Chapter 21. Offshore Hydrocarbon Industries

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1. Scale and significance of the offshore hydrocarbon industries and their social and economic benefits.

1.1 Location of offshore exploration and production activities

Offshore oil and gas exploration and development is focused in specific geographic areas where important oil fields have been discovered. Notable offshore fields are found in: the Gulf of Mexico (Fig. 1); the North Sea (Fig. 2); California (in the Santa Barbara basin); the Campos and Santos Basins off the coast of Brazil; Nova Scotia and Newfoundland in Atlantic Canada; West Africa, mainly west of Nigeria and Angola; the Gulf of Thailand; off Sakhalin Island on the Russian Pacific coast; in the ROPME/RECOFI area[1] and on the Australia's North-West Shelf.

1.2 Production

According to the United States of America National Research Council (2003) in a snapshot of the global offshore oil and gas industry, there were (in 2003) more than 6,500 offshore oil and gas installations worldwide in 53 countries, 4,000 of which were in the United States Gulf of Mexico, 950 in Asia, 700 in the Middle East and 400 in Europe. These numbers are constantly changing as the industry expands and contracts in different places in response to numerous factors involved in the global energy market. An indicator of this volatility is that by 2014 there were only 2,410 rigs in the United States Gulf of Mexico, for example.

Global crude oil production is currently 84 million barrels per day (BPD; CIA Factbook, 2012 figures) of which about 33 per cent is from the offshore (Fig. 3). Data compiled by Infield (2014) indicate that onshore crude production plateaued at around 65 million BPD as early as the 1990s and growth in offshore production has accounted for most of the increased global productivity since then. Production from deep water[2] (>100 m water depth and as deep as 2,900 m at Shell Oil's "*Stones*" field

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[1] Regional Organization for the Protection of the Marine Environment (ROPME) Members: Bahrain, Iran (Islamic Republic of), Iraq, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates. Regional Commission for Fisheries (RECOFI) Members: Bahrain, Iran (Islamic Republic of), Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates.

[2] Although Infield (2014) uses 500 ft (152 m) as the divide between shallow and deep water, there is no agreed definition of "deep water". The geomorphic continental shelf break is typically around 100

in the Gulf of Mexico) platforms accounted for about 1 per cent of production in 2000 but this figure had increased to 7 per cent by 2010 and is anticipated to reach 11 per cent of total global production by 2015 (Infield, 2014; Fig. 3).

Over 1,000 offshore oilfields are forecast to be developed between 2011 and 2015, about 80 per cent of which will be in shallow water depths (<100 m). Capital spending on shallow water platforms and pipelines is forecast to grow from an estimated 50 billion United States dollars in 2011 to nearly 60 billion United States dollars by 2015, whereas spending on deep water infrastructure is forecast to rise from 45 billion dollars in 2011 to nearly 80 billion dollars by 2015 (Infield, 2014).

Offshore natural gas production is geographically dispersed: key areas include the North Sea, Gulf of Mexico, Southeast Asia, Australia, New Zealand, Qatar, West Africa and South America. The geographic areas of major investment are (in order of decreasing numbers of projects): the North Sea; Southeast Asian seas; the Gulf of Mexico; Eastern Indian Ocean; and Gulf of Guinea.

In 2001, the United States received 23 per cent of its domestic natural gas from the Gulf of Mexico but by 2013 federal waters of the Gulf of Mexico provided only 5 per cent of United States production (EIA, 2014). The reason is the fracking (hydraulic fracturing) revolution combined with horizontal drilling into tight (i.e. low permeability) geological formations, which has led to a significant increase in the United States' production of onshore shale gas and shale oil such that domestic production will meet US requirements in the short to medium term (until the mid 2020s). Fracking is also employed in some offshore locations (e.g. off southern California).

The southernmost offshore petroleum facilities in production in the world are in gas fields located 70 km offshore Tierra del Fuego, Argentina. These fields are currently producing 15 million cubic metres of gas per day. The offshore platforms are designed to resist the roughest sea conditions and wind speeds of up to 180 km/hr. The northernmost facilities in production are the Prirazlomnoye oil fields, located off the coast of Russia in the Pechora Sea (adjacent to the Barents Sea). The field is estimated to hold 72 million tons of recoverable oil and production is expected to reach six million tons annually. In 2014, some 300,000 tons will be shipped out from waters that are ice-covered for 7-8 months a year (Barents Observer, 2014).

1.3 Exploration

Oil and gas explorers rely on seismic reflection surveys to produce images of the stratigraphy and structure of subsurface rocks. They use this information to determine the location and size of oil and gas reservoirs. Globally, there were about 142 specialized seismic vessels in operation in 2013 (Offshore Magazine, 2013) and each year the Bureau of Ocean Energy Management[3] gives permits for about 20 3-D

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to 200 m in depth (it is around 120 m deep in the Gulf of Mexico between Texas and Florida; Harris et al., 2014), so any rig in water deeper than this is located on the continental slope (deep water).

[3] On October 1, 2011, the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), formerly the Minerals Management Service (MMS), was replaced by the Bureau of Ocean

seismic surveys in the United States Gulf of Mexico. Every seismic vessel tows a seismic source comprising a number of compressed air-guns, and an array of hydrophones in a “streamer” to capture the sound waves reflected from sedimentary layers below. Multi-streamer marine seismic surveys can image the subsurface in 3 dimensions (3-D seismic), acquired by a vessel equipped with between 8 and 16 streamers towed 50 to 100m apart, each 3 to 8 km long. Seismic reflection surveys are not restricted to the exploration phase but may be periodically repeated during the production phase of an offshore field. Once in production, some oil fields are re-surveyed to assess how well the reservoir is drained over time (4-D seismic).

Exploratory drilling is carried out mainly by jack-up rigs, semi-submersibles, or drillships. A jack-up rig consists of a buoyant hull fitted with extendable legs that, resting on the sea floor, are capable of raising its hull over the surface of the sea. There are about 540 jack-up rigs currently in operation globally, normally limited to shallow water (<100 m) drilling.

In order to explore in deep water, either drillships or semi-submersible vessels (also referred to as Mobile Offshore Drilling Units, or MODUs) are used. These vessels must maintain their position over the well to within a percent or so of water depth, requiring either dynamic position capability (using powerful propeller “thrusters”) or anchoring to the seabed. The world fleet of offshore drilling ships currently comprises about 80 vessels of various sizes and capabilities. Semi-submersible vessels are built with ballasted pontoons with tall legs that support a platform. Once on location the pontoons are partly flooded so that they sink below the ocean surface and wave action, while holding the platform at a safe height above the waves. When oil fields were first developed in deep water offshore locations, drilling semi-submersibles were converted for use as combined drilling and production platforms. As the oil industry has progressed into deeper water, purpose-built production semi-submersible platforms were designed. There are currently about 40 semi-submersible, deep-water exploration vessels in operation globally (Offshore Magazine, 2013).

1.4 Social aspects of the offshore oil and gas industry

Over 200,000 people work on offshore rigs and platforms globally, although the exact number is difficult to estimate[4]. In 2011 there were 23,758 core offshore workers spending over 100 nights a year offshore on the United Kingdom’s North

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Energy Management (BOEM) and the Bureau of Safety and Environmental Enforcement (BSEE) as part of a major reorganization (http://www.boemre.gov).

[4] The estimate of over 200,000 offshore workers was derived by adding the number for the North Sea (about 24,000) to the number in the Gulf of Mexico (about 121,000) and multiplying by 1.5 to account for the remainder of the global workforce. It does not include shore-based staff. Another way to estimate the numbers working offshore is to use the average crew numbers (from www.oilpro.com) as follows: (A) 540 jack-up exploration rigs (crew = 55 per rig) total of ~30,000; plus (B) 142 seismic vessels (crew = 80 per vessel) total of ~11,000; plus (C) 80 drill ships (crew = 80 per ship) total of ~6,500. For each crew at sea there is another crew ashore (on leave) so multiply by 2, making over 100,000 personnel in total (oilpro.com), not including shore-based workers or the crews of fixed production platforms.

Sea oil rigs. According to the United States Bureau of Labor Statistics, there were 120,676 people employed in the Gulf of Mexico oil and gas industry in 2009 earning 15.6 billion United States dollars (average income of 129,000 dollars pa). Salaries of offshore oil and gas industry workers have a broad range (Hays, 2013). In Nigeria, expatriate workers are the highest paid in Africa with an average annual salary of 140,800 dollars whereas local workers in Nigeria's oil and gas sector have an average salary of 55,100 dollars (43 times higher than the average annual income in Nigeria, which is 1,280 dollars (World Bank, 2010)). Local oil and gas sector workers have average salaries ranging from 31,100 dollars in Sudan to 163,600 dollars in Australia (Hays, 2013). The average salaries paid to foreign workers are generally higher than local remuneration rates, ranging from 59,800 dollars in Sudan to 171,000 dollars in Australia (Hays, 2013).

Most offshore oil workers spend extended periods, often one or more weeks, at their workplace – usually a production platform or a MODU. They then leave to live at home onshore for a non-work period that is also commonly one or more weeks. The offshore accommodations, recreational facilities and food are provided by their employer, which also provides transportation between the workplace and some onshore "pick-up point", commonly a heliport. This work system is variously called "fly-in", "fly-in/fly-out", "FIFO" or "long-distance commute" employment (Shrimpton and Storey, 2001).

Like other employment systems, this work pattern offers advantages and disadvantages for offshore workers, their families and the communities and regions in which they live. However, it is important to note that there are important limitations to the understanding of offshore employment effects; for example, the research to date has focused on developed countries (mostly Australia, Canada, Norway, United Kingdom and of Great Britain and Northern Ireland and the United States), large operations and companies, fixed work schedules and married male workers.

This work system has implications for various interrelated work and family life issues, the most important of which are Health and Safety and Family Life:

Health and Safety: This includes issues relating to working in a hazardous environment, the remoteness of the operations, the hazardous and stressful nature of the commute, the use of extended shifts and rotations and in some instances the possible risk of abduction by pirates or militants.

Family Life: Offshore commute work presents challenges to family relationships, but these must be assessed in the context of an understanding of the range of advantages and disadvantages that the system can present. As identified by workers and their family members, these are:

- income from offshore work;
- secondary and family employment;
- separation of work and family life;
- access to services and facilities;
- independence and decision-making;

- inappropriate worker behaviour;
- family separation; and
- isolation from and within the community.

However, these advantages and disadvantages are not always experienced in the same ways and to the same degree, with the main factors underlying such variations being differences in the availability of alternative employment, the work environment and workers' experience of it, the regularity and security of employment, family members' experience and expectations of family life, and workers' and spouses' perceptions of the effects on the family.

Various responses and interventions may be appropriate in addressing family life challenges, including those that improve the compatibility of the work organization and family life, improve the compatibility of the work culture and home life, improve self-selection during hiring, help newhires and their families get used to a new work pattern, and provide counselling or other support to employees and family members.

Overall, while research has shown that commute operations have somewhat higher proportions of separated and divorced workers than do conventional ones, it is not clear that this is a direct consequence of the work system, because these workplaces seem to attract separated and divorced employees.

Piracy and abductions: (Kashubsky, 2011) compiled a database of 60 known attacks against maritime and petroleum infrastructure between 1975 and 2010. Out of these incidents, 41 have occurred since 2004, the majority of which have taken place in Nigeria (Kashubsky, 2011). The majority of incidents involved violence (whether actual use of violence or threat of violence), but 15 of 60 incidents (25 per cent) were non-violent.

Since 2006 there have been about 200 abductions in the Niger Delta of foreign workers from offshore platforms, survey vessels and pipe-laying barges. Such abductions are carried out by militant groups, especially the Movement for the Emancipation of the Niger Delta (MEND), whose stated goals are to localize control of Nigeria's oil and to secure reparations from the federal government for pollution caused by the oil industry.

1.5 Communities wholly or mostly dependent upon the offshore hydrocarbon industries

Offshore petroleum activity has had significant, and sometimes dramatic, effects on infrastructure development, education and training, and research and development (Stantec, 2012), primarily focused on such major centres of activity as Aberdeen (United Kingdom of Great Britain and Northern Ireland), Stavanger (Norway), Houston (United States), New Orleans (United States) and St John’s (Canada). Industry activity has also increased the entrepreneurship and competitiveness of local individuals and companies at the local level, and generated population growth, commonly reversing previous demographic trends.

Aberdeen is a good example of the way in which these effects can affect a port city. It receives many benefits from the petroleum industry but there are also “displacement and deterrence effects” on traditional industries (Harris et al., 1988). Displacement sees existing activity being crowded out by new activity, while deterrence sees new activity preventing other activity by making a region unattractive for it. The offshore petroleum industry generated upward pressure on wages and increased the price of housing and office space, although industrial property shortages were avoided due to an increase in warehouse and factory space. The high housing prices deterred outside workers from entering the region for employment.

As a result of these forces, several industries had local growth rates below their national averages, while ones that were already declining saw that decline accelerate. The industries that declined faster than average in the 1970s included: fishing, food and drink, clothing and footwear, building materials, and timber and furniture. Harris et al. (1988) conclude that “for every 100 jobs created by the oil industry in Aberdeen, at least eight jobs have been lost in traditional industries. By 1981, displaced and deterred employment amounted to more than 3,000 jobs. Of this, only about 25 percent has been absorbed by the oil sector.”

This decline of other industries resulted in a higher dependence on the oil industry. Newlands (2000) estimates that, in 1985, 40 percent of Aberdeen’s workforce relied upon oil. He also notes that, in the 1960s, “most businesses in Aberdeen were locally owned and controlled with only a few examples of external ownership [but] a survey conducted in 1984 suggested that the figure had fallen to as low as 11 percent”.

By contrast with the potential negative impacts on traditional sectors of the economy, there may also be benefits for them. Harris et al. (1988), note that “better communications… benefit individuals as well as firms. Indeed, they are just one example of the improvement in the range and quality of services available to people in Aberdeen which has taken place in recent years. There has been a marked increase in the number, variety, and quality of shops and restaurants. There are more entertainment spots such as wine bars, discos and nightclubs. These developments cannot be attributed wholly to the establishment of the oil industry in Aberdeen, but oil developments have undoubtedly influenced the extent and pace of change”. However, such benefits are concentrated in and around major centres of offshore petroleum activity.

Such changes have had significant positive consequences for tourism in Aberdeen, Stavanger, St. John’s and other activity centres. Various studies have shown the industry making a major contribution to tourism through improved air links, meetings, conferences, trade shows, corporate hospitality and the personal expenditures of petroleum industry personnel. Newlands (2000) notes that new hotels opened, and others expanded, in Aberdeen in the 1970s. This increased the number of hotel rooms by 27 percent between 1970 and 1975 and by 58 percent between 1975 and 1980. The number of restaurants rose from 17 to 36. A similar expansion and “cosmopolitanization” of the hospitality, accommodations and hence tourism sectors has been seen in St. John’s (Shrimpton 2002).

Generally speaking, management strategies have limited the negative biophysical environmental and other effects of offshore petroleum activity on Norway, the Shetland Islands, Nova Scotia, Newfoundland and Labrador, which continue to experience rapid growth in tourism, including eco-tourism and adventure tourism.

Harris et al. (1988) also note that: "the maintenance or improvement of services applies also to the public sector. There are better hospital facilities and a larger and more comprehensive educational system than would have been the case had oil developments not reversed the trend of economic decline and emigration from Aberdeen".

Given the nature of the offshore employment system (Section 1.4) it has a number of effects on the communities and regions where the workers live (Shrimpton and Storey, 2001), including those on:

- *Residential Patterns*: The commute system can give workers and their families considerable flexibility as to where they live. Depending largely on the schedule, transportation systems and employee preferences, they may live close to, or distant from, the workplace.
- *Expenditures*: Offshore work wage rates are often high, they are commonly combined with long hours of work and considerable amounts of overtime, and workers generally have few expenses or spending opportunities at the workplace. As a result, these workers generally also have high disposable incomes. Their expenditure patterns, including payment of taxes, are largely dependent on where they live, and can make a significant contribution to the economy of those communities and regions.
- *Non-Commute Employment*: Some offshore employees have secondary paid work while in their home communities. This can involve the use of oil industry work skills and/or involvement in traditional local farming or fishing activity. In the latter case, offshore oil labour and incomes can help sustain the local primary sector.
- *Community Life and Social and Recreational Services*: Offshore work removes some citizens from communities on a part-time basis, affecting their ability to participate in formal and informal social events and networks, including local service groups, sports teams and elected government.

1.6 Description of economic benefits to States

Daily global offshore oil production is currently about 28 million barrels (Fig. 3), which is worth between 1.4 billion dollars and 2.8 billion dollars per day (assuming 50 dollars and 100 dollars per barrel). Oil and gas production from the United Kingdom continental shelf (for example) has contributed 271 billion United Kingdom pounds (2008 money) in tax revenues over the last forty years. In 2008, tax rates on United Kingdom continental shelf production ranged from 50 – 75 per cent, depending on the field. The industry paid 12.9 billion pounds in corporate taxes in 2008-9, the largest since the mid-1980s, because of high oil and gas prices. This represented 28 per cent of total corporation tax paid in the UK. In addition to production taxes, the supply chain contributes another 5-6 billion pounds per year in corporation and payroll taxes (UK National Archives, 2013).

In Australia, from 1999 to 2013, the offshore petroleum industry has contributed over 21.9 billion Australian dollars in petroleum resource rent tax in addition to corporate taxes (data.gov.au, 2014).

The offshore oil and gas industry accounts for about 1.5 per cent of United States GDP, 3.5 per cent of the United Kingdom's GDP, 12 per cent of Malaysia's GDP, 24 per cent of Norway's GDP and 35 per cent of Nigeria's GDP (OPEC, 2013; EIA, 2014). In Norway, crude oil, natural gas and pipeline transport services accounted for about 100 billion dollars in 2010, nearly half of the value of Norway's total exports and 10 times higher than the export value of fish (Norwegian Petroleum Directorate, 2012). In Nigeria crude oil export was valued at around 94 billion dollars pa and accounts for about 70 per cent of total exports revenue (OPEC, 2013 figures). Thus the overall value of the offshore oil and gas industry accounts for a significant part of GDP but varies dramatically among countries in terms of its overall importance.

Offshore petroleum activity can have a range of other impacts, some of them negative, on the local economy. Some early literature described negative effects on the local economy. For example, Galenson (1986) argues that Norway's performance in curbing inflation was less than it might have been without oil revenues, and that they allowed the government to pursue policies that harmed manufacturing: “Oil money was used to preserve the existing pattern of industry. The restructuring necessary to meet changing market demands was slowed, if not stopped. New initiatives were not encouraged”. Mallakh et al. (1984) and Noreng (1980) argue that one of problems was that Norwegian government policy prevented labour from moving to more productive firms and sectors. It was not only prevented from moving to and from manufacturing, but from less to more productive uses within manufacturing.

However, petroleum taxes and royalties can help address the challenges posed by the fact that the sector is cyclical and involves a non-renewable resource, meaning that the state's revenue from it can be highly volatile. In 1990, Norway established a government pension fund to transfer capital from the state's petroleum revenue. The fund was designed to be invested for the long term, but in a way that made it possible to draw on when required. Its purpose is to support the government's long-term management of the petroleum revenues. The fund gives the government room for manoeuvring in fiscal policy should oil prices drop or the mainland economy contract. This facilitates economic stability and predictability. The fund also serves as a tool to manage the financial challenges of an ageing population and an expected drop in petroleum revenues.

There is growing interest, globally, nationally and locally, in creating sustainable economic development. Notwithstanding the fact that the offshore petroleum industry activity involves large technologically-complex projects and the exploitation of a non-renewable resource, the evidence from Canada, Norway, the United Kingdom, and other States indicates that it has been the engine for significant and sustainable (over many decades) economic development in a number of jurisdictions on both sides of the Atlantic. This is partly because it can make a major contribution to output, income, employment and government finances. Such activity has often also had a transformative effect, by helping to enhance the productive capacity of the economy through stimulating growth in the quantity and quality of factor inputs to the production process, thereby contributing to sustainable long-term economic development.

1.7 Emerging technologies and potential for future developments

An example of an emerging technology relevant to offshore oil and gas facilities is the design of structures that could be deployed on the seafloor (rather than floating). Equipment that can be fixed directly to the sea floor, where it is relatively protected from ice and violent weather, could be used for subsea produced water removal and re-injection or disposal, single-phase and multi-phase boosting of well fluids, sand and solid separation, gas/liquid separation and boosting, and gas treatment and compression (Sorenson, 2013). Re-injection of produced gas, water and waste increases pressure within the reservoir that has been depleted by production. Also, re-injection helps to decrease unwanted waste, such as flaring (because the gas that would have been flared is re-injected), by using the separated components to boost recovery.

Disadvantages of robotic (unmanned) seafloor mounted facilities include difficulties in monitoring their operation and implementing any necessary repairs. The 2010 Deepwater Horizon (DWH) underwater spill in the Gulf of Mexico took months to bring under control, partly because of the challenges imposed by the water depth of the structure. The added complications that would arise in an Arctic setting, where repairs may have to be undertaken in winter months beneath floating sea ice, are factors that any such operations would need to address.

Another new technology is Floating Liquefied Natural Gas (FLNG) production where the processing of gas from offshore fields takes place at sea. The world’s first FLNG vessel, Shell’s Prelude, is currently under construction in the Republic of Korea for deployment on Australia’s North-West Shelf. The LNG plant will be located on a large vessel that will be moored above the gas field – several hundred kilometres from the coast. The successful deployment of FLNG may allow for the production of gas from smaller or more remote offshore fields (Geoscience Australia and BREE, 2012).

A potential future development in the offshore energy sector is the possibility of mining methane gas hydrates from seabed deposits. Methane clathrate, also called methane hydrate, is composed of methane trapped within the crystal structure of water, forming a solid similar to ice, found in seabed sediments in water depths of greater than 300 to 500 m (Ruppel, 2011). When brought to the earth's surface, one cubic metre of gas hydrate releases 164 cubic metres of natural gas. Methane that forms hydrate can be both biogenic, created by biological activity in sediments, and thermogenic, created by geological processes deeper within the earth. A conservative estimate (Boswell & Collett 2011) for the global gas hydrate inventory is ~1,800 gigatons of carbon. While global estimates vary considerably, the energy content of methane occurring in hydrate form is immense, possibly exceeding the combined energy content of all other known fossil fuels. However, methane production from hydrate has not been documented beyond small-scale field experiments and its contribution to global gas supply has probably been delayed by several decades by the increasing development of onshore gas resources from shale, coal seams and other unconventional deposits (Geoscience Australia and BREE, 2012).

2. Environmental impacts from exploration, including seismic surveys, offshore facility development and decommissioning

2.1 Environmental impacts

Environmental impacts arise throughout petroleum exploration-drilling-production development operations as well as in the decommissioning of facilities once the oil field is no longer economic, although the nature and degree of impact varies (Swan et al., 1994). Seismic surveys, oil and gas production, transportation and decommissioning all have associated environmental impacts; these are described briefly below.

The risks of impact from oil spills are greatest during transport, from pipeline rupture and vessel loss or spillage, when large volumes of oil can be released suddenly. It is important to realize that accidental (anthropogenic) spills occur against a background of continuous leakage from the seafloor. Crude oil is a naturally-occurring substance. An amount of oil approximately equal to that spilled accidentally by humans enters the oceans each year through natural seepage (Kvenvolden and Cooper, 2003; National Research Council, 2003). Natural seepage is a gradual, ongoing process and ecosystems have evolved that use it as a food source. Spills are ecologically damaging because they result in unnatural concentrations of oil at a particular site that are incompatible with local marine life.

Also it should be noted that accidental oil spills account for only a small percentage of the total volume of oil that enters the oceans due to humans. Most oil enters the ocean mixed with sewage and urban stormwater runoff (GESAMP, 2007) but such diffuse sources do not have the same dramatic impact on ecosystems as a spill because the oil is delivered continuously in low concentrations over a broad area. The long-term effects of low-level oil pollution from diffuse sources are unknown (GESAMP, 2007).

2.2 Drilling and production activities

Drilling activities are carried out from ships or fixed platforms during exploration and to extract oil once it has been found. Direct damage to the seafloor is caused by the anchors used to hold the rig in place as well as by the impact of the well emplacement itself. Drilling requires the use of lubricant (drilling mud) and the disposal of drill cuttings onto the seabed at the drill site. Drilling mud and some of the drill-cuttings contain crude oil residues, polycyclic aromatic hydrocarbons (PAHs) and heavy metals that can be toxic. The environmental impacts of drilling may include smothering the seabed by blanketing it with dense drilling mud and cuttings and toxicity effects (Swan et al., 1994). The initial impact is generally confined to the immediate surrounds, typically within 150 m of the drill site. However, Olsgard and Gray (1995) reported that barium, total hydrocarbons, zinc, copper, cadmium and lead contamination sourced from production platforms on the Norwegian shelf had spread considerably after a period of 6 to 9 years, so that evidence of contamination was found 2 to 6 km away from the platforms. This led to a ban in the North Sea on discharging oil-based muds or cuttings contaminated with them from 1993. The ban gradually decreased the affected zone around drilling installations from several km to approximately 500 m (Bakke et al., 2013).

During the production of oil and gas, water from the hydrocarbon reservoir is also brought to the surface. This is known as “produced water” (PW), is a by-product of oil production and it is either disposed of into the ocean or may be re-injected into the well to promote oil recovery (Swan et al., 1994). Produced water can also include sea-water injected into the well to promote recovery. Compared with ambient seawater, PW may contain elevated concentrations of heavy metals (e.g. arsenic, mercury, barium, copper, lead and zinc), radium isotopes, as well as hydrocarbons. The proportion of oil/water varies between locations but generally the proportion of water increases over time as the oil deposit is depleted (i.e. older wells discharge more PW than new wells). The proportion of water produced per barrel of oil typically ranges from around 3:1 to 7:1 although the relative amount of PW increases over time, such that in extreme cases the fluid pumped from a well might be 98 per cent water and only 2 per cent oil (Holdway and Heggie, 2000). At the production platform, most of the PW is separated from the oil, treated (typically to around 30 mg/L hydrocarbon) and disposed of into the ocean. Because the increase in the absolute amount of PW discharged leads to an increase in the absolute amount of oil discharged, unless the proportion of oil in the PW discharged is decreased, regulatory measures have been adopted in some areas, such as the North Sea, which have resulted in reductions between 2001 and 2006 of around 33 per cent in the amount of oil discharged in PW (OSPAR Decision 2001/1; OSPAR 2010).

PW forms a buoyant plume because it is typically 40° to 80°C warmer (and therefore less dense) than ambient seawater and thus it will be dispersed by wind and currents away from the production platform. Mixing and dilution with seawater results in toxic effects of PW being generally confined to within 1 km of production platforms, although PW plumes may be detected in surface waters for distances exceeding 10 km from the point source (Jones and Hayward, 2003). Cases of coral discolouration (coral bleaching) have been attributed to dilute (~12 per cent) PW concentrations (ITOPF, 2007). Hence, the situation of production platforms in relation to prevailing winds and currents and to the proximity of sensitive habitats is a consideration for offshore petroleum development.

There are additional environmental consequences of the emplacement of rigs and floating platforms into the marine environment, which include effects on migratory birds and artificial habitat. Electric lights used on the rigs have been shown to interfere with the natural migration pathways of some species of birds, causing them to accidently collide with platform structures. Although the actual numbers of birds killed due to having collided with platforms is unknown, modelling has shown that the numbers could be significant (OSPAR, 2012b). Any seafloor disturbing activities such as anchor placement and retrieval, drilling, construction and decommissioning activities, and jetting into the seafloor for pipeline trenches has the potential to disturb or cause permanent and irreversible damage to natural and cultural resources. Underwater cultural heritage such as shipwrecks and submerged prehistoric sites are especially vulnerable to seafloor disturbing activities as these resources are finite and each site is unique. Natural resources such as coral reefs, fish habitat, and deepwater chemosynthetic communities can also be impacted by these activities. In order to reduce the risk of damage in United States waters, the United States Bureau of Ocean Energy Management (BOEM) requires the operator to conduct high-resolution geophysical surveys to identify potential resources before the operator can receive their permit and commence seafloor disturbing activities.

Once in place, the legs (jacket) of an offshore platform become habitat for some species of fish and sessile marine biota and can create a local area of elevated biomass and biodiversity. This is because access to the immediate area around the platform is restricted for reasons of safety such that the platform creates a zone that acts as a de facto marine reserve. In addition, the steel structure provides a hard substrate for colonization that would otherwise not be present, thus artificially increasing the local biodiversity (Page et al., 1999; Shaw et al., 2001; Whomersley and Picken, 2003).

Over the lifespan of a platform, shell debris derived from molluscs that colonize the platform legs accumulates at the base of the platform. The shell accumulation is draped over drill cuttings (described above) forming a characteristic, mound-shaped deposit. The shell drape provides a new habitat that has different properties from the surrounding seabed and thus offers habitat to different species. Disturbance of the shell drape will expose the (potentially toxic) drill cuttings that are a factor for consideration for rig decommissioning.

Because of the biological colonization of MODUs, the relocation of the vessel between drilling locations has been identified as a vector for the introduction of non-native species (Paula and Creed, 2005; Sammarco et al., 2010).

2.3 Seismic surveys and their impact on marine mammals and other ocean life

Marine acoustic survey equipment is used by the oil and gas industry as well as by the military, marine industries and academic researchers to map the seafloor, study the sediments beneath the seafloor and image the water column. Depending on the purpose, sonars differ in frequency, source level and beam pattern. Sonar signals diminish as they propagate, affecting different parts of the water column with different biological consequences. Towed, low frequency systems (such as seismic air guns) are omni-directional, radiating sound in all directions. Hull-mounted systems are higher frequency (kHz or greater) and utilize beam forming to obtain higher resolution images at lower source levels.

Airguns employed to acquire seismic reflection data are far more powerful (225 to 255 decibels re 1 micro-Pascal peak; Richardson et al., 1995) than equipment used for marine research or normal ship navigation. Airguns used in seismic reflection surveys emit sound at a frequency of typically ~100 Hz which overlaps with the range of marine mammals' hearing and is therefore most likely to affect marine mammals and other marine life (McCauley et al., 2000; O'Brien et al., 2002; NRC, 2003; Boebel et al., 2005; Nowacek et al., 2007; 2013; CBD, 2014).

Cetaceans have been observed avoiding powerful, low frequency sound sources. A study by McCauley et al (2000) has shown that migrating humpback whales will leave a minimum 3 km gap between themselves and an operating seismic vessel, with resting humpback whale pods (groups) containing cows exhibiting increased sensitivity and leaving an increased gap of 7–12 km. Conversely, the study found that male humpback whales were attracted to a single operating airgun as they were believed to have confused the low-frequency sound with that of whale breaching behaviour. In addition to whales, sea turtles, fish and squid all showed alarm and avoidance behaviour in the presence of an approaching seismic source. While there has not been any documented direct linkage between seismic surveys and the beaching of marine mammals, Gordon et al., (2004) noted that concerns over the stranding of beaked whales in two separate incidents was sufficient for United States courts to agree to a restraining order on seismic operations by the RV *Maurice Ewing*. Nowacek et al. (2007) noted that displacement (relocation to an un-impacted area) is a common response of mammals, which may cause harm if the impacted site is an important feeding ground (see also Cerchio et al., 2014). Lucke et al (2009) found that harbour porpoises consistently showed aversive behavioural reactions at received sound pressure levels above a certain threshold level produced using a seismic airgun.

The historical record of cetaceans stranding themselves prior to the industrial age includes the English Crown holding rights on stranded cetaceans from at least 1324, when they were known as "fishes royal" since the Crown had first claim on them (Fraser, 1977). Thus cetacean stranding occurs under natural environmental conditions. Additional evidence in support of this conclusion is the occurrence of marine mammal strandings within the geological record (Pyenson et al., 2014).

It is not known whether there has been any increase in whale strandings that can be attributed directly to seismic surveys. Nowacek et al. (2007; 2013) conclude that major data deficiencies are: the lack of studies linking animal responses to received acoustic level data; gaps in species representation; and poor understanding of habituation, sensitization and tolerance. In the case of marine animals other than cetaceans, there is some evidence for short-term displacement of seals and fish by seismic surveys, but there is little literature available (Thompson et al., 2013; see also Chapter 37).

2.4 Pipeline construction, main causes of leaks and decommissioning

In order to bring oil and gas ashore to refineries and transport systems, pipelines are laid across the seabed, in places forming complex networks (Fig. 2).[5] Before a pipeline can be laid, the proposed route is surveyed using acoustic seabed mapping technology and underwater cameras to identify any obstacles such as natural bedrock formations, boulders, seabed valleys or migrating sand dunes as well as

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[5] The following summary of pipeline construction is based primarily on Palmer and King (2004).

shipwrecks, other cables and pipelines and dumped ammunition. The pipe is then laid along the surveyed route using either a specialised pipe-laying vessel or else a pull/tow system where the pipeline is built onshore and then towed by ship to its desired location. The first process usually involves one pipe-laying vessel supported by barges that supply the ship with pipe sections plus other support ships that monitor the seabed. Pipe sections are welded together on board, the joints tested (by ultrasound) and the pipe coated with an anticorrosion application.

The diameter of the pipe varies between 0.15 to 1.4 m, but is ~0.3 m in most cases. A distinction is made between a flowline and a pipeline. Flowlines are intrafield pipelines used to connect subsea wellheads, manifolds and the platform within a particular development field. Pipelines (export pipelines, also called trunk lines) are used to bring the resource to shore.

Problems that affect the stability and integrity of submarine pipelines are: (1) expansion/contraction of the steel pipe causing lateral or upheaval buckling; (2) erosion of the seabed around the pipeline by storms, waves and currents leaving unsupported spans of pipeline vulnerable to fracture; and (3) corrosion. Solutions to the expansion/contraction problem are: adding expansion joints; burial; anchoring; applying a concrete or rock cover; or laying the pipe in an “S”- shaped configuration (S-lay). Problems of seabed erosion can be overcome by burial (Xu et al., 2009; Yang et al., 2012). Burial of the pipeline is also required in areas where vessels might anchor, where bottom fishing activities occur or where the pipeline crosses the shoreline. However, burial is more expensive than simply laying the pipeline along the seabed, so it is not used unless necessary (or a legal requirement).

Pipelines are maintained and inspected using a “pig,” a tool that can be inserted in one end of the pipeline and pushed by the fluid to the other end. The most basic pigs are used to clean the inside of the pipes; highly-complex “smart pigs” can inspect the condition and thickness of the pipeline and detect points of corrosion or fracturing. Smart pigs are used more in the North Sea than in the Gulf of Mexico because the majority of existing Gulf of Mexico lines were not originally designed or built to accommodate smart tool pigs (MSL, 2000).

Pipelines are monitored for leakage by analog and computer-assisted systems (Stafford and Williams, 1996). The mass balance approach simply measures the amount of oil going in the pipeline and the amount coming out. Real-time transient modelling compares actual measured data with a computer model. If the results are outside normal operating limits, an alarm alerts the operator to take appropriate action. Other methods of monitoring pipelines include chemical and radioactive tracers, acoustic emission, neural networks, fibre-optic sensors and pressure point analysis (Stafford and Williams, 1996).

Woodson (1990) compiled a database of 1,047 submarine pipeline failures reported in the Gulf of Mexico between 1967 and 1990. The results indicate that a pipeline failure occurred in the Gulf of Mexico on average once every 5 days over the period of data collection. The source of failure was reported in 916 incidents in which the main causes were attributed as follows: 50 per cent (456 out of 916 incidents) due to internal or external pipeline corrosion; 12 per cent (106 incidents) due to storms and hurricanes; 14 per cent (124 incidents) due to damage from ship’s anchors and fishing gear; 10 per cent (94 incidents) due to material failure of valves, gaskets or other joints; and 15 per cent (136 incidents) due to other or unknown causes. Pipelines over 10 years in age had a greater number of failures due to corrosion than younger pipelines; there was a trend of an increasing rate of failure due to corrosion in the last 5 years of the database (1986-1990), presumably attributable to the aging of the pipeline network. Pipelines damaged by storms (in which pipes are excavated by waves and currents exposing an unsupported span that is liable to fracture) were not buried in 40 out of 52 cases (Woodson, 1990).

In its review of offshore pipeline safety, the United States Marine Board Committee on the Safety of Marine Pipelines (Marine Board, 1994) cited the work of Woodson (1990) and noted that during the 1990s, transmission and production pipeline leakage and accidents accounted for about 98 per cent of accidental releases by offshore production activities. However, although corrosion is the most commonly cited cause of pipeline failure, corrosion-related ruptures do not result in significant release of oil into the environment. Rather, damage caused by a few major incidents involving ship's anchors caused pipe leakage that is attributed to 95 per cent of the 250,000 barrels that leaked from pipelines in the Gulf of Mexico from 1967 to 1990 (Marine Board, 1994).

The National Research Council (NRC) (1997) noted that, in the United States Gulf of Mexico "no agency coordinates the collection of information and the available data on offshore pipeline failures are correspondingly "incomplete". Data on pipeline failures from state waters are collected by states (when collected) and may not be readily accessible. This is in spite of the fact that pipelines in state waters are commonly the oldest and most exposed to collision with ships (Marine Board, 1994). Since 2006, data on offshore pipelines (outside of state waters) has been the responsibility of the Bureau of Safety and Environmental Enforcement (BSEE).

In Europe, a pipeline data base complied by PARLOC (2001) includes records from 1971 to 2000 during which time there were 542 pipeline incidents including 96 pipeline leaks into the environment plus 92 leaks of pipeline fittings. The cause of failure of pipeline fittings is not recorded (PARLOC, 2001); for pipelines the database shows that corrosion is the major cause of failure (51 per cent) followed by maritime actions such as anchoring (23 per cent), material failure and other or unknown causes (26 per cent).

Less than 2 per cent of the North Sea pipeline inventory has been decommissioned as of 2013 (Oil and Gas UK, 2013). Of North Sea pipelines that have been decommissioned, 80 per cent are less than 16 inches (40.64 cm) in diameter. Half of the larger diameter pipelines (16 inches (40.64 cm) or greater) decommissioned to date were removed (i.e. 10 per cent of decommissioned pipelines were removed). Cleaning and purging is carried out following cessation of production, pipeline system depressurisation and removal of bulk hydrocarbons. Cleaning involves chemical cleaning to detach hydrocarbon residue from the pipe wall and bi-directional magnetic, disc and brush cleaning to remove ferrous and other loose debris using a specialist pig (Oil and Gas UK, 2013; see also Chapter 20).

The Gulf of Mexico offshore oil and gas has been operating since 1936 (Owen, 1975) and more of the pipeline infrastructure has been retired than in other parts of the world. Rach (2013) reported, based on data from the United States Bureau of Safety and Environmental Enforcement, that the inventory of Gulf of Mexico pipelines (as of mid-2013) includes 24,126 miles (38,827 km) that are in active use, 2,409 miles (3,877 km) proposed for installation, 12,628 miles (20,323 km) that have been abandoned, 2,264 miles (3,643 km) proposed to be abandoned and 2,425 miles (3,902 km) of pipeline that are out of service. Thus 42 per cent of existing (66,695 km) pipelines in the Gulf of Mexico are either abandoned, proposed to be abandoned or are no longer in service.

Apart from leakage of oil, other environmental and economic consequences of abandoned pipelines are their impacts on fishing (inhibiting bottom-trawling), other pipe and cable-laying activities and creating artificial habitats.

2.5 Rig decommissioning, dismantling and disposal, "Rigs to Reefs" programme

In its assessment of environmental governance in 27 developing countries, the World Bank (2010) found that governments lack a policy and process for decommissioning and abandonment and do not routinely assess, determine, or assign the future liability costs of decommissioning and abandonment. Only about 50 per cent of countries have an established process for managing the decommissioning and abandonment of oil and gas projects. Disposal of man-made structures (including platforms) at sea and abandonment or toppling on site of man-made structures falls under the scope of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (1972 London Dumping Convention) (LDC) and the1996 London Protocol (LP). These treaties are global agreements and provide relevant dumping management policies, provisions, and assessment guidelines (London Convention and Protocol/UNEP, 2009). The 1989 International Maritime Organization (IMO) guidelines provide for the removal of offshore installations in order to leave 55 metres of clear water over any remains left in place (IMO, 1989).

In the United States, the BSEE has jurisdiction over decommissioning of wells and structures, pipelines, and the so-called "Rigs-to-Reefs" program. The Rigs-to-Reefs programme is the practice of converting decommissioned offshore oil and gas rigs into artificial reefs, which has occurred mostly in the Gulf of Mexico. However, less than 10 per cent of rigs decommissioned in the Gulf of Mexico have so far been converted to reefs; 90 per cent are removed (The Economist, 2014; BSEE data). Apart from a few platforms converted to reefs in Brunei Darussalam and Malaysia, opposition to the practice has meant that none have been allowed off California or in the North Sea to date (Day, 2008; Macreadie et al., 2011, 2012; Jørgensen, 2012). In the North Sea, 122 decommissioned installations were brought ashore between 1999 and 2010, and four large concrete installations and the footings of one large steel installation have been left in place (OSPAR 2010). One estimated cost of removing the existing North Sea production platforms, in the United Kingdom sector alone, was over 14 billion dollars (Prince, 2004). About 60 rigs are nearing the end of their working life in Australia (Macreadie et al., 2011).

The BSEE has granted permits for about 420 platforms to be converted to artificial reefs in the Gulf of Mexico. There are three methods for converting a non-producing platform into an artificial reef: (1) partially remove the platform; (2) topple the platform in place; or (3) tow-and-place the platform to one of about 28 sites designated as an artificial reef area. Partial removal typically relies on non-explosive means to cut the platform below the sea surface, leaving the legs in their vertical position. Toppling in place uses non-explosive or explosive severance to cut the platform from its legs and lay the platform legs on their side (the platform itself is removed). The tow-and-place method entails removing the platform and detaching the structure from the seafloor before towing it to a designated artificial reef area for disposal.

In the United States Gulf of Mexico there were about 2,996 production platforms as of March 2013, of which 813 (27 per cent) are no longer producing. In 2010, the United States Government issued notices to companies requiring them to set permanent plugs in nearly 3,500 nonproducing wells and dismantle about 650 unused oil and gas production platforms (Rach, 2013). Decommissioning means ending operations and returning the lease or pipeline right-of-way to a condition that meets the requirements of regulations of BSEE and other agencies that have jurisdiction over decommissioning activities. The regulations apply to any installation, other than a pipeline, that is permanently or temporarily attached to the seabed. Very few deep sea (>200 m depth) oil and gas fields have as yet been depleted, hence decommissioning of infrastructure has not yet become an issue (Macreadie et al., 2011).

Regulations for the decommissioning of a platform vary between countries. The United States requires plugging the well(s) supported by the platform and severing the well casings 15 feet (5 m) below the seabed; cleaning and removing all production and pipeline risers supported by the platform; removing the platform from its foundation by severing all bottom-founded components at least 15 feet (5 m) below the seabed; disposing of the platform onshore or placing the platform at an artificial reef site; and cleaning the platform site to ensure that no debris or potential obstructions remain. Over the lifespan of a platform a mound of debris accumulates beneath the platform that may contain toxic chemicals; removal of such mounds is also a requirement for decommissioning.

In the North Sea, OSPAR Decision 98/3 requires the topsides of all decommissioned installations to be removed to shore and all sub-structures or jackets weighing less than 10,000 tons to be completely removed. The regulations stipulate that, where there may be practical difficulty in removing installations (i.e. the footings of large steel platforms weighing over 10,000 tons, the concrete gravity based platform sub-structures, or concrete anchor bases and other structures with significant damage or deterioration, which would prevent removal), a decision may be taken to leave parts of the structure on the seabed, on a case-by-case basis.

3. Offshore installation disasters and their impacts, including longer-term effects.

3.1 Impacts of offshore installation disasters

Impacts of offshore oil and gas installation disasters include loss of human life, loss of revenue and environmental impacts. Offshore disasters have resulted in loss of life on several occasions in the history of the offshore oil and gas industry. In March 1980, the “flotel” (floating hotel) platform Alexander L. Kielland capsized in a storm in the North Sea with the loss of 123 lives. In February 1982, the Ocean Ranger semi-submersible mobile offshore drilling unit sank on the Grand Banks of Newfoundland; none of the 84 crew members survived. In July 1988, 167 people died when Occidental Petroleum's Piper Alpha offshore production platform exploded in the United Kingdom sector of the North Sea after a gas leak. In 2001 Petrobras-36 in Brazil exploded and sank five days later killing 11 people. In April 2010, the Deepwater Horizon platform exploded, killing 11 people. The Kolskaya floating oil rig capsized and sank in the Sea of Okhotsk in December 2011, killing 53 crew members. In December, 2013, a rig owned by Saudi Arabia's state-run petroleum company, Aramco, sank in the ROPME/RECOFI area, killing three crew members. Such disasters have resulted in the imposition of new regulations on industry (Turner, 2013); for example, the Piper Alpha disaster resulted in the United Kingdom Government passing the 1992 Offshore Installations (Safety Case) Regulations. However, there have been subsequent disasters around the world and the industry, as a whole, has continued to make the changes needed to improve its safety record (Harris, 2013).

From 2001 to 2010, the United States Minerals Management Service reported 69 offshore deaths, 1,349 injuries, and 858 fires and explosions on offshore rigs in the Gulf of Mexico. During 2003–2010, the United States oil and gas extraction industry (onshore and offshore, combined) had a collective fatality rate seven times higher than that for all United States workers (27.1 versus 3.8 deaths per 100,000 workers; Centers for Disease Control and Prevention, 2013). Catastrophic events attract intense media attention but do not account for the majority of work-related fatalities during offshore operations. A report by Baker et al. (2011) found that helicopter crashes were the most frequent fatal event in this industry.

Economic impacts stemming from offshore oil and gas installation disasters include the direct loss of income for the period that the facility remains offline, the costs to repair the facility, the costs to other industries (e.g. fishing and tourism) affected by the disaster and other compensation. As a result of the Deepwater Horizon oil spill, BP established a Trust Fund of 20 billion dollars for natural resource damages, state and local response costs and individual compensation. Other industry-wide consequences may follow such disasters. For example, exploration drilling in the Gulf of Mexico was slow to recover from the moratorium that followed the Deepwater Horizon oil spill in 2010. By 2012 36 rigs were back working off Louisiana and 4 off Texas, compared with 21 and 2, respectively, in late 2010. On 3 June, 2008, a high-pressure 12 inch export sales gas pipeline (SGL), critically weakened by a region of external corrosion, ruptured and exploded on the beach of Varanus Island off the coast of Western Australia. There was approximately 60 million Australian dollars in damage to the plant. Plant closure led to up to 3 billion dollars of losses to the West Australian economy, which lost 30 per cent of its gas supply for two months.

A blowout of the Montara wellhead platform on 21 August 2009, on Australia's remote North-West Shelf, leaked an estimated 30,000 barrels of crude plus an unknown quantity of gas until 3 November 2009 (total of 74 days), when the leak was finally stopped. The rig later caught fire but all 69 workers on the rig were safely evacuated with no injuries or fatalities. The company spent about 5.3 million Australian dollars on clean-up, about 300 million dollars in lost revenue and repair bills and was fined 510,000 dollars in August 2012 by the Australian Government (ABC News, 2012); the well finally went into production in June, 2013. However, fishermen and seaweed farmers in Indonesia are seeking compensation with support from the Australian Lawyers Alliance (ALA), claiming that environmental damage caused by the spill has cost them more than 1.5 billion dollars per year in lost earnings (ALA, 2014).

In 1980, within the ROPME/RECOFI area, the Hasbah Platform Well 6 blew out for 8 days, spilling 100,000 barrels of oil and costing the lives of 19 men. However, the worst disaster in the region occurred during the 1991 war between Iraq and Kuwait, when there were 22 incidents that spilled amounts of oil variously estimated at between 2 and 11 million barrels into the ROPME/RECOFI area (Khordagui and Al-Ajmi, 1993; Elshorbagy, 2005). The coast of Saudi Arabia was the most heavily impacted by the spill. Initial assessments of the environmental damage caused by the spilled oil were optimistic of rapid recovery (e.g. Fowler et al., 1993), but more recent studies have documented lingering effects of oil trapped in intertidal sediments and salt marshes over broad spatial scales (Michel et al., 2005; Barth, 2007). As of 2011, the Government of Saudi Arabia had invested 180 million United States dollars and the United Nations had spent U45 million dollars in rehabilitating impacted areas.

Natural disasters also take a toll on offshore oil and gas facilities. In August 2005, Hurricane Katrina affected 19 per cent of United States oil production by destroying 113 offshore oil and gas platforms, damaging 457 oil and gas pipelines, and spilling an unquantified amount of oil (http://www.bsee.gov/Hurricanes/2005/katrina/).

Environmental consequences of offshore oil and gas installation disasters are perhaps the most widely publicized aspect of such events. In the 2010 Deepwater Horizon (DWH) Gulf of Mexico oil spill, it is estimated that around 4.9 million barrels (about 670,000 tons, assuming a specific gravity of 0.88) was discharged into the sea before the well was capped, approximately 16 times more oil than was spilled by the Exxon Valdez in 1989 (about 37,000 tons of crude oil; Crone and Tolstoy, 2010; Oil Spill Commission, 2011). The impact of this huge volume of oil on deep water habitats in the Gulf of Mexico is unknown at the time of this writing (April, 2014). Prior to the DWH incident, the total volume of oil spilled in the Gulf of Mexico between 1964 and 2009 is estimated to be 517,847 barrels (Mufson, 2010).

Numerous smaller-sized spills have also occurred in recent years. Examples include a North Sea spill of 200 tons in August 2011 that occurred at Shell's platform Gannet

Alpha; in 2012 Chevron suspended activities after two oil leaks (of around 5,000 barrels) occurred in a space of four months off the Brazilian coast; in March 2012 the platform Elgin-Franklin, operated by the Total group in the North Sea, was evacuated after an uncontrollable gas leak of an estimated 300 million cubic feet over a 45 day period (Beall and Ferreti, 2012).

The number of accidents reflects the massive scale of the offshore drilling and production enterprise. For every accident there are environmental consequences. Before the Deepwater Horizon accident, such major incidents were anticipated to occur with such extreme rarity that they were not considered relevant. One explanation could be that risk assessments are performed for single wells and not for whole areas (or on an industry-wide basis). However, a study of accidental oil spills based on global historical data has shown that the DWH accident was not an outlier, but an accident that can happen every 17 years with an uncertainty interval from 8 to 91 years (5−95 per cent). When the DWH accident was excluded from the data set, the resulting frequency was 23 years with an uncertainty interval from 10 to 177 years (Eckle et al., 2012).

Accidents that occur in coastal waters have the most severe environmental impact. Most oil floats on the sea surface where it can be readily delivered to the shoreline, where the concentrated consequences are evident. The coast is also a habitat for a diversity of species of birds, mammals, invertebrates and marine plants. For this reason spills that impact the coast, such as the Exxon Valdez spill that occurred in Alaska in 1989, have the greatest impact on the ecosystem (Shaw, 1992). The speed of ecosystem recovery is generally slower for colder and deeper habitats than it is for warmer and shallower habitats (Harris, 2014). However, every ecosystem is different and recovery times are difficult to estimate. For example, oil spilled in the Niger Delta over the last 50 years has penetrated up to 5 m into the soil profile and caused groundwater contamination in 8 out of 15 sites investigated that could take up to 30 years to clean up (UNEP, 2011).

3.2 Impact of oil spills on the marine ecosystem

The impacts of oil spills range from the immediate effects of oiling to longer term consequences of habitats being modified by the presence of oil and tar balls. Traces of hydrocarbons can remain in coastal sediments for many years after an oil spill (Hester and Mendelssohn, 2000). For example, for some of the rocky shores where oil stranded after the Exxon Valdez spill in 1989, oil is still found subsurface, only slightly weathered (Irvine et al., 2014). Similarly, oil from the 1991 Gulf War is still apparent in intertidal sediments and in salt marshes along the coast of Saudi Arabia (Michel et al., 2005; Barth, 2007).

There is no clear relationship between the amount of oil spilled in the marine environment and the likely impact on wildlife. A smaller spill at a particular season of the year and in a sensitive environment may prove much more harmful than a larger spill at another time of the year in another or even the same environment. Even small spills can have very large effects. Species that use the sea surface are most vulnerable (birds and mammals) and the eggs and larvae of many other species can be damaged by oil (Alford et al., 2014).

Some species may exhibit reduced abundance due to spills (Sánchez et al., 2006) although direct causal evidence is not always available (Carls et al., 2002). Some opportunistic species are able to take advantage of the changed habitat conditions and the attendant reduced abundance of impacted species, giving rise to a short-term increase in local biodiversity (Edgar et al., 2003; Yamamoto et al., 2003); this is an example of why biodiversity statistics alone are not a reliable indicator of environmental health. Recovery time for sites varies as a function of the type of oil spilled, the biological assemblage impacted, substrate type, climate, wave/current regime and coastal geomorphology and ranges from years to decades depending on these and other factors (Ritchie, 1993; Jewett et al., 1999; French-McCay, 2004).

There are a number of pathways for oil to reach the oceans, namely:

- Land-based sources (urban runoff, coastal refineries);
- Oil transporting and shipping (operational discharges, tanker accidents);
- Offshore oil and gas facilities (operational discharges, accidents, blow-outs);
- Atmospheric fallout;
- Natural seeps.

Figures published by National Research Council (2003) range from an average of 470,000 tons to a possible 8.4 million tons per year for the sum of all of these sources. It is generally agreed that the largest single source is the land-based (urban runoff, coastal refineries) input, although there is little agreement on the absolute values for any source terms.

When oil enters the sea, it reacts according to physical, chemical and biological processes that change the properties of the oil and consequently, its behaviour. Factors include:

- The quantity and duration of the discharge/spill;
- The time of the year at which it occurs;
- The temperature of the air and the receiving water body;
- The weather and sea (e.g. waves and currents) conditions;
- The species composition in the area affected;
- The properties of the shoreline (rocky, sandy, mud flats, mangroves, etc.).
- The presence and abundance of oil-degrading micro-organisms;
- The concentration of dissolved oxygen in the water.

Different types of oil have different physical properties, which affect the way the oil will react in the environment (Table 2).

Table 2. Oil classification for four groups having different physical properties according to the International Tanker Owners Pollution Federation Limited (ITOPF; http://www.itopf.com/marine-spills/fate/models/).

Group	Density	Examples
Group I	< 0.8	Gasoline, Kerosene
Group II	0.8 - 0.85	Gas Oil, Abu Dhabi Crude
Group III	0.85 - 0.95	Arabian Light Crude, North Sea Crude Oils
Group IV	> 0.95	Heavy Fuel, Venezuelan Crude Oils

Oil, when spilled at sea, will normally break up and be dissipated or scattered into the marine environment over time. This dissipation is a result of a number of chemical and physical processes that change the compounds that make up oil when it is spilled. The key natural processes are evaporation, dispersion, dissolution, oxidation, emulsification, biodegradation and sedimentation. The addition of chemical dispersants (also surfactants) can accelerate this process of natural dispersion.

Lighter components of the oil will evaporate to the atmosphere. The amount of evaporation and the speed at which it occurs depend upon the volatility of the oil. Evaporation of oil with a large percentage of light and volatile compounds occurs more quickly than one with a larger amount of heavier compounds.

Waves, currents and turbulence at the sea surface can cause all or part of a slick to break-up into fragments and droplets of varying sizes. These become mixed into the upper levels of the water column.

Water soluble compounds in oil may dissolve into the surrounding water. This depends on the composition and state of the oil, and occurs most quickly when the oil is finely dispersed in the water column. Components that are most soluble in sea water are the light aromatic hydrocarbons compounds, such as benzene and toluene. However, these compounds are also those first to be lost through evaporation, a process which is 10-100 times faster than dissolution.

Oils react chemically with oxygen either breaking down into soluble products or forming persistent compounds called tars. This process is promoted by sunlight although it is very slow even in strong sunlight such that thin films of oil break down at no more than 0.1 per cent per day. The formation of tars is caused by the oxidation of thick layers of high viscosity oils or emulsions. This process forms an outer protective coating of heavy compounds that results in the increased persistence of the oil as a whole. Tar balls, which are often found on shorelines and have a solid outer crust surrounding a softer, less weathered interior, are a typical example of this process.

Emulsification occurs when two liquids combine, one suspended in the other. Emulsification of crude oils refers to the process whereby sea water droplets become suspended in the oil. Oils with an asphaltene content greater than 0.5 per cent tend to form stable emulsions which may persist for many months after the initial spill has occurred. Emulsions may separate into oil and water again if heated by sunlight under calm conditions or when stranded on shorelines.

Sea water contains a range of micro-organisms or microbes that can partially or completely degrade oil to water soluble compounds and eventually to carbon dioxide and water. Many types of microbe exist and each tends to degrade a particular group of compounds in crude oil (Hazen et al., 2010).

Sinking usually occurs due to the adhesion of particles of sediment or organic matter to the oil, in which case the oil accumulates in the seabed sediments. In the ROPME/RECOFI area for example, Elshorbagy (2005) reported that oil-contaminated seabed sediments occur, particularly in coastal areas. The highest levels of hydrocarbons were 1600 µg l^{-1} found near Bahrain compared with background levels of 10 to 15 µg l^{-1}. Oil washed ashore at Pensacola Beach, Florida, from the DWH spill resulted in weathered oil petroleum hydrocarbon concentrations in beach sands ranging from 3.1 to 4,500 mg kg^{-1} (Kostka et al., 2011).

4. Significant environmental aspects in relation to offshore hydrocarbon installations.

Drilling operations may require the use of many chemicals. In the OSPAR region, chemicals are categorised in four colour classes depending on degradability, octanol-water coefficient and toxicity. The green category means it “shall pose little or no risk to the environment”. Chemicals in the black category should be prohibited and chemicals in the red category should be substituted. Chemicals in the yellow category have characteristics between the red and the green class and are considered to be environmentally acceptable.

Other operational discharges are drill cuttings and small spills of oil and chemicals connected to exploration, production or transport.

For the offshore industry in the North East Atlantic, OSPAR has agreed on several decisions and recommendations to reduce discharges of oil and chemicals. These include Recommendation 2001/1: Management of PW and 15 per cent reduction target for oil discharged with PW, in addition to agreements on decisions and recommendations for use of chemicals offshore, decommissioning and environmental management (OSPAR, 2010).

OSPAR reports discharges, spills and emissions from oil and gas installations. Between 2001 and 2007 an average of between 400 and 450 million m^3 yr^{-1} PW were discharged (OSPAR 2009). For 2010 a sum of 361 million m^3 PW was discharged in this area. The main contributing countries were Denmark (25 million m^3), Norway (131 million m^3) and United Kingdom (196 million m^3; OSPAR, 2010). The numbers account for the whole OSPAR region, but the main region of activities is the North Sea. Oil content in PW was reported as dissolved and dispersed oil, and annual average oil content was reported to be 12 and 13 mg/l, respectively. Annual average oil content in dissolved and dispersed oil was 4,227 tons and 4,746 tons, respectively, giving a total of 8,972 tons in 2010. Annual quantity of injected PW was

81 million m^3 (OSPAR, 2012a). Yearly discharge of approximately 400 million m^3 PW has been relatively constant since 2001 (OSPAR, 2010).

Most of the concern regarding negative effects on ecosystems due to operational discharges from offshore oil and gas activities has been directed to the oil fraction of PW discharges, and less towards the added chemicals. This is due to the content of polycyclic aromatic hydrocarbons (PAHs) and alkylated phenols from the oil fraction. PAHs have received focus because they can be metabolically activated in fish and bound to DNA as DNA adducts. PAHs are also shown to damage early developmental stages of fish creating several effects at low doses, including effects on heart development (Incardona et al., 2004; Brette et al., 2014). Alkylated phenols have received focus because some of these compounds have hormone-mimicking effects (Heemken et al, 2001).

Norway monitors the levels of contaminants in sediments, deployed fish and mussels and in wild caught fish, in addition to effect studies in fish and mussels. Monitoring of sediments shows very small areas with increased total hydrocarbon content or disturbed fauna. Mussels and fish deployed in cages for 6 weeks around different platforms did not show effects in distances further than 1 km (Brooks et al., 2011). No increased levels of contaminants were found in fillets of wild caught fish, although in some cases wild caught fish had increased levels of PAH metabolites in bile. The most surprising findings have been levels of DNA adducts in haddock liver from the North Sea, at levels giving rise to environmental concern in 2002 (Balk et al., 2011) and in 2011 (Grøsvik et al., 2012) because the levels were above the environmental assessment criteria (EAC) for DNA adduct in haddock liver (ICES, 2011).

5. Gaps in capacity to engage in offshore hydrocarbon industries and to assess the environmental, social and economic aspects.

The hydrocarbon industry is an extremely technical endeavour and it has evolved over a period covering more than 70 years. The offshore industry must deal with the fact that the hydrocarbon resource lies hidden, often several kilometres beneath the seafloor. Therefore, the industry employs highly skilled specialists and advanced technologies to image and sample the seafloor to find the hidden hydrocarbons. In general, oil and gas resource development requires the deployment of considerable technology to access, control, and transport the hydrocarbons.

In many parts of the world, massive oil revenues have not overcome high levels of poverty. Indeed, in some cases, they have led to significant social problems. Many oil and gas companies do not publish information what royalties, taxes and fees they pay country by country, and there is thus often a lack of transparency about these transactions. (FESS, 2006; Ross, 2008).

Only 80 out of the known 974 sedimentary basins on earth contain exploitable hydrocarbons (Li, 2011). Therefore, huge risks and uncertainty are inherently associated with hydrocarbon exploration activities. Many “dry” exploration wells are drilled for every winner (for example, see BSEE web site). The industry invests expertise, money and time to reduce risk and uncertainty so that the maximum amount of hydrocarbons is found with minimum effort and investment.

Exploration and production companies are international and operate with sophisticated technologies to make discoveries, across international boundaries wherever hydrocarbons may be found. Individual fields may cross international boundaries, further complicating their development and adding risk to investors; the Timor Gap, an area of disputed seafloor located on the border between Australia and Timor-Leste is a good example (Nevins, 2004).

In the initial stages of their development, many oil-endowed countries lacked the highly specialized knowledge or the substantial funds required to successfully find and produce offshore hydrocarbons. So, offshore hydrocarbon exploration became a primarily private-sector activity worldwide, dominated by international oil companies with the relevant skills, experience and finances needed to take on significant risk.

Over the past few decades there has been a significant shift in ownership of the offshore oil and gas global enterprise. In the 1970s, 85 per cent of all offshore oil reserves were owned by seven international oil companies (IOCs). By 2012, 18 of the top 25 oil and gas producers were National Oil Companies (NOCs), controlling 75 per cent of oil production and holding 90 per cent of the world's oil reserves (Wagner and Johnson, 2012). NOCs have competed with IOCs developing new technologies and productive resource capacity to potentially overtake the largest IOCs in size and scope. NOC’s like Brazil's Petrobras, Malaysia's Petronas and Norway's Statoil have specialized in deepwater drilling technologies, once monopolized by the IOCs (Wagner and Johnson, 2012). This is an example of technology transfer that has benefitted developing countries by allowing them to participate in (if not dominate) the offshore oil and gas industry.

Assessing the environmental impact of offshore oil and gas development in developing countries has not progressed at the same pace as the capacity to develop and exploit the resource. In its assessment of environmental governance in 27 oil-producing developing countries, the World Bank (2010) found there was a “lack of a sufficiently organized administrative structure that enables efficient regulatory compliance and enforcement. Additionally, the human and financial resources needed for effective environmental governance are generally lacking.” A case study from Trinidad and Tobago published by Chandool (2011) illustrates the key issues: paucity of accessible data, lack of public participation, lack of post-approval enforcement and lack of quality control in environmental impact assessment (EIA) practice.

In Malaysia, companies are required to complete an EIA that is prepared by a registered consultant (Mustafa, 2011). The industry was found to have breached its license to operate in 28 cases that went to court in 2009, with fines totalling Ringgit Malaysia (RM) 250,000 (about 76,000 dollars or an average fine of 2,700 dollars). Given the overall value of the industry (Petronas alone had a net worth in 2012 of over 157 billion dollars and had nearly 40,000 employees), there is a *prima facie* lack of proportion between the potential damage from the offences and the deterrent level of such fines.

More broadly, there are gaps in monitoring the offshore oil and gas industry by the responsible government departments. It has already been mentioned above (Section 2.4) that the collection of information on offshore pipeline failures is not coordinated in the Gulf of Mexico between state and federal jurisdictions (NRC, 1997). The data that are collected by government departments charged with monitoring the offshore oil and gas industry are often incomplete or not strategic. For example, PARLOC (2001) notes that whilst corrosion has been identified as one of the major causes of leaking pipes in the North Sea, corrosion protection data are not currently recorded in the pipeline database, so it is not possible to derive failure rates for specific types of corrosion prevention. The lack of coordination between different agencies having a share of responsibility in managing the offshore oil and gas sector was identified as a key issue by the Australian Government's Montara Commission of Inquiry Report (2010), whose conclusion was: "A single, independent regulatory body should be created, looking after safety as a primary objective, well integrity and environmental approvals. Industry policy and resource development and promotion activities should reside in government departments and not with the regulatory agency. The regulatory agency should be empowered (if that is necessary) to pass relevant petroleum information to government departments to assist them to perform the policy roles."[6] Thus, there is a gap in the capability of the responsible government departments to collect and share relevant information among different departments and authorities.

Another gap is with respect to the capacity for local communities to engage with the offshore oil and gas industry in decision-making. As has been already noted above for Trinidad and Tobago, lack of public participation in environmental impact assessments is a clear capacity gap (Chandool, 2011). The Australian company, Santos, engaged with local communities in Indonesia's Jawa Timur Province, who were concerned with the impact of offshore oil activities on their coastal habitats (Anggraeni, 2013). Although the community expressed concerns over Santos' air quality risk management and employment opportunities for local people, a dialogue was established allowing for a more satisfactory outcome for the local community (Anggraeni, 2013).

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[6] Partly in response to this conclusion, the Australian Government established, on 1 January 2012, the National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA; http://www.nopsema.gov.au), to be the national regulator for health and safety, well integrity and environmental management for offshore oil and gas operations.

Figures

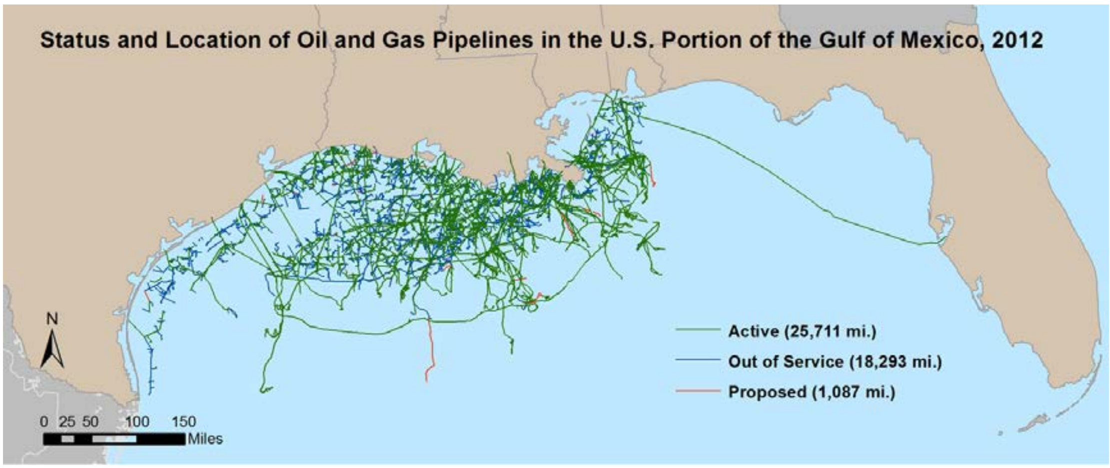


Figure 1. Map of offshore oil and gas pipelines in the United States section of the Gulf of Mexico (from NOAA). http://stateofthecoast.noaa.gov/energy/gulfenergy.html.

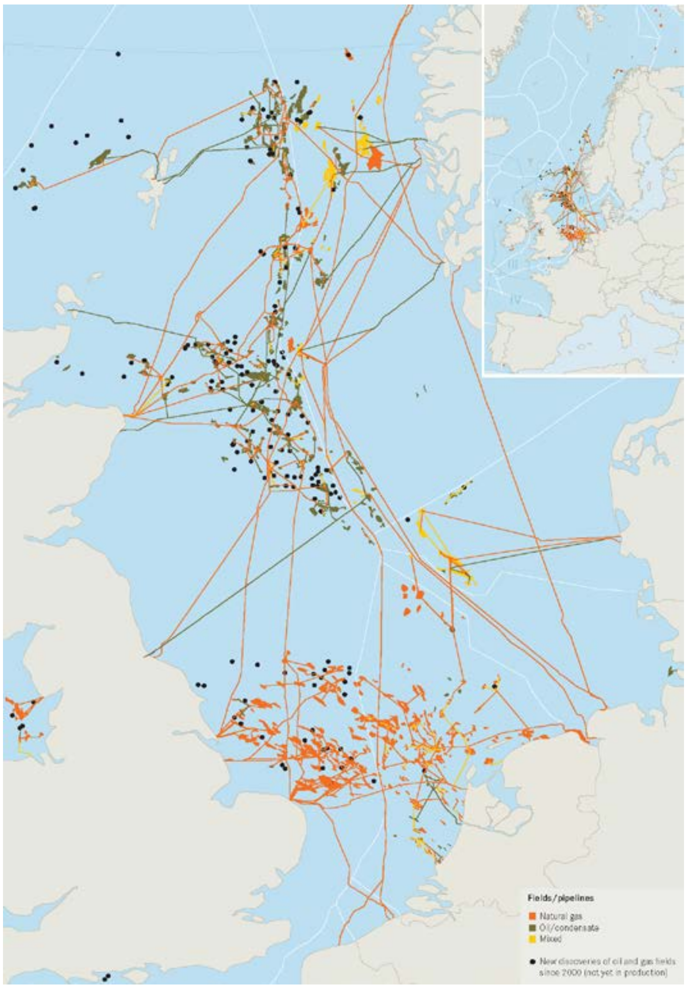
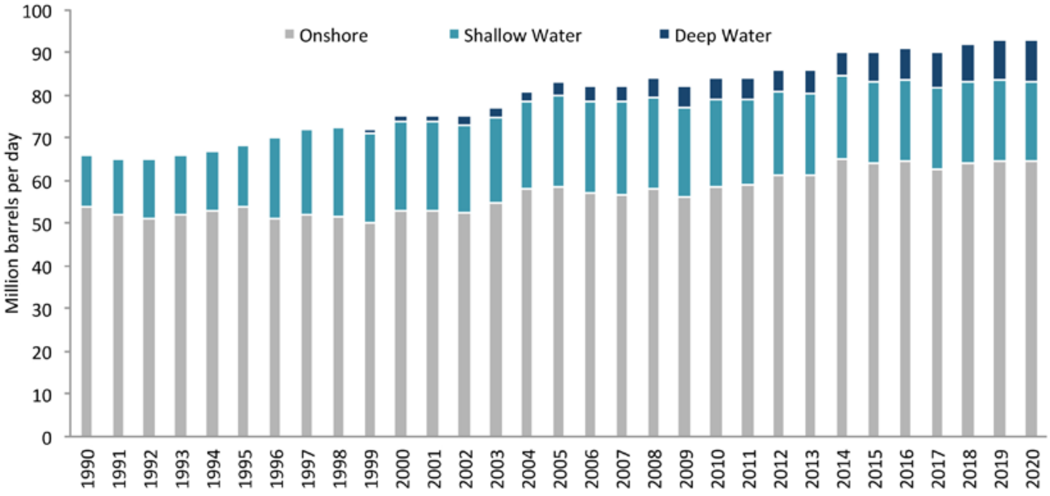


Figure 2. Offshore oil and gas fields under exploitation, new discoveries not yet in production and pipelines in the North Sea in 2009. Figure taken from OSPAR, 2010. (http://qsr2010.ospar.org/en/ch07_01.html).



Sources: Infield Systems, BP Statistical Review 2014

Figure 3. Global crude oil production, comparing onshore, shallow offshore (<100 m water depth) and offshore deep (>100 m water depth) production (from Infield, 2014).

Whereas onshore production has remained stable at around 50-60 million barrels per day since the early 1970s, offshore production has grown steadily over the last four decades. Deep water production has accounted for nearly all growth since about 2005.

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