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Can a mature resource-based industry become high-tech? Transformations of sectoral innovation systems in upstream petroleum industry

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Abstract

This article analyzes the transformation of sectoral innovation systems in upstream petroleum industry and its drivers. The evidence collected shows that this sector has experienced three distinctive phases since the early 1970s over which both upstream industry architecture and innovation systems have changed in configuration and performance. This study shows that the major driver behind transition from the first to the second period was collapse of oil prices. However, the major factor behind transition from the second to the third period was emergence of 'qualitatively' different demand for complex upstream projects in harsh and less accessible environments which drove innovation opportunities and pushed emergence of integrated service companies. In contrast to the conventional industry life cycle model, this study shows that a mature and established industry can transform to a high-tech sector, when major agents in the sector actively participate in the innovation system to meet the new technical requirements. It also shows transformation of sectoral innovation systems can be analyzed in terms of interaction between changes in architectural changes and innovation dynamics.

Keywords: Sectoral Innovation Systems. Upstream Petroleum Industry, Industry Life Cycle.

1. Introduction

When Colonel Drake drilled the first oil hole in 1869 in Pennsylvania, he never imagined he was launching a new era. An industry emerged which for some became a blessing, but for others brought curse [1]. The modern industrial era was built upon black gold as source both of energy and raw material for many economic activities. Its supply security became a main concern of the international community. [2&3].

Although petroleum has been introduced "as necessary to the economy as blood to the human body" [2], the industrialization experience of some countries like Japan and Korea shows that what matters is not necessarily oil ownership, but control over supply. On the other hand, the resource curse story suggests that this industry can be the source of misfortune if is not managed properly [1]. Nonetheless, some advanced countries have benefited hugely from their oil reserves. The benefits are not limited to enormous revenues, but include industrial and technological capabilities [4].

If the natural resource based countries are to enjoy the long term benefits of their resources, it is necessary to revise the conventional view of resource industries and understand their capacity for innovation and technical changes. This article aims to put forward a long term view of upstream petroleum industry to increase our understanding of its innovative capacities, their transformations and reconfigurations.

The analytical framework presented is the sectoral innovation system (SIS), because it puts learning and innovation processes at the centre of analysis and highlights their role in industrial dynamics and transformations [5].

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The advantage of this framework is its systemic, integrated and dynamic approach and focus on technological regimes of specific sectors. The aim is to understand innovation dynamics in upstream petroleum and the factors shaping the technological base of the industry. The drivers and consequences of technological innovation in upstream petroleum industry are discussed, together with changes in the industry architecture.

We explore changes in the division of labour between different actors and how it may affect the innovation performance of the sector. We also discuss how innovation dynamics may change the industry architecture in order to explain the transformations of sectoral innovation systems. Patent information in upstream petroleum industry from 1970 to 2005 used in order to evaluate the innovation dynamics of the sector and track major transformation in this SIS. In addition to this primary data source, a variety of secondary sources (such as scholarly publications, business and industry reports, companies' websites, professional journals and the views of industry analysts) are employed to complete the analysis and provide interpretations. We use historical analysis in order to track changes and find out the driver and consequences of transformations in upstream petroleum industry.

The main finding is that the upstream petroleum sector has gone through three main phases of transformation distinguished by different industry architectures and innovation systems. The main innovators however are major players from within the sector, confirming upstream as an active and dynamic 'high-tech' industry. This neither fits with conventional wisdom nor the standard industry life cycle model [6] which often sees mature resource-based industries as low-tech sectors exhausted of innovations [7]. Nonetheless, the role of different companies has evolved and their innovation share has changed over time.

These original findings offer novel contributions to SIS literature, extending its empirical scope to non high-tech resource-based industries which have rarely been studied. We find that the systemic and dynamic nature of SIS framework provides a more comprehensive picture of industry evolution which the standard industry life cycle model is unable to show. The SIS approach captures both supply and demand factors and their evolving interactions combined with industry architecture dynamics to analyse the industrial dynamics of the sector.

This article is organized in 8 sections. After this introduction, section 2 introduces sectoral innovation systems as our analytical framework. The methodological issues of this study are addressed in the section 3. In section 4, a historical background of upstream petroleum industry is presented. Section 5 analyzes the changes in the industry architecture and its drivers. Section 6 discusses the dynamics of innovation within SIS framework to shed new light on sector innovative performance. Section 7 explore the relationship between changes in the industry architecture and innovation dynamics and discusses how and why the role of different companies in the innovation processes has evolved over time. The last section summarizes findings and concludes.

2. Sectoral Innovation Systems

> *"A sectoral system of innovation and production is a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products" [5].*

The concept of SIS draws from the traditions of evolutionary economics and systemic approaches to innovation. Attention to knowledge and learning processes, central focus on competencies and the dynamic approach come from the evolutionary camp. In this dynamic approach, SIS has broad relevance to the industry life cycle literature [8&9], as well as the research stream on long-term evolution of industries, as found in the writings of Schumpeter, Kuznetz and Clark [5].

It borrows its systemic approach from innovation system literature [10], which focuses on actors, their relationship and interactions, and their institutional environment. This concept is best understood as complementary to other similar concepts. National innovation systems focuses on national boundaries [11-13]; and regional/local innovation systems takes a regional boundary [14]. Technological systems focus on networks of agents involved in the generation, diffusion and utilization of particular technologies [15-17]. Although they vary in terms of analytical boundary, all consider the systemic nature of innovation processes.

While SIS has many commonalities with these concepts in terms of core analytical approach, it departs from all of them in its delimitation boundary at sectoral level. Accordingly, the central question that this approach tries to answer is “How and why does innovation differ across sectors?” [18]. In this view, sectors are often defined based on related or substitutable product groups which serve a given or emerging demand with an underlying common sector specific knowledge. Building on these intellectual traditions, SIS provides a multidimensional, integrated and dynamic view of sectors in order to understand and explain structure and organization of innovative activities.

This approach often proposes three main building blocks to define and analyse sectoral systems: (for more information see references [18-21])

- Knowledge and technological domain
- Actors and networks
- Institutions

2-1 Knowledge and technological domain

The specific knowledge base, technologies and inputs are important elements of a sector. They can set the boundaries for the sector in a dynamic perspective. Accordingly, as the knowledge base and working technologies of a sector change, its boundaries also change. Additionally, complementariness and technological interdependencies are important in defining relationships between sectors. The particular focus of the SIS approach on the role of knowledge base and its characteristics in shaping structure and organization of innovative activities is its attractive and relevant feature for the current analysis.

2-2 Actors and networks

A sector is composed of heterogeneous actors of both firm and non-firm organizations (individuals, universities, research organizations, etc.). They are involved in the generation and introduction of innovations and production of goods and services. In the SIS approach, they are characterized by specific sets of beliefs, objectives, expectations, capabilities and learning processes [18]. They may have different types of interactions and relationships with each other. These relationships form the networks in which actors may have both market and non-market interactions.

The types of networks and the structure of relationships may differ among sectors. They are shaped by knowledge base characteristics, learning processes, underlying technologies and their complementarities and interdependencies [18]. The structure and pattern of innovative activities may change over time in the same sector, as a consequence of changes in the knowledge bases and relevant learning processes. So, the role of different actors and their relative position in the innovation network may change when new divisions of labour emerge.

2-3 Institutions

Institutions are defined as norms, rules, laws, common habits and practices which shape actors’ cognition, actions, interactions and behaviour. They include both formal types such as rules which are legally binding or informal types which are established and accepted through practices [18].

In addition to these three building blocks, demand is often considered as a key part of the system. It is shaped by different types of users, their goals and learning processes, and their interaction with other types of agents. User-producer interactions are considered very important in the innovation process. Transformation of the nature of demand plays an important role in the dynamics and evolution of systems [18].

2-4 Transformations of sectoral innovation systems

SIS is a dynamic system which may change over time in response to several processes. According to the evolutionary view, two very general processes of variety creation and variety selection can be identified. Variety creation and selection can refer to products, technologies, firms, institutions as well as actors' strategies and behaviours with regard to R&D and innovation. More specifically, a sectoral system may experience evolution and transformation due to co-evolution of its various elements. In this dynamic view, transformation of existing sectoral systems as well as emergence of new ones is at the centre of analysis [2&22].

For example, integration and creation of interdependencies between previously separated knowledge and technologies can change the system configuration and relationship between actors. It may lead to creation of new actors and removal of old ones [21]. Of particular interest in this research is to analyze how changes in the knowledge base and learning processes could induce the process of change in the sectoral system of the upstream petroleum industry.

The transformation of SIS is related to other concepts are used in this article. The first is the Industry life Cycle (ILC) and the other is Industry Architecture (IA). ILC is often regarded as one of the main intellectual roots of SIS approach [5]. Particularly, attention to the dynamics and transformations of sectors and the role of innovation and technical change in industrial dynamics in SIS approach partly come from this concept. Nonetheless there are some important differences. While ILC tend to takes a *universal* and uniform approach to cyclical developments of industry, the SIS approach highlights tentative *differences* between industries created by their technological regimes like appropriability conditions and their institutional environment. These conceptual and methodological differences privilege SIS for the purpose of this study [23].

The Industry Architecture concept (IA) [24&25] is introduced in response to inadequacies in the conventional view of industry where the boundaries are implicitly fixed and given. Although the general questions the two concepts are seeking to answer are broadly different, they have some common methodological elements. While SIS approach is more concerned with structure and organization of innovative activities in different industries, IA focuses more on the analysis of vertical structure of the sectors in their production processes and organization of value chains. The concept of IA aims at capturing the rapidly changing boundaries of industries and shifting *'roles and rules'* over time [24]. The dynamics of IAs capture evolutionary changes and pay attention to the stable but evolving relationships between different players along the value chain. It seeks to understand what makes sectors swing between integration and disintegration and how knowledge integration happens in the production processes [25]. I use the term IA in this article to describe the evolution of the vertical division of labour among different agents in upstream petroleum industry.

Geographical boundaries of sectoral systems could be set at local, national and global levels and may also change over time, depending on the objectives of the study. In this article I look at SIS of upstream petroleum industry at global level. SIS approach is also flexible in product boundaries which could be defined very broadly or narrowly. The advantage of a broad definition is that interdependencies, linkages and transformations spanning over wide range of products, processes, actors and functions are taken into account. This article applies a broad definition, covering all activities involved in exploration, development and production of oil reserves and other supporting activities which classified in upstream petroleum industry.

3. Methodological issues

In order to analyze the transformations of sectoral innovation systems in upstream petroleum industry, both primary and secondary data sources are used. My primary data source is the Derwent Innovating Index, the patent database which classifies all upstream petroleum industry patents in class H01. This class covers exploration, drilling, well services and stimulations, production and their sub segments of the upstream petroleum industry. In order to control for quality of the data and the possibility of inter-sectoral comparisons, I rely only on the patents registered in the US patent office. Patent counts are used as a proxy to capture of dynamics of innovative performance of the sector.

While the primary data source for this study is patent information, a variety of secondary sources (such as scholarly publications, business and industry reports, companies' websites, professional journals and the views of industry analysts) are employed to get deeper insights. These data sources provide valuable information regarding the historical context in which transformations happened and the main drivers operated at different levels. We match the patterns obtained from the patent data with this historical information in order to provide a consistent picture of industrial dynamics. Potentially, other innovation data such as R&D investments, new products and services could have completed our analysis. Unfortunately, they have not been available to the author to be used in this study.

Patent data is the only rigorously classified information about technological innovation covering both long time periods and a wide range of countries, all of which are essential to answer the research questions of this research. Patent data are unique and rich information for studying innovation and technical change, although it has its own limitations. This information nowadays is often published on government's patent office websites. The requirements of the legal process for patent applications imply the formation of qualified patent databases with the detailed classified information on the nature of invention (its novels aspect, technical fields, industrial applications, etc.), and its assignee and inventors. As a result, patent data have been an invaluable source of information for empirical studies of innovative activities and technical change for many years (see [26]. It is also accelerated recently by the availability of powerful computational technology.

The advantages and limitations of patent data for the analysis of innovative activities is a widely discussed issue in the literature. It is particularly important to consider the limitations and disadvantages such as systematic biases in the data which may produce distorted results, if they are not treated properly. The main disadvantages include [27-30]:

- Not all inventions are legally patentable. The classic example is software which is often protected by copyright. Moreover, the patenting scope may differ from one country to another depending on their particular patent law.
- Although some international agreements have become effective, in the end patents are binding within national territories. Because of different institutional structures in different countries which affect the length, time and effectiveness of protection, the inventor's interest may differ in terms of the countries where they seek protection.
- Patents are not the only or even the major tool to protect inventions. There are alternatives such as lead time and industrial secrecy.
- The patenting propensity is different among firms and industries. For some industries, a patent is a major competitive tool, while for some other industries it is not.

As a result, patents are only imperfect measures of innovation order. We should consider these limitations in our analysis. For example, patents are biased towards advanced manufacturing and therefore underestimate innovation in services. Firms and countries that are specialized in service segments of a sector may seem less innovative in patent data, in spite of the knowledge intensive nature of innovation in services.

Although these limitations suggest that patents are imperfect proxies for innovative activities, we believe that results of this study are not seriously affected. This is because almost all of the conclusions in this study are drawn based on the analysis of the *trends* rather than actual *levels* of the suggested variables. Therefore, we expect imperfections to shift levels up or down without influential impact on the trends.

4. Historical background[1]

Historically, the Standard Oil Company dominated the American oil market from its creation in 1870 until 1911. A vertically integrated strategy, from upstream to downstream, was a tool used to control this profitable business. This legacy was an important barrier to easy entry of new companies. Large financial obligations created an oligopolistic market structure first in US and then at international level. However, Standard Oil was broken into smaller companies (New Jersey as Esso then Exxon; New York as Mobil; California as Chevron) following US antitrust policy. Together with four other newly created companies (Texaco, Gulf, Royal Dutch Shell and Anglo-Persian which later became BP in 1951), they formed 'majors' controlling a majority of the world oil production chain. The term '*seven sisters*' were coined to describe the close relationships between these Anglo-Saxon companies. Their hegemony came to an end in 1980s after more than half a century, when national oil companies emerged and upgraded their position [2][31].

The Great War taught some governments how important oil independence was for victories in international affairs. Anglo-Persian and Royal Dutch Shell were key for energy independence in British and Netherlands governments. Similarly, the French government established CFP (Compagnie française des pétroles), later named Total in 1991 [2]. After the Second World War, some other European countries continued to establish their own government backed oil companies to secure their energy independence. ENI in Italy, ELF as the second national French oil company were two examples. IFP[3] also was established in France in 1944 seeking long-term oil independent by training, R&D and production of knowledge, technology and equipment.

From the late 1940s, the relationship between international oil companies and producing countries began to change as a consequence of the Second World War. Under pressure for a greater share of national wealth, Iranian petroleum was nationalized in 1979. Intensive competition and over supply of crude oil pushed down oil prices in late fifties. This triggered the establishment of OPEC[4] in 1960 by the main producing countries to restore declining oil prices. In addition, other political and economic events such as oil nationalizations in other Arab countries, the Six Day War, increasing oil consumption, and widespread concerns about world limited reserves prepared the scene in the sixties and early seventies for the first oil shock in 1973. The Iranian revolution in 1979 was the main source of the second oil shock which was exacerbated and continued by the Iran-Iraq war in 1980s pushing oil prices up to $38/bbl. The trend of oil prices after 1970 and the main influential factors is shown in the figure 1.

Continued high oil prices and political instability in the Middle East encouraged western and other countries to diversify their supply sources. Concerns of scarcity and high oil prices also increased R&D investments making extraction from high exploitation-cost fields in harsh environments and deep offshore economically feasible. A counter shock happened in 1986 as a result of unilateral decision of Saudi Arabia when so-called 'net back contracts' were introduced. Although this decision was abandoned soon by OPEC, it was not very effective due to the increasing share of non-OPEC producing countries. This structural balance stabilized low oil prices for nearly two decades, in spite of short time fluctuations. Technological innovation in upstream petroleum industry became a key to bring challenging reservoirs into stream, particularly in deep offshore.

1- This historical background is largely drawn from Babusiaux et al (2004)

2- For more information about history of seven sisters see referecne [32].

3- Institut français du pétrole

4- Organization of the Petroleum Exporting Countries

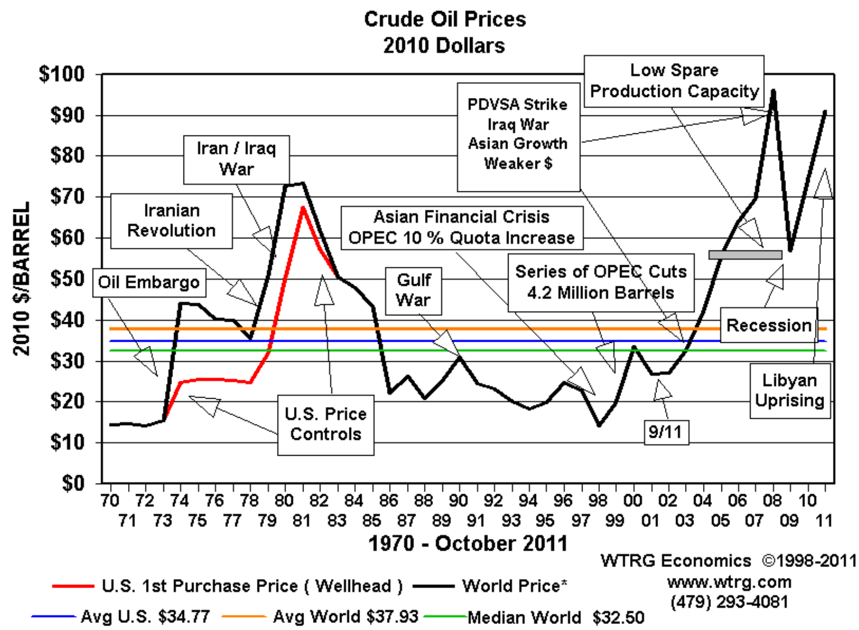


Figure 1. Crude oil prices (based on 2010 adjusted dollar for inflation) [33]

After the turn of the century, oil prices began to increase again relatively rapidly, except for a short period driven by the financial crisis in 2008. There are good structural reasons to expect that this increase will last into the medium to long term. The main driver is suggested as increasing demand in big industrializing countries such as China and India. While there are structural limits on the supply side, these countries have rapidly expanded demand due to high economic growth rates. This is not limited to petroleum but applies to most commodities and resources [34&35]. This short history of the industry shows the high level of volatility and great involvements of politics and government policy. This historical perspective is helpful to explain the changes in industry architecture and dynamics of innovation in the sector, as will be shown in the section 5 and 6.

5. Dynamics of Industry Architecture

Upstream petroleum industry is one of the sectors known for several restructuring and industrial dynamics wherein different range of players has changed their role and boundaries of their activities. In this section we explore major dynamics in order to understand the nature, driver and consequences of change in the industry architecture. We trace how and why the division of labour among important players of the sector have changed over time. This analysis paves the way to understand the possible relations between industry architecture and innovative performance of the sector, as will be seen in the next section. We argue that similar changes in industry architecture such as formation of M&As could be of different nature, driven by different mechanism and involve different consequences.

The historical division of labour encompassed oil entrepreneurs, prospectors (experienced geologists), drillers, roughnecks (skilled labour) and roustabout (semi-skilled labour). The main defining lines of the industry have remained similar, distinguishing two main types of companies, i.e. oil operators and service and supply companies. While operators compete in markets for crude oil and gas, service and supply companies compete in the market for equipment and services required in upstream projects [31].

To understand the industry, it is necessary to recognize the varieties of both operator and service companies. National Oil Companies (NICs) and private International Oil Companies (IOCs also known as majors) are the two types of operators, most of them also cover[1] midstream, downstream and even petrochemicals.

While IOCs mostly emphasise business and financial objectives, NOCs usually follow wider goals combining national, social, political and economic interests. In addition, independent companies are also becoming important players, focusing only on upstream operations. These operators are usually active in small or mature oil deposits, which are not attractive enough for big companies and do not need advanced technology.

There are a diverse range of supply and service companies in the upstream sector, competing in different segments. In one perceptive, two main types of supply and service companies are observable. Integrated service companies provide a different range of services. They tend to provide integrated and total solutions. Drilling rig operations, EPC (Engineering, Procurement, and Construction) projects and full packages of logging and data services are examples of their activities [30]. In contrast, there are specialized companies with a narrower range of activities in particular segments. Onshore or offshore drillers, equipment producers, seismic services and transportation companies are examples of these more specialized companies.

Historically, IOCs became vertically integrated - upstream, midstream and downstream - to be able to manage the impacts of oil price volatility and avoid supply interruption for downstream activities [30]. Therefore, there was no technical reason to integrate upstream to downstream, but economic and political factors forced *backward vertical integration* [36]. In addition, *horizontal integration* in the form of mergers and acquisitions (M&As) has been one important feature of the upstream industry. One important wave of M&As among majors occurred in the early and mid-1980s to regain their position after nationalization of their assets in producing countries. However, M&As in that period were not particular to oil industry. Global forces such as technical change, globalization, privatization and instability pushed many other industries to consolidate [36].

Collapse of oil prices in mid 1980s was a major driver for industry restructuring and emergence of new industry architecture. As a result of sustained low oil prices, oil majors implemented cost reduction programs to increase their efficiency. Fluctuations around the average low prices drove them to change their cost structure from fixed to variable. They chose to lease many types of equipment from service companies which previously owned by them. The aim was to increase flexibility and responsiveness to change [36]. This created a massive opportunity for supply and service companies to takeover some parts of the activities previously done by operators. Technological progress in the industry and the need for specialization was probably another driver for this period of *vertical disintegration*.

These forces altered the division of labour between operators and supply and service companies. Oil operators re-evaluated their activities to explore their real competitive domain and redefine their core and non-core areas. Their new strategy was to focus on their competitive advantage. Exploration of productive reserves and efficient management of these assets over their long life cycle became the major competitive domain of operators. The provision of equipment and services in different phases of exploration, development and production of reserves became the responsibility of supply and service companies [31].

The 1986 counter shock was a key turning point for oil service companies, pushing them towards *vertical disintegration, and horizontal integration strategies* [2]. Similar to operators, service companies also restructured themselves in order to increase efficiency, faced with a declining market in the second half of 1980s. They redefined their portfolios, focusing on what they

1- In this case they are known as vertically integrated oil companies considered their main expertise, selling less relevant units. An external growth strategy was also undertaken by smaller specialized service companies in drilling and geophysical services [34]. The result was the relative expansion of specialized supply and service companies in the sector.

Subsequently, a number of major supply and service companies followed vertical and horizontal integration strategies via external growth. They began to provide a broad range of services to their clients to meet their expanding needs for bigger and more complex exploration and development projects. 'Total solution' or 'integrated solution' gained momentum as a customer relationship strategy when operators requested more packaged services instead of discrete activities. This increasing demand for integrated services pushed big supply and service companies to build project management and integration capabilities, which was previously the territory of operators [37].

Alteration of industry architecture and technological advancement resulted in productivity improvement and cost reduction in the industry. From the mid-1980s to mid-1990s, the average cost of finding and lifting oil fell considerably. This happened in spite of the upward trend expected, stemming from the aging of existing fields and decline in easy access deposits [38&39]. Nonetheless, there was a ceiling for this downward trend when exploration and production costs began to rise in the mid-1990s. Continued declining oil prices concurrent with natural rise of exploration and development costs got oil majors into trouble. Stock markets responded to low rate of returns. Funding new projects became difficult in the environment of volatile and declining income trends. The result was the rise of mega mergers in late 1990s and early 2000s to reduce the costs and risks of the industry and mobilize resources.[1]

In spite of these consolidations, IOCs underperformed financially in most of the last decade compared to NOCs and service companies [40]. This reflects the limited growth opportunities for IOCs under their current business model, as they were not able to replace depleted reserves while most NOCs control their national reserves. In addition, the IOCs' historical differentiating expertise – such as technological capabilities, financing capabilities, and system integration and project management capabilities - has been challenged. Less investment in technology and outsourcing of many technical and engineering parts to service companies transformed the role of IOCs. They changed from project executor with in-house capabilities to become a project orchestrator and system integrator relying on a network supply and service companies [40].

In fact, this third stage of evolution evolved from the second phase, triggered by a search for a fuller degree of integration and exploitation of interactions and synergies between different activities. Near the turn of the century from 1998 to 2001, service and supply industry experienced mega mergers in which very big companies expanded their size while at the same time refocused their activities. The overall result was an unprecedented record of industry consolidation, similar to what happened to major operators in the same period [37]. These architectural adjustments created a very concentrated service sector [2], where three service majors accounted for more than 70% of total oil and gas service market at the end of the century. The share of these giant companies reached over 90% in directional drilling and logging, the segments which are highly knowledge intensive. In 2009, the top four companies in the exploration and evaluation services market accounted for about 80% percent of market share [41].

The nature M&As in the sector over the last decade seems puzzling at first glance and needs explanation, when compared with the 1980s period. Prolonged low oil prices after 1986 began to reverse in 2002, expressing a sharp rising trend. Nonetheless, M&A activities have continued with an even stronger pace particularly since 2006 [42]. While low oil prices in late 1980s triggered M&A waves to enable service companies to survive, M&A activities continued in the

1- The list of merges is as follows: BP/Amoco/Arco; Total/Elf/Petrofina; Exxon/Mobile; Chevron/Texaco high oil price environment of 2000s when the service sector is performing well. This M&A trend is still ongoing and industry analysts expect much more to come [43&44]. This suggests that consolidations in both periods do not necessarily follow the same logic and must be explained according to different mechanisms.

Directly related to oil prices, demand for petroleum supply and services has been different among these two periods. A shrinking market and low demand triggered consolidations in the late 1980s and 1990s. In the post 2002 period "increasing demand and high crude prices are underpinning merger and acquisition activity" [44]. It is clear that downturn in the service market pushes consolidation, because it creates economy of scale and scope and higher returns for shareholders. We may call it 'market led' mechanism for consolidation operating under declining and low profit markets.

Clearly, the same argument cannot be applied to post 2002 period, because prices are high and the service market is growing fast. Experts' opinion on drivers of recent consolidations in service sector is informative. The Director of Energy at McGladrey Capital Markets and an expert in M&A activities, explained recent M&A activities as follows:

"Due to the service-intensive nature of unconventional wells, *large integrated service providers* are best suited for this type [i.e. unconventional] of drilling. These service-intensive development and exploration areas require the broad-based product and service offerings and global footprint that the *large integrated vendors* can provide. ... *Another catalyst for OFS*[1] *acquisitions is technology* as major players continue to look for companies that can deliver the innovative drilling technology required in areas such as shale extraction. The industry's shift toward horizontal drilling and advanced completion/stimulation techniques has been a seminal event for OFS vendors, transforming what had been a relatively sleepy, mature sector into a hotbed of activity and *technological innovation*." [43][Emphasis added]

Another example is the view of Chad Deaton; Bake Hughes' CEO arguing that acquisition of BJ services:

"will better position us to drive international growth and to compete for the growing large integrated projects by incorporating pressure pumping into our product offering," [45].

He also emphasises that companies should be large enough to afford the high R&D costs required for increasingly large complex projects.

It is evident from these quotes that change in the nature and 'quality' of demand (e.g. service-intensive nature of unconventional wells or size and complexity of the projects) and its technological imperatives play a key role in the recent M&A activities. We may call this post 2002 consolidation more 'technology led', because it is a route for access to, and integration of different advanced technologies enabling companies to operate in complex upstream projects. Compared with '*market led*' consolidations in 1980s and 1990s, '*technology led*' drivers seem dominant in post 2002 M&A discourse. Meeting these technological requirements involves high R&D costs which are not affordable by small companies. This new environment in upstream petroleum industry is more favourable to big vertically integrated companies in terms of innovation.

In sum, dynamics of industry architecture express three different phases since 1970. The first phase is the period of oil shocks when operators have a dominant role. The second phase is the period of collapse of oil prices. This triggered M&A activities among majors and service companies, and at the same time accelerated outsourcing strategies. The result was the relative expansion of specialized supply and service companies. The third phase is the period of both vertical and horizontal integration of major service companies. This enabled them to cope with the increasing demand for total and integrated solutions that operators called for. We addressed the dynamics of industry architecture or *sectoral production system* of upstream petroleum industry in this section.

1- Oil Field Service

The next section discusses the nature and dynamics of *sectoral innovation system*.

6. Transformations of SIS in Upstream petroleum industry

After a brief review of available literature on dynamics of innovation in upstream petroleum industry in this section, we follow a systemic view to explain the dynamics of innovation and explore transformation in this SIS. The trend of oil prices presented in figure 1 is analyzed as an important determinant of innovation. It is considered as a both supply and demand factor. It pushes innovation through higher R&D investments. It also pulls innovation through stimulation of demand for new techniques, because it makes more complex and expensive deposits economically viable. This trend is matched with innovation trend in upstream petroleum industry in order to explore main phases and transformations in the sector. We will argue that simple correlation analysis of supply and demand factors is not sufficient to explain these dynamics. In contrast, the SIS approach equipped with a systemic and evolutionary perspective not only considers the supply and demand factors, but also captures they interaction with dynamics of industry architecture presented in section 5. The combination of these factors shapes the rate of innovation in different periods and defines transformations.

6.1 Previous research

Isabelle [46] is perhaps one of the first attempts to explore dynamics of innovation in petroleum industry. She argued that incentives for innovation in the upstream petroleum industry remained very weak for about fifty years from the 1920s when it was internationalized. However from 1970s onward, technical challenges in the industry made innovation much harder. This was reinforced by the oil counter shock of the middle 1980s which induced fierce competition. She labels the first period as '*technological tranquillity*' and the second one as '*technological revolution*'.

Her theory of innovation recognizes two driving factors, technical demands operated from the 1970s, reinforced by competition pressures induced by low oil prices after 1986. From the technical point of view, industry was experiencing long-term diminishing marginal cost from 1920-1970s, relying on easy access to increasingly giant reserves. Reserves were found largely in the Middle East and in other parts of the world where international oil companies could operate. The formation of the seven sisters in 1928 created an oligopolistic structure where competitive forces for innovation remained weak. From the early 1970s the situation changed dramatically. Nationalization of the petroleum industry in many countries lowered easy access to cheap oil by international companies, and big reservoirs became insecure and limited. There was no alternative but to seek oil in remote harsh areas like Alaska and the North Sea which pulled emergence of new sophisticated technologies.

Thurston and Stewart [47] suggest a more comprehensive framework adding a supply-side technology push aspect to Isabelle's demand-pull theory. Their empirical analysis concludes that major shifts in supply of externally created technology and the expected demand for new techniques during high oil prices drove innovation in the petroleum industry. Their empirical evidence, however, has some inconsistencies with Isabelle's framework [46]. The first inconsistency is the '*technological tranquillity*' period before the 1970s. The collected evidence shows that both demand and supply side forces drove innovation in the sector, even before the 1970s. Second, the historical data they present do not support Isabelle's idea that the competitive environment induced by low oil prices after 1986 drove innovation. The reason seems to be lack of enough financial resources for R&D investment, even if competitive pressures increased, as Isabelle claims [46]. The typical behaviour of companies in weak market conditions is production at marginal costs where little profit is left for very risky activities like innovation. In addition, high exploitation cost reservoirs are not economically viable in low price conditions. Therefore demand for new advanced technology is weak.

Let's come back to the analysis of trend of oil prices. As figure 1 shows, there are two relatively long term high oil price periods. The first is between 1973 and 1986 covering two oil shock periods. Second, after a relatively long period of cheap oil since 1986, we have been observing sharp increases in oil prices from 2002. The exception is 2008 and 2009 when prices suddenly dropped in response to global financial crises. If the positive relationship between prices and innovation hold, we expect an innovation surge over these periods with some possible lags. As mentioned before, high oil prices can drive innovation though two different mechanisms. First, it makes financial resources availab to be invested in new methods and technologies. Second, high oil prices justify application of more advanced but expensive technologies to exploit high costs reservoirs. This second driver can be seen as a 'demand' based mechanism of innovation, as high prices create 'new' demand.

The latter mechanism is not just about creation of more 'quantity' of the same kind of demand, but also about the creation of 'qualitatively' different demand in upstream sector which requires innovative techniques to be offered. This kind of innovation demand is not necessarily linked to oil prices, but is directly related to the nature of upstream projects. The type of services, equipments, design and engineering in exploration and production projects is a function of geological location and geophysical characteristics of the reservoir in terms of shape, size, temperature, the type of rocks among others. All these features contribute to cost of finding and lifting oil. As time goes by, easy oil is depleted and companies look for more difficult less-accessible locations and more challenging types of material to extract. For instance, the share of offshore production began to rise in 1980s and it is going from shallow to deep and ultra deep offshore where exploration and production is much more challenging and technologically demanding [48].

In addition, as conventional oil and gas reservoirs are depleted, and prices are rising, non-conventional sources such as heavy and extra heavy oil, oil sands, oil shale, and shale gas and coal bed methane can replace them. Exploiting these unconventional resources is not possible without various ranges of technological breakthrough [49]. One example of association of nature and quality of demand and technology is horizontal drilling which is the primary method to develop non-conventional deposits. In this regard, the number of rigs involved in horizontal drilling increased sharply after 2005 compared to a downward trend in vertical drilling [42]. In addition to these new sources in new locations, current producing wells also require more and more advanced technologies, should their productivity be increased. As they get mature and extraction becomes challenging, enhanced oil recovery techniques (EOR) are put in place, again involving massive investment in new technologies.

6.2 Dynamics of patents

Figure 2 presents the innovation trend in the upstream petroleum industry according to the number of patent applications in the US patent office (solid line). The dash-line shows the trend of total patenting in USPTO at 1% scale to control for technology push factor. In other words, we can understand the extent to which observed dynamics of innovation in upstream sector are a reflection of technology push from other sectors, or the result of internal mechanisms within the sector.

According to figure 2, the dynamics of innovation in upstream petroleum industry presents three distinct periods over the last four decades. From the early 1970s until the mid-1980s, we observe a growing trend where the number of US patent applications doubled from about 700 per year in 1970 to about 1450 in 1984. The second period runs from 1984 to 1994, with a negative trend in innovation. Third period begins after 1994 when industrial innovation grows rapidly and the sector looks very innovative.

The first period corresponds to the first and second oil shock periods when oil prices were very high and worries of oil scarcity were dominant. These two factors both provided powerful motives for upstream

R&D investment. The aim was to open up more challenging reservoirs in harsh locations and the key was technology. These technological efforts were enormously successful to bring down exploration and production (E&P) costs and increasing reserve replacement ratios. The stable trend of total patenting (red dashed line in the figure 1) in this period suggests that the rise of innovation is not attributable to overall technology push factor and should be explained according to other factors.

Combined with other geopolitical factors [23], this technological progress consequently led to excessive supply, pushing down oil prices for more than one and half decades. This self-correcting mechanism brought the upstream industry into the second period when patenting took a negative trend from the mid-1980s to the mid-1990s. This negative feedback loop could be seen as a long term and indirect impact of oil prices on innovation in the sector.

According to Hotelling's law [2] oil price is a function of its scarcity. Scarcity is also subject to change according to available technology. Therefore, oil prices seemed to have negative impacts on innovation in the long term, although it drove innovation in the short term. This is because availability of better technology provided by R&D investments in the first period reduced the level of scarcity. In other words, technical progress enhanced access to more and cheaper resources which led to oversupply of crude oil and other fossil fuels. In the longer term, it decreased oil prices and weakened demand side forces for innovation.

In addition to interacting supply and demand forces, it is argued that firm size and industry structure is an important determinant of innovation. In an empirical analysis of the US oil industry in the 1970s [50], it is shown that industry divestiture has a harmful impact on innovation in the sector, particularly with regard to big high-risk and long-term R&D programs. The main explanation is that minimum scale economy will be lost in smaller companies. In addition, vertical disintegration prevents synergies between different parts of the value chain and may block interactions between research activities and applications. The argument favours more a concentrated and oligopolistic structure for technological leadership.

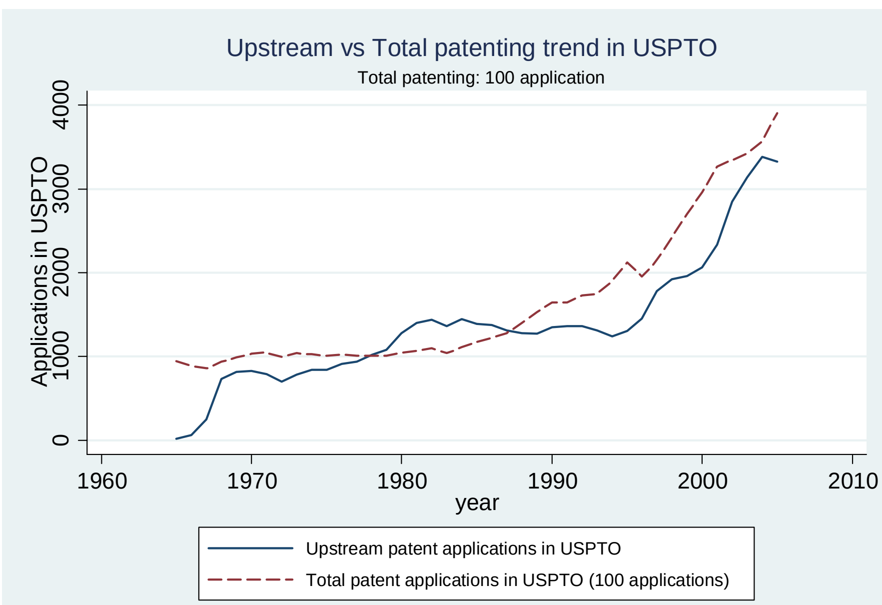


Figure 2. The number of US patent applications in upstream petroleum industry

The second period shows about a 15% decline in upstream innovation while total patent applications move in the opposite direction expressing more than 70% growth over that period. This suggests that low oil prices have been an important disincentive for innovation, although total patenting has been growing fast. In other words, availability of technological opportunities from other industries is not very effective when demand for innovation is week. As seen from the historical analysis, organizational innovations such as rationalization, reorganization and M&A activities might be more appropriate and less risky strategies. This rejects the proposition [46] that low oil prices stimulated innovation, as a result of more competitive environment.

The third period is more complicated to analyze. While there is neither large change in oil prices until 2002, nor technology-push trend (dash line in the figure 2) compared to the second period, the innovation performance of the industry has dramatically increased. The number of patent applications for upstream petroleum industry grew from about 1250 in 1994 to 3350 in 2005 experiencing about 170% growth. In fact, this period can be labelled a real ‘*technological revolution*’ or even ‘*technological explosion*’. The key question is what factors are responsible for this radical shift? What is striking is that oil prices stayed low for most of this period. In spite of low oil prices, the innovation trend in upstream petroleum took a sharp onward trend after 1994, at least 6 year before rising oil prices.

Several possible explanations could be suggested for this jump in patents. At first glance technology push theory could help. As is evident from figure 4.4, total patent applications increased from about 19,000 in 1994 to more than 39,000 in 2005 showing almost 105% growth, meaning 35% more than its growth rate in the second period. Although this seems acceptable as part of the answer, it is not sufficient for explaining the very radical shift in upstream innovation. The minus 15% growth rate in second period increased to about 170% over the third period, a 185% increase in growth rate. Ceteris paribus, we expect a 35% increase in innovation growth as the function of technology push mechanism. The rest of the gap should be explained by other factors.

Change in demand for innovation and emergence of a new industry architecture are helpful in this regard. Emergence of ‘qualitatively’ very different and powerful demand for innovation is partly responsible for the recent technological revolution of the industry. The cost of finding and lifting oil - which had a downward trend for about 15 years began to rise since 1995 [51]. This is a sign of approaching to the end of easy oil. The nature of services, equipment, design and engineering in upstream projects should be adapted to geological location and geophysical characteristics of the reservoir such as the shape, size, temperature, and type of rocks. As time goes by, easy oil available to international oil companies becomes very limited. They increasingly look for more difficult less-accessible locations and more challenging types of material to extract. Advanced and complex technology became a matter of survival, not just a tool for higher profits.

Nonetheless, available industry architecture, formed mostly of operators and specialized service companies, was not very efficient to cope with new technological imperatives of the sector. Given low oil prices and limited resources for innovation, more efficient industry architecture was required to increase the productivity of the innovation system [23]. As discussed at the end of previous section, integrated service companies emerged in the sector to cope with the increasing knowledge content and service intensity of the sector. These new types of companies became new systems integrators of the sector, playing a critical role in development and deployment of new integrated technological systems in upstream petroleum value chain. We will explore these architectural changes in the innovation system in the next section.

7. Architectural changes and innovation dynamics

This section explores the connections between architectural changes in upstream petroleum industry and dynamics of innovation. Upstream petroleum is sometimes understood as a kind of passive innovation system where the main source of innovation is outside of the sector. This view is embedded in resource curse theories [1&23] where resource based industries are not considered as technologically dynamic sectors. Technological innovation maybe considered marginal for the performance of the sector. It may also be assumed that the sphere of innovation is mostly the responsibility of other industries which produce new tools and techniques for oil exploration and production operations.

According to this view, the role of oil companies is to guide innovation processes as 'users' by articulating their needs and requirements. At most, they may play the role of 'lead users' [52] providing product concepts and design to facilitate the innovation process by external innovators, or fund R&D activities. In terms of Pavitt's taxonomy [53], this would be an example of supplier-dominated sectors such as textile and services where new technologies are embodied in new equipment and capital goods. Learning by doing and using is the dominant form of learning process. Nonetheless, Pavitt and Von Hippel have not explicitly talked about the upstream petroleum industry.

As will be seen in this section, this is a very simplistic view of the innovation process in this sector. Not only are a diverse range of actors within the upstream sector involved actively in the innovation processes, but their roles and patterns of interaction in innovation networks have changed, along with market and technological dynamics. Analysis of the upstream sector does not support a static and technologically passive picture. In contrast, the systemic and dynamic perspective of SIS approach sheds new light on the active and dynamic role of internal actors of the sector in innovation processes.

Table A-1 (Appendix A) presents the list of top 50 innovators in upstream petroleum industry ranked based on the number of the patents registered in the Derwent Innovation Index between 1965 and 2009. This table classifies the actors according to their role in the industry, distinguishing between integrated oil companies (IOCs), integrated service companies (ISCs), research and development institutes (R&D) and specialised service and supply companies (SSCs)[1]. The main business segments of the companies are also presented[2]. The patents of different affiliations of big companies are assigned to the parent company.

These figures clearly show that a range of companies both from within upstream sector and outside are the source of innovation in the sector, but the role of oil business companies is dominant. According to nature of top innovators, petroleum industry is not a passive recipient of innovation offered by other industries. Companies from within the industry search for problems actively, carry out research and perform development programs, and shape the technological environment of the industry. Nonetheless, the sector also benefits from innovations offered by other relevant industries such as chemical, metallurgy and electronics.

In order to explore the relationship between changes in industry architecture and innovation dynamics, we draw the trend of innovation by the top 50 patentees in figure 3, differentiating the share of different types of companies over time. Part (a) of the figure illustrates that these top 50 patentees together are roughly responsible for more than half of innovations with a relatively smooth share over time. The number of patents is presented by each type of company (b), their share among all patentees (c) and also among top 50 patentees (d).

There are some important facts in these figures which need consideration. Clearly,

1- The six top service companies which provide services and systems in different segments of upstream sector have been put in the category of integrated service companies, although the first three are often known as integrated service companies. Weatherford, Smith International, Dresser Industries were also added to this category because of their diverse range of products and services and also the similarity of their patenting behaviour. The scope of company activity is largely drawn from their websites and related Wikipedia. Apart from these 6 companies, other service and supply companies are classified as specialized supply and service companies, because they largely chose a particular scope of upstream activities.

2- The sources of this information are mainly company websites and related Wikipedia. A fuller summary of this information and the patenting trend of individual companies is available on request. There, it is specified how the data set has treated the companies after M&A activities. The simple rule is that major companies continued after M&A and smaller ones abandoned. For example, Exxon Mobile is a name assigned to Exxon after M&A and continued for the merged entity while Mobile is abandoned after 1999 when it was merged.

IOCs were the dominant innovators of the industry in early 1970s with about 35% of all patented inventions[1] and more than 60% among the 50 patentees. However, their share decreases until 1980 when they show a short term upward trend. This short term upward trend is probably driven by large R&D investments during oil shocks. If absolute trends are also taken into account (fig 3b), it is obvious that the increasing contribution of ISCs is mainly responsible for the long term decline in the share of IOCs. However IOCs' deceasing level of innovative activities over p2 has also accelerated this negative trend. With the exception of p2, IOCs present a more or less stable behaviour in other periods in terms of absolute level of innovative activities (fig 3b).

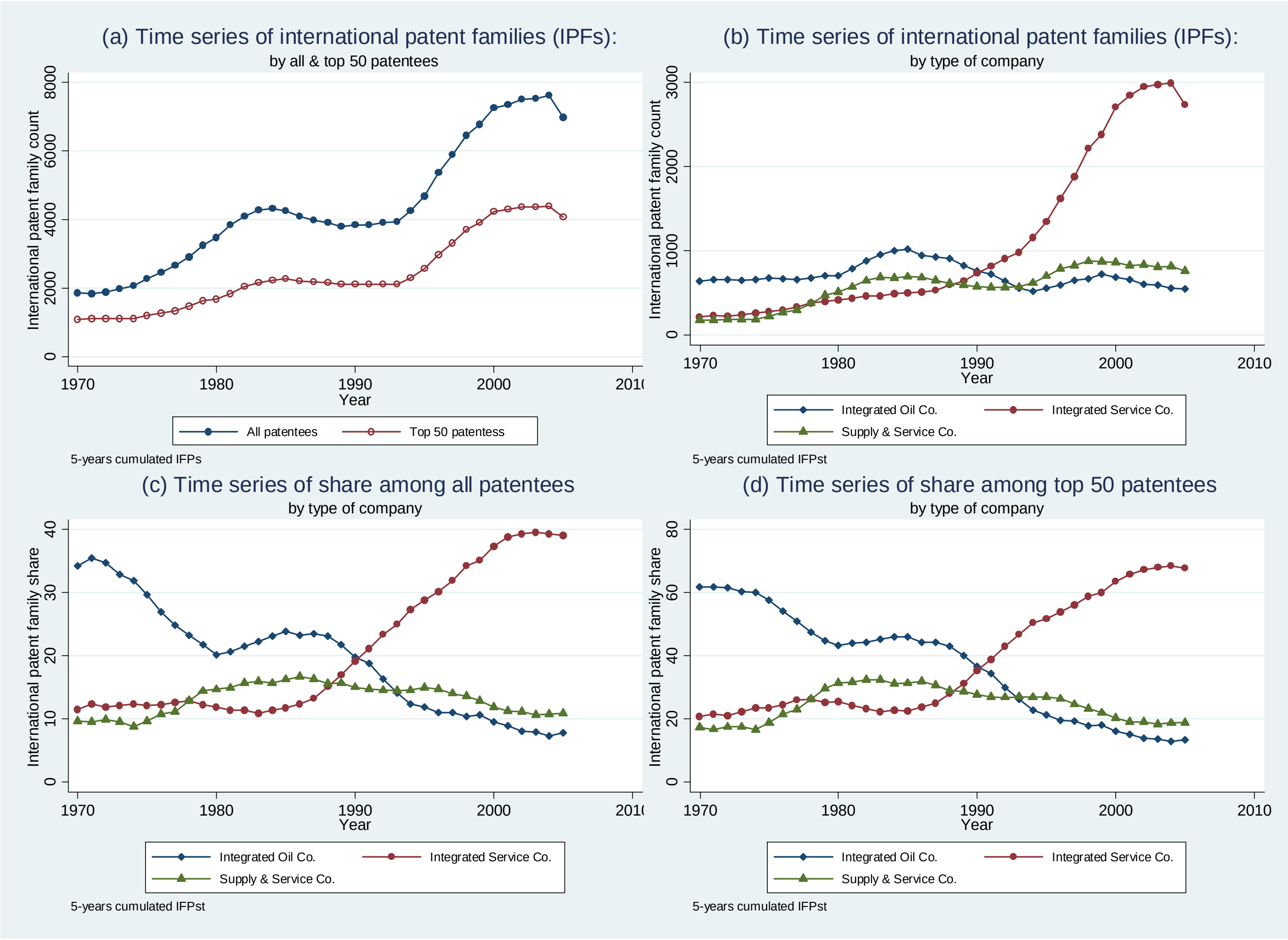
In contrast, the sharp increase of innovative activities by ISCs eroded the share of both IOCs and SSCs in 1990s and 2000s. In fact before 1990s, current ISCs were performing even less than SSCs. According to this data, the distinguishing concept of ISCs manifests itself only after the early 1990s. Before that, all supply and service companies present a more or less similar pattern. The formation of ISCs seems to have transferred the locus of innovation of the upstream sector from IOCs to ISCs, where ISCs became the leading technological innovators of the sector. In fact, ISCs were responsible for the largest share of resurgence of innovative activities after the mid-1990s, generating about 40% of total innovations and about 70% of the share of top 50 patentees. Compared to their marginal share in the early 70s, this considerable rise in the share of ISCs' innovative activities needs particular attention. As it is evident from the figure 3b, the very large part of innovation surge in upstream petroleum industry in p3 is performed by integrated service companies. This figure is also compatible with increasing R&D spending trend by service companies compared to declining trend of oil companies [54&55].

The emergence of new large integrated service companies could be seen as a key factor in the rise of productivity in the innovation system which enabled the sector to cope with increasing knowledge content and service intensity. Large scale M&A activities moved the sector to a more concentrated industry structure which is more favourable for systemic innovation. This systemic analysis suggests that reconfiguration of industry architecture was perhaps an organizational industry-wide response to the new technological requirements of the sector. Our evidence shows that innovation surge in the sector is correlated with emergence of ISC as both lead innovators and providers of integrated solutions. This industry restructuring enabled the sector to express a surge in innovation trend and cope with increasing complexity of upstream projects, in spite of continued low oil prices. This analysis suggests that a systemic and dynamic approach is helpful to explain the dynamics of innovation and sheds light on transformations of sectoral innovation systems. In addition to supply and demand related factors, SIS approach considers their dynamic interactions with industry architecture over time.

Although the petroleum industry is not usually recognized as an innovation and patent intensive sector, this traditional measure of innovative activity confirms that flow of innovation has experienced a ‘technological explosion’ since 1995. This picture is not compatible with the standard version of industry life cycle theory [6] which assumes that mature industries usually become exhausted of innovation. Our patent database does not cover the period after 2005. Yet, we expect that such acceleration in innovation trends has continued as a result of marriage of high oil prices, continued depletion of easily-accessible reserves, increasing share of unconventional reserves, and diffusion of general purpose technologies from other industries into the upstream sector.

1- International patent families (IPFs)

Figure 3. The trend of patenting by different types of companies



Integrated service companies have become major agents to exploit these innovation opportunities and locate themselves as the engine of integrated knowledge production and service provision. All in all, the service intensity of E&P activities and their knowledge content have increased incredibly over time, such that Surya Rajan from IHS Cambridge Energy Research Associates says:

> *"If all technological innovations produced by the oil and gas industry were added up, they would probably rival NASA's space program or the Industrial Revolution" [56].*

8. Conclusion

The aim of this article was to explore the transformations of sectoral innovations systems with particular focus on architectural changes and innovation dynamics. We tried to describe how upstream petroleum industry architecture has changed over time and to explain the major transformations in the industry. The purpose was to show historically how the companies' division of labour formed and evolved over time. In addition, the possible driving forces behind the evolution of the industry architecture are discussed. We discussed why a certain division of labour emerged in one period and was replaced by a new pattern in subsequent periods. In addition, we explored transformations of sectoral innovation systems in upstream petroleum industry and its relationship with architectural changes.

The main finding is that upstream petroleum industry has experienced three distinctive phases since the early 1970s over which both upstream industry architecture and innovation systems changed. In fact the dynamics of industry architecture and systems of innovation are closely related and interconnected. The first period - the early 1970s to the mid-1980s; the second - the mid-1980s to mid-1990s; and the third from the mid-1990s. Historical evidence suggests that the major driver behind the transition from the first to second period was collapse of oil prices and perhaps vertical industry divestures. The emergence of 'qualitatively' different demand for complex upstream projects in harsh and less accessible environments, combined with more-integrated industry architecture, were the major factors behind the transition from the second to third period.

The industry architecture of the first period was characterised by the historical dominance of integrated operators supplied by a different group of specialized supply and service companies. Geopolitical changes in producing countries and concerns of scarcity had pushed oil prices high, leading to oil shocks. While fears of scarcity motivated oil companies to look for oil reserves in geologically harsher and less accessible locations, high oil prices also provided resources to invest in R&D. At the same time high oil prices channelled innovation demand by making economically feasible more technologically demanding reserves. Availability of financial resources for technological innovation and strong demand created a dynamic SIS characterized by high innovation growth and declining exploration and production costs. The relatively vertically integrated structure of the industry was supportive for large, high risk and long term R&D programs. These dynamics were successful in increasing supply and bringing down oil prices, thanks to innovation driven productivity, the trend that launched transition of upstream sector to the second period.

The industry architecture of the second period is characterized by consolidation among operators and also among service companies through M&A activities. Yet, a wave of vertical divesture and outsourcing by operators to specialized service companies happened. The main motivations were rationalization and refocusing for higher operational productivity. As a result, M&A activities of this period seems more of a 'market let' type and a response of financial markets to shrinking profits. The upstream SIS seems to stagnate in this period, when innovation took a negative trend. Low innovation performance is explained by low oil prices which not only reduced innovation investment, but also innovation demand. In addition, vertical disintegration of the value chain, or what Teece and Armour [50] call divestiture, could have had a deleterious impact on R&D and innovation activities. Although low oil prices continued, innovation began a new take-off in the middle of the 1990s, expressing a new phase for upstream sector - a 'technological revolution'.

The industry architecture of the third period is characterized by vertical integration and expansion of boundaries in major service companies. They also extended their project management and orchestration capabilities. This was driven by requests from their customers (i.e. operators) for more integrated and 'total solutions' to cope with increasingly complex upstream projects. The technological imperatives of these complex projects as a 'qualitatively' different demand triggered a 'technological revolution' of the sector, in spite of low oil prices. Although 'market led' M&A activities among operators continued in this low oil price environment, M&A among service companies seems to be more 'technology led', enabling them to cope with technologically complex projects. The surge in the innovation trend and the nature of 'technology led' M&A activities among major integrated services companies over this period are interpreted as the signs of fundamental transformation of upstream sector towards higher technological complexity.

A related theoretical conclusion is that standard application of the conventional industry life cycle [6] is unable to explain innovation dynamics in an industry as mature as upstream petroleum. Industrial dynamics does not necessarily progress according to the standard s-shape models. Industry architecture may change in response to both external environment and firms endogenous strategies. New innovative agents may emerge within the sector and incumbents may reshape their organizational boundaries or disappear from the sector. This process could be related to the emergence of new technologies, their integration with existing technologies and/or obsolesce of old technologies. This architectural dynamic and its relationship with technical changes are often overlooked in conventional perspectives.

Analysis of upstream sectoral innovation system illustrates that it is a highly dynamic and innovative sector particularly in the most recent period. New technologies and products developed were highly influential in shaping the industrial dynamics of the sector. As a result, transformation of sectoral innovation systems in a mature resource-based industry could change to what looks like a knowledge intensive high-tech sector. My analysis of the main patentees confirms that the upstream industry is an active innovator so to view it as only a passive recipient of innovation from other sectors is wrong. A different range of operators, integrated service companies and specialized firms within the sector, in are involved in innovation processes in high-tech areas such as nanotechnology [57]. Integrated service companies are positioned at the top, signalling their critical role in innovation processes. The dynamics of innovation explored in this article suggests that resource-based economies can tap into the new innovation opportunities emerging in these sectors, providing they can manage accumulation of the relevant absorptive capacities [58].

The analysis of transformations of the sector presented clearly supports the advantage of the SIS approach to explain innovation dynamics. It shows that there is no simple linear relationship between supply/demand factors and rate of innovation. The nature of supply/demand relationship with innovation may change over time through interactive and co-evolutionary processes creating new industry architectures. The changes in industry architecture have strong implications for innovation dynamics. As the case of upstream petroleum industry suggests, supply/demand factors can shape industry architecture which affects innovation. This happed from p1 to p2 in upstream petroleum industry where low oil prices drove outsourcing and reduced innovation. Innovation also may affect supply/demand factors which can lead to alteration of industry architecture in the long term. This process is observable from p2 to p3 when request for total solutions pushed emergence of integrated service companies. This new industry architecture in p3 supported the surge in technological innovation in the sector to cope with increasing complexity of upstream projects. The SIS approach is relevant, because it takes an integrated, systemic view and considers complex interactive dynamics of different factors. The simple linear approach cannot sufficiently explain the dynamics of innovation. The SIS approach is therefore highly relevant to explain the transformations in upstream petroleum.

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Appendix A: Table A-1. Top 50 patentees in upstream petroleum industry over 1965- 2009 based on Derwent Innovation Index

Rank	Company***	Type*	IPF count	Active period	Main Business	Main M&A**
1	**Schlumberger**	ISC	3073	1966-2008	Integrated service company	1965 Forex(A); 1984 Sedco(A); 1985 Geco(%50A); 2000 Western Geophysical(%70A); 2006 Western Geophysical(%30A)
2	**Halliburton**	ISC	2560	1965-2008	Integrated service company	1998 Dresser(M)
3	**Baker Hughes**	ISC	1682	1968-2008	Integrated service company	1987 Hughes Tool Company(M)
4	**Shell**	IOC	1190	1966-2008	Integrated oil company	-
5	**Weatherford**	ISC	814	1973-2008	Integrated service company	1973 (F)
6	**Exxon Mobil Co.**	IOC	808	1965-2008	Integrated oil company	1999 Mobil(M)
7	**IFP**	R&D	749	1965-2008	Research institute in petroleum	-
8	**PRAD R&D**	R&D	638	1979-2008	R&D in particulate/multiphase processes	1979 (F)
9	**Texaco**	IOC	618	1966-2000	Integrated oil company	2001 Chevron(M)
10	**Smith International**	ISC	555	1969-2008	Supplies products to gas and oil production and exploration companies	2010 Schlumberger(M)
11	**Mobil oil corporation**	IOC	545	1967-2000	Integrated oil company	1999 Exxon(M)
12	**Dresser Industries**	ISC	456	1967-2004	Technology, products, and services used for developing energy and natural resources	1998 Halliburton(M); 2001 sepration again
13	**Camco International**	SSC	409	1968-2002	Drill bits - Completion equipment	1998 Schlumberger(M)
14	**Vetco**	SSC	351	1968-2008	Oil and gas equipment, services	1991 ABB (Owned); 2007 GE(Ac. By)
15	**ConocoPhillips**	IOC	314	1966-2007	Integrated oil company	2002 Phillips(M);
16	**Chevron**	IOC	311	1966-2007	Integrated oil company	2000 Texaco(A)
17	**BJ Services Co.**	SSC	298	1965-2008	Pressure pumping and oilfield services	1974 Hughes Tool Company(Ac. By); 1989 dissolved to be part of Baker-Hughes;
18	**Sofitech**	SSC	273	1988-2006	-	1988 (F)
19	**Amoco**	IOC	271	1967-1998	Integrated oil company	2001 BP(M)
20	**Otis Engineering Co.**	SSC	257	1971-1992	Elevators, escalators and moving walkways	-
21	**Elf Aquitaine**	IOC	254	1968-2000	Integrated oil company	2000 Total(M)
22	**BP**	IOC	243	1978-2008	Integrated oil company	1998 Amoco (M), 2000 Arco(M)
23	**Cooper Cameron**	SSC	227	1984-2008	Pressure control, processing, flow control and compression systems	1989 Cooper(M)
24	**Statoil**	IOC	226	1983-2008	Integrated oil company	1972(F)
25	**Hughes Tool Co.**	SSC	224	1966-1992	Oil drilling rigs	1987 Baker(M)
26	**Dowell Schlumberger**	SSC	223	1980-2001	Pumping services for the oil industry	-
27	**FMC Corporation**	SSC	221	1968-2007	Pumps and subsea systems	-
28	**Marathon Oil Co.**	IOC	220	1965-2006	Integrated oil company	
29	**Arco**	IOC	217	1965-1999	Integrated oil company	2000 BP(M)

30	**M-I SWACO**	SSC	216	1989-2008	Drilling fluids (mud)	1999 (F)
31	**Western Atlas**	SSC	197	1977-2000	Geophysical services	1998 Baker Hughes (Ac. by)
32	**The Dow Chemical Co.**	SSC	194	1966-2007	Plastics, chemicals, and agricultural products	-
33	**Varco**	SSC	179	1978-2006	Oil drilling rigs	2005 National Oilwell Varco(M)
34	**Phillips Petroleum Co.**	IOC	177	1965-2002	Integrated oil company	2002 Conoco(M)
35	**BASF**	SSC	159	1969-2008	Chemical company	
36	**Total**	IOC	147	1968-2008	Integrated oil company	1999 Petrofina(M); 2000 Elf(A)
37	**National Oilwell Varco**	SSC	141	1986-2008	Oil drilling rigs	1987 (F)
38	**Hydril**	SSC	133	1967-2007	Pressure Control technologies	-
39	**NL Industries**	SSC	133	1968-1988	Component and chemical products	-
40	**Sandvik**	SSC	128	1977-2008	Tooling, stainless steel alloys and materials technology, mining and construction	-
41	**Kvaerner**	SSC	127	1982-2007	All facets of engineering and construction, including shipbuilding, process technology, engineering and construction	2005 Aker(M)
42	**ABB Offshore Systems**	SSC	125	1983-2007	Oil and Gas Equipment, Services	2004 Vetco(Ac. By)
43	**Union Oil Co. of California**	IOC	125	1965-2002	Oil operator	2005 Chvron(M)
44	**Rhodia**	SSC	119	1990-2008	Chemicals and new technologies	-
45	**Petrobras**	IOC	119	1983-2008	Oil operator	-
46	**Sumitomo Metal Industries**	SSC	118	1970-2007	Manufacturing Seamless Pipes and Tubes	-
47	**Christensen**	SSC	115	1969-1990	Directional drilling company	1987 Baker Hughes(Ac. by)
48	**Nalco Chemical Co.**	SSC	106	1967-2006	Chemicals and water treatment	-
49	**Baroid Indust. Dril. Products**	SSC	105	1975-1997	Drilling products and services	1991 Haliburton (Ac. by)
50	**Cooper**	SSC	100	1985-1993	Pressure control, processing, flow control and compression systems	1989 Cameron(M)

* ISC: Integrated Service Companies; IOC: Integrated Oil Company; R&D: Research and Development Institute; SSC: Specialized Service and Supply Company
** These M&A information come from Wikipedia and companies' websites and only cover the main ones. Therefore, they should not be accounted as exhaustive list
(A): Acquisition; (M): Merge; (Ac. By): Acquired by; (F) Founded in
*** Merged entities are in grey