Recycling of Renewable Composite Materials in the Offshore Industry

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Glossary

Biocomposites They are a composite material formed by a matrix (resin) and a reinforcement of natural fibers.
Bulk molding compound (BMC) Polyester resin/glass fiber premix, for injection or transfer molding, also known as dough molding compound (DMC).
Carbon fiber Reinforcing fiber known for its light weight, high strength, and high stiffness.
Composite A material made up of resin and reinforcement (usually fiber).
Fiber-reinforced polymer (FRP) A general term for composite materials or parts that consist of a resin matrix that contains reinforcing fibers such as glass or fiber and have greater strength or stiffness than the resin. FRP is most often used to denote glass fiber-reinforced polymer.
Fiber A unit of matter of relatively short length, characterized by a high ratio of length to thickness or diameter.
Glass fiber Reinforcing fiber made by drawing molten glass through bushings. The predominant reinforcement for polymer composites, it is known for its good strength, processability, and low cost.
Impregnation Saturation of reinforcement with liquid resin.
Polymer A long-chain molecule, consisting of many repeat units.
Recyclates The raw material collected, taken to, and processed in a waste recycling plant or materials recovery facility that will be used in the manufacturing of new materials.
Recycling The process of converting waste materials into new materials, products and objects.
Reinforcement Key element added to resin (matrix) to provide the required properties; ranges from short fibers and continuous fibers through complex textile forms.
Resin Polymer with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. As composite matrices, resins bind together reinforcement fibers.
Scanning electron microscope (SEM) A type of electron microscope that is used to produce enlarged images of a sample by scanning the surface with a focused beam of electrons, like reinforced CFRP samples. When the samples are placed under the microscope, the electrons mix with the constituent atoms within the composite sample. This will produce different signals that contain information about the surface topography and composition of the sample.
Sheet molding compound (SMC) A flat prepreg material, comprising thickened resin, glass fiber, and fillers, covered on both sides with polyethylene or nylon film, ready for press-molding.
Thermoplastic A plastic that softens each time it is heated.
Thermoset A plastic that flows and then sets permanently on first heating, as a result of setting up a three-dimensional cross-linked molecular structure, and subsequently will not soften or dissolve.

Introduction and Background

Current trends in the use of composites have developed into more applications in various sectors. In the offshore industry, there are some challenges with the standards on the use of offshore composites, particularly as structural members. However, composites are lightweight and can be used on other areas of the offshore sector. Some research into the use of recycled composites, like other composites, show that they are good reinforcement materials, depending on the purpose of application (Gibson, 2003; Wei *et al.*, 2018; Hornsby and Bream, 2001). Boats and some leisure ships made of composites can also be recycled (Sponberg, 1999). Studies have also been carried out on the life cycle for both FRP and glass reinforced polymer (GRP) composites (ISO, 2006; Song *et al.*, 2009; Bachmann *et al.*, 2017). **Fig. 1** shows the offshore developments with different offshore structures showing the need for composites. As the offshore explorations go deeper into deep waters, more lengths of risers are required which also adds on the weight of the offshore platforms. Composites can be harnessed to reduce the weight as well as enable the technologies in these offshore operations. Composites have also been used to lighten the weight of automobiles and building products commercially, such as by ELG Carbon Fiber (ELG Carbon Fibre, 2016, 2017; Gehr, 2018) and Filon (Job *et al.*, 2016). Carbon fiber can be recovered, as shown in **Fig. 2**, by ELG Carbon Fiber. Recycled composites have also been used in fences from recycled carpets as structurally stable and fit for use (Sotayo *et al.*, 2015, 2016, 2018, 2019). These can also be deployed on offshore applications for hand rails, guard rails and safety fences in structures where the use of composites are permitted.

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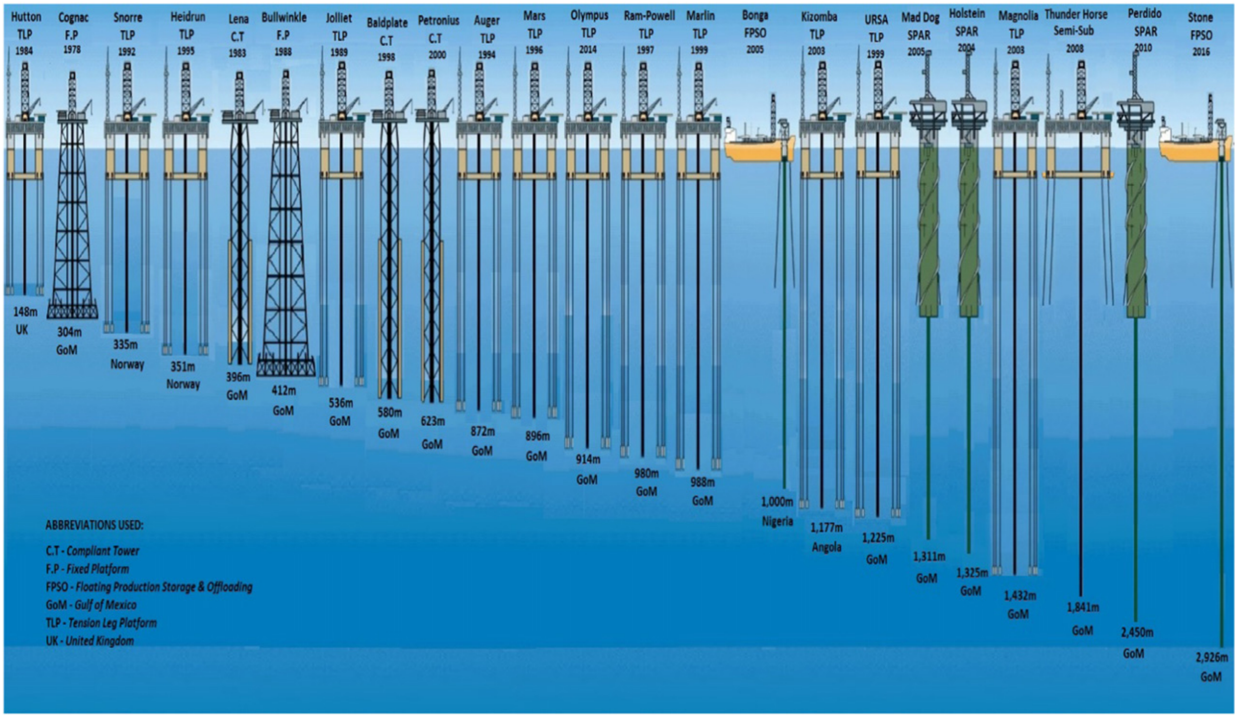

Fig. 1 History of offshore deep waters, showing the offshore structures and their water depths.

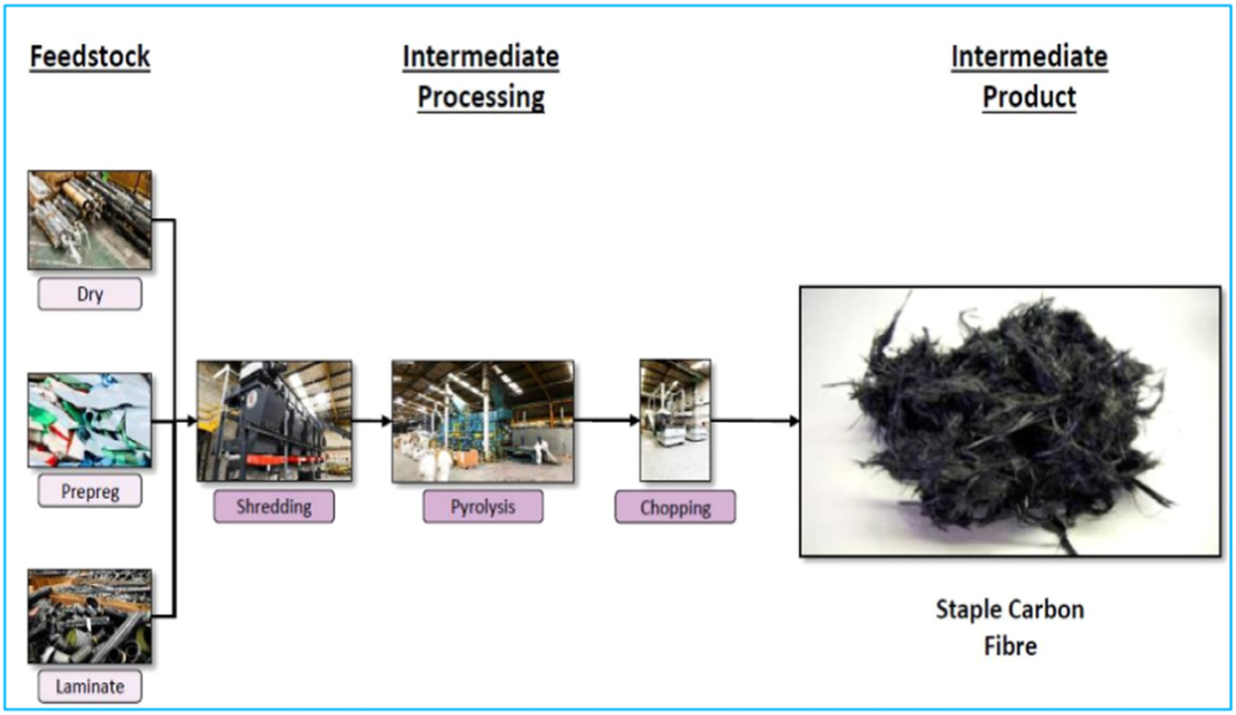

Fig. 2 Carbon fiber reclamation. *Source*: ELG Carbon Fiber, 2016. Reproduced from: ELG Carbon Fibre Recycled carbon fiber as an enabler for cost effective lightweight structures, Global Automotive Lightweight Materials (GALM), Detroit, 2016 ELG Carbon Fiber Ltd. Detroit Available at: http://www.elgcf.com/assets/documents/GALM_US_2016.pdf.

Due to the growing demand for more sustainable materials, there has been a global increase in the application of composites in the offshore industry. This includes composites for composite risers (Amaechi *et al.*, 2019a; Amaechi and Ye, 2017; Wang *et al.*, 2011a,b), composite tubes (Sparks *et al.*, 1992; Bhudolia *et al.*, 2015; Wang *et al.*, 2011a,b), submarine hoses (Amaechi *et al.*, 2019b), floating hoses, underwater vehicles, remotely operated vehicles, naval ships and submarines (Mouritz *et al.*, 2001), submersibles (Odijie, 2015; Odijie *et al.*, 2017a,b), SPARS (Amaechi *et al.*, 2019d) and floating production storage and offloadings (FPSOs). This trend for the demand of carbon material composites has also been observed in other industries. This includes the automobile industry, and the renewable energy (Doyle and Aggidis, 2019; Zhang *et al.*, 2019) and aerospace industry (Shi, 1996; Yang *et al.*, 2012).

ELG Carbon Fiber was the world's first commercial carbon fiber-recycler. They can take dry fiber, prepreg, and cured laminate waste. The waste is converted into the Carbiso range of products including chopped and milled fiber, oversized tow and nonwoven mats. Other products using recycled carbon fiber, including injection molding compounds, are under development. For glass fibers, there are presently the following options: In-house recycling, cement kiln, energy recovery, and landfills. For the in-house recycling, there may be ways you can recycle some of your GRP waste in-house, particularly if you use a spray-up or casting process. Grinding to fine filler is a proven route but is difficult to achieve economically. Ecowolf (Florida, USA) provides equipment for incorporating GRP regrind in spray-up processes. Conenor (Finland) provides advice/R&D services for multilayer extrusion that can incorporate GRP regrind. For the cement kiln (recycling/recovery), it involves mixing the shredded composite parts/offcuts with other waste to feed into cement kilns. Organic resin is burnt for energy; inorganic components become feedstock for cement. Carbon fibre reinforced polymer (CFRP) can also be treated this way but recycling is preferable. Agecko in UK and Neocomp in Germany (formerly operated by Zajons) promote this process specifically for the composites industry. For energy recovery, GRP wastes are sent for energy recovery, like to Viridor in Oxford, UK. The glass and filler will go to ash, but in some cases the bottom ash from incinerators is recycled rather than landfilled. Sometimes, the incinerator bottom ash will be recycled (as aggregate or in building products) or landfilled, and the waste can be exported for incineration overseas. The most common is the use of landfills as most GRP waste still goes to landfills.

The global demand for carbon fiber is estimated to greater than double to be between 150,000 t and 180,000 t by 2020. With the manufacturing techniques used today, there is approximately 30% of the overall demand for carbon fiber becoming waste both during the conversion phase and component-manufacturing phase of the recyclates. The remaining fiber is added into the finished parts, which will be disposed of later at the end-of-life (EOL). With the increase in the application of CFRP composites in components with shorter service lives, the EOL will range between 2 and 40 years, depending on the frequency of its usage (ELG Carbon Fibre, 2017).

The market drivers that determine the best disposal solutions of wastes from FRP composites are the market forces of demand and supply, the increasing cost of landfills, the increase in awareness on circular economy thinking, the markets for recycled products, government policies and legislations on recycled FRP composites. However, the most important driver on commercial viability of recycled FRP composites is the breaching of new markets (Brown *et al.*, 2018). With the increase in more composite recyclates, there is also an effect on the existing composite manufacturers, and their sources of raw materials. Currently, automobile manufacturers like BMW and VW (Volkswagen) are also researching on increasing the use of composites on their cars and also using recycled composites and biocomposites (Das *et al.*, 2016; Bharath and Basavarajappa, 2016; Mohanty *et al.*, 2018). This will also increase the economic viability of recycled FRP composites in the automobile industry. There is need to create more circular recycling on FRP composites, create higher value recycling routes to explore other areas of the market, and increate more economic exchanges and businesses both within the composites industry and with other industries such as the mainstream aviation industry, automobile industry, and construction industry.

There are four main drivers that influence the supply chain of recycling carbon fibers. They are the affordability, security, legislative policies, and environmental responsibility. The economic conversion of both the raw wastes from manufacturing and EOL components into different recycled carbon fiber shapes, forms, and component designs is very important. This material product can then be used technically for different applications, making these lightweight carbon fiber composites less expensive. With respect to the security of the supply chain, the application of recycled carbon fibers controls any supply side capacity risk by bringing in high tonnes of carbon fiber from existing production capacity, thus buffing it up. Legislation plays a very great role, as these policies are what guides the manufacturers and the end-users about the product and its circulation in the market. The need for environmental responsibility cannot be overemphasized. In the automotive industry, EU legislation requires 85% of a vehicle to be recyclable. Carbon fiber waste can be recovered and converted to new products using less than 10% off the energy required to produce the original carbon fiber, fulfilling legislative and sustainability targets (ELG Carbon Fibre, 2017).

Carbon Fiber and Glass Fiber Composites

Carbon fiber has been of high value in the composites market and can be also applied in the offshore industry. Currently, there are more carbon fiber-recycling companies that in operation and also thriving commercially. They include ELG Carbon Fiber, Filon, etc., as shown in **Tables 1–3**. Carbon fibers are composed of at least 92% carbon and most commonly have a diameter in the range 5–10 μm. They are polymers with a structure that is almost completely graphitic. This graphitic form of carbon fiber is a pure form of carbon in which the atoms are arranged in big sheets of hexagonal rings. The structure provides very high levels of stiffness and strength. Technically, carbon fibers have been produced and improved for many decades because of their excellent mechanical, thermal, and electrical properties, often exploited as carbon fiber composites for highly valuable applications in sectors including

Table 1 Current commercial composites recycling services for fiber-reinforced polymers GFRP and CFRP

Company/location	*Processes/capacity*	*Materials recycled*	*Recyclate market*	*Reference website*
ELG Carbon Fiber, (Formerly Milled Carbon), West Midlands, UK	Pyrolysis process, 2000 t/year recovered carbon fiber output	Dry carbon fiber waste, carbon fiber prepreg waste, carbon fiber laminates	Chopped/milled/pelletized carbon fiber. Carbon fiber random mats and discontinuous fiber yarns. Also preforms.	www.elgcf.com
Competitive Green Technologies	Uses natural fibers with PP and PE based polymer matrices and bioresins	Coffee beans, and some bio materials	Biocomposites like biodegradable bins, biodegradable cases, and carbon-based products.	www.competitive-greentechnologies.com
CFK Valley Stade Recycling, Germany	Pyrolysis, >1000 t/year, launched in 2011. Presorting, crushing, and sorting of materials according to type of fiber and state of processing: Dry carbon fiber scraps, prepreg materials, end-of-life parts. Pyrolysis using thermal treatment excluding oxygen to recover pure carbon fibers completely by means of thermal oxidation of pyrolysis gases.	CFRP waste materials of different types	Milled 80–500 μm. Fiberball/pelletized/chopped 1–100 mm (e.g., for PA, PC, PP reinforced compounds). Wet laid veil 10–30 g/m^2 (e.g., for surface optimization, EMI shielding). Air laid nonwovens 200–600 g/m^2 (e.g., for RTM process for structural parts, SMC & BMC process). Refined custom-made fiber surface. Cutting and processing of carbon fibers into models “chopped” and “milled” accurately cut to desired fiber length.	www.carbonxt.de, http://cfk-recycling.com, https://www.cfk-recycling.de/index.php?id=57
Materials Innovation Technologies – Reengineered Carbon Fiber (MIT-RCF), South Carolina, USA	Pyrolysis, current capacity 2000 t/year recovered carbon fiber output (room for expansion)	All kinds of CFRP waste materials	Nonwoven rolled goods. Chopped fiber for compounding and long fiber-reinforced thermoplastic (LFT) applications. Preforms (3-DEP process).	http://mitrcf.com
Reprocover, Belgium	Thermoset waste ground to max. 6 mm granules. 30% glass fiber flakes mixed with 70% thermoset granules, resin added, high pressure cold molded.	Thermosets, including GRP with or without fiber-reinforcement. Also wastes from dry glass fibers.	Utility boxes, rail infrastructure products (e.g., cable tray covers), flower boxes, bins, etc.	www.reprocover.eu
Global Composites Recycling Solutions, UK	Ground GRP and glass fiber is incorporated with other materials into Ecopolycrete. This is to be sold as a mix for polymer concrete type applications that can be precast or poured in place for railway sleepers, parking stops, and other construction products. The material has a steel-like compressive strength and very high fire resistance. Went commercial in Tennessee, USA, around September 2014, and later in Northamptonshire, UK.	Cured GRP and glass fiber	Ecopolycrete	www.ecopolycrete.com
Global Fiberglass Solutions, Bothell, WA, USA	Recycling services to industries worldwide, including the wind energy, aerospace, maritime, and manufacturing sectors. Infinitely recycles with GFS process.	Industrial carbon fiber and fiberglass waste	Wind blade recycling, ecopoly pellets, fiberglass recycling	https://www.global-fiberglass.com/

Hambleside Danelaw, UK	Have developed a process for mechanically recycling GRP to retain fiber length. These fibers have been utilized to form reinforcements both as chopped fiber and in nonwoven recycled fiber mats. The fibers have been used in both thermoset and thermoplastic composites to form products for the construction industry. Experimentation has also been carried out in using the fibers with concrete and with rubber to enhance the properties of these materials.	Cured GRP	GRP products, roof lights, cladding flashings, and the Dryseal flat roofing system.	https://www.hambleside-dane-law.co.uk/
Extreme Eco_2 Solutions, Netherlands	Have started collecting production and end-of-life waste, working with selected partners in the transport and dismantling sector. The intention is to shred the GRP and grind to powder. This would be transported to Norway for recycling, initially as an additive for polyethylene film products in a process that is under development.	Cured GRP including whole products (e.g., boats)	–	http://extreme-ecosolutions.com
Karborek RCF, Martignano, Italy	Pyrolysis process with energy recovery, to produce chopped/milled carbon fibers and carbon fiber felt. Capacity up to 1500 t/year. The plant was completed in October 2014, and production started around January 2015.	CFRP waste	Chopped carbon, milled carbon, fibers, and carbon fiber felt.	www.karborekrcf.it
Carbon Fiber-recycle Industry Co Ltd, Japan	Utilizing thermal decomposition by self-combustion process (6.7 MJ/kg-CF, 13.2 MJ/kg-CF), the company expects a recycling output of 1080 t/year.	CFRP waste	Recycled carbon fiber (and at pilot scale at time of data collection for other products).	https://cfri.co.jp/en/
Carbon Conversions (formerly MIT-RCF), South Carolina, USA	Milling and flocking, thermoplastic compounding and for SMC and BMC (high strength recycled carbon fiber-requirements, prepreg, closed & open mold infusion, thermoforming, pultrusion, compression molding, thermoforming closed mold infusion	CFRP waste	Chopped fiber, and nonwoven mat.	https://carbonconversions.com
Viridor, Oxford, UK	It separates glass, plastics, and polymers by polymer type including PET, HDPE, and PP pots, tubs, and trays	Plastics, glass, composites and other polymer wastes	EfW (energy from waste), some polymer products.	https://www.viridor.co.uk
Eco Waste Solutions, Burlington ON, Canada and Dublin, OH, USA	Uses a starved-air (pyrolytic style) process to convert the waste into a gas. Small waste generators with 100 kg to 15 t per day are best served by the EWS batch load waste system.	General wastes including composite wastes	EfW, some polymer products.	https://ecosolutions.com
Veolia, Rostock, Germany	Collection, sorting, then shredding to obtain PET flakes and washed in hot water. A mechanical and chemical recovery process transforms the flakes into a product suitable for food use. They are then purified before being packaged for shipment to bottle manufacturers. Up to 50% of recycled PET can be used to produce new bottles.	Plastic bottle wastes	PET flakes.	https://www.veolia.de
Reciclalia Composite, Madrid, Spain	Recycling company that optimizes composite waste management and minimize your carbon footprint	Carbon fiber and glass fiber wastes	Recycled fibers.	https://reciclaliacomposite.com

Abbreviations: BMC, bulk molding compound; CFRP, carbon fiber-reinforced polymer; GFRP, glass fiber-reinforced polymer; GRP, glass reinforced polymer; HDPE, high density polyethylene; LFT, long fiber thermoplastics; PET, polyethylene terephthalate; PP, polypropylene; SMC, sheet molding compound.

Table 2 List of the main manufacturers of various composite materials and resins

Type of composite	*Company*	*Reference website*
Thermoplastic composites	Milliken Tegris	tegris.milliken.com
Thermoplastic composites	Polystrand, Inc.	www.polystrand.com
Nonwoven fabrics (PolyWeb) and foam	Wm. T. Burnett & Co.	www.williamtburnett.com
Thermoplastic composites	Schappe Techniques	www.schappe.com
Thermoplastic composites	TechFiber	www.fiber-tech.net
Thermoplastic composites	TenCate	www.tencate.com
Thermoplastic composites	TherCom	www.thercom.com
Thermoplastic composites	Vectorply	www.vectorply.com
Composite materials: Resins and fibers	SF Composites	www.sf-composites.com
Formulation and manufacture of epoxy-based systems	SICOMIN	www.sicomin.com
Composite materials + resin, composite laminates	Lamiflex SPA	www.lamiflex.il
Composite materials + polyester	AMP Composite	www.amp-composite.il
Infusion, pultrusion, wet layup, prepreg, filament winding	Applied Poleramic Inc.	www.appliedpoleramic.com
Epoxy and polyurethane	Endurance Technologies	www.epoxi.com
Composite materials	Gurit	www.gurit.com
Advanced thermoset resins & adhesives	Huntsman Advanced Materials	www.huntsman.com/advanced_materials/a/Home
Advanced thermoset resins	Lattice Composites	www.latticecomposites.com
Kevlar	DuPont Kevlar	www.dupont.com/products-andservices/fabrics-fibersnonwovens/fibers/brands/kevlar.html
UHMWPEd ultra high molecular weight, high performance polyethylene material	DuPont Tenslyon	www.dupont.com
Innegra HMPP (polypropylene), high performance fiber	Innegra Technologies	www.innegratech.com
Spread tow fabrics	TeXtreme	www.textreme.com/b2b
Adhesives and sealants	3M	solutions.3m.com
Prepreg and resins	Axiom Materials Inc.	www.axiommaterials.com
Fabrics, resins, composite materials	Barrday Advanced Materials Solutions	www.barrday.com
Carbon prepreg	Hankuk Carbon Co., Ltd.	www.hcarbon.com/eng/product/overview.asp
Carbon fibers and prepregs	Hexcel	www.hexcel.com/Products/Industries/ICarbon-Fiber
Prepregs and compounds	Pacific Coast Composites	www.pccomposites.com
Prepregs and compounds	Quantum Composites	www.quantumcomposites.com

Note: Abramovich, H., 2017. Chapter 1 – Introduction to composite materials. In: Stability and Vibrations of Thin-Walled Composite Structures. Oxford, UK: Elsevier. pp. 3–4. doi:10.1016/B978-0-08-100410-4.00001-6.

aerospace, defense, wind energy, automotive, and sport. Specific examples of applications include aircraft wings (Wong *et al.*, 2017; Smith, 2013; Shi, 1996), wind turbine blades (WindEurope, 2017; Wong *et al.*, 2017), Tension Leg Platform tethers (Engineering and Freyssinet, 2000; Johnsrud, 1999), composite risers (Pham *et al.*, 2016; Amaechi *et al.*, 2019a,b), automotive (Akampumuza *et al.*, 2017; Vo Dong *et al.*, 2015; ELG Carbon Fibre, 2019), and tennis rackets.

According to Wise and Girard (2016), there are three main factors that influence the economy of carbon fibers. The first is the continued expansion in the market, especially in sectors such as automotive. Second is the drive towards a more cost-effective, high quality fiber that can be manufactured in large volumes. Thirdly, the availability of sustainable carbon fiber sources, including renewable precursors and routes for recycling carbon fibers from composites.

However, the challenge of recycling GRP, such as these waste trims and powdered wastes from the composites, is a stumbling block in industries where the pressure to recycle is high, as shown in **Figs. 2–5**. In Europe, the different processes have been tabulated to show the production volume from 2008 to 2018 by Industrievereinigung Verstärkte Kunststoffe - Federation of Reinforced Plastics (AVK) market reports, as presented in **Table 4** (Witten *et al.*, 2018; Sauer *et al.*, 2017; Witten *et al.*, 2016, 2015; Witten and Jahn, 2013; Jahn *et al.*, 2012; Witten and Jahn, 2011). It shows that there is an increase that is a function of the global economy, as a decreased production was recorded in 2008–2009. Some advances in the use of biocomposites show that they can have good strength for offshore applications, as shown in **Table 1**.

Review on Offshore Composites

It is pertinent to discuss the applications of composites in the offshore industry in general. A suitable application for a composite riser configuration like this would be marginal fields. Smaller vessels and lighter, redeployable risers would dramatically lower the cost of small pool field development and make these smaller reserves economically feasible. Composites are currently beating digital cameras on the innovation front – around a decade from inception to the first consumer product rather than 15 years. Changing attitudes toward the technology may be a driver for this and it were not be long before riser applications, in the form

Table 3 Typical properties of mostly used reinforced continuous fibers

Material	*Trade name*	*Density, ρ (kg/m^3)*	*Typical finer diameter (micro μ)*	*Young's modulus, E (GPa)*	*Tensile modulus (GPa)*
α-Al_2O_3 (aluminum oxide)	FP (USA)	3960	20	385	1.8
$Al_2O_3 + SiO_2 + B_2O_3$ (mullite)	Nextel 480 (USA)	3050	11	224	2.3
$Al_2O_3 + SiO_2$ (alumina-silica)	Altex (Japan)	3300	10–15	210	2.0
Boron (CVD[a] on tungsten)	VMC (Japan)	2600	140	410	4.0
Carbon (PAN[b] precursor)	T300 (Japan)	1800	7	230	3.5
Carbon (PAN[b] precursor)	T800 (Japan)	1800	5.5	295	5.6
Carbon (pitch[c] precursor)	Thornel P755 (USA)	2060	10	517	2.1
SiC (+ O) (silicon carbide)	Nicalon (Japan)	2600	15	190	2.5–3.3
SiC (low O) (silicon carbide)	Hi-Nicalon (Japan)	2740	14	270	2.8
SiC (+ O + Ti) (silicon carbide)	Tyranno (Japan)	2400	9	200	2.8
SiC (monofilament; silicon carbide)	Sigma	3100	100	400	3.5
E-glass (silica)		2500	10	70	1.5–2.0
E-glass (silica)		2500	10	70	1.5–2.0
Quartz (silica)		2200	3–15	80	3.5
Aromatic polyamide	Kevlar 49 (USA)	1500	12	130	3.6
Polyethylene (UHMW)[d]	Spectra 1000 (USA)	970	38	175	3.0
High-carbon steel	Piano wire, etc.	7800	250	210	2.8
Aluminum	Electrical wire	2680	1670	75	0.27
Titanium	Wire	4700	250	115	0.434

[a]CVD, Chemical vapor deposition.
[b]PAN, Polyacrylonitrile. About 90% of the carbon fiber produced worldwide is made from PAN.
[c]Pitch is a viscoelastic material that is composed of aromatic hydrocarbons. Pitch is produced by the distillation of carbon-based materials, such as plants, crude oil, and coal.
[d]UHMW ¼ ultra-high-molecular-weight polyethylene (or polyethene, the most common plastic produced in the world) is a subset of the thermoplastic polyethylene.
Source: From Harris, B., 1999. Engineering Composite Materials, the Institute of Materials. London, UK, p. 193. Jones, R.M., 1999. Mechanics of Composite Materials, second ed. Philadelphia, PA: Taylor & Francis, p. 519. Abramovich, H., 2017. Chapter 1 – Introduction to composite materials. In: Stability and Vibrations of Thin-Walled Composite Structures. Oxford, UK: Elsevier. pp. 3–4. doi:10.1016/B978-0-08-100410-4.00001-6.

Fig. 3 Carbon fiber sample. *Courtesy*: Wise, R., Girard, P., 2016. Carbon fibres: A review of technology and current market trends. Available at: https://www.ktn-uk.co.uk/articles/ktn-report-provides-extensive-overview-of-carbon-fibre-industry.

discussed or otherwise, will begin cutting costs in the oil and gas industry. Composites can be classified for matrix/reinforcement and by manufacturing process, as illustrated in **Figs. 6** and **7**, respectively. Due to the technological developments, composites can be reused and recycled, as presented in **Fig. 8**. An application of the state-of-the-art on composite materials in the offshore industry, is shown in **Fig. 9**.

The renewable composites used in the offshore industry are mostly limited to wind turbines, and lightweight composites used in offshore structures. There are challenges with using renewable composites on ships and offshore platforms due to restrictions

Fig. 4 Glass reinforced polymer trimmed waste. *Courtesy*: Filon products.

Fig. 5 Glass fiber dust waste from Strongwell's Extren laminated glass fiber composite sheet.

with the standards. Basic structural members in most of the offshore standard recommend the use of steel members, as the main reinforcing and load-carrying member of the platform (**Tables 3** and **5**).

Historically, the Chinese were the first to create oil pipes, using bamboo trunks as conduits from local oil wells. This trend later led to development of more sustainable materials that can be used to transfer oils. Thus, steel pipes came into existence. However, with the need to lighten the weight of the structures as explorations move deeper, composite risers (Amaechi *et al.*, 2019a; Amaechi and Ye, 2017; Gillett, 2018) are potentially a good option. Due to the different environmental conditions for oil explorations, such as that

Table 4 Glass reinforced polymer poduction volumes in Europe by processes/parts

	2008	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*	*2017*	*2018*
	kt (kilotonnes)										
SMC	210	160	198	198	188	184	190	191	198	202	204
BMC	70	56	69	69	70	71	74	74	76	78	81
∑ SMC/BMC	280	216	267	267	258	255	264	265	274	280	285
Hand lay-up	202	123	160	160	145	142	138	139	140	140	140
Spray-up	103	74	92	98	90	90	94	96	97	98	99
∑ Open mold	305	197	252	258	235	232	232	235	237	238	239
RTM	106	94	113	120	120	126	132	137	141	146	148
Sheets	69	56	72	77	78	84	84	86	89	93	96
Pultrusion	46	39	47	51	47	47	48	49	50	53	55
∑ Continuous processing	115	95	119	128	125	131	132	135	139	146	151
Filament winding	79	69	82	86	80	78	79	80	80	78	79
Centrifugal casting	62	55	66	69	67	66	66	68	68	67	69
∑ Pipes and tanks	141	124	148	155	147	144	145	148	148	145	148
GMT/LFT	95	75	100	105	108	114	121	132	140	145	152
Others	16	14	16	16	17	18	17	17	17	18	18
Total	1058	815	1015	1015	1010	1020	1043	1069	1096	1118	1141

Abbreviations: BMC, bulk molding compound; GMT, glass mat thermoplastic; LFT, long fiber thermoplastics; RTM, resin transfer molding; SMC, sheet molding compound.
Source: AVK Composite Market Reports 2011–2018.

may be harsh, benign, or squall, there are advances in the application of offloading systems adopted recently like Chinese lantern configurations (Amaechi *et al.*, 2019b) and lazy-S configurations (Amaechi *et al.*, 2019c) on CALM buoys. These systems have hose connections that are used to transfer oil and other fluids offshore and onshore. The materials used in the making of the offshore vessels and the submarine hoses have also composite materials in them. Airborne Oil and Gas (Jak, 2018; Smits *et al.*, 2018; Spruijt, 2018) and Magma Global (Wilkins, 2016; Hatton, 2012; Mintzas *et al.*, 2013) are currently two companies that have developed these offshore structures called composite materials.

The offshore industry has seen different technological advancements in recent years, which started when oil explorations in Texas and California increased creating more opportunities in oil, rather than gold. In the Gulf of Mexico (GoM), the Stone FPSO operates in 2926 m while the Perdido SPAR platform operates in 2450 m as they are currently the deepest offshore structures as shown in **Fig. 2**. However, there are still more developments on different offshore structures, as shown in **Fig. 3**.

Despite these applications of composites in the offshore industry, the industry has not been at the forefront in leading on the advances in composite applications. Some other industries have applied composites for decades successfully to improve performance and safety, like using composite handrails on ships. The marine industry has increased in the application of composites in hull making for ships, yachts, and leisure boats. However, the aerospace industry has notably used composites double every five years since 1987 (Murray, 2018). Composites have since been applied to the oil and gas industry (offshore and marine industries included), as they have changed the landscape of the industry. This allows reduction in airframe weights, less operating costs, and fuel savings. Composite materials are lightweight, with weight reduction ranging from 20% to 50% (Murray, 2018). The main characteristics of composites that make them more suitable in the composite industry are presented in **Tables 3** and **5**, for reinforced composites and biocomposites, respectively.

Dressed Landing String Joints

Landing String Solutions (LSS) LLC developed the concept of applying composites in their landing string scheme, and thus were the first in the offshore industry to use composites in buoyancy for landing strings. This concept provides the option of improving safe rig operations, optimizing critical path time and significantly decreases cost by reducing the hook load while running heavy enclosures and buoyancy casings (Murray, 2018). The challenge was to get the suitable material that will not be affected by the wellbore fluid used during drilling. It is important that all composites used in all drilling operations are very suitable for use in seawater. Secondly, drilling mud has a different mix of chemical components with their varying temperatures too.

Buoyancy Modules

Trelleborg developed some of their buoyancy modules for oil drilling and offloading operations using polymer-based composites that are syntactic buoyancy materials. The raw materials used include hollow glass microspheres powders that are talcum-looking

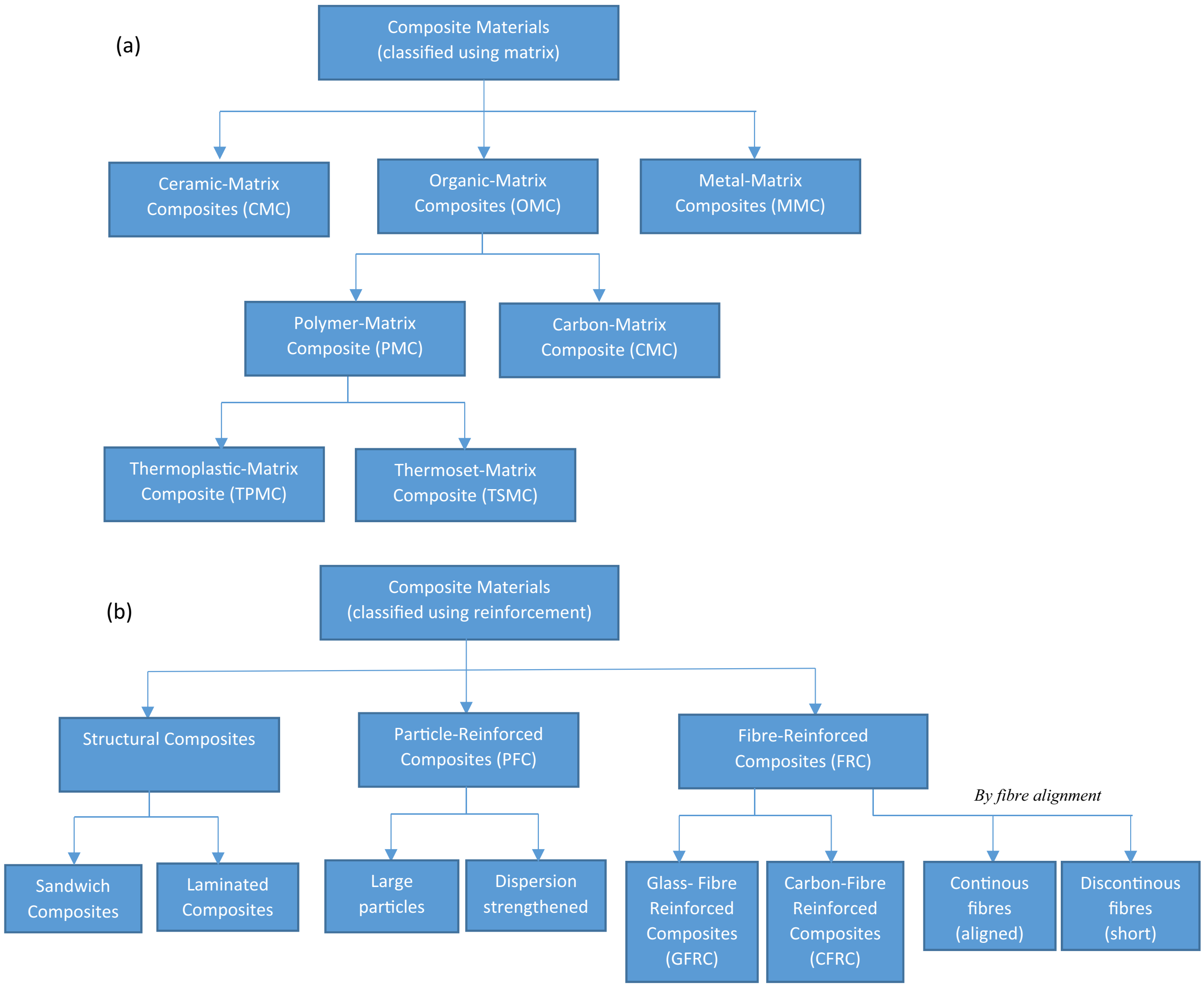

Fig. 6 Classification of composites by (a) matrix, and (b) reinforcement.

but of high strength glass bubble. The material is also used in aerospace applications because of its high strength characteristics. For the buoyancy modules, it is covered by a polyurethane skin to ensure that it provides high syntactic buoyancy service.

Composite Buoyancy System

Trelleborg and LSS developed the first composite buoyancy system that is deployed on a drillpipe landing string. According to Offshore Magazine (2015), the system is the first application of buoyancy in drilling riser. The application of buoyancy on the landing string enhances deployment of more number of casings, reduces the rig time and also reduces operational cost. The buoyancy was successfully tested in the a testing field located in the GoM, and has been proven to be successful up to an operational pressure of 41.36 MPa (6000 psi). By design, the new composite buoyancy system was designed to offset the landing string weight up to 80% but not in all cases. "In this particular application, this is not a better mousetrap. It's not a step change. This is a new trap altogether. This is an enabling technology. The composite-based system creates buoyancy once the casing/landing string is in the riser, which reduces the hook load, decreasing the risk of the vessel exceeding its maximum hook load rating. This gives a smaller and cheaper rig the opportunity to do the job safely which means potentially eliminating liner tiebacks and running longer casing strings" (Murray, 2018).

Composite Risers

Development of composite risers have progressed greatly from the first time composite risers were installed successfully on Heidrun platform in 2002 (Salama and Mercier, 1988; Ochoa and Salama, 2005; Salama *et al.*, 2002). Recent developments on composite risers include the composite thermoplastic pipes, Magma M-pipe (Hatton, 2012; Mintzas *et al.*, 2013; Wilkins, 2016), and Airborne composite riser pipe (Steuten and Van Onna, 2016; Onna *et al.*, 2014; Van Onna and O'Brien, 2011), composite

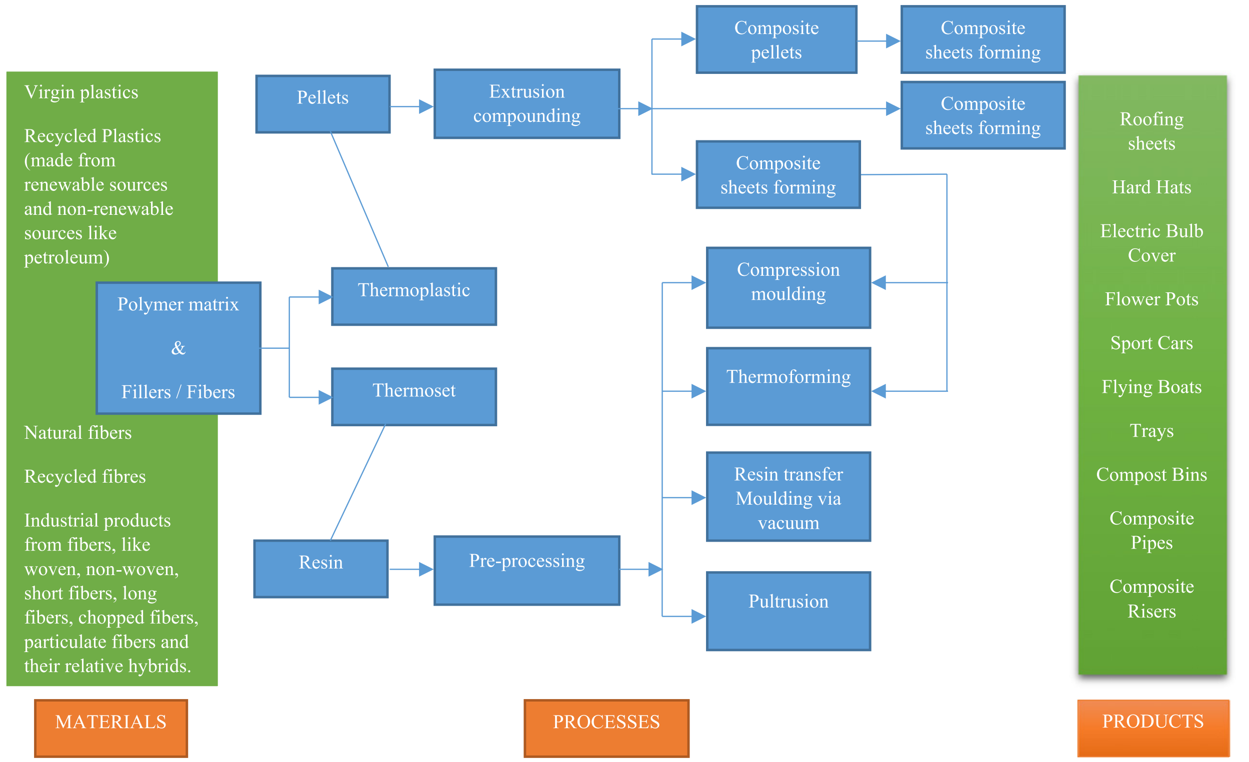

Fig. 7 From raw materials to manufacturing of composite product with some examples.

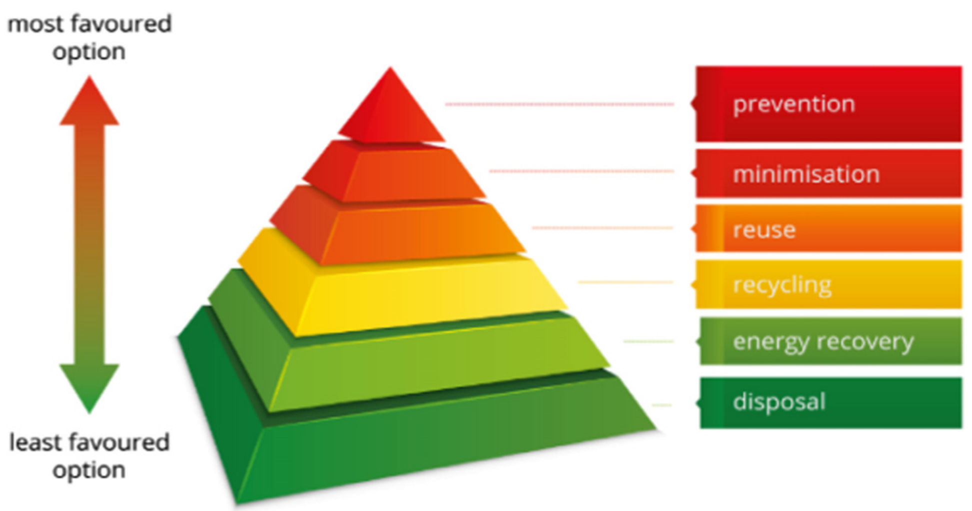

Fig. 8 Pyramid of reuse and recycling of composites.

flowline (Spruijt, 2018 and Jak *et al.*, 2018) and composite umbilicals (VisionGain, 2014; Van Onna and Lyon, 2017). Other design concepts on composite riser end-fittings (Amaechi and Ye, 2017; Amaechi *et al.*, 2019a; Hatton *et al.*, 2013) are presented in **Fig. 3**. The mechanical properties of composite risers can be seen in **Tables 6–8**.

Composite Choke and Kill Lines

Despite the various challenges, they are gain-worthy in the industry, academia, and research institutes. Developments in offshore composites kicked off trying to improve on its application in aerospace composite researches. The issue with offshore structures is the environmental loads, such as wave, excess pressure, internal pressure, manufacturing challenges, metal composite interface

Fig. 9 Reuse of offshore oil drums at Liverpool, UK as leisure furniture.

Table 5 Application of biocomposites showing mechanical strengths and sources

Resin	*Fiber/filler*	*Impact strength*	*Tensile strength*	*Tensile modulus*	*Comments*	*References*
Plastic waste (PE and PP)	Wood flour	2.9–6.2 kJ/m^2 Unnotch	6–13 MPa	2.3–3.9 GPa	MAPE compatibilization and lubricant utilization	(Turku *et al.*, 2017)
PP	Wood, poultry litter biochar	8.1 kJ/m^2 Notch	27 MPa	4.3 GPa	Hybrid biocomposites–MAPE compatibilization	(Das *et al.*, 2016)
PP	Flax fiber	751 J/m Unnotch	40 MPa	6.5 GPa	Needle-punch fiber mat composite	(Oksman, 2000)
Waxy maize starch	Neat and modified liquid crystalline cellulose, microcrystalline cellulose	–	505–790 MPa	22–32 GPa	Starch/cellulose hybrid biocomposites	(Rahman and Netravali, 2018)
Epoxy/acrylate	Glass fiber	237 kJ/m^2 Notch	532 MPa	37 GPa	Methacrylated epoxidized sucrose soyate resin/ glass fiber	(Hosseini *et al.*, 2016)
Biopolyurethane (BioPU)	Sisal fiber	–	57–119 MPa	1.2–2.2 GPa	Rubber seed oil polyurethane	(Bakare *et al.*, 2010)
PBS/PLA	Flax fiber	9.1–17.8 kJ/m^2 notch	39–55 MPa	3.6–7.4 GPa	Fully biodegradable composite	(Bourmaud *et al.*, 2015)
PLA	Carbon fibers, twisted yarns of jute fibers	–	57–185 MPa	5.1–19.5 GPa	Continuous fiber-reinforcement probed by 3D printing	(Matsuzaki *et al.*, 2016)

Abbreviations: MAPE, maleic anhydride–grafted Polyethylene; PBS, polybutylene succinate; PE, polyethylene, PLA, polylactide; PP, polypropylene.

end, fittings, and weight of steel. It has been found that composites can offer some advantages on it but the thickness of the wall has to be considered because it involves high pressure high temperature, and the weight of other lines like the flow lines, choke, and kill lines (Skaugset *et al.*, 2013) all contribute to the total weight of the riser joint assembly system. Thus the need to introduce lightweight materials have been found to reduce the top tension load on the riser system (Omar *et al.*, 1999; Skaugset *et al.*, 2013; Hatton, 2012).

Table 6 Physical properties of water, steel and other composite riser materials

Property	*Specific gravity*	*Density (kg/m³)*	*Thermal conductivity (W/m/°C)*	*Heat capacity (J/kg/°C)*	*Poisson ratio V_{12}*	*Young's modulus (GPa)*
Sea water	1.0	1030	0.6	4200	0.5	2.15
Steel	7.8	7850	50	480	0.30	200
Titanium	4.43	4430	19	540	0.342	113.8
Aluminum	2.78	2780	204.26	910	0.33	68.9
AS4-Epoxy	1.53	1530	–	–	0.32	–
AS4-PEEK	1.56	1561	–	–	0.28	66
P75/Epoxy	1.78	1776	–	–	0.29	–
P75/PEEK	1.77	1773	–	–	0.30	33
PEEK	1.32	1300	–	–	0.40	5.15
Composite riser	1.68	1680	0.5	1200	0.28	–

Abbreviation: PEEK, polyether ether ketone.

Table 7 Comparison of the key design aspects of steel risers and composite risers

Parameter	*Steel*	*Composite*	*Comments*
Max hang-off load (Te)	94	93	In an SLHR, the flexible jumper to the vessel acts as interface between the vessel and the vertical riser leg thus keeping the two isolated. Therefore negligible change in hang-off loads
Max hang-off bending moment (kNm)	261	282	
Max stress utilization	0.63	–	While stress is the driving criteria for steel, strain is the driving criteria for composites
MBR safety factor	–	2.76	MBR is larger than minimum acceptable
Max tension utilization	–	0.14	Tension is small in comparison to allowable
Buoyancy tank displacement (m)	247	211	Smaller drag area causes smaller buoyancy tank displacement
Buoyancy tank tension (Te)	451	258	43% less tension required
Max bending moment at base of URA (kNm)	116	62	Approximately 50% lower bending moment for both lower upper riser assemblies
Max bending moment at top of LRA (kNm)	581	270	

Abbreviations: LRA, lower riser assembly; MBR, minimum bend radius; URA, upper riser termination assembly.

Note: Hopkins, P., Saleh, H., Jewell, G., 2015. Composite riser study confirms weight, fatigue benefits compared with steel. Offshore Magazine 75 (9). Available at: https://www.offshore-mag.com/pipelines/article/16758323/composite-riser-study-confirms-weight-fatigue-benefits-compared-with-steel.

Table 8 TCP material selection by Airborne Oil & Gas

Glass-HDPE	*Carbon-PA12*	*Carbon-PVDF*
Fully qualified to 60–65°C	Temperature up to 80°C	High temperature up to 121°C
Used in permanent application	High pressure of 10 ksi	High pressure of 10 ksi
Medium pressure of 5 ksi	Low permeation	Lowest permeation
Low permeation	Used in an application	Highest chemical resistance
High chemical resistance	DNV qualified in 2018	DNV qualified in 2019

Abbreviations: DNV, det Norske Veritas; HDPE, high density polyethylene; PA12, polyamide 12; PVDF, polyvinylidene fluoride.

Note: Spruijt, W., 2018. Installation of the world's first subsea thermoplastic composite flowline for hydrocarbon service. In: Proceedings of the Offshore Technology Conference, OTC-28540, pp. 1–9. Kuala Lumpur, Malaysia: OnePetro/OTC.

Benefits of Composites in Offshore Industry

Composite materials give a variety of advantages that could enhance risk technology. Composites are lightweight and provide decent levels of strength. They can be easily formed into complex shapes due to their flexibility and can provide elevated levels of fatigue resistance and corrosion resistance. Maintenance needs are relatively low, and they can be installed via reel lay. Composite materials also a low axial and bending stiffness when compared to steel. However, composite materials have high material cost with limited track record offshore unlike steel, despite widespread applications in other industries. Currently, there are few codes and standards with direct applicability to composite risers.

Some of the benefits that composites may bring to the riser industry include cheaper installation costs (due to lessened weight), lower maintenance requirements in the offshore industry, lower roughness on internal bore (offering increased flow rates), and

Table 9 Benefits of composites for some offshore applications: Composite risers, composite propellers, composite choke and kill lines, and wind turbine blades

Composite risers	*Composite propellers*	*Composite choke and kill lines*	*Wind turbine blades*
Offer reduced weight of buoyancy and reduced size; lightweight (m-pipe is 1/10th of steel in air, and 1/5th in water); have excellent fatigue performance; reduce the variable deck load; ease of transport and deployment, like towing on site; enable drilling operations in ultradeep water and high reservoir pressures; have smooth bore for higher flow rate; reduced subsea project risk; require no upper riser assembly for deployment; have high pressure capability; offer lower life cost and lower system cost; have improved corrosion resistance	Enhance some weight saving on the ships; enhance fatigue performance of the structure; enhance the inception speeds with the use of thick flexible blades; enhance vibration-damping characteristics; enhance easier fabrication into more complex shapes; reduction of cost for fabricating the blades; reduction of the through-life maintenance costs; reduction of corrosion issues; reduction of noise signatures; reduction of electrical signatures; reduction of magnetic signatures; reduction of corrosion issues; reduction of wear on the shaft and gearbox; reduction of steel parts used in the propeller connections	Can have increased ID of choke and kill lines with same weight; extend operational envelope of an existing drilling rigs; have excellent fatigue performance; reduce the variable deckload; store more riser joints on the deck; have increased mud flow rate and better well control	Reduction of cost for fabricating the blades; reduction of the through-life maintenance costs; enhance some weight saving on the turbine; increase energy efficiency; ease installation of wind turbine; easier to form into complex shapes; low field life; less maintenance cost; resistance to corrosion; resistance to conductivity; resistance to fatigue damage; long field life; high-impact resistance; thermal stability; tolerance to damage

reduction in vessel hang-off loads (Hopkins *et al.*, 2015, 2014; Saleh, 2015). Despite these benefits, replacing steel with composite materials is unlikely to reduce the costs for existing designs. The real advantage composites offer is as an enabling technology for new concepts and operations in challenging locations and environments. Further concerns relate to damage to the sublaminar, which is hard to inspect on a manufactured pipe, and to the challenges of making up connections and end fitting design. A comprehensive review on the benefits of composites on some offshore applications is presented in **Table 9**.

Recycling Process of Renewable Composite Materials

There are different processes that are considered in the recycling of renewable composite materials in the composites industries that are beneficial for the offshore industry. There range from mechanical to thermal processes, as discussed in this section. Different literature present development of pyrolysis-based carbon fiber-recycling processes and these are now commercially available in several places since the launch of Milled Carbon (presently known as ELG Carbon Fiber) located in the West Midlands, UK (ELG Carbon Fibre, 2017; Job *et al.*, 2016; Job, 2013). However, the economic value of carbon fiber is about 10 times that of glass fiber. This inadvertently affects the commercialization of these recycling processes, making it quite challenging. It is noteworthy to state that although commercializing it has been a bit difficult, it has been "easier" than finding recycling routes for GRP, despite the much smaller volumes. According to AVK 2018 market report, in 2018, the carbon fiber-reinforced polymers (CRP) were estimated at 128,000 tonnes while the total European GRP market had an estimated total of 1.141 million tonnes with predicted growth rate of 2.1 % (Witten *et al.*, 2018). This was higher than that of the AVK 2012 market report, which presented 76,000 t of CRP compared to about 1 million tonnes GRP parts produced in Europe in 2012 (LinseT, 2013; Job, 2013; Sauer *et al.*, 2017).

The recycling process supported by European Composites Industry Association (EuCIA), and available in Germany, involves the addition of GRP waste to cement kilns. This gains value from all parts of the composite and is commercially active in Germany through the route known as Compocycle, operated by Zajons and feeding Holcim's cement kilns. However there is still a significant gate fee for the process. In Germany regulations leave no option to landfill so the volumes of GRP waste are sufficient to justify such a process. Composite manufacturers such as Fiberline in Denmark have supported that process, being close enough to take advantage of it. But this route reduces the value of the material to that of calcium carbonate and at present is not economic compared with landfill where landfill is an option.

There are several processes that are either commercially exploited or under development whereby discontinuous fibers are converted into intermediate products. Several companies produce nonwovens using short carbon fibers. In many cases these are still virgin fibers and come from offcuts, weaving selvedge, etc. The nonwoven textiles can be made by the air laying, carding, or wet-laid processes. The other approach being employed is to chop the fibers to a fairly short length (a few millimeters) and then mix these with either a thermosetting resin to make a sheet or bulk molding compound or with a thermoplastic melt to produce a compound for injection molding. Care has to be taken during mixing to avoid fiber breakage. Recovery of the fibers from parts already impregnated with resin is more complex, but can be done by pyrolysis or solvolysis. The advantage of these recycling solutions is that it will lower the cost of carbon fiber (Holmes, 2017; Boucherat, 2016). According to an ELG Carbon Fiber report, 30% of the carbon fiber manufactured worldwide each year becomes waste, which is equal to about 18,000 tonnes per year. The carbon fiber industry has moved away from being a niche industry only producing 100 tonnes per year; as such the issue of waste needs to be tackled.

Recycling, which is a means of returning the material back to the composite market, will create the possibility for stability, longevity, and extra source of supply to the industry.

Mechanical Recycling Process

The composite waste is first sorted then it is milled or ground using a hammer mill or related tools to obtain the required sizes. Researches on mechanical recycling show that energy is used in this process (Howarth *et al.*, 2014). The reduction of sizes is used to convert the grades of the wastes into different fractions and then it is sieved into powders. Different fractions of the fillers ad ground resins as well as other fibers of varying lengths are all embedded into the resin. Also contained in the recyclates are flakes of the materials, which are seen in SMC, BMC as seen in GRP composite wastes. One drawback here is that this method has very limited applications on CFRP composites. The ground composite materials are used for either fillers or as reinforcements. The fillers are not considered to be commercially profitable because of the low cost of the virgin fillers, for instance, silica and calcium carbonate. These fillers, which are the recovered powders from the mechanical process after sorting, can be incorporated into new materials. However, it must not be more than 10% in weight due to the breaking down of the molecules as a result of deterioration of the mechanical properties as well as more problems associated with processing higher filler contents due to higher viscosity of the compound. To this end, they have been applied as alternative energy sources due to the high organic compositions of the resins used. **Fig. 14** shows the steps carried out during mechanical recycling.

Recycling of GRP by mechanical grinding has been ongoing for some decades. As far back as in the 1970s, the late Wolfgang Unger was developing his proprietary Seawolf technology in Florida in the United States, to grind fiberglass scrap and use it for replacing rotten boat transoms or incorporate it using spray-up equipment for making bathtubs and other products (LinseT, 2013). Unger's company is now called Eco-Wolf (Unger, 2011) managed by his daughter Sabine Corinna Unger. Eco-Wolf in 2011 partnered with Global Fiberglass Solutions, which is seeking to build and manage facilities to collect and recycle fiberglass across the United States, having developed applications such as railroad ties (railway sleepers), just like Reprocover and 3B fibers did.

Another commercial outfit was ERCOM Composite Recycling GmbH established in Germany in 1990 to recycle automotive production and postuse waste by shredding and grinding graded parts into powder, to be used in new sheet molding compound (SMC) in proportions up to 20% (Marsh, 2001). ERCOM terminated in 2004. This approach of grinding GRP to fine powder for use as filler is well established in several industries, but as with the cement kiln route, it reduces the value of the material to that of calcium carbonate, which can be purchased at very low cost (around £200/t). In addition, it requires a significant amount of energy input to grind the material finely. Thus apart from some in-house recycling (see below), attempts to commercialize this as a recycling route have failed.

Thermal Recycling Process by Pyrolysis

Pyrolysis, according to Sponberg (1999), is the process of chemically decomposing or transforming a material into one or more recoverable substances by heating it to very high temperatures in an oxygen-depleted environment. This process differs from incineration, which is carried out in an open atmosphere. Pyrolysis is a thermal process that is carried out at a temperature range of 450–600°C, subject to the environmental conditions and the resin used. In other words, pyrolysis is the decomposition of the resin using heat. This can be achieved by applying a batch process with the use of an inert atmosphere or vacuum. This decomposes the resin to a mixture of chemicals, which tend to volatilize from the resin and then condense in the outlet as pyrolysis oil, which can be burnt as a fuel or distilled to recover chemicals. Although, the process also generates a char which is a hard glassy (noncrystalline) carbon and this can be well adhered to the fibers and bond fibers together. The higher temperatures are used for the epoxies and thermoplastics of high performance like PEEK composites, while the lower temperatures are used for the polyester resins. Thermal degradation of the resin matrix produces oil, gases and solid products made up of fibers, char and possibly fillers. To reduce the amount of char produced, it is oxidized using small quantity of oxygen. Char can only be removed here by oxidation. With this method, the recovery of fibers, fillers as inserts are possible (Job *et al.*, 2016; Castro *et al.*, 2013; Thakur *et al.*, 2007). The breakdown of the resin into molecules of low-weight, lower-weight, and much lower-weight produces the gases and oil fraction, which can be recovered chemically into other chemicals, and sometimes burnt to generate energy such as EfW energy recovery processes. Pyrolysis has been successfully applied on plastic wastes as well as composite wastes (Sekula and Leszczynski, 2009; Kennerley *et al.*, 1995) as well as in the offshore industry (Demirbas and Taylan, 2015).

As stated earlier, the product from pyrolysis depends on the conditions, and thus affects the resulting mechanical properties of the fibers. For glass fibers, the tensile strength can be varied between 52% and 64% while the tensile strength of carbon fibers can be varied between 4% and 85%. This shows the influence of temperature on the resulting fiber properties. A pyrolysis temperature of 450°C is usually the lower limit while the temperature range between 500°C and 550°C appears to be the upper limit of the thermal process of pyrolysis. As this temperature range, an acceptable fiber strength that is typically viable commercially for carbon fiber is achieved.

Any thermal or chemical process strips the sizing off the fibers. In the case of glass fiber, this results in dramatic loss of strength and handling/processability. Thus, thermal and chemical treatments are not suitable for GRP unless the fibers are posttreated. A

Table 10 Comparisons between different recycling technologies

Recycling technologies	*Strengths*	*Weaknesses*	*Points of attention*
Mechanical recycling	Efficient waste management process (high throughput rates)	High decrease of (mechanical) properties	It requires full use of PPEs.
		Material undergoes downcycling	Fine dust released into the surrounding atmosphere.
		Recyclate with a high content of other material (including polymers, contaminants, paint, coatings)	Potential of fibers to stick into human skin or mucous membranes causing irritation.
		Small, unstructured, coarse, and nonconsistent fibers	
		High operational costs and capital investment (running costs, installations)	
		Has up to 40% material waste	
Pyrolysis	Pyrolysis gas and oil can be used as energy source making it a self-sustained process	Fiber product may retain oxidation residue or char	Potential combustible gases leakage from waste treatment chambers
	Wax recyclate can be used as fuel or intermediate for chemicals production	Sizing degradation of glass fibers leads to changes in the composition (chemical structure)	
	Easily scaled-up to multitonne capacity		
	Microwave pyrolysis involves heating the material at its core with microwave radiation		
	It creates room for easier control of the heating process leading to decreased induced damage to the fiber material		
Cement kiln (coprocessing)	Highly efficient and fast process: Residence time of 4–5 s in cement kilns	Complete loss of material characteristics (fiber form)	Emissions from pollutants and particulate matter
	Large quantities can be processed	High processing temperatures	
	Up to 75% substitution of cement raw materials which significantly reduces CO_2 that is emitted by the cement industry		
	No ash left over, minerals are trapped in the matrix of the clinker		
Solvolysis	Recovery of clean fibers in their full length	Insufficient efficiency (throughput) of the technology	Gas emissions (depending on catalysts potentially toxic, e.g., from alkali catalysts)
	Recovery of resin (like polymers or oligomers) that can be reused	High energy consumption due to the high-temperature and high-pressure	Human health impact and ecotoxicity
		Use of large amounts of solvents	High water consumption (although reuse options could be explored)
High voltage pulse fragmentation	Able to treat industrial quantities, which produces sufficient scalability of the process to treat larger capacities	Only laboratory- and pilot-scale machines are available	Working near high voltage
	Low investments required to reach the next level	Heavily decreased modulus of glass fibers	
Gasification (fluidized bed)	Highly flexible (in terms of different process capabilities) and simple process	Low fiber qualities for glass fibers (significantly reduced fiber tensile strength)	Emissions (e.g., CO_2) related to the process
	High efficiency of heat transfer	Will only be economically viable if it reaches capacities of more than 10,000 t per year (Yang *et al.*)	Quite stable and efficient performance in case of reactor operability and safety concerns
		Defluidization is problematic: Fluidized bed can locally collapse	

Abbreviations: CO_2, carbon dioxide; PPE, personal protective equipment.

Fig. 10 Offshore wind turbine as composites application in offshore renewable energy.

Fig. 11 Image of space rocket module in NASA facility, USA.

posttreatment to recover glass fiber properties after thermal treatment has been proposed in literature (Thomason *et al.*, 2016; Bashir *et al.*, 2017; Tajeddin, 2017) as well as other methods to recover the strength of the glass fibers. According to Job *et al.* (2016), an increase in the scale upwards to produce glass fibers that can compete with virgin glass fibers would require the substantial application for chopped glass fibers, for instance, automotive thermoplastic composites. However, it is difficult to achieve this without economic loss, because glass fiber has comparatively low value. There are three novel methods in pyrolysis, namely continuous pyrolysis, chain conveyor pyrolysis, and fluidized bed pyrolysis.

Continuous Pyrolysis

To achieve the continuous pyrolysis, the process has to have steady supply of high temperature. Carbon fibers are comparatively oxidation-resistant up to about 500°C, thus it is possible to burn off the resin and with careful control of the conditions inside the furnace still avoid a significant loss in strength. This is the method employed at ELG carbon fibre company (ECF) in a patented furnace process called continuous pyrolysis. Combustion of the resin depletes the oxygen levels in the furnace so the oxidation of

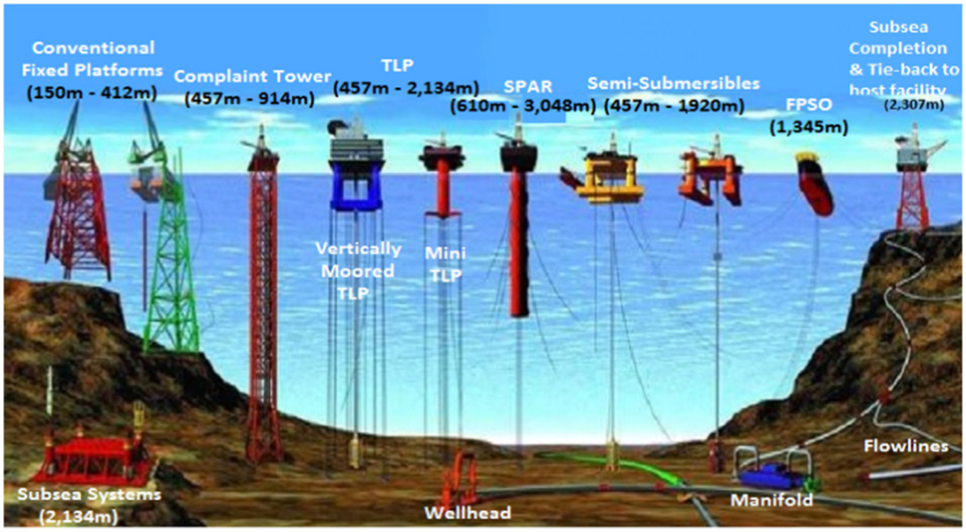

Fig. 12 Offshore deep water systems showing the platforms and riser types. Modified with permission, NOAA.

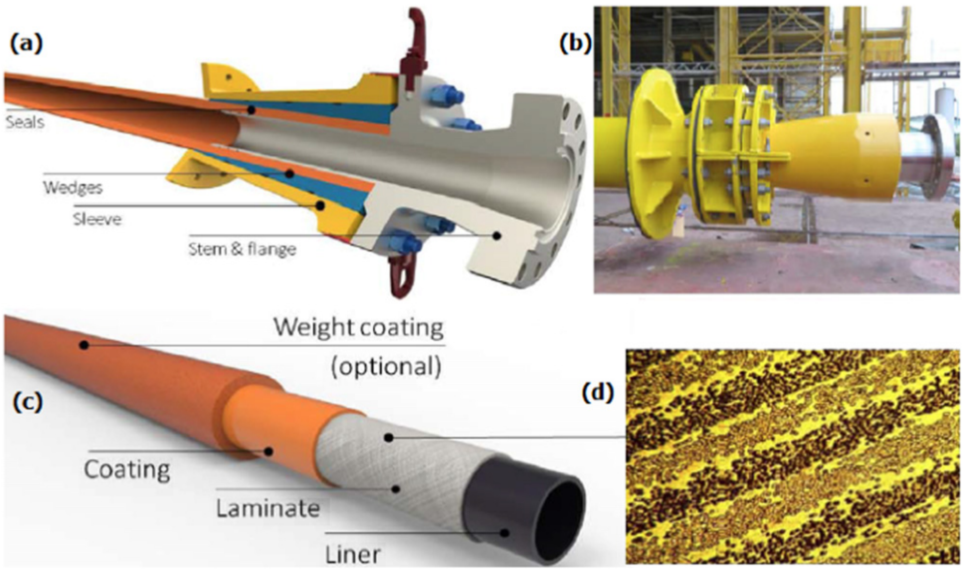

Fig. 13 Thermoplastic composite pipe (TCP) with (a) end-fitting concept, (b) installed 6-in. ID end-fittings installed on an I-tube, (c) TCP pipe concept, and (d) laminate microscopy. *Courtesy*: Spruijt, W., 2018. Installation of the world's first subsea thermoplastic composite flowline for hydrocarbon service. In: Proceedings of the Offshore Technology Conference, OTC-28540, pp.1–9. Kuala Lumpur, Malaysia: OnePetro/OTC.

the fiber is minimized. The presence of oxygen minimizes char formation because entropy considerations do not favor char formation over combustion and any char that is formed oxidizes faster than the fibers. Regardless of how the fibers are won from the waste, they are liberated as discontinuous, poorly aligned fibers. Subsequent processing is necessary to take this low bulk density material to convert it to products that the industry wants to buy (Harris, 2017; SNW, 2019).

Thermal Recycling Process by Solvolysis

Solvolysis has also been applied to recycle composites and plastic polymers as a chemical process (Prinçaud *et al.*, 2014; Oliveux *et al.*, 2017; Yang *et al.*, 2014). In solvolysis the resin matrix is decomposed or dissolved by a solvent. As composite resins are generally engineered to be durable in typical service conditions, they tend to have excellent resistance to chemicals. Dissolving the resin therefore requires aggressive chemicals and/or elevated temperatures and pressures. For example, it is known that carbon

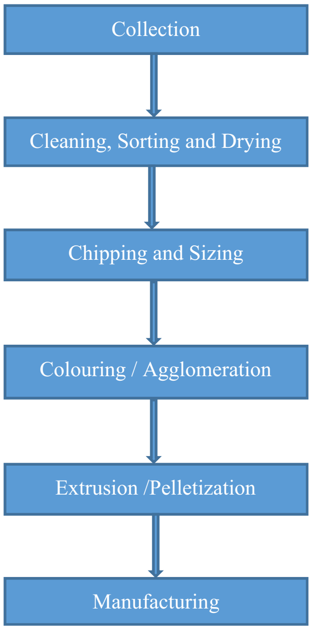

Fig. 14 The steps for mechanical recycling.

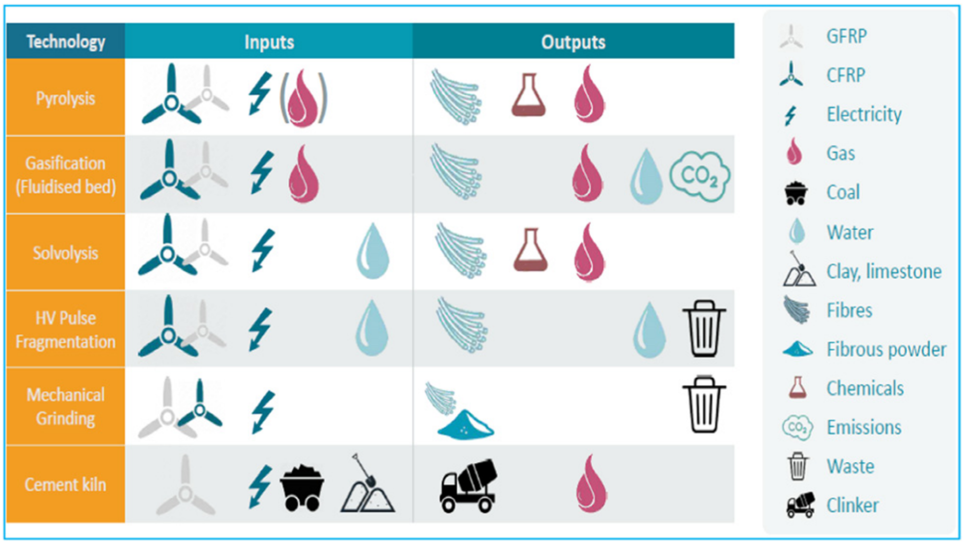

Fig. 15 Inputs and outputs for recycling technologies for wind turbines. *Source*: Reproduced from Ierides, M., Reiland, J., Dierckx, A., 2019. Wind turbine blade circularity: Technologies and practices around the value chain. In: Proceedings of the WindEurope Conference & Exhibition, 2-4 April 2019, pp. 1–38, Workshop on Blade Disposal. Bilbao: Bax & Company.

fibers can be liberated from an epoxy laminate by boiling it in concentrated nitric acid for several hours (ISO 14127). It has also been proven that a supercritical acetone/water mix (320°C, 170 bar) also dissolves the resin. Neither method has been scaled up to tonnage quantities and there are still significant challenges to be addressed before this technology becomes commercially viable.

Thermal Recycling Process using Cement Kiln

The application of cement kiln in recycling glass fiber composites is one of the recommendations of EuCIA (2011). According to the European Composites Industry Association (EuCIA), GRP is "recyclable and compliant with EU legislation." The process of incineration of the GRP wastes is impractical because relatively 50%–70% of the GRP material is composed of minerals and ends up as ash, which ends up in landfills. To coprocess these using the cement kilns, the sizes of the GRP composite parts are reduced and then mixed together with other composite wastes to introduce into the cement kilns. Typical GRP composite is made up of E-glass, which is mostly alumino-borosilicate, organic resin, and some calcium carbonate filler. Once the mix is sent into the cement kiln, the organic resin burns providing energy (about 12 MJ/kg of waste) while the mineral constituents provide feedstock used as the cement clinker (LinseT, 2013; Job, 2013). Usually, the clinker is ground to form cement paste or powdered cement, and the calcium carbonate calcines (which releases

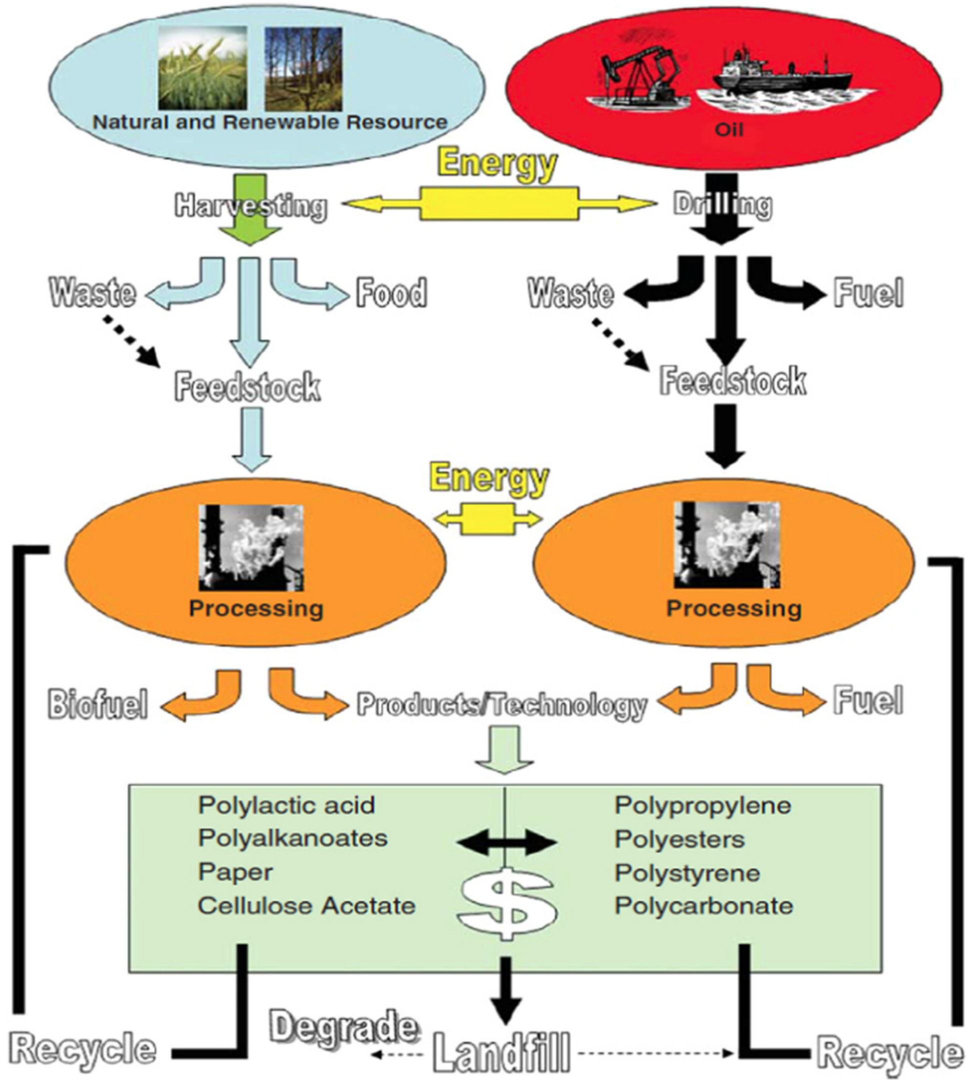

Fig. 16 Summary of renewable materials vs. oil production indicating stages of energy input. Reproduced from Eichhorn, S.J., Gandini, A., 2010. Materials from renewable resources. MRS Bulletin, 35(3), 187–193.

carbon dioxide) to calcium oxide, which is the primary component of Portland cement. Alumina and silica also have cementitious properties in an alkaline environment and are typically present in Portland cement at about 25%, and in much higher proportions in cement alternatives from fly ash and slag. Boron, which is found in most E-glass, can cause a reduction in early strength during the setting of cement, but as long as proportions are kept low it is not considered a problem (Pickering, 1993, 2006).

Comparisons Between the Recycling Options

Considering the different recycling options discussed, we can use a diagram to compare the different recycling options, as presented in **Fig. 15** and **Table 10**. Different researches have been reviewed to attain the results on the comparisons between the recycling options. Details can be found in literature (Liu *et al.*, 2017; Pickering, 2006; Oliveux *et al.*, 2015) (**Tables 7**, **8** and **10**).

Case Study of Energy for Waste

Waste minimization, reuse, and recycling are essential to achieve more sustainable waste management. There are, however, technical and commercial reasons why all waste cannot be recycled. There will always be some residual waste. It is important that local authorities and businesses have a way to manage residual waste and recover maximum value. There is a view that EfW is competing with recycling. Experience across Europe shows that best practice can involve high levels of recycling combined with EfW for the remaining waste that cannot be reused or recycled. Switzerland, the Netherlands, Sweden, and Denmark, for example, all have high levels of EfW as an integral part of their waste management strategies. These countries also have high waste recycling rates. **Fig. 10** is an application of offshore wind turbine which can be used in the description of the EfW process (Eichhorn and Gandini, 2010) (**Figs. 11** and **12**).

Case Study of Building Recycled Boats

One of the earliest reports made of building recycled boats was first noted in Sweden (Sponberg, 1999). According to the author, Ryds Battindustri AB, the Swedish largest boatbuilder as of 1999, was producing about 3600 small powerboats yearly in 36 models ranging in size from 3.3 m (11 in.) to 5.95 m (20 in.) using a lot of fiberglass composites. Ryds partnered with the Swedish Institute of Composites to develop on manufacturing boats using closed loop recycled scrap, which accounted for about 10% of its layup production. The result was a 4.75 m (15.5 in.) concept boat, containing about

Fig. 17 Mechanical recycling of wind turbine blades after demolition, in pretreatment stage. Courtesy: *Source*: Estevez, D.G., 2019. Demonstration of wind turbine rotor blade recycling into the coal clough windfarm decommissioning opportunity. In: Proceedings of the Wind Europe Conference & Exhibition, 2-4 April 2019, pp. 1–16, Workshop On Blade Disposal. Bilbao: LIFE + Brio.

20% recycled fiberglass by weight. The original single-skin laminates of sprayed-polyester fiberglass in the hull and deck were cut back by 50% and replaced with a sprayable polyester mixture containing 33%–40% ground scrap. Scrap mixture was used to replace the core materials, such as Coremat, plywood, and Divinycell. The boat's laminates had equal or better strength in all respects and, where the recycled compound replaced plywood, screw-holding power improved significantly. Other applications of composites can be seen on offshore ind turbines, NASA's space craft modules, offshore composite risers and leisure boats (**Figs. 10–13**).

The equipment for processing the scrap mix includes a grinder, a high/low shear mixer, and eight specially designed spray equipment (see photos above), all developed by and licensed from Seawolf Industries, which is owned by Wolfgang Unger. The grinder can quickly grind scrap to predetermined fiber lengths and keep fibers intact, which is important to the strength of boat laminates. In addition, compound additives developed by Seawolf resolved problems of premature catalyzation, viscosity, and fibers settling to the bottom of the mix. Seawolf now sells its machinery to any fiberglass manufacturer who wants to start recycling. Ryds anticipated its concept boat would go into production at about 50 boats per year. Unfortunately, recycled production boats did not go on as they planned at that time (Sponberg, 1999). Over time, other boat makers started to try fiberglass recycling.

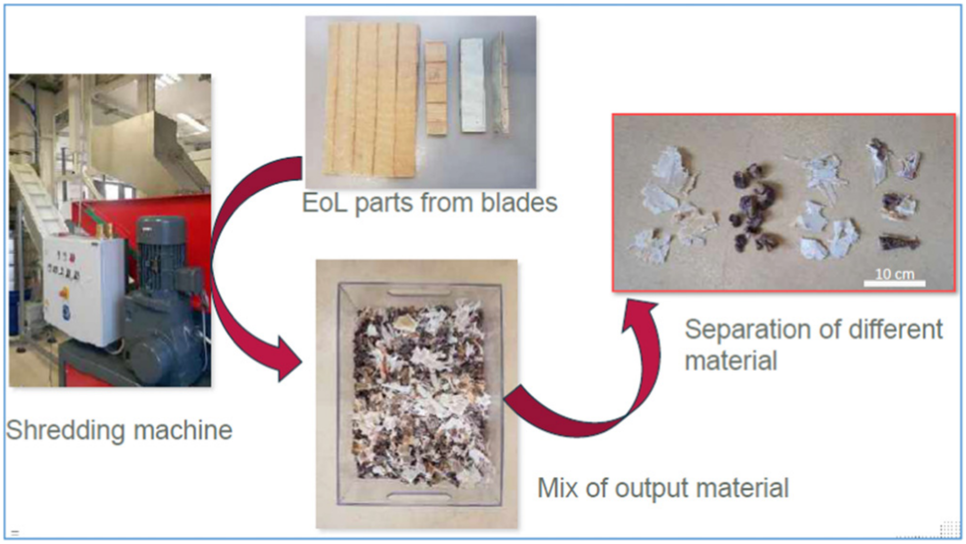

Fig. 18 Mechanical recycling. Courtesy: FiberEUse. *Source*: Garcia, S., Arcarazo, A., 2019. Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites. In the proceeding WindEurope Conference & Exhibition, pp. 1–12. 2-4 April 2019, Workshop on blade disposal. Bilbao: FiberEUse.

Fig. 19 Thermal recycling for wind turbine blades. Courtesy: FiberEUse. *Source*: Garcia, S., Arcarazo, A., 2019. Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites. In the proceeding WindEurope Conference & Exhibition, pp. 1–12. 2-4 April 2019, Workshop on blade disposal. Bilbao: FiberEUse.

Fig. 20 Thermal recycling of aeronautic waste. Courtesy: FiberEUse. *Source*: Garcia, S., Arcarazo, A., 2019. Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites. In the proceeding WindEurope Conference & Exhibition, pp. 1–12. 2-4 April 2019, Workshop on blade disposal. Bilbao: FiberEUse.

Fig. 21 Thermal recycling of construction wastes. Courtesy: FiberEUse. *Source*: Garcia, S., Arcarazo, A., 2019. Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites. In the proceeding WindEurope Conference & Exhibition, pp. 1–12. 2-4 April 2019, Workshop on blade disposal. Bilbao: FiberEUse.

Offshore Wind Turbine Blade Recycling

The recycling of wind turbine blades involves the integration of innovative remanufacturing technologies addressed to develop profitable reuse options for mechanically or thermally recycled EoL GFRP and CFRP composites. Different steps are involved in mechanical recycling process of composites, as illustrated in Figs. 14 and 15. Each process has its limitation and process capacity, as presented in Tables 1 and 10, depending on the source of raw materials and the recycling company's capacity.

Challenges of Recycling Renewable Composites

The renewable composites used in the offshore industry are not limited to lightweight composite pipes and offshore wind turbine blades, as illustrated in Figs. 13 and 15, respectively. Despite the application, there are challenges that are faced in composite applications in the offshore industry. According to ECF, the main challenges in recycling carbon fiber composites have included dealing with the complex nature of the waste streams. Even relatively clean waste streams from composites manufacturing still contain resins of varying chemical composition and unwanted materials such as paper or plastic backing films, and the recycling process has had to be optimized to ensure the complete removal of these unwanted materials without damaging the fibers. The second challenge is classification of the fibers. The composites industry has grown up with a wide variety of carbon fiber grades available from different manufacturers. Although the recycling process has only a small effect on the properties of the fiber, it is not desirable to retain the original fiber designation after fiber recovery. ECF has addressed this by introducing a generic classification system based on the Young's modulus and tensile strength range of the recovered fibers. Wind turbine blade recycling and reuse is a current practice in the industry. In addition, other natural renewable materials can also be sourced and recycled such as basalt and flax. An example is presented in Fig. 16, depicting the stages of energy input and recycling from agro industry and the oil

Fig. 22 Wind turbine blade waste disposal. *Courtesy*: Agecko.

Fig. 23 The result from recycling a wind blade made of glass fiber. *Courtesy*: Reciclalia.

and gas industry. More wind turbine wastes generated are also disposed to recycling plant, as shown in **Figs. 17–23**. According to Liu and Barlow (2017) the expected blade material usage in the future will continue to increase, as shown in **Fig. 24**.

Qualification

First is the issue of qualification of the offshore composite structures (Skaugset *et al.*, 2013; Wilkins, 2016; Johnson *et al.*, 1998). Based on the qualification process that is applied in the development of composite structures and the failure mechanism that can occur after testing, these may be as a result of the design load not in line with predictions, failure predictions as a result of coupon strength, the type of loading (collapse, burst, bending, or long term loading). This can also be seen in the cycles depicted in mechanical recycling of composites by Estevez (2019) and Garcia and Arcarazo (2019), as depicted in **Figs. 18–21**. An example of the product of recycling wind turbine blades is presented in **Fig. 23**. Other applications of recycled composites is on the railway track as shown in **Fig. 25**. With the increase in the researches on recycled composites, more qualification is expected on application of recycled composites on ship decks and cars, as presented in **Figs. 26** and **27**.

Standardization

Another issue is standardization; however, newer standards are under development (Van Onna and Lyon, 2017; Gibson *et al.*, 2002; Echtermeyer and Steuten, 2013). In boats, FRP composites have been in use about 70 years as boat making materials. Thus, most boats and motorsports are made from composites and even half of the structural airframes of modern aircrafts, like the Boeing 787 Dreamliner and the Airbus A380. They have also been used in the automobile industry as seen in **Table 2**. FRP bridges also have been in existence for over a decade. Composites have been an enabling technology in the offshore industry, as seen in wind turbines blades and oil wells with deeper risers. However, while the standards allow

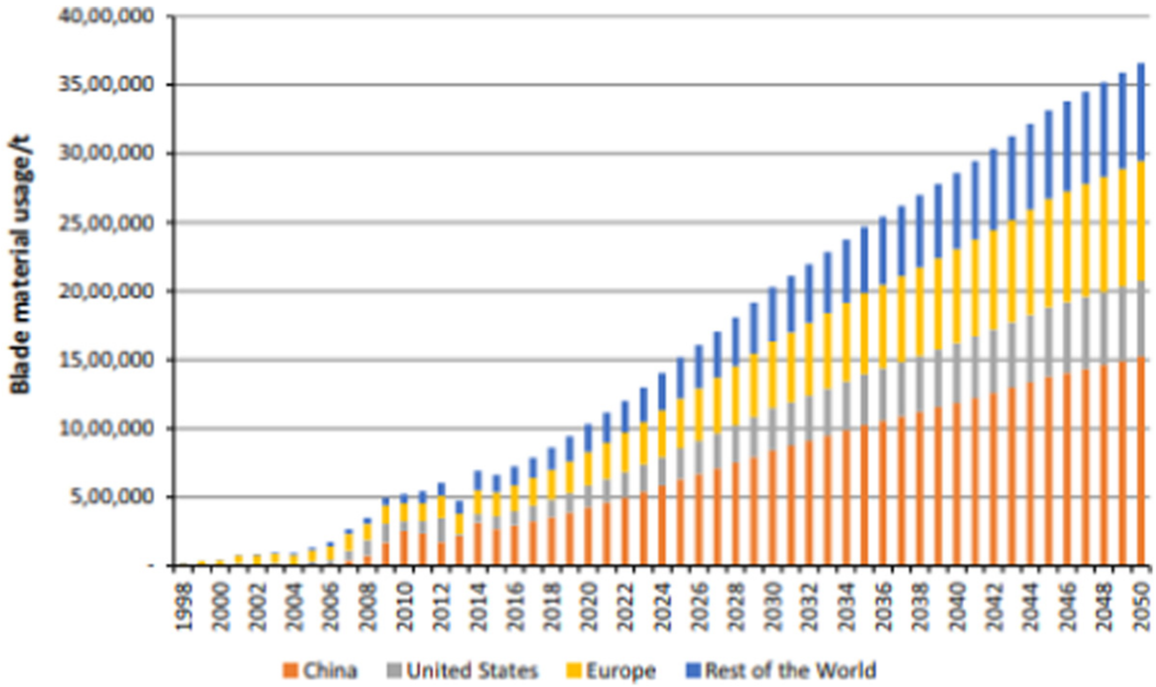

Fig. 24 Predicted blade waste in Europe until 2050. Reproduced from Liu, P., Barlow, C.Y., 2017. Wind turbine blade waste in 2050. Waste Management 62, 229–240. doi:10.1016/j.wasman.2017.02.007.

Fig. 25 Level crossing panels including recycled Glass Reinforced Polymer and phenolics from car parts. *Courtesy*: Reprocover.

small boats, leisure boats, and work boats to be built using composites, the IMO and SOLAS regulations restrict the use of composites and greatly prohibits the structural use of composites due to reasons like combustibility (Job, 2015, 2014). Currently, some recycled wind turbine blades are used in makeing pedestrian bridges, to show that they are structural of high strength, although the service life is not high.

Fig. 26 The 1000-t deckhouse of destroyer USS Zumwalt (DDG 1000) is craned toward the deck of the ship at General Dynamics Bath Iron Works. The deckhouse is primarily made from balsa-cored carbon fiber using vacuum assisted resin transfer molding. Reproduced from Job, S., 2015. Why not composites in ships? Reinforced Plastics 59 (2), 90–93. doi:10.1016/j.repl.2014.12.047.

Fig. 27 Application of composites on automotives. *Courtesy*: Malnati, P., 2018. Recycled waste products get new life as lightweight, cost-effective auto parts. Plastics Engineering, 74(6), 18–25. Available at: http://read.nxtbook.com/wiley/plastics_engineering/june_2018/recycled_waste_products_get_n.html.

Conclusion

Carbon fibers and glass fibers are high performance materials widely used in many fields thanks to their specific properties. As a result, research and development in this field is very active and one major driver is cost reduction. However both FRP and GRP do not have equal amount of usage as renewable offshore composites. This study has looked at major offshore applications of renewable composites in the industry, and a brief history of their usage and recycling technologies. Some comparative studies were also presented on the technologies and their options for a circular economy. For easier reference, this study also present some current commercial recycling facilities as well as some composite facilities, but not a fully comprehensive list due to the scope of the work.

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