The Role of Innovation and Technology in Sustaining the Petroleum and Petrochemical Industry*

Hossein Hassani† Emmanuel Sirimal Silva‡
Ahmed Mohamed Al Kaabi§

March 21, 2017

Abstract

Innovation and Technology go hand in hand within the petroleum and petrochemical industry. Oil price volatility, geopolitics, and economic uncertainty, all contribute towards the continued need to innovate and technologically advance if petroleum and petrochemical companies are to survive in this highly competitive industry. This review paper looks at identifying the importance of innovation and technology in the petroleum and petrochemical industry by referring to evidence in the public domain. Thereafter, the focus shifts towards identifying both quantifiable and non-quantifiable impacts of technology and innovation within the petroleum and petrochemical industry.

Keywords: Innovation; technology; sustainability; oil; gas; petroleum.

1 Introduction

1.1 Background

Petrochemicals can be defined as 'chemicals produced from natural gas, natural gas liquids, or refinery products derived from crude oil distillation, or cracking' (Samuel et al. 2013, p. 395). The demand for such petrochemicals has grown

*Disclaimer: Any views expressed are solely those of the author(s) and therefore cannot be taken to represent those of the Organization of the Petroleum Exporting Countries (OPEC), UAE Ministry of Energy, University of the Arts London or to their policy. This paper should therefore not be reported as representing the views of Organization of the Petroleum Exporting Countries (OPEC), UAE Ministry of Energy and University of the Arts London. This article was accepted for publication in Technological Forecasting & Social Change. DOI: 10.1016/j.techfore.2017.03.003.

†Organization for Petroleum Exporting Countries, Vienna, Austria, email: hassani.stat@gmail.com.

‡Fashion Business School, London College of Fashion, University of the Arts London, 272 High Holborn, London, WC1V 7EY, UK, email: e.silva@fashion.arts.ac.uk.

§Ministry of Energy, United Arab Emirates.

rapidly and dominated the global chemicals market over the last 10 years (Luff et al., 2013). As a result, the petroleum and petrochemical (referred to as P&P hereafter) industry itself has continued to grow (Hussain et al., 2006) and remains a key factor underlying the economies of every industrial nation. However, the P&P industry has experienced many challenges recently. For example, the cost of production of a barrel is 60% more than it was 10 years ago (Tidey, 2015), and oil prices have dropped by approximately 70% since peaking in 2014 (Decker et al., 2016). International events, like China's devaluation of the Yuan and the possible lifting of sanctions on Iran (Sebastian, 2015) are resulting in more oil price volatility and increased uncertainty within an industry that is already wary of Hubbert's peak (Hubbert, 1956).

For those unknowing, Hubbert (1956) presented an unwelcome forecast which gained popularity as Hubbert's Peak and then transformed into the concept of peak oil. Hubbert was of the view that oil production in the U.S. would peak around 1970, and decline steadily thereafter. Years later, his predictions came true as U.S. oil production peaked at approximately nine million barrels per day in 1970 before declining to about six million barrels of oil per day by 2005 (Goodstein, 2005). In his book, Goodstein (2005) subscribed further to the peak oil concept as he wrote that based on Hubbert's calculation, oil consumption must peak in the next decade. However, the concept of peak oil is increasingly proving to be a misleading idea (Mitchell et al., 2012) as a result of the technology and innovation within the P&P industry which have lead to the introduction of shale oil and tight oil. In fact, the technologies underlying U.S. shale hydrocarbons and innovations in drilling and extraction have resulted in the fastest growth in oil production over the last hundred years (Decker, et al., 2016; Mills, 2015). The ongoing decline in fuel prices is expected to result in further innovation driven differentiation within the industry (Evans, 2016), and with the concept of peak oil being rejected, the importance of technology has further increased for upstream reserve growth (Mitchell et al., 2012). As Kleinschmidt (2016) asserts, the low price of oil is both a challenge and opportunity for the industry.

However, as Deffeyes (2001) asserts, the P&P industry should exploit innovation where it fits best, instead of seeking to apply same broadly to the entire industry. The industry itself is no stranger to the concept of innovation with one of its first successful innovation processes dating back to 1913 (Enos, 1962). Figure 1 summarises the innovations in the P&P industry between 1900 and 1960. It is evident that by the early 20th century, innovations such as thermal cracking and thermal reforming replaced atmospheric distillation (Yin, 1994) and thereby enabled a refinery to yield 35% more gasoline per barrel of crude oil (McLean and Haigh, 1954). This was followed by innovations in Catalysis techniques such as Catalytic cracking and Catalytic reforming which replaced thermal reforming (Yin, 1994). Finally, the innovation of Hydrocracking replaced Catalytic cracking via improved efficiency and environmental effects (Lakhani, 1975). Accordingly, given geopolitics, economic uncertainty and the recent developments within this technology dependent industry (Pillai, 2006), it is opportune to understand the role of technology and innovation in sustaining the P&P industry. As this paper relies heavily on innovation and technology, in what follows, we present a concise discussion of these topics.

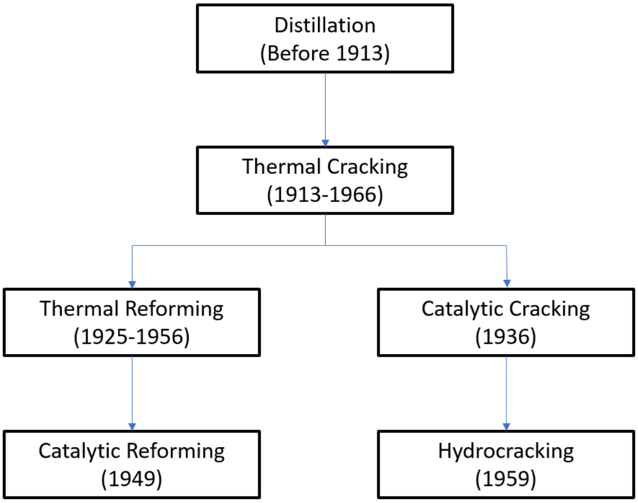

Figure 1: Historical innovations in petroleum refining processes (Yin, 1994).

1.2 Invention Vs Innovation

Prior to delving into the gist of this paper, it is important to clearly define and distinguish between the concepts of invention and innovation. Initially, innovation was thought of as a relatively simple, one-directional process which begins with basic research and then moves on from applied research to technology development and diffusion (Schumpeter, 1934). The basic understanding underlying this linear model of innovation was that the best way to increase the output of new technologies was via increased resource allocations for research and development (Schumpeter, 1934). However, as Yin (1994) pointed out, technological change is not a linear process. Whilst the linear model of innovation was more supply side focussed, the demand-pull perspective gained popularity in the 1950's whereby it was believed that the demand for goods and services was more influential in stimulating inventions than advances in the state of knowledge (Hanna et al., 2015). Today, both the supply side and demand side perspectives are accepted as important, but not in its simplistic introductory forms (Nemet, 2007). More prominence is given to the complex, systemic feedbacks between the supply and demand sides (Hanna et al., 2015; Foxon, 2003). In spite of its simplicity and desirability, the linear model of innovation (Bromley 2002; Bromley 2004) was abandoned as a result of the associated high risk, uncertainty, time and resource requirements (Sekhar and Dismukes, 2009). However, an approach known as 'open innovation' was introduced to help clear up the confusions underlying the linear model of innovation (Grove, 1996; Chesbrough and Rosenbloom, 2002; Chesbrough, 2003; Chesbrough and Spohrer, 2006). In brief, the open innovation concept recognizes the cooperative nature of partners in industrial innovation instead of complete reliance on the classical vertical integration of all innovation functions in one corporation.

At this juncture, it is pertinent to note the importance of technology, especially, as it has been recognized as the key driver of innovation since the mid 20th century (Schumpeter, 1939; Mensch, 1982; Dismukes, 2005). Those interested are referred to Sekhar and Dismukes (2009) where a concise account on the evolution of technology as a key ingredient for innovation was presented. The concept of technological forecasting is also of interest as in terms of invention and innovation, this includes all systematic attempts to predict and comprehend the direction, rate, characteristics, and effects of technological change (Coates, 2001). Moreover, the term innovation was historically used to describe processes which exploited new technology and knowledge to create new or improved products (Porter, 1990). For the OECD (1997), innovation was the adoption of technologically enhanced or new production methods. Here, it is noteworthy to refer readers to Marquis (1969) and Henderson and Clark (1990) where innovation was classified into several groups such as radical, incremental, system, architectural, and modular innovation. However, there are other authors who classified innovation as basic, radical, disruptive, discontinuous, next generation, incremental, imitative, new to the company, and new to the world (Mueser, 1985; Shenhar et al., 1995; Betz, 2003; Garcia and Calantone, 2002; Dismukes, 2005). Whilst there exists no universally accepted typology for innovation, Dismukes (2005) relies on classifying innovation as incremental (continuous) or radical (discontinuous). Along these lines, both Schumpeter (1942) and Bers et al. (2009) agreed that radical innovations lead to technological revolutions. In their review of radical innovation, Bers et al. (2009, p. 166) learnt three important lessons. Firstly, that radical innovation requires a major disruptive event; secondly, that all major innovations progress along a technology life cycle; and thirdly, that every innovation builds upon prior achievement. These lessons indicate that disruptions within the P&P industry should not always be seen as a threat as it has the potential to open up opportunities in the long run. In addition, it also indicates the importance of having a clear account of prior achievements within the P&P industry; as innovative practices are more likely to build upon historical achievements. As such, we believe the information reviewed for the P&P industry in the following sections would stimulate more radical innovations in the future.

The radical innovation growth (activity) equation can be found in Sekhar and Dismukes (2009). This growth equation was derived from the pattern equation which was originally defined by Yerramilli and Sekhar (2006). These growth equations are extremely useful when seeking to understand invention and innovation. However, not all authors agree with the concept of radical innovation. For example, Yin (1994) showed with evidence from the petroleum refining industry, that incremental improvements to initial radical innovations would generate higher returns than the latter. Yet, one may argue on behalf of radical innovation because given the challenges currently faced by the P&P industry, focusing on returns alone may not guarantee long term survival. Moreover, Sekhar and Dismukes (2009) believed that radical innovation enables to maximize profits from inventions. Regardless of which type of innovation takes precedence, the role of technology cannot be underscored. As Yin (1994) explains, radical innovation and incremental innovation are essentially two different technological changes where the former represents 'a revolutionary change that contains a high degree of new knowledge' (p. 265) whilst the latter is 'a renovation and adjustment of current technology with a low degree of new knowledge' (p. 266). The roots of both radical and incremental innovation dates well back in time as radical innovation is essentially what Enos (1958) referred to as the alpha phase whilst incremental innovation is what was referred to as the beta phase.

Enos (1962) believed that innovations include several elements and that each of these elements required an invention. Beyond the new millennium, Garcia and Calantone (2002) were of the view that innovation is an iterative process which is a combination of technological development of an invention, market entry and diffusion. According to Jessua et al. (2006), innovation is the process of transforming a new idea, invention or scientific principle into a commercially viable product or service, whilst Miller et al. (2006) added to this discussion by noting that innovation is both the development and implementation of an invention. Grubler and Wilson (2014) defined invention as the origination of an idea as a technological solution to a problem whilst innovation was defined as putting ideas into practice via iterative design, testing, application and improvement processes. More recently, Grafstrm and Lindman (2017) presented the view that innovations do not always require new inventions, and that they can consist of several older inventions. This view ties in with Bers et al.'s (2009) notion that every innovation builds upon prior achievement. In general, as Dismukes (2005) and Age (1995) asserts, the complexity of innovation makes it extremely difficult to present a general theory of innovation. As a result, numerous models which have been proposed to explain the innovation process continue to struggle with limitations (Porter and Cunningham, 2005).

In an age where scientific technologies of thinking are expected to form the basis for innovation (Sekhar and Dismukes, 2009; Betz, 2003), several authors have sought to explain and expand upon the concept of innovation. Dismukes (2005) proposed the concept of Accelerated Radical Innovation (ARI) (developed by Dismukes (2004) and Bers and Dismukes (2004)) which is presented graphically in Bers et al. (2009, p. 167) and is therefore not reproduced here. The ARI process was introduced to speed up and improve the radical innovation process. As Dismukes (2005) and Bers et al. (2009) write, the ARI process was aimed at reducing the time for profitable commercialization and improving the radical innovation effectiveness by 10 times. Those interested are also referred to Figure 2 in Bers et al. (2009, p. 168) where the authors present and discuss a framework of the 10-step 2nd generation ARI methodology, and also the conclusion (p. 175) where the five ideas which enable the ARI methodology to accelerate the innovation cycle have been summarised.

For the ARI process, there is evidence of interest in developing a model and a holistic methodology that is grounded in theory and practice (Dismukes, 2004; Dismukes et al., 2005; Suh, 1999; Suh, 2004; Suh, 2005). Schumpeter (1942), Erwin and Krakauer (2004) and McGraw (2007) made significant contributions in terms of defining inventions and innovations. On the other hand, Yerramilli and Sekhar (2006) presented the first life cycle model which fit the production data for five metals. The foundation laid in Yerramilli and Sekhar (2006) and Sekhar and Dismukes (2009) enabled the authors to clearly define the boundaries for innovation and invention based on the overall long-term life cycle. Through the pattern equation, Sekhar and Dismukes (2009) documented a four stage life cycle for products as the Initial Stage (I), the Lift-Off and Decay Stage (II), the Revival and Rapid Growth Stage (III) and the Survival Stage (IV). Figure 2 presents a graphical representation of the four stage life cycle. Connelly et al. (2011) contributed by adding a fifth stage to the life cycle termed as Stage V (final death stage) to indicate the end of an innovation.

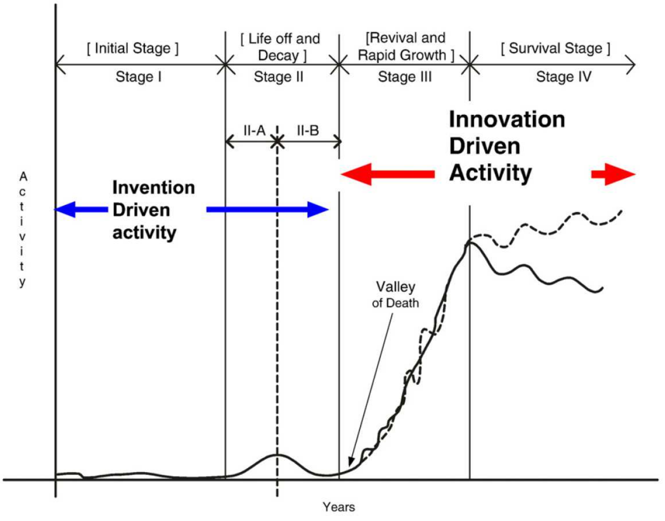

Figure 2: An example of the four stage life cycle for products, through invention to innovation (Sekhar and Dismukes 2009, p. 196).

As Connelly et al. (2011) and Connelly and Sekhar (2012) note, Stages I and II are the inventive stages whereas Stages III and IV are the innovation stages. Stages I and II are where the invention itself is being developed into a market innovation and are therefore technically driven, whilst Stages III and IV are driven by market, teaming and financial factors (Connelly et al., 2011). Also, a key finding from previous research was that the transition between Stages III to IV was a result of innovation enhanced supply (Connelly and Sekhar, 2012). Connelly et al. (2011) explained the life cycle further as follows. Stage I, the developmental stage begins with the discovery and the primary invention of a process and ends when the development of the technology is enough to begin low-scale production (Connelly et al. 2011, p. 305). Stage II begins with the rise in the production activity and ends at the low point of the activity (Connelly et al. 2011, p. 305). Stage III begins after the low point has been crossed and continues through the product's full growth potential with the take-off in activity typically being at a high rate (Connelly et al. 2011, p. 305). Stage III ends at the onset of Stage IV where the product has reached maturity and the activity has leveled off or has begun to die (Connelly et al. 2011, p. 305). The stages of the pattern equation can also be related to the S-shaped growth curve for technological diffusion presented in Lakhani (1975) where the author refers to an initial stage, acceleration stage, and deceleration stage. For example, a closer look at the explanations underlying the derivation of the growth curve in Lakhani (1975) can help understand the reasons for an innovation to rarely peak immediately, reasons for eventually peaking and then declining. Moreover, the S-shaped growth curve also ties in with Dismukes et al.'s (2009) classification of the three stages of innovation as exploration, acceleration, and maturation. In the modern age, patents are increasingly being used as a proxy for measuring innovation. For example, Connelly et al. (2011) and Grafstrm and Lindman (2017) consider the quantity of patents as a measure of innovation as patents are features of both the invention and innovation stages (Yerramilli and Sekhar, 2006).

In terms of the P&P industry, both invention and innovation has long been discussed, see for example Enos (1962). Innovation indeed had a role to play initially in the transition from coal-based to petrochemical based industries. However, according to Colombo (1980) and Freeman and Perez (1997), innovation in the petrochemical industry is dominated by process innovation as opposed to product innovation. Based on experience from the electronic and petrochemical industries, Dismukes (2005) proposed an adaptive innovation template that can be applied within the innovation cycle. Also noteworthy is that the integrated collaboration between academia and industry during the 5-Year Period of WWII helped accelerate breakthrough innovations (Sekhar and Dismukes, 2009). Years later, increased collaboration continues to remain a pivotal factor which can foster thinking differently whilst encouraging creativity, in addition to fostering technological advancements (Meehan and Hughes, 2015). Accordingly, in the following subsection we briefly summarize the evolution of innovative technology in the P&P industry.

1.3 The Evolution of Innovation and Technology in the P&P Industry

Mcgrath (2011) recognized the rotary drill from the 1880s as one of the first innovations for improving oil drilling. This was followed by hydraulic facturing in the 1940s, and remotely operated vehicles for deep water drilling in the 1970s (Mcgrath, 2011). The development of innovative techniques in 1967 for the extraction of a BTX fraction from petroleum refining had a significant role to play in the transition to petroleum based industries (Bennett and Pearson, 2009). Another oil extraction technique which remains in use is surface mining, and its roots date back to 1967, whilst methods such as water flooding and cold production are also noteworthy (Shah et al., 2010). Other innovations, such as the integration of gas turbine for steam cracking was visible since 1970 (Ren, 2009). In contrast, ceramic coils were yet to be exploited and were undergoing R&D in 2009 (Ren, 2009) whilst the use of synthetic zeolites in petrochemicals was a ground breaking innovation (Magee and Mitchell, 1992; Moulijn et al., 2001, Vermeiren and Gilson, 2009). By 2010, microwave and radio frequency technology was being exploited to recover oil and gas from oil shale and oil sands (Mutyala et al., 2010). The application of microwave technologies for oil extraction in the P&P industry up until 2010 have been reviewed in Mutyala et al. (2010), and as such the details are not reproduced here.

Petroleum's information age is said to have begun in 1924 in the Brazoria County of Texas, with the first two-dimensional (2D) seismic map (Mills, 2013). Since then, Geologists played a major role in oil exploration by studying surface rock formations, magnetic fields and variations in gravity (Mcgrath, 2011). Several international oil companies now recognize technology as a strategic priority (Kulkarni, 2011; Parshall, 2011; Chazan, 2013) and evidence shows that spending on R&D and innovation has increased dramatically over the past few years (Perrons, 2014). Those interested in a timeline of key technological innovations in the petroleum industry since the beginning of the 19th century are referred to the Society of Petroleum Engineers[1].

Whilst on the topic of the information age, it is important to briefly touch upon the contributions of Big Data to the P&P industry. Big Data, which is a relatively new phenomenon, is influencing the P&P industry on a major scale. Energy exploration happens to be one of the most significant Big Data applications within the P&P industry (Barney, 2015), and Big Data was used to smarten the drilling platforms and pipeline infrastructure in order to enable anticipation of issues and prevention of failures (Seshadri, 2013). It is believed that digital oilfield technologies (which are discussed further in the sections which follow) could increase the net present value of oil and gas assets by 25% (Elatab, 2012). With the world running out of easy oil and gas, the P&P industry is banking on Big Data analytics to boost production by exploiting sensors, high-speed communications, and data mining techniques to monitor and fine-tune remote drilling operations(Leber, 2012). A brief review of recent Data Mining applications can be found in Ghodsi (2014).

Based on the several discussions presented above, it is evident that innovation and technological advancements have been crucial ingredients for the growth and success of the P&P industry over the years. Accordingly, in what follows, this paper aims at initially understanding and summarizing the continued need for innovation and technology within the P&P industry, prior to focussing on the benefits from the latest innovations and technological advancements in terms of time savings, cost reductions, sustainable growth and improved efficiency. In brief, Spencer-Ogden (2016) states that the benefits of technological investments will include increased production and efficiency, improved safety and lower maintenance costs.

The remainder of this paper is organized such that, Section 2 focuses on identifying and explaining the need for technology and innovation within the P&P industry with Section 3 focusing entirely on a discussion around the impact of innovation and technology. Section 4 focuses on the environmental impacts of innovation and technology in the P&P industry, and the paper concludes in Section 5.

[1] `http://www.spe.org/industry/history/timeline.php`

2 Why is Technology and Innovation needed in the P&P Industry?

Given the nature of this review, it is important to understand what fuels the continued importance of technology and innovation in the P&P industry. In response to the question, 'Why is Technology and Innovation needed in the P&P industry?', we find the following factors underlying this need, and these are discussed at length below. Accordingly, technology and innovation is needed for;

1) sustainable petroleum consumption and production; 2) competing with other industries; 3) automating high cost, dangerous and error prone tasks; 4) overcoming issues surrounding the depressed price of oil; 5) accessing future oil and gas resources.

Historically, a key reason for companies within the P&P industry to innovate and develop new technologies was the call for, and pressure exerted by international organizations for ***sustainable petroleum consumption and production*** via the Rio Earth Summit (UNCED, 1992). Al-Sharrah et al. (2010) noted that whilst some producers saw the increasing pressure as a hindrance, in reality it was offering business opportunities for the creative and technologically innovative producers to exploit the market.

Few years into the new millenium there were other industries which noticed the boom in the P&P industry, and thereby began innovating to try and find alternative solutions to capture some of the P&P industry's market share. There is evidence which suggests that ***innovation and technological enhancements in competing industries*** were also another reason for the need to innovate and continuously evolve in terms of technology within the P&P industry. In fact, literature suggests that competition has been a key factor driving innovation in the petroleum industry (Stobaugh, 1998). As noted in Al-Sharrah et al. (2010), innovation and technology plays a vital strategic (as opposed to the historically tactical) role in the P&P industry's overall strategy. For example, Figure 3 clearly shows how oil and gas dominated the UK primary energy market with an increasing trend up until the late 1980's. However, as other forms of energy began competing, there was a clear drop in oil and gas which picked up again, only to increase at a comparatively declining rate between 1989 and 2004. Note how energy sources such as nuclear and hydro power are seen increasing at a very slow, yet comparatively better rate in relation to the 1960's.

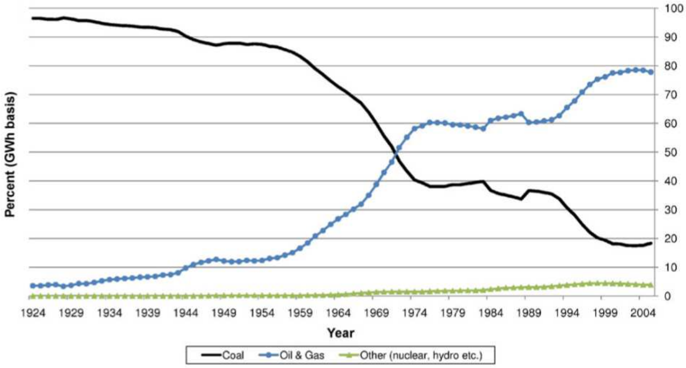

Figure 3: Transitions from coal to oil and gas in UK primary energy (Bennett and Pearson, 2009).

Since then, innovation and technological developments in other energy sources have only improved further and thereby poses a significant threat to the continuity of the P&P industry. For example, Iles (2008) and Bennett and Pearson (2009) states that renewable raw materials based on biomass were beginning to replace petroleum products and were offering more sustainable alternatives to consumers who are increasingly more concerned about the environment. In addition, it is no secret that the vehicle, ship and aircraft industries are also investing in technology with a view to avoiding the use of petroleum (Mitchell et al. 2012). As such, if the P&P industry fails to innovate and improve their technologies for sourcing, producing and transporting oil and gas, then the industry is likely to find itself going out of business as demand could drop rapidly owing to successes in innovation and technology in competing industries.

Operating within the P&P industry is not only a costly affair, but also highly risky. As such, the emergence of Big Data and analytics can help oil and gas companies to ***automate high-cost, dangerous, or error-prone tasks*** which not only results in improved safety via minimized risks to human lives, but also has the potential to significantly improve profitability whilst enabling efficiency gains (Martinotti et al., 2014). Figure 4 below shows the impact that automation can have upon upstream activities in the P&P industry. It is evident from this figure that the highest impact is likely to be in production operations. Another sound example would be the non-destructive testing (NDT) technology created by Eddyfi, which can identify where corrosion or erosion is affecting the integrity of equipment before a failure results in a costly emergency repair (Kendon, 2016).

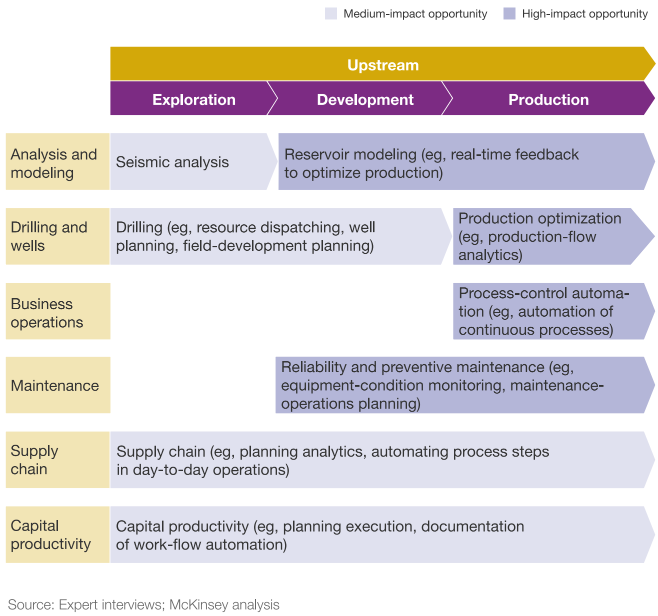

Figure 4: The impact of automation opportunities in upstream (Martinotti et al., 2014).

Today, the ***depressed price of oil*** is one of the most prominent reasons underlying the need for technology and innovation. In fact, some authors are of the view that the depressed oil price is good news for innovation in the P&P industry. For example, Meehan and Hughes (2015) present the argument that when oil prices are high, asset teams are busy keeping up with activity that there is little or no time for innovation. Other authors note that falling oil prices create new waves of innovation (Mawji, 2016; Sider and Ailworth, 2015) as producers must compete vigorously to survive under highly volatile economic conditions. As Mawji (2016) noted, the focus is now on reducing the cost of producing oil - especially in countries like U.S. where 50% of oil production comes from the expensive U.S. shale. Initial estimates by analysts stated that the break-even price for shale would be at $75 per barrel, but analysts now believe that innovation in U.S. shale drilling technology has enabled producers to push the break-even price down to $30-$35 per barrel (Mawji, 2016) and remain competitive in the world market. Meehan and Hughes (2015) stress on the importance of innovation by terming it as the key for survival amidst falling oil prices, and noting that the current declining oil prices present ‘a great time for innovation’.

Yet another factor fuelling the need for more innovation and technological advancements in the P&P industry happens to be ***access to future oil and gas resources***. It is problematic as the oil and gas resources are likely to be deeper, harder to find and in environments which are comparatively and significantly more difficult to access (Kleinschmidt, 2016; Perrons, 2014). It was reported that 53.3% of world oil reserves are in the form of restorable oils such as heavy oil, extra heavy oil, oil sand, tar sands, oil shale, and bitumen

(Demirbas et al., 2016). As such, there are numerous calls for increased collaboration on innovation and technological advancements within the P&P industry which can hopefully lead to significant breakthroughs as opposed to innovation simply drawing on a range of technologies (Meehan and Hughes, 2015). Farris (2012) adds to this discussion by noting that oil is increasingly more difficult to find with reservoirs lying up to 35,000 feet below the earth's surface. For example, Figure 5 indicates that there is a rapidly increasing amount of unconventional and offshore oil reserves, of which some are yet undiscovered. Thus, it is evident that new and improved technologies will be of utmost importance for these reserves to materialize. According to Mills (2013), IDC, the global IT consultancy, is of the view that unconventional reserves (such as shale gas and tight oil) will be a driving force behind innovation alongside the expanded use of Big Data. Those interested are referred to Demirbas et al. (2016) where the authors review the heavy oil upgrading processes and their associated challenges.

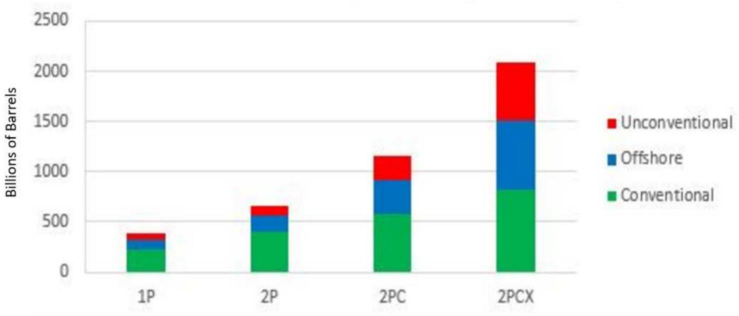

Figure 5: World oil remaining reserves in billions of barrels (Nysveen, 2016). Note: 1P - proved reserves, 2P - proved + probable reserves, 2PC - most likely estimate for existing fields and discoveries, 2PCX - most likely estimate for existing fields, discoveries and yet undiscovered fields.

Given the various factors that continue to influence the need for innovation and technology in the P&P industry, we now shift our focus on to the impact of innovation and technological advancements within the P&P industry. The discussion which follows is mainly centred around time and cost savings, efficiency gains, and sustainable growth with quantified evidences from various real life examples.

3 The Impact of Innovation and Technology in the P&P Industry

In this section, we seek to concisely explain the impact of innovation and technology in the P&P industry whilst quantifying the impact, where possible. In the process, we also discuss the latest technological developments which are enabling the P&P industry to reap the maximum benefits underlying innovation and technological advancements.

In brief, new oil drilling technologies are expected to increase the worlds petroleum supplies six-fold in the coming years to 10.2 trillion barrels (Woody, 2013). Moreover, technology is to enable the extension of the life of a well by several years and boost the amount of recoverable oil by 33% (Sider and Ailworth, 2015). In addition, a report published by the McKinsey Global Institute states that by 2025 the potential economic impact of mobile and internet technologies could exceed $100 billion per annum in oil, metal and mineral extraction industries (PLH Group, 2015). Therefore, it is not entirely surprising that Li (2016) calls for smart factories within the petrochemical industry and better exploitation of virtual reality.

The impact of innovation and technology in the P&P industry can be broadly classified into: (i) Cost reduction and time saving; (ii) efficiency gains; and (iii) sustainable growth. In what follows, we exploit fact boxes to summarize the quantifiable impact of innovation and technology and then expand further on the various innovations and technologies which have enabled the growth of this industry.

3.1 Cost Reduction & Time Saving

Quick Fact Box

Fact 1: Digital oil fields have enabled operating and staffing costs to be reduced by 10-25% (Elatab, 2012).
Fact 2: Technology has brought down the average shale barrel production cost to between $7-$15 (Mills, 2013).
Fact 3: Dell's EMC technology can reduce IT administration costs by 68% and Big Data storage costs by 40% (EMC, 2015).
Fact 4: Mixing solvents with steam can lower crude extraction costs by 1/3rd (Lewis, 2015).
Fact 5: Automation can reduce operating expenditure (OPEX) by 70% and capital expenditure (CAPEX) by 3-15% (IHS Markit, 2016).
Fact 6: Digital technology can reduce CAPEX and OPEX by 20% and 3-5% in upstream operations (Boman and Staff, 2016; Choudhry et al., 2016).
Fact 7: Smart Reamer technology could save the offshore oil industry £1 billion per annum (GOV.UK, 2016).
Fact 8: The Miraah project enables cost savings by reducing Enhanced Oil Recovery (EOR) gas consumption by 80% (Werber, 2016).
Fact 9: Better use of existing technology can provide up to $1 billion in cost savings or production increases (Ward, 2016).
Fact 10: Using advanced analytics for predictive maintenance can reduce maintenance costs by up to 13% (Choudhry et al., 2016).
Fact 11: The Industrial Internet of Things helps prevent unplanned outages and can thereby save up to $3 million per week (Kendon, 2016).
Fact 12: Digital enabled marketing and distribution can lower costs by up to 10% via optimized pricing models and supply chains (Choudhry et al., 2016).

Cost reduction is crucial for the P&P industry because despite its supernormal revenues, profit margins of the oil and gas majors is said to be between 8-9% (Farris, 2012). Moreover, with less easy oil available and alternatives for oil and gas becoming increasingly popular, reducing production costs are imperative for the survival of the P&P industry (Kleinschmidt, 2016). Given that oil is expensive to produce, owing to the science, machinery and manpower involved, falling oil prices will undoubtedly have significant negative impacts on the bottom lines of producers in the P&P industry. However, evidence suggests that firms who embrace innovation and technological change are managing to overcome the issues related with declining oil prices. For example, According to Mills (2013) technological advancements have resulted in the average cost of producing a shale barrel to drop to the $7-$15 range. Given the ongoing decline in world oil prices, such cost reductions are exactly what the industry needs to ensure that the firms continue to remain a going concern. By exploiting technological advancements, firms can maintain their market position amidst volatile pricing conditions and also protect its human capital by doing away with the need for layoffs as an option for cost reduction. A more recent breakdown of the cost of producing a barrel of oil and gas can be found in the Wall Street Journal's Barrel Breakdown[2], and those interested are referred to this informative page.

Technology and ***supercomputers with advanced algorithms*** play a pivotal role in helping reduce the cost and time involved in oil and gas exploration (Barney, 2015). An example is reverse time migration (RTM) computations by Intel. RTM is an algorithm used for the generation of more accurate images of the subsurface, so that the cost and time involved in discovering petroleum deposits under water and rock can be reduced (Barney, 2015). The speed and accuracy offered by super computers can be extremely useful to the P&P industry as high cost of data acquisition, drilling and production is said to reduce average profit margins to less than 10 percent (Barney, 2015).

Big Data is a revolutionary phenomenon in the modern age. A basic example of Big Data can be the large amounts of data that is generated as a result of the process involved in finding and producing hydrocarbons (Farris, 2012). More formal definitions of Big Data are based around the increasing volume, variety, and velocity of data (Farris, 2012). The technology and advanced algorithms underlying supercomputers has the capability of processing Big Data swiftly to produce lucrative models for the earth's structure and layers below the surface (Farris, 2012). Such developments help analyze machine performance, pressure and oil flow rates (Farris, 2012). Dell's EMC data management technology was seen reducing 68% in petro-technical IT administration costs, 40% in Big Data storage costs and providing a 80% return on investment to a large independent Oil and Gas company (EMC, 2015). In a world where 'time is money', the efficiency gains which technological developments can bring in to a company can undoubtedly result in significant cost reductions by automating otherwise time consuming tasks and enabling better resource allocations, and doing away with the need for massive storage spaces when all information can be stored and protected on the cloud.

Virtual reality is also playing an increasingly important role in the P&P industry. Siemens is enabling technicians to prepare themselves for maintenance assignments by immersing themselves in virtual 3D drilling platforms

[2] http://graphics.wsj.com/oil-barrel-breakdown/

which saves both time and costs (Kleinschmidt, 2016; Kendon, 2016). Eelume, a snake-like robot used for underwater repair does not need the support of a remotely operated vehicle (ROV) and can therefore reduce the costs of first-line inspection and maintenance of undersea installations (Kendon, 2016). A more recent development is ground penetrating radar (GPR), an innovative technology used for subsurface investigation and exploration which allows the gathering, analysis and processing of Big Data and reduces extraction costs (OilVoice, 2016).

Elatab (2012) discussed the concept of ***digital oil fields***. In brief, it refers to IT instruments constantly reading data pertaining to exploration and extraction, which provides Big Data for improving the decision making processes in the P&P industry, whilst being a solution to the possible lack of qualified skilled labour in future (Elatab, 2012). A McKinsey report outlined how digital oil fields have enabled one oil company to cut operating and staffing costs by 10-25% and still increase production by 5% (Elatab, 2012). A more recent research by McKinsey & Co. noted that the use of digital technologies in the oil and gas sector could reduce capital expenditures by up to 20% and cut operating costs in upstream by 3-5%, and by about half that in downstream (Boman and Staff, 2016). These are clear examples of the power of technology when coupled with Big Data in enabling productivity gains with meaningful cost reductions which are appearing to be increasingly important for surviving in the P&P industry. Interestingly, digital technologies also have the potential to transform operations and create additional profits from existing capacity, if exploited appropriately (Choudhry et al., 2016).

Oil extraction is a high risk job, usually conducted in remote environments. According to Elatab (2012), advanced video conferencing allows the diagnosis and treatment of patients remotely, and thereby enables considerable cost savings. In fact, the use of automation and robust communication networks to operate remotely can reduce operating costs by 70% and capital expenditure by 3-15%, provided oil companies redesign their facilities to reflect lower staffing levels (IHS Markit, 2016). Here in lies a possible negative impact of technological advancement on employability in the P&P industry, as automation is more likely to replace unskilled labour as opposed to skilled labour. Such scenarios could lead to severe financial and social problems for low income families who are more likely to maintain their living by employing their unskilled labour. According to Marr (2015), Shell Gas has been developing the idea of a 'data-driven oilfield' with hopes of bringing down the cost of drilling for oil. Shell Gas now exploits fitted sensors on machinery to collect performance data which can help minimize downtime and enable more efficient replacement of parts in order to reduce overheads (Marr, 2015).

Sebastian (2015) asserts that timely reporting and dissemination of actionable data is saving individual companies approximately $100 million per year. There is also evidence to support the argument that sensors placed deep in wells or on drilling equipment can feed in real time information to help mitigate technical risks and enable better maintenance (Gutierrez, 2016; Bertocco and Padmanabhan, 2014). Yet another interesting concept is the Industrial Internet of Things. This enables General Electric (GE) and BP to connect 650 deep sea oil wells and then use GE's Predix Software Platform to monitor and predict the performance and failure of wells (Kendon, 2016). Kendon (2016) further notes that prevention of unplanned outages via the Industrial Internet of Things can save an operator up to $3 million per week which would otherwise have to be spent if a well goes out of production.

Quick, safe and cost affective assessments of target areas and their likely prospectivity is crucial for oil and gas exploration (Shell Gas, 2014). Looking in the wrong place is not an option when drilling a deep water oil well often costs over $100 million (Marr, 2015). As Mills (2013) noted, ‘its always been about knowing where to look, where exactly to drill.’ However, accessing oil and gas reserves is turning out to be an arduous task. Figure 6 below provides an animated representation of conventional and non-conventional oil reserves which require extraction. Under such conditions, ***Seismic Imaging*** can also be associated with technologies enabling cost reductions (Barney, 2015). The aim of seismic imaging is straightforward: ‘create a clear, accurate picture of the Earths subsurface and identify all of the major components of the hydrocarbon systems’ (Farris, 2012).

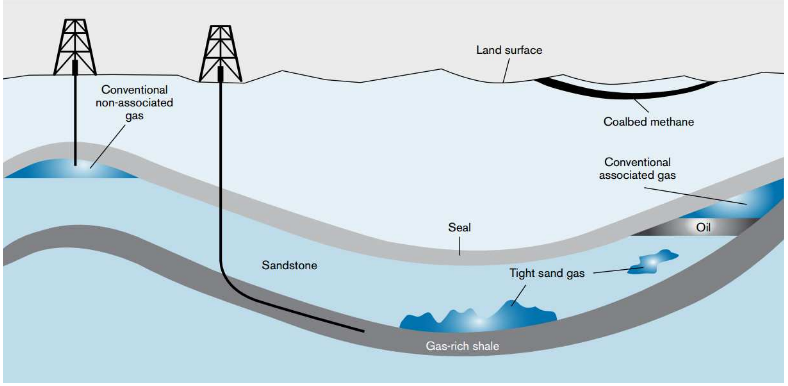

Figure 6: A schematic of the different sources of conventional and non-conventional gas (Mitchell et al. 2012, p. 32).

3D seismic imaging is considered to be one of the key innovations in oil exploration, and according to Farris (2012) it was one of the most impactful scientific breakthroughs in the P&P industry. However, the first use of 3D seismic mapping was by Exxon back in the 1960-1970’s, and years later it continues to transform the exploration process (Mitchell et al., 2012; Mills, 2013). Unlike 2D seismic imaging which uses one source of vibration, 3D seismic technology employs acoustics imaging to create a perimeter where multiple acoustic receivers, rather than microphones, are established prior to capturing seismic shots that lie between two patches which enables one to obtain uniform reflection information from a subsurface area (Dome Energy, 2014). Dome Energy (2014) noted that 3D seismic imaging has revolutionized the drilling industry with the greatest returns on investment which in turn helps increase profitability in the P&P industry. It is no surprise that by 2014, seismic reflection imaging was the most widely used geophysical technique in hydrocarbon exploration (Shell Gas, 2014). Those interested are referred to Shell Gas (2014, pp. 16-17) where they can find a clear timeline of technological developments in geophysical imaging.

Another way in which seismic imaging helps reduce costs is by aiding the identification of a suitable drill site (Kargbo et al., 2010). This is achieved via sound waves which are sent deep into the earth, with the sounds that bounce back up being received via geophones, which are then studied by engineers and geophysicists to determine different layers of rock formation (Mcgrath, 2011). This helps save both time and costs as it increases the probability of drilling at a location with actual oil and gas at the bottom of the surface as opposed to wasting colossal amounts of money at the wrong place.

Shell Gas (2014) used Wide Azimuth Ocean Bottom Sensing (WAOBS) technology whilst British Petroleum (BP) introduced the use of Wide Azimuth Towed Streamer technology (WATS) for subsalt imaging (BP, 2016). According to BP (2016) WATS is able to capture data from many angles (referred to as azimuths) to effectively bypass huge salt canopies above oil and gas reservoirs. It is noteworthy that BP's various innovations in seismic imaging also include: Ocean Bottom Nodes for driving efficiency, new algorithms for improving resolution such as Full Waveform Inversion and Synthetic Data Simulation, and Integration Engine, 4D seismic tools, Distributed Acoustic Sensing and Geophysics for seismic reservoir characterization via improved calibration (BP, 2016).

Drilling Technology can also enable cost savings for explorers. The UK Government believes that oil price volatility has sharpened the focus on costs of production as never before (GOV.UK, 2016). According to GOV.UK (2016), a new British drilling technology called 'Smart Reamer' provides an accurate way of measuring deep water bore holes whilst cutting costs for oil explorers with a potential to save the off-shore oil industry £1 billion per annum. In brief, the Smart Reamer technology sends information back to the surface enabling realtime adjustments by sitting above the cutters, using acoustic and magnetic sensors to take continual measurements which are then fed back in a continuous loop to optimise the cutting operation (GOV.UK, 2016). Meanwhile, Recon Technology has developed a fracking method called 'Frac BHD' which is a multi-stage stimulation system that is used in open-hole horizontal well fracturing, and can enable significant cost savings in terms of extracting oil from shale (Vanderbruck, 2015).

Solar powered oil fields are expected to reduce oil production costs by doing away with the need for natural gas in thermal enhanced oil recovery techniques (Earls, 2015). Thermal intervention is a process which injects steam into wells to extract heavy oils or oil sands, however it consumes a considerable amount of energy to generate the required steam (Woody, 2013). Figure 7 shows how Glasspoint's solar steam generator can easily integrate with existing surface facilities. Studies from Petroleum Development Oman and Stanford University found that solar could reduce EOR gas consumption by 80% via the Miraah project (Glasspoint.com, 2016; Werber, 2016).

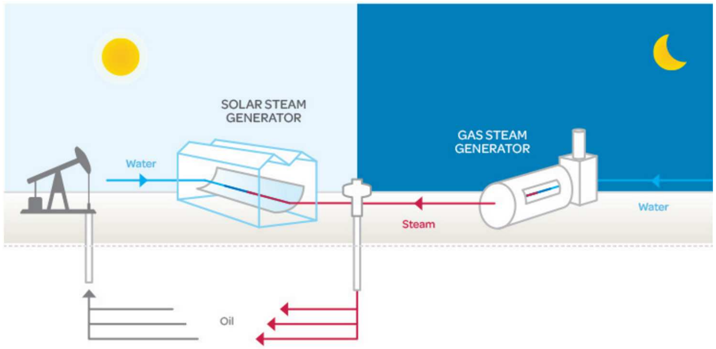

Figure 7: Glasspoint's solar steam generator (Glasspoint.com, 2016).

Rig efficiency is also playing an important role via the improvements following adoption of pad drilling technology, which enables drilling of multiple wells in the same spot without the need for expensive and time-consuming disassembly, relocation, and reassembly (Decker et al., 2016). In hope of low cost crude extraction, oil sands companies are increasingly looking at the possibility of mixing solvents such as butane, condensate and other petroleum liquids with steam at well sites (Lewis, 2015). This approach has the potential to boost production rates at steam-driven plants by 30% while lowering costs by about 1/3rd (Lewis, 2015). It is interesting that in contrast to automation related technological advancements, innovations such as solvents can enhance productivity and lower costs without having a negative impact on jobs within the P&P industry.

In brief, supercomputers and advanced algorithms, digital oil fields, seismic imaging technology, and drilling and extraction technology have played a significant role in enabling cost reductions and time saving within the P&P industry. However, P&P companies should also take into consideration the impact of technological advancements and innovation on employment within the industry in an age where corporate social responsibility is a key factor for all organizations around the globe. In what follows we consider reviewing the impact of innovation and technology in enabling efficiency gains within the P&P industry.

3.2 Efficiency Gains

Quick Fact Box

Fact 1: Technology has improved the productivity of America's shale fields between 200-300% (Mills, 2013).
Fact 2: Chemical EOR is expected to be 20% more efficient than water flooding (Woody, 2013).
Fact 3: A Malaysian experiment showed that Microbial EOR can increase oil production by 47% (Woody, 2013).
Fact 4: Zipper Fracking can double the volume of a typical well (Badiali, 2014).
Fact 5: Advances in Big Data analytics can increase oil production by 6-8% (Bertocco and Padmanabhan, 2014).
Fact 6: Improving production efficiency by 10% can increase profitability by \$220-\$260 million (Martinotti et al., 2014).
Fact 7: Well delivery management software can reduce planning/drilling lead times by an average of 5% (Sebastian, 2015).
Fact 8: Steam Assisted Gravity Drainage (SAGD) enabled Oman to produce 1 million barrels per day (Mawji, 2016).
Fact 9: The enhanced view of reservoirs from 4D seismic imaging increases the recovery rate by 40% (Choudhry et al., 2016).
Fact 10: The Plunger Lift Optimization Tool (PLOT) project can increase production by 30% (Ward, 2016).

The depressed oil price has companies focussing on efficiency in order to get the most petroleum for the least amount of money (Sider and Ailworth, 2015). According to Mills (2013), technology has improved the productivity of America's shale fields between 200-300% and explains the reason for U.S. to record the fastest worldwide oil production growth. The author believes that the productivity boom could be sustained as a result of Big Data. This is because, Big Data when coupled with Data Mining techniques can enable companies to continuously improve and enhance their production processes by analysing various different factors simultaneously. Research done by McKinsey & Company has shown that improving production efficiency by 10% can yield up to \$220 million to \$260 million bottom-line impact on a single brownfield asset (Martinotti et al., 2014). Such findings justify the consideration given to efficiency gains in particular as part of this review paper and Figure 8 adds to the justification by showing the potential impact of innovation in terms of benefits via productivity gains.

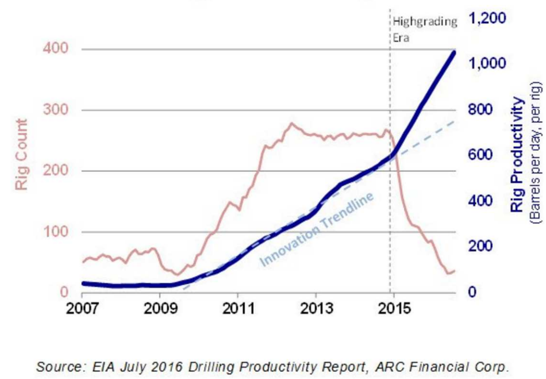

Figure 8: Eagle Ford monthly rig productivity, January 2007 - July 2016 (Tertzakian, 2016).

Seismic Imaging Technology not only provides cost benefits, but also has various efficiency related benefits to offer. Seismic data can be useful to determine the amount of oil or gas in new or previously overlooked oil wells (van Rijmenam, 2015). Another complement with seismic imaging is Least Squares Migration (LSM) which is an imaging technique that can improve the quality of seismic images by estimating angle-dependent reflectivity through minimizing the difference between observed data and the primary reflection data synthesized from that reflectivity (Shell Gas, 2014). However, it should be noted that not all technological developments come at a low cost. For example, 4D seismic monitoring has the potential to increase recovery efficiency, but it is estimated that it will add $1/bbl or more to the cost of producing oil from a field (Fanchi et al., 2010). Fanchi et al. (2010) defines 4D seismic imaging as the comparison of changes in 3D seismic surveys as a function of the fourth dimension, time. This is made possible via the comparison of differences in measurements of properties such as travel times, reflection amplitudes, and seismic velocities, and changes in the elasticity of the subsurface (Fanchi et al. 2010).

Thermal technologies are also becoming increasingly important given their abilities to improve yields even from dead wells via the use of superheated steam. Moreover, advanced thermal integration and cogeneration of multiple products have lead to energy efficiency improvements in the P&P industry (Dijkema, 2004; Korevaar, 2004; Patel et al., 2005). Meanwhile, combined thermal analysis methods have enabled lowering the energy requirement for the oxidation/cracking reactions and accelerating reaction rates (Liu et al., 2016).

Fracking is one of the most common, yet controversial oil drilling technologies where chemical-laced water is injected to break up subterranean rock formations (Woody, 2013). An improved alternative to fracking, known as ***Zipper Fracking***, was introduced in 2012 whereby instead of drilling down and then horizontally, operators would drill two wells side by side and frack at the same time (Badiali, 2014). By cracking two wells side by side, the rocks are cracked more deeply and efficiently in relation to a single well, and the process allows both wells to produce more oil and gas (Badiali, 2014). Figure 9 illustrates the zipper fracking process which according to Badiali (2014), resulted in doubling the volume of a typical well in Barnett Shale Texas.

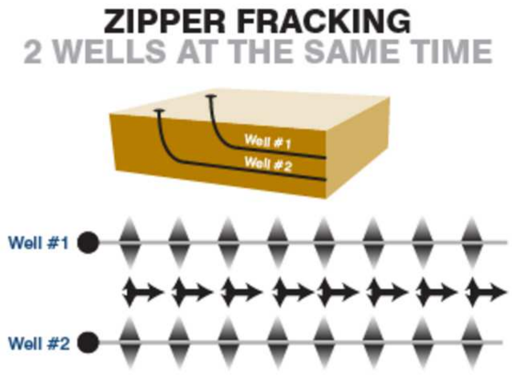

Figure 9: Zipper fracking two wells at the same time (Badiali, 2014).

Yet another innovation that is resulting in efficiency gains is the concept of ***Stacked Laterals*** which focuses on drilling wells close to each other, given that shale is a uniform layer of rocks (Badiali, 2014). Table 1 below shows how drilling innovations like Zipper Fracking and Stacked Laterals have dramatically increased shale production.

Table 1: Barrels of oil produced per drilling rig in all major shale plays (Badiali, 2014).

Shale Region	Production (June 2011)	Production (June 2014)	% Change
Niobrara (Colorado)	95 barrels per day	361 barrels per day	280%
Marcellus (Pennsylvania)	2427 mcf per day	6516 mcf per day	168%
Eagle Ford (Texas)	198 barrels per day	476 barrels per day	140%
Bakken (North Dakota)	213 barrels per day	505 barrels per day	137%

Note: Production statistics are per drilling rig.

According to Bertocco and Padmanabhan (2014) ***advances in Big Data analytics*** has the potential to increase oil production by 6-8%. It is evident that securing the ability and skills to exploit the power of 'data' will continue to be of utmost importance for the P&P industry in the foreseeable future. Bertocco and Padmanabhan (2014) identify three areas with the potential to improve via Big Data analytics. These include, geology interpretation, new well delivery, and well and field optimization. In brief, Bertocco and Padmanabhan (2014) further explain as follows. Geology interpretation is the potential to characterize shale basins with less trial and error by analyzing the geology below the surface and comparing it against well performance. New well delivery performance can be improved by transmitting microseismic, 3D imaging over fibre-optic cables (Bertocco and Padmanabhan, 2014). Marr (2015) notes that Shell Gas now uses fibre optic cables, created in a special partnership with Hewlett-Packard for transmitting seismic imaging data. This enables explorers to obtain a comparatively enhanced and clearer image of what lies beneath. The vast amounts of data gathered via 2D, 3D, and 4D seismic data imaging can be analysed fast with multiple parallel processing Big Data analytic platforms which can then help predict the real-time success of drilling operations (van Rijmenam, 2015). In addition, companies are using lasers and data analytics before drilling to ensure that new wells deliver the most crude for the money spent (Sider and Ailworth, 2015).

Well delivery management software enables the management of various core activities on one platform, and thereby helps reduce the lead-time associated with planning and drilling by an average of 5%, which converts into daily savings between $30,000/rig - $100,000/rig as a result of improved rig scheduling and utilization (Sebastian, 2015). Geospatial analytics is enabling the P&P industry to increase the efficiency of their supply and distribution networks via location planning and route optimization (Choudhry et al., 2016). Ward (2016) notes that the PLOT project enabled ConocoPhillips to increase production by 30% through the robotic process automation. In brief, PLOT is a technology which copies the processes executed by the engineering team, and then improves upon them by using automation and knowledge of the hidden commands contained in every major software tool (Ward, 2016). These findings indicate that software developers will have an influential role to play within the P&P industry in future as firms will seek to optimize their IT systems and make the most out of the Big Data that keeps flowing in.

BP (2016) is evaluating the use of Independent Simultaneous Source (ISS) technology for speeding up large scale 3D surveys at a lower cost by using multiple sources surveying simultaneously. Technological advancements have also led to the creation of ceramic proppant which can increase production rates and total amount of oil recovered whilst reducing the environmental impact of fracking via mixing of said particles with fracking fluid so that fractures can be held open (Elatab, 2012).

Measurement-while-drilling technology (MWD) can be exploited to provide realtime information on the status of drilling and improve the viability of horizontal drilling (Mcgrath, 2011). MWD technology relates information such as gamma rays, temperature and pressure, as well as the density and magnetic resonance of the rock formations to help operators drill more efficiently whilst preventing threats (Mcgrath, 2011). Mud pulse telemetry is the technique used to transfer information whilst drilling in the form of binary code which is decoded on the surface (Mcgrath, 2011). According to Sider and Ailworth (2015), ***refracking*** old wells with the latest fracking technology in hope of extracting more oil is now common. For example, a special nutrient mix which stimulates the growth of microbes is exploited to help break up and dislodge the oil and thereby increase production (Sider and Ailworth, 2015). Estimates suggest that approximately 10,000 horizontal shale oil and gas wells drilled over the last five years in North America are candidates for refracking (Sider and Ailworth, 2015). Figure 10 below shows the positive impact that various drilling technologies have had on productivity gains by increasing the number of wells a rig can drill each month. In fact, ***Pad Drilling Technology*** which allows a rig to drill multiple wells from the same spot without the need for expensive relocation is identified as the main driver of this improved rig efficiency.

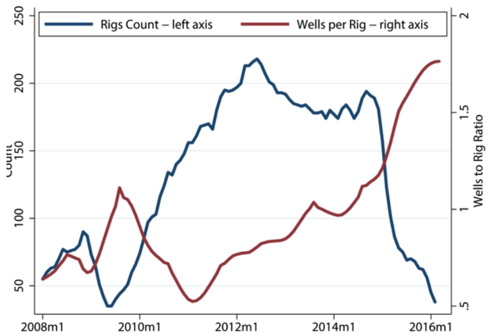

Figure 10: Rig counts and wells per rig in the Bakken region, U.S. (Decker et al., 2016).

Chevron (2016) is working on a new, safer and more efficient drilling technology called Subsea MudLift Drilling (SMD) for deepwater drilling. This was formerly known as dual-gradient drilling and the new SMD technology ensures the riser and ocean pressure match by filling the riser with seawater-like fluid, and thereby overcoming issues pertaining to high pressure created by the sea water weight and other formations at the bottom of the ocean (Chevron, 2016).

Sider and Ailworth (2015) note that in order to maximize the oil produced by a well, there is considerable reliance on software and sensors to determine the exact places for using sand, water and chemicals. According to Decker et al. (2016), increased and more efficient use of water, sand and proppants have improved the productivity of wells via increasing the extraction from these new wells in their first month of production by trippling extraction in relation to 2008. Figure 11 below illustrates the well decline curves calculated with data from the Department of Mineral Resources, North Dakota.

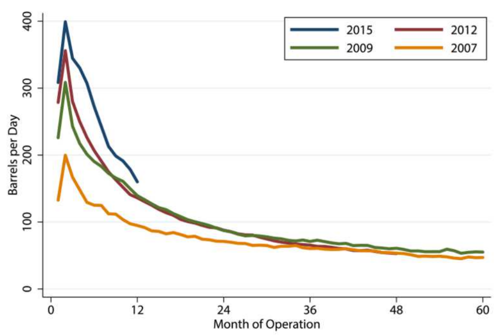

Figure 11: Average well decline curve by cohort for Bakken region, U.S. (Decker et al., 2016).

Several ***Enhanced Oil Recovery (EOR) techniques*** have been developed recently and these have aided significant production gains within the P&P industry. Those interested in an in-depth discussion of these technologies up until 2010 are referred to Shah et al. (2010). Steam assisted gravity drainage

(SAGD) is one such example whilst Toe-to-heel air injection (THAI) is another (Mawji, 2016; Shah et al., 2010). According to Lim (2016), oil companies are increasingly replacing surface mining with in-situ technologies like SAGD which inject steam into the ground to liquify the oil so that it can be pumped back out (Lim 2016). SAGD in particular has enabled Occidental Petroleum (OXY) to help boost Oman's oil production from the Mukhaizna field by 15 times in comparison to 2005 levels and set all time records of 1 million barrels per day (Mawji, 2016), see Figure 12.

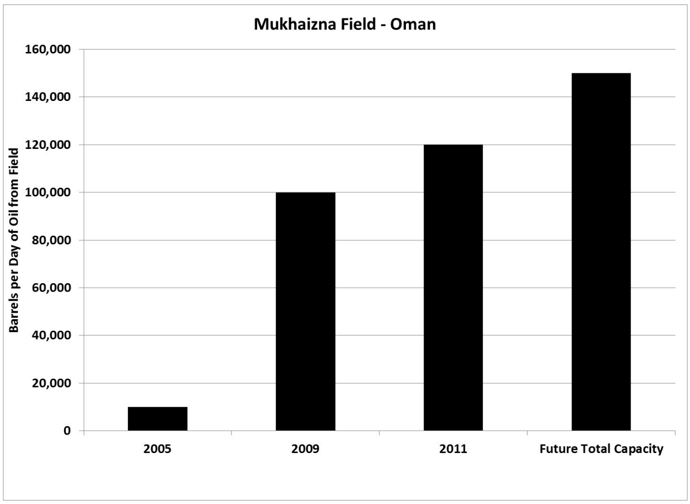

Figure 12: Oil production at Mukhaizna field in Oman (Mawji, 2016).

Chemical EOR, lead by the China National Petroleum Corporation, injects polymers and alkaline compounds into oil fields to help loosen oil from rock formations and push it into production wells (Woody, 2013). Chemical EOR is expected to be 20% more efficient than flooding wells with water in order to bring oil to the surface(Woody, 2013). However, it has its limitations when faced with high temperatures and high levels of salt and sulfur, in addition to being potentially harmful near water supplies (Woody, 2013). A more appropriate alternative is Microbial EOR which exploits environmentally benign microorganisms to break down heavier oils and produce methane, which can then be pumped into wells in order to push out lighter oil (Woody, 2013). According to Woody (2013), an experiment in Malaysia showed that Microbial EOR can increase oil production by 47%.

In summary, efficiency gains have been primarily made possible by the evolutionary phenomenon of Big Data and related technology, Seismic Imaging, thermal, drilling and extraction technologies, and enhanced oil recovery techniques. Whilst all these innovations and technologies are driving cost reductions and efficiencies, a crucial factor which we look into next is the influence of such innovations and technologies at fuelling sustainable growth within the P&P industry.

3.3 Sustainable Growth

Quick Fact Box

Fact 1: Measurement-while-drilling (MWD) Technology enables environmentally safer digging of wells (Mills, 2013).
Fact 2: A newly developed solvent enables oil sands surface mining without air pollution or the need for water (Jacobs, 2014).
Fact 3: Project Miraah is expected to reduce carbon dioxide emissions by 300,000t per year (Earls, 2015).
Fact 4: Halliburtons RapidFrac system reduces the water needs for fracking in half (Vanderbruck, 2015).
Fact 5: A propane based gel is used to completely eliminate the need for water for fracking (Vanderbruck, 2015).
Fact 6: New oil sands technology can reduce emissions intensity by 25% (Lewis, 2015).
Fact 7: Solar powered EOR techniques are the future of cleaner energy (Werber, 2016).
Fact 8: Project Miraah saves water by recapturing 90% of used water (Meineke, 2016).
Fact 9: Horizontal drilling leaves a smaller environmental footprint in comparison to drilling multiple vertical wells (Chevron, 2016).

According to Ron (1998), sustainable production refers to producing goods which satisfies the needs and wants of the present society without compromising the ability of future generations to satisfy their needs and wants. Alternatively, O'Brien (1999) defines sustainable production as an industry's ability not only to create wealth, but also to ensure that the creation process leads to sustainable economic development.

van Rijmenam (2016) believes that ***Big Data*** presents opportunities for oil and gas companies to get more oil or gas out of new or existing wells whilst mitigating environmental risks. For example, the collection and analysis of real time data via Big Data analytics enables early identification of drilling anomalies so that decisions can be made in time to shut down operations to prevent any large environmental risks (van Rijmenam, 2016). Barney (2015) and Farris (2012) assert that, ***supercomputers*** complement Big Data, and aid in reducing the negative impact on the environment by exploiting Big Data more efficiently to analyze machine performance.

In 2013, the first ***solar powered EOR*** extraction plant was set up in Oman, thereby enabling offsetting the total carbon footprint of steam induced oil extraction operations (Chakravorty, 2013). By 2015, Petroleum Development Oman (PDO) was planning to partner with Californian solar power start-up Glasspoint to build the world's largest solar farm with a view to powering some of its oil production activities (Earls, 2015). This initiative is expected to reduce PDO's carbon dioxide emissions by 300,000t per year as they will no longer rely on 15%-25% natural gas that is required otherwise to generate steam for thermal EOR (Earls, 2015). This reduction in carbon dioxide emissions is equivalent to removing 63,000 cars from Oman's roads (Meineke, 2016). In fact, the adoption of solar powered oil fields is expected to convert into savings of 5.6 trillion British thermal units (BTUs) of natural gas each year (Earls, 2015; Meineke, 2016) and thus proving to be a successful and cleaner source of energy (Werber, 2016). Yet another advantage of solar powered oil fields is the potential to save water. According to Meineke (2016), Miraah (the name given to the solar farm project) has an automated washing system which can recapture 90% of used water and thereby help ease the rising pressure on the region's water-food-energy nexus and costly desalination projects.

Horizontal drilling, which can probe thousands of feet horizontally through the shale, is said to leave a smaller environmental footprint in comparison to drilling multiple vertical wells (Chevron, 2016). ***MWD technology*** enables an operator to steer a drill in different directions and this in turn helps ensure that wells are dug safely under environmentally sensitive land (McGrath, 2011). The need for re-drilling can be reduced by exploiting a system called 'HIWAY' which mixes fibers into the grit that blasts out shale oil, enabling the newly blasted channels to be kept open (Vanderbruck, 2015). Cost reductions and minimization of environmental impacts can be attained via Halliburton's 'RapidFrac' system which reduces the water needs for fracking in half (Vanderbruck, 2015). The need for water in fracking has been completely eliminated by a Canadian company, GasFrac, which uses a propane-based gel instead (Vanderbruck, 2015). Meanwhile, a method termed as 'cryogenic fracturing' is under development and it will cause fissures through contact with liquid nitrogen (Vanderbruck, 2015).

A newly developed ***solvent (invented by a Russian scientist) that acts as a surfactant*** is able to strip off more than 99% of the hydrocarbons from oil sands and is providing new hope to oil sands surface mining which is considered a controversial extraction method (Jacobs, 2014). According to the company developing same, this process is the most cost-effective and environmentally sound way to develop oil sands as there is no water involved and no air pollution (Jacobs, 2014). Lewis (2015) notes that new oil sands technology involving the use of solvents can lower emissions intensity by 25% when compared with the status quo.

GPUSA Inc. (2016) has developed a ***Distributed Seismic Source technology*** which can improve the economics (requiring only 2-3% of capital expenditure otherwise required for a Vibroseis truck) and reduce the environmental impact of finding and producing oil and gas whilst being a high frequency Downhole Seismic Source which can be carried in one hand. In addition, its revolutionary Safe & Sound Marine Vibrator helps minimize the harm to marine mammals, unlike with controversial explosive air gun seismic sources (GPUSA Inc, 2016).

As evident, Big Data, supercomputers, solar powered EOR techniques, exploration and drilling technologies are the key innovations and technologies enabling sustainable growth within the P&P industry. Whilst sustainable growth is important for any given industry in the modern age, we take a closer look at the environmental impact of innovation and technology in the P&P industry in the next section.

4 Environmental Impact

Quick Fact Box

Fact 1: There exists 10 proven methane emission control technologies which can collectively capture more than 80 percent of the methane currently going to waste (Harvey et al., 2012).
Fact 2: Software focussed on optimization can reduce nitrogen oxide emissions by 12-14% (Giglio, 2013).
Fact 3: Infrared cameras can spot leaks at fracking sites and help reduce methane emissions by 40% by 2018 (Kiger, 2014).
Fact 4: Solar powered pumps could eliminate an 5.9 billion cubic feet of methane emissions annually (Kiger, 2014).
Fact 5: Lower-bleed designs could reduce emissions by 35 billion cubic feet annually (Kiger, 2014).
Fact 6: In-situ production saves nine-tenths of the land above a reservoir by leaving it intact (Economist, 2014).
Fact 7: Mixing oil based solvents to steam can reduce the amount of water that has to be heated by 15% (Cunningham, 2014).
Fact 8: Carbon Capture and Storage can theoretically prevent 75-90% of generated CO_2 being released into the environment (Grantham Institute, 2015).
Fact 9: Use of radio waves has the potential to cut the need for water and reduce energy use by up to 75% (Bickis, 2015).

Oil and Gas exploration, production and transportation can have negative effects on the environment (EIA, 2015). However, as El-Badri (2011) stated, the early development and deployment of new technologies can help reduce the P&P industry's environmental footprint regardless of challenges in terms of cost and efficiency. For example, cleaner storage systems and new transportation materials have reduced environmental risks, and innovations such as Carbon Capture and Storage can help in ensuring that fossil fuels are environmentally friendly (El-Badri, 2011). Carbon Capture and Storage in particular can theoretically prevent 75-90% of the CO_2 generated from a power plant being released into the environment (Grantham Institute, 2015).

Whilst some propose reductions in carbon dioxide emissions by growing the share of natural gas (Kiger, 2014) relative to coal in the energy mix, methane leakage resulting from natural gas also remains a problem (Grantham Institute, 2015). Especially as methane is a potent greenhouse gas, 34 times stronger than carbon dioxide (Kiger, 2014). Methane, a global warming pollutant which accelerates climate change makes up 90% of natural gas, and is often vented into the atmosphere (Gowrishankar, 2012). It is said that capturing and selling this methane would not only result in less pollution and improved air quality, but also generate more than $2 billion of additional revenue each year (Gowrishankar, 2012). The use of infrared cameras to spot leaks at fracking sites can redue methan emissions by 40% by 2018 at a cost that is equivalent to 1 cent per 1000 cubic feet of natural gas produced (Kiger, 2014). Lower-bleed designs, a U.S. wide initiative, could reduce emissions by 35 billion cubic feet annually whilst replacing conventional chemical pumps used in the fracking process with solar powered pumps (Kiger, 2014). This has the potential to eliminate 5.9 billion cubic feet of methane emissions annually (Kiger, 2014).

As Gowrishankar (2012) asserts, there are 10 proven methane emission control technologies which together can capture more than 80 percent of the methane currently going to waste. These are, Green Completions (to capture oil and gas well emissions), Plunger Lift Systems (to mitigate gas well emissions), Tri-Ethylene Glycol Dehydrator Emission Controls and Desiccant Dehydrators (to capture emissions from dehydrators), Dry Seal Systems (to reduce emissions from centrifugal compressor seals), Improved Compressor Maintenance (to reduce emissions from reciprocating compressors), Low-Bleed or No-Bleed Pneumatic Controllers (to reduce emissions from control devices), Pipeline Maintenance and Repair (to reduce emissions from pipelines), Vapor Recovery Units (to reduce emissions from storage tanks), and Leak Monitoring and Repair (to control fugitive emissions from valves, flanges, seals, connections and other equipment) (Harvey et al., 2012). Figure 13 below shows the possible reductions in methane emissions if the above technologies are exploited.

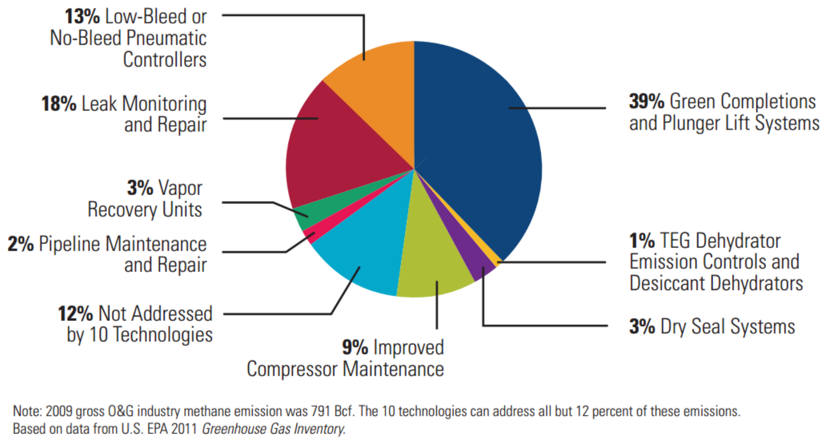

Figure 13: Oil and Gas Industry Methane Emission Reduction Potential by Technology (Harvey et al., 2012).

Several technological developments are aimed at making fracking greener. Gas Frac uses a gelled fluid containing propane which eliminates the need for water, and as gel retains sand better than water, it is possible to get the same results with 1/8th of the liquid and a smaller footprint (Kiger, 2014). Halliburton's UniStim can create a highly viscous fluid from any quality of water and allows operators to use recycled "gray" water or brine for fracking (Kiger, 2014). A company named Apache was the first to eliminate diesel powered equipment and use natural gas instead in a bid to cut down on carbon emissions, whilst an innovation named SandCastle vertical storage silo powered by solar panels for the sand used in fracking was introduced by Halliburton to obtain a sizeable reduction in emissions (Kiger, 2014). Halliburton also uses positively charged ions and bubbles to remove particles from the water at the fracking site whilst GE employs a desalination process called membrane distillation that allows the water to be reused without being diluted with freshwater (Kiger, 2014).

Production techniques such as 'in-situ' production helps reduce the environmental impacts from oil sands. It extracts bitumen without strip mining, by injecting high-pressure steam (heated to more than 300C) into deep boreholes and this steam which emerges from millions of slits in a steel borehole liner, liquefies the bitumen allowing it to be pumped out (Economist, 2014). Steam extraction saves nine-tenths of the land above a reservoir by leaving it intact, and water recovered from the bitumen can be cleaned with distillation for reuse (Economist, 2014). Moreover, adding oil based solvents (butane and propane) to steam reduces the amount of water that has to be heated by 15% and thereby reduces emissions (Economist, 2014; Cunningham, 2014).

The PLH Group (2015) asserts that mobile technology is being used in the P&P industry 'to help meet increased regulatory and monitoring requirements and create data archives, which then builds and stores long-term histories of compliance and environmental protection efforts'. Meinecke (2015) reports on a mobile system known as Geo-spatial Measurement of Air Pollution (GMAP) which assesses oil and gas production facilities, refineries, and shipping terminals to detect possible pollutants by drawing air into the system and then reading the levels of emissions. Computer software can be used to optimize existing plants and evidence from a coal-fired plant in Baldwin, Illinois, U.S. showed a 12-14% reduction in nitrogen oxide emissions, 15-20% reduction of ammonia consumption, and reduction in GHGs, mercury, and particulates (Giglio, 2013).

GE and Statoil are developing technologies to help the environment by reducing water usage in onshore oil and gas production through water treatment via a nano-sponge, ice crystals and an evaporator tornado, and high powered laser beams that make pipes super water repellant (Hardcastle, 2016). In Canada, through a collaborative effort, research is currently taking place to ascertain the possibility of using radio waves rather than energy-intensive steam in underground heavy oil extraction with the potential to reduce energy use by up to 75%, cut the need for water, and thereby lower the environmental impact (Bickis, 2015).

5 Conclusion

This review paper fills a gap in literature by reviewing and summarizing the role of innovation and technology in sustaining the P&P industry. It begins by taking a look at the definitions of invention and innovation prior to assessing the need for innovation and technology in the P&P industry. Based on past literature, we identify that sustainable production and consumption practices, competition from other industries, automation of high cost and high risk tasks, the depressed oil price, and accessing future oil and gas resources to be the key influencers of innovation and technological development.

Thereafter, the paper considers reviewing the impact of technology and innovation in the P&P industry by focussing on innovative and technological developments aimed at cost reduction and time saving, efficiency gains, sustainable growth, and safeguarding the environment as a whole. Within each of these sections we also identify quantifiable impacts to provide the reader with a clear idea of the importance underlying each innovation and technological development.

Table 2 presents a concise summary of the impacts and the various innovations/technologies enabling these impacts within the P&P industry. There are few interesting observations. Firstly, supercomputers and advanced algorithms, seismic imaging technology and drilling and extraction technologies appear to be the most prominent sources of innovations and technologies for cost reduction and time saving in the P&P industry. However, the industry should continue to focus more on exploiting digital oil fields which present many opportunities for useful cost reductions. Given the emergence of Big Data, it is evident that the importance of digital oil fields will continue to grow and it is high time that P&P companies began embracing same. Secondly, for efficiency gains, at present the P&P industry appears to be primarily exploiting technologies and innovations related to Big Data analytics, EOR and drilling and extraction. The P&P industry should continue to concentrate more on seismic imaging and thermal technology in particular and determine how these could be used more effectively for efficiency gains. Thirdly, EOR techniques are seen influencing efficiency gains, but we did not see it enabling significant cost reductions and time savings at present. Given that EOR techniques are becoming increasingly popular, added collaboration between companies could enable them to better exploit these and create synergies which can help reduce the costs involved. In terms of sustainable growth, innovations in drilling technologies are the primary influencer of same at present. There appears to be a lot of potential for research and development in relation to Big Data, supercomputers and solar power related EOR techniques to help further sustainable growth within this industry in future.

The contents of this paper can be highly useful for academics and researchers alike as to the best of our knowledge there exists no such papers at present which seek to review, identify, and quantify the impact of technology and innovation in the P&P industry. As innovative practices are more likely to build upon historical achievements, we believe the information reviewed and summarized in this paper would help stimulate more radical innovations within the P&P industry in the future.

Table 2: A summary of the innovation and technology by its impact.

Cost Reduction & Time Saving	**Efficiency Gains**	**Sustainable Growth**
(i) Super Computers and Advanced Algorithms:	*(i) Big Data:*	*(i) Big Data:*
RTM computations by Intel.	Sensors.	Realtime data analysis.
Dell's EMC data management technology.	Big Data analytics.	
Virtual 3D drilling platforms by Siemens.	Fibre Optics.	*(ii) Supercomputers*
Ground Penetrating Radar (GPR) technology.	Lasers and data analytics.	
BP's Full Waveform Inversion algorithm.	Well delivery management software.	*(iii) Solar Powered EOR.*
BP's Synthetic Data Simulation algorithm.	Geospatial analytics.	
BP's Distributed Acoustic Sensing algorithm.	ConocoPhillips' Plunger Lift Optimization Tool.	*(iv) Exploration Technology:*
Elume - underwater repair robot.	BP's Independent Simultaneous Source (ISS) technology.	GPUSA Inc.'s Distributed Seismic Source technology.
		GPUSA Inc.'s Safe and Sound Marine Vibrator.
(ii) Digital Oil Fields:	*(ii) Seismic Imaging Technology:*	
Advanced video conferencing.	Least Squares Migration imaging.	*(v) Drilling Technology:*
Automation.	4D Seismic monitoring.	Horizontal Drilling.
Shell Gas' data-driven oil fields.		Measurement-while-drilling technology.
Industrial Internet of Things.	*(iii) Thermal Technology:*	HIWAY system for mixing fibres into grit.
	Advanced Thermal integration.	Halliburton's RapidFrac.
(iii) Seismic Imaging Technology:	Combined Thermal Analysis methods.	Use of propane based gel.
3D Seismic Imaging.		Cryogenic fracturing.
Seismic Reflection Imaging.	*(iv) Drilling and Extraction Technology:*	Oil sands technology using solvents.
Shell Gas' Wide Azimuth Ocean Bottom Sensing.	Zipper Fracking.	
BP's Wide Azimuth Towed Streamer technology.	Stacked Laterals.	
BP's Ocean Bottom Nodes.	Ceramic proppant.	
BP's 4D Seismic Imaging.	Measurement-while-drilling Technology.	
	Mud Pulse Telemetry.	
(iv) Drilling and Extraction Technology:	Refracking with special nutrient mixes.	
UK's Smart Reamer technology.	Pad Drilling Technology.	
Recon Technology's Frac BHD.	Chevron's Subsea MudLift Drilling.	
Solar Powered Oil fields.		
Thermal intervention.	*(v) Enhanced Oil Recovery Techniques:*	
Glasspoint's Solar Steam Generator.	Steam assisted gravity drainage.	
Pad Drilling Technology.	Toe-to-heel air injection.	
Use of Solvents like Butane and Condensate.	China National Petroleum Corporation's Chemical EOR.	
	Microbial EOR.	

References

[1] Age, J. O. (1995). Development of a Model for Technological Innovation Process. *Research-Technology Management*, **38**(2), 291–292.

[2] Al-Sharrah, G., and Elkamel, A., and Almanssoor, A. (2010). Sustainability Indicators for Decision-making and Optimisation in the Process Industry: The Case of the Petrochemical Industry. *Chemical Engineering Science*, **65**, 1452–1461.

[3] Badiali, M. (2014). 2 New Drilling Techniques that Will Shatter US Oil Expectations. Available via: `http://dailyreckoning.com/2-new-drilling-techniques-that-will-shatter-us-oil-expectations/`. [Accessed: 04.10.2016].

[4] Barney, L. (2015). How Supercomputers aid Oil and Gas Seismic Research. Available via: `http://www.scientificcomputing.com/article/2015/10/how-supercomputers-aid-oil-and-gas-seismic-research`. [Accessed: 14.10.2016].

[5] Bennett, S. J., and Pearson, P. J. G. (2009). From Petrochemical Complexes to Biorefineries? The Past and Prospective Co-evolution of Liquid Fuels and Chemicals Production in the UK. *Chemical Engineering Research and Design*, **87**, 1120–1139.

[6] Bers, J. A., and Dismukes, J. P. (2004). Roadmap for a Radical Innovation Community of Research and Practice. Unpublished Whitepaper; 2005, Paper submitted to PICMET05, Portland, OR, July 2005.

[7] Bers, J. A., Dismukes, J. P., Miller, L. K., and Dubrovensky, A. (2009). Accelerated radical innovation: Theory and application. *Technological Forecasting & Social Change*, **76**(1), 165–177.

[8] Bertocco, R., and Padmanabhan, V. (2014). Big Data Analytics in Oil and Gas: Converting the Promise into Value. Available via: `http://www.bain.com/Images/BAIN_BRIEF_Big_Data_analytics_in_oil_and_gas.pdf`. [Accessed: 11.10.2016].

[9] Betz, F. (1998). *Managing Technological Innovation: Competitive Advantage From Change*. John Wiley & Sons, New York, NY.

[10] Betz, F. (2003). *Managing Technological Innovation: Competitive Advantage From Change*. 2nd Edition, John Wiley & Sons, New York, NY.

[11] Bickis, I. (2015). Oil and Gas Industry Struggles to Balance Costs and Environmental Pressures. Available via: `http://globalnews.ca/news/2281464/oil-and-gas-industry-struggles-to-balance-costs-and-environmental-pressure` [Accessed: 23.10.2016].

[12] Boman, K., and Staff, R. (2016). Digital Tenacity Key to Implementing Technology in Oil, Gas Industry. Available via: http://www.downstreamtoday.com/(X(1)S(wlydaq55svg2ty55bhiyhsqp))/news/article.aspx?a_id=53301&AspxAutoDetectCookieSupport=1. [Accessed: 19.10.2016].

[13] BP (2016). Seismic Imaging. Available via: http://www.bp.com/en/global/corporate/technology/technology-now/seismic-imaging.html. [Accessed: 14.10.2016].

[14] Bromley, D. A. (2002). Science, Technology and Politics. *Technology in Society*, **24**(1-2), 9–26.

[15] Bromley, D. A. (2004). Technology Policy. *Technology in Society*, **26**(2), 455–468.

[16] Chakravorty, S. (2013). Solar-Powered Oil Extraction Technology. Available via: http://www.energyandcapital.com/articles/solar-powered-oil-extraction-technology/3409. [Accessed: 05.10.2016].

[17] Chazan, G. (2013). Cutting-Edge Technology Plays Key Role for Repsol in Hunt for Oil. Financial Times. Available via: https://www.ft.com/content/a20c0066-b420-11e2-b5a5-00144feabdc0. [Accessed: 15.10.2016].

[18] Chesbrough, H., and Rosenbloom, R. S. (2002). The Role of the Business Model in Capturing Value from Innovation: Evidence from Xerox Corporation's Technology Spin-off Companies. *Industrial and Corporate Change*, **11**(3), 529–555.

[19] Chesbrough, H. (2003). *Open Innovation: The New Imperative for Creating and Profiting from Technology.* Harvard Business School Press, Boston, MA.

[20] redChesbrough, H., and Spohrer, J. (2006). A Research Manifesto for Services Science. *Communications of the ACM*, **49**(7), 33–40.

[21] Chevron. (2016). A Bit of Drilling. Available via: https://www.chevron.com/technology/drilling. [Accessed: 04.10.2016].

[22] Choudhry, H., Mohammad, A., Tan, K. T., and Ward, R. (2016). The Next Frontier for Digital Technologies in Oil and Gas. Available via: http://www.mckinsey.com/industries/oil-and-gas/our-insights/the-next-frontier-for-digital-technologies-in-oil-and-gas. [Accessed: 29.01.2017].

[23] Coates, V. (2001). On the Future of Technological Forecasting. *Technological Forecasting & Social Change*, **67**(1), 1–17.

[24] Colombo, U. (1980). A Viewpoint on Innovation in the Chemical Industry. *Research Policy*, **9**(3), 205–231.

[25] Connelly, M. C., Dismukes, J. P., and Sekhar, J. A. (2011). New Relationships Between Production and Patent Activity During the High-growth Life Cycle Stage for Materials. *Technological Forecasting & Social Change*, **78**(2), 303–318.

[26] Connelly, M. C., and Sekhar, J. A. (2012). U. S. Energy Production Activity and Innovation. *Technological Forecasting & Social Change*, **79**(1), 30–46.

[27] Cunningham, N. (2014). Can New Technology Help The Oil Sands Industry Clean Up Its Act? Available via: `http://oilprice.com/Energy/Crude-Oil/Can-New-Technology-Help-The-Oil-Sands-Industry-Clean-Up-Its-Act.html`. [Accessed: 23.10.2016].

[28] Decker, R., Flaaen, A., and Tito, M. (2016). Unraveling the Oil Conundrum: Productivity Improvements and Cost Declines in the U.S. Shale Oil Industry. *Feds Notes*. Available via: `https://www.federalreserve.gov/econresdata/notes/feds-notes/2016/unraveling-the-oil-conundrum-productivity-improvements-and-cost-declines-i` `html`. [Accessed: 05.10.2016].

[29] Deffeyes, K. S. (2001). *Hubbert's Peak: The Impending World Oil Shortage.* Princeton University Press, Princeton, NJ.

[30] Demirbas, A., Bafail, A., and Nizami, A-S. (2016). Heavy Oil Upgrading: Unlocking the Future Fuel Supply. *Petroleum Science and Technology*, **34**(4), 303–308.

[31] Dismukes, J. P. (2004). Accelerate Radical Innovation Now! *Research-Technology Management*, **47**, 2–4.

[32] Dismukes, J. P. (2005). Information Accelerated Radical Innovation from Principles to an Operational Methodology. *The Industrial Geographer*, **3**(1), 19–42.

[33] Dismukes, J. P., Bers, J. A., Miller, L. K., and McCreary, W. N. (2005). Technologies of Thinking Seen Key to Accelerated Radical Innovation. *Research-Technology Management*, **48**, 2–4.

[34] Dismukes, J. P., Miller, L. K., and Bers, J. A. (2009). The Industrial Life Cycle of Wind Energy Electrical Power Generation: ARI Methodology Modeling of Life Cycle Dynamics. *Technological Forecasting and Social Change*, **76**(1), 178–191.

[35] Dijkema, G. (2004). *Process System Innovation by Design: Towards a Sustainable Petrochemical Industry.* PhD thesis, Delft University of Technology, Delft, The Netherlands.

[36] Dome Energy. (2014). How 3D Seismic Imaging Revolutionized the Drilling Industry. Available via: `https://www.domeenergy.com/3d-seismic-imaging-changed-drilling-industry/`. [Accessed: 14.10.2016].

[37] Earls, E. (2015). Solar-powered Oil Fields: Could They Help Build a Greener Future for Oil Production? Available via: http://www.power-technology.com/features/featuresolar-powered-oil-fields-could-they-help-build-a-greener-future-for [Accessed: 18.10.2016].

[38] Economist. (2014). Canada's Oil Sands: The Steam from Below. Available via: http://www.economist.com/news/science-and-technology/21615488-new-technologies-are-being-used-extract-bitumen-oil-sands-steam. [Accessed: 23.10.2016].

[39] EIA. (2015). Oil Crude and Petroleum Products Explained: Oil and the Environment. Available via: http://www.eia.gov/energyexplained/?page=oil_environment. [Accessed: 23.10.2016].

[40] Elatab, M. (2012). 5 Trends in Oil & Gas Technology, and Why You Should Care. Available via: http://venturebeat.com/2012/03/28/5-trends-in-oil-gas-technology-and-why-you-should-care/. [Accessed: 04.10.2016].

[41] Enos, J. L. (1958). A Measure of the Rate of Technological Progress in the Petroleum Refining. *Journal of Industrial Economics*, **6**(3), 180–197.

[42] Enos, J. L. (1962). Invention and Innovation in the Petroleum Refining Industry. In: *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Princeton University Press.

[43] El-Badri, A. S. (2011). New Frontiers in the Oil & Gas Industries: The Technological Difference. *In: The 15th IIES Conference & Exhibition*, 1-2 November 2011, Tehran, Iran.

[44] EMC. (2015). Oil & Gas Operational Efficiency. EMC Executive Briefing. Available via: https://www.emc.com/collateral/emc-perspective/h14217-ep-emc-oil-and-gas-operational-efficiency.pdf. [Accessed: 19.10.2016].

[45] Erwin, D. H., and Krakauer, D. C. (2004). Insights into Innovation. *Science*, **304**(5674), 1117–1119.

[46] Evans, K. (2016). Digital Tech Drives Innovation For Oil & Gas Companies. Available via: http://www.digitalistmag.com/digital-economy/2016/06/10/digital-tech-drives-innovation-for-oil-gas-companies-04258338. [Accessed: 19.10.2016].

[47] Fanchi, J. R., Pagano. T. A., and Davis, T. L. (2010). State Of The Art Of 4D Seismic Monitoring: The Technique, The Record, And The Future. *Oil & Gas Journal*, **97**(22). Available via: http://www.ogj.com/articles/print/volume-97/issue-22/in-this-issue/general-interest/state-of-the-art-of-4d-seismic-monitoring-the-technique-the-record-and-the html. [Accessed: 14.10.2016].

[48] Farris, A. (2012). How Big Data is Changing the Oil & Gas Industry. Available via: `http://analytics-magazine.org/how-big-data-is-changing-the-oil-a-gas-industry/`. [Accessed: 11.10.2016].

[49] Foxon, T. (2003). *Inducing Innovation for a Low-carbon Future: Drivers, Barriers and Policies - A Report for The Carbon Trust.* The Carbon Trust. London.

[50] Freeman, C., and Perez, C. (1997. The Economics of Industrial Innovation. Pinter, London.

[51] Garcia, R., and Calantone, R. (2002). A Critical Look at Technological Innovation Typology and Innovativeness Terminology: A Literature Review. *Journal of Product Innovation Management*, **19**(2), 110–132.

[52] Ghodsi, M. (2014). A brief review of recent data mining applications in the energy industry. *International Journal of Energy and Statistics*, **2**(1), 49–57.

[53] Giglio, R. S. (2013). New Technologies Reduce Environmental Impacts of Coal-fired Plants. Available via: `http://www.engineerlive.com/content/22603`. [Accessed: 23.10.2016].

[54] Glasspoint.com (2016). Oil Field Integration. Available via: `https://www.glasspoint.com/technology/integration/`. [Accessed: 18.10.2016].

[55] Goodstein, D. (2005). *Out of Gas: The End of the Age of Oil*. W.W. Norton & Company, New York.

[56] GOV.UK. (2016). Smart Reamer: Drilling Technology Can Cut Costs for Oil Explorers. Available via: `https://www.gov.uk/government/case-studies/smart-reamer-drilling-technology-can-cut-costs-for-oil-explorers`. [Accessed: 07.10.2016].

[57] Gowrishankar, V. (2012). Leaking Profits: The U.S. Oil and Gas Industry Can Reduce Pollution, Conserve Resources, and Make Money by Preventing Methane Waste. Available via: `https://www.nrdc.org/resources/leaking-profits-us-oil-and-gas-industry-can-reduce-pollution-conserve-reso`
[Accessed: 23.10.2016].

[58] GPUSA Inc. (2016). GPUSA a California Technology Company Leading a Seismic Shift in the Exploration and Production of Oil and Gas. Available via: `http://www.prnewswire.com/news-releases/gpusa-a-california-technology-company-leading-a-seismic-shift-in-the-explo`
`html`. [Accessed: 07.10.2016].

[59] Grafstrm, J., and Lindman, A. (2017). Invention, Innovation and Diffusion in the European Wind Power Sector. *Technological Forecasting & Social Change*, **114**, 179–191.

[60] Grantham Institute. (2015). How Can an Oil and Gas Company Prepare for a Low Carbon World? Available via: https://granthaminstitute.wordpress.com/2015/10/29/how-can-an-oil-and-gas-company-prepare-for-a-low-carbon-world/. [Accessed: 23.10.2016].

[61] Grove, A. S. (1996). *Only The Paranoid Survive: How To Exploit the Crisis Points that Challenge Every Company.* Doubleday, New York, NY.

[62] Grubler, A., and Wilson, C. (2014). *Energy Technology Innovation: Learning from Historical Successes and Failures.* Cambridge University Press, Cambridge.

[63] Gutierrez, D. (2016). Big Datas Big Impact Coming to Oil and Gas. Available via: http://insidebigdata.com/2016/08/16/big-datas-big-impact-coming-to-oil-and-gas/. [Accessed: 11.10.2016].

[64] Hanna, R., Gross, R., Speirs, J., Heptonstall, P., and Gambhir, A. (2015). *Innovation Timelines from Invention to Maturity: A Rapid Review of the Evidence on the Time taken for New Technologies to Reach Widespread Commercialisation.* UKERC Working Paper, UK Energy Research Centre.

[65] Hardcastle, J. L. (2016). Meet the Technologies GE, Statoil Say Will Revolutionize Oil & Gas Water Management. Available via: http://www.environmentalleader.com/2016/02/05/meet-the-technologies-ge-statoil-say-will-revolutionize-oil-gas-water-mana [Accessed: 23.10.2016].

[66] Harvey, S., Gowrishankar, V., and Singer, T. (2012). *Leaking Profits*. Available via: https://www.nrdc.org/sites/default/files/Leaking-Profits-Report.pdf. [Accessed: 23.10.2016].

[67] Henderson, M. R., and Clark, B. K. (1990). Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly*, **35**(1), 9–30.

[68] Hubbert, M. K. (1956). Nuclear energy and the fossil fuels. Shell Development Company, Exploration and Production Research Division, Houston, TX, Publication No. 95. Available via:http://www.energybulletin.net/node/13630. [Accessed: 14.01.2017].

[69] Hussain, R., Assavapokee, T., and Khumawala, B. (2006). Supply Chain Management in the Petroleum Industry: Challenges and Opportunities. *International Journal of Global Logistics & Supply Chain Management*, **1**(2), 90–97.

[70] IHS Markit. (2016). Technology and Innovation Key to Cost Reduction and Capital Efficiency as Companies Strive to Meet Future Energy Demand, IHS Says. Available via: http://press.ihs.com/press-release/bp-technology-review/

technology-and-innovation-key-cost-reduction-and-capital-efficien. [Accessed: 19.10.2016].

[71] Iles, A. (2008). Shifting To Green Chemistry: The Need for Innovations in Sustainability Marketing. *Business Strategy and the Environment*, **17**(8), 524–535.

[72] Jacobs, T. (2014). New Oil Sands Technology Debuts in Utah. Available via: http://www.spe.org/news/article/new-oil-sands-technology-debuts-in-utah. [Accessed: 04.10.2016].

[73] Jessua, C., Labrousse, C., and Vitry, D. (2006). *Dicionar de tiine Economice*. Editura Arc, Bucureti.

[74] Kargbo, D. M., Wilhelm, R. G., and Campbell, D. J. (2010). Natural Gas Plays in the Marcellus Shale: Challenges and Potential Opportunities. *Enivornmental Science & Technology*, **44**, 5679–5684.

[75] Kendon, P. (2016). 5 Innovative Technologies Changing Maintenance Management in the Oil and Gas Sector. Available via: http://www.solufy.com/blog/5-innovative-technologies-disrupt-maintenance-management. [Accessed: 29.01.2017].

[76] Kiger, P. J. (2014). Green Fracking? 5 Technologies for Cleaner Shale Energy. Available via: http://news.nationalgeographic.com/news/energy/2014/03/140319-5-technologies-for-greener-fracking/. [Accessed: 23.10.2016].

[77] Kleinschmidt, A. (2016). The Future of Oil and Gas: Why We Will Still Need Oil and Gas in the Future. Available via: http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/the-future-of-oil-and-gas-trends.html [Accessed: 29.01.2017].

[78] Korevaar, G. (2004). *Sustainable Chemical Processes and Products*. PhD thesis, Delft University of Technology, Delft, The Netherlands.

[79] Kulkarni, P., (2011). Organizing for Innovation. *World Oil*, **232**(3), 69–71.

[80] Lakhani, H. (1975). Diffusion of Environment-Saving Technological Change: A Petroleum Refining Case Study. *Technological Forecasting and Social Change*, **7**(l), 197–219.

[81] Leber, J. (2012). Big Oil Goes Mining for Big Data. Available via: https://www.technologyreview.com/s/427876/big-oil-goes-mining-for-big-data/. [Accessed: 11.10.2016].

[82] Lewis, J. (2015). Oil Sands Companies Turn to Solvents for Low-cost Crude Extraction. Available via: http://www.theglobeandmail.com/report-on-business/industry-news/energy-and-resources/oil-sands-companies-turn-to-solvents-for-low-cost-crude-extraction/article27072248/. [Accessed: 05.10.2016].

[83] Li, D. (2016). Perspective for Smart Factory in Petrochemical Industry. *Computers and Chemical Engineering*, **91**, 136–148.

[84] Liu, P-G., Pu, W-F., and Ni, J-H. (2016). Catalytic Effect Analysis of Clay Minerals on Low-temperature Oxidation of Crude Oil through Combined Thermal Analysis Methods. *Petroleum Science and Technology*, **34**(4), 343–349.

[85] Lim, A. (2016). Canadas Latest Oil Extraction Methods Put New Pressures on Environment. Available via: `http://america.aljazeera.com/multimedia/2015/7/canadas-oil-extraction-pressures-environment.html.` [Accessed: 04.10.2016].

[86] Luff, D., Baker, P., Apoteker, T., Watson, N., and Bynoe, M. L. (2013). *Strategies for Sustainable Long Term Economic Development in Curacao.* Ministry of General Affairs, TAC: Applied Economic & Financial Research.

[87] Magee, J. S., and Mitchell, M. M. Jr. (1992). *Fluid Catalytic Cracking: Science and Technology.* Elsevier, Amsterdam.

[88] Marr, B. (2015). Big Data In Big Oil: How Shell Uses Analytics To Drive Business Success. Available via: `http://www.forbes.com/sites/bernardmarr/2015/05/26/big-data-in-big-oil-how-shell-uses-analytics-to-drive-business-success/#4c23292f74b9`. [Accessed: 11.10.2016].

[89] Martinotti, S., Nolten, J., and Steinsbø, J. A. (2014). Digitizing Oil and Gas Production. Available via: `http://www.mckinsey.com/industries/oil-and-gas/our-insights/digitizing-oil-and-gas-production`. [Accessed: 19.10.2016].

[90] Marquis, D. G. (1976). The Anatomy of Successful Innovations. *Corporate Strategy and Product Innovation*, 14–25. New York, Free Press.

[91] Mawji, O. (2016). The Crude Crash Has Created Oils Technological Superpowers. Available via: `http://oilprice.com/Energy/Crude-Oil/The-Crude-Crash-Has-Created-Oils-Technological-Superpowers.html`. [Accessed: 04.10.2016].

[92] Mcgrath, J. (2011). Top 5 Innovations in Oil Drilling. *HowStuffWorks.com.* Available via: `http://science.howstuffworks.com/environmental/energy/5-innovations-oil-drilling.htm`. [Accessed: 04.10.2016].

[93] McGraw, T. K. (2007). *Prophet of Innovation: Joseph Schumpeter and Creative Destruction.* The Belknap Press of Harvard University Press, Cambridge, MA.

[94] McLean, J. G., and Haigh, R. W. (1954). *The Growth of Integrated Oil Companies in Western Europe*. Glower, Paris, pp. 6–15.

[95] Meehan, D. N., and Hughes, B. (2015). Innovation Beyond Technology: The New Imperative. *World Oil Magazine*, **236**(12). Available via: http://www.worldoil.com/magazine/2015/december-2015/industry-leaders-outlook-2016/innovation-beyond-technology-the-new-imperative. [Accessed: 15.10.2016].

[96] Meinecke, S. (2015). 5 Ways Tech Will Save the Environment. Available via: http://www.makeuseof.com/tag/5-ways-tech-will-save-environment/. [Accessed: 23.10.2016].

[97] Meineke, M. (2016). Oman Explores Solar-Powered Oil Recovery. *MIT Technology Review Arab Edition*. Available via: http://technologyreview.me/en/energy/oman-explores-solar-powered-oil-recovery/. [Accessed: 18.10.2016].

[98] Mensch, G. (1982). *Stalemate in Technology: Innovations Overcome The Depression*. Ballinger Publishing Company, Cambridge, MA.

[99] Mills, M. P. (2013). Big Data And Microseismic Imaging Will Accelerate The Smart Drilling Oil And Gas Revolution. Available via: http://www.forbes.com/sites/markpmills/2013/05/08/big-data-and-microseismic-imaging-will-accelerate-the-smart-drilling-oil-a #6f6e6e9548b2. [Accessed: 14.10.2016].

[100] Miller, L., Miller, R., and Dismukes, J. (2006). The Critical Role of Information and Information Technology in Future Accelerated Radical Innovation. *Information Knowledge Systems Management*, **5**(2), 63–69.

[101] Mills, M. P. (2015). Oil Glut Part 4: The (Next) Shale Technology Revolution That Worries OPEC. Available via: http://www.forbes.com/sites/markpmills/2015/06/03/oil-glut-part-4-the-next-shale-technology-revolution-that-worries-opec/#185a739d36a0. [Accessed: 05.10.2016].

[102] Mitchell, J., Marcel, V., and Mitchell, B. (2012). *What Next for the Oil and Gas Industry?* Chatham House, London.

[103] Moulijn, J. A., Makkee, M., and van Diepen, A. (2001). *Chemical process technology*. John Wiley & Sons, Chichester.

[104] Mueser, R. (1985). Identifying Technical Innovations. *IEEE Transactions on Engineering Management*, **EM-32**(4), 158–176.

[105] Mutyala, S., Fairbridge, C., Par, J. R. J., and Blanger, J. M. R. (2010). Microwave Applications to Oil Sands and Petroleum: A Review. *Fuel Processing Technology*, **91**, 127–135.

[106] Nemet, G. F. (2007). *Policy and Innovation in Low-carbon Energy Technologies*. PhD dissertation, University 14 of California.

[107] Nysveen, P. M. (2016). United States Now Holds More Reserves than Saudi Arabia. Available via: http://www.rystadenergy.com/NewsEvents/PressReleases/united-states-now-holds-more-oil-reserves-than-saudi-arabia. [Accessed: 18.10.2016].

[108] OBrien, C. (1999). Sustainable Production A New Paradigm for a New Millennium. *International Journal of Production Economics*, **6061**, 1–7.

[109] OECD. (1997). *Oslo Manual: Proposed Guidelines for Collecting and Interpreting Technological Innovation.* 2nd edition. Organization for Economic Co-operation and Development (OECD)/Eurostat, Paris.

[110] OilVoice. (2016). How Has GPR Proven to Be an Inevitable Technology Oil Exploration Industry? Available via: http://www.oilvoice.com/n/How-Has-GPR-Proven-to-Be-an-Inevitable-Technology-Oil-Exploration-Industry 8a5fd5cdeead.aspx. [Accessed: 07.10.2016].

[111] Patel, M., Crank, M., Dornburg, V., Hermann, B., Roes, L., Husing, B., Overbeek, L., Terragni, F., and Recchia, E. (2005). *Medium and Longterm Opportunities and Risks of the Biotechnological Production of Bulk Chemicals from Renewable Resources (the BREW project).* Department of Science, Technology and Society at Utrecht University, Utrecht, The Netherlands. See also at: http://www.chem.uu.nl/brew/BREW_Final_Report_September_2006.pdf [Accessed: 27.09.2016].

[112] Parshall, J. (2011). Shell: Leadership Built on Innovation and Technology. *Journal of Petroleum Technology*, **63**(1), 32–38.

[113] Perrons, R. K. (2013). How Innovation and R&D Happen in the Upstream Oil & Gas Industry: Insights from a Global Survey. *Journal of Petroleum Science and Engineering*, **124**, 301–312.

[114] Pillai, J. (2006). Importance of Clusters in Industry Development: A Case of Singapore's Petrochemical Iqndustry. *Asian Journal of Technology Innovation*, **14**(2), 1–27.

[115] PLH Group (2015). Four ways mobile technology affects oil and gas industry. Available via: http://plhgroupinc.com/mobile-technology-affects-oil-and-gas-industry/. [Accessed: 23.10.2016].

[116] Porter, M. E. (1990). *The Competitive Advantages of Nations.* New York, Macmillan.

[117] Porter, A. L. and Cunningham, S. W. (2005). *Tech Mining: Exploiting New Technologies for Competitive Advantage.* John Wiley & Sons, Hoboken, NJ.

[118] van Rijmenam, M. (2015). If Big Data Is The New Oil, The Oil and Gas Industry Knows How To Handle It. Available via: https://datafloq.com/read/big-data-oil-oil-gas-industry-handle/133. [Accessed: 11.10.2016].

[119] Ren, T. (2009). Barriers and Drivers for Process Innovation in the Petrochemical Industry: A Case Study. *Journal of Engineering and Technology Management*, **26**, 285–304.

[120] Ron, A. J. (1998). Sustainable Production: The Ultimate Result of a Continuous Improvement. *International Journal of Production Economics*, **5657**, 99–110.

[121] Samuel, V. B., Agamuthu, P., and Hashim, M. A. (2013). Indicators for Assessment of Sustainable Production: A Case Study of the Petrochemical Industry in Malaysia. *Ecological Indicators*, **24**, 392–402.

[122] Schumpeter, J. A. (1934). *The Theory of Economic Development*. Harvard Univerisity Press, Cambridge MA.

[123] Schumpeter, J. A. (1939). *Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalistic Process*. McGraw-Hill, New York, NY.

[124] Schumpeter, J. A. (1942). *Capitalism, Socialism and Democracy*. Harper & Brothers Publishers, New York.

[125] Sebastian, J. (2015). Optimizing Operational Efficiency. Available via: `http://www.ogfj.com/articles/print/volume-12/issue-9/features/optimizing-operational-efficiency.html`. [Accessed: 19.10.2016].

[126] Sekhar, J. A., and Dismukes, J. P. (2009). Generic Innovation Dynamics Across the Industrial Technology Life Cycle Platform Equation Modeling of Invention and Innovation Activity. *Technological Forecasting & Social Change*, **76**(1), 192–203.

[127] Seshadri M. (2013). *Big Data Science Challenging The Oil Industry*. CTO Global Services, EMC Corporation.

[128] Shah, A., Fishwick, R., Wood, J., Leeke, G., Rigby, S., and Greaves, M. (2010). A Review of Novel Techniques for Heavy Oil and Bitumen Extraction and Upgrading. *Energy & Environmental Science*, **3**, 700–714.

[129] Shell Gas. (2014). Geophysical Imaging. Available via: `http://www.shell.com/energy-and-innovation/overcoming-technology-challenges/finding-oil-and-gas/_jcr_content/par/textimage.stream/1444725407967/f916a9f8105fef5080cee8e860dcfb6e17497306f03bd155935b69e187e4be36/geophysical-imaging-brochure-2014.pdf`. [Accessed: 14.10.2016].

[130] Shenhar, A. J., Dvir, D., and Shulman, Y. (1995). A Two-Dimensional Taxonomy of Products and Innovations. *Journal of Engineering and Technology Management*, **12**(3), 175–200.

[131] Sider, A., and Ailworth, E. (2015). Oil Companies Tap New Technologies to Lower Production Costs. *The Wall Street Journal*. Available via: `http://www.wsj.com/articles/oil-companies-tap-new-technologies-to-lower-production-costs-1442197712`. [Accessed: 04.10.2016].

[132] Spencer-Ogden. (2016). The Importance of Technological Innovation in the Drilling Industry. Available via: https://www.spencer-ogden.com/industrynews/the-importance-of-technological-innovation-in-the-drilling-industry-535117 [Accessed: 19.10.2016].

[133] Stobaugh, R. (1988). *Innovation and Competition: The Global Management of Petrochemical Products.* Harvard Business School Press, Boston.

[134] Suh, N. P. (1999). A Theory of Complexity, Periodicity and Design Axioms. *Research in Engineering Design*, **11**(2), 116–131.

[135] Suh, N. P. (2004). On Functional Periodicity as the Basis for Long-term Stability of Engineered and Natural Systems and its Relationship to Physical Laws. *Research in Engineering Design*, **15**(1), 72–75.

[136] Suh, N. P. (2005). *Complexity: Theory and Applications.* Oxford University Press, Oxford, UK.

[137] Tertzakian, P. (2016). Is The Oil Production Efficiency Boom Coming To An End?. Available via: http://oilprice.com/Energy/Crude-Oil/Is-The-Oil-Production-Efficiency-Boom-Coming-To-An-End.html. [Accessed: 19.10.2016].

[138] Tidey, A. (2015). Breaking the Cycle? Cost Efficiency in Upstream Oil and Gas. Available via: https://www.woodmac.com/blog/breaking-the-cycle-cost-efficiency-in-upstream-oil-and-gas/. [Accessed: 19.10.2016].

[139] UNCED (United Nations Conference on Environment and Development). (1992). Agenda 21: Programme of Action for Sustainable Development. In: United Nations Conference on Environment and Development, Rio de Janeiro, Brazil. United Nations, New York.

[140] Vanderbruck, T. (2015). Current Oil Prices Create Opportunities. Available via: https://ourworld.unu.edu/en/current-oil-prices-create-opportunities. [Accessed: 16.10.2016].

[141] Vermeiren, W., and Gilson, J. -P. (2009). Impact of Zeolites on the Petroleum and Petrochemical Industry. *Topics in Catalysis*, **52**(9), 1131–1161.

[142] Ward, R. (2016). A Billion-dollar Digital Opportunity for Oil Companies. Available via: http://www.mckinsey.com/industries/oil-and-gas/our-insights/a-billion-dollar-digital-opportunity-for-oil-companies. [Accessed: 29.01.2017].

[143] Werber, C. (2016). The Oil Industry is Using Solar Power in an Ironic New Way. Available via: http://qz.com/618391/the-oil-industry-has-invented-an-ironic-new-use-for-solar-power/. [Accessed: 18.10.2016].

[144] Woody, T. (2013). New Drilling Technologies could give us so much Oil, the Climate wont stand a Chance. Available via: http://qz.com/117504/new-drilling-technologies-could-give-us-so-much-oil-the-climate-wont-stand [Accessed: 04.10.2016].

[145] Yerramilli, C., and Sekhar, J. A. (2006). A Common Pattern in Long-term Metals Production. *Resources Policy*, **31**(1), 27–36.

[146] Yin, J. Z. (1994). Managing Process Innovation through Incremental Improvements: Empirical Evidence in the Petroleum Refining Industry. *Technological Forecasting & Social Change*, **47**(3), 265–276.

Biographical Endnotes

Dr. Hossein Hassani is the recipient of a B.Sc. with honours in Statistics, M.Sc. with honours in Mathematical Statistics and a Ph.D. in Statistics from the School of Mathematics, Cardiff University, UK. He is an internationally recognized researcher in Singular Spectrum Analysis (SSA) and its applications particularly in analyzing and forecasting economic and financial time series. His research interests include Statistics (theoretical and practical), Time Series Analysis and Forecasting, Energy, Data Mining, Econometrics, Biostatistics, Biomedical Engineering and statistical applications in different fields.

Dr. Emmanuel Sirimal Silva is a graduate from the University of Southampton with a B.Sc. (Hons) in Economics and Actuarial Science and a M.Sc. in Risk Management. He completed his Ph.D. in Statistics at Bournemouth University in UK. His research interests include time series analysis and forecasting with a focus on the application and development of the Singular Spectrum Analysis technique. His research work focuses on energy, tourism, genetics and related fields. At present he serves as a Lecturer in Quantitative Methods at the Fashion Business School, University of the Arts London.

Ahmed Mohamed Al Kaabi obtained his Bachelors degree from the United States of America and Masters degree in oil and gas from the French Institute of Petroleum in Paris in 2008. Al Kaabi enjoys a vast experience in oil market economics, prior to joining the Energy Ministry. He is a member of the World Petroleum Council (WPC) and also the head of UAE Youth Petroleum Council. His research interests include technology and innovation in oil, gas, and petroleum industries.