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OPPORTUNITIES FOR COMPOSITES IN THE ENERGY INDUSTRY

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ABSTRACT

The management of energy resources has come under increasing scrutiny in recent years; from the Kyoto Agreement on global warming, to a recent European Commission Green Paper which highlighted the dependence of the European Union on imported energy, currently at 50% and expected to rise to 70% in the next 20 to 30 years.

In several fields, the use of composite materials has been shown to provide significant developments, either through technological improvements in current practices or by making them more economic. The large size of the energy industry means that even small additional involvement will result in significant activity and growth in the composites industry.

A review of the current and potential future uses of composite materials in the energy industry sector has been undertaken, with particular emphasis on identifying those areas where UK industries are most heavily involved. The review identified the three main application fields as electrical insulation and power transmission, storage and transportation of pressurised fuels, and renewable energy resources. The review concludes that while there are several areas in which composites have captured a large share of the potential market, for example in boats and wind turbine blades, they are meeting strong resistance to change from traditional materials.

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1. INTRODUCTION

Traditionally the largest markets for composite materials have been the aerospace, electrical, marine and sports sectors. Until recently, more than 60% of all carbon fibre-reinforced composites were being used for aerospace applications, and the major use of glass-reinforced plastics was for the manufacture of small boats. However, over the last decade composites manufacturers have been looking to increase their market share in other sectors. One of the most promising sectors in which composites have made an impact, and could play an important role in the future, is in the energy industry. In many areas of this industry composites have been shown to have several advantages over the materials that have traditionally been used for years.

The recent European Commission Green Paper "Towards a European Strategy for the Security of Energy Supply" [COM(2000) 769] highlighted the dependence of the European Union on imported energy, with the current level of 50% expected to rise to 70% in the next 20 to 30 years. In 1999 this amounted to 6% of total imports, with a value of 240 billion Euros. The EU has set a target that 12% of primary energy should come from renewable energy sources by the year 2010.

Composite materials can make an input into the current energy business by making economies in current practices, and also in future developments, whether by enabling oil drilling in deeper water or by facilitating the commercial generation of power through renewable resources such as wind or wave power. The large size of the energy industry means that even small additional involvement will result in significant activity and growth in the composites industry.

The definition of "energy industry" is a subjective one and in many areas the industry overlaps with other areas such as transport, off-shore and civil engineering. For the purposes of this review the term "energy industry" has been taken to include all aspects of the means of producing and/or transmitting energy for end products, so that for example composites used in the electrical transmission coupling of a train are considered to fall within the scope of this review, but any composites used for the structural body of the train are not. Equally, the opportunities for savings in energy through the use of composites in building construction due to their low thermal conductivity are not included here.

Using the above definition, there are three main areas where composites are used:

- electrical power transmission,
- gas and oil transportation and storage,
- production of energy from alternative (renewable) energy sources.

The review examines each of these sectors in turn and highlights some of the current uses for composite materials, and their potential use in the future. In addition some other areas in which composites are used, albeit in a very limited way, will be discussed.

Composite type		
Polymer matrix composite	**Metal matrix composite**	**Ceramic matrix composite**
Transmission line poles and towers Electrical insulators and switchgear Pressure vessels Oil and gas pipelines Oil drilling risers Blast walls and fire-resistant structural elements Wind turbine blades Passive solar energy collectors Flywheel energy storage devices Flue gas desulphurisation towers	Electrical transmission lines Flywheel energy storage devices	Facing walls for nuclear fusion reactors High-temperature jet engines Radiant gas burners

Table 1 Current and potential uses of composites in the energy industry

2. ELECTRICAL POWER TRANSMISSION AND GENERATION

Glass fibre-reinforced epoxy composite insulators in the field of electricity transmission are one of the longest-established uses of composites in energy. As well as their increasing use as insulators in overhead transmission lines, they are also widely used in switchgear, and to a lesser extent in current collectors on trains. Their applicability as a replacement for long-established porcelain insulators and, in particular, for the poles and lattice tower structures that support electrical transmission lines has been demonstrated.

2.1. TRANSMISSION AND DISTRIBUTION LINE POLES AND TOWERS

The market for transmission towers and poles for local distribution is very small at present (currently estimated at less than 0.5% of the market in the USA, the world's biggest user of composite poles), but offers one of the biggest potential growth areas for composites in the future. The two countries where composite distribution poles have made an impact to date are the USA and Italy, both of which have a number of manufacturers active in this field. The early success of composites used for small added parts like insulators and cross-arms has expanded into the manufacture of the poles themselves, and some progress has been made in using metal matrix composites for the transmission lines. Although small, the market for composite poles has been increasing at a slow but steady rate, and manufacturers are optimistic about prospects for the future. In the USA wood poles dominate the market, but the network is ageing and four million poles require replacing each year[1].

Strongwell-Ebert LLC, a wholly-owned subsidiary of the Strongwell Corporation, the world's largest manufacturers of pultrusions, manufactures both utility poles and transmission lattice towers. The lattice tower is manufactured in pultruded segments that require no bolting together: the structure is assembled via a series of interlocking joints instead. This design won the top award for Innovation in Civil Engineering from the US Civil Engineering Research Foundation in 1999. Strongwell-Ebert specialises in the manufacture and distribution of larger structures for transmission cables, where the strength-to-weight ratio and lack of suitable-sized timber works to the advantage of composite structures. The Shakespeare Company is another of the leading players in the composite pole market, selling small distribution poles for specialised cases all over the world including the UK, where it manufactures poles at a factory in Northern Ireland[1].

Figure 1 Composite distribution pole (courtesy of Strongwell Corporation)

Tests have been carried out comparing the properties of a variety of composite poles available on the market and poles made from two species of wood commonly used for poles in the USA. The results showed that the composites poles were in general lighter yet stronger: one particular composite pole was 56% lighter, yet 48% stronger in bending and 50% more flexible than the wooden pole[2]. Companies within the UK manufacture hollow filament wound and spun poles[3] and have also developed a system for manufacturing small insulating support and access towers by continuously wound trusses[4].

Composite poles have a number of advantages over traditional wood and steel poles that make them an attractive alternative:

- Lightweight – approximately 25-33% lighter than standard wooden poles. This means that a fully assembled pole can be transported and airlifted in one piece to remote areas where access is difficult by road, and can be installed with less difficulty, equipment and labour.
- Non-conductive – the transmission lines can be placed closer together as a result, which also means that the required height may be reduced and that the poles use less land than a tower, thereby making less of a visual impact on the environment.

- Corrosion-resistant – wooden poles require chemical treatment (see following point) to resist corrosion in certain soil types, which is not necessary for composites.
- Environmentally-friendly – concern about the deforestation necessary to provide suitable wood for poles and the possible effects of the anti-corrosive treatment chemicals leaching into the soil have brought proposals for new regulations from the Environmental Protection Agency in the US which would increase the cost of wooden poles.
- Consistent performance – knots and other weak spots in wood can affect its performance but composite poles can be manufactured using controls which ensure consistency.
- Maintenance – maintenance costs are much lower as composite poles are more resistant to degradation.

The brackets and cross-arm supports that hold the lines on the poles can now be made from a single moulded composite part, normally glass fibre-reinforced plastic (GRP). Their high insulation properties are an advantage as they do not interfere with the system's electrical transmission, allowing the transmission lines to be placed closer to each other than with steel structures without causing electrical arcing. This reduces the range of the electromagnetic field caused by the lines, an issue which has started to cause more concern to the general public in recent years.

The ability to increase the market share of composite transmission poles is hampered by the reluctance of many electricity companies to switch from wood or steel to a material whose properties are not as well-known. In most developed countries the electricity network is now almost complete and the need for the manufacture of new towers is small and likely only to be required for replacement rather than new schemes. A lack of test methods and specifications for composite poles is cited as a problem in the more widespread acceptance of the new technology: many test methods were written specifically for wood or steel poles, which are not applicable to composites. However, the increase in schemes in the USA where a private contractor is responsible for the building and upkeep of a new transmission line, rather than the electricity company themselves, may stimulate more opportunities for composite manufacturers. The USA's largest company in this field, the Composite Power Corporation, has recently announced its involvement in two such schemes[5]. There may also be more opportunities to use composite towers on a far greater scale in some less developed countries, which still have a relatively basic network and often less accessible terrain.

The Composite Power Corporation has also announced plans to manufacture their newly-developed transmission cable, an aluminium core with a metal matrix composite coating, which is expected to transmit at least 50% more power than conventional cables[6]. As far as the energy industry is concerned, transmission cables appear to provide the best opportunities for metal matrix composites in the future. In the USA the MMC division of 3M has developed an aluminium matrix cable reinforced with aluminium oxide ceramic fibres that has been tested by Electricité de France over a 230-metre test span facility for 18 months. The initial trial programme, which concluded last year, has measured tensile strength and modulus, electrical resistivity, thermal expansion coefficients, creep and vibration fatigue. The basic evaluation has concluded that the MMC cable achieved the predicted performance levels and that its use is feasible. The remaining two years of the project will be devoted to further testing and full characterisation. Compared to standard power transmission cables, the MMC cable is expected to provide up to four times the electrical conductivity, two to three times the strength-to-weight ratio, less than half the thermal expansion, and improved corrosion resistance[7].

2.2. TRANSMISSION LINE INSULATORS

Composites have been used for some time in power transmission to provide the insulators for overhead transmission lines and railway tracks, among others. Early insulators were ceramic, most commonly porcelain. However, glass fibre-reinforced insulators are starting to become more widespread as the old porcelain insulators are being replaced due to ageing, failing to meet new safety requirements, or having suffered from vandalism. Porcelain insulators are heavy, fragile and require frequent cleaning to function properly. They are susceptible to voltage line drops, and will shatter when hit by projectiles, causing a potential hazard to people and animals either from the remnants themselves or the fire hazard from the oil that is frequently encapsulated within them. This last topic has become a particular concern to companies who are searching for alternative materials that will comply with stricter safety regulations and can be less easily damaged by acts of vandalism.

Composite insulators have many advantages over porcelain ones: they are much lighter, tougher, do not require oil inside them, are far less prone to shattering under impact, and can be made smaller than porcelain insulators and therefore present a less attractive target for vandals. They are also more chemically resistant and are less susceptible to current leakage. Current standard composite insulators normally consist of a solid cylindrical rod of glass fibre-reinforced plastic with metal fittings at each end, with a rubber cover (shed) in order to provide protection from the weather and contaminants[8]. New designs are being developed in which the solid composite core is replaced by a hollow core in cylindrical, conical and barrel shapes, and very recently plans have been put forward to manufacture the entire insulator from composite materials, removing the need for a rubber shed.

Composite material insulators now appear to have established themselves as a genuine alternative in the market, and the focus of current testing has moved away from their economic viability to the long-term behaviour of the composite/rubber interface (where present) under the combination of mechanical/electrical stresses and environmental factors that they experience in service. The major drawback of composites compared to porcelain insulators is the lack of data on their long-term ageing effects under these conditions. The two main factors that can affect the composite insulator’s performance are porosity and moisture intake. The presence of voids in the composite reduces its strength and creates uneven voltage distributions through the component. This encourages electrical discharges across the void, resulting in charring of the surrounding composite and further weakening the component. Voids also help to speed up the ingress of moisture: any electrical discharge within a composite containing moisture can result in corrosive chemicals being formed that attack the composite from within.

These problems could be resolved in the near future with the introduction of new methods of fabrication which will see the traditionally slow and costly manufacturing procedure of filament winding replaced by wet fabric wrapping, which reduces the amount of porosity in the product. In addition, the new fabrication technique has been shown to dramatically reduce the manufacturing time and halve the cost of manufacture[9].

2.3. SWITCHGEAR AND OTHER ELECTRICAL DEVICES

A further related application in this sector is switchgear. The insulators in these have been made from porcelain in the past, but are now being replaced by composites for the same reasons as previously detailed for transmission line insulators. Switchgear are often subject to heavy loading conditions: bending stresses caused by winds, short and sudden dielectric stresses and electrical arcs during switching, possible sudden over-current during short-circuits, heating effects caused by the permanent current and switching process, and standard outdoor environmental considerations: low and high temperatures, ultra-violet light, humidity, etc. A series of tests has been carried out on switchgear manufactured from composites to determine their suitability for this application and their conformity to current IEC electrical standards[10]. These tests included mechanical (bending and pressure), dielectric, gas leakage and ageing tests. The composite switchgear passed all the tests comfortably, but as with the insulators, it was noted that further work is required on ageing tests.

In addition, the switchgear are often hollow and filled with a pressurised gas, sulphur hexafluoride (SF_6), instead of air, which can encourage discharges to take place. However, if discharges do take place within the switchgear and moisture is also present, decomposition will take place to form hydrofluoric acid which will attack the composite. To avoid this a coating or polyester fabric is used to line the inside of the switchgear bore.

The current collection systems on electric trains are increasingly made from a glass fibre-reinforced epoxy component. As train speeds have increased in recent years, the need for a material strong enough to cope with the mechanical forces placed upon it during service, combined with the need for excellent insulation properties, has led to GRP becoming the material of choice in many cases. Stringent safety regulations, particularly for rail transit systems that run underground, require high levels of electrical insulation and resistance to arcing and surface tracking, while also demanding excellent resistance to fire and very low levels of toxicity. Permali Composites has developed a range of glass-fibre reinforced materials named Permaglass which are used by London Underground, among others, in a variety of situations where insulation is required, such as shoebeams, arc boxes and rail joints[11].

Glass fibre/epoxy composites are also being used in generators, mainly in the shrouding rings which are filament wound.

3. GAS AND OIL EXTRACTION AND TRANSPORTATION

The two fossil fuels of oil and gas represent a large share of the energy market. In 1996 oil and gas together provided about 64% of the world's total energy requirements. In the UK in particular there has been a sharp rise in the percentage of electricity generated by natural gas, which has risen from less than 1% at the beginning of the decade to 33% of the total in 1999[12], replacing coal and oil as fuel for consumption by industrial and domestic users. UK oil continues to be produced in large quantities despite reduced home consumption, resulting in the UK being a net exporter for all but four years out of the last twenty. 1997 was also the first year for the UK as a net gas exporter. It is clear therefore that both oil and gas are set to continue to provide a significant part of this country's energy needs well into the next century, and that as an exporter of both fuels their extraction and transportation becomes an important issue.

Composites have a potentially important role to play in all stages of the process. Their markedly better resistance to the corrosive marine environments found in offshore applications have seen them begin to replace parts of the oil rigs and drilling components traditionally made from steel, and their lighter weight has promoted their use in pipelines and in the manufacture of pressurised vessels for storage or over-land transportation. With over 6000 oil rigs world-wide, there is a huge potential for composites to be used in replacing and retrofitting components that have come to the end of their working life or which require maintenance.

3.1. EXTRACTION

Glass fibre-reinforced composites have been used for some years now as standard materials for the manufacture of a variety of deck structures onboard oil rigs. These include handrails, ladders, gratings, cable trays and storage tanks - non-structural applications where their high strength-to-weight ratio coupled with strong resistance to the hostile environmental conditions found at open sea have made them the first-choice material. Tests for flammability and toxicity may also see them used in the near future for living quarters and fire walls.

Although widely used on deck, up until recently composites were not considered for use in the drilling and piping equipment itself. However, the gas and oil companies are seriously considering the wider use of composites in offshore extraction for two reasons. Firstly, the replacement of ageing steel "riser" tubes from the sea bed with composite materials would eliminate much of the maintenance work required due to corrosion. Replacing steel pipework is an expensive business as oil extraction has to cease completely while the pipe is removed and replaced. It is cheaper to bandage the existing pipe with CFRP: plant operation does not have to be halted during this process. There have already been several instances where corroded steel pipes and blast walls have been reinforced or lined with carbon-fibre wraps. The lighter composite tubes would also reduce the manufacturing and operational costs. The second reason for the greater interest in composites is that as the more accessible fields begin to run dry, the companies' attention is turning to the more remote and difficult fields, which up until now have been too expensive to develop with the conventional technology. In this respect the light weight of composites and their ability to withstand harsh environments and reduce the amount of service time and costs becomes more advantageous over the tradition steel pipes[13].

The National Institute of Science and Technology (NIST) in the USA has managed four projects in this area under their Advanced Technology Program. Two of these, which lasted five years and have just been completed, investigated the possibility of replacing steel "riser" tubes with composite ones. The aim at the end of these projects was to demonstrate that composites could be used instead of steel on a reliable, cost-effective basis and would allow the exploitation of previously untappable fields to become a reality. A further five-year project was proposed to develop "spoolable" continuous lengths (between 10,000 and 30,000 feet long) of composite tubing for easy storage and transportation to the deepwater sites. The last project, a three-year programme completed in 1998, was concerned with developing new methods of replacing the traditional flange joints in steel tubes, such as integral flanges and improved adhesive bonding techniques. Major petrochemical companies were heavily involved in all of these projects, demonstrating the importance of the new technology to the industry[14].

Future Pipe Industries, a worldwide company with its headquarters in the Netherlands, produces a range of glass-reinforced industrial pipes with either epoxy, polyester or vinyl ester as the matrix, depending upon the application. Its "Wavistrong" glass-reinforced epoxy pipes have been used in a variety of petrochemical and offshore installations due to their strong corrosion resistance[15].

The sucker rods used in pumping oil from the ground have traditionally been made from steel, but the industry is now finding that replacing them with rods manufactured from fibre-reinforced plastics reduces their weight by up to two-thirds. The lighter weight means that less energy is required to pump the oil to the surface, resulting in either energy savings or an increase in the pumping rate. The rods are being used at depths of up to 3 km where corrosion can be a problem for metal sucker rods, but to date the composite rods have shown no major problems[16].

Riser support systems such as the riser arch trays are also starting to be manufactured from composite materials, where their curved shape makes them difficult to manufacture from steel. This is probably the first real demanding use of composites in an offshore environment. DML Composites has manufactured nearly fifty riser arch trays for offshore use[13].

Carbon fibre-reinforced composites are also being researched as "tethers" for floating oil-drilling platforms. Compared with steel tethers, composites could increase the depth to which a drilling rig can operate from 1500 metres to3000 metres.

The successful use of composites in manufacturing onshore storage tanks (see Section 2.2.2) has led to their consideration for offshore purposes. Low-pressure glass-reinforced plastic filament-wound tanks have been used on offshore platforms for water, fuel and brine.

The major concern over GRP piping is its pressure capability limit: most GRP pipes in the oil industry are limited to about 20 bar pressure. There is also a lack of data about the long-term behaviour and durability of composites when subjected to corrosive environments, elevated temperatures and fire resistance, a combination of which may be encountered under service conditions. An additional potential problem encountered with gas extraction is the presence of sand and other particulates which could cause erosion at the high velocities found in gas pipes (the velocities in oil pipes are generally significantly lower). A report by the Institut Français du Pétrole[17] attempted to address some of the concerns about durability with a series of tests carried out on low-pressure firewater pipes on the platforms, high-pressure drilling pipes and risers, and flexible risers. The majority of problems with composite pipes are not due to degradation of the material but failure at the joints, either due to poor alignment in installation or inadequate adhesive bonds or bolts. Since then the Universities of Newcastle and Manchester have carried out tests which validate fire requirements for composite marine structures, and underwater repair tests have also been completed successfully.

Following the Piper Alpha platform disaster much of the fire and blast wall protection on oil platforms has had to be fitted retrospectively, and composites have proved ideal for these situations due to their ease of handling and light weight which can be easily accommodated by the existing structure. Extensive fire and blast testing has shown that composite protection can withstand blast of 2.5 bar and jet fire for more than two hours[13].

DML Composites is also leading a research programme aimed at qualifying 120-year lifespans for composites used in the offshore industry. This includes extensive static and fatigue testing, and an assessment of the effects of fatigue, chemicals and the environment on composite structures and structures repaired using composites.

An ISO standards committee is in the process of developing a new international standard specifically designed for offshore use of GRP piping (ISO 14629), although it is intended to be equally applicable to onshore use, since the pipes can also be used in water deluge systems.

3.2. STORAGE AND TRANSPORTATION VESSELS

As natural gas supplies have increased in importance to become a widely-used fuel, the partial or total use of composites for vessels to store and transport liquid gas under pressure has become widespread. Up until the 1980s the storage tanks had been made from steel or aluminium: this had made them heavy and difficult to handle. Composite materials started to be introduced into the manufacturing process initially by wrapping glass fibre reinforcements in the hoop direction around the metal cylinders. With the fibres taking part of the hoop loads the thickness of the metal wall was not as great, thereby reducing the overall weight and increasing the amount of gas that could be transported. It has been reported that using carbon fibres increases storage efficiency by 30% and reduces the weight by up to 75% when compared with glass hoop-wound steel tanks[18]. Although the use of composites increases the initial cost of the tank compared with one made entirely from metal, the lighter weight means that the fuel efficiency of the transportation vehicle is increased and the initial outlay can be recouped fairly quickly.

In the last twenty years the incorporation of composites has greatly increased, from fully wrapping the tank around an internal aluminium liner with fibres aligned not just in the hoop direction but in others as well to relieve more of the pressure loads, and recently to all-composite tanks made from filament-wound glass or carbon fibre-reinforced plastic with an inner thermoplastic liner. There are numerous companies throughout the world that manufacture storage vessels in various shapes and sizes for a variety of products such as water and sewage, oil and petroleum products, and processing chemicals. In situations such as offshore environments or long-distance transportation, their resistance to harsh environments and loading conditions makes them ideal. The tanks should also be maintenance-free throughout their life, and have a greater resistance than metals to the harsh and potentially corrosive environments to which they are subjected during transportation[19].

There is also plenty of potential to use composite tanks in vehicles powered by propane, or liquefied petroleum gas (LPG) as it is also known. Propane is widely available in the United States as a fuel for heating or cooking, but increasingly it is being used to power vehicles as well. It is estimated that more than four million vehicles run on LPG worldwide, including more than 80,000 taxi, bus and delivery services in the US alone[20]. This number is likely to increase in the future as alternative fuels to replace oil and petrol are sought, and propane is a leading contender as it provides more miles to the gallon than any other alternative fuel, and gives off a dramatically reduced amount of carbon monoxide and other pollutants when burnt. As most propane is produced as a by-product of extracting natural gas or oil, and with a delivery network already in place in the US, it is relatively easy to switch to using propane as vehicle fuel. The use of composite materials is expected to increase as the use of propane becomes more widespread, since a lighter vehicle chassis would mean less fuel is required to transport the vehicle.

Composite tanks made from a combination of glass and carbon fibre-reinforced material are also used to store air in breathing apparatus. As well as diving equipment, they are used in hazardous situations such as fire-fighting, where their main advantages over metal cylinders are their light weight (essential for the comfort of the wearer) and their non-conductivity (will not transmit heat as quickly to the wearer or build up static charges). An EC directive on the maximum allowable weight of breathing apparatus makes composites the best material to fulfil this requirement.

4. ALTERNATIVE ENERGY SOURCES

Energy obtained from renewable sources such as wind, solar and hydroelectric power has made few inroads to date in the total energy market, mainly due to the high costs involved, the inefficiency of most of the methods in producing useful energy or electricity, and a lack of government support in the UK. Renewable energy sources currently supply just 1.5% of the UK's electricity needs[12] of which the vast majority is produced from burning biomass fuels, and despite government obligations to increase the use of renewables as part of the recent Kyoto summit agreement to cut greenhouse gas emissions, progress remains slow. Nevertheless, in the places where these technologies are in use, composite materials play an important role.

A recent EU proposal has set each member state a target of supplying 12% of its electricity requirements using renewable energy resources by the year 2010. In addition to this the UK Government has produced five Non Fossil Fuel Obligation (NFFO) orders since 1991, the most recent being in late 1998. These orders require the electricity generating companies of the UK to produce a government-specified amount of electricity to be generated from renewable energy resources. The higher generating cost incurred by the electricity utilities when they contract renewable energy projects is reimbursed via the Fossil Fuel Levy which is paid for by their customers' electricity bills. Early in 2000 the levy was axed by the government as it was felt that renewable technologies had developed sufficiently and were cost-effective enough to be able to compete directly in the marketplace, and that future grants would only cover pilot schemes, not commercial ones. It was replaced in April 2001 by the Climate Change Levy, which forces the electricity companies to generate a certain percentage of their electricity from renewable energy sources. The Levy has received some criticism and it remains to be seen how this will affect the growth of these emerging industries in the future.

4.1. WIND ENERGY

The production of electricity from wind power has been promoted for some years. Interest in the technology has grown rapidly world-wide in the last decade and with it have come advances, such as improved technology and better siting, that have reduced the cost of generating electricity to prices comparable with those for standard fossil fuels. It is currently the fastest-growing sector in the power-generating industry, supplying 4.5 GW of electricity to around 30,000 Europeans in 1999, and this figure is projected to rise to 60 GW by 2010 and 150 GW by 2020, according to estimates from the European Wind Energy Association. These estimates were recently upwardly-revised in view of the steady growth rates of about 40% per annum of the last few years. In the UK, wind energy projects, along with landfill gas programmes, have consistently attracted the most attention from the generating companies as the best means of attaining their NFFO contract target. Although relatively expensive to build, there are virtually no running costs once they are operational and hence the energy payback period is normally as short as three or four months. A variety of European government proposals have also helped to promote interest in wind energy as a viable energy source and have resulted in European firms dominating the technology: 90% of the world's wind turbine manufacturers are European, with the majority of them located in Denmark and, to a lesser extent, the

Netherlands, countries whose limited fossil resources and flat countryside have made the use of wind power an attractive option. Danish firms are heavily involved in the UK wind energy industry, either by ownership of the major manufacturers or by providing the main export market.

Composite materials play an important role in the construction of wind turbines. The vast majority of all wind turbine blades and the turbine nacelles are predominantly made from glass-fibre reinforced plastics and composite sandwich structures. The strength-to-weight ratio of composites is the major advantage they have over other materials: their lighter weight means they need less wind energy to start their rotational momentum which results in less mechanical and frictional loss in transferring this energy to the turbine. However, as they require a good and constant wind supply they are normally situated in suitable locations such as high ground or on shorelines. These sites also have the disadvantage of being subjected to occasional strong winds and harsh environments, and so the blades must also be robust enough to withstand theses factors.

As potentially viable locations on land become scarcer, attention is turning more to offshore developments. These have several advantages over land-based wind farms: wind speeds are usually higher and more consistent than on land (due to the topography of the land creating turbulence), and the turbines can be placed away from where they may be considered noisy and an eyesore. It will allow much larger and more powerful turbines to be built than those currently used on land, and will see an increase in the blade sizes used. By 2000 there were five offshore wind farms in northern Europe, with a further nine proposed applications under scrutiny. The UK is particularly suited to the development of electricity generated from offshore wind farms, as it is the windiest country in Europe. The UK's first offshore farm, comprising two 2MW turbines half a mile out from Blyth Harbour in Northumberland, was officially opened in December 2000 and currently supplies electricity to 1500 homes. A Crown Estates report from April 2001 announced 18 further potential sites for offshore wind turbine development which, if all were developed to their full potential, would provide electricity for one and a quarter million homes in the UK[21, 22].

Figure 2 The two turbines of the offshore wind farm at Blyth Harbour, now in operation (courtesy of AMEC Border Wind Ltd)

At present there seems to be little consensus as to the best material to use in the blades. The material selection is heavily influenced by the rotor size, the number of blades, its siting and hence the weather conditions it is likely to experience, and the speeds the rotor is designed to operate at. In addition to these criteria each country's local health regulations and experience of using certain types of material for past products must also come into consideration. The Danish manufacturers who dominate the market almost exclusively use glass fibre-reinforced polyester for their blades, probably as a result of local health regulations which limit the use of epoxy resins, while many British suppliers still use wood in the construction of their blades. Glass/epoxy blades are also manufactured in large quantities all over the world. Carbon-fibre and glass/carbon-fibre hybrid blades are relatively rare and are still being evaluated, primarily in Germany, but could take the place of glass-fibre blades in the future. The increasing interest in offshore wind farms with their higher rotor speeds and ever-increasing turbine size will mean a continuing increase in the length of blades and thus result in a move towards stiffer and stronger carbon fibre-reinforced blades. As the price of carbon fibres drop this becomes an increasingly viable option. Carbon fibre materials have the added advantages of excellent fatigue properties and of requiring less material to produce the same properties as glass fibre-reinforced blades. With the increasing automation in the blade manufacturing process from hand lay-ups to resin transfer moulding which further reduces costs, it seems that carbon fibre blades will gain in acceptance in the not too distant future. Although steel has also been used in the past, being cheap and stiff, its higher density and the necessity for welding blade components together, leading to localised weak spots, has seen it abandoned as a practical material for use in blades[23].

Aerolaminates, formerly part of the Taylor Woodrow group and now owned by Danish firm NEG Micon, is one of the major manufacturers of wind turbine blades in the UK and manufactures all its blades using a combination of wood veneers and foam cores covered with a skin of glass/epoxy laminates. There are several other companies in the UK who manufacture wind turbine blades and other small specialist companies who produce complete wind turbine systems for domestic household or business use.

Although there are not many manufacturers of the end product in the UK, there is a large sector associated with the raw materials for the blades. One of the largest businesses is SP Systems which manufactures prepregs for the home and export markets. Having started out as suppliers to the marine industry, it has branched out into areas such as wind energy where it has become one of Europe's leading suppliers of prepregs. A recent £100 million contract to supply composite materials to the leading Spanish wind turbine company has led to an expansion of its premises in the UK and the building of a second factory in Spain.

Future advances in the manufacturing of turbine blades is likely to centre on the development of resin infusion processes and the use of prepregs in the lay-up process. The use of prepregs would involve heating the resin during the bonding process and this could cause a potential problem due to the presence of moisture in the wood; this is an area which is currently under investigation[24].

All of the above suggest that this is an area in which composites will find an increasing market, in the near future at least. After many years which saw the majority of planning applications for land-based wind farms turned down, mostly due to pressure from environmental groups, and the majority of blades manufactured in the UK exported for use in European countries instead, the prospects for wind energy in the UK are looking more hopeful. The manufacturers hope that in the future with the development of more offshore wind farms which may be more acceptable to environmental campaigners, the Government's policy on wind power will become more favourable and that the UK market will pick up. It is significant that several companies with a traditional base in oil and gas exploration, such as Shell and BP Amoco, have set up separate renewables divisions within their organisations in the last few years and are now actively involved in the construction of wind farms around the world (Shell UK is one of the partners involved in the construction of the offshore wind farm at Blyth).

4.2. WAVE ENERGY

Extracting energy from the waves has been a goal for several decades now, without ever becoming a serious proposition. The waters of the Atlantic Ocean around Britain and Ireland provide some of the best opportunities of anywhere in the world to put the theories of wave energy into practice. An initial enthusiasm during the 1970s saw the first trials of “Salter’s ducks”, developed by Professor Stephen Salter and his Wave Power Group at the University of Edinburgh, but the high costs of producing electricity from the ocean led to a lack of funding throughout the 1980s and eventually the complete cessation of the government’s wave power programme in 1994. The last couple of years have seen a revived interest in wave power as new technology and increased efficiencies have reduced the generating costs tenfold to about 7p/kWh. In September 1999 the British government outlined their plans for an official wave energy programme as part of the DTI’s New and Renewable Energy Programme, and the following month the Scottish Parliament announced they were setting up an independent commission to investigate the feasibility of wave power. Most recently the Government announced they were considering building a link from the wave power generators to the national grid.

Britain’s only successful venture into harnessing wave power to date has been two oscillating water columns (OWC) designed and built on the Scottish island of Islay in a collaboration between Queen’s University, Belfast and Inverness company Wavegen (formerly Applied Research Technology). The basic construction of an OWC is shown in Figure 3: when the sea surges into the concrete “box” constructed on the shoreline cliff-face, the air pocket inside the box is forced through the turbine situated at its top end. This Wells turbine, named after its inventor Professor Alan Wells who set up the Wavegen company, is constructed in such a way that it continues to rotate in the same direction when the sea ebbs and the air is sucked back through the turbine. The first experimental prototype plant was commissioned in 1988 and had an output rating of 75 kW. The second, larger 500 kW plant was opened in December 2000 and is the first commercial plant powered by wave energy, supplying electricity to the Scottish electricity grid for a 15-year contract period.

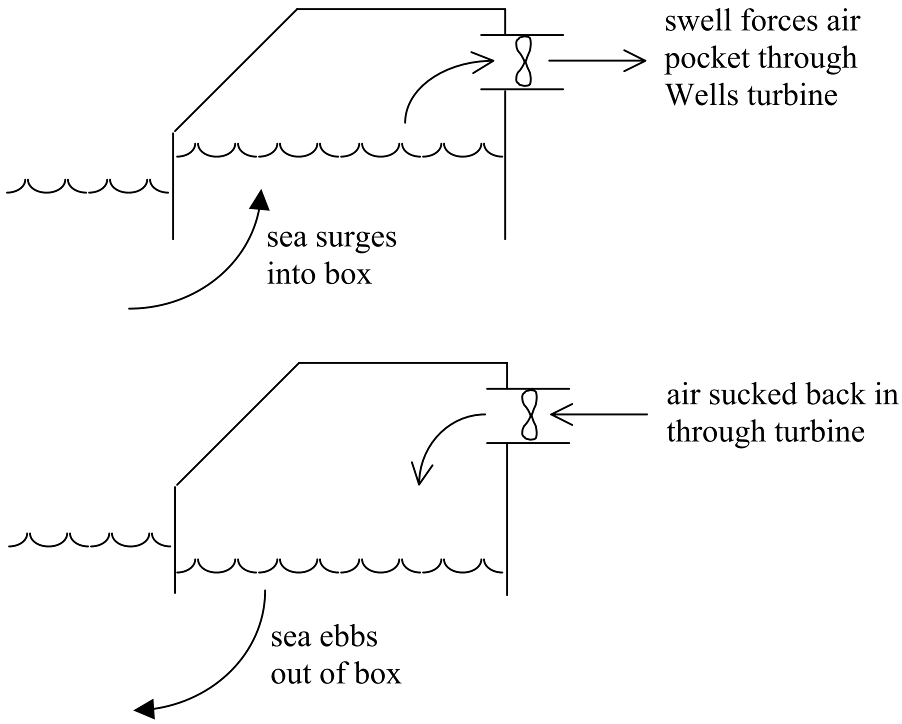

Figure 3 Schematic representation of an OWC

Among the new ideas that have sprung up is a variable-pitch turbine, also developed by the Wave Power Group at Edinburgh and which is due to be installed in an EU-funded trial OWC on the island of Pico in the Azores. Salter has shown that the blades within a Wells turbine will only work properly with an incident angle between 2º and 13º. By developing a digital controller which can alter the blades' pitch up to ten times a second, it should prove possible to keep the blades within the range of optimum angles for longer periods and thus greatly increase the efficiency of the turbine. Ideally the blades would be made from titanium, but the expense of the super-plastic forming diffusion bonding process required has led to their design from partially foam-filled hollow carbon fibre/epoxy instead, with a nickel coating in order to prevent erosion. In addition to this there are a few small components (mainly fairings) on the turbine manufactured from glass-reinforced polyester with expanded polystyrene foam cores. Trials are currently underway at the test site in Portugal[25].

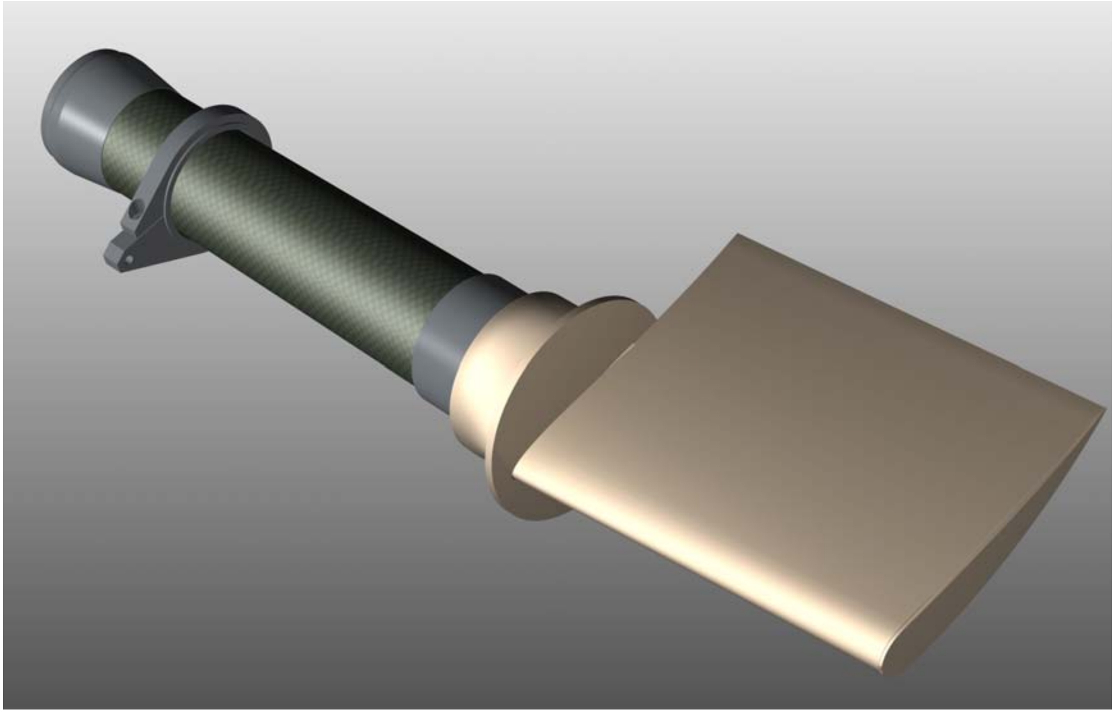

Figure 4 Rendered CAD drawing of composite blade and spar for variable-pitch turbine (courtesy of Wave Power Group, University of Edinburgh)

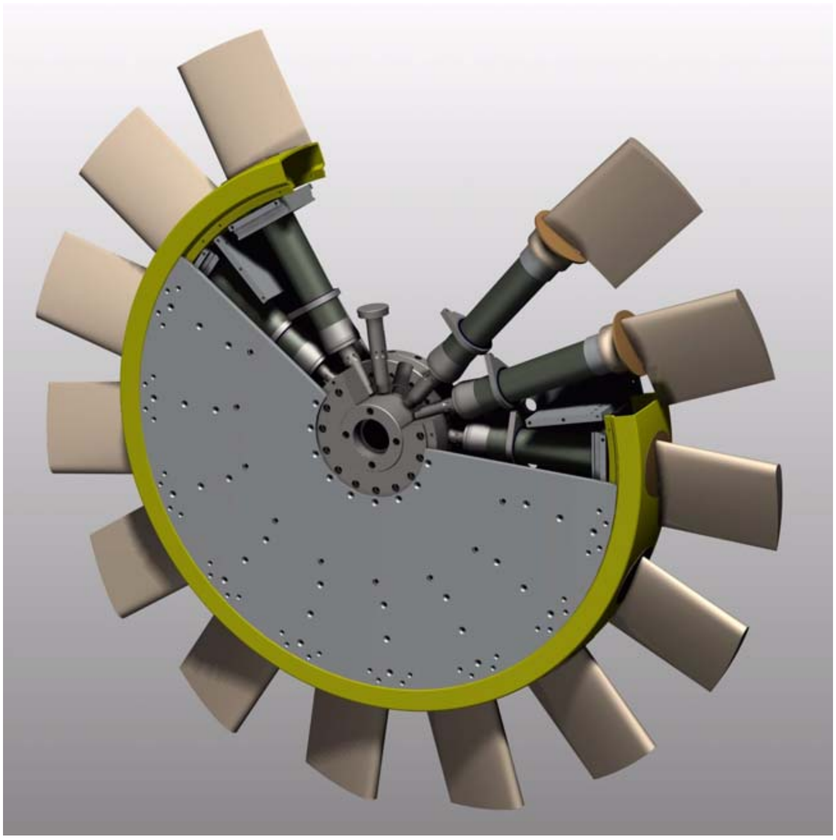

Figure 5 Rendered CAD drawing of turbine assembly for variable-pitch turbine (courtesy of Wave Power Group, University of Edinburgh)

4.3. SOLAR ENERGY

There is only a very small market for composite materials in the solar energy market, as most work tends to concentrate on photovoltaics. Any composite use in this field is in active solar power, a method which uses the sun's energy by trapping heat like a greenhouse, and using this to heat buildings. All that is required is a dark material that will absorb sunlight and convert it into heat energy, and a glazing material covering it that will prevent the heat escaping. GRP is often used as a glazing material: it can withstand higher temperatures than the polymethylmethacrylates (PMMA), polyesters and polyvinyl fluorides that are also used, and will not weather like polycarbonates. It has been suggested that in the future there may be a place for carbon fibre/epoxy composites as absorbers due to their dark surfaces resulting in low emissivity of infra-red radiation[26].

4.4. FLYWHEELS

A flywheel is a means of storing energy in a rotating mass. Power is put in to start the mass rotating, but when the power is switched off the wheel continues to rotate under its own momentum and thus provides the power itself. As the energy stored in the flywheel is related to the speed of rotation, the weight of the flywheel and its tensile strength become important considerations. Carbon fibre or hybrid glass/carbon fibre flywheels made by filament winding or weaving are prime candidates for use in this area, as in order to provide a commercially viable amount of power flywheels have to rotate at speeds far in excess of those that would cause fatigue failure in metals such as steel, which has traditionally been the most commonly-used material. The weight of steel is also a serious disadvantage as it means the wheel can only operate at low speeds and with a low efficiency due to severe power loss through the bearings.

Although they provide an attractive method of energy storage and provision, the major stumbling block to large-scale production of these flywheels in the past was the cost of developing and manufacturing the flywheels as compared to the alternatives. The initial focus was on the large-volume market as an alternative to batteries in general-purpose uninterruptible power supplies or to smooth out power loading in vehicles such as buses, where the stop-start nature of their use resulted in heavy fuel consumption. Recently, the focus has shifted towards management of electrical power supplies in specialised industries, particularly those that rely on a constant power output for continuous processes. Electrical power supply can suffer from the problems of power cuts or voltage "spikes". Although these power fluctuations are usually only momentary, the damage and loss of information they cause to continuously operating machinery and computer systems can be extremely expensive to correct: in the USA alone it is estimated that such fluctuations result in the loss of about $12 billion every year. Flywheels also have a future in mass transit systems around the world. The heavy power demands and heat dissipation, caused by a large number of trains on the system accelerating and decelerating, can be reduced using flywheels to store the braking energy when they reach the station and then using this energy to accelerate the trains when they move off again.

Interest in flywheel technology first appeared in the 1970s when the oil crisis prompted several companies to look at alternative methods of providing power for road vehicles. Development was virtually abandoned during the 1980s as oil became cheap and plentiful again, but the 1990s saw renewed interest from many large companies, particularly in the USA, where there are several studies currently underway. Dow-United Technologies Composite Products carried out an eighteen month project, funded by NIST and completed in April 1996, to develop flywheels for electric vehicles[14]. In 1998 Boeing announced its intention to develop a flywheel for potential use as an energy storage and load levelling source for electricity companies, and possibly as a replacement for batteries in space satellites[27]. This is an area of particular interest for many companies involved in the space programme as conventional lead-acid batteries are heavy and eventually run down[28]. Other programmes in the USA are looking to use flywheels to store energy in public transport and electric vehicles where they can improve fuel efficiency[29, 30], and they have also been used on wind turbines to smooth out the erratic gusts and lulls that occur to provide a steady electrical output.

There have been a few projects in the UK in the last quarter-century that have attempted to develop composite flywheels for industrial use, notably those of British Petroleum (BP) and British Nuclear Fuels Ltd (BNFL). Partly as a result of the oil crisis of the 1970s, BP developed a flywheel made from a glass-reinforced epoxy with a hybrid glass/aramid fibre rim, named KESS. It was tested for use on public transport buses, thought to be one of the most promising applications because of their constant starting and stopping. With the flywheel rotating at 16,000 revolutions per minute, enough energy could be provided by the flywheel to move a single-deck bus from a stationary position up to a speed of 20 miles per hour without the use of fuel. It was estimated that this could result in fuel savings of up to 30%[31]. However, the project was abandoned before the completion of vehicle trials for non-technical reasons.

The BNFL flywheel was developed from the same technology used to produce their uranium enrichment centrifuges. In 1995 BNFL set up a subsidiary company, International Energy Systems (IES), dedicated to developing commercial flywheels. However, IES was closed after three years due to ongoing problems with the product and inability to meet the target commercial cost of the flywheel. The technology was retained by Urenco, another partial subsidiary of BNFL that had been involved in the project, who continued to develop the flywheel technology in conjunction with Siemens, basing the design on its existing gas centrifuge systems. In early 1999 its first commercially available flywheel energy storage system, the PQ100, was launched onto the market. The PQ series flywheel is filament wound from carbon and glass fibres and is cylindrical in shape, rather than disk-shaped. The reasoning behind this is that a cylinder will fail by bending, rather than catastrophically bursting as a disk would. This results in contact being made between the cylinder and the containment walls that cause the cylinder to skid to a halt, thus providing a safer design. The composite also includes powdered permanent magnetic material which is magnetised during operation to provide magnetic bearings for the flywheel and eliminating the need for conventional magnets in the rotor which could suffer from dynamic problems at the flywheels top speeds.

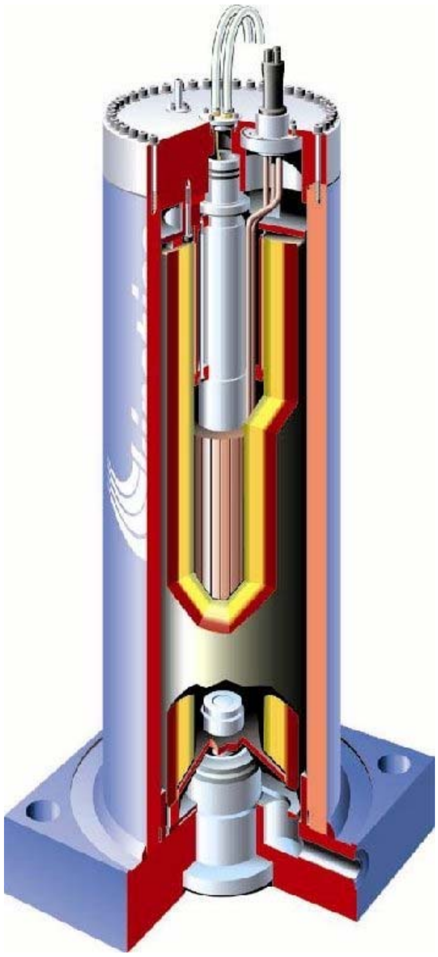

Figure 6 Cutaway section of PQ series flywheel (courtesy of Urenco Power Technologies Ltd)

The PQ series flywheel rotates at speeds up to 36,000 rpm and can reach full power in less than 5 milliseconds, with an output of 450 kVA that can be sustained for 18 seconds. Extensive tests have reported no problems. It is hoped that it will provide a valid application as a means of providing power during voltage dips for companies requiring a constant electrical supply. Urenco itself provided an ideal test site for the flywheels as it suffers from several voltage dips each year that affect the equipment on its centrifuge lines and disrupt production. Two 105 kW PQ100 flywheels operating in parallel have been connected to a Siemens SIPCON power quality converter at the plant and shown to successfully compensate for voltage losses of up to 40%. Extensive testing has also been carried out by London Underground Ltd who hopes to employ the technology to smooth out the power on the underground system. Urenco is currently in discussion with a number of other potential users of its technology and is confident of establishing flywheels as a serious alternative to batteries in this market. The high initial cost has a payback period of around four years and there is very little maintenance required once the system is up and running[32, 33].

Figure 7 PQ Series flywheel installed at Urenco's plant in Cheshire (courtesy of Urenco Power Technologies Ltd)

One of the major remaining problems with composite flywheels is that they have poor transverse tensile properties and hence the radial stresses encountered during operation must be minimised, either by pre-stressing the flywheel in compression or by including radially-woven fibre in the manufacture. The KESS flywheel was manufactured using three types of fibre (two glass, one aramid) to minimise the transverse stresses. 3M has announced the production of a hoop-reinforced aluminium matrix composite flywheel. It is claimed that this has the advantage over a polymer matrix flywheel as it allows a smaller flywheel to be produced, due to a better balance between longitudinal and transverse strength[8].

5. OTHER USES OF COMPOSITES IN ENERGY

The applications described in the three sections above represent the majority of uses of composites in the energy industry. However, there are a few other areas in which they play a small but increasingly important role, which are detailed below.

5.1. FLUE GAS DESULPHURISATION

Over the last twenty years increasing concern over the levels of sulphur dioxide being released into the atmosphere has led to several countries in the developed world imposing regulations that require fossil fuel power stations to remove or reduce the amount of harmful by-products released. The two major ways of achieving this are by switching to a fuel with a lower level of sulphur or by scrubbing technology. While scrubbing has proved to be an efficient means of removing the by-products, it is prone to problems with the stainless steel or other steel alloys traditionally used to make the absorbers in the stacks and in the ducts. These alloys are normally resistant to sulphuric acid, but the combustion processes in the plants also release chlorides: these attack the metal and remove its protective layers, thus leaving it open to attack from the acids. Previous solutions using lining material made from high nickel alloys have proved effective but are they also extremely expensive and very sensitive to variations during use.

Glass reinforced plastics are about one-third of the cost of the nickel liners but have similar levels of durability. The resin is usually a vinyl ester because despite lower chemical resistance than polyester resins, it has a much better resistance to fatigue and the thermal and mechanical shocks found in normal service conditions. A study to compare the properties of glass fibre/vinyl ester stacks with stainless steel and the commonly-used nickel alloy C-276 has been carried out[34]. The composite displayed heat ageing, chemical and fatigue resistance properties as good or better than those of the nickel alloy, in addition to being one-third of the price. Problems with the combination of heat and moisture that can affect vinyl ester resins can be reduced by lining the composite wall with an acid-resistant heat shield brick. Resistance to other aggressive chemicals in the waste by-products, such as sodium hypochlorite, can be improved by changing the formulation of the resin and its cure.

Composite piping for flue gas desulphurisation is now widely used around the world for many fossil fuel power stations. In the USA some plants have been using composite pipes for 25 years and have shown little deterioration, providing the industry with some valuable data on long-term ageing. The use of composite pipework in power plants is likely to increase in the future as utilities see it as a viable and cost-effective alternative to replacing metallic pipework now suffering from corrosion[35].

5.2. NUCLEAR AND CONVENTIONAL POWER STATIONS

Glass fibre-reinforced epoxy and ceramic matrix composites (CMCs) are starting to find uses in the nuclear power industry and other conventionally-fuelled power plants. GRP has been used extensively in non-critical pipework around plants (e.g. waste transportation, cooling water) where the pipes may be up to 2 metres in diameter and

25 mm thick, in addition to fan blades in cooling tower couplings, valves and pumps. In the more critical and highly-stressed situations, such as compression pumps, glass has been replaced by the superior strength of carbon as the fibre reinforcement. CMCs have attracted interest as a first facing wall in the reactor core of the new generation of experimental fusion reactors.

Clearly the most important factor in the use of composites in the nuclear industry is their integrity and ability to withstand ageing, fire and a variety of mechanical and thermal stresses, both normal in-service and sudden stresses such as water hammer or earthquakes. It is the lack of data on these effects and the materials' susceptibility to impact damage that has limited the use of composite pipes to non-critical areas such as cooling water transportation, although there are one or two plants around the world that have used them in critical applications. For non-critical applications, however, their excellent corrosion resistance, light weight and minimal maintenance requirements have made them first choice for many engineers when considering materials for pipe networks.

The process of nuclear fusion involves burning a plasma comprising the hydrogen isotopes deuterium and tritium. Their fusion does not directly result in the production of radioactive particles as a standard fission reactor would, but instead produces neutrons which penetrate the plasma facing components (the first wall and diverter) of the reactor and into the blanket behind it, causing them to become radioactive. In addition, the core of a nuclear fusion reactor reaches a substantially higher temperature than a fission reactor (up to 1000ºC). The requirements of the first wall therefore are a combination of high temperature resistance and strength, combined with the ability to absorb neutrons so that a radioactive material with a rapid decay time is produced in order to minimise the risk of contamination beyond the reactor walls. The early graphite reactor walls have been superseded by C-C (carbon fibres in a carbon matrix), and more recently SiC-SiC (silicon carbide fibres in a silicon carbide matrix). These ceramics take the form of tiles brazed onto a metal skeleton of stainless steel tubing in order to provide the necessary thermal conductivity and resistance against thermo-mechanical stresses. Although C-C composites are still widely used at present, they suffer from erosion due to chemical interaction with the plasma and hence carbon doped with silicon or SiC-SiC ceramics, both of which have greater resistance to erosion, are being investigated more fully. One of the major concerns with SiC-SiC tiles is that they are prone to microcracking and as a result some gas leakage can occur. Other problems common to both types of ceramics are a lack of data regarding their behaviour and properties under irradiation at very high temperatures, their reactions to thermal shock, and the joining methods that would be required to prevent possible gas leakage at the joins. The nuclear fusion technology is still at the experimental stage with only a few prototype reactors in existence in the world, so the use of CMCs in this area has been very limited and will require extensive further testing[36, 37]. It has been reported that metal matrix composites containing boron isotopes to absorb the neutrons are also under investigation[38].

Nuclear fusion is estimated to be about 40 years away from being a viable source of producing energy. However, if it does become a widely used energy provider then it appears that ceramic matrix composites will play a major role in the construction of fusion reactors.

5.3. COMBUSTOR GAS TURBINES AND JET ENGINES

For some time manufacturers have been looking to develop larger gas turbines and jet engines and to operate them at higher temperatures. This would see an increase in their performance and allow larger aircraft to be built. However, up until now the operating temperatures of these engines has been limited by the metallic components used throughout the engine. Ceramic matrix composites would appear to be ideally suited for replacement of these parts due to their higher temperature capabilities than many metals, and as a result CMC blades, nozzles and combustor linings have all been developed. After experimenting with numerous types of ceramic composites over several years, almost all the world's research now involves SiC-SiC composites.

Several research programmes over the last decade, mainly in the USA, have been evaluating their performance. The Advanced Turbine Systems (ATS) Program was one of the largest of these, a $700 million eight-year programme jointly funded by industry and the US Department of Energy and with the aim of developing cleaner, cheaper and more efficient gas turbines for utility and industrial electric power generation. Two companies involved in the programme, Solar Turbines Incorporated and the Allison Engine Company (now part of Rolls-Royce plc) undertook testing of ceramic components in their gas turbines. The tests demonstrated that the use of CMCs allows turbine inlet temperatures to be increased, while the need for air-cooling (essential for the equivalent metallic components) is eliminated, and NO_x and CO emissions are reduced.

Solar Turbines was also involved in one of the follow-up programmes, the Ceramic Stationary Gas Turbine Development Program, and has recently published data on SiC-SiC liners that have been successfully tested for more than 10,000 hours in total over four different engines, including 5000 hours on one engine liner alone. The engines functioned normally throughout and emissions of NO_x and CO were reduced to levels well below US guidelines on emissions[39].

The Allison Engine Company has been running another project under the ATS Program to develop ceramic first-stage stator vanes. This involved the design analysis and construction of the vanes, testing for thermal shock, and running a long-term test under operating conditions[40].

The successful use of CMCs in gas turbines and jet engines has been hampered by their brittleness. Under dry oxidising conditions a silica layer will form on the ceramic which will protect it from degrading rapidly but the presence of moisture at high temperatures and pressures, as typically found in combustion environments, will quickly degrade the silica layer and attack the CMC. This causes embrittlement which can result in catastrophic failure. In recent years continuous fibre ceramic composites (CFCCs) have been developed to overcome the problems of embrittlement by bridging cracks in the matrix, and environmental barrier coatings for the ceramics are being developed to protect them. The tests detailed above carried out by Solar Turbines used CFCC liners, and while the liners were able to complete the tests and still function they were found to have undergone heavy oxidation. Tests which were begun in April 1999 are the first in which Solar has used environmental barrier coatings and evaluation is still in progress. Tests are being carried out at the Oak

Ridge National Laboratory in the US to determine suitable barrier coatings. These need to have good resistance to moisture degradation and corrosion at high temperatures, good adhesion to the SiC matrix and stability of mechanical properties at high temperatures. There is a lack of data on barrier coating durability under high-temperature corrosion conditions or thermomechanical stability in high-pressure water vapour, and this is currently being addressed. Early indications are that to achieve all these requirements several layers of different types of environmental barriers will be required[41].

The use of CFCCs as last-stage blades in gas turbines is also being explored, as in the future these could be up to 1m in length. At this length the weight of the blade would make it impossible to use metals so a material which is strong but lightweight is of primary importance. Several projects were initiated in the USA under the Department of Energy's CFCC Program which are developing continuous fibre ceramic composites for potential use in radiant burners, diesel engine valve guides, hot gas filters, high-pressure heat exchanger tubes, and combustor gas turbine blades, nozzles, liners and shrouds[42]. The programme was due to conclude in 2000 but a large-scale take-up of the new technologies is not expected for several years until they prove to be cost-effective. The Société Européene de Propulsion in France, the world's largest user of ceramics, believes that the use of CMCs in gas turbines will not occur before 2010.

6. CONCLUSIONS

This review has highlighted some of the areas in the energy industry for which composite materials will find applications in the future.

Their main advantages are:

- high strength-to-weight ratios;
- good mechanical and thermal properties;
- good electrical resistance;
- excellent chemical resistance.

Their main disadvantages are:

- high initial manufacturing cost, despite potential savings in the long term;
- lack of agreed data regarding long-term durability and property degradation;
- inability to recycle materials in many cases.

These last three factors are making businesses reluctant to change from tried and tested metallic materials to unknown composite materials, and in some areas improved production methods have led to renewed interest in the use of steel and aluminium. However, the continuing reduction in the price of carbon fibres down towards £5 per kilogram should start to make them economically viable for a variety of products where previously their high cost had ruled them out.

- The main areas in which composites are now regarded as the number one material of choice are wind turbine blades and pressurised gas storage vessels.
- Composites are starting to become serious contenders in the fields of insulators, switchgear and pipework where corrosion or chemical attack is a serious concern.
- The potential exists for composites to make headway as first walls in nuclear fusion reactors. They are also starting to replace steel or wooden electrical transmission poles in areas where accessibility or environmental concerns are a major factor.
- Old oil and gas pipelines are being replaced and many new ones are being built using composite pipelines which have superior chemical resistance.

It is also of some concern that few businesses in the UK are involved with any of the technologies detailed in the review: most of the research currently being carried out is in the US and Japan. The only areas of energy applications in which the UK appears to be involved substantially are in the manufacture of wind turbine blades and in the development of flywheels for power load levelling, and even here much of the end product seems destined for markets abroad.

A summary of applications, with their advantages and disadvantages are shown in Table 2.

Application	**Advantages**	**Current disadvantages**
Electrical insulators and switchgear	Lightweight Chemically resistant Shatter-resistant	Poor weather resistance (moisture) Lack of data concerning long-term properties
Transmission line poles and towers	Lightweight - easier transportation and installation Better insulation properties Less maintenance Corrosion resistant	Lack of data concerning long-term properties Not required on a large scale in most developed countries
Electrical transmission lines	Less power loss during transportation	Expensive Still under development
Pressure vessels	Lightweight - easier handling and decreased transport costs Less maintenance Chemically resistant	Long-term impact properties
Oil and gas pipelines	Corrosion resistant	Limited pressure capabilities
Wind turbine blades	Lightweight but strong	Expense of producing energy Environmental concerns
Passive solar energy collectors	Low emissivity High temperature High warpage resistance	Cost-effectiveness
Flywheel energy storage devices	Lightweight but strong - can withstand high rotational speeds High fatigue resistance	Expensive Still to identify target market
Flue gas desulphurisation absorbers	Good chemical and corrosion resistance Good fatigue resistance Cheaper than metal plating Long-term properties now available - little deterioration	Poor heat and moisture absorption
Facing walls for nuclear fusion reactors	High temperature resistance Mechanical and thermal stress resistance	Lack of data on thermal shock and radiation ageing resistance
Radiant gas burners	High temperature resistance	Interface becomes brittle in oxidising atmosphere Not yet cost-effective

Table 2 Summary of advantages and disadvantages of composites used in the energy industry

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