Journal of Petroleum Science and Engineering 124 (2014) 301–312

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

How innovation and R&D happen in the upstream oil & gas industry: Insights from a global survey

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ARTICLE INFO

Article history:
Received 19 September 2013
Accepted 27 September 2014
Available online 7 October 2014

Keywords:
oil
gas
innovation
technology
survey

ABSTRACT

Few would disagree that the upstream oil & gas industry has become more technology-intensive over the years. But how does innovation happen in the industry? Specifically, what ideas and inputs flow from which parts of the sector's value network, and where do these inputs go? And how do firms and organizations from different countries contribute differently to this process? This paper puts forward the results of a survey designed to shed light on these questions. Carried out in collaboration with the Society of Petroleum Engineers (SPE), the survey was sent to 469 executives and senior managers who played a significant role with regard to R&D and/or technology deployment in their respective business units. A total of 199 responses were received from a broad range of organizations and countries around the world. Several interesting themes and trends emerge from the results, including: (1) service companies tend to file considerably more patents per innovation than other types of organization; (2) over 63% of the deployed innovations reported in the survey originated in service companies; (3) neither universities nor government-led research organizations were considered to be valuable sources of new information and knowledge in the industry's R&D initiatives; and (4) despite the increasing degree of globalization in the marketplace, the USA still plays an extremely dominant role in the industry's overall R&D and technology deployment activities. By providing a detailed and objective snapshot of how innovation happens in the upstream oil & gas sector, this paper provides a valuable foundation for future investigations and discussions aimed at improving how R&D and technology deployment are managed within the industry. The methodology did result in a coverage bias within the survey, however, and the limitations arising from this are explored.

1. Introduction

Oil & gas have been mainstays of the world's energy mix for decades (BP, 2012), and this trend will probably endure for many years to come (Longwell, 2002; Cook, 2007; Fischer, 2007; World Economic Forum, 2008; Bullis, 2009; Yergin, 2009). While the global demand for these energy sources continues, however, the industry that provides them is changing in two fundamental ways. First, with much of the world's "easy oil" already consumed (Urstadt, 2006; Weijermars, 2009), upstream oil & gas companies will have to use increasingly sophisticated technologies to find and produce tomorrow's hydrocarbons (Tillerson, 2006; Lord, 2007; Paul, 2007). Future oil & gas resources—especially in non-OPEC countries—will tend to be deeper, harder to find, and in environments that are significantly more difficult to access than they used to be (Managi et al., 2004, 2005b; Hinton, 2010). Second, high-profile disasters like the *Piper Alpha* incident in 1988 (Paté-Cornell, 1993), the *Exxon Valdez* oil spill in 1989 (Plater, 2011; Coll, 2012), Shell's *Brent Spar* incident in 1995 (Frynas, 2003; Sluyterman, 2007, 2010), and the recent *Deepwater Horizon* accident (Flournoy, 2011; Perrons, 2013) have brought about a marked change in the expectations placed upon oil & gas companies with regard to environmental stewardship, safety, and human welfare (Mirvis, 2000; Managi et al., 2005a; Hofmeister, 2010). In the face of these kinds of challenges, technology will clearly play a pivotal role in the success or failure of tomorrow's oil & gas firms (Longwell, 2002; Mitchell et al., 2012).

Despite the strong case for technology, however, the industry has a reputation for being slow to develop and adopt innovations. The shared equity structure of many upstream oil & gas assets frequently makes it difficult for companies to keep new innovations proprietary (Acha, 2002; Sharma, 2005; Perrons and Watts, 2008), thereby creating a problem of "free ridership" within the sector that frequently erodes the competitive advantage that technology might otherwise deliver to an innovating firm. Also,

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http://dx.doi.org/10.1016/j.petrol.2014.09.027
0920-4105/

the extreme risks (Daneshy, 2003a, 2003b; Rao and Rodriguez, 2005) and high cost of failure associated with being a first user of new technologies are such that companies frequently prefer to be “fast followers” (Daneshy and Donnelly, 2004, p. 28), and the industry's innovations consequently take an average of 16 years to progress from the concept phase to widespread commercial adoption (NPC, 2007).[1] The sector has accordingly been characterized in the literature as “slow clockspeed” (Fine, 1998, p. 239), “low- and medium-tech” (von Tunzelmann and Acha, 2006, p. 408), and “technologically timid” (Lashinsky, 2010, p. 88). Oil & gas producers have also been categorized as “low R&D intensity” because they have historically invested less than 1% of their net revenue in research and development (R&D) (von Tunzelmann and Acha, 2006; Moncada-Paternò-Castello et al., 2010).[2]

The industry seems to be changing, however. Several international oil companies (IOCs) have pointed to technology as an increasingly important strategic priority (e.g., Kulkarni, 2011; Parshall, 2011; Chazan, 2013), and spending on innovation and R&D by both IOCs and national oil companies (NOCs) has risen dramatically over the past few years (Thuriaux-Alemán et al., 2010). These efforts to increase the amount and pace of innovation within the upstream oil & gas sector give rise to a few important questions. How does technology happen in the industry? Specifically, what ideas and inputs flow from which parts of the industry's value network, and where do these inputs go? And how do firms and organizations from different countries contribute differently to this process? The literature offers no shortage of anecdotal evidence (Daneshy and Donnelly, 2004), perspectives (Donnelly, 2006), and stories about individual technology programs (e.g., Artigas et al., 2012; Rassenfoss, 2013), but fails to give a comprehensive and holistic snapshot of how the industry's innovation system works overall.[3] Furthermore, the sheer size of the industry—seven out of the ten largest publicly listed firms in the world by revenues in 2011 were oil & gas companies with significant upstream operations (Fortune, 2012)—makes this sector an important part of the global economy. The specific mechanics of how new oil & gas technologies are created may therefore also be of interest outside the industry because of the larger strategic and geopolitical role that the sector often assumes.

As a step towards improving how the upstream oil & gas sector develops and deploys new technologies in the future, this paper sets out to deepen our understanding of how R&D happens within the industry at present. The structure of the paper is as follows. I first review the existing literature connected to R&D and technology management within the industry. I then describe a survey that was put together with the Society of Petroleum Engineers (SPE) to shed light on several different aspects of how the industry conducts R&D, and then put forward the results. Finally, I explain how these data constructively add to the existing body of research in this field, underline the practical implications of this evidence, and recommend potentially fruitful directions for future investigations.

2. Literature review and research questions

Prior to the IOCs' reduction in their in-house technology and innovation programs in the 1980s and 1990s, more than 80% of the industry's overall R&D investment was borne by just 11 oil & gas producers (Economides and Oligney, 2000). Technology had historically been an important strategic priority for several of the IOCs before this period (Wilkins, 1975; Howarth and Jonker, 2007; Priest, 2007), and most of them had previously supported fairly comprehensive in-house R&D programs (Sharma, 2005).

But things have changed significantly since that time. The costs associated with modern-day R&D projects in any industry are an increasingly daunting proposition (Kumpe and Bolwijn, 1988; Manders and Brenner, 1995), and technology “has become so sophisticated, broad, and expensive that even the largest companies can't afford to do it all themselves” (Leonard-Barton, 1995, p. 135). Whereas major breakthroughs in many industries frequently used to come about via in-house R&D teams working within a single company, today's researchers often reach out to outside organizations to broaden the radius of new ideas to which they can gain access (Quinn and Hilmer, 1994; Rigby and Zook, 2002). To these ends, many companies within the upstream oil & gas industry have embraced the concept of “open innovation” (Chesbrough, 2003a, 2003c) and more collaborative models of R&D that welcome ideas from other industries and technical domains (e.g., Verloop, 2006; Ramírez et al., 2011; Dennis et al., 2012). Oilfield service companies and a broad range of vendors, government agencies, and universities now potentially play important roles in the sector's R&D activities (Acha, 2002; Acha and Cusmano, 2005). Some firms in the upstream oil & gas industry have begun to experiment with various forms of venture capital to support potentially promising concepts outside their in-house R&D activities (Hansen and Birkinshaw, 2007; Shah et al., 2008), and several companies in the sector have even forged R&D alliances with direct competitors (Crump, 1997).

While it is clear that the industry's innovation processes are far more collaborative than they used to be, however, the specific details of these collaborations are less obvious. Different parts of the upstream oil & gas “ecosystem” have different resources and skill sets, and may therefore turn to different sources of information and knowledge throughout their innovation-related activities. This leads to:

> **Research Question 1**: What sources of information and knowledge do different types of organization use for innovation-related activities within the upstream oil & gas industry?

And with such a high degree of heterogeneity among the large number of organizations playing a role in the sector's innovation-related activities, each of these constituent groups may contribute

[1] While I do consider this to be a fair generalization of the industry, I also recognize that some companies within the sector are considerably more aggressive than others in developing and deploying innovations (Bohi, 1998; Anderson, 2000), and that companies within the industry often have different motivations for pursuing new technologies (Acha and Finch, 2003; Daneshy and Shook, 2004).

[2] It is important to note, however, that this is not true for most oilfield service companies. Whereas oil & gas producers in the United States have a R&D intensity of 0.21%, the country's oil equipment and service providers have a R&D intensity of 2.24% (Moncada-Paternò-Castello et al., 2010). Also, there are many people—like ExxonMobil CEO Rex Tillerson (2006), for example—who contend that the industry is more high-tech than is reflected in these kinds of statistical indicators. Chazan (2013) offers just one of many compelling pieces of evidence to support this alternative point of view: “BP's supercomputer complex in Houston was the world's first commercial research center to achieve a petaflop of processing speed.”

[3] Helfat (1994a, 1994b, 1997) makes several valuable contributions in this area by offering a very rigorous quantitative analysis of R&D in the oil & gas industry. But these investigations were based on data sets focusing on the period 1974–1981 and, as explained in this paper, the R&D landscape of the industry has changed dramatically since that time. Also, much like Grant (2003), Cibin and Grant (1996), Grant and Cibin (1996), Bastian and Tucci (2010), and Ollinger's (1994) contributions in this field, Helfat's work looks more or less exclusively at large oil producing companies, and pays little attention to the service companies and other members of the upstream oil & gas ecosystem that play such an important role in the sector's technology development and deployment efforts today. As Martin (1996) points out, the upstream oil & gas sector consists of a highly interconnected system of organizations, and is therefore most appropriately considered in a system-wide way. Finally, I should point out that Enos (1958, 1962, 2002) offers some extremely detailed accounts of R&D and innovation in the downstream and refining parts of the oil & gas industry (which are frequently quite detached from what happens in the upstream part).

differently to R&D outputs such as patents and deployed innovations. Thus:

Research Question 2a: What is the relative contribution of technology-related patents from each type of organization within the upstream oil & gas industry?

Research Question 2b: What is the relative contribution of deployed technologies from each type of organization within the upstream oil & gas industry?

Not all new technologies are the same, however. One frequently recurring basis for analysis among technology management researchers is the degree of change brought about by an innovation. Some technologies are characterized in the literature as "radical" because: (1) they require the innovating companies to acquire fundamentally new skill sets (Afuah, 1998); (2) they add entirely new performance features, dramatically improve existing performance features, or significantly reduce costs (Leifer et al., 2000); or (3) they dramatically and obviously change the world around them by creating entirely new lines of business (Bozdogan et al., 1998; McDermott, 1999; Gilbert, 2003). "Incremental" innovations, by stark contrast, usually offer comparatively modest cost or feature improvements, and move things ahead in a way that more or less preserves the status quo (Leifer et al., 2000). Prior discussions about the upstream oil & gas industry explain that the inherent riskiness of the sector has resulted in a pronounced emphasis on incremental innovation over the years (Daneshy and Donnelly, 2004), but more radical breakthroughs such as 3D seismic mapping and horizontal drilling have appeared from time to time (Managi et al., 2005b; Martin, 1996; Yergin, 2011). However, much of the literature in this area is highly anecdotal, and relatively little has been said about the origins of these new technologies on an industry-wide basis. This leads to:

Research Question 3: What is the relative contribution of radical innovations from each type of organization within the upstream oil & gas industry?

Another important distinction applied in the technology management literature is that between product innovations and process innovations (Afuah, 1998; Tidd et al., 2001; Burgelman et al., 2004). As Schilling (2010) explains, "product innovations are embodied in the outputs of organizations—its goods or services… [while] process innovations are innovations in the way an organization conducts its business, such as in the techniques of producing or marketing goods or services" (p. 50). But here, too, the literature sheds relatively little light on the specifics of the upstream oil & gas sector on a worldwide basis, hence:

Research Question 4: What are the relative contributions of product- and process-based innovations from each type of organization within the upstream oil & gas industry?

A considerable amount of research in the technology management domain also examines the geographic aspects of innovation (e.g., Stuart and Sorenson, 2003; Feldman, 2010; Fifarek and Veloso, 2010), and the uncommonly global nature of the upstream oil & gas industry (Yergin, 1991; Hatakenaka et al., 2006; Goldstein, 2009) makes this sector a particularly interesting backdrop for investigations concerning the spatial dimensions of R&D.[4] Although the sector's R&D efforts occur in many places around the world, however, these activities are by no means evenly distributed. Barlow (2000) notes that the upstream oil & gas industry has seen "a high degree of geographical clustering" (p. 980), and much of the R&D-related research that specifically examines the sector has consequently focused on this. There have, for example, been a broad range of investigations into the myriad technology hubs and clusters that have emerged in different geographic locations around the world, including Texas (Elliott, 2011; Hinton, 2012), Australia (Steen et al., 2013), the UK (Bower and Young, 1995; Crabtree et al., 2000; Cumbers, 2000; Cumbers and Martin, 2001; Cumbers et al., 2003; Chapman et al., 2004; MacKinnon et al., 2004), Norway (Hatakenaka et al., 2006; Fagerberg et al., 2009; Hatakenaka et al., 2011), Brazil (Dantas and Bell, 2009, 2011; Silvestre and Dalcol, 2009, 2010), France (Furtado, 1997), the Middle East (Henni, 2013), and Nigeria (Vaaland et al., 2012). Far less is known, however, about how the industry's innovation processes happen on a global level. Accordingly:

Research Question 5: What is the relative contribution of upstream oil & gas innovations from different countries?

3. Method

3.1. *The survey*

An online survey was carried out in collaboration with the Society of Petroleum Engineers (SPE) to answer the research questions presented in the previous section. With more than 110,000 members in 141 countries, the SPE is the largest individual-member organization within the upstream oil & gas industry around the world. A "data firewall" was established so that I did not have access to any of the specific details of the survey participants. I helped to set up the survey and assisted with processing the results, but the name and company behind each completed survey was never divulged by the SPE.

Although the upstream oil & gas industry includes several large multinational firms, these companies often have a noticeably different approach to managing innovation and new technologies from one part of the world to the next throughout their global operations.[5] To capture these region-by-region differences, this survey asked questions about how technology- and innovation-related activities are managed at the *business unit* level. Smaller companies and organizations that develop and deploy upstream oil & gas technologies in a consistent way throughout all of their operations around the world were instructed to consider their entire organization as a "business unit" for the purposes of this survey.

Consultancies, universities, and governments also play a potentially valuable role in the innovation and R&D processes within the upstream oil & gas industry. This survey therefore included them, too. Throughout the survey, their "business unit" was the part of their organization that interacts with upstream oil & gas companies in their region.

Consisting of 23 questions, the survey asked respondents about several aspects of their business unit's R&D and innovation-related activities. The survey also asked for several self-reported measures of R&D output from their business unit. Respondents were informed before completing the survey, however, that their results would be made anonymous and aggregated with data from other respondents, thereby removing any incentive to distort their responses or provide untrue data.

The survey and corresponding delivery strategy were put together according to the principles outlined in Dillman's (2000)

[4] Although the majority of research concerning the geographic aspects of innovation within the upstream R&D industry has tended to focus on spatial phenomena, Bastian (2009) argues that the sector's vast geographic reach necessarily carries with it a broad array of political risks that also impact the technology strategies of the industry's firms.

[5] For example, Shell's Smart Fields digital oilfield program has had noticeable differences in deployment strategy from one region to the next, and BP's use of the WITSML drilling data exchange protocol in the North Sea is markedly different from what the company does in the Gulf of Mexico.

"Tailored Design Method."[6] One practical concession had to be made that was a clear departure from the prescribed formula, however: whereas Dillman (2000) recommends a four-contact model for maximizing survey return rates, the SPE was uncomfortable with contacting its members that many times. Instead, the SPE allowed three contacts in February 2012: an official e-mail from the SPE inviting people to answer questions about the explanatory variables; a reminder one week later; and then a final e-mail two weeks after the survey began to ask questions about the dependent variables and close out the survey. Questions asking about explanatory and dependent variables were separated in time to minimize the impact of common method bias (Podsakoff et al., 2003).

Prior to its release, the survey was tested by six people—three from the oil & gas industry and three from academia—who were familiar with questionnaires and survey-based research. The survey's questions were iteratively refined and improved based on this feedback, thereby reducing the potential for measurement error in the survey instrument (Lindner et al., 2001). Respondents were asked at the end of the survey if they would object to being asked a few clarifying questions about their responses. Several said yes, and five follow-up discussions were carried out later to deepen our understanding of the survey results.

3.2. Sample

Potential respondents were initially identified from SPE membership records. These individuals had indicated in their SPE profiles that their positions were somehow related to R&D or technology. From this subset of the SPE population, 469 individuals were invited to participate in the survey. Invited participants were typically high-ranking managers who played a significant role with regard to R&D and/or technology deployment in their business unit. Only one potential participant was chosen from each business unit, but several large organizations had respondents from multiple business units in different parts of the world. Candidates were invited to participate via an e-mail sent from the SPE. Upon clicking on a link in the e-mail, respondents were directed to a web-based survey.

Of the 469 people invited to participate, a total of 199 people completed both the explanatory and dependent variables within the survey, yielding an overall usable response rate of 42.4%. The "extrapolation method" (Armstrong and Overton, 1977) was used to test for nonresponse bias. Respondents were grouped as early (first 20%) or late (last 20%) in the timing of their reply, and responses from the two groups were compared using *t*-tests (Lindner et al., 2001). No significant differences were found between the two groups' responses, so the results can be reasonably generalized to the target population (Miller and Smith, 1983). Fig. 1 outlines the breakdown of respondents according to the type of organization by which they were employed. Table 1 shows the location of the worldwide headquarters for the respondents' employing organizations, and Table 2 shows the geographic location of respondents' business units. Fig. 2 outlines the breakdown of respondents according to the number of people who were directly employed by their employing organization around the world.

It should be noted that this pool of respondents clearly does not provide a comprehensive picture of the entire industry's R&D activities, and the statistics captured herein do not reflect the totality of the industry's output with regard to innovation and new technologies. Nonetheless, the survey does provide a potentially valuable snapshot of the industry's R&D-related activities around the world. Absolute figures gleaned from this survey—like, for

[6] This protocol is essentially an updated, internet-savvy version of Dillman's (1978) "Total Design Method," which has been a workhorse of survey-based research for decades.

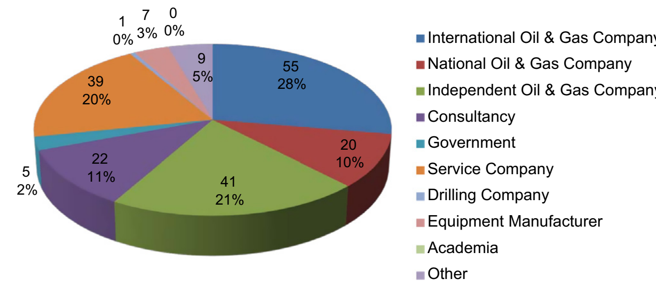

Fig. 1. Breakdown of respondents by type of organization.

Table 1
Breakdown of respondents by country where employing organization's global headquarters is located[a].

Country	Number of respondents	Percentage (%)
Australia	4	2.0
Austria	3	1.5
Canada	23	11.6
China	2	1.0
Denmark	6	3.0
India	6	3.0
Italy	3	1.5
Malaysia	2	1.0
Netherlands	23	11.6
Nigeria	4	2.0
Norway	8	4.0
Oman	4	2.0
Pakistan	3	1.5
Switzerland	3	1.5
United Arab Emirates	4	2.0
United Kingdom	18	9.0
USA	71	35.7
Other	12	6.0
Total	199	100.0

[a] *Note*: countries included in "other" category only had one respondent in them.

Table 2
Breakdown of respondents by location of their business unit.

Country	Number of respondents	Percentage (%)
Australia	7	3.5
Austria	2	1.0
Brunei	3	1.5
Canada	26	13.1
Denmark	3	1.5
France	2	1.0
India	7	3.5
Indonesia	2	1.0
Malaysia	8	4.0
Netherlands	10	5.0
Nigeria	4	2.0
Norway	6	3.0
Oman	7	3.5
Pakistan	3	1.5
Qatar	2	1.0
United Arab Emirates	3	1.5
United Kingdom	18	9.0
USA	74	37.2
Other[a]	12	6.0
Total	199	100.0

[a] *Note*: countries included in "Other" category only had one respondent in them.

example, the total number of innovations or patents reported by respondents—are of questionable value in and of themselves. But the *relative* measures and comparisons presented here do point to some interesting trends.

3.3. Measures

3.3.1. Explanatory variables

Much of the survey focused on the sources of knowledge that organizations rely upon throughout their R&D-related processes. What sources of information, data, and knowledge are most important as they develop new technologies? This part of the survey was modeled after the Eurostat Community Innovation Survey (CIS) of innovation, which has been used in over 60 academic articles for measuring the knowledge inputs that go into innovation-related activities (Laursen and Salter, 2005). As shown in Table 3, the framework consists of 16 potential sources of knowledge. Respondents were asked to identify the degree to which they had used each of the sources throughout the past three years, ranging from "not used" to "high use." In addition to the knowledge sources contained within the Eurostat framework, five more independent variables were added:

(1) Country in which the world headquarters for the respondent's company or organization resides.

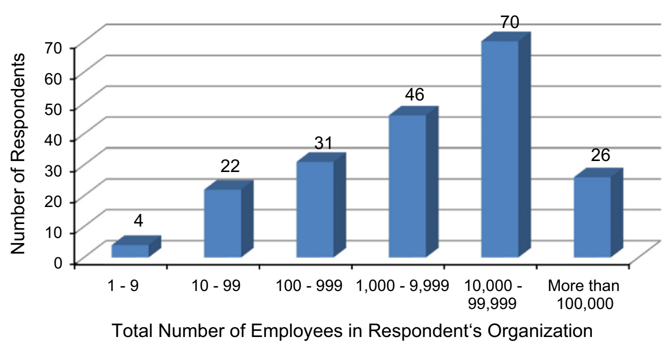

Fig. 2. Size of respondents' employing worldwide organizations.

(2) Country in which the local headquarters for the respondent's business unit resides.
(3) Number of employees in respondent's worldwide organization. This is conceptually similar to Laursen and Salter's (2005) "LOGEMP" variable.
(4) Number of employees in respondent's business unit. This is also similar to Laursen and Salter's (2005) "LOGEMP" variable.
(5) Type of organization for which the respondent works. These characterizations were gleaned from the SPE. Throughout their own surveys and data-gathering exercises over the years, the SPE has found that the following list contains organizational labels that are exhaustive, mutually exclusive, and that are understood by the overwhelming majority of people in the industry:
   (a) International Oil (or gas) Company;
   (b) National Oil (or gas) Company;
   (c) Independent Oil and/or Gas Company;
   (d) Consultancy;
   (e) Government;
   (f) Service company;
   (g) Drilling company;
   (h) Equipment manufacturer;
   (i) Academia;
   (j) Other.

3.3.2. Dependent variables

I used five proxies aimed at reflecting various types of innovative performance by business units:

(1) Following Chesbrough (2003b), the number of patents awarded in the last three years for which respondent's business unit played a leading role.
(2) Number of new technologies deployed within the last three years for which respondent's business unit played a leading role. Focusing on the rate of introduction of new products (Hagedoorn and Cloodt, 2003), this variable was used as an alternative measure of R&D output because patent statistics are frequently derided in the literature as being unreliable indicators of innovative performance (Archibugi,

Table 3
Sources of information and knowledge for innovation-related activities across all respondents.

Type	Knowledge source	Number of responses	Percentages			
			Not used	Low use	Medium use	High use
Market	Suppliers of equipment, materials, components, or software	143	6.2	23.1	33.6	37.1
	Clients or customers	141	19.2	16.3	33.3	31.2
	Competitors	142	19.7	45.8	28.2	6.3
	Consultants	144	18.8	45.8	23.6	11.8
	Commercial laboratories/R&D enterprises	141	24.8	37.6	22.7	14.9
Institutional	Universities or other higher education institutes	145	17.2	39.3	26.9	16.6
	Government research organizations	143	37.1	38.5	18.2	6.3
	Other public sector, e.g., business links, government offices	142	40.8	40.1	13.4	5.6
	Private research institutes	141	41.8	36.9	16.3	5.0
Other	Professional conferences, meetings	142	3.5	23.2	43.7	29.6
	Trade associations	142	31.1	38.7	22.5	7.7
	Technical/trade press, computer databases	141	15.6	31.9	36.9	15.6
	Fairs, exhibitions	141	15.6	36.2	38.3	9.9
Specialized	Technical standards	142	13.4	31.0	36.6	19.0
	Health and safety standards and regulations	142	16.1	31.0	26.1	26.8
	Environmental standards and regulations	141	14.8	29.8	28.4	27.0

1992). A "deployed technology" was defined in the survey as an innovation that has successfully gone through field trials, and that is ready to be used in revenue-generating activities.

(3) Number of radical innovations deployed within the past three years for which the respondent's business unit played a leading role. Using the definition put forward by Leifer et al. (2000), a "radical innovation" was defined in the survey as a new technology that fulfilled at least one of these criteria:
 (a) it delivered an entirely new set of performance features to the marketplace that simply were not available before;
 (b) it brought about an improvement in existing performance features of five times or greater;
 (c) it delivered a significant (30% or greater) reduction in cost.
(4) Number of innovations deployed within the past three years that were "new to the world," and for which the respondent's business unit played a leading role. This is conceptually similar to Laursen and Salter's (2005) "INNWORLD" variable.
(5) Characterization of nature of innovations created by respondent's business unit throughout the past three years. Options included:
 (a) majority were product/component innovations;
 (b) majority were process innovations;
 (c) an almost even mix of product and process innovations;
 (d) not applicable – did not create any innovations.

3.3.3. *Control variables*

Six control variables were also added to the survey so that I could assess the role of other potential factors and environmental influences that might affect the results. Specifically, these included:

(1) Did the global organization come into existence after 2008 (and should therefore be considered a startup)? (yes/no). This is conceptually similar to Laursen and Salter (2005) "STARTUP" variable.
(2) Did the business unit come into existence after 2008? (yes/no). This is also similar to Laursen and Salter's (2005) "STARTUP" variable.
(3) Following Laursen and Salter's (2005) "GEOMARKET" variable, a characterization of the largest market for respondent's business unit. Answers were limited to:
 (a) Local;
 (b) Regional;
 (c) National;
 (d) International.
(4) Much like for Laursen and Salter's (2005) "COLLAB" variable, has the respondent's worldwide organization been involved in any kind of collaboration arrangements pertaining to innovation-related activities—like, for example, a consortium, industry discussion group, or formal R&D partnership—within the past three years? (Yes/No).
(5) Also in the spirit of "COLLAB," has the respondent's business unit been involved in any kind of collaboration arrangements pertaining to innovation-related activities—like, for example, a consortium, industry discussion group, or formal R&D partnership—within the past three years? (Yes/No).
(6) In how many countries does the respondent's organization have offices and employees other than where the world headquarters are located?
 (a) 0;
 (b) 1–5;
 (c) 5–10;
 (d) 11–50;
 (e) 51–100;
 (f) More than 100.

4. Results and discussion

Based on the 16-item framework from the Eurostat CIS survey, Table 3 shows which sources of information, data, and knowledge were most important throughout the respondents' R&D and innovation-related activities. As noted earlier, respondents were asked to identify the degree to which they had used each of the sources throughout the past three years, ranging from "not used" to "high use." The data show that the largest sources of the industry's knowledge and inputs for innovation-related activities

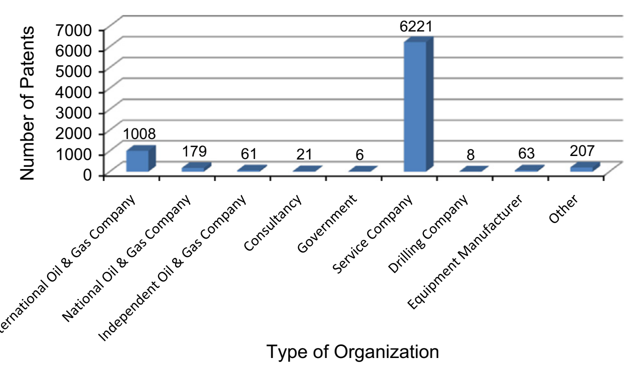

Fig. 3. Number of patents awarded in past 3 years for which respondent's business unit played a leading role.

Table 4
Percentage of respondents indicating "high use" for various knowledge sources throughout innovation-related activities in past 3 years.

Type of organization	Total responses to this question	Suppliers of equipment, materials, components, or software (%)	Clients or customers (%)	Professional conferences or meetings (%)	Health and safety standards and regulations (%)	Environmental standards and regulations (%)
International Oil & Gas Company	31	51.6	25.8	25.8	29.0	29.0
National Oil & Gas Company	14	42.9	21.4	28.6	42.9	42.9
Independent Oil & Gas Company	32	43.8	9.4	15.6	21.9	21.9
Consultancy	15	40.0	40.0	53.3	20.0	13.3
Government	5	20.0	60.0	40.0	60.0	60.0
Service Company	30	20.0	43.3	30.0	30.0	33.3
Equipment Manufacturer	7	28.6	42.9	14.3	0.0	0.0

are suppliers and clients. Professional conferences, health and safety standards, and environmental standards are also considered to be very important. By contrast, the industry places very little emphasis on government research organizations, universities, or public sector organizations where R&D inputs and knowledge are concerned.

Of the 16 potential knowledge sources, five were selected for more in-depth analysis because more than 25% of the total respondents had indicated that they relied on these particular knowledge sources as "high use" inputs. Table 4 answers Research Question 1 by showing how different types of organization rely differently on these top-five knowledge sources.

Of particular interest is the fact that IOCs relied on their suppliers more than any other knowledge source, but service companies relied very little on their suppliers. The tables are turned on "Clients or Customers," however: IOCs did not consider this to be a particularly valuable knowledge source, but service companies did. This suggests that IOCs' innovation-related activities are more guided by suppliers' activities than by feedback from their customers. Table 4 also shows that the industry's consultants seem to have relied quite heavily on professional conferences and meetings as knowledge sources. NOCs and government respondents put noticeably more emphasis on Health and Safety Standards and Environmental Standards as knowledge sources than did other types of organizations.

Towards answering Research Question 2a, I examined the number of patents reported by the respondents. As shown in Fig. 3, service companies generated about 80% of the patents reported in the survey. This statistic is all the more impressive when you consider that slightly less than 20% of the respondents worked for service companies. By contrast, relatively few patents were reported by independent oil & gas companies, effectively signaling that the developing of proprietary technologies was not a strategic priority for these firms. Also, significantly fewer patents were reported per responding business unit from NOCs than from IOCs.

To answer Research Question 2b, respondents were also asked about the number of technologies deployed within the past three years for which their business unit played a leading role. Perhaps unsurprisingly, Fig. 4 shows that the types of organizations deploying the most innovations also tended to file the most patents.

But an interesting trend emerges when the underlying numbers behind Figs. 3 and 4 are examined together: the relative number of patents filed per deployed technology varies quite significantly from one type of organization to the next. Table 5 shows that service companies filed an average of 8.0 patents per deployed technology; IOCs, by stark contrast, filed only 4.4, and most other types of organization produced even less. While the data point to a clear trend, however, they fail to explain why service companies put so much more emphasis on patenting their innovations than other parts of the industry. Upon reviewing the survey data, an executive from a service company offered this explanation:

> IP [that is, intellectual property] is typically used to defend a space in the marketplace for future business or defend products and service evolution in the businesses we are in. If you start to plot out "competitive threat vectors," the service side—especially the integrated service side—have the most degrees of competition (from direct competition, niche service players, tech start-ups, academia and customers)… As such, we typically have IP strategies that build protective layers around core ideas to make it more difficult for competitors to "design around."

This particular finding is important insofar as it highlights the distortions that can arise when investigations about the industry's R&D rely principally on patent statistics as a direct proxy for innovative output. Because service companies typically file many more patents per innovation than other types of organizations in the sector, any analysis on R&D activity based only on patent figures is quite likely to overstate the relative contribution of service companies.

Another important aspect of Research Questions 2a and 2b concerns whether or not the size of the respondent's organization impacted its R&D output. Are large organizations better positioned to create new innovations in the upstream oil & gas industry than small ones?

Table 6 shows that the majority of deployed technologies (74.8%) and patents (79.2%) from the past three years that were reported by respondents came from organizations with between 10,000 and 99,999 employees. This is not a surprising result, however, when one considers that many of the larger service companies fit comfortably within this profile.

To answer Research Question 3, respondents were asked to report the number of radical innovations that their organizations had deployed throughout the past three years. As shown in Table 7, smaller firms with fewer employees contributed relatively more to the creation of the industry's radical innovations than larger firms did. Nearly 15% of the reported radical technologies came from companies with less than 1000 employees, but these

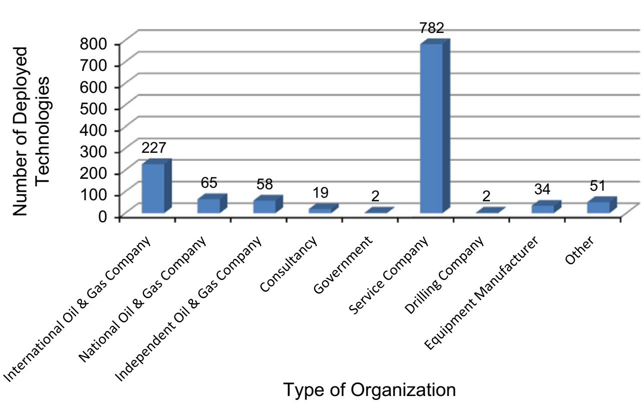

Fig. 4. Number of deployed technologies in past 3 years for which respondent's business unit played a leading role.

Table 5
"Patent intensity" of innovation: average number of patents received per deployed technology by organization type.

Type of organization	Number of deployed technologies in past three years for which respondent's business unit played a leading role	Number of patents awarded in past three years for which respondent's business unit played a leading role	Patents/ deployed technologies
International oil & gas company	227	1008	4.4
National oil & gas company	65	179	2.8
Independent oil & gas company	58	61	1.1
Consultancy	19	21	1.1
Government	2	6	3.0
Service company	782	6221	8.0
Drilling company	2	8	4.0
Equipment manufacturer	34	63	1.9
Other	51	207	4.1
Total	1240	7774	6.3

Table 6
Innovative output of firms vs. size of respondents' worldwide organizations.

Number of employees within organization	Number of respondents	Percentage of respondents (%)	Number of deployed technologies in past 3 years for which respondent's business unit played a leading role	Percentage of total deployed technologies in past 3 years (%)	Number of patents awarded in past 3 years for which respondent's business unit played a leading role	Percentage of total reported patents in past 3 years (%)
1–9	4	2.0	2	0.2	7	0.1
10–99	22	11.1	49	4.0	38	0.5
100–999	31	15.6	40	3.2	650	8.4
1000–9999	46	23.1	103	8.3	374	4.8
10,000–99,999	70	35.2	928	74.8	6156	79.2
More than 100,000	26	13.1	118	9.5	549	7.1
Total	199	100.0	1240	100.0	7774	100.0

Table 7
Output of radical innovations vs. size of respondents' worldwide organizations.

Number of employees within organization	Number of radical innovations deployed in past 3 years for which respondent's business unit played a leading role	Percentage of total radical technologies in past 3 years (%)
1–9	1	0.3
10–99	29	7.9
100–999	25	6.8
1000–9,999	39	10.6
10,000–99,999	241	65.7
More than 100,000	32	8.7
Total	367	100.0

Table 8
Radicalness of innovations by organization type.

Type of organization	**Number of deployed technologies in past 3 years for which respondent's business unit played a leading role**	**Number of radical innovations in past 3 years for which respondent's business unit played a leading role**	**Percentage of deployed technologies considered to be "radical"** (%)
International oil & gas company	227	83	36.6
National oil & gas company	65	54	83.1
Independent oil & gas company	58	30	51.7
Consultancy	19	12	63.2
Government	2	1	50.0
Service company	782	155	19.8
Drilling company	2	2	100.0
Equipment manufacturer	34	11	32.4
Other	51	19	37.3
Total	1240	367	29.6

firms were responsible for less than 8% of the total number of deployed technologies during that same period.

But the data also suggest that the same large firms—that is, those with 10,000–99,999 employees—that create most of the upstream oil & gas sector's new technologies also seem to be responsible for nearly two-thirds of the radical innovations. In other words, they may indeed have contributed fewer radical innovations on a proportional basis, but their sheer size and the overwhelming volume of new technologies that they provide in the industry mean that large companies contributed most of the industry's radical innovations in absolute terms.

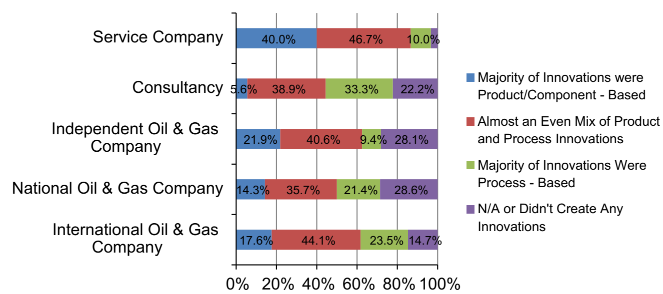

Fig. 5. Relative fraction of respondents focusing on process- and product-based innovations.

Table 8 shows the different emphasis on radical innovations by different types of organization within the industry. There is no shortage of qualitative evidence in the literature (e.g., Daneshy and Donnelly, 2004) suggesting that service companies tend to steer their R&D portfolios towards more incremental technologies that are essentially iterative improvements on existing product lines. The data presented here do not contradict this widely held belief. NOCs and independent oil & gas companies, on the other hand, behave very differently in that they do not create and deploy large numbers of technologies overall, but they consider what they do create to be fairly radical in nature.

Towards answering Research Question 4 concerning the relative focus on process- vs. product-based innovation in the industry, Fig. 5 shows that many respondents reported that their business units were almost evenly focused on product/component-based innovations and process-based innovations. Service companies had the highest fraction of respondents (40%) who believed that their business units were more focused on product/component types of innovation.

As explained earlier, the uncommonly global nature of the upstream oil & gas industry makes this sector a particularly interesting backdrop for investigations concerning the spatial dimensions of R&D. Table 9 addresses Research Question 5 by showing the geographic origins of the deployed technologies according to the country where the creating organization's head-quarters were located. Although only 35.7% of the respondents were from the USA, over 60% of the reported deployed technologies came from companies based in that country. This leaves little doubt that

Table 9
Geographic origin of headquarters for innovating organizations.

Country	Number of respondents whose organization's world HQ is in that country	Percentage of total respondents from this country (%)	Number of deployed technologies in past 3 years from organizations whose worldwide headquarters in that country	Percentage of deployed technologies that came from organizations whose headquarters are in this country (%)
Australia	4	2.0	6	0.5
Austria	3	1.5	7	0.6
Canada	23	11.6	37	3.0
China	2	1.0	0	0.0
Denmark	6	3.0	8	0.6
India	6	3.0	4	0.3
Italy	3	1.5	45	3.6
Malaysia	2	1.0	25	2.0
Netherlands	23	11.6	125	10.1
Nigeria	4	2.0	1	0.1
Norway	8	4.0	25	2.0
Oman	4	2.0	3	0.2
Pakistan	3	1.5	5	0.4
Switzerland	3	1.5	80	6.5
United Arab Emirates	4	2.0	8	0.6
United Kingdom	18	9.0	48	3.9
USA[a]	71	35.7	748	60.3
Other	12	6.0	65	5.2
Total	199	100.0	1240	100.0

[a] Although Schlumberger has principal offices in Houston, Paris, and The Hague, all of the respondents from that company pointed to the USA as their world headquarters.

Table 10
Geographic origin of business units where innovations were deployed.

Country	Number of respondents	Percentage of total respondents from this country (%)	Number of deployed technologies in past 3 years from respondents whose BUs are in that country	Percentage of deployed technologies that came from respondents whose BUs are in this country (%)
Australia	7	3.5	8	0.6
Austria	2	1.0	5	0.4
Brunei	3	1.5	0	0.0
Canada	26	13.1	39	3.1
Denmark	3	1.5	2	0.2
France	2	1.0	50	4.0
India	7	3.5	4	0.3
Indonesia	2	1.0	1	0.1
Malaysia	8	4.0	33	2.7
Netherlands	10	5.0	93	7.5
Nigeria	4	2.0	5	0.4
Norway	6	3.0	25	2.0
Oman	7	3.5	14	1.1
Pakistan	3	1.5	5	0.4
Qatar	2	1.0	6	0.5
United Arab Emirates	3	1.5	5	0.4
United Kingdom	18	9.0	60	4.8
USA	74	37.2	527	42.5
Other	12	6.0	358	28.9
Total	199	100.0	1240	100.0

the USA is still largely the epicenter of innovation and new technologies in the upstream oil & gas sector. The USA's dominance is supported further by the data in Table 10, which offers a breakdown of the deployed technologies according to the geographic location of each respondent's business unit. Almost certainly due to the presence of Royal Dutch Shell's headquarters in The Hague, the Netherlands plays an important role in the industry's R&D activities as well.

The relative contribution of new technologies from the UK was also surprising, but because of the meager number of innovations reported from that country. Despite the UK's significant footprint in the upstream oil & gas sector and the considerable body of research about oil & gas technology hubs in that country (Bower and Young, 1995; Crabtree et al., 2000; Cumbers, 2000; Cumbers and Martin, 2001; Cumbers et al., 2003; Chapman et al., 2004; MacKinnon et al., 2004), respondents from UK-based organizations reported relatively few deployed innovations. A total of 9% of the survey's respondents were employed by UK-domiciled companies, but only 3.9% of the deployed innovations captured in the survey came from those firms. And although Switzerland has comparatively little in the way of domestic oil & gas resources, respondents from Switzerland-based organizations reported a surprisingly large number of deployed technologies related to the upstream oil & gas sector.

5. Conclusions and recommendations

5.1. Implications for theory

By providing a detailed snapshot of how innovation happens in the upstream oil & gas sector, this paper provides a valuable foundation for future investigations and discussions aimed at improving how R&D and technology deployment are managed within the industry. Of the many statistics and trends discussed in the previous section, one stands out as being particularly helpful from a theoretical point of view: over 63% of the deployed innovations reported in the survey originated in service companies. As noted earlier, technology will clearly play a pivotal role in the success or failure of tomorrow's oil & gas firms, and the shift in the industry's technological center of gravity away from the IOCs towards the service companies may therefore go some way towards explaining the enormous transfer of market power that has occurred within the industry. As recently as 1972, seven IOCs—specifically, Exxon, Texaco, Socal, Gulf, Mobil, BP, and Shell—directly controlled 70% of the world's total oil production (Sampson, 1975, p. 241), but Western IOCs now manage less than 10% (Jaffe and Soligo, 2007). By contrast, the largest of the service companies, Schlumberger, has increased in value four-fold throughout the past decade (Economist, 2012) and, with a market capitalization of US$92 billion, is now bigger than all but the largest of its customers (PFC Energy, 2013). One would expect that the economic rewards in an industry that is increasingly technology-driven would increasingly go to the firms that create most of the innovations—and, indeed, that seems to be what is happening. In this way, the evidence presented in this paper usefully adds to theoretical discussions in the literature about this dramatic transfer of market power within one of the world's largest industries.

5.2. Implications for industry and policy

One other interesting finding from the survey was that neither universities nor government-led research organizations were considered to be valuable sources of new information and knowledge in the industry's R&D initiatives. Towards unlocking their local oil & gas reserves, several countries' government agencies and publicly funded universities—including high-profile institutions like the U.S. Department of Energy, the UK's Natural Environment Research Council, and the Norwegian Petroleum Directorate—currently spend many millions of dollars every year on R&D programs focusing on a wide variety of topics like offshore drilling and enhanced oil recovery. The evidence presented here draws into question the effectiveness of these types of investment strategies within this domain, however. These publicly funded bodies would therefore do well to find out why their R&D investments have been met with such a lukewarm reception by the industry before investing more money in these areas.

And the sheer size and uncommonly high profile of the industry cause some of the results presented here to carry with them larger strategic and geopolitical consequences, too. The USA's dominant role in the industry's overall R&D and technology deployment activities is an important example of this. As explained earlier, over 60% of the reported technologies deployed within the three-year timeframe of the survey originated in organizations whose headquarters were in the USA. This finding underlines the efficacy of American-led sanctions of oil-rich countries like Iran (e.g., Amuzegar, 1997; Jacobson, 2008) inasmuch as it shows how difficult it would be for these countries to monetize their hydrocarbon resources without any kind of American technology or expertise. U.S.-led sanctions tend to cause economic hardship and distress for practically any nation on the receiving end of this tactic (Selden, 1999), but the evidence presented here strongly hints that these policies are considerably more potent against nations whose economies heavily depend on oil & gas.

Also, beyond merely improving the future performance of technology development and deployment in the upstream oil & gas industry, the data presented here are also relevant to the topic of CO_2 mitigation and climate change. Carbon capture and sequestration (CCS) has been explored at length in the literature as an extremely promising strategy for reducing the amount of CO_2 emitted into the atmosphere (Anderson and Newell, 2004; Holloway, 2005; Gibbins and Chalmers, 2008). The oil & gas sector has considerable experience and know-how in many of the technical disciplines that will likely contribute to technical improvements in CCS, such as reservoir engineering and modeling, downhole measurement, and well engineering. It therefore follows that any gains that can be achieved with regard to how the upstream oil & gas sector manages innovation could also potentially translate to advances in the CCS domain. In this way, an improved understanding of how new technologies come about in the upstream oil & gas industry could be parlayed into better strategies for reducing the amount of CO_2 emitted into the atmosphere.

5.3. Recommendations for future research

Despite the potentially valuable insights that the data provide, however, this survey was clearly not without limitations. One unavoidable consequence of identifying prospective survey participants from SPE membership records is that it created a significant coverage bias within the sample. Coverage biases arise when the list or frame from which the sample is drawn fails to contain all of the subjects within the target population (Lindner et al., 2001). Using dues-paying members of the SPE to sample the population of R&D managers and executives within the upstream oil & gas industry clearly does introduce this kind of experimental error. Thus, even though I have no doubt that the number and quality of the respondents who participated in this survey was profoundly improved because of the SPE's participation in the project, I must concede that this strategy essentially created a different kind of methodological weakness. Moreover, in spite of the dozens of petroleum engineering departments and thousands of academics working in this domain at universities around the world, the pool of survey respondents did not include any academics working in this research space. Future investigations in this area should attempt to overcome these methodological shortcomings.

Finally, as diagnosed earlier, the survey data reveal that neither universities nor government-led research organizations were considered to be valuable sources of new information and knowledge in the industry's R&D initiatives, but this investigation fails to explain why this is the case. Yin (1994) points out that qualitative research methods are “the preferred strategy when ‘how’ or ‘why’ questions are being posed” (p. 1). Thus, one potentially fruitful line of questioning for the future would be to approach this phenomenon with a more qualitative methodology to explain why this widespread perception exists within the industry.

Acknowledgements

A practitioner-focused version of this paper, entitled “How Does Innovation Happen in the Upstream Oil & Gas Industry? Insights from a Global Survey” (paper no. SPE-166084-MS), was presented at the Society of Petroleum Engineers' Annual Technical Conference & Exhibition in New Orleans, USA, from September 30 to October 2, 2013. The highlights of this survey were also discussed in an article entitled “Who Drives E&P Innovation?” in the December 2012 issue of the SPE's *Journal of Petroleum Technology*, an oil & gas trade magazine. Special thanks to the SPE's John Donnelly and Jason Davis for their assistance throughout this project. They are the “invisible co-authors” of this document. I also wish to thank Robin Mills and two anonymous reviewers from this journal for comments made on earlier versions of this paper.

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