearboxes has increased demand for fully synthetic gear lubricants

Industrial applications

- Stationary diesel engines, paper machines and wind turbine gear boxes

Other lubricant applications

- Automotive hydraulic fluids in fill-for-life applications
- Bearing lubrications, particularly in miniature and instrument ball bearing industry

Non-lubricant application

- Heat transfer, dielectric and insulation fluids

1 Polyalphaolefins used in synthetic lubricants, i.e., not polyethylene or other polyolefins
2 Polyalphaolefins
3 Lower range assuming 20% recycling/reuse, upper range assuming no recycling/reuse
SOURCE: Analysis based on industry reports and interviews

D Overview of value chain and associated emissions

Integrated oil companies | Chemical companies

Overview of emissions across PAO value chain

Value chain

Basic chemicals → Intermediates → End product → Applications → End-of-life solutions

Basic chemicals: Naphtha, gas condensate, propane and ethylene production

Intermediates: LAO synthesis and oligomerisation

End product: PAO synthesis, distillation hydrogenation

Applications: Mixing with esters and additives

Ethylene → **Linear alphaolefins** (C4-C30) → **PAO basestock**

- Globally produced liquid commodity
- Produced from naphtha

- Includes several alphaolofins, mainly 1-decene
- Shortage in feedstock has forced PAO producers to vertically integrate

- Produced by either integrated oil companies or chemical companies, e.g. ExxonMobil and Dow

PAO-based lubricants
- Automotive crankcase oil
- Automotive gear oils
- Industrial applications
- Other lubricant applications

Non lubricant applications

~50% collectable
- 5% reclaimed and reused in original application
- 15% re-refined into lubricant base fluids
- 20% reprocessed to fuel or directly burnt
- 10% not collected

~ 50% released directly into the environment (e.g. combusted in engines)

Emissions[1]

End-of-life | Indirect | Direct

	Basic chemicals	Intermediates	Production	End-of-life[2]	Total
Per ton virgin PAO produced (tCO_2e)	1.4-1.6	0.3-0.7	0.3-0.7	2.5-3.5	4.5-6.5 (2.5-3.5; 1.6-1.8; 0.7-0.9)
Total European emissions[3] ($MtCO_e e$)	<0.1 / 0.2-0.3	~0.1 / <0.1	<0.1 / <0.1	0 / 0.4-0.7	0.1-0.3 / 0.7-1.1

Total: 0.8-1.4

1 Assuming same emissions as HDPE-production (given similarity in production method), one extra polymerization step is added to account for PAO synthesis. Polymerization steps also scaled up by up to 30% to represent higher complexity and lower scale in PAO production; 2 Assuming incineration is final end-of-life solution; 3 Lower range assuming 20% recycling/reuse rate, upper range assuming no recycling/reuse

SOURCE: Analysis based on industry reports and interviews

Key abatement levers across the value chain

Switch to bio-ethylene as feedstock

- Up to 50% of ethylene replaced with bio-ethylene by 2030, with 40% emission reduction per ton ethylene
- Possibility of using bio-ethylene varies, depending on lubricant characteristics and plant configurations

Increase collection rate

- Through technological advancements and legislation, share of lubricants that is collectable assumed to increase from 50% to 60%
- Share of collectable lubricants that is collected assumed to go from 80% to 95%
- Collection more viable within large applications (e.g ships)

Increase reuse and re-refining rate

- Today only 13% of collected synthetic lubricants are reused in similar applications, in addition 38% are re-refined into new base oils
- Total reuse-and re-refining rate assumed to increase to 75% of collected lubricants
- Separating PAO from other lubricants in collection face is a challenge

Move towards bio-based base oils

- Metathesis technology and BBOs2 are possible bio-based alternatives, with up to 80% lower GHG emissions than PAO
- Replaceability of PAO remains challenge. In 2030, up to 50% could be possible

Improve process and energy efficiency

- Continuous efficiency improvements in multiple process steps leading to a 25% reduction by 2030
- In line with historical emission and energy reductions

Switch to green energy throughout the value chain

- Non-fossil energy share of total electricity production assumed to increase from today's 46% to ~70%1, reducing CO2 emissions from electricity generation by ~50%

Switch group I-III lubricants for PAO

- More effective synthetic lubricants can reduce fuel consumption by 1-3%. This is applicable on 50% of the vehicle fleet
- PAO is used as base in 50% of more effective lubricants

1 Based on Enerdata Emergence Case; 2 Biosynthetic base oils
SOURCE: Analysis based on industry reports and interviews

CUSTOMER/ SERVICE INTENSIVE PRODUCTS: POLYALPHAOLEFINS

Overview of total emission reduction opportunity by 2030

$MtCO_2e$, 2030, assuming levers pursued in parallel[1]

Indirect | Direct

			Assumptions	Emission reduction
			Frozen technology 2030[2]	1.7
Scope 1 + 2	Shift to renewable feedstock	Switch to bioethylene as feedstock	▪ Up to 50% of ethylene replaced with bio-ethylene by 2030, with 40% emission reduction per ton output	~0.1
	Process and energy efficiency	Improve process and energy efficiency	▪ 1.5-2% process and energy efficiency improvement annually from 2011 to 2030	0.3-0.4
	Recycling/ re-use	Increase collection rate	▪ Share of collectable lubricants that is collected assumed to increase from 80% to 95%. Share of lubricants that is collectable supposed to remain at 50% ▪ Collection more viable within large applications (e.g ships)	~0.1
		Increase reuse and re-refining rate	▪ Today only ~50% of collected synthetic lubricants are reused or re-refined ▪ Total reuse-and re-refining rate to be increased to 65% of collected lubricants ▪ Separating PAO from other lubricants in collection face is a challenge	~0.1
	Shift to green energy	Move towards greener energy mix	▪ Non-fossil energy share of total electricity production assumed to increase from today's 46% to ~70%[1], reducing CO2 emissions from electricity generation by ~50%	~0.1
	Product/ materials substitution	Move towards bio-based base oils	▪ Metathesis technology and BBOs[3] are possible bio-based alternatives, with up to 80% lower GHG emissions than PAO ▪ Replaceability of PAO remains challenge. In 2030, up to 50% could be possible ▪ Net effect when assuming 50% replacement, and rest having implemented levers	~0.3 ← 55-60%[4]
			The full abatement potential is not commercially available	Total emissions, 2030: 1.0[4] 40-50%[5]
Scope 3	Enabling downstream and global emission reductions	Switch group I-III lubricants for PAO	▪ More effective synthetic lubricants can reduce fuel consumption by 2%. Applicable on 50% of the vehicle fleet. PAO is used as base in 50% of more effective lubricants ▪ Mineral oils less GHG intensive to produce, but has much shorter lifetime, making the net production effect ~0	3-5
		Global potential	▪ Largest global potential comes from spreading use of more effective lubricants to rest of the world. OEMs can work together with European lubricant manufacturers through recommendation and certification abroad ▪ Also possible to e.g. export use of BBOs and bio-ethylene, and increased recycling	5-15

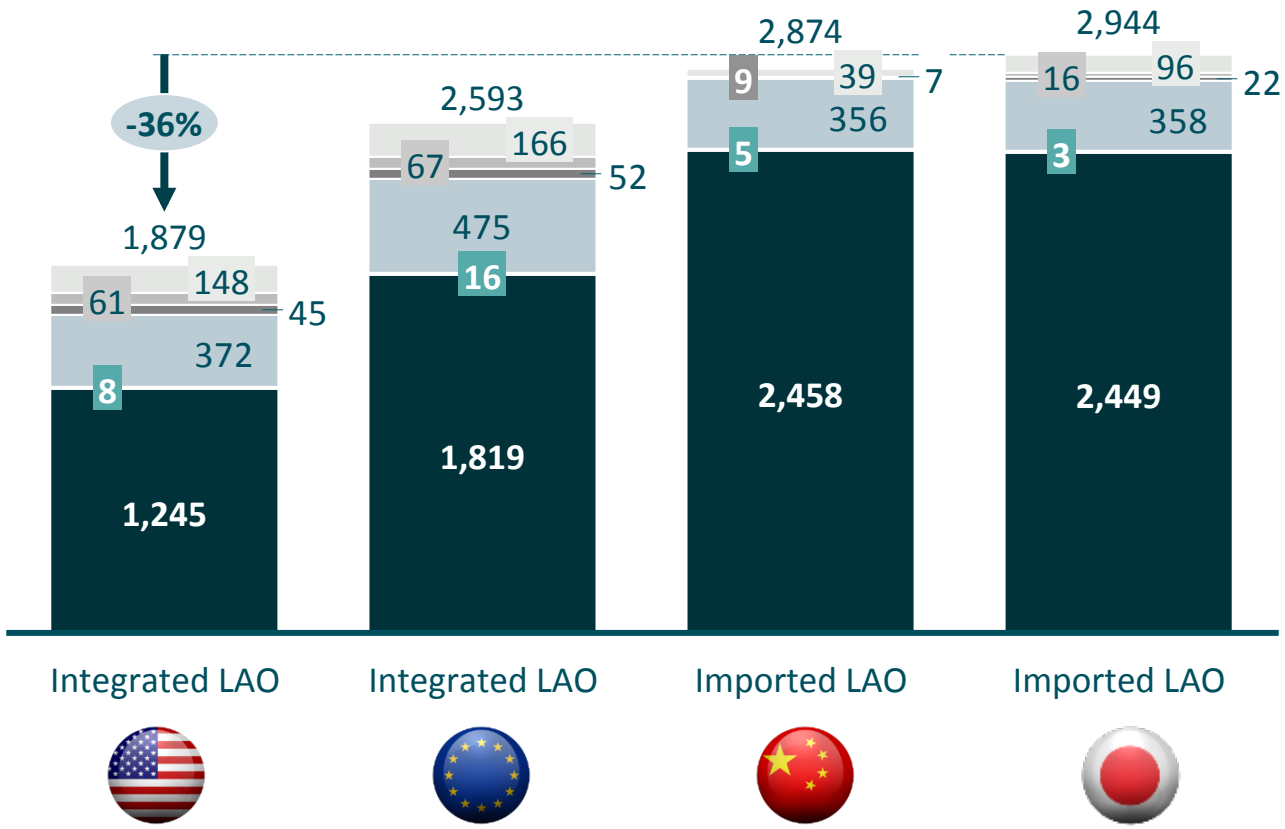
1 Individual levers have larger potential if pursued alone; 2 Assuming same carbon footprint as today with 2% production growth rate per year (European consumption growth prediction); 3 Biosynthetic base oils; 4 Including shift to bio-based base oils; 5 Excluding shift to bio-based base oils

SOURCE: Analysis based on industry reports and interviews

Polyalphaolefins regional production cost

SG&A | Direct labor | Electricity
Maintenance and plant overhead | Other variable cost | Raw materials

Plant gate cost for generation of polyalphaolefins across different geographies[1]
USD/ton PAO, 2012



- NA and WE cost significantly lower than China/NEA cost, primarily due to raw material costs
  - Asia requires LAO imports from Europe
  - NA ethylene lower cost than WE

1 65 kta PAO plant. US and WE plants integrated with LAO plant, NEA and China purchasing imported LAO from WE
SOURCE: McKinsey margin models

Contents

E Introduction to carbon fiber reinforced plastic

Introduction to CFRP

- CFRP (carbon fiber reinforced plastic) is made of carbon fiber and a resin (a matrix material)
  - Carbon fiber is a **long, thin strand of material** consisting of ~95% carbon
  - Most common resin is **epoxy**, another example is polyester
- Key properties of CFRP include **high stiffness, strength and durability**
- Widely used in **aerospace, automotive and wind energy sectors**
- **Highly expensive material,** which is the main barrier for broader use today, significant research ongoing

Key facts

- **Production of ~15 thousand metric tons** in **EU** 2012
- **Total emissions: 300-400 thousand metric tons CO_2e (~25-28 tCO_2e per ton CFRP)**
- Demand growth of **~15% between 2009 and 2012**, mainly driven by increased usage in production of aircraft
- Concentrated market where **few players control majority of the world's capacity,** e.g. Toray and Toho Tenax
- Different precursors can be used although **PAN precursor constitutes ~90% of production**

CFRP applications

Strong demand growth in many markets

- CFRP sees strong growth potential in all major markets from different drivers

Automotive

- Fuel efficiency trends increase need for lightweight constructions

Wind energy

- Regulations and incentives to cut CO_2 emissions and increase wind power
- Large diameter turbines off-shore

Aviation

- Increased use in aircrafts, replacing metal parts
- Growing aircraft deliveries

Engineering

- Growing demand in infrastructure repair and replacement market
- Applications include, e.g., bridges

Sporting goods

- Growth largely dependent on discretionary spending and shift of material

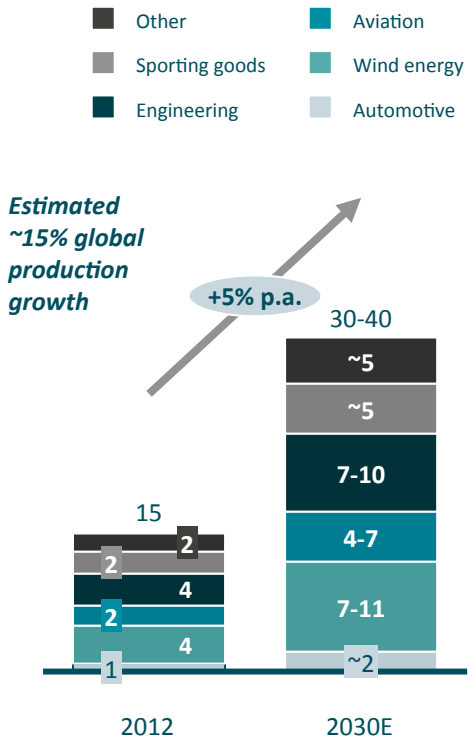
Other

- Growth areas include e.g. pressure vessels in natural gas vehicles and high-speed ferries

Estimated production growth

- Due to high labor and energy costs, growing demand in Europe will likely be met by increased imports to large extent
- Expected EU27 capacity growth of 0-5% p.a.- yet, significant upside

Production
EU27, thousand tons



SOURCE: Analysis based on industry reports and interviews

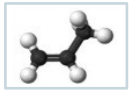
E Overview of value chain and associated emissions

Overview of emissions across CFRP value chain

Value chain (illustrated by floor pan example from PAN precursor)

Feedstock production → Production of precursor → CFRP production → Final product manufacturing → End-of-life solutions

Raw materials
- PAN precursor is made from acrylonitrile, commercial product that is colorless, liquid and poisonous
- Acrylonitrile is made from propylene, a gas made from naphtha



PAN precursor
- Organic polymer whose composition varies and is company specific
- Produced through polymerization, dissolution, spinning and washing

Fibers
- Strands of carbon, thinner than human hair
- Thermal stabilization and carbon-ization in oven

Part making using e.g. RTM process or SMC process[1]

Resin
- Common matrix material include epoxy and polyester

Final floor pan product
- Typically containing up to ~40wt% matrix material

End-of-life processes
- Strong R&D focus, recycling today limited

- Value chain illustrated for CFRP floor pan end product
- PAN is used as precursor in 90% of all carbon fiber production

Emis-sions

Per kg of CFRP floor pan produced (kg CO_2e)

Floor pan example

31 kg CO_2 emissions per kg fiber produced, ~60wt% kg fiber/ kg end part

Direct/ indirect | End-of-life

Emissions from carbon fiber production

Emissions from manufacturing and other materials used in end-product

Total CFRP emissions in Europe, (tCO_2e, thousands)

Raw materials	Precursor production	Fiber production	Resin production	Part forming	End-of-life	Total
40-50	130-150	90-110	10-20	50-60	~0[8]	300-400

Note: Based on total European production of 15 thousand metric tons 2012

1 RTM (resin transfer molding) used for high-volume production and SMC (sheet molding compound) used for low volume production, the fiber and resin can be combined through e.g. forming prepreg or preform ; 2 Include production/extraction of naphtha, propylene production from naphtha and acrylonitrile production from propylene; 3 Energy intensive step from spinning; 4 Include heating up to 1,500°C; 5 Assuming production emissions of 2.3 tCO2e/ ton polyester resin, 40wt% polyester/ kg CFRP; 6 Here illustrated by SMC; 7 Incineration most CO2 intensive choice of end-of-life solutions with ~3.3 ton CO2/ ton CFRP; 8 Currently little CFRP going EOL

SOURCE: Analysis based on industry reports and interviews

E Key abatement levers across the value chain

Shift to alternative precursors in carbon fiber production

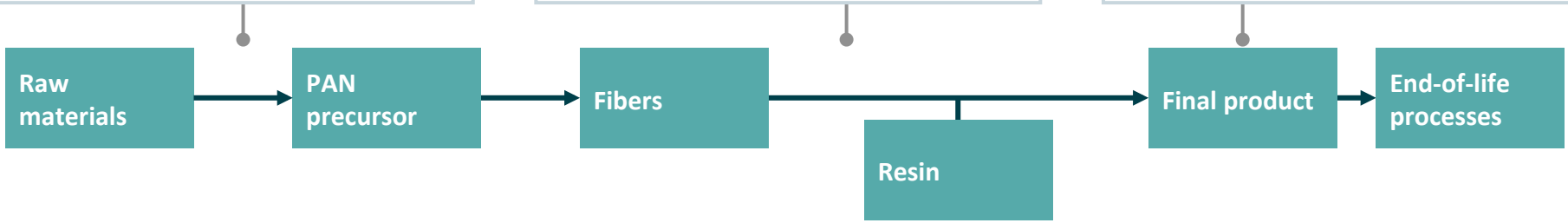
- 20% emission reductions in carbon fiber production if lignin can be industrialized compared to PAN-precursor based fibers
  - Still technical advancements required, research ongoing
- Shift to oil-based polyethylene
  - Less potential than lignin but more feasible

Increase use of recycled carbon fiber in production

- Currently only certain types of carbon fiber can be recycled
- Boeing has identified potential to reduce production costs with ~70% and energy use requirements with >98%

Replace steel used in cars with CFRP

- Replacing steel with CFRP in body structure can reduce weight of standard car by ~200kg
- Emission reduction of 8.4g/ 100kg weight reduction (standard car) per km
- Main barrier for large scale use is current cost, which is expected to decrease rapidly



Switch to green energy

- Non-fossil energy share of total electricity production to be increased from today's 46% to ~70%[1], reducing CO_2 emissions from electricity generation by ~50%

Improve process and energy efficiency

- Potential improvement of >50% in energy efficiency
- Energy efficiency not in focus today as stable processes are still deemed most important
- Areas of improvement include precursor production[2], precursor processing[3], and part making[4]

1 Based on Enerdata Emergence case
2 E.g., using melt-spinning rather than solution spinning
3 E.g., substitute for oven based process for fiber stabilization and oxidation
4 E.g., reducing cycle times by adapting faster curing resins
SOURCE: Analysis based on industry reports and interviews

E Overview of total emission reduction by 2030

$MtCO_2e$, 2030, assuming levers pursued in parallel[1]

			Assumptions	Emission reduction[3]
			Frozen technology[2]	0.8
Scope 1 + 2	Process and energy efficiency	Increase process and energy efficiency	▪ >40% improvements in energy efficiency by 2030 if stand-alone (less when pursued in parallel other levers) ▪ E.g. switch to melt-spinning in precursor production and improve fiber conversion	0.15-0.2
Scope 1 + 2	Product/ material substitution	Replace PAN with lignin or polyethylene	▪ Complete transition to lignin with 20% emission reduction per ton carbon fiber produced ▪ Switch to polyethylene today more feasible but with less abatement potential	<0.1
Scope 1 + 2	Recycling/ re-use	Increase recycling of CFRP	▪ Use 25% recycled carbon fiber in production (possible to recycle several times) ▪ Energy requirements reduced by ~75%[4]	0.05-0.15
Scope 1 + 2	Shift to green energy	Increase use of green energy	▪ Green energy share of total electricity production can be increased from today's 46% to ~70%, reducing CO2 emissions from electricity generation by 50%	0.15-0.25
			Total emissions, 2030	0.2-0.35 -60-70%
Scope 3	Enabling downstream emission reductions global emis-sion reduc-tions	Replace steel with CFRP in cars	▪ Additional emissions required to account for increased production, assuming emission intensity in production already reduced by 65% through above levers	1-4[5]
Scope 3	Enabling downstream emission reductions global emis-sion reduc-tions	Replace steel with CFRP in cars	▪ Weight reduction of 200 kg from using CFRP in frame, resulting in a ~17g CO_2 emission reduction/ km (8.4g/100kg/km) ▪ Lower limit assumes ~2% of produced car fleet having CFRP in 2030, upper limit 10%	2-8[6]
Scope 3	Enabling downstream emission reductions global emis-sion reduc-tions	Global potential	▪ Largest potential from spreading CFRP in cars to other regions. If European car producers would build lighter, more fuel efficient cars, this would put pressure on other manufacturers to do the same. European manufactured cars are also exported ▪ Strong incentives for others to follow improvements in process efficiency enabling cost reductions, both other CFRP manufacturers and other industries, e.g., automotive ▪ Also significant potential if breakthroughs in recycling and in alternative precursors	5-15

The full abatement potential is not commercially available

1 Individual levers have larger potential if pursued alone
2 Assuming 5% production growth from 2012
3 Split direct/ indirect estimated based on target steps of levers
4 Conservative vs. Boeing's estimates
5 Additional production emissions (not likely from production within EU) required to reach CFRP penetration of 2-10% in automotive, split on assumed car life time of 13 years
6 Annual emission reductions in the automotive industry
SOURCE: Analysis based on industry reports and interviews