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Vulnerability of the oil and gas sector to climate change and extreme weather events

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Abstract A changing climate and more frequent extreme weather events pose challenges to the oil and gas sector. Identifying how these changes will affect oil and gas extraction, transportation, processing, and delivery, and how these industries can adapt to or mitigate any adverse impacts will be vital to this sector's supply security. This work presents an overview of the sector's vulnerability to a changing climate. It addresses the potential for Natech hazards and proposes risk reduction measures, including mitigation and adaptation options. Assessment frameworks to ensure the safety of people, the environment, and investments in the oil and gas sector in the face of climate change are presented and their limitations discussed. It is argued that a comprehensive and systemic analysis framework for risk assessment is needed. The paper concludes that climate change and extreme weather events represent a real physical threat to the oil and gas sector, particularly in low-lying coastal areas and areas exposed to extreme weather events. The sector needs to take climate change seriously, assess its own vulnerability, and take appropriate measures to prevent or mitigate any potentially negative effects.

1 Introduction

A changing climate, including increased temperatures, changes in precipitation patterns, sea level rise, and more frequent extreme weather events, poses many challenges to the oil and gas sector. This sector depends on infrastructures that are complex, interconnected, expensive, and have long economic lifetimes. Major disruptions to any of these systems can have a ripple effect across other interlinked systems locally, regionally, and globally. Furthermore, damage to those systems can result in the release and spillage of hazardous materials

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(so-called Natech accidents). Such accidents represent significant safety and environmental risks, with potentially negative impacts on corporate image plus high insurance costs.

Unfortunately, much of the oil and gas infrastructure is located in low-lying coastal areas, offshore, or in areas that are likely to experience more frequent extreme weather events (Wilbanks et al. 2007; Paskal 2009). Extreme weather has already caused unprecedented damage and losses. In summer 2005, Hurricane Katrina and, a month later, Hurricane Rita, were responsible for one of the worst disasters in recent U.S. history; it was also the costliest for the U.S. offshore oil and gas industry in the Gulf of Mexico (GoM) and had economic repercussions around the globe (Cruz and Krausmann 2008, 2009; Sengul et al. 2012).

Other low-lying coastal areas are home to some of the world's largest oil and gas facilities (e.g., Ras Tanura, Saudi Arabia; Jamnagar, India; Jurong Island, Singapore; Rotterdam, The Netherlands; and major installations in the Niger Delta). Their location exposes them to coastal flooding and storm surge, rising sea levels, and ground subsidence and erosion (Paskal 2009). Sea level rise could make the existing infrastructure more prone to frequent or permanent inundation, and warmer temperatures and their greater variability could increase the costs of design, construction, maintenance, and operations.

Several studies analyze the potential impacts of a changing climate on various types of infrastructure: in the energy sector (Wilbanks et al. 2007; Mabey and Mitchell 2010); in transportation (Savonis et al. 2008); and in the Arctic region (ACIA 2004). None of these studies specifically analyzes the impacts on the oil and gas industry of climate change and extreme weather events with the potential for Natech hazards.

This paper assesses the vulnerability of the oil and gas sector to climate change and discusses the options available for mitigation and adaptation, as well as the main factors limiting the sector's ability to take appropriate mitigation and adaptation measures. In particular, it analyzes the potential for Natech accidents, which constitute a secondary risk to the population, the environment, and the economy, and the industry itself. Analytical assessment frameworks are presented and their limitations are discussed.

2 Vulnerability of the oil and gas sector to climate change, and mitigation and adaptation options

Previous research on the impacts of natural hazards on oil and gas industry activities (Cruz et al. 2001; Godoy 2007; Cruz and Krausmann 2008, 2009; Krausmann et al. 2011; 2010; Sengul et al. 2012) showed them to be vulnerable, among other hazards, to hurricanes, high winds, lightning, storm surge, and flooding. The following sections discuss the vulnerability of the sector according to natural hazard and activity type and present possible mitigation and adaptation measures both for reducing exposure or vulnerability and for increasing resilience.

2.1 Warmer temperatures

2.1.1 Oil and gas extraction and transportation

A reduction in sea ice caused by warmer temperatures may lead to increased offshore oil exploration (ACIA 2004). Recent studies indicate that the sea ice covering in the Arctic Ocean may have reduced by as much as 10 % and thinned by as much as 15 % over the past few decades. These trends suggest that there will be easier shipping access around the margins of the Arctic Basin, which has major implications not only for the transportation of products and materials, but also for the production of liquefied natural gas (LNG) and oil from these high-latitude basins (Wilbanks et al. 2007). However, these warmer temperatures will cause thawing of permafrost, which has the potential to severely affect not only the integrity of oil and gas extraction, but also the transportation infrastructure built upon it. Thawing permafrost has already reduced the number of days during which tundra travel in Alaska is feasible from over 200 days/year to fewer than 120 days/year. Economically, this has had strong negative impacts on oil and natural gas exploration (Wilbanks et al. 2007).

2.1.2 Oil refining

Oil refining will be impacted by warmer temperatures in a number of ways. High temperatures reduce steam turbine effectiveness, resulting in higher energy costs. Warmer water may affect plant design and operation requirements and materials, as well as process efficiency. Excessive biological growth (algae, mussels, clams, etc.) in cooling water condensers and heat exchangers can cause process upsets, affect safety systems (Glöckler 2010), or clog water intakes. Higher temperatures may also lead to increased temperatures in discharge water, affecting water discharge requirements.

Glöckler (2010) recommends taking measures to avoid clogging of the water intakes of safety-related equipment and other critical units, the installation of fixed or rotating drum screens and redundant paths for clean cooling water, and the treatment of cooling water condensers and heat exchangers to prevent biological growth.

2.1.3 Oil and gas delivery and distribution

While warmer temperatures will have a low impact on oil and gas delivery and distribution systems, temperature extremes have the potential to cause maintenance problems, according to a study of climate impacts on transportation systems in the U.S. GoM (Savonis et al. 2008). A higher frequency of very hot days will lead to a greater need for maintenance of roads and asphalt pavement, rail tracks and freight facilities, vehicles, and facility buildings and structures because of degradation of construction materials. A drying-out of the ground can result in pipeline breaks and undermine any infrastructure built on top of it. A drought in Austin, Texas, during summer 2011 caused water pipes to burst and building foundations to sink. More than 100 repairs were necessary during the week of 9 August, compared to 40 to 50 such repairs in a normal summer week (Lyon 2011). Temperature increases are also likely to increase cooling requirements and hence costs.

Mitigation and adaption measures should include a detailed risk assessment of road and rail transportation systems with respect to climate-related events. Such assessments would help identify critical nodes and infrastructures requiring additional protective measures or retrofitting to more stringent design requirements. Further development of environmental trend data and climate-model projections tailored to decision makers are needed to facilitate integration of climate information into transportation decisions (Savonis et al. 2008).

2.2 Storms, heavy rains, and river floods

Although the results of climate model runs are inconclusive with respect to precipitation, extreme rainfall events and storms with potential for flooding may be more likely in some areas (Wilbanks et al. 2007; NCADAC 2013). In areas where rainfall and flooding are already a concern, extreme rainfall events could exacerbate local conditions.

2.2.1 Oil and gas extraction

Inland oil fields located in or near flood plains may be liable to flood in the coming decades unless measures are taken to protect infrastructure. In the USA, shale oil fields (e.g., the Barnett Shale near Fort Worth, Texas, and the new Marcellus Shale which spans West Virginia, Pennsylvania, and southern New York State) may be likely to suffer more frequent severe storms with possible tornadoes and flooding. In 2007, onshore oil field extraction in Tabasco, Mexico, which accounts for 16 % of the country's daily output, was slowed considerably by extensive flooding. Although the oil fields around Tabasco escaped major damage, flooded roads and destruction of workers' homes obstructed oil field operations (Brosnan and Otis 2007).

2.2.2 Transportation

One of the preferred and safest methods for transporting oil and gas from production wells and platforms to storage terminals and refineries by land are pipelines. Although most major oil and gas pipelines generally run underground, past events indicate that they may be vulnerable to floods, particularly in areas where flooding can result in high water speeds that can cause soil erosion and lead to exposure of buried pipes. In 2000 in Mondego, Portugal, prolonged and heavy rains caused overtopping of dams and several levee breaks, exposing a major underground gas pipeline and posing a threat to nearby villages (Cruz et al. 2006).

Exposed pipeline sections such as valves, pumping stations, and river crossings may be even more vulnerable. Severe flooding in the San Jacinto River flood plain near Houston, Texas, in 1994 caused eight pipeline ruptures and undermined 29 others at river crossings and in new channels gouged by the waters out of the flood plain. As a result, more than 35,000 barrels of petroleum and petroleum products were released into the river. Ignition of the released products inside flooded residential areas resulted in burn and inhalation injuries to 547 people and over US$23 million in financial losses (NTSB 1996). Savonis et al. (2008) state that a better understanding is needed of flood and other weather-related damage to pipeline sections that have been exposed or are underground and where sea level changes can cause changing water tables and soil subsidence, as damage of this type has, to date, largely been overlooked.

Oil and gas are transported around the world by vessels that may also be liable to hazards from severe storms and high offshore winds, as well as to storm surge and flooding when navigating inland through rivers and channels. For example, the Mississippi River was completely closed to navigation following Hurricane Katrina because of the high storm surge and debris swept along by the storm. Docked vessels can break anchor and be moved inland by high storm surge. If they are connected to loading and unloading arms, battering waves and storm surge could result in pipe connections being broken, leading to oil spills and/or gas leaks.

2.2.3 Oil refining

Oil refineries have been impacted by severe storms and flooding. In 2007, a refinery in Coffeeville, Kansas, was flooded when a levee was breached (Bushell 2007). This resulted in the spillage of 150 m^3 of crude oil which contaminated floodwaters and flowed into streets, homes, and businesses, forcing the evacuation of some 2,500 residents. The spill also contaminated the Verdigris River, sparking fears about contamination of lakes downstream in Oklahoma (Gillam 2007).

Included in high water hazards at oil refineries and other oil and gas production and refining facilities is flooding of electrical equipment, causing short circuiting or power failure. This may result in process upsets and the unexpected shutdown of unitary processes, or it may affect refinery utilities such as steam boilers, cooling towers, process air, pumps, and electrically operated safety-control mechanisms. Heavy rains on floating tank roofs can make tanks sink or tip, leaving oil exposed and thus constituting a fire hazard (Cruz et al. 2001).

Flooding around storage tanks can make these float off their foundations. Flooding of containment dikes can also cause empty, or nearly empty, storage tanks to float off, potentially ripping away pipe connections and resulting in releases of hazardous materials (Cruz et al. 2001; Cozzani et al. 2010). In 1979, flooding of the Illinois River near Meredosia caused floating off of diesel fuel tanks at an oil terminal. Thousands of liters of oil spilled out of vents on the tank roofs or from broken pipes at their bases. The spill-containment dike around the tank farm was under water, allowing winds to move the oil out and over flooded farmland (Tanos 1981).

Internal plant drainage systems containing waste oil can flood, causing oil to float up and out of the drainage system. If a lightning storm or other fire source were to cause this oil to ignite, a large-scale fire or explosion could be triggered (Cruz et al. 2001). This type of event occurred in Morocco's Samir refinery in Mohammedia, where flooding of the El Maleh River in 2002 resulted in water levels of about 1.5 m inside the refinery, causing fires and explosions. As a result, two people died and over 70 % of the thermoelectric power plant that was part of the refinery complex was destroyed (Krausmann and Mushtaq 2008).

Many countries limit or prohibit development in 100-year flood plains. However, such laws generally apply to new construction, and existing infrastructures within the 100-year flood plains may not be protected. Changing precipitation patterns and more frequent extreme rainfall events, due to climate change, may result in 100-year flood events occurring more often. Thus, any new development should not only rely on existing flood-hazard zoning or flood-hazard maps, but should include a flood-hazard assessment that takes climate change into account.

There are ways of protecting building functionality and contents: i) flood protection and adaptation measures, including reassessment of flood-prone zones; ii) avoiding building in flood-prone areas where possible; iii) waterproofing (of buildings, equipment); iv) adoption of slowing, steering, and blocking water techniques; and v) elevation of buildings or building components above the 100-year flood contour level.

2.2.4 Oil and gas delivery and distribution

Oil and gas are delivered and distributed by vessel, pipeline, road, and rail. As discussed above, vessels and pipelines may be vulnerable to storm and flood-induced disruption and damage.

Road and rail transportation may be affected by increased rainfall, which could lead to more rapid deterioration of infrastructure, raising costs and affecting product delivery and distribution. Excessive rainfall and flooding can cause land subsidence and heave of embankments, in some cases completely destroying roads, bridges, and rail overpasses, or resulting in landslides that could directly impact cargo trains and tankers with consequent oil spills and releases of hazardous materials.

Mitigation and adaption measures include improvements in engineering design and construction methods and in materials, regular maintenance and monitoring of infrastructure conditions, and improved planning and preparations for service delays or cancellations.

2.3 Tropical cyclones

Tropical cyclones[1] can be particularly destructive, as they can have impact radii of up to 500 km and are usually accompanied by high wind speeds and hurricane-spawned tornadoes, heavy rains and flash floods, dangerous storm surge and flooding, as well as lightning. Direct losses to the energy industry in 2005, due to heavy rains and flooding caused by cyclones, were estimated at $15 billion, with millions more dollars being incurred in restoration and recovery costs (Wilbanks et al. 2007).

Climate change is predicted to increase the frequency of intense tropical cyclones in the coming decades. Moreover, future tropical cyclones are expected to become more intense, with higher wind speeds and heavier precipitation (NCADAC 2013). Thus, the occurrence of future storms of the severity of, for example, Hurricane Katrina is very likely. Much of the infrastructure destroyed in the GoM in 2005 was rebuilt in the same location, leaving it exposed to similar weather events (Paskal 2009). In fact, in 2008, hurricanes Gustav and Ike destroyed 60 platforms in the GoM, which caused a spike in oil prices (Paskal 2009). Preventive evacuation and shutdown of on- and offshore oil and gas infrastructure, and accompanying fears of a supply shortage, can also affect the oil price. In the wake of Hurricane Irene in 2011, expected refinery shutdowns and the anticipated disruption in oil supplies led to a rise in gasoline prices (Businessweek 2011).

2.3.1 Oil and gas extraction and transportation

Hurricane winds, strong storm surge, and coastal flooding have wreaked havoc in the U.S. oil and gas industry in the GoM in recent years. Hurricane Ivan in 2004 resulted in US$14.2 billion in damage and losses in the United States. In total, the lost production in the GoM for the three months following Hurricane Ivan was 38 million barrels of oil and 151 billion ft^3 of gas. Apache Corporation, which owns a number of offshore platforms and rigs, reported US$94 million in repair costs due to the hurricane (Heinrichs 2005).

In 2005, hurricanes Katrina and Rita once again demonstrated that both the offshore and onshore oil and gas industry remain vulnerable to the impacts of hurricanes. In total, they destroyed 113 offshore platforms and severely damaged at least 163 others (MMS 2006; Energo Engineering 2007). High winds and storm surge during the two hurricanes caused significant damage to offshore platforms due to wave inundation of the decks and the failure of rig tie-down components (Cruz and Krausmann 2008; Energo Engineering 2007). Underwater currents caused mooring failure and subsequent loss of station keeping, setting adrift 19 mobile offshore drilling units (MODUs). Transocean Inc. spent US$135 million on repairing damage from Katrina and Rita to its semisubmersible drilling rigs (Baskin 2006). Drifting MODUs, with their dragging anchors, damaged oil and natural-gas pipelines and other subsea facilities. Other areas in the world are also vulnerable. In 2006, a severe storm set adrift a drilling rig in the North Sea off the coast of Norway (Paskal 2009).

Mitigation and adaptation measures to protect offshore oil and gas facilities should include a reevaluation of the adequacy of design standards, as the current design criteria are based on the severity of a 100-year hurricane and may not sufficiently protect the offshore infrastructure in a future climate. Consequently, the industry needs to update its disaster preparedness, as well as its response and recovery planning. A compromise is necessary between increasing safety and controlling costs so that expensive redesigns can be avoided that may force some operators out of business. However, both regulators and

[1] Tropical cyclones are known as hurricanes in the Atlantic Basin and as typhoons in the Pacific Basin.

companies agree that upgrading their infrastructure to make it more resilient to hurricanes is a business necessity that will help save money in the long run (Baskin 2006). Drilling companies invested significantly in upgrading their rigs after hurricanes Katrina and Rita. According to Rigzone, Noble Petro, Inc., a commercial supplier and wholesale distributor of refined petroleum products, was reported to have spent US$10-15 million per rig to increase the number of anchors from eight to twelve on several of its rigs (Baskin 2006).

With the damage to the underwater pipeline network delaying the start-up of production, it was recognized that the root causes and failure modes of pipelines need to be better understood (Cruz and Krausmann 2008).

Despite upgrades on design, and operating and emergency procedures, hurricanes Gustav and Ike demonstrated that the oil and gas industry in the GoM will continue to experience problems in the years to come. As more easily accessible oil and gas sites in the United States and elsewhere are depleted, more difficult offshore and coastal production may gain in importance, which would place more and more infrastructure at risk of major hurricane impacts (Paskal 2009).

2.3.2 Oil refining

Hurricane and tornado-force winds may damage refinery buildings and structures by toppling processing units or storage facilities and dislodging roofs on refinery structures. A tornado spawned by Hurricane Georges in 1998 caused extensive damage to a cooling tower at an oil refinery in Pascagoula, Mississippi (Cruz et al. 2001). Particularly vulnerable to wind-induced failure are empty tanks, roof tops, piping, and the connections between storage and process units. High wind speeds may also cause power failure or short circuiting, leading to process upsets. Objects launched into the air by wind can damage equipment, break pipes and connections, and puncture tanks (Cruz et al. 2001).

Tropical cyclone-induced storm surge can affect coastal facilities. Strong storm surge and flooding caused floating off and complete displacement of two large oil storage tanks at Bass Enterprises in southern Louisiana during Hurricane Katrina. More than 65,000 barrels of oil were released into the environment due to tanks being deformed and connected pipelines ruptured. In 2012, storm surge and flooding from Hurricane Sandy caused rupture of at least two diesel tanks and the release of 1,136 m^3 of diesel at a refinery in New Jersey (Kessler 2012).

Storm surge and consequent flooding can affect refinery infrastructure even when it is not located directly on the coastline. Storm surge can result in abnormal rise in the water levels of canals, lakes, and rivers that are directly connected to the sea. The multiple failures at several locations of the regional New Orleans flood protection system during Hurricane Katrina led to flooding of a refinery in Chalmette causing a major oil spill (ILIT 2006). Failure of a large storage tank due to the flooding and possible debris impact at the Murphy Oil refinery resulted in the release of over 3,900 m^3 of oil. The spill contaminated 1,800 homes and resulted in a US$330 million class action settlement (Steinberg et al. 2008).

Land-use planning restrictions should limit industrial development in coastal areas exposed to tropical cyclones. However, this is usually not feasible in already heavily industrialized areas. Therefore, existing facilities should review the design of their installations and — given current and future potential increases in wind, storm surge, and flood loads due to climate change — evaluate if any retrofitting or enhanced emergency preparedness is needed. Measures could be, for example, the filling of empty tanks to avoid floating or wind buckling of the shell, tying down of components to reduce the risk of missile creation during high winds, or the special protection or relocation of safety-critical systems to avoid wave loading and water intrusion.

Furthermore, facilities can take various structural and non-structural prevention and mitigation measures to help reduce potential damage and losses. Concrete walls and dikes can slow, block, and/or steer floodwater away from critical structures. At the Chevron Pascagoula Refinery in Mississippi, a 50-foot dike was constructed around the refinery at a cost of US$10 million. Although the dike did not completely block the effects of Hurricane Katrina, the refinery did not flood (Van der Meer et al. 2008). The planting of forests or the protection of mangroves in certain settings serve the same purpose. In both cases, these barriers could have the added benefit of keeping debris driven by storm surge or floods from washing into a facility where collision with equipment could lead to damage. Additional prevention and mitigation measures include waterproofing of equipment and buildings, securing of equipment (e.g., anchoring storage tanks, restraining gas cylinders), and adequate emergency-response and contingency planning to help minimize downtimes.

2.3.3 Oil and gas delivery and distribution

Hurricanes can severely disrupt ground transportation by damaging roads, bridges, and railroad tracks generally through storm surge and flooding. Furthermore, hurricane-strength winds and tornadoes can overturn tanker trucks and train tankers carrying oil and products. In fact, hurricanes Katrina and Rita exposed not only a fragile oil and gas infrastructure due to the loss of production they caused, but a weak delivery and distribution system. Following the storms there were hardly any options available to deliver the products to the markets because of the onshore devastation (Fletcher 2006) that led to a shortage of fuel at pumping stations in several states.

2.4 Lightning

Numerous studies indicate that lightning strikes are the natural hazard that most frequently triggers accidents in processing and storage activities (e.g., Rasmussen 1995; Chang and Lin 2006). The frequency of lightning events is expected to increase with the predicted rise in the frequency and/or intensity of the accompanying meteorological hazards, such as thunderstorms, hurricanes, and tornadoes (IPCC 2007).

2.4.1 Oil and gas transport

Pipelines for the transport of oil and natural gas are susceptible to lightning strikes, which play a more important role in pipeline failure than was previously thought. Direct lightning strikes can pierce the pipeline and create small holes. This occurred in July 1994 in Cideville in France, where a natural-gas pipeline, buried 1.2 m deep, was struck by lightning that ignited the flammable gas (Kinsman and Lewis 2000). Even if the lightning energy is not sufficient to penetrate the pipeline wall, it can still disable the corrosion-protection equipment and produce pitting, thereby creating weak points that could corrode and fail months after the initial lightning strike. In an accident in Texas, a lightning strike damaged the power supply to the control system of a crude-oil pipeline's pumping station (ARIA 2010). As a consequence, the computer erroneously ordered one of the pipeline's valves to close. The pipeline ruptured due to overpressure, and an estimated 340 m^3 of crude oil were spilled. A small amount of crude spread through the local water network to Corpus Christi Bay.

The International Standard for lightning protection (IEC 62305–3) sets out protection measures for long-distance pipelines (Bouquegneau 2007). Moreover, regular inspections and maintenance of lightning protection systems are indispensable, as over the years their components tend to become less effective due to chemical corrosion, weather-related damage like lightning strikes, and mechanical damage.

2.4.2 Oil refining

A recent study by Renni et al. (2010) concluded that the up- and downstream oil and gas sector, as well as the petrochemical industry, appear to be particularly vulnerable to lightning impact. In addition to posing a safety risk due to the possible release of hazardous materials, the damage caused by lightning in refineries, storage sites, and tank farms can also affect the security of the energy supply. An illustrative example is the explosion and fires at a United Kingdom refinery, where lightning strikes resulted in power loss and subsequent power dips throughout the installation. As a consequence, hydrocarbons were accidentally released and ignited. The associated damage to property amounted to US$77,500,000 (in 1994 dollars). The damage caused a downtime of 4.5 months, which translates into US$70,000,000 in losses due to business interruption, and a loss of 10 % of the total refining capacity in the United Kingdom in 1994 (Marsh Risk Consulting 2003).

The type of equipment most frequently involved in lightning-triggered accidents are atmospheric tanks for the storage of liquid flammable hydrocarbons, such as crude oil (Renni et al. 2010). These tanks are commonly found at refineries and fuel storage depots. Because of their high storage capacity, they can generate severe accident scenarios with a domino-effect potential should they undergo loss of containment. In fact, the most frequently observed accident scenarios involving storage tanks are fires and explosions, which may in turn damage nearby equipment and thus aggravate losses.

With the potential for increased weather-related events, and hence for an increased number of lightning strikes per year, attention needs to be paid to the dangers of lightning, particularly where hazardous materials are present, so that the risk of both accidents and supply-chain interruptions can be reduced.

Existing lightning-protection measures, for example, grounding of equipment or use of lightning rods or circuit breakers, may not be sufficient to protect equipment from damage or failure (Goethals et al. 2008; US EPA 1997). Moreover, there is no specific methodology for the analysis of lightning risk at industrial facilities. More research into the dynamics of lightning impact on equipment is required to guarantee sufficient protection of oil and gas infrastructures from lightning strikes in the future.

3 Assessment methodologies

In many countries, environmental impact assessments need to be developed for large engineering projects such as new refinery construction or development of new oil fields. Generally, the purpose of such an assessment is to ensure proper consideration of environmental protection and public safety by identifying the project's potential impacts on people, property, and the environment. However, environmental impact assessments rarely require an assessment of the potential impact of the environmental and possible climate change on the projects. Paskal (2009) notes that, even if environmental change is considered in the design of new energy infrastructure, precise projections may be very difficult or even impossible, given the added problem that while some change may be broadly predictable, wide variability in some areas is also likely. The science is improving, but there are still many unknowns and a lack of fine graining. This, in itself, is sometimes used as a justification for not carrying out any change at all.

Another problem is that, usually, natural hazards are not explicitly addressed in process-safety analysis, industrial vulnerability and risk assessment, and emergency response planning (Cruz and Okada 2008; Antonioni et al. 2009; Krausmann and Baranzini 2012). This is largely due to a lack of detailed knowledge about the dynamics of a natural-hazard impact on the oil and gas industry and consequently the absence of guidance and dedicated tools for risk assessment. Moreover, industrial design codes and standards to protect a facility from weather-related hazards do not necessarily consider the fact that equipment containing hazardous materials can exacerbate damage and losses if a release takes place. Thus, the potential for natural hazard-induced disruption and damage to the oil and gas industry remains, and it could increase with climate change.

Furthermore, most industrial risk assessment requirements concern individual facilities and rarely include systemic risks. Hydro-meteorological hazards have the potential to impact large swaths of territory, inflicting damage on everything in their path, often simultaneously affecting other facilities and infrastructure, lifeline systems, local governments and citizens, and emergency-response resources. The analysis of the potential impacts of climate change and, in particular, extreme weather events, will therefore require a comprehensive analytical approach that encompasses the industrial facilities, the built environment, including lifelines, the community, and the emergency response-capacity and resources.

Although it is difficult to accurately predict the impact of an extreme event, a comprehensive risk assessment followed by a cost-benefit analysis, as well as adequate planning and preparedness, can help facilities better prepare for future extreme weather events in a cost-effective way. Once the risk assessment has identified the priority areas where further protective action is required, possible prevention and mitigation strategies that help achieve the desired level of safety are selected. A trade-off may be necessary based on the ratio of additional costs and benefits gained. Additionally, business contingency and continuity planning can help ensure that a facility will be back in operation in the shortest time possible, thereby reducing potential losses due to prolonged downtime and loss of production. The success of the hurricane protection measures adopted around the Chevron refinery at Pascagoula, Mississippi, and tested during Hurricane Katrina in 2005, serves to show that proper risk assessment based on sound scientific knowledge and data can pay off (Van der Meer et al. 2008).

4 Conclusions and recommendations

The oil and gas sector has been affected by climate-related events in the past, which in many cases have led to oil spills and releases of hazardous materials, thus providing lessons on better preparing for extreme weather events in the future. The impacts of a changing climate will vary depending on location. However, most studies show that oil and gas facilities and infrastructure in low-lying coastal areas and areas subject to severe weather will be most vulnerable.

The economic, social, and environmental impacts caused by the disruption of and damage to the oil and gas sector could be huge, with global repercussions, as demonstrated by hurricanes Katrina and Rita. Given the complex and interconnected nature of the oil and gas sector, a more comprehensive risk assessment and analysis framework is needed in order to adequately capture the full range of future potentially disruptive scenarios. This requires the development of dedicated methodologies and tools, as well as guidance for operators and authorities on how to consider hydro-meteorological hazards in industrial risk assessments.

Overall, we conclude that climate change and extreme weather events represent a real physical threat to the oil and gas sector, which needs to take climate change seriously, assess its own vulnerability, and take appropriate measures to prevent or mitigate any potentially negative effects.

Mitigation and adaptation options in some cases will require possibly large investments to upgrade facilities, build redundancy and robustness into the systems, and protect critical infrastructure to ensure that it remains operational following an extreme weather event. Adequate contingency planning plus emergency-response and recovery planning and preparedness will also be essential to ensure the safety of people, property, and the environment, as well as business continuity. However, for these mitigation and adaptation options to be economically viable and not force businesses to close down, a balance needs to be struck between the degree of protection that should reasonably be achieved and the accompanying costs.

Incentives from policymakers can promote the development and implementation of effective mitigation and adaptation measures in situations where the cost of managing climate change impact is becoming a major challenge. Insurance companies can also drive the implementation of protection measures by adding a price tag to risk and adapting their insurance premiums accordingly. This could be a powerful incentive for industry to take a proactive stance toward protecting its assets from gradual climate change and extreme weather events, given that premiums are bound to increase when insurance companies reprice the risk due to climate change.

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