Quantifying Technology Management in the Energy Transition: Evidence from the Oil & Gas Industry

by

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Abstract

Technology plays a critical role in how companies manage and strategically reposition during periods of change, including the current transition to lower-carbon energy in the Energy Transition. While previous research has indicated associations between technology management and the Energy Transition, the ability to quantify the relationship and its characteristics has been limited due to a lack of differentiation in the public data.

This thesis explores the degree to which technology management has shifted during the Energy Transition for twelve representative companies in the Oil & Gas industry. A novel method was developed to differentiate technology patents based on the Cooperative Patent Classification's Y02–Y04 schema for tagging Climate Change Mitigating Technology (CCMT), resulting in a three-tiered subclassification. Results of this method show that high-value innovation in the Oil & Gas industry can be categorized, on average, as 89.4% Incremental Energy, 8.3% Sustaining CCMT, and 2.3% Disruptive CCMT.

Next, this study utilized the differentiated patent data to perform Spearman rank order correlation analysis to establish the association between technology trends, corporate R&D metrics, net sales and oil price. Findings show positive correlation between Disruptive CCMTs and both Sustaining CCMTs ($r_s[202] = .55,\ p = < .001$) and Total R&D Patenting ($r_s[202] = .49,\ p = < .001$), indicating internal R&D spillover between teams.

Finally, the differentiated CCMT patent data and the correlation analyses were evaluated alongside global patenting trends to assess the rate of technological change in the Energy Transition. The findings indicate that the Oil & Gas industry has produced high-value innovations on par with the broader Energy Transition, exhibiting an Average Annual Growth Rate of 24.9% for Disruptive CCMTs and 21.4% for Sustaining CCMTs compared with an average of 24.6% for Global CCMTs. The findings also highlight an ongoing period of transition with indications of future demarcation in technology strategies. As a result of these investigations, suggestions have been identified for future research.

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List of Acronyms

AAGR Average Annual Growth Rate.

bbl U.S. Barrel of Oil (42.0 gallons or 158.9 litres).

BERD Business Enterprise Expenditure on R&D.

BP British Petroleum.

CCMT Climate Change Mitigation Technology.

CCUS Carbon Capture, Utilization, and Storage.

CET Clean Energy Technology.

CORS Company-Operated Retail Sites.

CPC Cooperative Patent Classification.

CPI Consumer Price Index.

CVC Corporate Venture Capital.

DOE Department of Energy.

EC European Commission.

ECLA European Classification System.

EDA Exploratory Data Analysis.

EIA Energy Information Administration.

EPC European Patent Convention.

EPO European Patent Office.

FOM Figure of Merit.

GHG Greenhouse Gases.

GPI Global Patent Index.

ICT Information and Communication Technology.

ICTSD International Centre for Trade and Sustainable Development.

IDE Integrated Desktop Environment.

IEA International Energy Agency.

INPADOC International Patent Documentation.

IP Intellectual Property.

IPC International Patent Classification.

IPF International Patent Family.

IPO International Patent Office.

IPR Intellectual Property Rights.

IRI Industrial Research and Innovation.

IT Information Technology.

JPO Japan Patent Office.

KIPO Korean Intellectual Property Office.

KPI Key Performance Indicator.

LCE Low-Carbon Energy.

M&A Mergers and Acquisitions.

MIT Massachusetts Institute of Technology.

NASA National Aeronautics and Space Administration.

NPV Net Present Value.

NZE Net-Zero Emissions.

O&G Oil and Gas.

OECD Organization for Economic Cooperation and Development.

OPS Open Patent Service.

PATLIB Patent Library.

PATSTAT Worldwide Patent Statistical Database.

PCT Patent Cooperation Treaty.

R&D Research and Development.

ROI Return on Investment.

RTA Revealed Technological Advantage.

SEC Securities Exchange Commission.

SME Subject Matter Expert.

SPE Society of Petroleum Engineers.

TM Technology Management.

TRL Technology Readiness Level.

UKIPO U.K. Intellectual Property Office.

UN United Nations.

UNEP United Nations Environment Programme.

USD U.S. Dollar ($).

USPC United States Patent Code.

USPTO United States Patent and Trademark Office.

VC Venture Capital.

WIPO World Intellectual Property Organization.

Y02 Classification Scheme for Climate Mitigation Technologies.

Y02A Technologies for Adaptation to Climate Change.

Y02B CCMTs Related to Buildings.

Y02C Greenhouse Gases: Capture or Storage/Sequestration or Disposal.

Y02D ICT Technologies Aiming at Energy Reduction.

Y02E Greenhouse Gases: Emission-Reduction Technologies Related to Energy Generation, Transmission or Distribution.

Y02P CCMTs in the Production or Processing of Goods.

Y02T CCMTs Related to Transportation.

Y02W CCMTs Related to Waste.

Y04S Smart Grids-Related Technologies.

Chapter 1

Technology Management and the Energy Transition

This opening chapter introduces the challenges and opportunities of the Energy Transition, particularly for the Oil & Gas industry. First, the relationship between the Energy Transition and technological innovation is briefly introduced, followed by the unique R&D opportunities and challenges this presents to the Oil & Gas industry. Second, the author introduces the research questions for this thesis and lays out the scope for the research. In conclusion, a short overview of the chapters in this thesis is presented.

1.1 The Scale and Complexity of the Energy Transition

Dr. Fatih Birol, the Executive Director of the International Energy Agency (IEA), opens the Foreword to the IEA's 2020 global climate-change report, *Energy Technology Perspectives*, with the practical, yet optimistic, forecast that "Technology will largely determine our energy future" (IEA, 2020, p. 3). Here, there is clear awareness that the innovation of new technologies for the Energy Transition will need to be supported by forward-looking policy, smart governmental regulations, and opportunities for growth (IEA, 2020). Dr. Birol notes that, even in the height of the COVID-19 global pandemic, investments in clean-energy start-ups in 2019 by venture capital funds and companies broke new records (IEA, 2020, p. 4). At the same time, the central focus of the IEA's *Energy Technology Perspectives*

2020 report is to spotlight the required technological advancements necessary to facilitate a transition to lower-carbon energy sources to meet climate targets. It is technology, and not policy, that underpins the Energy Transition:

> “While technology is not the only ingredient to a cleaner energy future, there is no credible path to net zero emissions without a significant and speedy ramping up of clean energy technologies across the entire energy sector” (IEA, 2020, p. 31).

This ramp-up will require the innovation and commercialization of many technologies still in early stages of development, including many technologies at a low Technology Readiness Level (TRL). The IEA estimates that the technological innovation required to cut over one-third of the targeted emissions to achieve the Sustainable Development Scenario are currently under development—and this number rises to over 50% in the Faster Innovation Case (IEA, 2020, p. 25). Most of the innovation needs to occur in the areas of electrification, Carbon Capture, Utilization, and Storage (CCUS) (25%), bioenergy (20%), and hydrogen (5%) (IEA, 2020).

The complexity of the Energy Transition is increased by the speed at which the new technologies are needed. The IEA states that "quicker progress towards net-zero emissions will depend on faster innovation" (IEA, 2020, p. 25). Similar findings on the overall rapid pace of the Energy Transition are reported in the literature (Bel & Joseph, 2018; Probst et al., 2021). The 2010 report by United Nations Environment Programme (UNEP) states:

> “Addressing [climate change] requires an unprecedented mobilisation of human and financial resources to alter our patterns of production, consumption and energy use. The large-scale development and diffusion of technologies is the key to making such a transition possible” (UNEP/EPO, 2010).

António Campinos, the President of the European Patent Office (EPO), sums up the challenge in the Foreword to the joint April 2021 report by the EPO and the IEA, *Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation*:

> “The energy transition needed to mitigate climate change presents challenges of unparalleled scale and complexity. Many of the technologies needed to cut greenhouse gas emissions are not yet fully mature, whilst the time window available for bringing them to market is closing rapidly” (EPO/IEA, 2021, p. 2).

And the Oil & Gas industry, according to Dr. Fatih Birol in the *Energy Technology Perspectives* report, has a role to play in the Energy Transition, with "some oil and gas majors betting their futures on becoming lower-carbon energy companies (IEA, 2020, p. 3).

1.2 Tailwinds and Headwinds for Innovation in the Oil & Gas Industry

The "quicker progress" and "faster innovation" galvanized by the Energy Transition presents both opportunities and challenges for the Oil & Gas industry. As a tailwind, the Oil & Gas industry has a long history with technology and innovation, with more than one company claiming that it is primarily a "technology" company (Parshall, 2011). Based on the results of large survey published in conjunction with the Society of Petroleum Engineers (SPE), Perrons (2014) summarizes the broad sentiment of the Oil & Gas industry that "technology will clearly play a pivotal role in the success or failure of tomorrow's oil & gas firms" (Perrons, 2014, p. 301). Similarly, Daneshy (2003) organized innovation focus with technology managers from the Oil & Gas industry and found that "“There is broad consensus among executive management of all companies that technology holds a key to future growth and profitability of the industry” (Daneshy, 2004, p. 1). Connecting the strengths between technology innovation and energy management, Bob Dudley, group chief executive of BP, observes that "the transition to a lower-carbon energy system is opening up a wide range of business possibilities" (BP Energy Economics, 2019).

At the same time, the opportunities and rapid changes of the Energy Transition present challenges for the Oil & Gas industry. Corporate Research and Development (R&D) faces several high hurdles in the energy industry. Building on Perrons (2014), Daneshy (2004), and Popp et al. (2020), the following are key headwinds for technological change in the Oil & Gas industry:

- ***Commodity Nature of Energy***. As a largely interchangeable commodity there is little differentiation between brands for consumers and therefore less incentive for competitors to innovate (Popp et al., 2020, p. 6). Popp et al. (2020) notes that this feature is a key driver for the focus on process efficiency and down-time optimization in the Oil & Gas industry.

- ***Long Time Horizon***. Kleinberg & Fagan (2019) notes that the development of new technology in the Oil & Gas industry takes over a decade to develop and effectively commercialize, while the National Petroleum Council predicts that the average length of time for an innovation to move from idea to commercialization is closer to 16 years (National Petroleum Council, 2007).

- ***Market Uncertainty***. Closely related to the long time horizon for many Oil & Gas research and development projects, market uncertainty can jeopardize project delivery. In their review of multiple R&D innovations that came out of the Oil & Gas industry, Kleinberg and Fagan illustrate that major innovations "span across oil cycles" further increasing market and investor uncertainty (Kleinberg & Fagan, 2019, p. 17). Daneshy (2004) records that there is market risk even for large-scale technological development with application to traditional hydrocarbon production, noting the examples of intelligent-well design and coil-tubing drilling techniques that did not commercially justify the large R&D costs.

- ***High Development Costs***. According to Nanda et al. (2014) and Popp et al. (2020), economies of scale play a significant role in the development of large energy projects where project cost can exceed several hundred million dollars (De Neufville & Scholtes, 2011). This barrier can prevent the entry of newcomers to spur more competitive innovation (Nanda et al., 2014).

- ***Technology Spillover and Free-Ridership***. Multiple researchers have found that the "shared equity structure" of some projects limits the ability of a developing company to "keep new innovations proprietary" (Perrons, 2014, p. 301). This technology spillover can create free-riders that reduce the incentive to engage in expensive R&D in the pursuit of establishing competitive advantage through technology development (Perrons, 2014; Acha, 2002).

- ***Fast Followers***. Related to the uncertainty of technological spillovers, Kleinberg & Fagan (2019) further differentiate the uncertainty that the market advantage of becoming a first mover for a novel innovation in the in Oil & Gas industry can be "minimized or quickly overcome by a technically adept fast follower" in the industry (Kleinberg & Fagan, 2019, p. 19). This hurdle relates to the commodity nature of energy.

- ***Efficient Market Commercialization***. Based on the SPE global survey, Perrons & Donnelly (2012) identified the limitation of international companies to possess the know-how or value chains to effectively market innovations outside of large capital-intensive projects. Daneshy (2004) explains that market commercialization is a major hurdle for Service Providers and, further, that Service Providers face a risk of Oil & Gas Producers not utilizing developed technologies.

Kleinberg & Fagan (2019) find that Oil & Gas industry, and particularly companies in the United States, have attempted to manage the risk caused by the mismatch between technology cycles and price cycles through outsourcing technology development

(Kleinberg & Fagan, 2019). Similarly, Daneshy (2004) notes that executives and technology managers in the Oil & Gas industry have managed this uncertainty with a focus on capital stewardship, reduction in operating costs, and shorter-term technology projects. But, Daneshy concludes by noting: "The danger is that this will lead to “incrementalism” and delay investments in more risky revolutionary technologies that have the best potential for a step change" (Daneshy, 2004, p. 1). Summarizing results from a global survey with the Society of Petroleum Engineers, Perrons finds that a majority of O&G professionals recognize that the industry "has a reputation for being too slow to develop and adopt innovations" (Perrons, 2014, p. 301).

1.3 Research Questions

Taking into account the above challenges and opportunities that the Energy Transition presents to energy companies, this thesis explores the broad, high-level question of how Oil & Gas companies are adapting their technology management and R&D endeavors during the ongoing Energy Transition. To better frame and answer this high-level question, this thesis will utilize analytical methods to address seven research questions.

- ***Research Question #1.*** Are the classical R&D benchmarking metrics sufficiently descriptive to quantify how Oil & Gas companies have expanded their technology efforts during the Energy Transition? (Chapter 2)
- ***Research Question #2.*** How much high-value innovation is classified as Climate Change Mitigation Technology (CCMT), and which technology focus areas are being researched and developed in the Oil & Gas industry? (Chapter 3)
- ***Research Question #3.*** How are companies apportioning their R&D portfolios between incremental energy technology, Climate Change Mitigation Technology (CCMT), and Disruptive Technology? (Chapter 4)
- ***Research Question #4.*** Is there a positive correlation between the in-house organizational capability to produce incremental energy technology and either Climate Change Mitigating Technologies or Disruptive CCMTs? (Chapter 5)
- ***Research Question #5.*** How are R&D Spend, R&D Intensity and R&D Productivity linked to the innovation of high-value Climate Change Mitigating Technology, and is the question of time lag a concern? (Chapter 5)

- ***Research Question #6.*** How significantly are an organization's overall R&D effort and R&D innovation capability correlated with year-to-year fluctuations, including net sales and oil price? (Chapter 5)
- ***Research Question #7.*** How does the Oil & Gas industry's R&D focus on Climate Change Mitigating Technologies (CCMTs) compare with the broader, global technology trends driving the Energy Transition? (Chapter 6)

1.4 Research Scope

This thesis attempts to explore how technology management has responded to the broader movements of the Energy Transition.[1] Specifically, the proposed research method is designed to identify, collect and sort Climate Change Mitigation Technology (CCMT) data and lay the framework for an initial analysis of how this new data source—alongside traditional R&D metrics, a corporation's net sales, and the exogenous influence of the price of oil—can be analyzed with quantitative methods. This section lays out what is in scope, out of scope, and several initial limitations of this inquiry. Additional limitations will be documented throughout the thesis.

This study will focus on the public data for twelve representative Oil & Gas companies. The size of this sample set is a balance between permitting a detailed exploration of the Climate Change Mitigating Technologies being explored by each company and the need to have a sufficiently diverse sample set. Each of these companies was selected for known R&D activity due to overall size, to ensure diversity between Oil & Gas Producers and Oil & Gas Service Providers, and to enable geographical comparison between Europe, the United States, and China. In alphabetical order, the twelve companies in the study include: (1) BP; (2) Chevron; (3) China Petroleum; (4) ConocoPhillips; (5) Equinor; (6) ExxonMobil; (7) Halliburton; (8) PetroChina; (9) Schlumberger; (10) Shell; (11) TotalEnergies; and (12) Weatherford. To increase the readability of the many tables and graphs in this thesis, the author will use "Conoco" for ConocoPhillips, "Exxon" for ExxonMobil, and "Total" for TotalEnergies. In order to differentiate between the two sectors and the three geographic regions, this thesis uses the following six groups:

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[1] Appendix A presents a high-level timeline of the Energy Transition.

1. ***All O&G Companies***. This group includes all twelve companies.
2. ***O&G Producers***. This group includes BP, Chevron, China Petroleum, Conoco, Equinor, Exxon, PetroChina, Shell and Total. At times in this thesis, the two Chinese companies will be removed in order to draw attention to the seven international oil majors. This will be indicated by the label, O&G Producers (No China).
3. ***O&G Service Providers***. This group of three includes Halliburton, Schlumberger and Weatherford.
4. ***O&G Producers – Europe***. This group of four includes BP, Equinor, Shell and Total.
5. ***O&G Producers – U.S.*** This group of three includes Chevron, Conoco and Exxon.
6. ***O&G Producers – China***. This group includes China Petroleum and PetroChina.

This research design does not evaluate the "radicalness" or "originality" of the published technology patents including those labeled Climate Change Mitigating Technology, however this established field of inquiry is recommended for additional research on the interplay between CCMTs and the Energy Transition (Popp et al., 2020; Shane, 2001). Likewise patent citations are not used to measure the reach of the CCMT (Trajtenberg, 1990). Finally, and following on several established studies, this research only uses awarded international patent families—which will be described in detail in Chapter 3—as a proxy for the overall R&D research focus of a company (Griliches, 1991; Bel & Joseph, 2018). An evaluation of how companies are using Corporate Venture Capital (CVC) to expand and outsource Research Development is not explored (Popp et al., 2020). For this study, the lack of available public data can limit the analysis of trends in technology management. As noted by Trajtenberg in an early influential analysis of patenting, "the study of technological change has been hampered all along by the scarcity of appropriate data" (Trajtenberg, 1990, p. 172). This complexity is increased by at least two limitations that should be discussed. First, while this research covers twenty years of technology development over the years 2000 to 2020, this time period may not be sufficient to establish long-term trends in how technology is evolving particularly in face of the commodity price cycle of oil. Cyclic trends may be masked as this study covers only one oil boom-bust cycle (Dargay et al., 2007; Popp et al., 2020). Lastly, and as the world is well aware, the Energy Transition has not been the only large-scale disruptive event over the last three years (Tian et al., 2022). Following de Weck et al. (2011), the COVID-19 global pandemic can be classified as a "massive disruption" and, thus, the overarching socio-technical ramifications can be difficult to separate from the cyclical effects of oil price. This point will be highlighted in the final chapter, Recommendations for Future Work (see Chapter 8).

1.5 Thesis Structure

This thesis is structured to present the research and findings in a linear fashion, where each chapter builds upon the results of the previous chapters.

Chapter 2 introduces the data sources for both historical average oil prices and the three primary metrics used to evaluate a corporation's commitment to research and development. After two of the R&D metrics are calculated, a high-level analysis is performed to evaluate the relationship between R&D metrics, historical oil price and the Energy Transition.

Chapter 3 describes a powerful research method to sort patent data into climate-change mitigating technologies (CCMTs) and presents findings at the company and industry level. Here, CCMTs provide a window onto the technology-focus areas that firms are exploring in the Energy Transition.

Chapter 4 describes a novel approach to further differentiate patent data into three classes of technology, including Disruptive CCMT, Sustaining CCMT, and Incremental Energy Technologies.

Chapter 5 uses the collected findings from Chapter 2, 3 and 4 to perform quantitative analysis on the results. First, time-lag analysis is used to assess the impact of lag on R&D Expenditure and patenting activity. Next, Spearman correlation analysis is conducted on the R&D metrics, R&D patenting activity, net sales and oil price. Results provide insights on the overall interaction of technology management.

Chapter 6 utilizes the results of the correlation analysis to return to global patenting trends and the results from the Oil & Gas industry to explore the degree that companies are optimizing their technology portfolios during the Energy Transition.

Chapter 7 and **Chapter 8** conclude the thesis with conclusions and recommendations for future work.

Chapter 2

R&D Metrics and High-Level Trends in Technology Management

This chapter introduces the three Research and Development (R&D) metrics commonly utilized in business, government and academia to quantify a corporation's financial commitment to technological capacity and innovation. First, the primary source of yearly average oil price and corporate financial data for this research is introduced. Subsequently, definitions are provided for R&D Expenditure, R&D Intensity, and R&D Productivity, including their central pros and cons for technology management. Analysis of the data is then presented with reference to both oil price and the rough timeline of the broader Energy Transition. This chapter concludes with the finding that corporate R&D Metrics are insufficient to establish a direct link to how companies may or may not be adjusting their technology management during the Energy Transition.

2.1 Overview of the R&D Metrics

2.1.1 R&D Expenditure

The first R&D metric for assessing a company's commitment to Research and Development (R&D) is R&D expenditure, which is variously labeled R&D spending, R&D investment, or R&D budget in the literature (Kleinberg & Fagan, 2019; Schilling, 2020; de Weck, 2022). For American publicly-traded companies, R&D expenditure can be listed as R&D costs in corporate SEC 10-K filings (ExxonMobil, 2021b). In this report, R&D Expenditure will be used as a formal metric and it will be capitalized.

R&D Expenditure is defined as the total amount of money allocated in a given year to corporate Research and Development. Inside the company, R&D Expenditure is an output of the Capital Rationing process that distributes available funds across the company during the yearly budgeting cycle (Schilling, 2020, p. 146). Outside the company, this metric is commonly used to hierarchically rank companies, industries, and geographical regions on overall R&D investment (Schilling, 2020).

As the primary financial driver of the amount of technological innovation that a company can pursue, R&D Expenditure can be a proxy for the overall R&D effort of a given company (Helfat, 1994; Kleinberg & Fagan, 2019). In an analysis of the Oil & Gas industry, Helfat finds: "The expenditure levels for the various R&D activities provide a measure of the resources devoted to the R&D efforts, and also reflect company policies for allocation of R&D funds" (Helfat, 1994, p. 1726). Kleinberg & Fagan (2019) also evaluate R&D spending as a proxy for company policy and further equates the input with the overall "innovation effort" of a firm.

At the same time, R&D Expenditure can be a problematic metric when used in isolation. The limitation of R&D Expenditure is that it is difficult to quantify a commitment to R&D without additional reference or comparison to other corporate performance data, such as net sales, profitability or number of employees (Helfat, 1994). In this way, R&D Expenditure does not always permit easy comparison and benchmarking between companies of different sizes and market position. Moreover, R&D Expenditure is not always the best way for a company to evaluate its own present performance with respect to past performance, especially if the company has significantly expanded or contracted in size or market share. Yearly trends that focus only on R&D Expenditure may obscure larger corporate trends that may help to paint a fuller picture of why expenditure is changing. These can include loss of profits, increase in sales, or a substantial resizing of the workforce. As we will see below, both R&D Intensity and R&D Productivity address this weakness.

2.1.2 R&D Intensity

The second R&D metric considered in this analysis is R&D Intensity, a practical metric used by technology managers for benchmarking relative commitment to innovation.

R&D Intensity is a calculated metric and is defined as the fraction of R&D Expenditure to the total yearly Net Sales of a company.[1] The popularity of this metric is that it allows technology managers to "directly control" for the market size of the company on the total R&D budget (Helfat, 1994). Unlike the absolute value of R&D Expenditure, R&D Intensity provides a normalized or proportional perspective on how much money a company is committing to innovation in relation to their total market share. Hartmann et al. (2006) explain: "The R&D intensity benchmark often serves as a test of reasonableness that the level of investment is in the right range" (Hartmann et al., 2006, p. 28).

Multiple studies in the literature have explored that relationship of R&D Intensity with both corporate funding and overall strategies in technology management. Coombs & Bierly III (2006) recount work connecting R&D Intensity with "Absorptive Capacity", a topic that will be discussed in more detail in Chapter 5 and Chapter 7. On the overall behavior of R&D Intensity to Net Sales, Scherer (1992) provides quantitative evidence that R&D Expenditure increases "approximately linearly" (Helfat, 1994, p. 1728).

In a landmark study on the relationship between technology management and R&D activities, "Benchmarking Global Strategic Management of Technology," Roberts (2001) presents findings that associate R&D Intensity with both increased profitability and the overall "newness" or technological maturity of a firm. Roberts advances:

> “R&D as a percentage of annual revenue correlates strongly with annual sales growth rate, percent of sales from new products, and profitability. Strategically, R&D Intensity also correlates strongly with overall newness of the firm’s technology, but it relates negatively to improving break-even time and to perceived competitive performance in satisfying manufacturing” (Roberts, 2001, p. 28).

Likewise, Schilling reports the strong positive association between R&D Intensity and profitability, sales, and growth rate in her leading textbook, *Strategic Management of Technological Innovation* (Schilling, 2020, p. 22). Finally, Roberts shows that R&D Intensity can

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[1] At least one author has suggested using CAPEX in place of Net Sales (Acha, 2002).

correlate positively to overall Technological Leadership defined as a measure of strategic positioning relative to primary competitive peers (Roberts, 2001).

Notwithstanding the evidence which favors R&D Intensity, the Oil & Gas industry has long maintained a low to very low average intensity (Perrons, 2014, p. 302). Companies have historically invested under 1% of net sales into research and development (Perrons, 2014; Von Tunzelmann & Acha, 2006; Moncada-Paternò-Castello et al., 2010; Popp et al., 2020).

Low R&D Intensities have ranked the Oil & Gas industry well outside of the "top 10" intensities for global industries (Schilling, 2020). For example, Schilling (2020) calculates the average industry R&D Intensities for the year 2016 based on Compustat data:

1. Drugs, biological products, and diagnostics: 20%
2. Special industry machinery: 13%
3. Semiconductors and electronic components: 11%
4. Software and computer programming services: 10%
5. Medical equipment: 8%
6. Communication equipment: 7%
7. Measuring equipment and instruments: 7%
8. Computers and peripherals: 7%
9. Nonstore retailers: 7%
10. Motor vehicles and motor vehicle equipment: 4% (Schilling, 2020, p. 147).

Writing around the same time as Schilling's 2016 table on industry R&D Intensity, Perrons (2014) reports that Oil & Gas Producers in the United States have an average R&D Intensity closer to 0.21% (Perrons, 2014; Moncada-Paternò-Castello et al., 2010).

One important distinction is that Oil & Gas Service Providers have historically had much higher R&D Intensities. Again, Perrons (2014) cites Service Providers having an average intensity of 2.4% (Moncada-Paternò-Castello et al., 2010). This, interestingly, would place Service Providers just below "Motor vehicles and motor vehicle equipment" at 4% intensity in Schilling's 2016 table Schilling (2020).

The reason for this low level of R&D Intensity, and the corresponding low underlying amount of R&D Expenditure, connects back to structural challenges and opportunities presented in Chapter 1.

Finally, it should be noted that the common definition of R&D Intensity—as R&D Expenditure per Sales—differs from definitions utilized by several economic and governmental organizations concerned with regional R&D trends, particularly technology reports published in the European Union. At the Organization for Economic Cooperation and Development (OECD) and eurotat, the Business Enterprise Expenditure on R&D (BERD) calculates R&D intensity as a percentage of value added for a sector, region or country (European Commission, 2004). This alternative calculation allows policymakers to compare broader competitiveness as opposed to assessing the individual corporate strategic decisions that drive R&D expenditure (European Commission, 2004).

2.1.3 R&D Productivity

The third corporate metric used for benchmarking trends in strategic technology management can be labeled R&D Productivity. Whereas R&D Intensity normalizes spend to net sales, R&D Productivity is defined as the ratio of a firm's R&D Expenditure to the total number of full-time employees (Morbey & Reithner, 1990). As a ratio, it is worth noting that R&D Productivity can increase due to either an increase in yearly R&D Expenditure or a decrease in a firm's headcount. Thus, corporate downsizing with layoffs will result in higher R&D Productivity, while Mergers and Acquisitions (M&A) that absorb workforce will result in a reduction to R&D Productivity.

In their groundbreaking paper, Morbey & Reithner (1990) describe two reasons why R&D Productivity is a better description of a firm's commitment to strategic technology development over time. First, R&D Productivity can exhibit less short-term variation than R&D Intensity due to a lower yearly fluctuation in employee count than in net sales (Morbey & Reithner, 1990). Building on the empirical study examining the productivity of R&D programs by Hill & Snell (1989), the authors find that R&D Productivity is "more robust" in evaluating a firm's "long-term commitment to innovation" (Morbey & Reithner, 1990, p. 12).

Second, R&D Productivity has been shown to have higher significant correlation with both subsequent Profit Margin and Sales Per Employee than R&D Intensity (Morbey & Reithner, 1990, p. 13). This key insight will be returned to in Chapter 5 where the correlation between R&D metrics will be examined alongside net sales, profit and—central to the argument of this thesis—patenting trends for Climate Change Mitigating Technologies.

2.2 Data and Methodology

This study uses publicly available governmental data to analyze the three R&D metrics for the Oil & Gas industry. This section will briefly explain the data sources used for analysis.

2.2.1 U.S. EIA Data Set for Average Yearly Nominal Oil Price

This research uses the data set from the U.S. Energy Information Administration (EIA) for historical yearly oil prices. This publicly available data set is updated routinely and includes subsections for Monthly, Quarterly and Yearly average oil prices in both Nominal and Real dollars (Energy Information Administration (EIA), n.d.). For this analysis, the yearly nominal oil price in U.S. dollars per barrel (USD/bbl) was used to better represent oil price around the world, since the EIA's real price is adjusted for the Consumer Price Index (CPI) in the United States (Energy Information Administration (EIA), n.d.).

2.2.2 E.C. IRI Data Set for World Top R&D Investors

The corporate financial and R&D data used for this research is from the European Commission (EC)'s Industrial Research and Innovation (IRI) division. The IRI is tasked with providing "robust empirical scientific-sound evidence" on global and regional trends in R&D to inform industry, academia and policymakers both inside and outside of Europe.

The IRI publishes both the "World Top 2500 R&D Investors" and the "EU Top 1000 R&D Investors" and makes the collected corporate R&D data available to the public (Industrial Research and Innovation, n.d.). Started in 2004, the "World Top 2500 R&D Investors" data sets provide consistent financial and R&D data on global companies. The IRI data set was selected for this study for the following reasons:

- ***Accessibility***. The IRI data sets are publicly available and not protected by a paywall. This feature allows future studies to reproduce the results of this research.
- ***Completeness***. The IRI data sets contain the twelve Oil & Gas companies selected for this research. This includes the three Oil & Gas Service Providers (Halliburton, Schlumberger, and Weatherford) and the two Chinese Producers (China Petroleum and PetroChina).
- ***Time Frame***. The IRI data sets cover data from 2004 to 2020. While there was sufficient data in the 2004 data set to back-calculate values for 2003 and 2002, this thesis uses only published data for analysis.
- ***Financial Standardization***. The IRI data sets contain yearly financial values already converted to a base currency (here, the Euro (€)) and adjusted to the given year's exchange rate. This feature greatly reduced the required post-processing of the financial data, particularly for the two Chinese companies. Had the information been individually collected from company reports (including Securities Exchange Commission (SEC) 10-K's for the companies filed in the U.S.), normalizing the multiple currencies to common currency could introduce greater error than the standardized IRI reports.
- ***Pre-Ranked***. The IRI data has companies preranked based on size of yearly R&D Expenditure. For this study, this ranking facilitated easy ranking for top R&D Expenditure among the twelve Oil & Gas companies in the study.
- ***Accuracy***. The publication of the reports by European Commission's Industrial Research and Innovation (IRI) division implied a consistent level of data accuracy and vetting.

It should be noted that all IRI values are extracted directly from corporate filings and are not adjusted for inflation (Potters, 2022, p. 23). Additionally, financial values in the IRI data sets have been converted to euro. However, this does not impact the calculation of either R&D Intensity or R&D Productivity. And as will be shown in Chapter 5, the unit of currency does not affect correlation analysis testing to determine association between the R&D metrics and the patent data.

To ensure accuracy of the IRI data, financial data and employee count for US corporations were verified with Securities Exchange Commission (SEC) 10-K financial filings. As shown in Table B.1 in Appendix B, the IRI data set accurately captured 10-K information overall. For this study, several corrections were made to the IRI data sets. For example, the recorded IRI data for ExxonMobil inaccurately recorded the Number of Employees between 2004–2010 as being the sum of both Regular Employees and auxiliary employees at Company-Operated Retail Sites (CORS). These employment values were updated in the data to accurately reflect the 10-K filings (ExxonMobil, 2021b).

2.3 Results for R&D Metrics

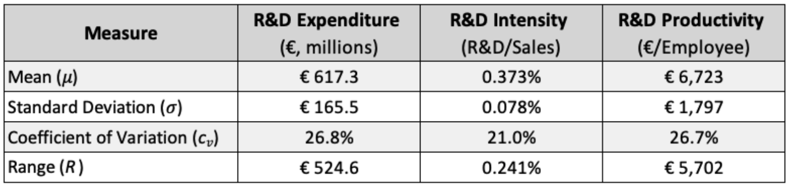
2.3.1 Results for R&D Metrics by Company

The collected data and calculations for the three R&D metrics are documented in Appendix C. All currency values are listed in euro (€), and for improved readability both Net Sales and R&D Metrics are in units of one million euro (€, millions). Each of the twelve tables contains the collected IRI data for R&D Expenditure, Net Sales and Employees, and the calculated values for R&D Intensity and R&D Productivity over the time period of 2004 to 2020. The twelve tables include: BP (Table C.1), Chevron (Table C.2), China Petroleum (Table C.3), Conoco (Table C.4), Equinor (Table C.5), Exxon (Table C.6), Halliburton (Table C.7), PetroChina (Table C.8), Schlumberger (Table C.9), Shell (Table C.10), Total (Table C.11), and Weatherford (Table C.12).

2.3.2 Summary Statistics for R&D Metrics by Sector and Region

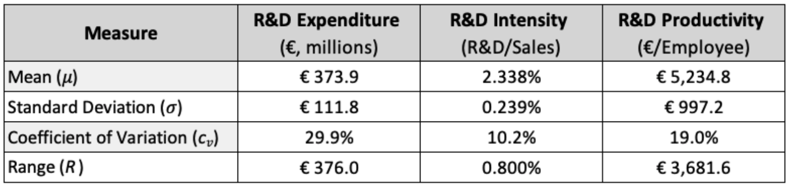
To compare the different R&D results between both Oil & Gas companies and geographic regions, summary statistics were calculated for the five key groupings for this study: All Producers (Table 2.1), Service Providers (Table 2.2), Producers – Europe (Table 2.3), Producers – US (Table 2.4), and Producers - China (Table 2.5). Following previous studies, the combined results of Producers and Service Providers is not included because of the large difference in R&D Intensity as discussed above (Perrons, 2014; Moncada-Paternò-Castello et al., 2010; Perrons & Donnelly, 2012).

Each table of summary statistics includes Mean (μ), standard deviation (σ), coefficient of variation (c_v), and Range (R). Here, Range is a measure of dispersion and is the difference between the maximum value for a data range and the minimum value.



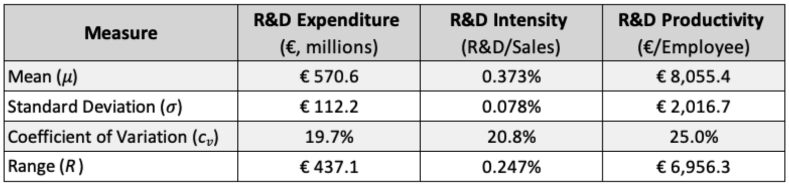
Measure	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
Mean (μ)	€ 617.3	0.373%	€ 6,723
Standard Deviation (σ)	€ 165.5	0.078%	€ 1,797
Coefficient of Variation (c_v)	26.8%	21.0%	26.7%
Range (R)	€ 524.6	0.241%	€ 5,702

Table 2.1: Summary Statistics for R&D Metrics for O&G Producers, 2004–2020. Nominal values are unadjusted for inflation. Source: Based on IRI data.



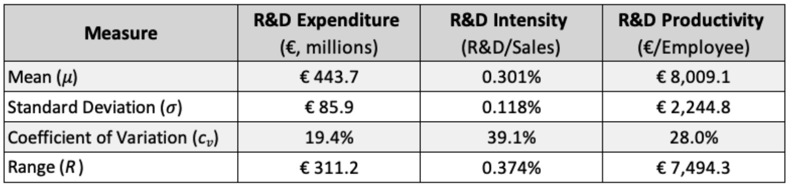
Measure	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
Mean (μ)	€ 373.9	2.338%	€ 5,234.8
Standard Deviation (σ)	€ 111.8	0.239%	€ 997.2
Coefficient of Variation (c_v)	29.9%	10.2%	19.0%
Range (R)	€ 376.0	0.800%	€ 3,681.6

Table 2.2: Summary Statistics for R&D Metrics for O&G Service Providers, 2004–2020. Nominal values are unadjusted for inflation. Source: Based on IRI data.



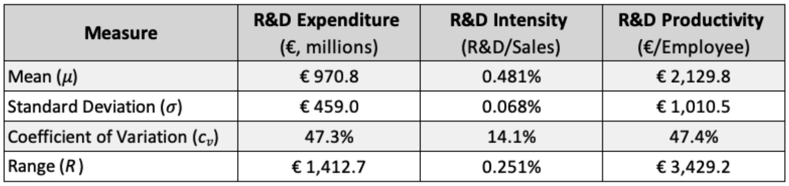
Measure	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
Mean (μ)	€ 570.6	0.373%	€ 8,055.4
Standard Deviation (σ)	€ 112.2	0.078%	€ 2,016.7
Coefficient of Variation (c_v)	19.7%	20.8%	25.0%
Range (R)	€ 437.1	0.247%	€ 6,956.3

Table 2.3: Summary Statistics for R&D Metrics for O&G Producers – Europe, 2004–2020. Nominal values are unadjusted for inflation. Source: Based on IRI data.



Measure	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
Mean (μ)	€ 443.7	0.301%	€ 8,009.1
Standard Deviation (σ)	€ 85.9	0.118%	€ 2,244.8
Coefficient of Variation (c_v)	19.4%	39.1%	28.0%
Range (R)	€ 311.2	0.374%	€ 7,494.3

Table 2.4: Summary Statistics for R&D Metrics for O&G Producers – U.S., 2004–2020. Nominal values are unadjusted for inflation. Source: Based on IRI data.



Measure	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
Mean (μ)	€ 970.8	0.481%	€ 2,129.8
Standard Deviation (σ)	€ 459.0	0.068%	€ 1,010.5
Coefficient of Variation (c_v)	47.3%	14.1%	47.4%
Range (R)	€ 1,412.7	0.251%	€ 3,429.2

Table 2.5: Summary Statistics for R&D Metrics for O&G Producers – China, 2004–2020. Nominal values are unadjusted for inflation. Source: Based on IRI data.

2.4 Analysis of R&D Metrics

2.4.1 Analysis of R&D Expenditure

Figure 2.1 charts the collected corporate data for R&D Expenditure for the twelve Oil & Gas companies in the sample set with respect to oil price volatility and a rough timeline of the Energy Transition. Each company is depicted on the graph in a separate color and its curve represents the recorded amount of R&D Expenditure for the given year based on the IRI data set. The primary axis displays the total amount of current R&D Expenditure shown on a scale of millions of euro (€), non-adjusted for inflation. Thus, the value on the primary axis of €1,000 million is equal to €1,000,000,000 or €1 billion euro. On the right side of the graph, the secondary axis shows the EIA's Average Oil Price in nominal dollars for one American barrel (bbl) of oil, non-adjusted for CPI or inflation. The Oil Price curve is shown as a dashed gray line on the graph. Finally, a high-level timeline of three events relating to the Energy Transition is listed along the top (see Appendix A for more details). These dates are approximate and do not indicate a specific start date of the Energy Transition (Markard, 2018; IEA, 2020; Smil, 2019).

The graph displays a gradual linear increase in the yearly spend for R&D Expenditure from 2002 to 2014/2015. This increase in intensity corresponds with a more pronounced increase in the price of oil from just over $20/bbl to over $100/bbl in 2011. In 2004, companies were spending in a range between €100 million and €600 million euro in total R&D Expenditure. By 2012, this yearly budget grew to between €200 million and €1,000 million.

An interesting observation here is that, if total R&D Expenditure is somehow reflective of the increasing oil prices, then its yearly growth rate is well under that of the increase in oil. Here, the curves indicate some degree of positive correlation between oil prices and R&D Expenditure at least for a majority of the companies. Likewise, there appears to be some degree of "lag" in the R&D Expenditure curves when compared with the price of oil. By "lag" it means that the reaction or response to a correlated feature is delayed by one or more years (Griliches, 1998; Trajtenberg, 1990). Lag can occur for several reasons: (1) Market conditions occur after yearly budgeting has been set, thus requiring adjustments in subsequent years; (2) Loss of sales or profit may need to be recouped based on

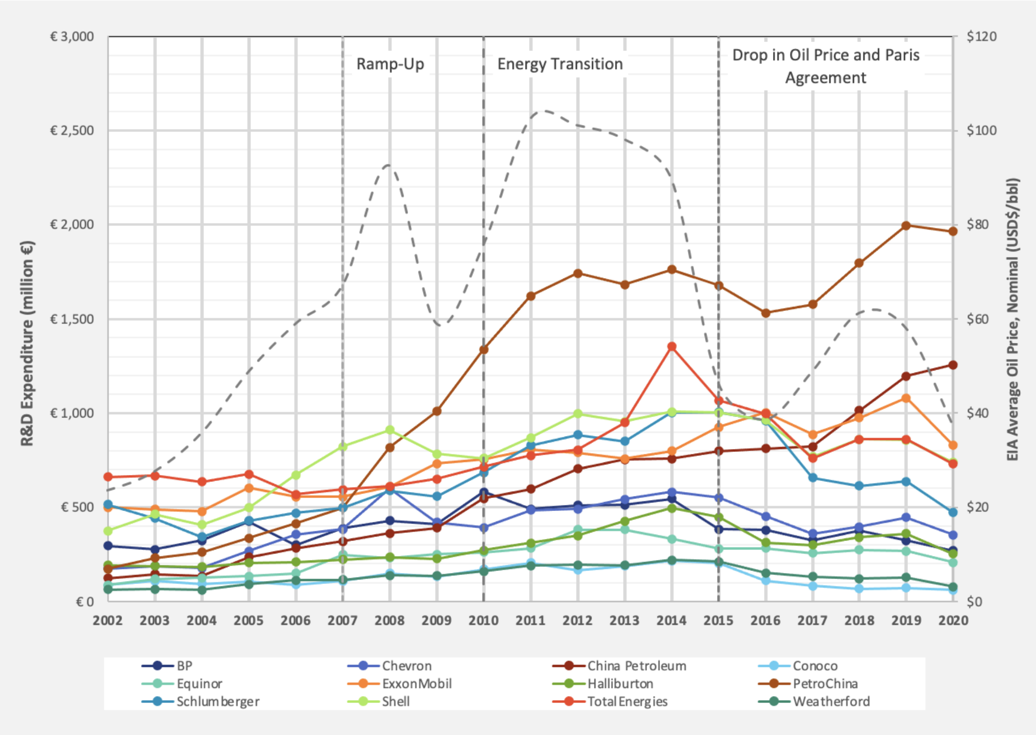


Figure 2.1: R&D Expenditure for All O&G Companies with Oil Price, 2002–2020. Curves show the yearly R&D Expenditure for each company with reference to the average oil price and a rough timeline of the Energy Transition. Values reflect current, nominal prices and are unadjusted for inflation. Source: Based on IRI and EIA data.

fluctuations in market conditions; and, most importantly, (3) The output of a R&D program, including successfully published patents, can lag the initial expenditure. What is striking in this chart is the variability in how firms adjusted their R&D Expenditure following the rapid drop in oil prices between 2014 and 2015. Several adjustments stand out. Schlumberger (Medium-Light Blue) decreased its yearly R&D budget by nearly 50% or from approximately €1,000 million to €500 million between 2015 and 2020. First, the dedicated yearly commitment to R&D spend responds faster when oil prices drop than when prices increase. (Figure 2.2 shows the R&D Expenditure for the O&G Producers (No China).) This data confirms the econometric finding by Kleinberg & Fagan (2019) that there is an "asymmetric R&D spending response". Asymmetric R&D spending response means that when oil price increases, R&D Expenditure slowly increases over time; but when oil prices fall, spending more "precipitously" levels off with less noticeable lag (Kleinberg & Fagan, 2019, p. 4). This concept can also be found in Dargay et al. (2007).

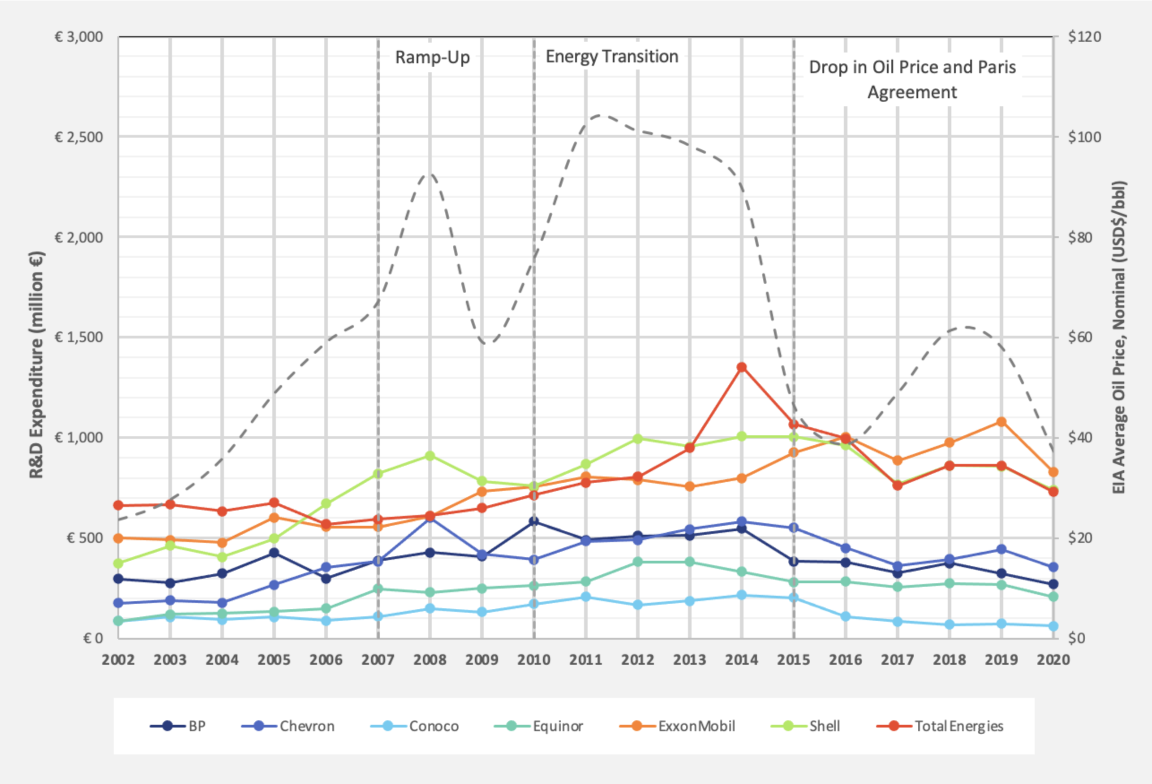


Figure 2.2: R&D Expenditure for O&G Producers (No China) with Oil Price, 2002–2020. Curves show the yearly R&D Expenditure for each company with reference to the average oil price and a rough timeline of the Energy Transition. Nominal values are unadjusted for inflation. Source: Based on IRI and EIA data.

2.4.2 Analysis of R&D Intensity

Figure 2.3 charts the calculated R&D Intensity as defined as the R&D Expenditure divided by Net Sales for the twelve Oil & Gas companies in the sample set. This graph has the same layout with R&D Intensity now plotted on the primary axis.

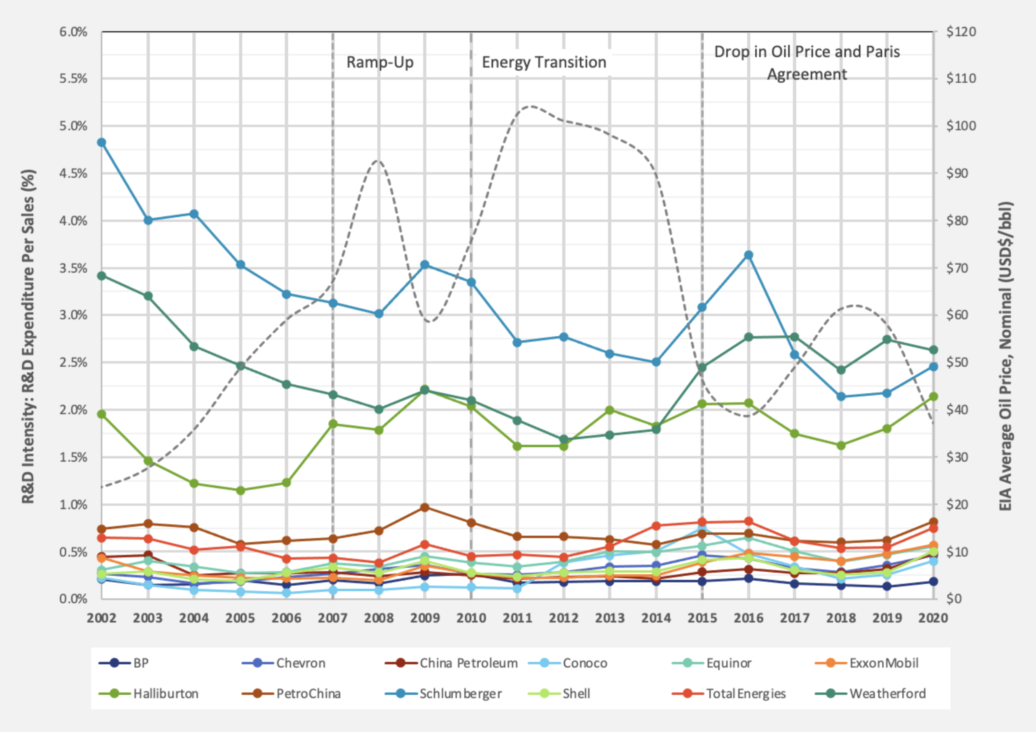


Figure 2.3: R&D Intensity for All O&G Companies with Oil Price, 2002–2020. Curves show the calculated yearly R&D Intensity for each company with reference to the average oil price and a rough timeline of the Energy Transition. Nominal values are unadjusted for inflation. Source: Based on IRI and EIA data.

What is immediately evident from this figure is the difference between R&D Intensity for Oil & Gas Service Providers and Oil & Gas Producers. Using this figure, and Figure 2.4 which provides a closer zoom of intensities for the major producers, it is shown that Oil & Gas Producers have held R&D Intensities over the last twenty years in the range of 0.2% and 0.5% with some expected variation. Figure 2.4 shows that all majors have surpassed 0.4% intensity, with the exception of BP. As expected, the calculated intensities using the publicly available IRI data sets confirm previous findings in the literature of an average R&D Intensity for producers below 1% (Perrons, 2014; Von Tunzelmann & Acha, 2006; Moncada-Paternò-Castello et al., 2010; Popp et al., 2020).

The three curves for the Service Providers tell a different story. Recent 2020 R&D Intensities are nearer 2.25% to 2.5% of total net sales. Beyond the difference in magnitudes, the range of intensities for the Service Providers exhibit greater variability than the producers. Beginning in 2002, all three service providers show a decrease in company R&D intensity although oil prices were increasing during this time. Halliburton was the first to adjust its R&D spending in 2007, followed by Schlumberger and Weatherford in 2009. The data supports the findings by Perrons (2014) and Moncada-Paternò-Castello et al. (2010) of an average intensity of 2.4% for Service Providers.

At the same time, the curves obscure the dynamics of the level of coupling of R&D Intensity with oil price. For example, the year 2016 appears to present that Service Providers had weathered the storm of depressed oil prices. However, a closer look at the underlying data indicates the impact of decreasing Net Sales. Take Schlumberger for example: In 2014, the IRI reports it had €1,002.4 million invested in R&D Expenditure with €40,013 million in Net Sales for a calculated intensity of 2.51% (as shown on Figure 2.3). Were the changes in R&D Intensity in 2016 driven by an increase in funding or an underlying shift in technology management? Probably neither. The IRI data records that, in 2016, Schlumberger's R&D budget dropped to €960.1 million but its Net Sales had dropped to €26,382 million for a 2016 R&D Intensity of 3.64%. With this information, the period between 2015 and 2017 on Figure 2.3 portrays a classic example of how rapidly decreasing net sales can effectively increase the apparent R&D Intensity of a company even when underlying R&D budgets are decreasing. This example underscores the finding by Morbey & Reithner (1990) and Hill & Snell (1989) that fluctuation in net sales can result in R&D Intensity lacking the necessary robustness to successfully serve as a metric for, what (Morbey & Reithner, 1990) call, "long-term commitment to innovation" (Morbey & Reithner, 1990, p. 12). Figure 2.4 is a close-up of the producers without China and provides a better view of the trends in R&D intensity for these companies.

And it may give two additional insights for the Oil & Gas industry. First, R&D Intensity can be less robust in the Oil & Gas industry than in other industries due to the commodity impact of the price of oil on overall net sales. Short-term variability can mask actual R&D effort. This claim will be examined in more detail in Chapter 5. Second, Service

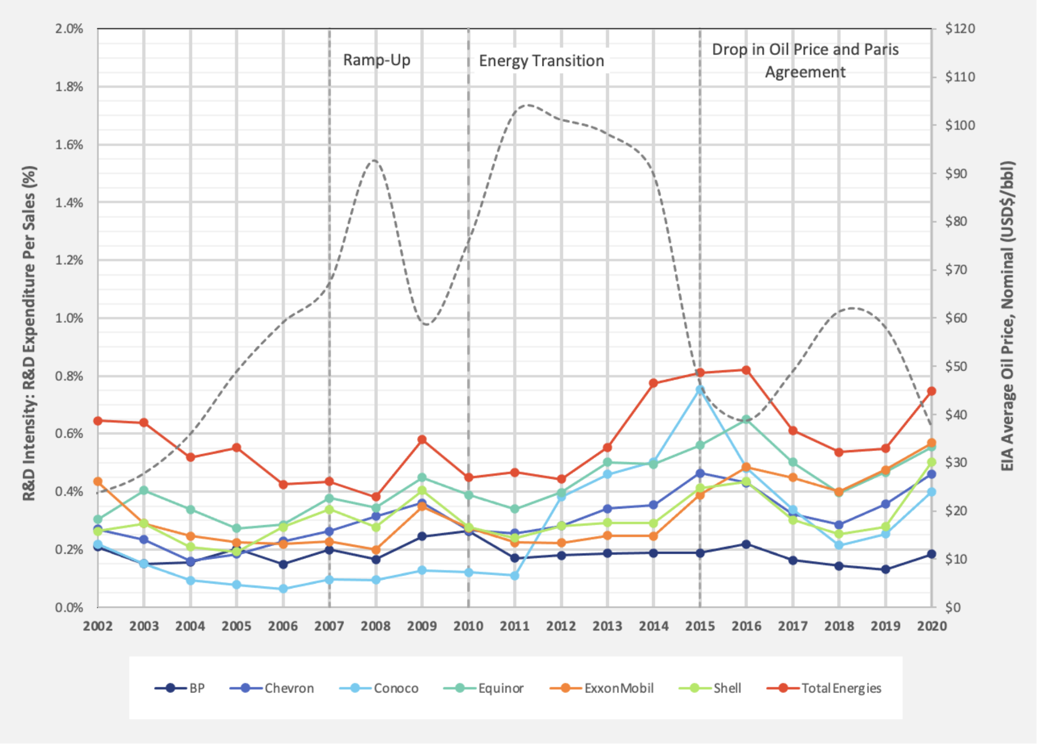


Figure 2.4: R&D Intensity for O&G Producers (No China) with Oil Price, 2002–2020. Curves show the calculated yearly R&D Intensity for each company with reference to the average oil price and a rough timeline of the Energy Transition. Nominal values are unadjusted for inflation. Source: Based on IRI and EIA data.

Providers must react not only to the price of oil but also to the lagged reaction of Oil & Gas Producers, who are their primary customers. Thus, there may be an additional time lag in how Service Providers respond to commodity shocks, including how and when to reduce their R&D expenditure when necessary.

2.4.3 Analysis of R&D Productivity

Figure 2.5 shows the calculated trends for R&D productivity for all twelve Oil & Gas companies in the sample set. Like the charts for R&D Expenditure and R&D Intensity, the chart covers the time period of 2002 to 2020 in relation to both the price of oil and three broad categories for the Energy Transition. On the left side of the graph, the primary axis shows the calculated R&D Productivity in units of €/employee. So, for example, €10,000 indicates that €10,000 euro per full-time employee is invested in research and development.

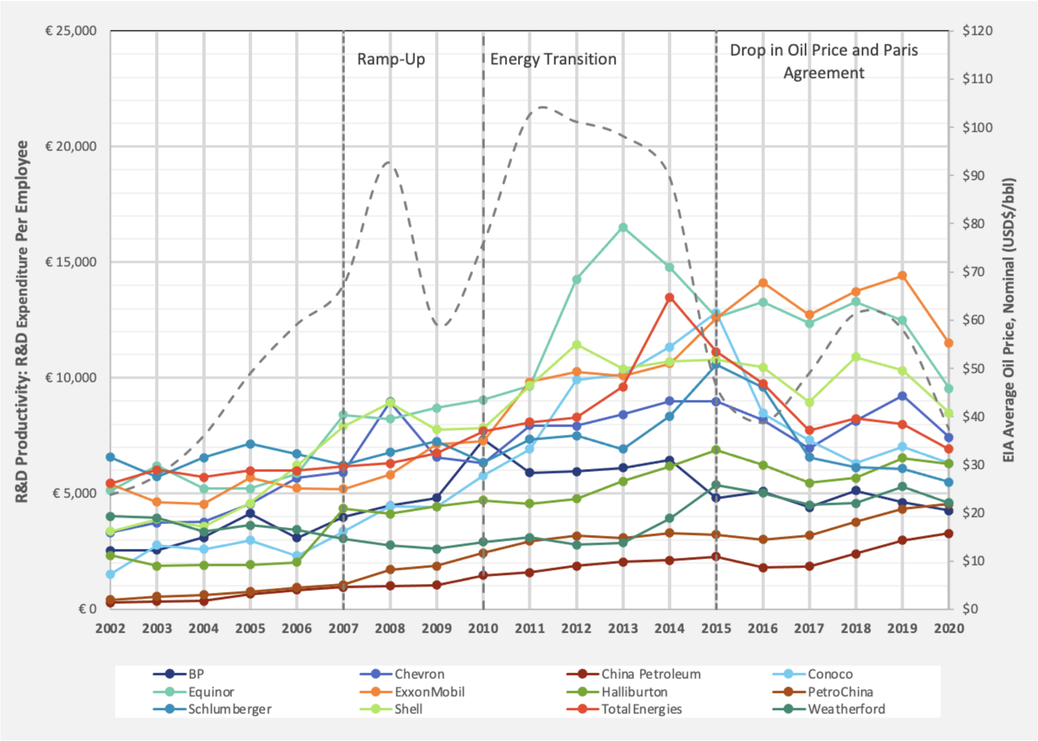


Figure 2.5: R&D Productivity for All O&G Companies with Oil Price, 2002–2020. Curves show the calculated yearly R&D Productivity for each company with reference to the average oil price and a rough timeline of the Energy Transition. Nominal values are unadjusted for inflation. Source: Based on IRI and EIA data.

Importantly, the graph shows that there has been a steady rise in R&D Productivity for the sampled firms during the period of increasing oil prices.

2.5 Key Takeaways

This chapter used corporate financial and Research and Development (R&D) data to develop a high-level view of how companies are strategically managing their technology portfolios during the Energy Transition. The following are the key takeaways:

1. R&D Expenditure, R&D Intensity, and R&D Productivity are quantitative metrics that provide insight on a firm's high-level commitment to technological innovation.
2. R&D Expenditure is a year-end financial metric that reports the total budgeted investment in absolute terms. Both R&D Intensity and R&D Productivity are normal-

ized metrics and can represent a more stable picture of technology management over time.

3. There is high variance in the range of R&D Expenditure value for the twelve companies in the sample.

4. Since 2004, European Producers are investing a mean of €570.6 million/year (σ = €112.2 million/year, c_v = 19.7%) compared to American Producers with a mean of €443.7 million/year (σ = €85.9 million/year, c_v = 19.4%).

5. Oil & Gas Producers have a mean R&D Intensity of 0.373% (σ = 0.078%, c_v = 21.0%), while O&G Service Providers are significantly higher at 2.338% (σ = 0.239%, c_v = 10.2%), confirming previous studies. These low R&D intensities are likely related to structural challenges confronting large-scale research and development in the commodity energy industry.

6. R&D Productivity—defined as the total R&D expenditure per employee—is a normalized, stable metric with significant correlation to net sales and profit. Both European Producers and American Producers have near identical R&D Productivity at €8,055/employee and €8,099/employee, respectively. This metric for China is significantly lower at €2,130 due to headcount. O&G Service Providers have a mean R&D Productivity of €5,235/employee.

7. Graphical trend analysis shows a yearly increase for R&D Expenditure over time with some variation for oil price.

8. Periods of disruption create opportunity for firms to reevaluate R&D baselines and peer grouping for competitive benchmarking.

9. R&D Intensity is a normalized metric that is defined as the ratio of R&D Expenditure to Net Sales. This metric broadly serves as a measure of a company's commitment to innovation and overall technology management.

10. R&D Productivity is a normalized metric that evaluates the ratio of R&D Expenditure to total employees. Broadly, this metric serves as a proxy for the overall

productivity of a firm's R&D program. This metric has strong statistical correlation with both Net Sales per Employee and, at times, Profit (This relationship will be explored in Chapter 5).

11. Of the three metrics, R&D Productivity shows the highest variation between the twelve companies with a range of €3,000/year to €12,000/year in 2020.

12. Overall, traditional R&D metrics provide a high-level snapshot of commitment to technology management over time. However, these metrics alone are not sufficient to indicate repositioning of technology strategies. This is due partly to the masking effect of oil price on net sales, profit, and overall R&D budgeting.

Chapter 3

Trends in Patenting and Climate Change Mitigating Technologies

The last chapter concluded with the generalized finding that traditional corporate R&D metrics lack the detail to clearly identify how technology management might be adapting to the opportunities of the Energy Transition. While there were positive indications of strategic repositioning in the data, differentiation between the cyclical fluctuation in commodity prices and any broader trends in technology management was not possible.

This chapter will introduce patent data for the twelve Oil & Gas firms in the sample set. First, the author will introduce the new Cooperative Patent Classification (CPC) system for Climate Change Mitigating Technology that is jointly managed by the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO). Second, the research method used to collect and process the patent data will be presented. Third, the author will detail the results and analyze the high-level trends presented by the CCMT patent data.

3.1 The Cooperative Patent Classification (CPC)

The Cooperative Patent Classification (CPC) is a joint partnership between the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) aimed at "harmonizing" the United States Patent Code (USPC) and the European Classification

System (ECLA) into one shared, common language for categorizing patented technologies (Cooperative Patent Classification, n.d.-a). This partnership was launched in October 2010 with the added mandate to ensure that the joint system was compatible with the global classification standards of the World Intellectual Property Organization (WIPO) and the structure of the International Patent Classification (IPC) (Cooperative Patent Classification, n.d.-a). The CPC website states that the final, jointly administered CPC system was built more strongly on the ECLA framework, requiring additional transition for the USPTO (Cooperative Patent Classification, n.d.-a). The USPTO officially replaced the pre-existing United States Patent Code (USPC) with the CPC on January 1, 2013 (USPTO, n.d.).

The adopted CPC system is comprised of multiple taxonomy levels that facilitate fine-tuned classification of each technology patent. At the highest level, there are nine Sections, including:

- A: Human Necessities
- B: Performing Operations; Transporting
- C: Chemistry; Metallurgy
- D: Textiles; Paper
- E: Fixed Constructions
- F: Mechanical Engineering; Lighting; Heating; Weapons; Blasting
- G: Physics
- H: Electricity
- Y: General Tagging of New Technological Developments (Cooperative Patent Classification, 2022).

Beneath the Section level, technologies are further classified by Class, Subclass, Main Group and Subgroup. Impressively, this multi-leveled classification results in approximately 250,000 distinct classification entries (European Patent Office, n.d.-b).

3.2 Section Y and the Y02–Y04 Tagging System

A strength of the finalized CPC system is the inclusion of the ninth Section, "Y: General Tagging of New Technological Developments". While this tagging scheme was not part of the USPTO system, it was in early development by the EPO during the formation of the CPC (Veefkind et al., 2012). In fact, the Y02–Y04S schema was publicly released by the EPO in June 2010, and the ability to perform tagged searches on the EPO's public patent search engine, named Epacenet, quickly followed (Veefkind et al., 2012, p. 108), a launch date that predated the formal joint partnership of the CPC in October 2010 by several months (Cooperative Patent Classification, n.d.-a).

As detailed by Veefkind et al. (2012), the early pre-CPC development of the Y02–Y04 classification system was built on two earlier approaches to track the development and proliferation of technologies aimed at reducing and controlling greenhouse gases.[1] First, the early Y02–Y04S schema simplified the effort by the WIPO to classify existing patents into a "Green Inventory" of "Environmentally Sound Technologies" based on a catchword index used for patent searching (Veefkind et al., 2012). However, as noted by Veefkind et al., the WIPO's approach to accessing technologies in the "Green Inventory" was cumbersome for lay users and required significant time, skill and resources to perform accurate and complete searches (2012). Near the same time, the EPO experimented with a new label of "Y01N" of nanotechnologies to help group emerging technologies that were filed under numerous Subclass, Main Group and Subgroup listings (Veefkind et al., 2012). The success of the "Y01N" tagging for nanotechnology led to the broader "Y02–Y04" groupings (Veefkind et al., 2012; Igami & Okazaki, 2007; Scheu et al., 2006).

The heart of the Y Section is the unique inclusion of the Y02 and Y04 tags.[2] The power and simplicity of the Y02–Y04 tagging scheme—particularly when compared with the earlier WIPO model of using an index of catchwords—is that it is a "purely complementary" tagging classification that operates in parallel to the existing Cooperative Patent Classification (CPC) taxonomy (Veefkind et al., 2012; Cooperative Patent Classification, 2022). The requirement of the Y02–Y04 schema is defined by the CPC in its definition for CPC Section Y:

> "In this section, classes Y02 and Y04 are only to be used for tagging documents which are already classified or indexed elsewhere and which relate in

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[1] The influential paper by Veefkind et al. (2012) predates the official adoption of the CPC by the USPTO.

[2] Additionally, the final EPO–USPTO Y Section contains the "Y10" class which specifically covers older patent classifications under the USPTO's USPC (Cooperative Patent Classification, 2022).

> a broad sense to specific major technical fields, these fields being defined by the notes following the title of the subclasses of this section” (Cooperative Patent Classification, 2022).

Thus, the Y02–Y04 tags enable cross-labeling technologies that are concurrently indexed under at least one of the eight CPC sections, as detailed above (Cooperative Patent Classification, 2022).

3.2.1 Y02: Technologies or Applications for Mitigation or Adaptation Against Climate Change

The Y02 class is significantly larger and more detailed than Y04, and includes the bulk of the subclasses to describe and cover Climate Change Mitigation Technology (CCMT). According to the Cooperative Patent Classification (2022), the Y02 class is defined:

> “This class covers selected technologies, which control, reduce or prevent anthropogenic emissions of greenhouse gases [GHG], in the framework of the Kyoto Protocol and the Paris Agreement, and also technologies which allow adapting to the adverse effects of climate change” (Cooperative Patent Classification, 2022).

This formal definition of Y02 captures a number of important features. First, technologies tagged with "Y02" are specifically tied to the Kyoto Protocol and the Paris Agreement and, therefore, the broader Energy Transition. Second, the formal CPC definition is scoped to include all technologies that reduce, control, and prevent GHG, in addition to those that facilitate adaptation to climate change. Third, this definition can serve as a proxy definition for Climate Change Mitigation Technology (CCMT) as a whole. The final wording of the Y02 class builds on language from earlier definitions for CCMT based on the United Nations Framework Convention on Climate Change (UNFCCC) (Veefkind et al., 2012, p. 106).[3]

It should be noted that the eight subclasses of the Y02 class are listed in detail, as they will play a role later in this chapter and in Chapter 4 when the research examines "Disruptive" and "Sustaining" technologies. The eight subclasses of the Y02 class are defined (Cooperative Patent Classification, 2022):

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[3] The UNFCCC glossary referenced by Veefkind et al. (2012) no longer contains an entry for Climate Change Mitigating Technology (CCMT).

1. Y02A: Technologies for Adaptation to Climate Change
2. Y02B: Climate Change Mitigation Technologies Related to Buildings, e.g., Housing, House Appliances or Related End-User Applications
3. Y02C: Capture, Storage, Sequestration or Disposal of Greenhouse Gases (GHG)
4. Y02D: Climate Change Mitigation Technologies in Information and Communication Technology (ICT), i.e. Information and Communication Technologies Aiming at the Reduction of Their Own Energy Use, Capture, Storage, Sequestration, or Disposal of Greenhouse Gases (GHG)
5. Y02E: Reduction of Greenhouse Gases (GHG) Emissions, Related to Energy Generation, Transmission or Distribution
6. Y02P: Climate Change Mitigation Technologies in the Production or Processing of Goods
7. Y02T: Climate Change Mitigation Technologies Related to Transportation
8. Y02W: Climate Change Mitigation Technologies Related to Wastewater Treatment or Waste Management (Cooperative Patent Classification, 2022).

Each of these eight subclasses is further divided into groups and subgroups, resulting in hundreds of potential Y02 technology classifications.

3.2.2 Y04: Information or Communication Technologies Having an Impact on Other Technology Areas

The "Y04" class contains technologies that, by definition, impact other technology areas. Unlike the larger number of subclasses in the Y02 class, the Y04 class is currently delineated by only one subclass, Y04S (Cooperative Patent Classification, 2022). Even though it falls outside of the classification of "Technologies or Applications for Mitigation or Adaptation Against Climate Change", Y04S is related to the Energy Transition because it covers systems technologies related to electrical power, generation, distribution and smart grids (Cooperative Patent Classification, 2022).

3.3 Methodology for Patent Search

This section lays out the formal research plan utilized to conduct the patent search for this study. Specific detail is provided to allow replication of the search results and application of the proposed method to study other industries.

3.3.1 Patent Search Query

Patent queries for this research were run using the EPO's Espacenet patent search engine between June 23 and June 27, 2022 (European Patent Office, n.d.-c). Prior to conducting the research, Espacenet was compared with the USPTO's Patent Public Search, Google Patents, PatentScout, PatSnap, and the EPO's Global Patent Index (GPI). Espacenet was selected as the preferred patent search engine for five reasons:

1. ***Accessibility***. Espacenet, Google Patents and USPTO's Patent Public Search are free-access public databases. Although PatentScout and PatSnap offer analytical tools on top of the search engine, these sites are limited by a paywall and are not accessible by all academic researchers.[4] In theory, the EPO's Global Patent Index (GPI) and Worldwide Patent Statistical Database (PATSTAT) are available for public use, however administrative approval is required for access.[5]

2. ***Searchability***. The Espacenet engine provides intuitive Advanced Search capability to perform focused searches on a company's patents that have the CPC's Y02 or Y04S tag to identify it as a Climate Change Mitigation Technology (CCMT) (Veefkind et al., 2012, p. 110). Similar functionality was not discovered with Google Patents, Patent Public Search, or PatSnap.

3. ***Filterability***. Related to Searchability, the Espacenet search engine allowed collecting patent-landscape data for the occurrence of Y02–Y04S tags in the CPC Main Groups and CPC Subgroups (Veefkind et al., 2012). The ability to generate statistics at the CPC Main Group and CPC Subgroup level per Year and per Company was not discovered in any of the other search engines, although it is likely available in PatSnap in an unsorted format. Additionally, Espacenet allowed easy visual identification to toggle searches between International Patent Family (IPF) and individual publications.

4. ***Quality***. Espacenet generated extremely consistent search results achieved from testing the same search parameters on different search attempts. The reproducibil-

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[4] The MIT School of Engineering and Sloan Business School provide access to both PatentScout and PatSnap for all current MIT students and faculty.

[5] The author requested academic access to GPI on 6/23/2022 and was unable to secure access.

ity of searches was enhanced by the added feature on Espacenet which reviews as many as 100 previous searches with a list of all key search parameters.

5. ***Comparability***. Lastly, the Espacenet search engine along with Worldwide Patent Statistical Database (PATSTAT) was utilized by the European Patent Office (EPO) and the International Energy Agency (IEA) in their influential report, "Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation" (EPO/IEA, 2021). As will be discussed in Chapter 6, this report contains global benchmarks for quantifying how technology management is shifting during the Energy Transition. The use of the same database for this research will facilitate comparison of findings from the Oil & Gas industry with those from the EPO/IEA joint report.

3.3.2 Patent Assignee Names

The identification of assignee names—meaning the multiple names that a given company may patent under, particularly for global companies—is a critical step in ensuring consistent data quality in a patent landscape study (Angelucci et al., 2018; Helm et al., 2014, p. 12). This study utilized a combination of software features in the Espacenet search engine, together with the known company name, as well as the subsidiary and merged corporate names over the years of this study, 2000–2020. First, a list of corporate assignee names was compiled based on corporate reports. Second, the Advanced Search feature in Espacenet was used used to enter all appropriate assignee names with appropriate Boolean operators. Third, the Filter tool in Espacenet was used to manually review all of the Assignee names produced from the Advanced Search. Here, company names not directly associated with the primary parent company were reviewed and removed. A partial example of this method is illustrated in Appendix E: Research Design for Patent Searching in EPO's Espacenet Database. While there may be remaining mismatches in the compiled results, this method was applied consistently between all twelve companies in the study.

3.3.3 Patent Families

Generating a patent landscape for corporations in different countries presents the additional challenge of differentiating between diverse patenting behaviors and the underlying value of the patented technology (Probst et al., 2021; Dechezleprêtre et al., 2017; Harhoff et al., 1999; Svensson, 2022). Building on the methodology presented in several influential patent studies, this research utilized International Patent Families to both normalize and high-grade innovation (EPO/IEA, 2021; Helm et al., 2014; Probst et al., 2021).

An International Patent Family (IPF) is generated when the same invention or underlying technology is patented in two or more countries or regions. For example, a patent family would be generated if an invention was independently patented through the Japan Patent Office (JPO) and the Korean Intellectual Property Office (KIPO). Likewise, this hypothetical patent family would grow if it were subsequently patented with the European Patent Office (EPO) and United States Patent and Trademark Office (USPTO) (Svensson, 2022).

There are two primary reasons to use patent families. First, Helm et al. (2014) note that a patent family can be "regarded as a proxy for innovation" due to the higher overall cost to patent a technology in more than one country. Here, the added R&D effort and resources to ensure Intellectual Property (IP) protection under multiple patent offices is an indicator of the perceived value of the invention due to the barrier to entry (Svensson, 2022). For this reason, Probst et al. recommend using patent families for landscaping because they represent a "high-value invention" (2021, p. 4). For this study, the author did not attempt to construct an evaluation or weighting scheme to the individual patents outside of the value of belonging to a published international patent family based on the difficulty presented in the literature (van Zeebroeck & van Pottelsberghe de la Potterie, 2011; Griliches, 1991; Svensson, 2022).

Second, using patent families as a "common metric" can help to standardize the difference in patenting activities between countries and regions (Probst et al., 2021).

Drawing on research design for patent landscaping, this study utilizes patent families, or International Patent Family (IPF), to standardize the patent search between companies, countries and regions. Specifically, the Espacenet search requires that all patent be published in both the US with the USPTO and in the European Union with either the EPO or the WIPO. An example of these search parameters in the Espacenet engine is shown in Appendix E.

These patenting agencies were selected because they provided the largest number of patent families for the twelve Oil & Gas companies in this study. Of the twelve selected companies, five companies are headquartered primarily in Europe (BP, Equinor, Schlumberger, Shell, Total) and four companies are located primarily in the US (Chevron, Conoco, ExxonMobil, Halliburton), while Weatherford International is an Irish public limited company headquartered in the US.

The selection of the USPTO and either EPO or WIPO likely penalizes the two Chinese companies, China Petroleum and PetroChina, thus reducing the reported number of both total patent families and CCMT patent families. By selecting USPTO and either EPO or WIPO, this selection of search parameters effectively has a bias toward technologies patented outside of China. However, the overall impact of this bias on the two Chinese companies may be less than anticipated. For example, a Y02–Y04S search on Espacenet for PetroChina results in only 24 patent families in China, 18 patent families in the US, and 15 patent families with the EU/WIPO. Here, patent families in both China and US result in 16 patent families, while EU/WIPO and US results in 11 patent families. This indicates that, while there is some penalty for the two Chinese companies, there is a larger indication that Chinese Oil & Gas companies are prolifically patenting within China, but they are not regularly seeking outside patent protection with USPTO, EPO, JPO or others. This trend has been identified by Probst et al. who document that China is only responsible for approximately 5% of high-value inventions when measured by patent families (Probst et al., 2021, p. 4).

3.3.4 Search Boundaries and Limitations

Following Helm et al. (2014), this patent research has limited the search boundary to international patent families containing the Y02 or Y04S tag, with limited review of the individual patent applications. Continuing with the methodology outlined by Helm et al., the removal or addition of patents to queried patent searches was generally avoided to allow for replication of the search results and to maintain consistency across the searches (2014, p. 13). Additionally, the overall current status of the patent family was not assessed, including whether published patents were practically implemented by the company in question.

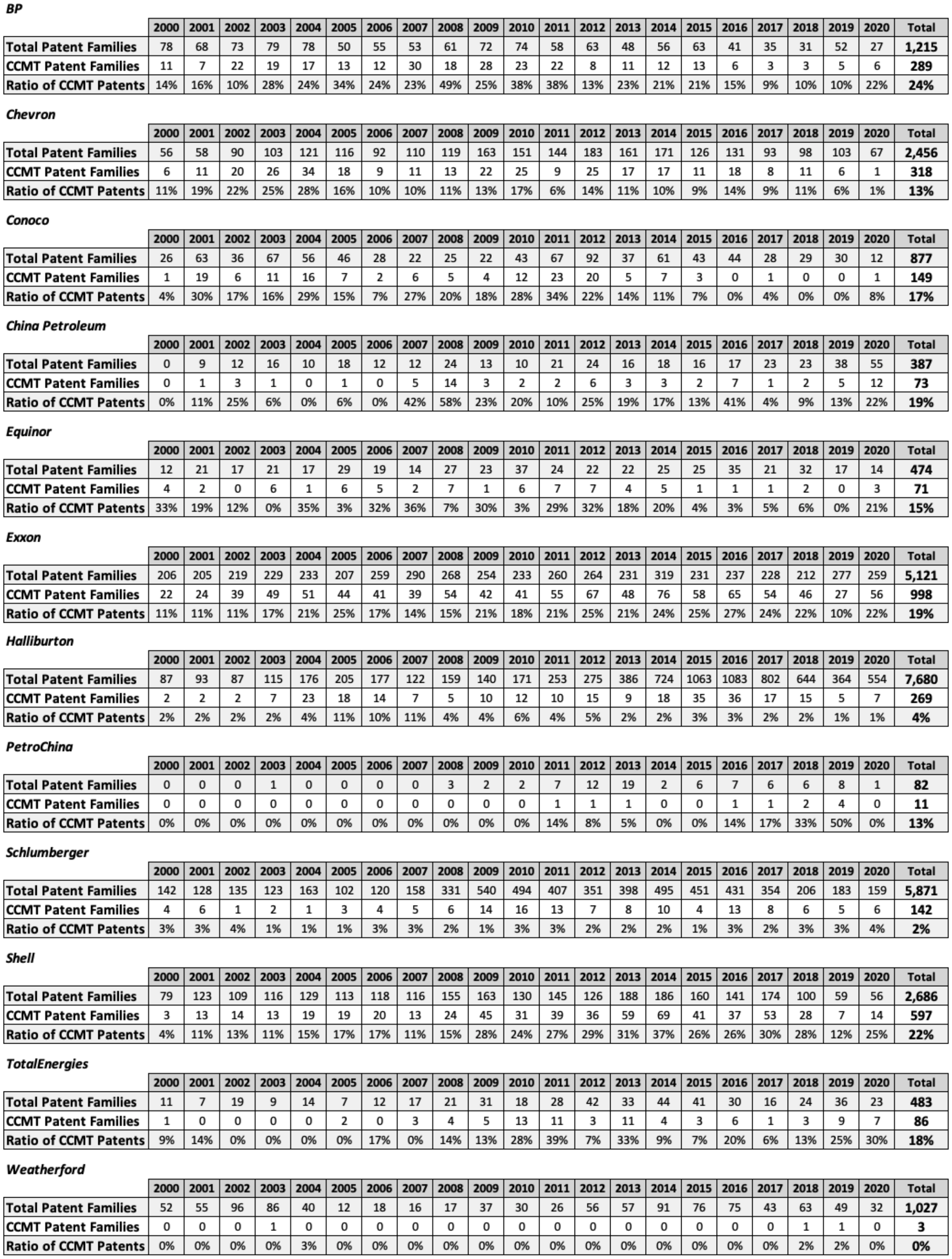
3.4 Results of Espacenet Patent Search

The application of the above search method resulted in the first snapshot of Climate Change Mitigation Technology (CCMT) in the Oil & Gas industry—no previous studies in the literature are known to have explored CCMT trends for this industry.

3.4.1 Results of Espacenet Patent Search by Company

Table 3.1 documents the Espacenet search results for all companies between 2000–2020 collected during the patent search research window. The following definitions are used to present the results:

- ***Total Patent Families***. The total count for all international patent families, including CCMTs, that were published by the company during a given year.
- ***CCMT Patent Families***. The total count for all international patent families tagged with one or more of the CPC's "Y02–Y04S" tags, that were published by the company during a given year.
- ***Ratio of CCMT Patents***. This is a calculated percentage determined by CCMT Patents (as dividend or numerator) divided by Total Patents (as divisor or denominator) resulting in a percentage of CCMT Patents.



BP

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	78	68	73	79	78	50	55	53	61	72	74	58	63	48	56	63	41	35	31	52	27	**1,215**
CCMT Patent Families	11	7	22	19	17	13	12	30	18	28	23	22	8	11	12	13	6	3	3	5	6	**289**
Ratio of CCMT Patents	14%	16%	10%	28%	24%	34%	24%	23%	49%	25%	38%	38%	13%	23%	21%	21%	15%	9%	10%	10%	22%	**24%**

Chevron

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	56	58	90	103	121	116	92	110	119	163	151	144	183	161	171	126	131	93	98	103	67	**2,456**
CCMT Patent Families	6	11	20	26	34	18	9	11	13	22	25	9	25	17	17	11	18	8	11	6	1	**318**
Ratio of CCMT Patents	11%	19%	22%	25%	28%	16%	10%	10%	11%	13%	17%	6%	14%	11%	10%	9%	14%	9%	11%	6%	1%	**13%**

Conoco

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	26	63	36	67	56	46	28	22	25	22	43	67	92	37	61	43	44	28	29	30	12	**877**
CCMT Patent Families	1	19	6	11	16	7	2	6	5	4	12	23	20	5	7	3	0	1	0	0	1	**149**
Ratio of CCMT Patents	4%	30%	17%	16%	29%	15%	7%	27%	20%	18%	28%	34%	22%	14%	11%	7%	0%	4%	0%	0%	8%	**17%**

China Petroleum

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	0	9	12	16	10	18	12	12	24	13	10	21	24	16	18	16	17	23	23	38	55	**387**
CCMT Patent Families	0	1	3	1	0	1	0	5	14	3	2	2	6	3	3	2	7	1	2	5	12	**73**
Ratio of CCMT Patents	0%	11%	25%	6%	0%	6%	0%	42%	58%	23%	20%	10%	25%	19%	17%	13%	41%	4%	9%	13%	22%	**19%**

Equinor

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	12	21	17	21	17	29	19	14	27	23	37	24	22	22	25	25	35	21	32	17	14	**474**
CCMT Patent Families	4	2	0	6	1	6	5	2	7	1	6	7	7	4	5	1	1	1	2	0	3	**71**
Ratio of CCMT Patents	33%	19%	12%	0%	35%	3%	32%	36%	7%	30%	3%	29%	32%	18%	20%	4%	3%	5%	6%	0%	21%	**15%**

Exxon

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	206	205	219	229	233	207	259	290	268	254	233	260	264	231	319	231	237	228	212	277	259	**5,121**
CCMT Patent Families	22	24	39	49	51	44	41	39	54	42	41	55	67	48	76	58	65	54	46	27	56	**998**
Ratio of CCMT Patents	11%	11%	11%	17%	21%	25%	17%	14%	15%	21%	18%	21%	25%	21%	24%	25%	27%	24%	22%	10%	22%	**19%**

Halliburton

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	87	93	87	115	176	205	177	122	159	140	171	253	275	386	724	1063	1083	802	644	364	554	**7,680**
CCMT Patent Families	2	2	2	7	23	18	14	7	5	10	12	10	15	9	18	35	36	17	15	5	7	**269**
Ratio of CCMT Patents	2%	2%	2%	2%	4%	11%	10%	11%	4%	4%	6%	4%	5%	2%	2%	3%	3%	2%	2%	1%	1%	**4%**

PetroChina

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	0	0	0	1	0	0	0	0	3	2	2	7	12	19	2	6	7	6	6	8	1	**82**
CCMT Patent Families	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	1	2	4	0	**11**
Ratio of CCMT Patents	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	14%	8%	5%	0%	0%	14%	17%	33%	50%	0%	**13%**

Schlumberger

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	142	128	135	123	163	102	120	158	331	540	494	407	351	398	495	451	431	354	206	183	159	**5,871**
CCMT Patent Families	4	6	1	2	1	3	4	5	6	14	16	13	7	8	10	4	13	8	6	5	6	**142**
Ratio of CCMT Patents	3%	3%	4%	1%	1%	1%	3%	3%	2%	1%	3%	3%	2%	2%	2%	1%	3%	2%	3%	3%	4%	**2%**

Shell

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	79	123	109	116	129	113	118	116	155	163	130	145	126	188	186	160	141	174	100	59	56	**2,686**
CCMT Patent Families	3	13	14	13	19	19	20	13	24	45	31	39	36	59	69	41	37	53	28	7	14	**597**
Ratio of CCMT Patents	4%	11%	13%	11%	15%	17%	17%	11%	15%	28%	24%	27%	29%	31%	37%	26%	26%	30%	28%	12%	25%	**22%**

TotalEnergies

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	11	7	19	9	14	7	12	17	21	31	18	28	42	33	44	41	30	16	24	36	23	**483**
CCMT Patent Families	1	0	0	0	0	2	0	3	4	5	13	11	3	11	4	3	6	1	3	9	7	**86**
Ratio of CCMT Patents	9%	14%	0%	0%	0%	0%	17%	0%	14%	13%	28%	39%	7%	33%	9%	7%	20%	6%	13%	25%	30%	**18%**

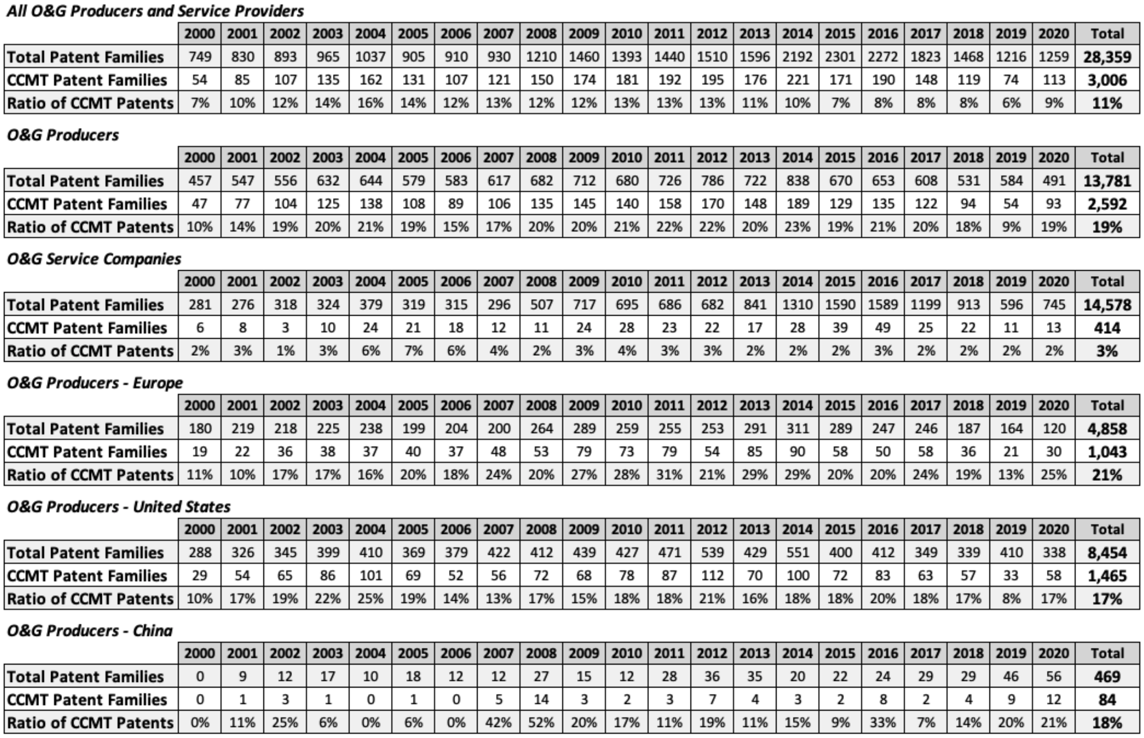
Weatherford

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	52	55	96	86	40	12	18	16	17	37	30	26	56	57	91	76	75	43	63	49	32	**1,027**
CCMT Patent Families	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	**3**
Ratio of CCMT Patents	0%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	2%	0%	**0%**

Table 3.1: Results of Espacenet CCMT Patent Search by Company, 2000–2020. This combined table records the Total Patent Families (including CCMT and non-CCMT patents), Total CCMT Patent Families based on the Y02–Y04S schema, and the ratio of CCMT Patents to Total Patents. Results are presented per year and as a summed total in the last column. Source: Based on EPO and USPTO data from the Espacenet patent database.

3.4.2 Results of Espacenet Patent Search by Industry and Region

Table 3.2 shows the overall results for the CCMT patent search organized by the six key groupings, including: (1) All O&G Producers and Service Providers; (2) O&G Producers; (3) O&G Service Companies; (4) O&G Producers – Europe; (5) O&G Producers – United States; and, (6) O&G Producers – China.



All O&G Producers and Service Providers

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	749	830	893	965	1037	905	910	930	1210	1460	1393	1440	1510	1596	2192	2301	2272	1823	1468	1216	1259	**28,359**
CCMT Patent Families	54	85	107	135	162	131	107	121	150	174	181	192	195	176	221	171	190	148	119	74	113	**3,006**
Ratio of CCMT Patents	7%	10%	12%	14%	16%	14%	12%	13%	12%	12%	13%	13%	13%	11%	10%	7%	8%	8%	8%	6%	9%	**11%**

O&G Producers

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	457	547	556	632	644	579	583	617	682	712	680	726	786	722	838	670	653	608	531	584	491	**13,781**
CCMT Patent Families	47	77	104	125	138	108	89	106	135	145	140	158	170	148	189	129	135	122	94	54	93	**2,592**
Ratio of CCMT Patents	10%	14%	19%	20%	21%	19%	15%	17%	20%	20%	21%	22%	22%	20%	23%	19%	21%	20%	18%	9%	19%	**19%**

O&G Service Companies

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	281	276	318	324	379	319	315	296	507	717	695	686	682	841	1310	1590	1589	1199	913	596	745	**14,578**
CCMT Patent Families	6	8	3	10	24	21	18	12	11	24	28	23	22	17	28	39	49	25	22	11	13	**414**
Ratio of CCMT Patents	2%	3%	1%	3%	6%	7%	6%	4%	2%	3%	4%	3%	3%	2%	2%	2%	3%	2%	2%	2%	2%	**3%**

O&G Producers - Europe

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	180	219	218	225	238	199	204	200	264	289	259	255	253	291	311	289	247	246	187	164	120	**4,858**
CCMT Patent Families	19	22	36	38	37	40	37	48	53	79	73	79	54	85	90	58	50	58	36	21	30	**1,043**
Ratio of CCMT Patents	11%	10%	17%	17%	16%	20%	18%	24%	20%	27%	28%	31%	21%	29%	29%	20%	20%	24%	19%	13%	25%	**21%**

O&G Producers - United States

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	288	326	345	399	410	369	379	422	412	439	427	471	539	429	551	400	412	349	339	410	338	**8,454**
CCMT Patent Families	29	54	65	86	101	69	52	56	72	68	78	87	112	70	100	72	83	63	57	33	58	**1,465**
Ratio of CCMT Patents	10%	17%	19%	22%	25%	19%	14%	13%	17%	15%	18%	18%	21%	16%	18%	18%	20%	18%	17%	8%	17%	**17%**

O&G Producers - China

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Total Patent Families	0	9	12	17	10	18	12	12	27	15	12	28	36	35	20	22	24	29	29	46	56	**469**
CCMT Patent Families	0	1	3	1	0	1	0	5	14	3	2	3	7	4	3	2	8	2	4	9	12	**84**
Ratio of CCMT Patents	0%	11%	25%	6%	0%	6%	0%	42%	52%	20%	17%	11%	19%	11%	15%	9%	33%	7%	14%	20%	21%	**18%**

Table 3.2: Results of Espacenet Patent Search by Industry, Sector and Region, 2000–2020. Source: Based on EPO and USPTO data from the Espacenet patent database.

Impressively, the collected results for All O&G Producers and Service Providers exhibit a high number of patents for Climate Change Mitigation Technology (CCMT). Overall, all companies combined result in approximately 11% of all patent families being CCMT, or 3,006 CCMT Patent Families out of 28,359 Total Patent Families. Review of the yearly Ratio of CCMT Patents highlights a relatively stable production of yearly percentages of CCMTs with a high of 16% in 2004 and a low of 6% in 2019. There is a decrease in the ratio of CCMTs beginning in 2015 with indication of recovery by 2020.

The overall number and percentage of CCMTs increases dramatically for the O&G Producers once the Service Providers are removed. As a group, the O&G Producers are delivering an average of 19% of their yearly technological innovation as Climate Change Mitigation Technology (CCMT) with a high of 23% in 2014 and a low of 9% in 2019. What stands out in this table, including a comparison with All O&G Producers and Service Providers, is that O&G Producers published 86% of all CCMTs (2,592 out of 3,006).

The combined numbers for the O&G Service Providers present the finding that, while these three companies are patenting prolifically (14,578 patent families compared with 13,781 patent families for *all nine* O&G Producers), there is a significantly lower emphasis on technologies that are labeled CCMTs. They show an average of 3% of patents as CCMTs (414 of 14,578) and contributed just 14% of the total CCMTs of the combined cohort of twelve companies (414 of 3,006). On a yearly basis there is very little variance in the publication of CCMTs, recording a high of 7% in 2005 and a low of 1% in 2002 and a consistent 2–3% over the last decade.

On average, Oil & Gas Producers are publishing an average of 14.4 CCMTs/year and Service Providers are publishing 6.9 CCMTs/year. Regionally, producers in the United States are generating the greatest number of high-value CCMTs with an average of 24.4 CCMTs/year. European producers are delivering 13.0 CCMTs/year, while the two Chinese producers have the lowest number at 2.1 CCMTs/year.

Perhaps the most striking results shown in Table 3.2 are the regional comparisons between O&G Producers in Europe and the United States. European Producers demonstrate an average of 21% of all patents as Climate Change Mitigation Technology (CCMT) compared with 17% for American Producers. On the other hand, American Producers are more prolific overall than European Producers (8,454 to 4,858) and produce a greater number of CCMT patents in total (1,465 to 1,043, respectively). The yearly data indicates that there is greater yearly variance in the publication of CCMTs for European Producers; they have a high of 31% and a low of 10%, in contrast to American Producers with a high of 25% and a low of 8% in 2019.

The results for the two Chinese Producers show a far lower count for Total Patent Families and CCMT Patent Families. As discussed in the previous section, there is likely some bias based on the selection of patent families used in the search criteria. At the same time, it is interesting that the combined percentages for these two producers closely align with the overall results for both European and American Producers. Chinese Producers are showing an average 18% of patents as CCMTs, with a variant yearly total ranging from a high of 52% in 2008 to a low of 0% in 2000, 2004 and 2006.

3.4.3 Number of CCMT Patents for All O&G Companies

Figure 3.1, shown below, displays the results for the total number of CCMT patent families published each year, recognizing the constraints and limitations of this study.

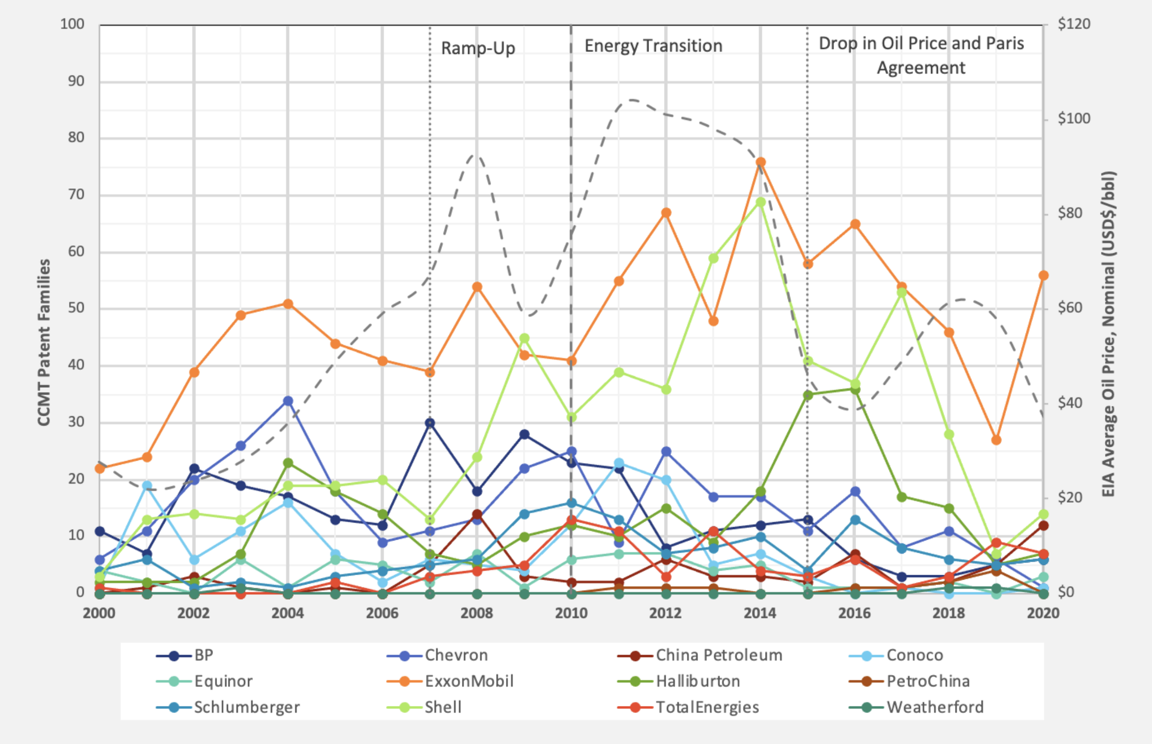


Figure 3.1: Number of Climate Change Mitigation Technology (CCMT) Patent Families for All O&G Companies, 2000–2020. Curves show the number of published CCMT patent families by both the USPTO and either the EPO or the WIPO with reference to the Energy Transition. Source: Based on EIA, IRI, and EPO/USPTO data.

Several generalized observations are possible based on these results:

- From 2000 to 2014, companies are publishing between 10–20 CCMT patent families per year, with outliers producing none and others publishing 35–55 patent families.
- There is trending that indicates an increase in CCMT patenting, which coincides with both the increase in oil price and the rough kick-off of the Energy Transition.

- Most companies exhibit a peak in CCMT patenting between 2008 and 2014, and then CCMTs generally drop following the decrease in global oil price in 2014–2015.
- The patenting trends of several companies appear to graphically indicate a "lag" to previous years with a higher oil price. For example, it is possible that the 2014 CCMT patenting results for either Exxon (Orange) or Shell (Light Green) "lag" back to 2011 or 2012.
- CCMT patenting decreased during the period of 2014/2015 and 2019 with indications of increased CCMT activity in 2020. As will be shown later in Chapter 6, this exhibited trend in the Oil & Gas industry largely follows global trends in total CCMT patenting across all industries and companies (EPO/IEA, 2021).
- There are no pronounced differences between the average patenting trends by European Producers and American Producers. The data shows that American Producers are publishing CCMT patent families on par with European Producers. The two Chinese producers show low CCMT patenting but with an increase overall in the last several years of this study.
- Service Providers are publishing far less CCMT patents than Producers. This trend is shown in Figure 3.2, which is a close-up of the European and American Producers.

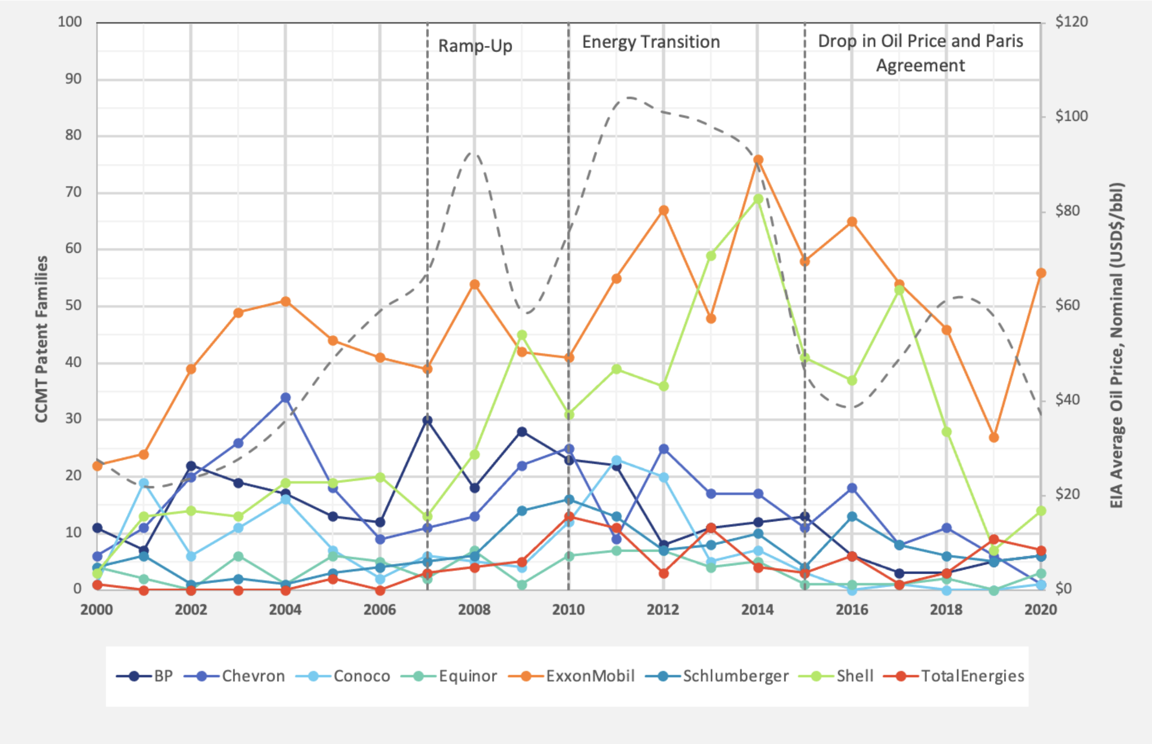


Figure 3.2: Number of Climate Change Mitigation Technology (CCMT) Patent Families for O&G Producers (No China), 2000–2020. Curves show the number of published CCMT patent families by both the USPTO and either the EPO or the WIPO with reference to the Energy Transition. The dashed gray line depicts the price of oil over the same time. Source: Based on EIA, IRI, and EPO/USPTO data.

3.4.4 Percentage of CCMT Patents for All O&G Companies

Much like the issue of scaling discussed in Chapter 2 which arises when comparing budgets for R&D Expenditure between companies or countries, it should be noted the total CCMT patenting count as shown in the previous Figure 3.1 can overstate the relative commitment to CCMT by companies of different size and market share. For this reason, it may be instructive to view compiled data for CCMT as the percentage of CCMT Patents to Total Patents for each given year. Here, the calculated percentage of CCMT patents to Total patent families can normalize the relative output achieved by a company. These results are shown below in Figure 3.3:

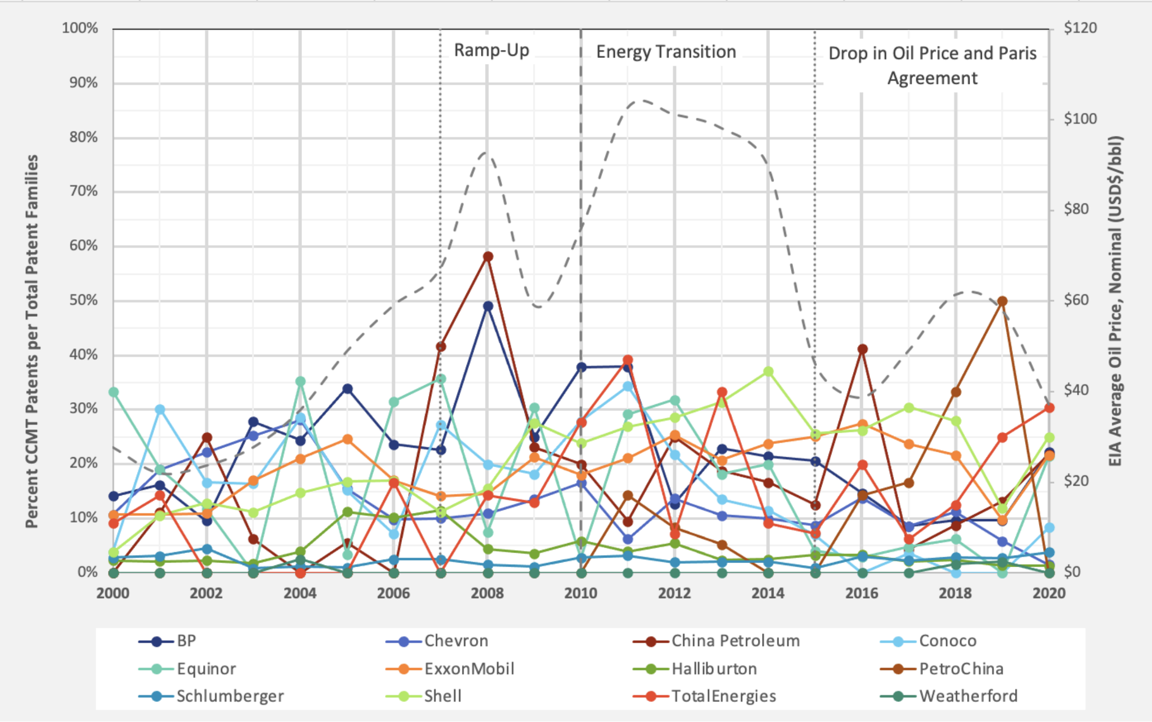


Figure 3.3: Percent of Climate Change Mitigation Technology (CCMT) Patent Families for All O&G Companies, 2000–2020. Curves show the percentage of published CCMT patent families by the USPTO and either the EPO or the WIPO as compared to the total patent families published with reference to the Energy Transition. Source: Based on EIA, IRI, and EPO/USPTO data.

Key generalized findings include:

- On average, All Oil & Gas Companies have produced between 10% to 20% of their total high-value, international patent families as Climate Change Mitigation Technology (CCMT).

- The normalized metric of percent CCMT to total patents shows an affinity in patent publication between companies.

- In general, percentage of CCMT patenting increases as oil price increases. This trend can be clearly noted in curves from Conoco (Light Blue), Shell (Light Green), and BP (Dark Blue).

- The percentage of CCMT patenting drops with decreasing oil prices in 2014/2015, however the impact of oil price on percent CCMT is less pronounced than for Total Patents in Figure 3.1. This is due to a general decrease in all patenting activity during periods of lower oil price.

- One possible explanation for the increase in CCMT in 2008 for both China Petroleum (Rust Red) and BP (Dark Blue) is that, as oil prices increased up through 2008, previously completed Research and Development (R&D) may have been filed as an international patent family based on higher oil prices.

- The time period following the decrease in oil prices in 2014/2015 exhibits some degree of changing trends between companies. Graphically, it is possible to contend that the slump in percentage of CCMT patenting in 2019 "lags" back to the general oil-price slump of 2015/2016, resulting in approximately a 3-year lag in percent CCMT to oil price.

- The data shows no stark difference between the percent CCMT patents between European and American Oil & Gas Producers. A close-up of these producers is shown in Figure 3.4, following.

- Service Providers have produced a lower percentage of CCMT patents when compared with Producers. All three Service Providers show a ratio of CCMT to total patents under 5% for the time period in this study. For most years in this specific patent study, Weatherford (Dark Blue-Green) produced zero percent of their patents as CCMT.

- The percent CCMT patenting trends of the two Chinese companies are intriguing. It should be noted the relatively small amount of overall patent families (as discussed above) can skew these results. That said, there is indication that the two Chinese Oil & Gas companies have increased the percentage output of CCMT patents. As will be shown below, these CCMT patents are in technology areas distinct from Oil & Gas Producers in Europe and the US.

- As a normalized metric, Percent CCMT to Total Patents can serve as a new, powerful metric for companies to track, expand and benchmark their Climate Change Mitigation Technology (CCMT) activities.

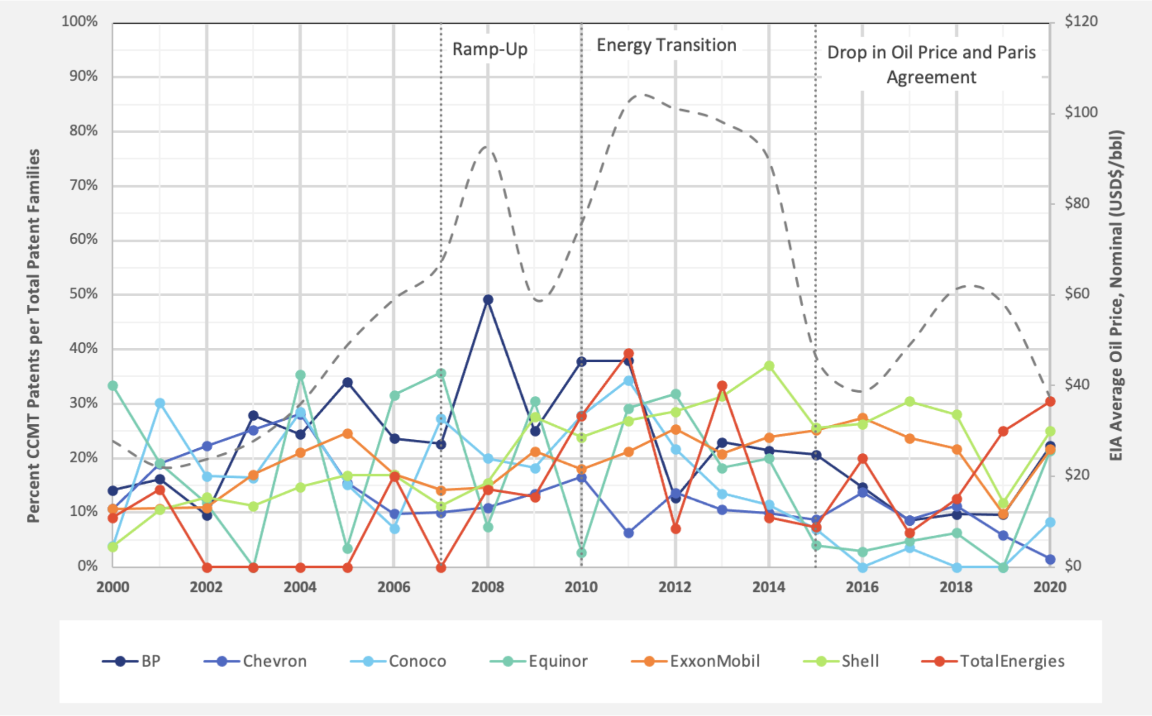


Figure 3.4: Percent of Climate Change Mitigation Technology (CCMT) Patent Families for O&G Producers (No China), 2000–2020. Curves show the percentage of published CCMT patent families by the USPTO and either the EPO or the WIPO as compared to the total patent families published with reference to the Energy Transition. Source: Based on EIA, IRI, and EPO/USPTO data.

3.5 CCMT Focus Areas by Company, Sector and Region

This section expands on the advantages of aggregating CCMT tags across companies, sectors and regions. Here, the Y02–Y04S tagging schema is used to highlight the primary areas of technological concentration for CCMTs in the Oil & Gas industry.

A novel method to display the aggregated technological focus areas for an industry is developed. A previous example of this approach to analyzing the CCMT focus areas of an industry was not found in the literature, to the best of the author's knowledge.

Analysis of CCMT technology focus areas can reveal indications of sector specialization, niche skills, competitive advantage, and strategic technology management. Here it is informative to introduce the concept of Revealed Technological Advantage (RTA). Traditionally, RTA is utilized by governments seeking to quantify their technological comparative advantage in relation to the technology progress in other countries to assess strengths and weaknesses (EPO/IEA, 2021). The EPO and IEA (2021) formally define Revealed Technology Advantage as:

> “An RTA is defined as a country’s share of IPFs in a particular field of technology divided by the country’s share of IPFs in all fields of technology.... The RTA index indicates a country’s relative specialization in a given technology innovation in relation to other countries” (EPO/IEA, 2021, p. 56).

The value of this concept is the development of a quantitative method that can be used to evaluate the "relative specialization" between technology competitors. Although this formal definition is applied to countries and regions, it is reasonable to extrapolate this concept to highlighting the RTA of companies.[6] For this work, the concept of Revealed Technological Advantage (RTA) is applied broadly through association of the percentage of Climate Change Mitigation Technology (CCMT) patents with a unique Y02–Y04 tag in relation to their total CCMT and Total patenting activity. Building on the language of the EPO and IEA, this level of detail can highlight "relative strengths" in specific CCMT focus areas and indicate an "overall capacity for innovation" (EPO/IEA, 2021).

3.5.1 Methodology for CCMT Focus Areas

The combined data from the Espacenet patent search was filtered to sort the prevalence of specific Y02–Y04S tags in the Cooperative Patent Classification (CPC) system. For this study, Y02–Y04S tags were sorted at the Main Group level and not the Subgroup level to increase the statistical relevance of each group. However, future studies in other industries may find reason to sort at the Subgroup level depending on the population size and detail of the available data. It should be noted that the author will use the Subgroup level as will be described in Chapter 4 when exploring "Sustaining" and "Disruptive" technologies.

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[6] This research will not calculate an RTA index as described by EPO/IEA (2021), although such an analysis is possible and recommended for internal company benchmarking (see Recommendations for Future Work in Chapter 8).

3.5.2 Results for CCMT Focus Areas by Company

The collected CCMT Focus Areas by company are documented in Appendix F. These tables record the overall prevalence for the top ten Y02–Y04 tags by company. Listed on each table is the CPC reference code, official CPC definition, and the Total Number of Y02–Y04S tags between 2000–2020. Additionally, two calculated percentages are included. First, the percent prevalence of the specific Y02–Y04 tag to all Y02–Y04 tags by the specific company (Y02–Y04S Tags to All Tags). Second, the prevalence of the specific Y02–Y04 tag to all patent families (Y02–Y04S Tags to All Patents). The twelve tables include: BP (Table F.1), Chevron (Table F.2), China Petroleum (Table F.3), Conoco (Table F.4), Equinor (Table F.5), Exxon (Table F.6), Halliburton (Table F.7), PetroChina (Table F.8), Schlumberger (Table F.9), Shell (Table F.10), Total (Table F.11), and Weatherford (Table F.12).

3.5.3 Results for CCMT Focus Areas by Industry

Table 3.3 presents the occurrence of all CPC Codes at the Main Group level for all twelve companies in the research. The official CPC Definition of the given CPC Code is provided for insight into the technological focus areas. Finally, the Combined Count shows the total number of CCMT patents for this CPC Code, along with the percentage of occurrence among the top occurring CCMTs.

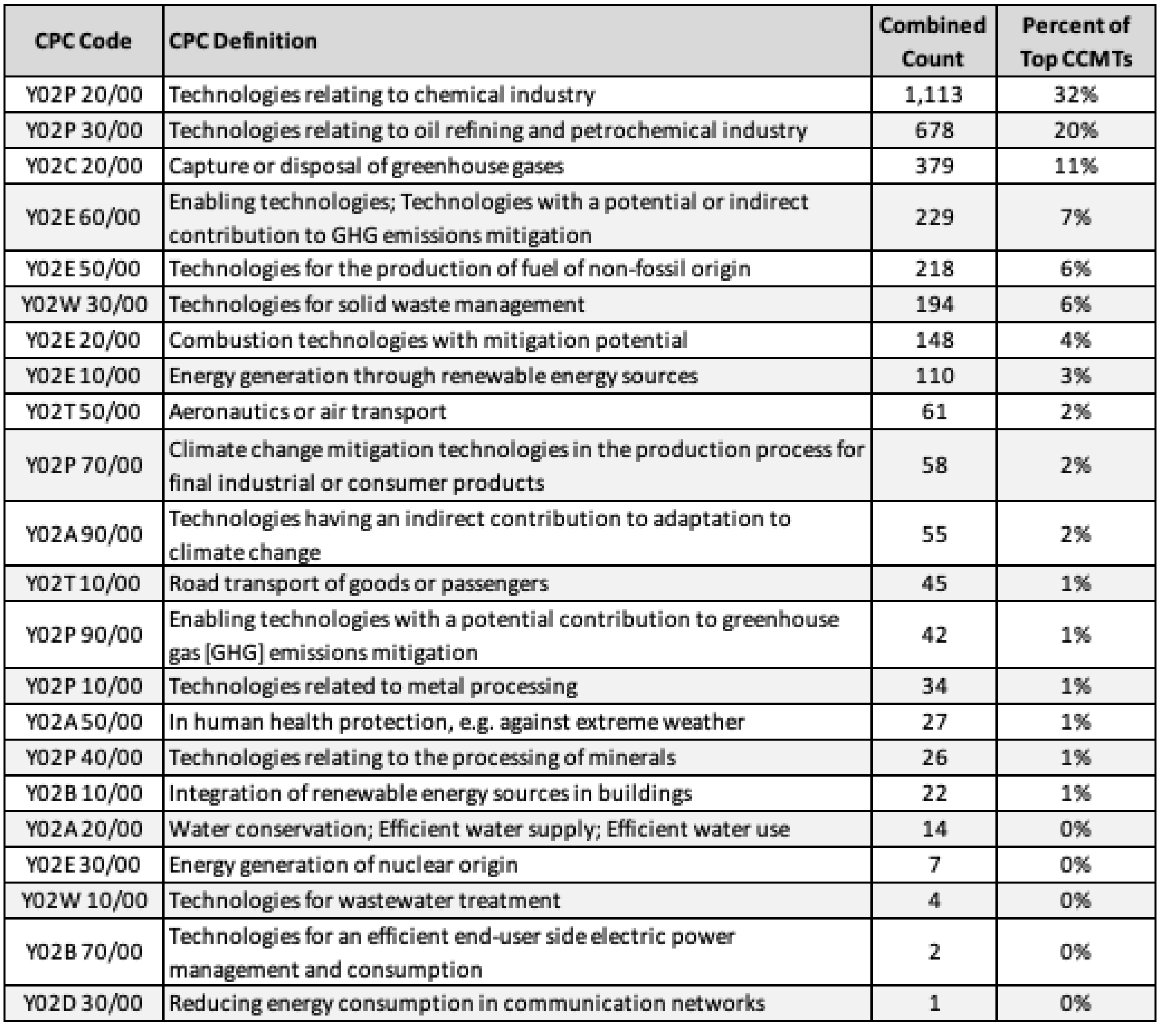
The top occurring CPC Code for the Oil & Gas industry is Y02P 20/00, or Technologies relating to chemical industry, at 32% of all CCMT patents for the test sample between 2000–2020. The Y02P 20/00 Main Group is one of the largest and most detailed Main Groups in the CPC Y02–Y04S schema with 19 listed Subgroups (Cooperative Patent Classification, n.d.-c). Several examples of Climate Change Mitigation Technology (CCMT) covered by Y02P 20/00 include:

- Y02P 20/10: Process efficiency.
- Y02P 20/129: Energy recovery, e.g., by cogeneration, H_2 recovery or pressure recovery turbines.
- Y02P 20/143: Feedstocks; the feedstock being recycled material, e.g., plastics.
- Y02P 20/151: Reduction of greenhouse gas [GHG] emissions, e.g., CO_2.

- Y02P 20/52: Improvements relating to the production of bulk chemicals using catalysts, e.g., selective catalysts.

At 20% of CCMT patents, Y02P 30/00 defines Climate Change Mitigation Technology as "Technologies relating to oil refining and petrochemical industry" (Cooperative Patent Classification, n.d.-b). A relatively small Main Group with only two Subgroups, Y02P 30/00 covers CCMT related to bio-feedstocks and ethylene production (Cooperative Patent Classification, n.d.-b).

The third most prevalent Climate Change Mitigation Technology (CCMT) for the Oil



CPC Code	CPC Definition	Combined Count	Percent of Top CCMTs
Y02P 20/00	Technologies relating to chemical industry	1,113	32%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	678	20%
Y02C 20/00	Capture or disposal of greenhouse gases	379	11%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	229	7%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	218	6%
Y02W 30/00	Technologies for solid waste management	194	6%
Y02E 20/00	Combustion technologies with mitigation potential	148	4%
Y02E 10/00	Energy generation through renewable energy sources	110	3%
Y02T 50/00	Aeronautics or air transport	61	2%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	58	2%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	55	2%
Y02T 10/00	Road transport of goods or passengers	45	1%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	42	1%
Y02P 10/00	Technologies related to metal processing	34	1%
Y02A 50/00	In human health protection, e.g. against extreme weather	27	1%
Y02P 40/00	Technologies relating to the processing of minerals	26	1%
Y02B 10/00	Integration of renewable energy sources in buildings	22	1%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	14	0%
Y02E 30/00	Energy generation of nuclear origin	7	0%
Y02W 10/00	Technologies for wastewater treatment	4	0%
Y02B 70/00	Technologies for an efficient end-user side electric power management and consumption	2	0%
Y02D 30/00	Reducing energy consumption in communication networks	1	0%

Table 3.3: Ranked CCMT Focus Areas for All O&G Companies, 2000–2020. Table shows the ranked prevalence and percentage of top Y02–Y04 classifications for all CCMT patent families compiled from the twelve companies in the study. Source: Based on EPO and USPTO data from the Espacenet patent database.

& Gas industry based on results in the study is Y02C 20/00, Capture or disposal of greenhouse gases. At 11% of all CCMT patents, this group is focused on the capture, storage, sequestration or disposal of greenhouse gasses (GHG), including nitrous oxide (N2O), methane, and CO2. In this study, the vast majority of the 678 CCMT patents for this CPC Code fall under the Subgroup Y02C 20/40 for the capture or disposal of CO2.

It is interesting that Y02E 60/00 for "Enabling Technology in relation to energy generation and transmission" is the fourth most common CPC Code for overall CCMT in the Oil & Gas industry. Defined as "Technologies with a potential or indirect contribution to GHG emissions mitigation", these technologies account for 7% of published CCMT patent families. Globally, the EPO and IEA have noted an increased publication in enabling technologies (EPO/IEA, 2021). Key technology focus areas include:

- Y02E 60/10: Energy storage using batteries
- Y02E 60/30: Hydrogen technology
- Y02E 60/36: Hydrogen production from non-carbon containing sources, e.g., by water electrolysis
- Y02E 60/50: Fuel cells.

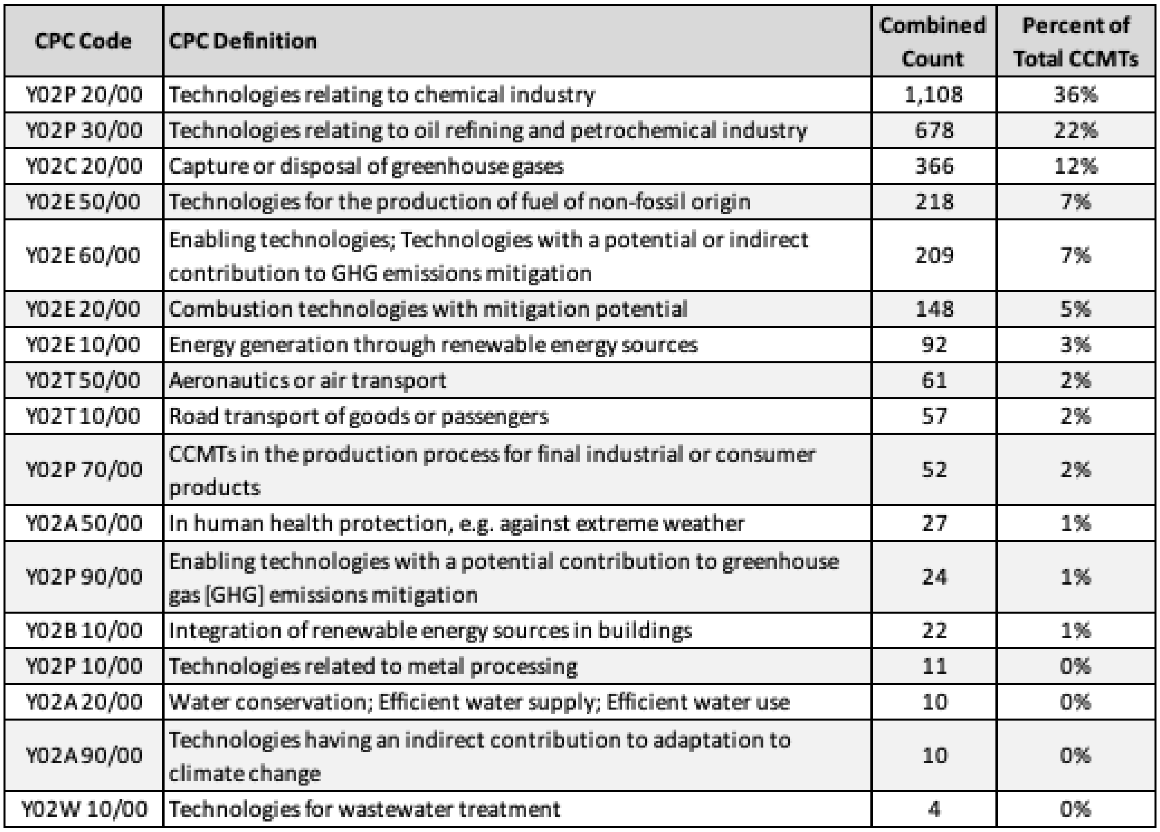
The fifth focus area for the Oil & Gas industry in Climate Change Mitigation Technology (CCMT) is CPC Code Y02E 50/00, Technologies for the production of fuel of non-fossil origin (6%). This CPC group includes technologies that focus on bio-fuels (including biodiesels) and also the generation of fuel from waste (including synthetic alcohol and diesel).

Rounding out the top ten most common technology focus areas for the Oil & Gas industry are: (6) Y02W 30/00: Technologies for solid waste management (6%); (7) Y02E 20/00: Combustion technologies with mitigation potential (4%); (8) Y02E 10/00: Energy generation through renewable energy sources (3%); (9) Y02T 50/00: Aeronautics and air transport (2%); and, (10) Y02P 70/00: Climate change mitigation technologies in the production process for final industrial or consumer products (2%). Here, it is worth highlighting that the category Y02T 50/00: Aeronautics and air transport CCMT is used predominantly for patenting wind turbines and associated technology to support wind-power generation.

3.5.4 Results for CCMT Focus Areas by O&G Producers

Next, this method was replicated for both O&G Producers and O&G Service Providers to identify the similarities and differences in the technology focus areas of these two sectors. Shown below in Table 3.4 are the collected technology focus areas for O&G Producers.

There is little change in the overall CCMT technology focus areas for Producers than those listed in the combined results in Table 3.3. As expected, this is due to the overall low publication of CCMT patent families by O&G Service Providers as shown in 3.2.



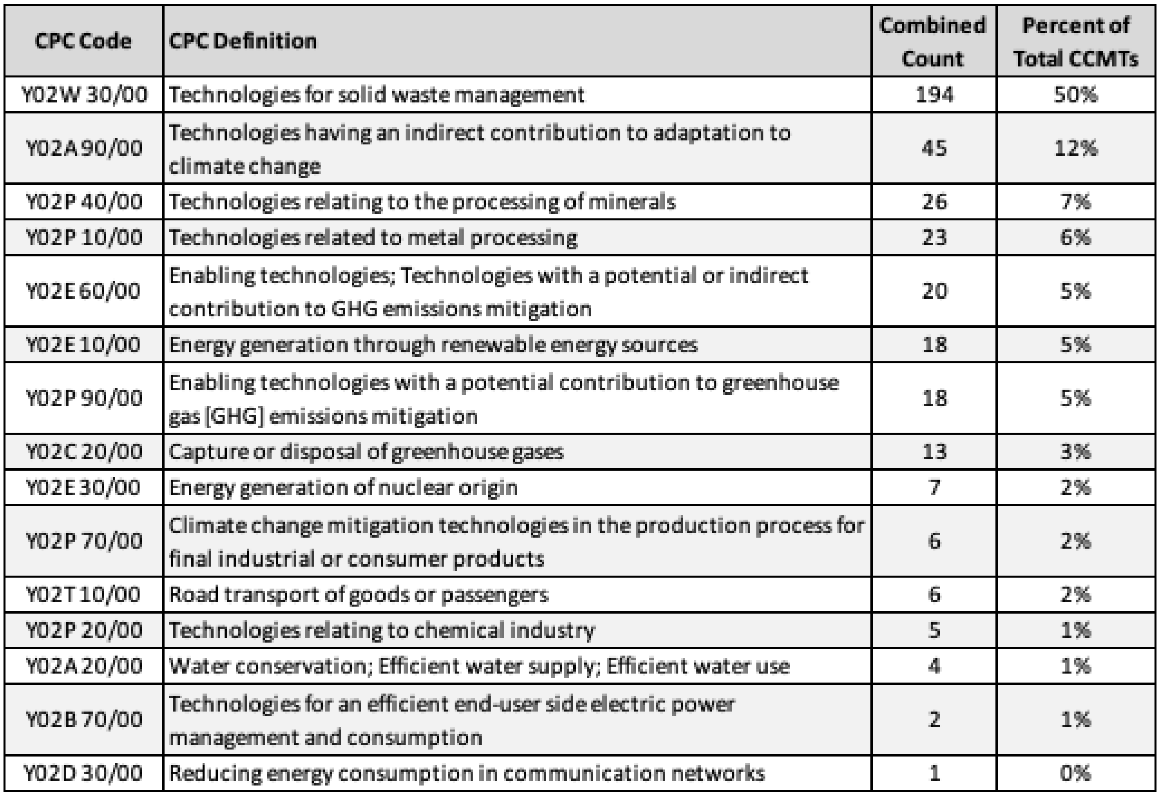
CPC Code	CPC Definition	Combined Count	Percent of Total CCMTs
Y02P 20/00	Technologies relating to chemical industry	1,108	36%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	678	22%
Y02C 20/00	Capture or disposal of greenhouse gases	366	12%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	218	7%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	209	7%
Y02E 20/00	Combustion technologies with mitigation potential	148	5%
Y02E 10/00	Energy generation through renewable energy sources	92	3%
Y02T 50/00	Aeronautics or air transport	61	2%
Y02T 10/00	Road transport of goods or passengers	57	2%
Y02P 70/00	CCMTs in the production process for final industrial or consumer products	52	2%
Y02A 50/00	In human health protection, e.g. against extreme weather	27	1%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	24	1%
Y02B 10/00	Integration of renewable energy sources in buildings	22	1%
Y02P 10/00	Technologies related to metal processing	11	0%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	10	0%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	10	0%
Y02W 10/00	Technologies for wastewater treatment	4	0%

Table 3.4: Ranked CCMT Focus Areas for O&G Producers, 2000–2020. Table shows the ranked prevalence and percentage of top Y02–Y04 classifications for all CCMT patent families compiled from the nine Oil & Gas Producers in the study. Source: Based on EPO and USPTO data from the Espacenet patent database.

In the top five, Y02E 50/00: Technologies for the production of fuel of non-fossil origin advances from fifth spot to fourth spot (7%). Y02E 60/00 Enabling technologies moves closely to number five (7%). Tellingly, Y02W 30/00: Technologies for solid waste management drops out of the top, as this is a top technology focus area for Service Providers. But, again, this represents only a marginal increase in understanding of the technology focus areas of Producers due to the low CCMT output of Service Providers.

3.5.5 Results for CCMT Focus Areas by O&G Service Providers

There are noticeable differences between the technology focus areas of Service Providers and the Producers. As shown below in Table 3.5, Service Providers publish not only a lower number of CCMT patent families but also in different CPC Codes.



CPC Code	CPC Definition	Combined Count	Percent of Total CCMTs
Y02W 30/00	Technologies for solid waste management	194	50%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	45	12%
Y02P 40/00	Technologies relating to the processing of minerals	26	7%
Y02P 10/00	Technologies related to metal processing	23	6%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	20	5%
Y02E 10/00	Energy generation through renewable energy sources	18	5%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	18	5%
Y02C 20/00	Capture or disposal of greenhouse gases	13	3%
Y02E 30/00	Energy generation of nuclear origin	7	2%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	6	2%
Y02T 10/00	Road transport of goods or passengers	6	2%
Y02P 20/00	Technologies relating to chemical industry	5	1%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	4	1%
Y02B 70/00	Technologies for an efficient end-user side electric power management and consumption	2	1%
Y02D 30/00	Reducing energy consumption in communication networks	1	0%

Table 3.5: Ranked CCMT Focus Areas for O&G Service Providers, 2000–2020. Table shows the ranked prevalence and percentage of top Y02–Y04 classifications for all CCMT patent families compiled from the three O&G Service Providers in the study. Source: Based on EPO and USPTO data from the Espacenet patent database.

At 50% of all CCMT patents, Y02W 30/00 dominates the technology landscape for Service Providers. Y02W 30/00 represents Climate Change Mitigation Technology (CCMT) related to technologies for solid waste management. This CPC Main Group is quite extensive with 18 unique subgroups. For the Oil & Gas Service Providers in this study the vast majority of the Y02W 30/00 patents fall under the Subgroup Y02W 30/91: Use of waste materials as fillers for mortars or concrete. Generally, these CCMT patents are related to innovations in cementing technologies utilized for securing and safeguarding hydrocarbon wells.

3.6 Key Takeaways

This chapter covered a large amount of ground. It introduced the CPC's Y02–Y04S schema, outlined the research methodology for conducting the patenting search, presented the CCMT results, and highlighted the key CCMT Focus Areas by company, sector and region. The key takeaways are summarized below:

1. Published international patent families are an ideal proxy for quantifying high-quality technological innovation, enabling normalized comparison between companies, industries and countries.

2. The CPC's Y02–Y04S classification system is a powerful tool for R&D trends in Climate Change Mitigating Technologies and for improved technology management benchmarking.

3. There is wide variability in the distribution of CCMT patenting activity between individual companies, sectors and regions. Overall, the Oil & Gas industry is producing near 11% of total technology patenting on Climate Change Mitigating Technologies.

4. Nearly 19% of all yearly technological innovation by O&G Producers is Climate Change Mitigating Technology (CCMT). In contrast, O&G Service Providers are patenting just under 3% as CCMTs.

5. Oil & Gas Producers are publishing an average of 14.4 CCMTs/year and Service Providers are publishing 6.9 CCMTs/year. Overall, O&G Producers publish a total higher count of CCMT patents than O&G Service Providers, delivering 2,592 CCMTs out of a total of 3,006 CCMT patent families. This finding shows that while O&G

Service Providers continue to produce more total patents this generalization is not true for CCMT patenting.

6. Regionally, O&G Producers in the United States are generating the highest number of high-value CCMTs with 24.4 CCMTs/year, followed by European producers at 13.0 CCMTs/year, and Chinese producers at 2.1 CCMTs/year. However, European Producers are producing a higher relative percentage of CCMTs per year (21%) compared to US Producers (17%) and Chinese Producers (18%). This finding advances the results of previous work by showing that the dominant position of the United States in technological innovation also includes Climate Change Mitigating Technologies.

7. The top three prevalent Y02–Y04 tags for CCMTs are Y02P 20/00: Technologies relating to chemical industry (32% of total CCMTs), Y02P 30/00: Technologies relating to oil refining and petrochemical industry (20%), and Y02C 20/00: Capture or disposal of greenhouse gases (11%).

8. Enabling Technology is the fourth most common CCMT Focus Area at 7%, indicating technology that can fast-track future innovation. This finding mirrors broader global patenting trends in CCMT and enabling technologies.

9. O&G Producers broadly exhibit a CCMT Focus Area on Y02E 50/00: Technologies for the production of fuel of non-fossil origin at 7% of total Climate Change Mitigating Technologies. Additionally, both Y02E 10/00: Energy generation through renewable energy sources, and Y02T 50/00: Aeronautics or air transport (wind power) are in the top ten CCMT Focus Areas.

10. The extensive classification system for CCMTs allows close analyses of the technology focus areas and clusters that companies are investing R&D dollars, which can indicate Revealed Technological Advantage (RTA).

Chapter 4

Parsing Patent Data as Sustaining and Disruptive Technologies

This chapter directly builds on the results presented in the previous chapter that exhibited the statistics and technology focus areas for the Climate Change Mitigation Technology (CCMT) in the CPC's Y02–Y04 classification system. In this chapter, a novel method is developed based on the influential terminology of Clayton Christensen (2016; 2013) and Rebecca Henderson and Kim Clark (1990) to further sub-classify the CCMT patent families into "Sustaining" CCMTs and "Disruptive" CCMTs. As will be argued, this method presents a practical yet powerful technique to differentiate the relative technological impact of large patent data sets, particularly in reference to periods of transformative change like the Energy Transition. Importantly, the results of this chapter will also be used in Chapter 5 to perform correlation analysis between the patent types, R&D metrics, and the impact of the price of oil.

4.1 Methodology for Identifying Technologies

4.1.1 Defining Disruptive Technology in the Y02–Y04 Schema

As described in the previous chapter, the Cooperative Patent Classification (CPC) Y02–Y04 schema is an incredibly specific classification system that is jointly managed by the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO). With approximately 250,000 distinct classifications under the system, the taxonomy permits detailed classification of any patented technological innovation (European Patent Office, n.d.-a).

Leveraging this specificity of the Y02–Y04 schema, this research uses a novel method which has been developed to further sub-classify the CCMT and patent families. This approach qualitatively analyzes whether the technological description of each Y02–Y04 subsection matches with the existing base businesses and value chains of the industry in question. Technologies in Y02–Y04 subsections that are predominantly related to the existing business of an industry are labeled *Sustaining CCMT*, while technologies that are generally unrelated are labeled *Disruptive CCMT*.

There is an additional advantage to this method when examining technologies in the Energy Transition: All published patent families in the study that are *not* tagged as Y02–Y04 CCMTs can be also be labeled *Incremental Energy Technology*. The combination of these three types of results in an innovative three-tiered sub-classification for all patent families in the study. These three sub-classes are defined as follows:

1. **Incremental Energy Technology.** Any international patent family that is not tagged with a CPC Y02–Y04 classification. These technologies are not specifically related to the Energy Transition, but may reduce cost, increase efficiency, or support socio-technical systems.
2. **Sustaining CCMT.** A Climate Change Mitigation Technology (CCMT) tagged with a CPC Y02–Y04 classification where the CPC definition for the tag broadly aligns with the core businesses, existing value chains, or established markets of the industry, sector, or company being studied. These technologies are directly related to the Energy Transition.
3. **Disruptive CCMT.** A Climate Change Mitigation Technology (CCMT) tagged with a CPC Y02–Y04 classification where the CPC definition for the tag is meaningfully independent or outside of the core businesses, existing value chains, or established markets of the industry, sector, or company being studied. These technologies are directly related to the Energy Transition.

These three definitions are purposefully broad and are applicable to other studies focused on the Energy Transition, including those outside of the Oil & Gas industry. For example, these definitions could be used for an analysis of the chip manufacturing industry or aviation businesses.

These definitions can accommodate the many types of innovation identified in the technology management literature (de Weck et al., 2011; Schilling, 2020). Using several of the frequent classifications that are included in the Glossary, we can generalize that Sustaining CCMT will likely include some Emerging Technology, significant Incremental Innovation, a majority of Modular Innovation and Architectural Innovation, and occasionally some Radical Innovation that is intertwined with existing value chains or core businesses. Contradistinctively, Disruptive CCMT will predominantly contain Emerging Technology and Radical Innovation. Enabling Technology can be either Disruptive or Sustaining, with a tilt toward Sustaining: Even if an Enabling Technology supports a Disruptive CCMT, it is likely that the underlying Technology Drivers of the enabler is itself not disruptive, perhaps adhering to existing Targets, Milestones and Figures of Merit (FOMs) (de Weck, 2022; de Weck et al., 2011).

This coupling of the proposed definitions with the broader concepts and definitions used in industry and research support that alternative names for these definitions are possible. Perrons & Donnelly (2012) built their prominent case study on innovation in the Oil & Gas industry using the theoretical framework of Leifer et al. (2000) and Henderson & Clark (1990), designing their industry-specific survey with the borrowed terminology of "incremental innovation" and "radical innovation" (Perrons & Donnelly, 2012; Perrons, 2014). This study opted to use the classical terminology from Christensen (2016, 2013) despite the complexities and open questions with the theory of disruptive innovation (A. A. King & Baatartogtokh, 2015; Christensen et al., 2018).[1] Future studies could swap terminology without affecting the outcome of the underlying research method.

The CPC's taxonomy allows for multiple Y02–Y04 tags at the subgroup level (USPTO, n.d.). While it allows for the specificity that defines the schema, it does present an added methodological challenge of numerically counting the "Sustaining CCMT" and "Disruptive CCMT" patent families. As will be detailed below, the study used a simple propor-

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[1] Perrons & Donnelly (2012)'s definition for "radical innovation" in the Oil & Gas industry was highly qualitative and could not be applied to the current focus on R&D metrics and CCMT patenting. Perrons & Donnelly (2012) define "radical innovation" for the Oil & Gas survey: "as a new technology that fulfilled at least one of these criteria: 1) It delivered an entirely new set of performance features to the marketplace that simply were not available before. 2) It brought about an improvement in existing performance features of five times or greater. 3) It delivered a significant (30% or greater) reduction in cost."

tional normalization to account for the effect of known CCMT patent families having potentially both Sustaining and Disruptive tags. Here, a simple ratio of the respective count of "Sustaining" and "Disruptive" tags over the sum of the total tag count was used as a multiplier with the total known CCMT patent count. This approach, though an approximation, enabled an expedient way to differentiate patents with multiple tags while maintaining the known count of total patents and CCMT patents.

There is an added benefit to this approach. Debate on whether to label a technology as "Sustaining" or "Disruptive" will not change the overall count of CCMT patents or the total percentage of CCMT patents to total patents. In this way, as long as the selection of subgroups as Disruptive CCMT or Sustaining CCMT are applied *consistently* to all companies in a research study, the results will provide a uniform comparison of the technology programs.

4.1.2 Limitations

There are several limitations to the proposed method. Foremost, the classification of Y02–Y04 subgroups as either Disruptive or Sustaining requires input and review from Subject Matter Experts (SMEs) familiar with the specific technology of the given industry, sector or company. The selection of the Y02–Y04 subgroups is a largely qualitative process based on an interpretation of the CPC definitions and their relationship to technologies and existing value chains. Thus, it is imaginable that this process could at times be time-intensive, contentious, and political in regards to how different researchers, senior engineers or technologists evaluate the subgroup as Disruptive or Sustaining. Of course, if corporate or business unit performance metrics and/or incentive packages are tied to the number of Sustaining CCMT and Disruptive CCMT, the resources required to reach consensus will likely increase (Bahcall, 2019a; Christensen, 2016).

However, this limitation can be overcome by tracking both the general Cooperative Patent Classification (CPC) Section classification in addition to the Y Section tagging. If, for example, a high percentage of patents are in a subgroup related to an established value chain and established product line, then many innovations in this space are likely sustaining technologies. For this reason, it is reasonable to classify the overall subgroup as Sustaining, even if they might be concurrently described as Modular Innovation or Architectural Innovation under Henderson & Clark's classification system (1990). Here, a reasonability test can go a long way: The proposed qualitative method should raise red flags if a large, proactive SkunkWorks-style R&D laboratory is filtered to have under, say, 2% Disruptive technologies. Likewise, it is unlikely though not impossible, for an underfunded R&D laboratory focused on product-line improvement to produce a large percentage of Disruptive R&D.

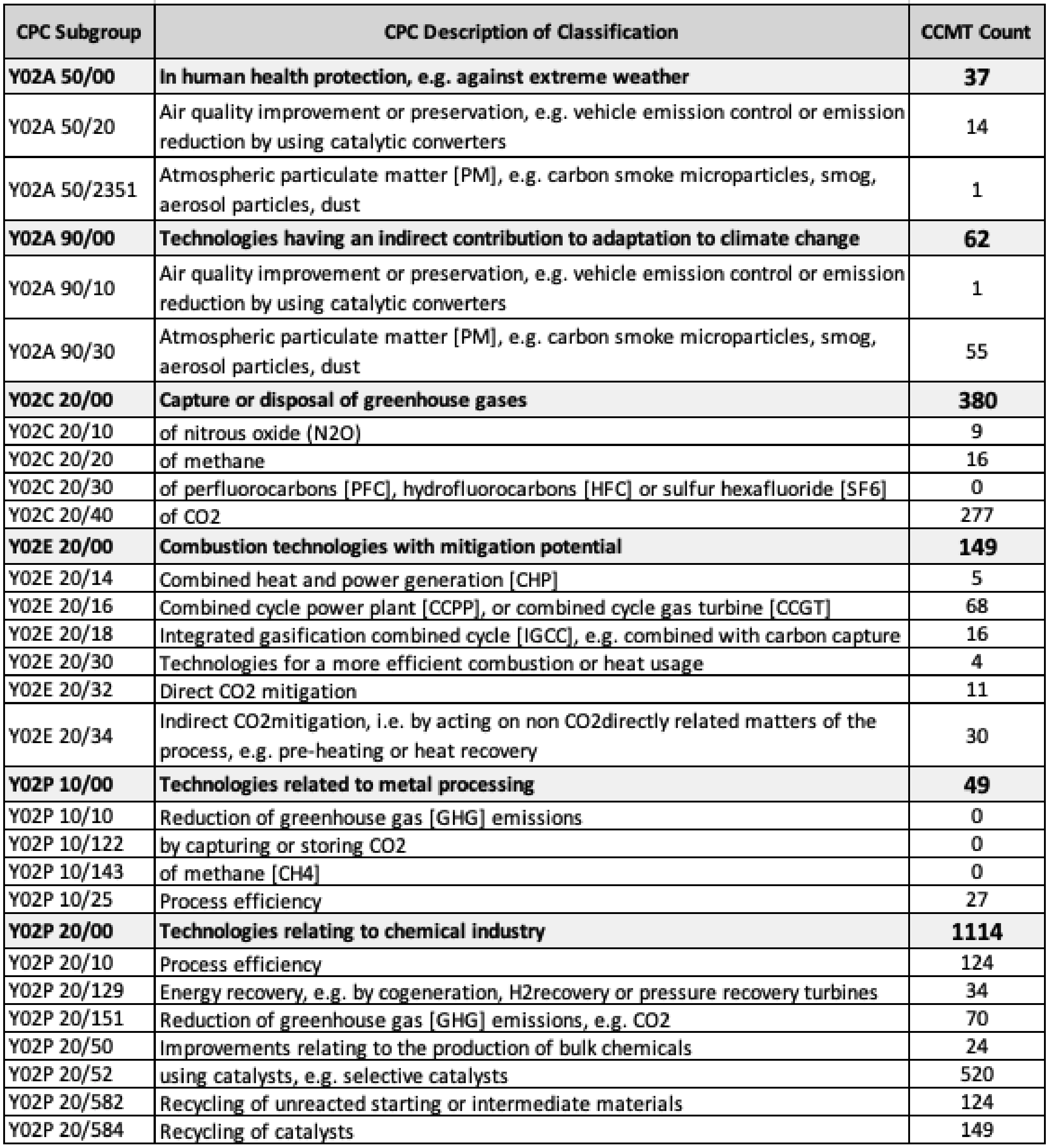
4.1.3 Selection of Sustaining Subgroups for the Oil & Gas Industry

After the patent search and initial data analysis was performed on the patents in Chapter 3, all of the CPC subgroup definitions were reviewed for direct connection to the established base businesses and value chains in the Oil & Gas industry. Second, a comparison of the CPC definitions with the sorted count of the patents was performed to identify areas of strong technology focus and concentration. Third, the individual patent abstracts were verified in Espacenet to confirm whether the CPC definition was best matched with "Sustaining CCMT" or "Disruptive CCMT" relative to the base businesses and value chains of the Oil & Gas industry. If a majority of individual patents in a CPC subgroup were related to base businesses or existing value chains, then the group was identified as "Sustaining CCMT". Conversely, if patents indicated a variability in theme or focus and were broadly in a category unrelated to base business and value chains, then they were tagged "Disruptive CCMT".

For this study of the Oil & Gas industry, there are more CPC subgroups for disruptive technology than for sustaining technology. Listed below in Table 4.1 and Table 4.2 are the final results of evaluating all of the Y02–Y04 subgroups for their generalized relationship to the Oil & Gas industry.

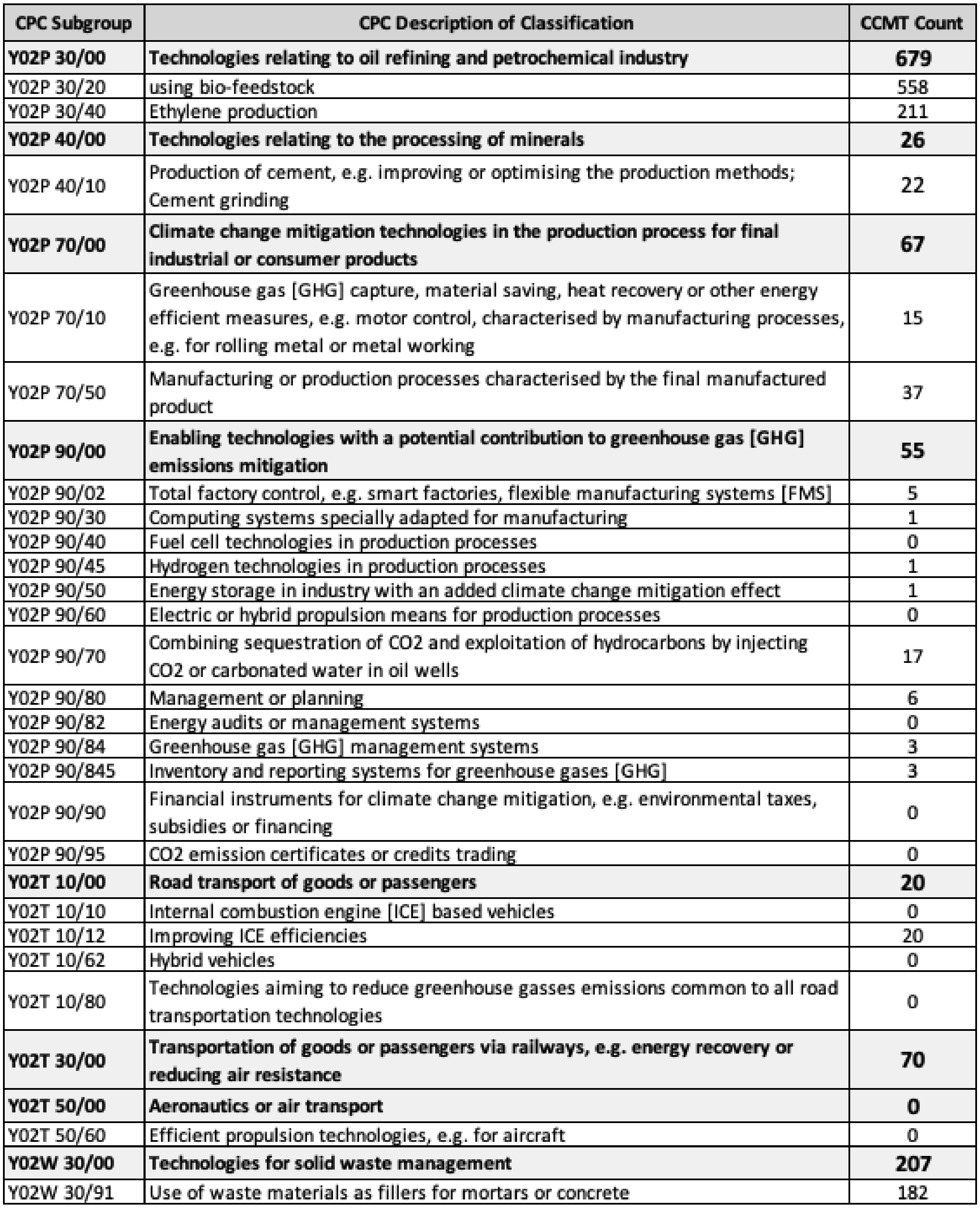
Several key areas of technological research that are classified as "Sustaining" may raise questions on why they are not better tracked as "Disruptive" technologies. Here, the author will explain the evaluations likely to be regarded as contentious:

- **Y02C 20/40: Capture or disposal of Greenhouse Gases – CO_2.** The importance



CPC Subgroup	CPC Description of Classification	CCMT Count
Y02A 50/00	**In human health protection, e.g. against extreme weather**	**37**
Y02A 50/20	Air quality improvement or preservation, e.g. vehicle emission control or emission reduction by using catalytic converters	14
Y02A 50/2351	Atmospheric particulate matter [PM], e.g. carbon smoke microparticles, smog, aerosol particles, dust	1
Y02A 90/00	**Technologies having an indirect contribution to adaptation to climate change**	**62**
Y02A 90/10	Air quality improvement or preservation, e.g. vehicle emission control or emission reduction by using catalytic converters	1
Y02A 90/30	Atmospheric particulate matter [PM], e.g. carbon smoke microparticles, smog, aerosol particles, dust	55
Y02C 20/00	**Capture or disposal of greenhouse gases**	**380**
Y02C 20/10	of nitrous oxide (N2O)	9
Y02C 20/20	of methane	16
Y02C 20/30	of perfluorocarbons [PFC], hydrofluorocarbons [HFC] or sulfur hexafluoride [SF6]	0
Y02C 20/40	of CO2	277
Y02E 20/00	**Combustion technologies with mitigation potential**	**149**
Y02E 20/14	Combined heat and power generation [CHP]	5
Y02E 20/16	Combined cycle power plant [CCPP], or combined cycle gas turbine [CCGT]	68
Y02E 20/18	Integrated gasification combined cycle [IGCC], e.g. combined with carbon capture	16
Y02E 20/30	Technologies for a more efficient combustion or heat usage	4
Y02E 20/32	Direct CO2 mitigation	11
Y02E 20/34	Indirect CO2mitigation, i.e. by acting on non CO2directly related matters of the process, e.g. pre-heating or heat recovery	30
Y02P 10/00	**Technologies related to metal processing**	**49**
Y02P 10/10	Reduction of greenhouse gas [GHG] emissions	0
Y02P 10/122	by capturing or storing CO2	0
Y02P 10/143	of methane [CH4]	0
Y02P 10/25	Process efficiency	27
Y02P 20/00	**Technologies relating to chemical industry**	**1114**
Y02P 20/10	Process efficiency	124
Y02P 20/129	Energy recovery, e.g. by cogeneration, H2recovery or pressure recovery turbines	34
Y02P 20/151	Reduction of greenhouse gas [GHG] emissions, e.g. CO2	70
Y02P 20/50	Improvements relating to the production of bulk chemicals	24
Y02P 20/52	using catalysts, e.g. selective catalysts	520
Y02P 20/582	Recycling of unreacted starting or intermediate materials	124
Y02P 20/584	Recycling of catalysts	149

Table 4.1: Selection of Sustaining Technologies to Define Disruptive Technologies in CPC Y02–Y04 Schema (1 of 2). These two tables document the CCMTs directly related to the base businesses, existing value chains and established markets for the Oil & Gas industry. All other CPC Y02–Y04 tags are classified as Disruptive Technologies for this industry. Source: Based on EPO and USPTO data from the Espacenet patent database.



CPC Subgroup	CPC Description of Classification	CCMT Count
Y02P 30/00	**Technologies relating to oil refining and petrochemical industry**	**679**
Y02P 30/20	using bio-feedstock	558
Y02P 30/40	Ethylene production	211
Y02P 40/00	**Technologies relating to the processing of minerals**	**26**
Y02P 40/10	Production of cement, e.g. improving or optimising the production methods; Cement grinding	22
Y02P 70/00	**Climate change mitigation technologies in the production process for final industrial or consumer products**	**67**
Y02P 70/10	Greenhouse gas [GHG] capture, material saving, heat recovery or other energy efficient measures, e.g. motor control, characterised by manufacturing processes, e.g. for rolling metal or metal working	15
Y02P 70/50	Manufacturing or production processes characterised by the final manufactured product	37
Y02P 90/00	**Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation**	**55**
Y02P 90/02	Total factory control, e.g. smart factories, flexible manufacturing systems [FMS]	5
Y02P 90/30	Computing systems specially adapted for manufacturing	1
Y02P 90/40	Fuel cell technologies in production processes	0
Y02P 90/45	Hydrogen technologies in production processes	1
Y02P 90/50	Energy storage in industry with an added climate change mitigation effect	1
Y02P 90/60	Electric or hybrid propulsion means for production processes	0
Y02P 90/70	Combining sequestration of CO2 and exploitation of hydrocarbons by injecting CO2 or carbonated water in oil wells	17
Y02P 90/80	Management or planning	6
Y02P 90/82	Energy audits or management systems	0
Y02P 90/84	Greenhouse gas [GHG] management systems	3
Y02P 90/845	Inventory and reporting systems for greenhouse gases [GHG]	3
Y02P 90/90	Financial instruments for climate change mitigation, e.g. environmental taxes, subsidies or financing	0
Y02P 90/95	CO2 emission certificates or credits trading	0
Y02T 10/00	**Road transport of goods or passengers**	**20**
Y02T 10/10	Internal combustion engine [ICE] based vehicles	0
Y02T 10/12	Improving ICE efficiencies	20
Y02T 10/62	Hybrid vehicles	0
Y02T 10/80	Technologies aiming to reduce greenhouse gasses emissions common to all road transportation technologies	0
Y02T 30/00	**Transportation of goods or passengers via railways, e.g. energy recovery or reducing air resistance**	**70**
Y02T 50/00	**Aeronautics or air transport**	**0**
Y02T 50/60	Efficient propulsion technologies, e.g. for aircraft	0
Y02W 30/00	**Technologies for solid waste management**	**207**
Y02W 30/91	Use of waste materials as fillers for mortars or concrete	182

Table 4.2: Selection of Sustaining Technologies to Define Disruptive Technologies in CPC Y02–Y04 Schema (2 of 2). These two tables document the CCMTs directly related to the base businesses, existing value chains and established markets for the Oil & Gas industry. All other CPC Y02–Y04 tags are classified as Disruptive Technologies for this industry. Source: Based on EPO and USPTO data from the Espacenet patent database.

of technologies that capture or dispose of GHG cannot be understated for the Energy Transition. The IEA states that Carbon Capture, Utilization, and Storage (CCUS) technology must play a "substantial and varied role" in meeting all net-zero targets, contributing to nearly 15% of cumulative reduction of CO_2 (IEA, 2020, p. 103). Even as a critical CCMT, this study classifies Y02C 20/40 as "sustaining CCMT" because the Oil & Gas industry has been a key innovator in developing existing CCUS technology.

- **Y02E 20/16: Combined cycle power plant (CCPP) or combined cycle gas turbine (CCGT)**. Technologies in this subgroup can increase the efficiency of gas-powered turbines by over 60% resulting in reduced cost and GHG (General Electric, 2017). Even as a critical CCMT, this study classifies Y02E 20/16 as "sustaining CCMT" since the Oil & Gas industry has been a key innovator in developing existing CCPP and CCGT technology.

- **Y02P 20/52: Technologies relating to the chemical industry–using catalysts, e.g. selective catalysts**. These Climate Change Mitigation Technology (CCMT) are predominantly related to improved, environmental methods for processing, recycling and utilizing catalysts. This study classifies Y02P 20/52 as "sustaining CCMT" because the Oil & Gas industry has been a key innovator in developing existing chemical and catalyst technology.

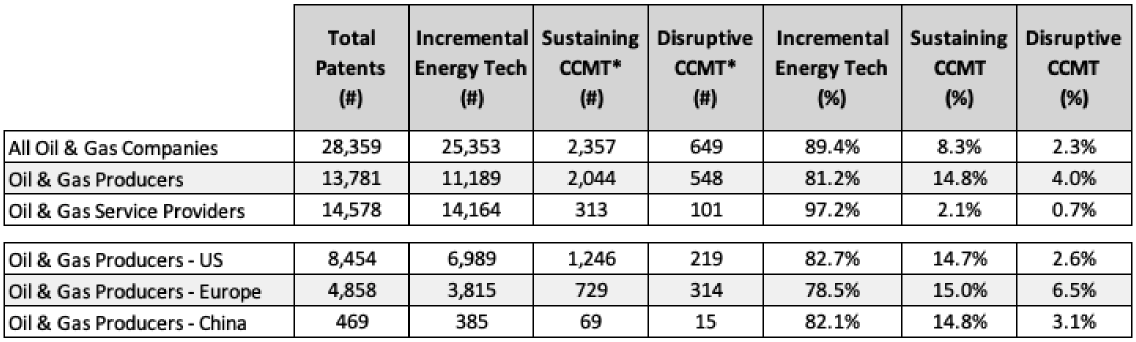
This sub-classification of technologies is neither exact nor absolute. It is important to note that the selection of Sustaining CCMT and Disruptive CCMT can evolve over time—it is not unreasonable for technologies considered as "sustaining" to be later grouped as "disruptive" if there is a shift in the technology landscape. The primary value of this tool is to provide additional differentiation across an industry or sector. Methodologically, it is critical to apply the same selection to all companies, sectors, or geographic regions in the study.

4.2 Results for Sustaining and Disruptive Technologies

Before examining the results of sorted patents into Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT, several high-level notes are in order:

- The count of Total Patents and CCMT Patents is based on IPFs as described in Chapter 3. This number does not represent the total number of all patents awarded.
- Total Patents is equal to the sum of Incremental Energy Tech, Sustaining CCMT and Disruptive CCMT.
- CCMT patents can have multiple Y02–Y04 tags, including those classed as Sustaining CCMT, and Disruptive CCMT. To adjust for this tagging, the patent count for each was proportionally normalized based on total Y02–Y04 tags for a given year. In the following charts, both Sustaining CCMT and Disruptive CCMT are marked by an asterisk (*).

Table 4.3 shows the collected results for all twelve companies in this study over the time period of 2000–2020. Based on the methodology detailed in Chapter 3 and this chapter, all twelve companies in this study show an aggregate of 28,303 Total Patents of which 25,297 are Incremental Energy Tech, 2,357 are Sustaining CCMT and 649 are Disruptive CCMT. With the cohort of twelve companies as a proxy for the larger Oil & Gas industry, we can report the finding that 10.6% of total international patent families are Climate Change Mitigation Technology (CCMT) of which 8.3% are Sustaining CCMT and 2.3% are Disruptive CCMT.



	Total Patents (#)	Incremental Energy Tech (#)	Sustaining CCMT* (#)	Disruptive CCMT* (#)	Incremental Energy Tech (%)	Sustaining CCMT (%)	Disruptive CCMT (%)
All Oil & Gas Companies	28,359	25,353	2,357	649	89.4%	8.3%	2.3%
Oil & Gas Producers	13,781	11,189	2,044	548	81.2%	14.8%	4.0%
Oil & Gas Service Providers	14,578	14,164	313	101	97.2%	2.1%	0.7%
Oil & Gas Producers - US	8,454	6,989	1,246	219	82.7%	14.7%	2.6%
Oil & Gas Producers - Europe	4,858	3,815	729	314	78.5%	15.0%	6.5%
Oil & Gas Producers - China	469	385	69	15	82.1%	14.8%	3.1%

Table 4.3: Results for Incremental Energy Technology, Disruptive CCMTs, and Sustaining CCMTs by O&G Sector and Region, 2000–2020. Patent count for Total Patents and CCMT Patents are based on international patent families. Due to multiple Y02–Y04 tags, both Sustaining CCMT and Disruptive CCMT have been proportionally normalized. Source: Based on EPO and USPTO data from the Espacenet patent database.

Results show O&G Producers generating approximately 18.8% total CCMT patents with 14.8% Sustaining CCMT and 4.0% Disruptive CCMT. Comparatively, O&G Service Providers are publishing 2.8% of their total international patent families as CCMT patents with 2.1% as Sustaining CCMT and 0.7% as Disruptive CCMT.

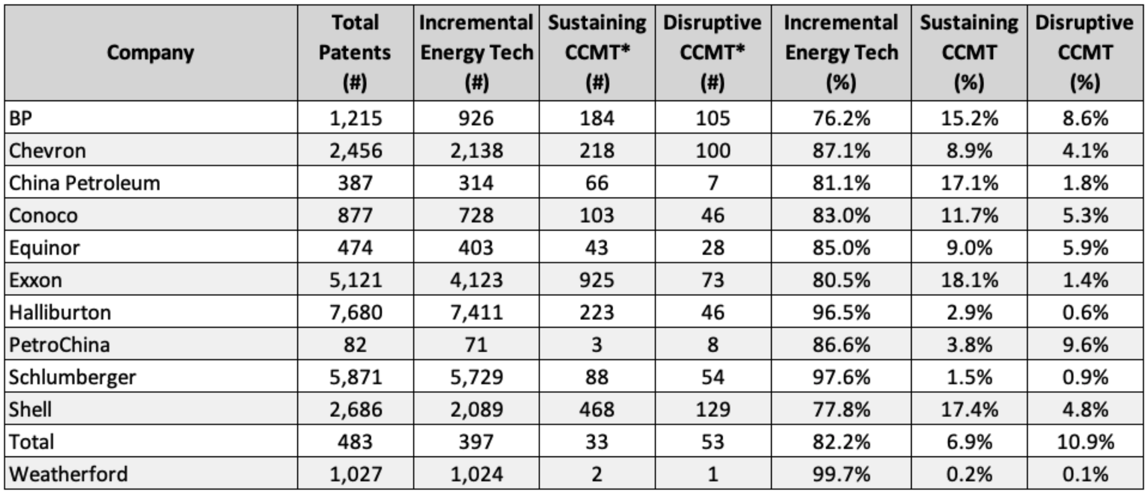
Oil & Gas Producers publish not only more CCMT patents in total when compared to O&G Service Providers, they also produce a greater number of Disruptive CCMT. This quantitative finding supports the qualitative finding based on an industry-wide survey published by the Society of Petroleum Engineers (SPE) that "nearly two-thirds of radical innovation" is generated by large, international oil producers (Perrons & Donnelly, 2012, p. 67). Working from the assumption that these companies fairly represent the broader make-up of the Oil & Gas industry, we can see from Figure 4.3 that Oil & Gas Producers are generating nearly 87% of all Sustaining CCMT and 85% of Disruptive CCMT, even though Service Providers are publishing an impressive 56% of all Incremental Energy Technology patents (14,164 of 25,297). These results broadly support the finding that there is a fundamental difference in how Service Providers manage their R&D focus, especially in technologies related to the Energy Transition. It further supports the finding by Perrons & Donnelly that "service companies tend to steer their portfolios toward more incremental technologies that are essentially an iterative improvement on an existing technology" (Perrons & Donnelly, 2012, p. 67).

What stands out in Table 4.3 is the general pattern of consistency between the three geographic regions. Among Oil & Gas Producers there is small to minimal difference between producers in the United States, Europe and China. In terms of absolute count between the producers, American Producers are publishing roughly 61% of Sustaining CCMTs (1246 to 2044) and 40% of Disruptive CCMTs (219 to 548), while European Producers are publishing nearly 36% of Sustaining CCMTs (729 to 2044) and 57% of Disruptive CCMTs (314 to 548). The two Chinese producers are far less influential when based on total CCMT patent count, with under 4% of Sustaining CCMTs (69 to 2044) and a mere 3% of Disruptive CCMTs (15 to 548). It is interesting to note that the absolute results for the two Chinese Producers, though limited by sample size, does support the previous finding reported in the literature that China, on average, is only producing around 5% of global high-value international patent families (Probst et al., 2021, p. 4).

Looking at regional technology portfolios, European Producers demonstrate total CCMT patents at 21.5% with 15.0% as Sustaining CCMTs and 6.5% as Disruptive CCMTs. American Producers, which generated nearly twice as many Total Patents over the time period of this study, come in at 17.3% CCMTs patents with 14.7% Sustaining CCMTs and 2.6% Disruptive CCMTs. Compared with European Producers, American Producers are publishing approximately 70% more Sustaining CCMT patents (1246 to 729) but approximately 70% less Disruptive CCMT patents (219 to 314). Results for China are based on the two companies in this study but show relatively similar numbers to their European and American counterparts, with 14.8% Sustaining CCMTs and 3.1% Disruptive CCMTs.

Table 4.4 reports the results for Sustaining and Disruptive CCMT for each of the twelve companies in the study. However, the recorded results can be misleading: A higher overall commitment to internal R&D, which includes Incremental Energy Technology, can indicate a lower relative percentage for Sustaining CCMTs and Disruptive CCMTs. For example, BP and Chevron produced approximately the same absolute number of Sustaining CCMTs (184 and 218, respectively) and Disruptive CCMTs (105 and 100, respectively). However, Chevron produced over twice as many Incremental Energy Technology innovations when compared with BP (2138 to 926, respectively) over the same time period. This difference in the overall productivity of the R&D portfolios results in BP recording higher portfolio percentages for Sustaining CCMTs (15.2% to 8.9%) and Disruptive CCMTs (8.6% to 4.1%). Thus, the calculated percentages at the company level are a better benchmark for examining the internal allocation of R&D focus than as a comparison of R&D output.

From a high-level perspective across all companies, the results show a high degree of heterogeneity between the companies in their technological capacity and R&D output, confirming previous qualitative evidence for the Oil & Gas industry (Perrons, 2014). At the same time, the data show similar alignment in total output of Disruptive CCMTs between BP (105), Chevron (100), and Shell (129).



Company	Total Patents (#)	Incremental Energy Tech (#)	Sustaining CCMT* (#)	Disruptive CCMT* (#)	Incremental Energy Tech (%)	Sustaining CCMT (%)	Disruptive CCMT (%)
BP	1,215	926	184	105	76.2%	15.2%	8.6%
Chevron	2,456	2,138	218	100	87.1%	8.9%	4.1%
China Petroleum	387	314	66	7	81.1%	17.1%	1.8%
Conoco	877	728	103	46	83.0%	11.7%	5.3%
Equinor	474	403	43	28	85.0%	9.0%	5.9%
Exxon	5,121	4,123	925	73	80.5%	18.1%	1.4%
Halliburton	7,680	7,411	223	46	96.5%	2.9%	0.6%
PetroChina	82	71	3	8	86.6%	3.8%	9.6%
Schlumberger	5,871	5,729	88	54	97.6%	1.5%	0.9%
Shell	2,686	2,089	468	129	77.8%	17.4%	4.8%
Total	483	397	33	53	82.2%	6.9%	10.9%
Weatherford	1,027	1,024	2	1	99.7%	0.2%	0.1%

Table 4.4: Results for Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT by O&G Company, 2000–2020. Patent count for Total Patents and CCMT Patents are based on international patent families. Due to multiple Y02–Y04 tags, both Sustaining CCMT and Disruptive CCMT have been proportionally normalized. Source: Based on EPO and USPTO data from the Espacenet patent database.

4.3 Examples of Disruptive CCMT, Sustaining CCMT, and Incremental Energy Tech

As highlighted by the previous sections, the Oil & Gas industry patents a wide range of technological innovation. This provides several specific examples of technology patents in order to better illustrate the differences between Disruptive CCMTs, Sustaining CCMTs, and Incremental Energy Technology.

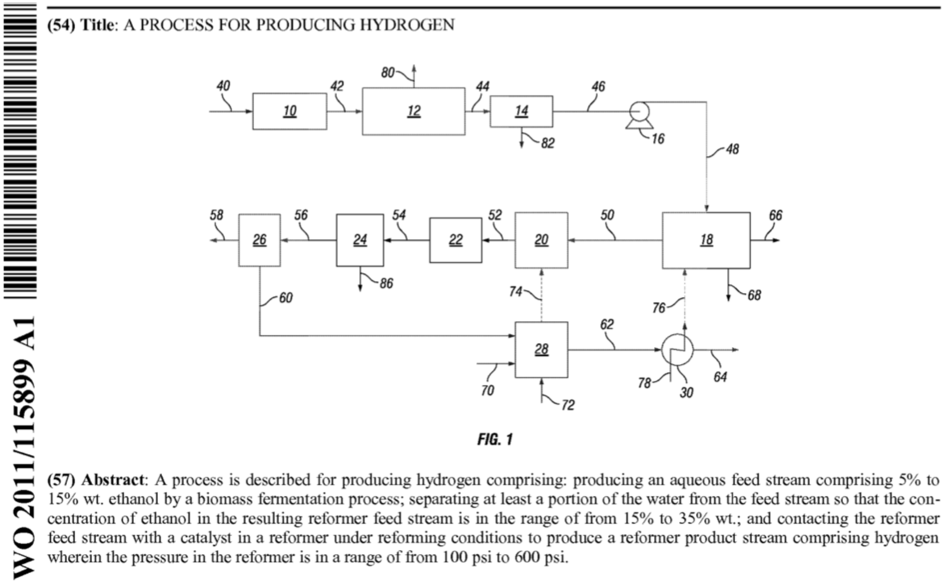
The following examples were selected because they exemplify the differences in the classification. Additionally, each of the published patent filings provided at least one diagram or schematic that further illustrated the category. Finally, one example is given at the end of this section of a technology that may be incorrectly classified under the proposed method.

4.3.1 Example of Disruptive CCMT: Shell and Equinor

Two examples are provided of published international patent families that were classified as Disruptive CCMTs under the sorting method.

As shown below in Figure 4.1, the first example is a 2011 patent from Shell that outlines a process for producing hydrogen (WO2011/115899A1). This patent application had three separate Y02-Y04 tags: Y02E50/30, Y02P20/10, Y02P30/00. According to the sorted Sustaining Y02-Y04 tags in Table 4.1 and Table 4.2, both Y02P20/10 and Y02P30/00 are classified as Sustaining technologies. However, the Y02E50/30 tag for "Technologies for the production of fuel of non-fossil origin" is not on the list and, thus, the patent can be classified as a Disruptive CCMT.

A closer look at this example suggests that the Disruptive CCMT tagging is appropriate. This example from Shell highlights a novel process for producing hydrogen through a biomass fermentation process in a reformer with a pressure range between 100 psi to 600 psi. The published patent application claims that this novel method will result in a "smaller carbon footprint than conventional hydrogen production processes" (WO2011/115899A1). It should be noted that this technology also has application within the established value streams of the Oil & Gas industry, as evidenced by both the Y02P20/10 and Y02P30/00 tags and the practical ability to utilize hydrocarbon feedstock in addition to biofeedstocks. This example highlights that the sorting of Y02-Y04 tags can have crossover and there may need to be adjustments to include or exclude cross-tagged technologies.



WO 2011/115899 A1

(54) Title: A PROCESS FOR PRODUCING HYDROGEN

FIG. 1

(57) Abstract: A process is described for producing hydrogen comprising: producing an aqueous feed stream comprising 5% to 15% wt. ethanol by a biomass fermentation process; separating at least a portion of the water from the feed stream so that the concentration of ethanol in the resulting reformer feed stream is in the range of from 15% to 35% wt.; and contacting the reformer feed stream with a catalyst in a reformer under reforming conditions to produce a reformer product stream comprising hydrogen wherein the pressure in the reformer is in a range of from 100 psi to 600 psi.

Figure 4.1: Example of Disruptive CCMT: Shell's Process for Producing Hydrogen, WO2011/115899A1. Source: Based on EPO and USPTO data from the Espacenet patent database.

As shown in Figure 4.2, the second example of a Disruptive CCMT is from a recent 2022 published patent from Equinor titled "Wind Turbine Control" (EP3954895A1). This patent application has only tone Y02-Y04 tag which is Y02E10/72 for "Wind Energy: Wind turbines with rotation axis in wind direction" (EP3954895A1). Based on the proposed classification system, this patent unambiguously falls into the category of Disruptive CCMT. However, it is arguable that this level of technology is no longer truly "disruptive" since the general technology is well established. This example highlights that the proposed method evaluates technologies in relation to the base businesses and value streams of a given industry or sector. For example, this patent would likely be labeled Sustaining CCMT if it was examined from the perspective of mechanical engineering companies focused on wind-power generation.

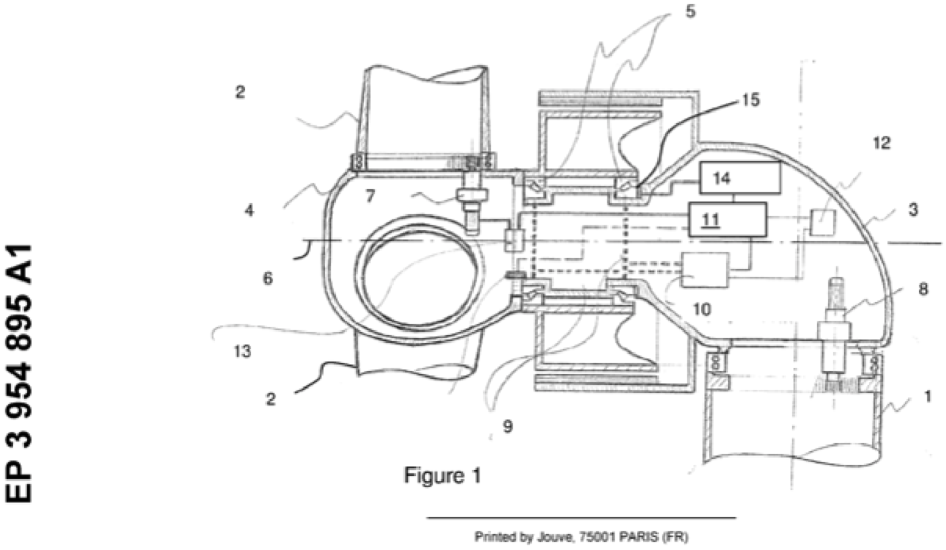


Figure 4.2: Example of Disruptive CCMT: Equinor's Wind Turbine Control, EP3954895A1. Source: Based on EPO and USPTO data from the Espacenet patent database.

4.3.2 Example of Sustaining CCMT: BP

There is a wide variety of technologies that can be tagged as Sustaining CCMT, including those that are highly innovative even if they are not classified as Disruptive. As shown in Figure 4.3, this example of a Sustaining CCMT showcases a published 2020 patent from BP that forwards a method for creating a Digital Replica (or "Digital Twin" in everyday language) of an offshore Oil & Gas production facility. This published patent had one Y02-Y04 tag, Y02P90/80, which indicates "Management or planning: Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation". This Y02-Y04 tag classifies this technology as a Sustaining CCMT based on Table 4.1 and Table 4.2. In this case, the classification appropriately classifies the innovation. Although it is focused on the cutting-edge research field of Digital Twins, this technology is aimed at improving the efficiency, safety, and inspection of offshore production facilities. As in the above example with Equinor, this patent highlights that it could be classified as a Disruptive CCMT under different circumstances. For example, a Digital Twin of an offshore wind-farm installation would classify as Disruptive, if it were cross-tagged.

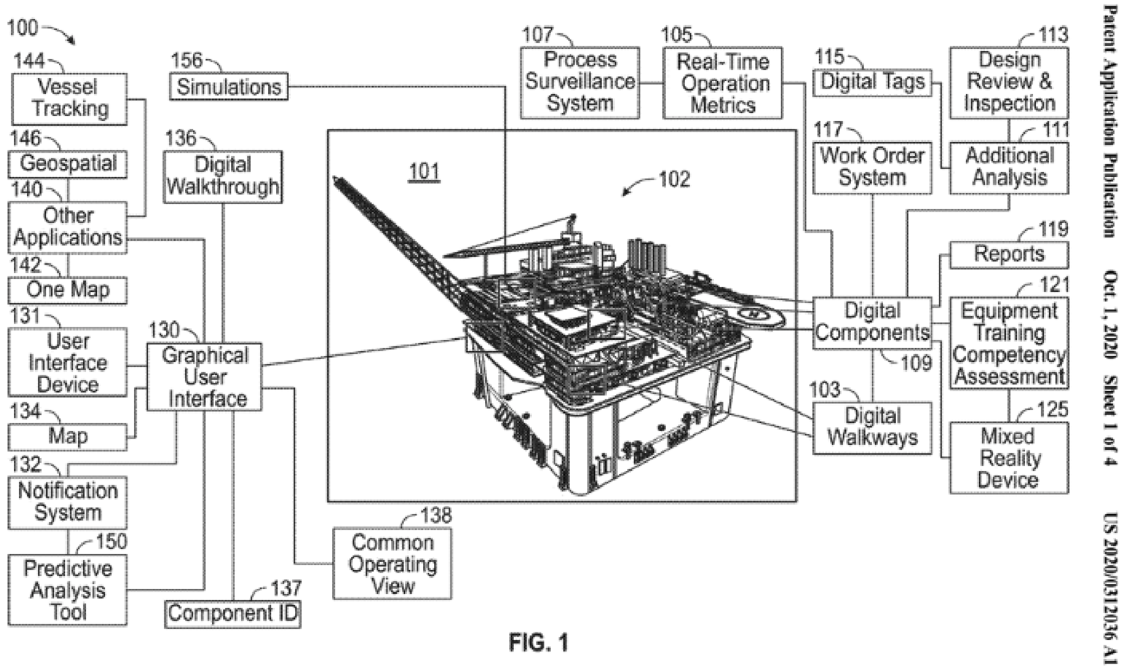


FIG. 1

Figure 4.3: Example of Sustaining CCMT: BP's Digital Replicas of Production Facilities, US2020312036A1. Source: Based on EPO and USPTO data from the Espacenet patent database.

4.3.3 Example of Incremental Energy Technology: Exxon

This example examines an Incremental Energy Technology patented by Exxon in 2018. As shown in Figure 4.4, this patent highlights a method for developing a long-term strategy for allocating a supply of liquefied natural gas (US10013663B2). This innovation has no Y02-Y04 tags, even though it is an international patent family and published in several countries. The patent is broadly concerned with optimizing supply chains and efficient scheduling, but it did not meet the hurdle for Y02-Y04 tagging for reduction in GHG. However, this type of innovation importantly highlights that Incremental Energy Technology can have large positive impact on facilitating existing fuel supplies, distribution, and global access to energy.

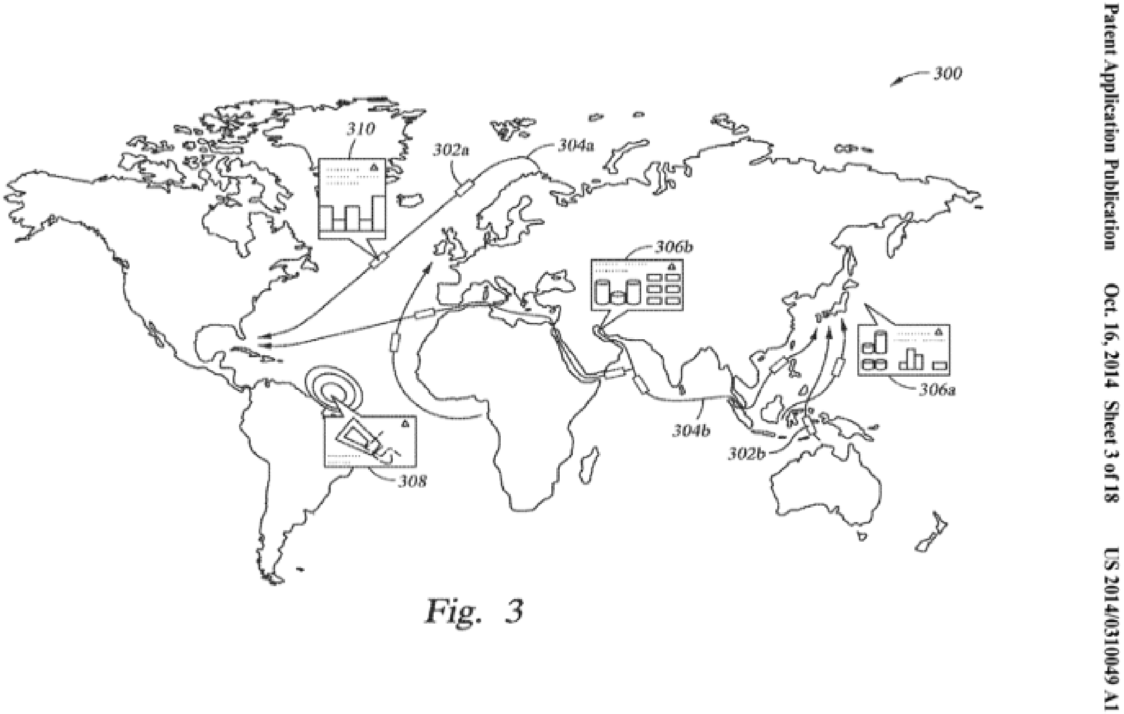


Figure 4.4: Example of Incremental Energy Technology: Exxon's Method for Optimized Shipping Schedule for LNG Delivery, US2014310049A1. Source: Based on EPO and USPTO data from the Espacenet patent database.

4.3.4 Example of Borderline Disruptive CCMT: Schlumberger

The proposed classification system is based on sorting at the level of the Y02-Y04 tag, and not the individual content of the patent application (Verhoeven et al., 2016). As discussed, more advanced methods could be developed that could additionally scan text in the title or abstract. This said, it is reasonable for some technologies to be mislabeled as Disruptive or Sustaining. As shown in Figure 4.5, the last example of this section looks at a fantastic innovation published in 2020 by Schlumberger that patented a "System and Method for Noise, Vibration, and Light Pollution Management on Rig Systems" (US10,669,783B2). This patent had only one Y02-Y04 tag and was classified as Disruptive CCMT based on the Y02B20/40 tag being defined as "Energy efficient lighting technologies, e.g. halogen lamps or gas discharge lamps: Control techniques providing energy savings, e.g. smart controller or presence detection". Although the patent presents several novel methods to dampen noise and vibration pollution, it is arguable that the technology is better counted as a Sustaining CCMT since it is specifically focused on hydrocarbon drilling worksites. This patent highlights that, depending on how the sorting method is utilized, there may be several technologies that are mislabeled or that could fit in either Disruptive or Sustaining categories.

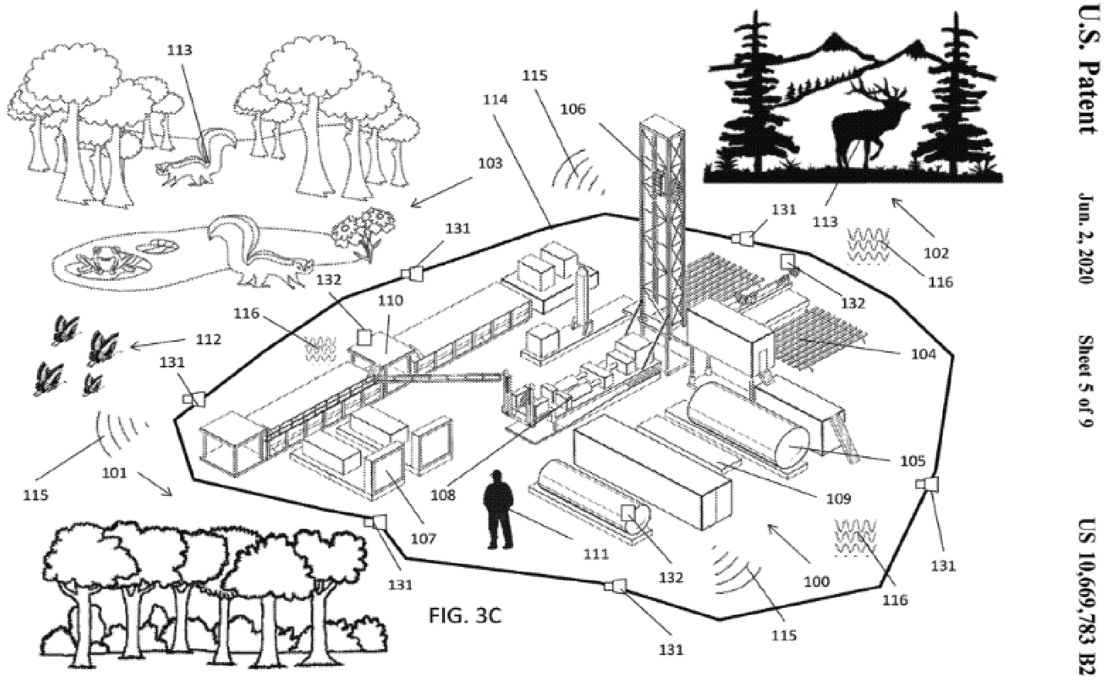


Figure 4.5: Example of Borderline Disruptive CCMT: Schlumberger's System for Noise, Vibration, and Light Pollution on Rig Systems, US10,669,783B2. This technology is tagged Y02B20/40 and classified as Disruptive CCMT, although it may better be re-classified as Sustaining CCMT due to its focus on providing base-business services in the Oil & Gas industry. Source: Based on EPO and USPTO data from the Espacenet patent database.

4.4 Key Takeaways

1. The CPC's Y02–Y04 tagging scheme for Climate Change Mitigation Technology (CCMT) enables a powerful yet practical method to delineate between Disruptive and Incremental Energy Technologies.
2. Incremental Energy Technology broadly aligns with all innovations that support the core businesses, existing value chains, or established markets of the target study.
3. Disruptive CCMTs are all innovations outside or unique to the core businesses, existing value chains, or established markets of the target study.
4. Sustaining CCMTs are innovations tagged under the Y02-Y04 schema as climate change mitigating technology that also support base businesses or existing value chains.
5. As a proxy for the broader Oil & Gas industry, the twelve companies show an average of 89.4% Incremental Energy Technology, 8.3% Sustaining CCMT, and 2.3% Disruptive CCMT.
6. Oil & Gas Producers generate significantly more technological innovation related to the Energy Transition than Service Providers. In absolute number count, Producers generate approximately 87% of Sustaining CCMT (2044 of 2357) and 84% of Disruptive CCMT (548 of 649).
7. The twelve companies show greater heterogeneity in R&D output including technologies related to the Energy Transition than exhibited in a comparison of the three R&D metrics (Expenditure, Intensity, and Productivity).
8. The percentage of an individual company's R&D mix can be a valuable tool for internal benchmarking and selection of high-graded projects.

Chapter 5

Correlation Analysis of Technology, R&D Metrics, Sales and Oil Price

This section presents a methodology for modeling the correlation between the key drivers that shape technology management during periods of transitional change. The goal of this exploration is threefold. First, to address the question of whether the lag between R&D expenditure and patenting needs to be adjusted prior to conducting correlation analysis. Second, to establish whether statistical correlation confidently exists between our technology variables, particularly between CCMT patent families and the three corporate R&D metrics. And, third, to quantify the relationship of oil prices to patenting. This final step will provide additional support for assessing whether firms are adjusting their technology management focus in light of the Energy Transition.

5.1 Time-Lag Analysis

5.1.1 The Question of Lag

At the big-picture level, R&D expenditure in a given year is regarded as an input to the research and development of both new and existing projects in a company. This money does not immediately produce R&D output; rather there is a some degree of "lag" between the injection of R&D funding and the output of R&D as patenting activity (Hartmann et al., 2006; Griliches, 1998; Hall, 2002). This spread is defined as "lag" and has been the focus of a significant number of analytical studies (Hall et al., 1984; Griliches, 1998, 1991).

At first sight, lag appears as a critical question that needs to be answered before quantitative assessment with patents and R&D data can take place. At the practical level, there is the technology management question of how long it takes for money invested in R&D to materialize as completed research and development. And this is related to the corporate question of the length of time between completed R&D and broader commercialization that can increase net sales and overall profitability (Morbey & Reithner, 1990). However, Griliches (1998) argues that the ability to attribute increased productivity to specific yearly R&D patenting with econometric models is "doubtful", because of both the "long and variable lag" and that this combined "aggregation over many inventions and many lag structures is likely to smooth them out further, beyond recognition" (Griliches, 1998, p. 333).

Even if the output of R&D as specific patents cannot be successfully lagged to future performance, there remains the question of whether R&D expenditure can be time-adjusted to match patenting trends. Key research from Trajtenberg (1990), Griliches (1998), and Hall et al. (1984) show that, on average, the highest correlation between R&D Expenditure and Patents is "lagged just five months" (Trajtenberg, 1990, p. 183). This period of "short gestation" of average lag is found independently by Griliches (1998, 1991). Here, Griliches states:

> “To the extent that one does observe correlations between patent numbers and contemporaneous productivity numbers, the causality is most likely running the other way, from productivity as a measure of the economic environment to patents as a measure of inventive “effort” rather than from the impact of inventive “output” on subsequent productivity....
>
> There is also a statistically significant relationship between R&D and patents in the within-firm time series dimension, but it is weaker there. The bulk of the effect is contemporaneous, implying possibly also some reverse causality: successful research leading to both patents and to the commitment of additional funds for the further development of the resulting ideas” (Griliches, 1998, pp. 333–335).

Here, the final conclusion by Griliches is unexpected: *R&D Expenditure may often better correlate with patenting if it is lagged into the future*, and not the past (Griliches, 1998;

Trajtenberg, 1990).

However, the addition of Climate Change Mitigating Technology (CCMT) patents introduces an additional level of complexity to the question of time, one that is only increased by the further differentiation between Sustaining CCMT and Disruptive CCMT. Can R&D Expenditure be better lagged to Disruptive technologies? Is there a difference in lagging behavior between geographic regions with different approaches to technology management? Current research has not addressed these questions.

5.1.2 Testing for Time Lag

This study will test for time lag to confirm or reject the general findings from Griliches (1998) and Trajtenberg (1990). At the same time, this time-series analysis will further test the difference in lagging between total patenting, Disruptive CCMT, and Sustaining CCMT that were differentiated in Chapter 4. This approach will then support the follow-up analysis at the end of this chapter that examines the overall correlation between all of our R&D and patenting variables.

Testing for time lag was conducted using the R programming language's `ccf` function, which is part of the inbuilt `stats` package. This function calculates the cross-correlation of two univariate series over a designated time period (RDocumentation.org, n.d.). The advantage of this R function is that it returns the calculated lag as units of time on the x-axis, allowing for visible interpretation. Importantly, this function also time-lags into the future. A second function, `lag2.plot` was also used to better graphically present the data distributions over periods of lag.

5.1.3 Results for Time Lag

Figure 5.1 presents the aggregated time-lag correlation results between all individual pairs of R&D Expenditure and total patents per year for each of the twelve companies in the study. The top figure depicts the combined cross-correlation when patents are held constant and R&D Expenditure is lagged both into the past (the left side of the graph) and into the future (the right side of the graph). The dashed blue line represents the confidence interval of the the uncorrelated series (Rdocumentation.org, n.d.-a).

The results are unexpected. For all companies in the study, the time-lag cross-correlation shows that R&D expenditure is negatively correlated with future patent delivery, though insignificantly. On the right of the graph, R&D Expenditure is showing positive correlation when it is lagged into the future, giving indication of support of Griliches (1998)'s finding, though at the extreme end. These results are likely skewed by the high number of non-CCMT patents published by the three Service Providers: Halliburton, Schlumberger and Weatherford.

Figure 5.2 reduces the overall number of patents—including the high volume of non-CCMT patents from the three Service Providers—and presents only the Sustaining CCMT Patents as counted in Chapter 4. This figure supports two of the key findings from Griliches (1998) and Trajtenberg (1990): (1) The strongest correlation is approximately six months in the past as indicated to the left from the zero mark; and (2) R&D Expenditure shows some "reverse causality" where successful patenting promotes additional follow-up funding in future years.

Figure 5.3 presents a finding from this research that challenges the accepted model. The data from this study show that R&D Expenditure can exhibit strong positive correlation when lagged into the past with only Disruptive CCMT patent data. Here, the results demonstrate that R&D funding lags approximately 9–11 years before published, high-value patent families.

Appendix H further compares the results of Total Patents, Sustaining CCMT and Disruptive CCMT for both Oil & Gas Producers in Europe and the United States. Both European and American time-lag behavior support the general findings with a propensity for forward positive lagging (Griliches, 1998). Notably, the total patents for both regions remove much of the noise exhibited in the Total Patent time-lag (Figure 5.1).

Again, the results for the association between R&D Expenditure and Disruptive CCMT patenting is unique and outside of orthodox theory. As shown in Figure H.3 and Figure H.6, R&D Expenditure exhibits positive correlation when lagged to the past with Disruptive technologies. There are several explanations for this behavior. First, because of the reduced number of Disruptive CCMT Patents, the actual matching with past R&D spend may avoid the smoothing that Griliches (1998) identified as a cause of masking recognition. Second, it is not inconceivable that Disruptive CCMT Patenting was developed after earlier periods of increased investment, perhaps due to increased oil price.

The time-series test was performed individually for each of the twelve companies, with largely similar results.[1] By and large, each individual company showed the strongest positive correlation in either Year 0 or Year -1, and then a decreasing correlation further into the future and into the past.

These results give ample support to *not* apply a generic time-lag to the R&D Expenditure and patent data in this study or to attempt an individual time-lagging per company. Instead, this study will keep data non-lagged but will include notes, when necessary, to highlight that related findings or results could be impacted by this modeling assumption.

However, before correlation analysis can be performed, the overall normality of the data sets must be determined. This will be the focus of the next section.

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[1] The time-lag results for each individual company are not included in the Appendix due to space, but can be furnished by the author on request.

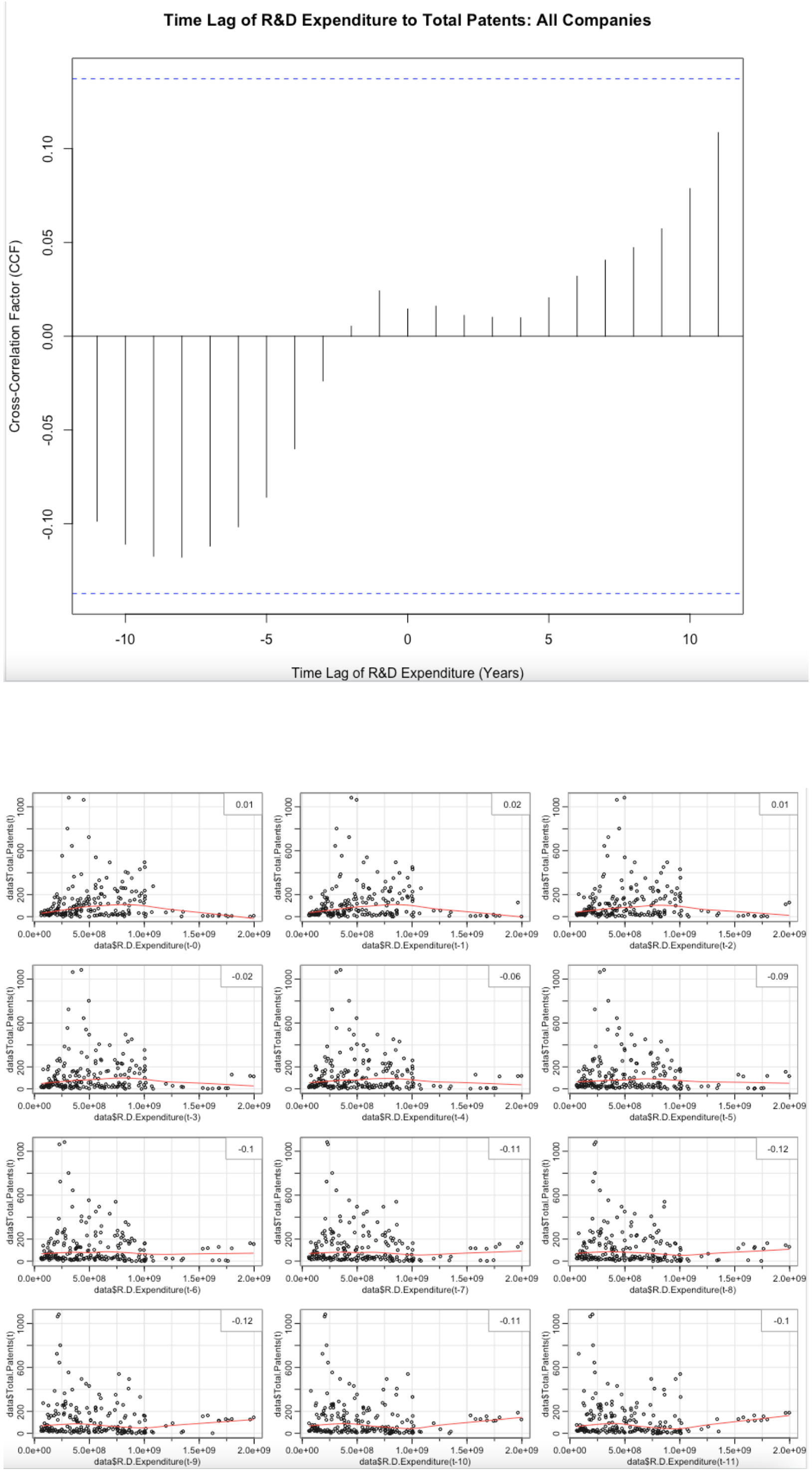


Figure 5.1: Lag of R&D Expenditure to Total R&D Patenting Activity: All O&G Companies, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Total Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

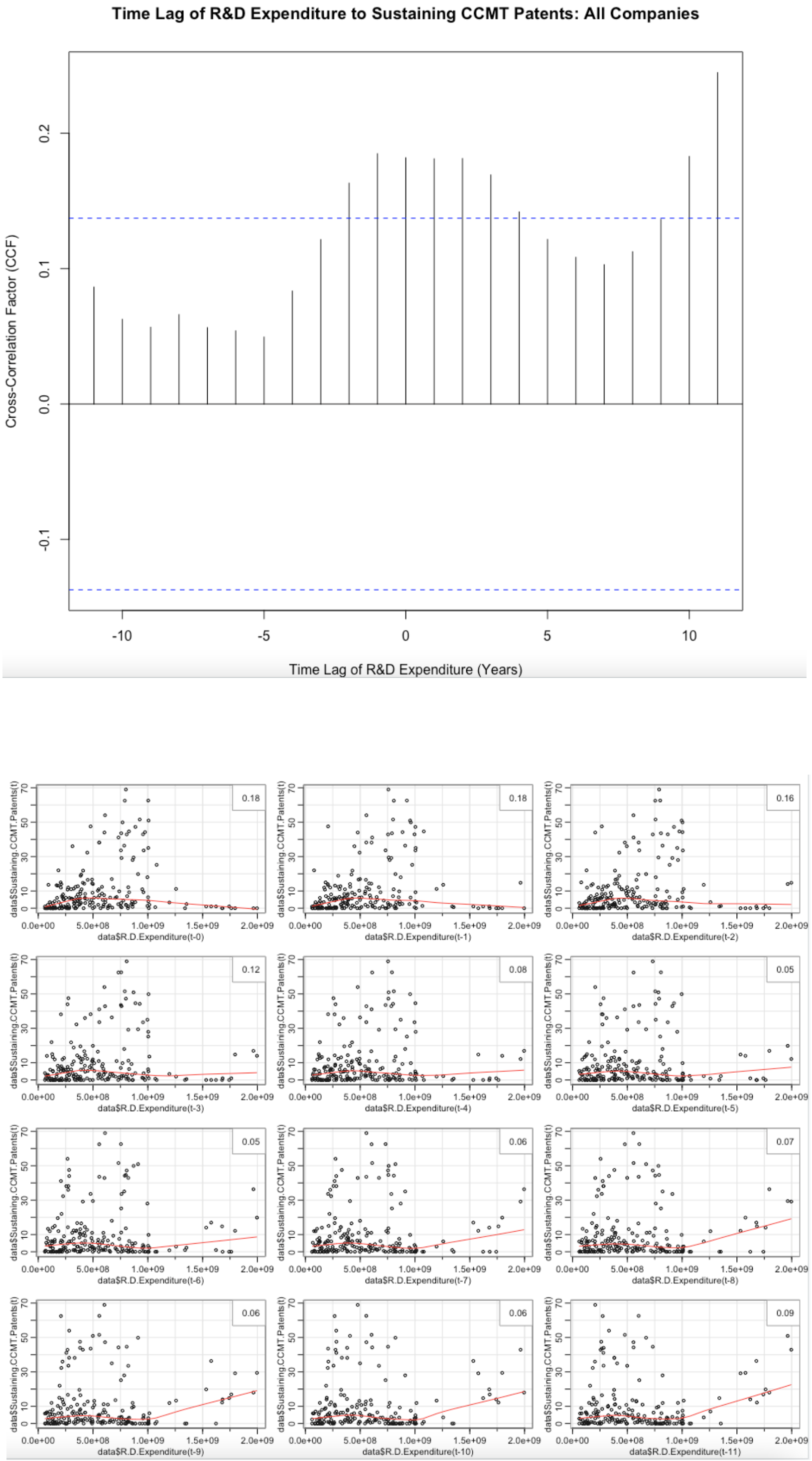


Figure 5.2: Lag of R&D Expenditure to Sustaining CCMT Patenting Activity: All O&G Companies, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Sustaining CCMT Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

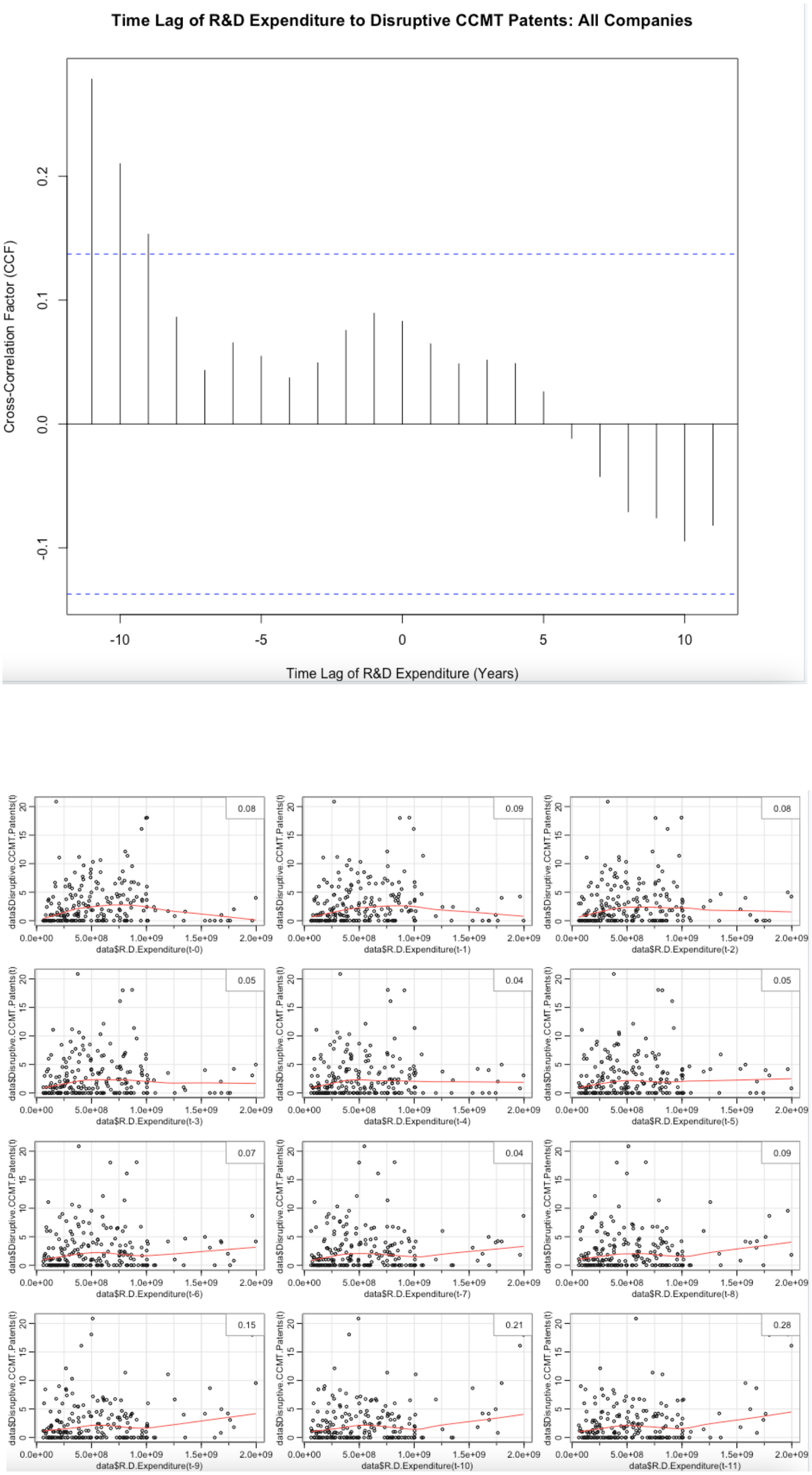


Figure 5.3: Lag of R&D Expenditure to Disruptive CCMT Patenting Activity: All O&G Companies, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Disruptive CCMT Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

5.2 Methodology for Correlation Analysis

5.2.1 Testing for Normality

As overviewed in Section 2.1.3, groundbreaking work on the relationship between R&D Productivity and Sales Per Employee and Profitability was published by Morbey & Reithner (1990). Beyond the seminal contribution of correlating Research and Development with overall business profitability, Morbey & Reithner made the important methodological observation that the three R&D metrics—R&D Expenditure, Intensity, and Productivity—are better evaluated using non-parametric rank-order statistics. Based on their research, it was not possible to provide significant explanation through the use of linear econometric models based on normal distributions; and, instead, the Spearman rank-order test was implemented to establish statistical correlation (Morbey & Reithner, 1990, p. 14).[2]

Based on the above finding by Morbey & Reithner, the first step for evaluating the overall correlation between technology patenting, R&D metrics, Sales and Oil Price was to determine whether the current data sets of the twelve representative Oil & Gas companies could be evaluated using linear/normal calculations with the Pearson correlation coefficient or if the Spearman rank correlation coefficient was required.

To test the three patenting variables (Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT) for normality, two methods were utilized. First, the Shapiro–Wilk test was applied to test for normality. Second, results of the Shapiro-Wilk test were spot-checked with Q–Q probability plots to ensure consistency. Both methods will be briefly described.

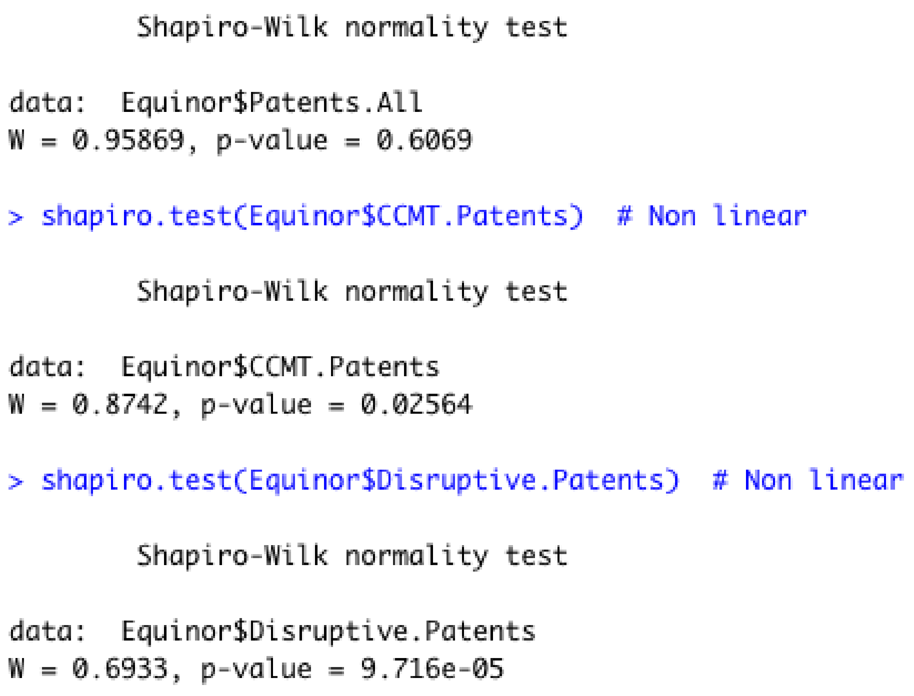
The Shapiro-Wilk test is part of R's standard statistics package `stats (3.6.2)` as the function `shapiro.test` (Rdocumentation.org, n.d.-b). This `shapiro.test` function returns approximate *p*-values based on the earlier algorithm work by Royston (Rdocumentation.org, n.d.-b; J. P. Royston, 1982a,b; P. Royston, 1995). A common statistical significance test, the Shapiro-Wilk is based on a null-hypothesis that the tested population has a normal distribution (Wikipedia, 2022a; J. P. Royston, 1982a). Normality

---

[2] Helfat (1994) reports the Pearson coefficients for his study on the path dependence of R&D spending in "Evolutionary Trajectories in Petroleum Firm R&D" but then provides a footnote that the results were confirmed with Spearman ranked correlation coefficients.

is confirmed by a p-value greater than the defined alpha level of the test, set typically at 0.5 for many tests. On the other hand, the null-hypothesis test cannot be rejected—and therefore the data cannot be assumed to be normally distributed—if the p-value is less than the defined alpha value (Wikipedia, 2022a; J. P. Royston, 1982a).

Normality testing for Total Patents, Total CCMT Patents, and Disruptive CCMT Patents was conducted for each of the twelve companies based on the need to properly model the correlation of the Climate Change Mitigation Technology with other technology-management variables. The Shapiro-Wilk test confirmed that many, but not all, of the variables were non-normal. Shown below in Figure 5.4 is an example of the results of the Shapiro-Wilk test for Equinor as an output from the Integrated Desktop Environment (IDE), RStudio:



```
        Shapiro-Wilk normality test

data:  Equinor$Patents.All
W = 0.95869, p-value = 0.6069

> shapiro.test(Equinor$CCMT.Patents)  # Non linear

        Shapiro-Wilk normality test

data:  Equinor$CCMT.Patents
W = 0.8742, p-value = 0.02564

> shapiro.test(Equinor$Disruptive.Patents)  # Non linear

        Shapiro-Wilk normality test

data:  Equinor$Disruptive.Patents
W = 0.6933, p-value = 9.716e-05
```

Figure 5.4: Example of Shapiro-Wilk Normality Test based on Equinor's Total Patents, Total CCMT Patents, and Disruptive CCMT Patents. The R output shows that Total Patents are normally distributed, but that Total CCMT Patents and Disruptive CCMT Patents are non-normally distributed based on p-values < 0.05.

In the uppermost Shapiro-Wilk test, the distribution of Equinor's Total Patents is confirmed as normal based on the p-value of 0.6069 being greater than the selected alpha value of 0.05. However, the same test run independently for both Total CCMT Patents and Disruptive CCMT Patents indicates non-normality, with *p*-values of 0.02564 and 9.716e-05 being under the defined 0.05 threshold.

To confirm the non-normality of the data, key populations were double-checked with Q–Q probability plots to assess overall linear distribution of population's data points. This test was performed using R's `ggqqplot` function from the `ggpubr` add-on package to the standard `ggplot2` package. The function conveniently depicts the normality of the population within an error window. Shown below as Q–Q plots, Figure 5.5 again uses Equinor as an example for the normally distributed Total Patents (*p*-value = 0.6069) and the non-normal Disruptive CCMT Patents (*p*-value = 9.716e-05):

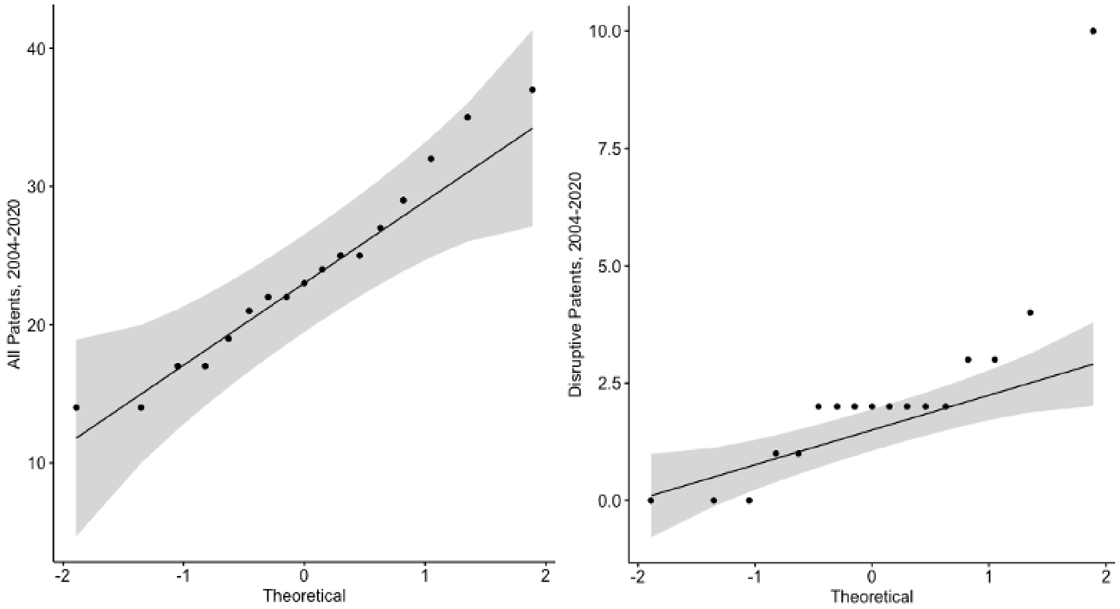


Figure 5.5: Example of Q–Q Plot for Normality based on Equinor's Total Patents (left) and Disruptive CCMT Patents (right). The left panel shows the general linear nature of the Total Patent data plotted over a normal distribution range, confirming the *p*-value of 0.6069. The right panel shows the non-normal distribution of the Disruptive CCMT Patent data. Here, note the prevalence of data points outside the error band and the data outlier in the top right (*p*-value = 9.716e-05). This confirms the result of the Shapiro-Wilk test CCMT patent data is non-normal.

The results of the Shapiro-Wilk tests and the Q–Q plots confirm the generalized methodological finding in Morbey & Reithner (1990) that non-parametric rank-order statistics are preferred for performing correlation analysis on combined patent, R&D metrics, Sales and Oil Price data set.

5.2.2 Spearman Rank Correlation Coefficient

The R package `PerformanceAnalytics (version 1.5.3)` was selected for correlation analysis based on the range of available econometric functions, the option of selecting normal and non-normal correlation methods (including Spearman Rank Correlation Coefficient), and the standardized correlation matrix that enables straightforward analysis between multiple input variables on one graph (Peterson, 2019).

5.2.3 Interpreting the Spearman Matrix

Before reviewing the results of the Spearman correlation models and analyzing how these enrich an understanding of how technology management might be repositioning during the Energy Transition, a quick overview of how to read the matrix is instructive.

As shown below in Figure 5.6, the 11 x 11 matrix is an output of the eleven populations associated in the model, with each named variable running along the diagonal squares of the matrix. The eleven variables included in this analysis are: Total R&D Patenting, Incremental Energy Patenting (all non-CCMT patents), Sustaining CCMT Patents, Disruptive CCMT Patents, R&D Expenditure, R&D Intensity, R&D Productivity, Employees, Net Sales, Sales per Employee, and Oil Price.

This matrix layout facilitates easy visual correlation between each pair of variables. Here, the matrix can be read by finding the square intersected by the two variables of interest. For the upper section of the matrix this involves selecting the first variable of interest on the diagonal and then tracing horizontally to line up with the second variable of interest. In this way, each pair of variables share exactly one square in the upper right section and one square in the lower left section. For example, Total Patents aligns with Oil Price in the uppermost right square and the lowermost left square, while R&D Expenditure and R&D Intensity share the two center squares in common.

Below the diagonal of the input variables and on the lower half of the matrix are the bivariate scatterplots with a fitted line for each pair of correlated variables. Following normal correlation convention, the fitted line depicts positive correlation as a monotonic diagonal increasing from the lower left of the plot to the upper right of the bivariate scatterplot, while negative correlation is a monotonic diagonal decreasing from the upper left of the y-axis to the lower right side of the x-axis. Spanning a total of 17 years between 2002–2020 and using 12 companies, each bivariate scatterplot on Figure 5.6 contains 204 separate correlation calculations. The total count of 17 data points per company is easier to see on the individual matrix for each company. For example, see the matrix for Chevron (Figure I.2, Appendix I).

On the top portion of the matrix is the calculated Spearman rank correlation coefficient for each paired sample. Each rank correlation conveys an estimate of the association in the range of [-1,1] with 0 indicating no correlation, +1 indicating perfect positive association, and -1 indicating perfect negative association Peterson (2019); Wikipedia (2022b). The size of the reported numbers are scaled to reflect the overall positive or negative rank-based correlation of each paired sample (Peterson, 2019).

The red stars above the Spearman coefficient indicate the significance or *p*-value for the ranked sample pair (Peterson, 2019). This research uses the baseline values included in the R package, as shown in Table 5.1, below:

Significance Code	**Range of *p*-Values**
"****"	[0, 0.001]
"***"	[0.001, 0.01]
"*"	[0.01, 0.05]
"."	[0.05, 0.1]
" "	[0.1, 1]

Table 5.1: Significance Codes for Spearman *p*-Values

It is worth highlighting that it is unclear whether the lower significance ranges match those presented by Morbey & Reithner (1990). Without providing ranges, they tabulate their results with "*" equal to 99.0% significance and "****" equal to 99.9% significance (Morbey & Reithner, 1990, pp. 12–13). Importantly, the "****" coding matches, however R's "***" code aligns with Morbey & Reithner's "*". This distinction allows the standardized R statistics package to have a p-value of 0.05 correspond with "*".

5.3 Results and Analysis of Correlation Testing

5.3.1 Results of Correlation Testing by Company

The collected results of Spearman rank-order correlation testing are documented in Appendix I. The twelve figures include: BP (Figure I.1), Chevron (Figure I.2), China Petroleum (Figure I.3), Conoco (Figure I.4), Equinor (Figure I.5), Exxon (Figure I.6), Halliburton (Figure I.7), PetroChina (Figure I.8), Schlumberger (Figure I.9), Shell (Figure C.10), Total (Figure I.11), and Weatherford (Figure I.12).

5.3.2 Correlation Analysis of All O&G Companies

The first test examines the entire sample set of twelve Oil & Gas companies over the time period of 2004–2020. The results of the Spearman rank-order correlation are shown below in Figure 5.6. As a reminder, these results present same-year, non-lagged correlations.

- ***Sustaining CCMT Patents***. There is strong positive correlation between Sustaining CCMT Patents and Incremental Energy Patenting, with $r_s(202) = .66,\ p = < .001$. This significant result highlights that the development of Sustaining Climate Change Mitigation Technology is more closely tied to the base-business patenting of a corporation than to its Disruptive CCMT patenting activities, with $r_s(202) = .55,\ p = < .001$. It is interesting to highlight that Sustaining CCMT Patenting is the most significant association with same-year R&D Expenditure, at$r_s(202) = .28,\ p = < .001$, indicating that on average the total yearly number of Sustaining CCMT patents increases as the budget grows.

- ***Disruptive CCMT Patents***. There is strong positive correlation between Disruptive CCMT Patents and Sustaining CCMT Patents, as reported above. It is important to note that Disruptive CCMT Patents are more closely tied to Sustaining CCMT

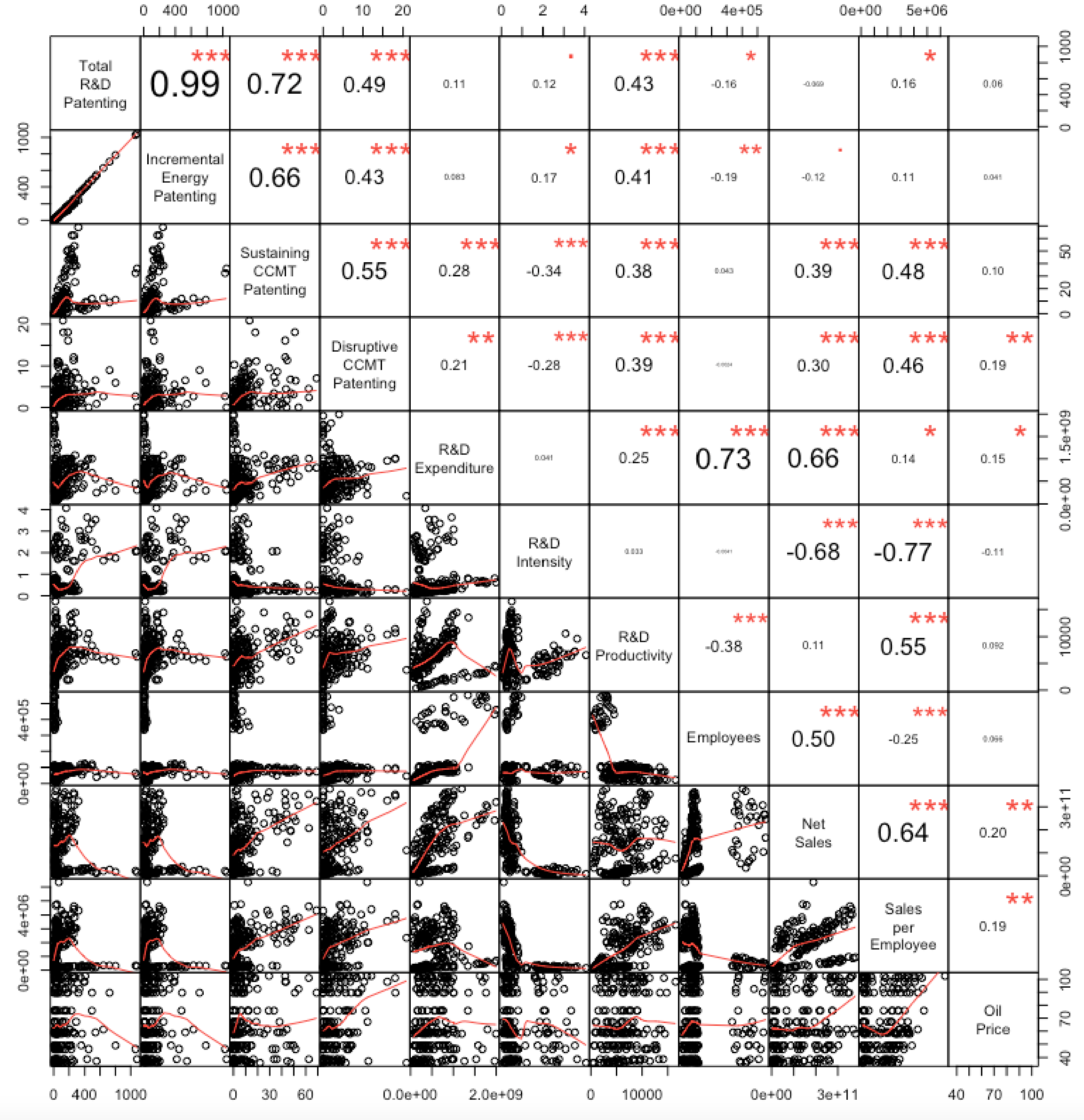


Figure 5.6: Correlation of Total R&D Patenting Activity with R&D Metrics, Sales and Oil Price: All O&G Companies, 2004–2020. This matrix captures the Spearman rank order coefficient for the eleven, same-year, non-lagged pairs. Patent count for Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT is separated to avoid collinearity. Source: Based on IRI data and EPO/USPTO data.

Patents than to Incremental Energy Patents or the overall Total R&D Patenting portfolio. At $r_s(202) = .55,\ p = < .001$ compared to Incremental Energy Patenting at $r_s(202) = .43,\ p = < .001$, this broadly indicates that there is organizational affinity and learning between the development of unrelated Sustaining CCMT Patents and Disruptive CCMT Patents. As expected, Disruptive CCMT Patents have slightly lower correlation to Total R&D Patenting when compared with Incremental Energy Technology or Sustaining CCMT Patenting. This provides evidence that the overall productivity of Disruptive CCMT Patenting is less tied to larger-scale R&D efforts. Additionally, we can observe that, on average, Disruptive CCMT innovation is only moderately related to R&D Expenditure ($r_s(202) = .21,\ p = < .01$), however it has higher statistical significance with both R&D Productivity ($r_s(202) = .39,\ p = < .001$) and Sales Per Employee ($r_s(202) = .46,\ p = < .001$).

In general, the organizational capability to deliver traditional technology patents translates into a correlated ability to produce patents for more unrelated technologies, including Sustaining CCMT and Disruptive CCMT technologies. This generalized relationship, however, does not hold across all of the individual firms. For example, Exxon has routinely had one the highest output of overall published patents in this study yet this high patent count associates with neither Sustainable CCMT Patents nor Disruptive CCMT Patents (See Figure I.6, Appendix I).

- ***R&D Expenditure***. As reported above, there is moderate positive correlation between R&D Expenditure and both Sustaining CCMT Patents and, to a lesser degree, Disruptive CCMT Patents. What is noteworthy here is that absence of association between R&D Expenditure and both Incremental Energy Patenting and Total R&D Patenting. This highlights a high-level finding on how technology is being managed: on average, base-business R&D—with much of it likely modular or incremental, and operating on a given performance trajectory of known quantitative metrics and targets (Christensen et al., 2018; de Weck, 2022)—is less correlated to the year-to-year fluctuations in Net Sales and R&D Expenditure compared to either Sustaining CCMT or Disruptive CCMT innovation. By extension, this highlights that Incremental Energy Patenting is less likely to be the R&D cut during market adjustments or periods of low oil price. Figure 3.3 demonstrates that the relative percentage of CCMT Patents decreased compared to Totals Patents during periods of lower oil prices.

- ***R&D Intensity***. Surprisingly, there is little insight to be gained from this metric. It appears that fluctuations in Net Sales are overshadowing increases in R&D Expenditure, thus creating a metric that negatively correlates with patent performance and, as expected, Net Sales. These average results show there is no correlation between R&D Expenditure and R&D Intensity, underlying the inflated influence of Net Sales on this metric. This highlights a key limitation that Helfat (1994) found in the path-dependency of the R&D Intensity metric:

  > "With regard to persistence in R&D, the use of R&D intensity could understate the degree of path dependence in R&D if sales revenues fluctuate more than do R&D expenditures" (Helfat, 1994, p. 1728).

  Confirming Helfat's concern, this secondary role for R&D Intensity is foreshadowed by the fact that Net Sales has a stronger positive correlation with both Sustaining CCMT and Disruptive CCMT patenting, compared to R&D Expenditure.

- ***R&D Productivity and Sales Per Employee***. As same-year, non-lagged pairs, there is a moderately strong positive correlation between R&D Productivity and Sales Per Employee, with $r_s(202) = .55,\ p = < .001$. Though non-lagged, this shows a similar finding as Morbey & Reithner (1990). At the same time, this association may be partly reflective of the correlation between Net Sales and R&D Expenditure ($r_s(202) = .66,\ p = < .001$) which has an associated effect on R&D Productivity.

- ***Employees***. A higher employee headcount is correlated with increased Net Sales and higher R&D Expenditure. But, on average, employee count is not significantly correlated to same-year Incremental Energy Technology Patents, Sustaining CCMT Patents, or Disruptive CCMT Patents.

- ***R&D Productivity and R&D Intensity***. In general, R&D Productivity is a better predictor of higher innovative activity than R&D Intensity. R&D Productivity has moderate and significant association with all three patenting groups and the overall Total Patents and, further, the correlation is nearly the same across Disruptive CCMTs, Sustaining CCMTs, and Incremental Tech. On one hand, this suggests that innovative activity increases as the money per person increases. It may also suggest that a workforce is generally more innovative if there is a greater availability of funds for experimentation and creativity. Here, importantly, the data suggests that technical innovation is related to the quality of the workforce and their generalized access to resources.

- ***Oil Price***. The unexpected finding from this Spearman matrix is the low level of correlation between same-year Oil Price and the other ten features. Oil Price shows a weak positive correlation to both Net Sales and Sales Per Employee, with $r_s(202) = .20,\ p = < .01$ and $r_s(202) = .19,\ p = < .01$, respectively. Same-year R&D Expenditure shares only faint correlation, as does Disruptive CCMT Patenting. The quick explanation is that the correlation of oil price is lagged to the other features, outside of Net Sales. While this is most definitely true for large one-year changes in oil price, this explanation does not account for a lack of correlation during relative stable periods of increase or decrease in oil price. Returning to Figure 2.1, a key takeaway may be that higher than average oil prices are less correlated to R&D Expenditure than initially surmised.

5.3.3 Correlation Analysis of O&G Producers (No China)

Based on our previous review of the companies in the data set, it is informative to look at several smaller sub-groupings. First, a quick look will be given to O&G Producers (No Service Providers) and O&G Producers (No China). Then, second, the next subsection will compare results for European Producers and American Producers.

Figure 5.7 exhibits the results for the Spearman rank-correlation testing for the O&G Producers (No Service Providers) and Figure 5.8 shows the results for O&G Producers (No China). Based on on our previous analysis, removing the Service Providers removes three companies with high Total Patents, low CCMT patents, and moderate R&D budgets. Likewise, removing the Chinese Producers removes two companies with very high R&D budgets, and relatively low Total Patents and CCMT Patent, but that have had moderately high percent of CCMT to Total Patents based on lower patent families.

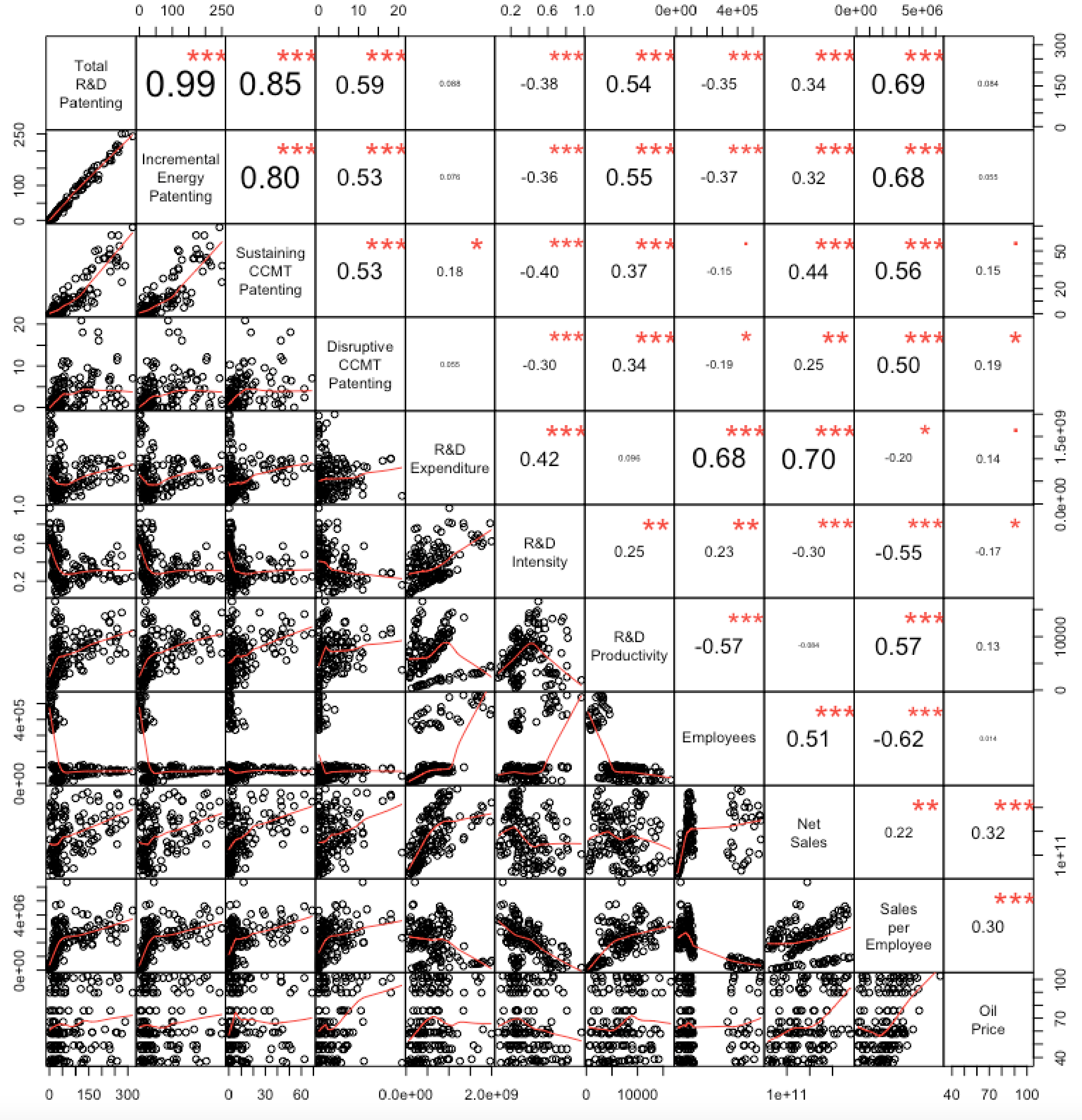


Figure 5.7: Spearman Correlation of Total R&D Patenting Activity with R&D Metrics, Sales and Oil Price: O&G Producers, 2004–2020. This matrix captures the Spearman rank order coefficient for the eleven, same-year, non-lagged pairs. Patent count for Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT is separated to avoid collinearity. Source: Based on IRI data and EPO/USPTO data.

As shown below in Figure 5.8, O&G Producers (No China) exhibits moderately strong positive correlation between R&D Expenditure and both Sustaining CCMT Patents ($r_s(117) = .50,\ p = < .001$) and Total Patents ($r_s(117) = .48,\ p = < .001$), and moderately weak association with Disruptive CCMT Patents $r_s(117) = .29,\ p = < .01$). These results suggest a direct correlation between same-year R&D Expenditure and un-lagged patenting for the seven O&G Producers in Europe and the US. Additionally, same-year Net Sales has a stronger correlation with Sustaining CCMT Patents ($r_s(117) = .68,\ p = < .001$) and Total Patents ($r_s(117) = .65,\ p = < .001$).

5.3.4 Correlation Analysis of European and American Producers

The final analysis of Spearman correlations will examine the similarities and differences between European Producers and American Producers to evaluate whether there is insight on differences in technology management. For this analysis, there are four European Producers (BP, Equinor, Shell, and Total) and three American Producers (Chevron, Conoco, and Exxon). As expected, the number of statistical pairings for the rank correlation decreases for these two smaller data sets.[3] A side-by-side comparison of the results for European Producers in Figure 5.9 and for American Producers in Figure 5.10 display relative similarity between the regions.

A closer examination shows several regional nuances that may highlight technology strategies. In Figure 5.9, European Producers demonstrate a higher positive correlation between Disruptive CCMT Patents and all other variables than the American Producers. For example, European Producers show strong positive correlation between Disruptive CCMT Patents and both Sustaining CCMT Patents and Total R&D Patents, with $r_s(66) = .50,\ p = < .001$ and $r_s(66) = .57,\ p = < .001$ respectively. Contradistinctively, American Producers show low correlation between Disruptive CCMT Patents and either Sustaining CCMT patents or Total R&D Patents, with $r_s(49) = .38,\ p = < .01$ and $r_s(49) = .35,\ p = < .05$ respectively. This indicates that Disruptive CCMT Patents—here a proxy for the development of technologies that create new value streams—are more closely tied to the everyday technology management and R&D programs of the European Producers. However, it is likely that these results are skewed due to the patenting data from Exxon. As shown in Figure I.6, Appendix I, the analysis of Exxon's public data

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[3] For the Spearman test, degrees of freedom are defined as the available number of matched pairs minus two ($n - 2$). With 17 years covered in the 2004–2020 data used for the Spearman correlations, this equates to a degree of freedom of 66 for European Producers and 49 for American Producers.

demonstrates no significant same-year correlation between patents and the three R&D metrics. This is contrasted by the results for both Chevron in Figure I.2 and Conoco in Figure I.4 that in general show stronger positive correlation between Disruptive CCMT Patents and both CCMT Patents and Total Patents.

On average, the American Producers show a stronger positive correlation between R&D Expenditure and both Sustaining CCMT Patenting ($r_s(49) = .83,\ p = < .001$) and Total Patenting ($r_s(49) = .91,\ p = < .001$), and between R&D Expenditure and Net Sales ($r_s(49) = .82,\ p = < .001$). European Producers show only moderate positive association between R&D Expenditure and both Sustaining CCMT Patenting ($r_s(66) = .42,\ p = < .001$) and Total Patents ($r_s(66) = .47,\ p = < .001$).

Likewise, the association between R&D Expenditure and Net Sales for European Producers is less correlated than for American Producers ($r_s(66) = .58,\ p = < .001$). One explanation is that during capital allocation for determining early budgets, European Producers may try to allocate R&D funding based on targeted benchmarks as opposed to adjusting the funding amount based on projections of Net Sales. The stronger correlation for American Producers could indicate that final R&D funding for a given year is more tied to same-year market performance.

5.4 Key Takeaways

1. Time-lag analysis indicates that the "lag" of R&D Expenditure to overall R&D patenting activity is complex. In general, R&D Expenditure lags from zero to one year in the past, with 5 months in the past as the average (Trajtenberg, 1990; Griliches, 1998).

2. Time-lag analysis exhibits the counter-intuitive finding that R&D Expenditure frequently lags into the future, indicating that successful R&D innovation can further enable increased future R&D and/or funding (Griliches, 1998).

3. This study provides evidence that R&D Expenditure does positively lag Disruptive innovation, here represented as Disruptive CCMT Patents. This general finding

is presented in Figure 5.3, as well as the Appendices H.3 and H.6, suggesting the correlation is likely due to the decreased number of Disruptive innovations.

4. R&D Intensity and R&D Productivity generally exhibit non-normal distributions, confirming earlier studies (Morbey & Reithner, 1990).

5. Spearman rank-order correlation testing provides a convenient method to analyze the association of multiple non-normal pairs, particularly when combined with graphical matrix tools.

6. On average, there is a moderately strong positive correlation between Disruptive CCMT Patents and both Sustainable CCMT Patents and Incremental Energy Tech Patents (see Figure 5.6). This finding indicates a degree of shared organizational capacity and portfolio management across the research groups.

7. R&D Productivity provides more explanatory power than R&D Intensity, due to the strong dependence of R&D Intensity on fluctuating Net Sales (Helfat, 1994). R&D Productivity shows moderate same-year positive correlations with Disruptive CCMT Patents, Sustaining CCMT Patents, and Incremental Energy Patents. As shown by Morbey & Reithner (1990), there is a moderately strong positive association between R&D Productivity and same-year Sales per Employee (see Figure 5.6).

8. Oil Price exhibits only weak correlation to same-year patenting or R&D Expenditure. Oil price has low correlation with same-year Net Sales.

9. On average, European Producers exhibit a stronger positive correlation between Disruptive CCMT Patents with both Sustaining CCMT Patents and Incremental Energy Patents, while US Producers demonstrate higher association among Sustaining CCMT Patents and overall patenting, and greater positive correlation between the R&D Expenditure and Total R&D Patenting. Both show similar strong positive correlation between Net Sales and same-year patenting (see Figures 5.9 and 5.10).

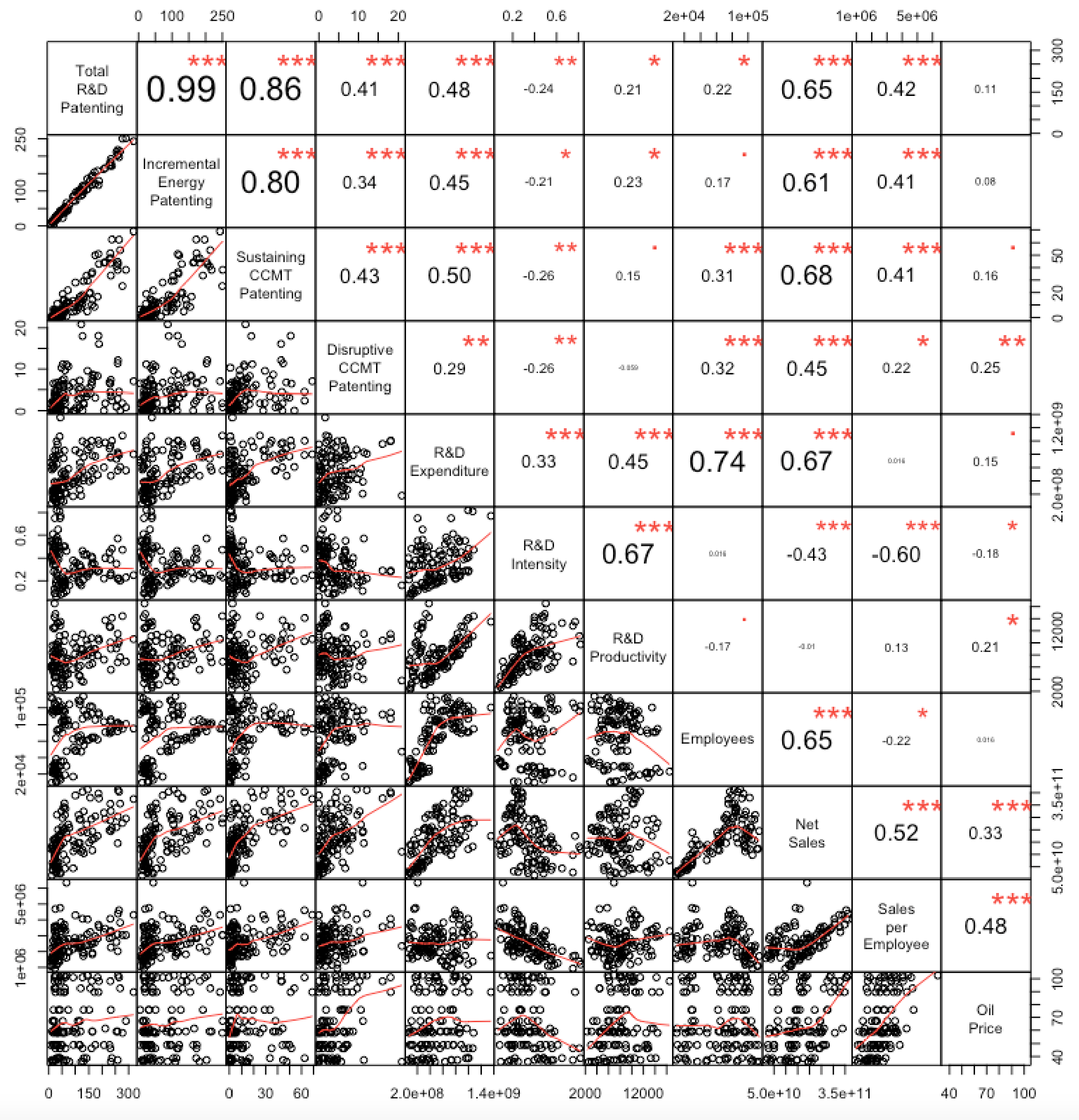


Figure 5.8: Spearman Correlation of Total R&D Patenting Activity with R&D Metrics, Sales and Oil Price: O&G Producers (No China), 2004–2020. This matrix captures the Spearman rank order coefficient for the eleven, same-year, non-lagged pairs. Patent count for Disruptive CCMT, Sustaining CCMT, and Incremental Energy Tech is separated to avoid collinearity. Source: Based on IRI data and EPO/USPTO data from Espacenet search engine.

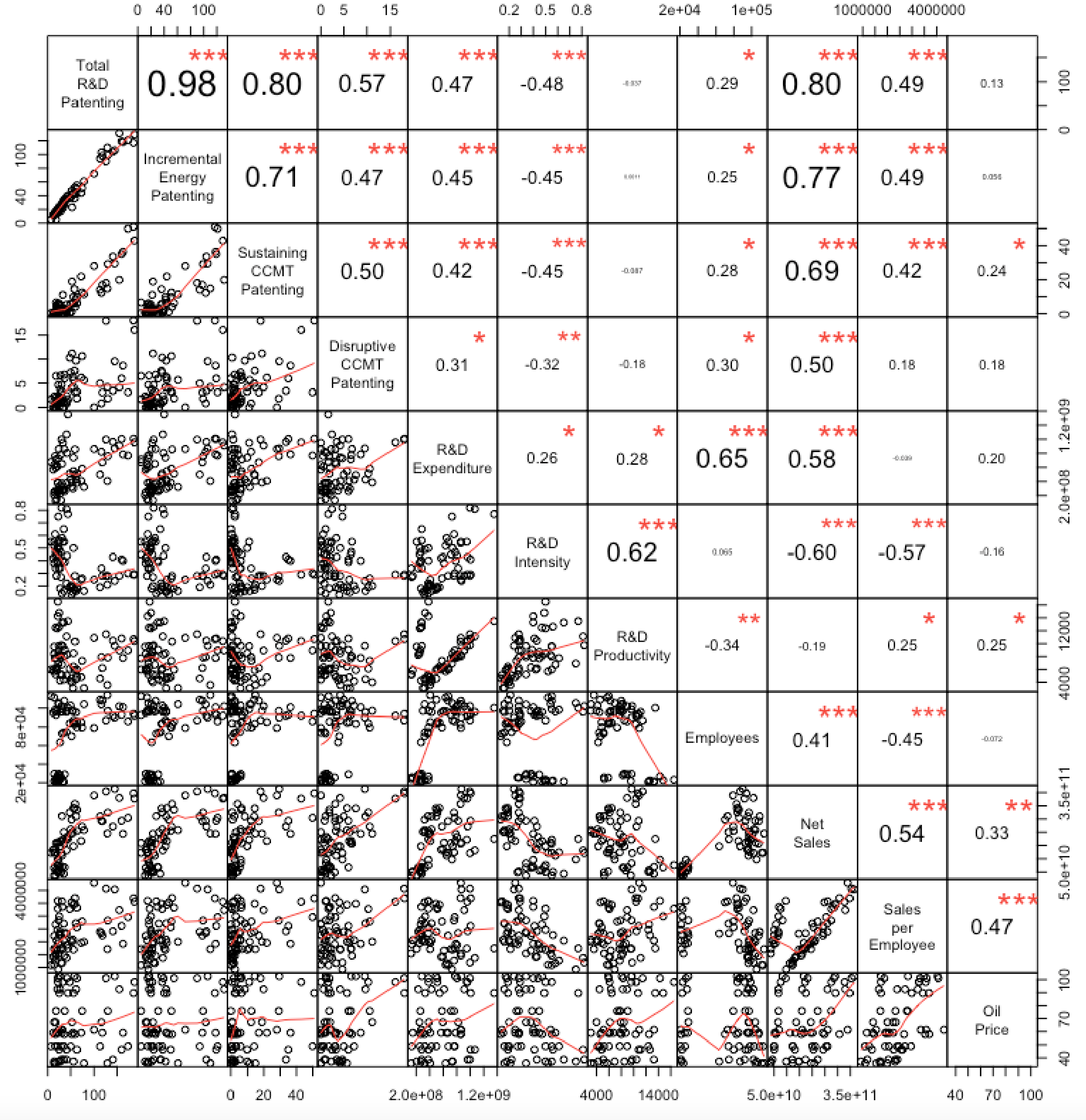


Figure 5.9: Spearman Correlation of Total R&D Patenting Activity with R&D Metrics, Sales and Oil Price: European O&G Producers, 2004–2020. This matrix captures the Spearman rank order coefficient for the eleven, same-year, non-lagged pairs. Patent count for Disruptive CCMT, Sustaining CCMT, and Incremental Energy Tech is separated to avoid collinearity. Source: Based on IRI data and EPO/USPTO data.

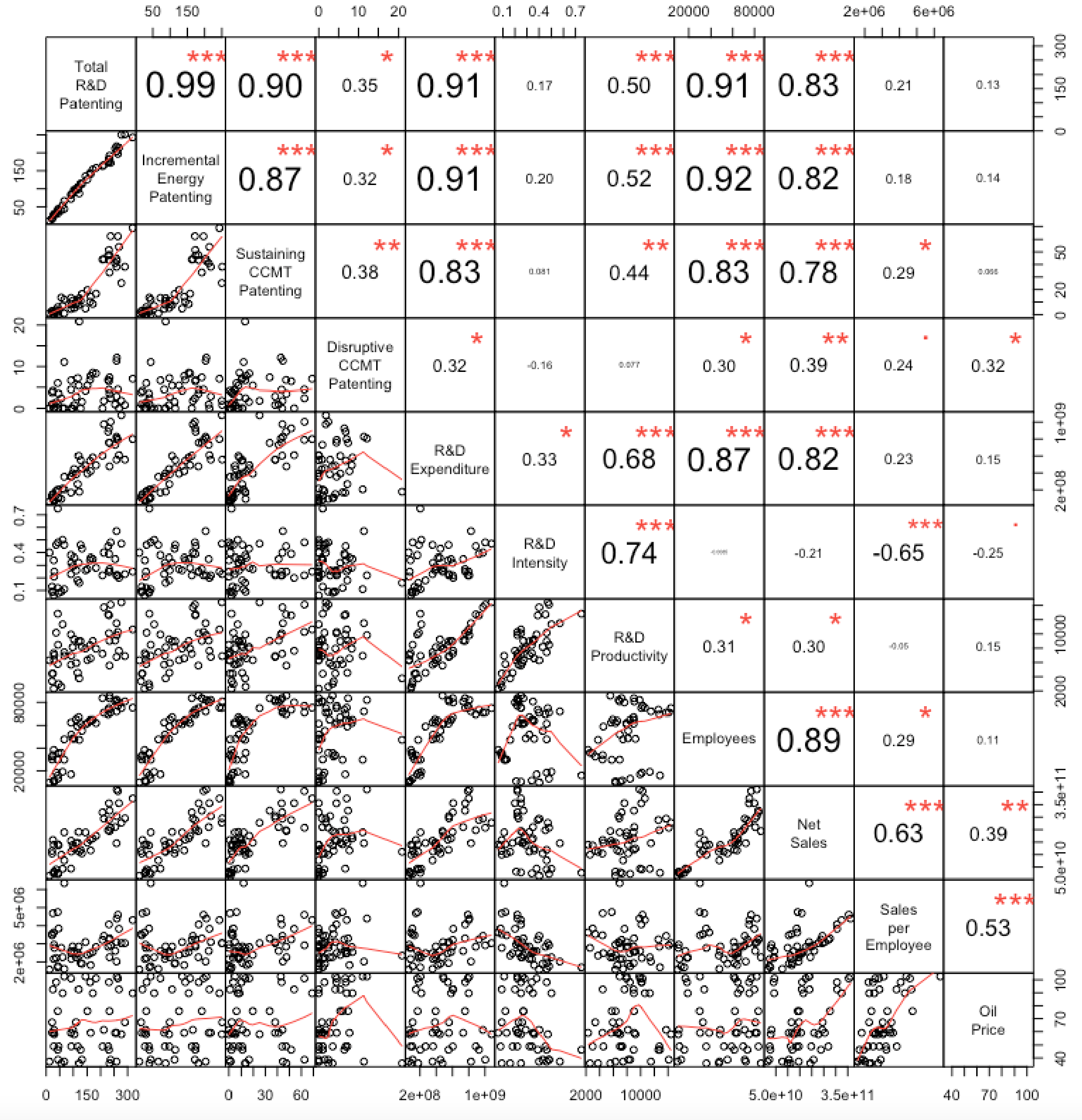


Figure 5.10: Spearman Correlation of Total R&D Patenting Activity with R&D Metrics, Sales and Oil Price: American O&G Producers, 2004–2020. This matrix captures the Spearman rank order coefficient for the eleven, same-year, non-lagged pairs. Patent count for Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT is separated to avoid collinearity. Source: Based on IRI data and EPO/USPTO data.

Chapter 6

Global Patent Growth, CCMTs and the Energy Transition

This final chapter compares fluctuations in global patenting statistics with the results we have presented in this thesis to identify potential trends and directions in technology management. Several steps are necessary to make this connection. First, we review the global technology trends that the EPO and IEA have identified as being tied to the larger Energy Transition. These trends will point to ongoing shifts in the direction of technology management and patenting. Second, statistics for the Oil & Gas industry will be computed to align with the time frame of the EPO and IEA study, including a reproduction of the EPO and IEA data sets. Third, the Disruptive CCMT, Sustaining CCMT, and Incremental Energy Technology patent data from this thesis will be graphically related to the broader global trends.

6.1 Patent Growth and the Energy Transition

A landmark study titled "Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation" was jointly published by the European Patent Office (EPO) and the International Energy Agency (IEA) in April 2021. This comprehensive, 72-page report lays out a definitive view of how Climate Change Mitigation Technology (CCMT) patenting trends are evolving during the Energy Transition. While recognizing that energy policy and governmental regulation play a critical roles in the Energy Transition, the EPO and IEA argue that the Energy Transition can be analyzed through the "changing technology landscape" of energy innovations (EPO/IEA, 2021, p. 9).

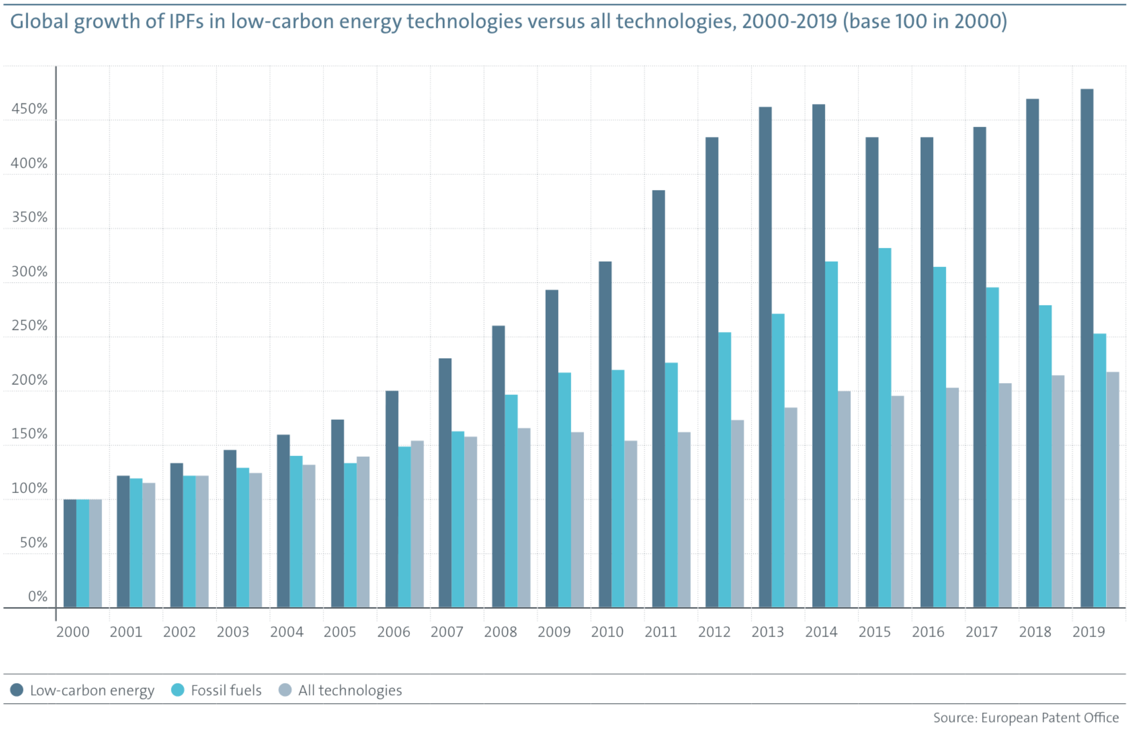
Importantly, the EPO and IEA build the case for utilizing the evolving trends in the patenting of high-value energy innovations as an analytical framework for assessing technological progress in the Energy Transition (EPO/IEA, 2021). To monitor this change over time, the EPO and IEA have tracked published international patent families for three main patenting trends, (1) Low-Carbon Energy (LCE), (2) Fossil Fuels; and (3) All Technologies. Here, it should be noted that a formal definition of Low-Carbon Energy (LCE) is not provided in "Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation". The report describes LCE technologies as "fuel-switching and energy efficiency technologies", "renewables (like wind, solar, geothermal or hydroelectric power)", and also "cross-cutting technologies such as batteries, hydrogen and smart grids, as well as carbon-capture, utilization and storage (CCUS), that serve as key enablers of the energy transition" (EPO/IEA, 2021, p. 11). We will return to this definition later in this chapter when we analyze the trends in the Oil & Gas industry for Climate Change Mitigation Technology (CCMT).

Figure 6.1 presents the EPO and IEA's landmark graph, presented as a bar chart, that illustrates both how patenting trends have changed over time and how these changes indicate an evolving Energy Transition. Copied directly from the EPO/IEA report, this bar chart was originally labeled Figure E1 in "Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation" (EPO/IEA, 2021, p. 10). According to the EPO and IEA, Figure 6.1 tells the developing global story of the Energy Transition. With the data for the three groupings of trend data normalized at Year 2000 at 100%, this figure shows the yearly global growth rate in international patent families between 2000 and 2019. The EPO and IEA state:

> "After a rapid rise in the period to 2013, patenting activity in LCE technologies slumped between 2014 and 2016. However, the latest data show three years of growth in LCE, which is a particularly encouraging trend when contrasted with the simultaneous decline of patenting in fossil energy—a four-year decline that is unprecedented since the second World War....

> However, the average annual growth rate of LCE patents in recent years (3.3% since 2017) has been considerably lower than the 12.5% average growth in the period 2000–2013" (EPO/IEA, 2021, p. 10).

A closer look at Figure 6.1 graphically depicts the average yearly growth of 12.5% between the years 2000 and 2013. This growth rate in Low-Carbon Energy (LCE) technologies—or, for convenience in this study, Climate Change Mitigation Technology (CCMT)—can be compared with the growth rate for both Fossil Fuel Technologies and All Technologies, which are both positive but lower than the growth of LCEs.


Global growth of IPFs in low-carbon energy technologies versus all technologies, 2000-2019 (base 100 in 2000)

Source: European Patent Office

Figure 6.1: EPO/IEA's Analysis of Patent Activity and the Energy Transition. This graph is from the EPO's and IEA's 2021 report, *Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation.* It charts a global decrease in CCMT patents (here called Low-Carbon Energy (LCE), depicted in Dark Blue) during the 2014–2015 drop in global oil price, which also resulted in a drop in Fossil Fuel patents (Light Blue) and overall Technology patents (Gray). Changing trends in patent recovery may indicate the Energy Transition. Data is normalized to base 100 in year 2000. Source: European Patent Office and International Energy Agency (EPO/IEA, 2021).

The critical argument laid out by the EPO and IEA is that an overall shift in the technology landscape is revealed by the patenting data following the growth adjustments in 2013. Now, LCEs (or CCMTs) continue to grow, albeit at a slower growth rate, while Fossil

Fuel Technologies begin to decline. As noted in the quoted passage above, the EPO and IEA state that this decline in the patenting activity in Fossil Fuel Technologies is the first sustained decrease since the second World War (EPO/IEA, 2021).

These findings by the EPO and IEA are supported by a handful of recent studies. In the recent research article, "Global Trends in the Innovation of Climate Change Mitigation Technologies", Probst et al. (2021) detail findings similar to the growth rates calculated by the EPO and IEA. However, and importantly, Probst et al. (2021) connect the drop in both LCE patenting and overall patenting to the global drop in oil price that occurred between 2014–2016. As detailed in Chapter 2, global oil price dropped from a high of above \$100/bbl in 2014 to under \$40/bbl in 2015–2016. As shown in the reproduced Figure 6.2, Probst et al. (2021) calculate a negative 6% growth rate for CCMTs following the reduction in oil prices. Probst et al. (2021) calculate an Average Annual Growth Rate (AAGR) of 10.4%, leading up to the oil drop, whereas the EPO/IEA calculated a 12.5% over a shorter time period. Probst et al. (2021) summarizes the global decrease in CCMT patenting as "likely driven by declining fossil fuel prices and, possibly, a readjustment of investors' expectations and a stagnation of public funding for green R&D after the financial crisis" (Probst et al., 2021, p. 2). Still, this study is limited by its time duration: the study only utilizes patent data up through 2017 and this prevents capturing the rebound in patenting growth rates as shown by the EPO and IEA study that examined patenting activity through 2020 (Probst et al., 2021, p. 13).

In Figure 6.3, Probst et al. (2021) present a graph of the normalized percentage of yearly CCMT patents to the total number of technology patents compared with the oil price. (Here, it is worth noting that Probst et al. (2021) normalize their graph to year 1995 with base 1, similar to how the EPO and IEA normalized their findings to base 100 in 2000.)

The findings of EPO/IEA (2021) and Probst et al. (2021) raise important questions to answering how technology management has changed in the Oil & Gas industry during the Energy Transition. And, this ties directly the Research Question #7: How does the Oil & Gas industry's R&D focus on Climate Change Mitigating Technologies (CCMTs) compare with the broader, global technology trends driving the Energy Transition? The next sections will describe an approach to quantifying this question.

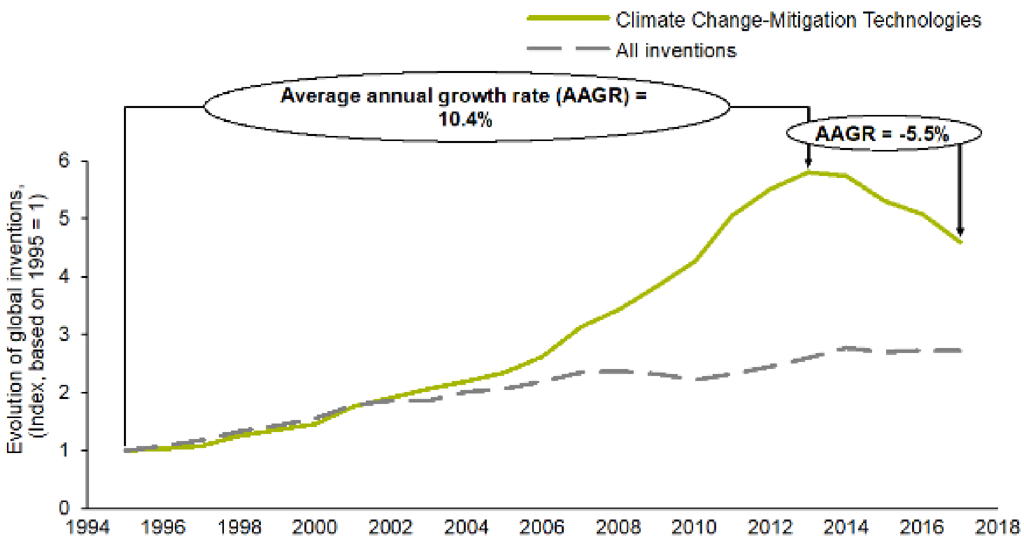


Figure 6.2: Probst et al. (2021)'s Analysis of Patent Activity, Oil Price and the Energy Transition, 1994–2017. This graph charts the percentage of normalized growth for global CCMT Patents as compared with total global patents, indicating an average yearly growth of 10.4% for CCMT patents from 1994 to 2014, and -5.5% from 2014 to 2015. Source: Probst et al., 2021, p. 13. Accessed at https://www.researchsquare.com/article/rs-266803/v1. This work is licensed under a Creative Commons Attribution 4.0 International License.

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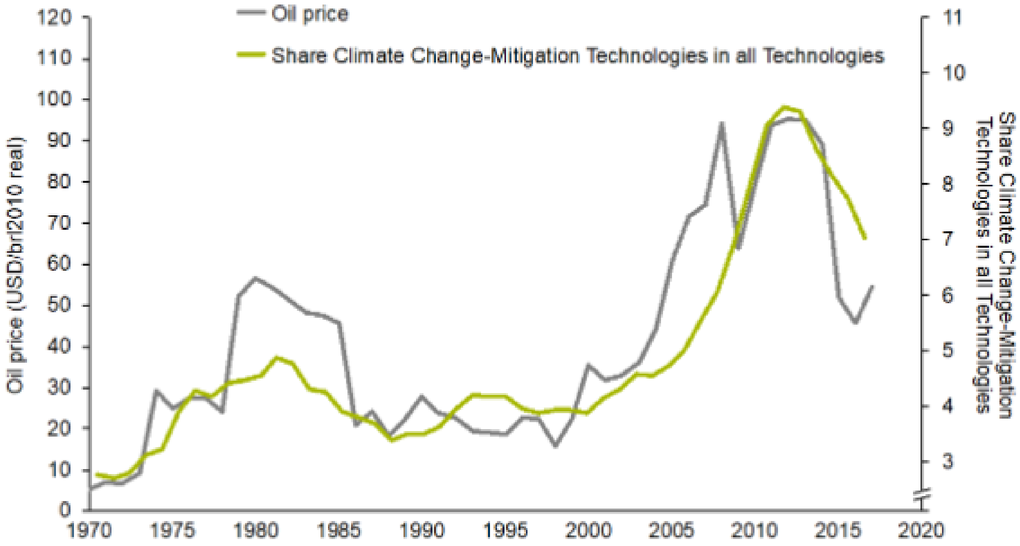


Figure 6.3: Probst et al. (2021)'s Normalized Percentage of CCMT Patent Activity to Total Patents with Oil Price, 1970–2017. This graph charts the percentage of normalized growth for global CCMT Patents as compared with trends in global oil price, indicating a high decree of coupling. Source: Probst et al., 2021, p. 13. Accessed at https://www.researchsquare.com/article/rs-266803/v1. This work is licensed under a Creative Commons Attribution 4.0 International License.

6.2 Methodology

6.2.1 Data Collection

This section overviews a method to quantitatively assess the growth rates for Climate Change Mitigation Technology (CCMT) and all technologies in the Oil & Gas industry, thus allowing a comparison with overall global trends.

First, the Espacenet patent search engine was used to approximate the total patent counts as presented by the EPO and IEA in Figure 6.1. This was achieved by using a similar search strategy as employed in Chapter 3 for Y02–Y04S patents, but without restricting the global search by company name, and thus including all international patent families. This approximated the "Low-Carbon Energy" data as shown on Figure 6.1. Likewise, a second search was conducted for total internal patent families that did not require the Y02–Y04S tags. This recreated the "All Technologies" data as shown on Figure 6.1.

The EPO/IEA search for "Fossil Fuels" patents could not be replicated in Espacenet because the search criteria used for this query was not detailed in their report (EPO/IEA, 2021). However, for this study, the data collected in Chapter 3 for "Incremental Energy Technology" can substitute as technologies directly related to fossil fuels and without a direct connection to CCMT. This substitution is reasonable based on the assumption that the twelve Oil & Gas companies in this study are largely representational of the overall industry.

Finally, and following the work by Probst et al. (2021), the EIA data for average yearly oil prices that was introduced in Chapter 2 is charted along with the total family of curves.

6.2.2 Verification of Results with EPO/IEA Data

Figure 6.4 presents the results of recreating the global patenting trends depicted by the EPO/IEA in Figure 6.1. Additionally, Figure 6.4 captures Global CCMT Patent Families, O&G Incremental Energy Tech (as a proxy for the EPO/IEA's Fossil Fuel patents), and Global Patent Families.

The Espacenet patent search results are highly consistent with the EPO/IEA report.

Several points of alignment are noted:

- Global CCMT Patent Families (Blue) grow from 100% in 2000 to approximately 440% in 2013. This compares with the EPO/IEA's Low-Carbon Energy (Dark Blue) growing from 100% to 460% in 2013, as shown in Figure 6.1.

- Global CCMT Patent Families (Orange) decrease in 2014–2015 by roughly 25%, while the EPO/IEA curve decreases by roughly 25%. Both decrease for nearly two years before increasing in 2017. Both curves had shown a cumulative growth of over 300% by 2015. O&G Incremental Energy Tech patents peak in 2015, fully aligning with the EPO/IEA data for Fossil Fuels patents, as shown in Figure 6.1.

- Global Patent Families (Green) continue to grow after 2015, but at a slightly decreased rate. This aligns with the All Technologies curve on Figure 6.1.

As a result, the alignment between the data sets provides confidence in using the EPO/IEA methodology to further examine how the Oil & Gas industry has managed technology through the Energy Transition.

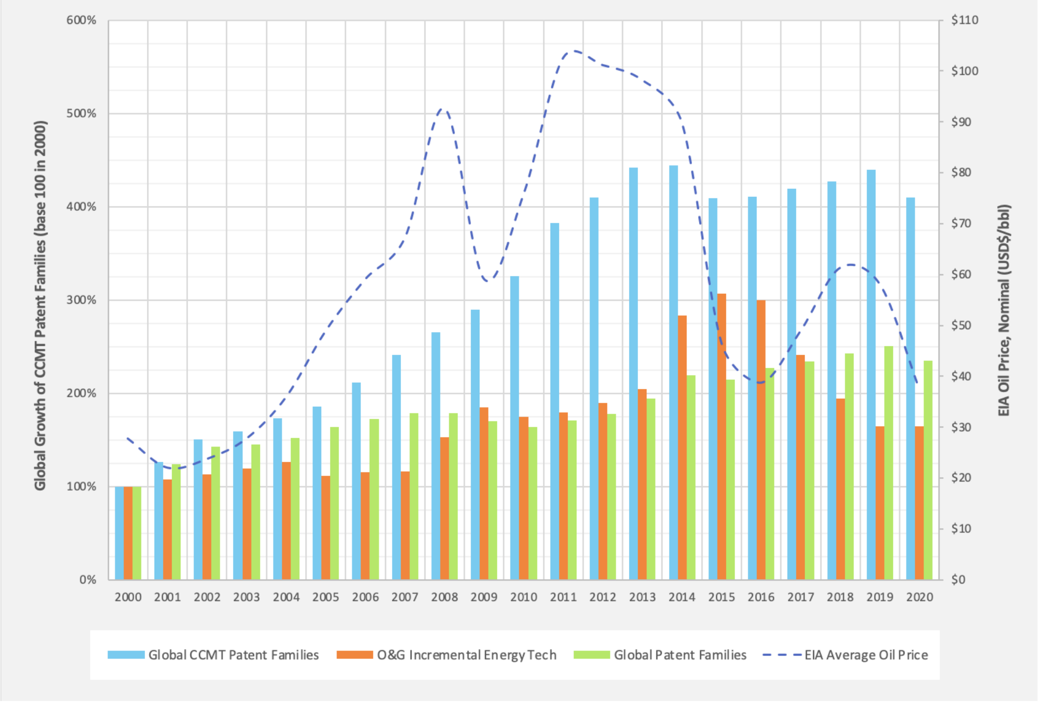


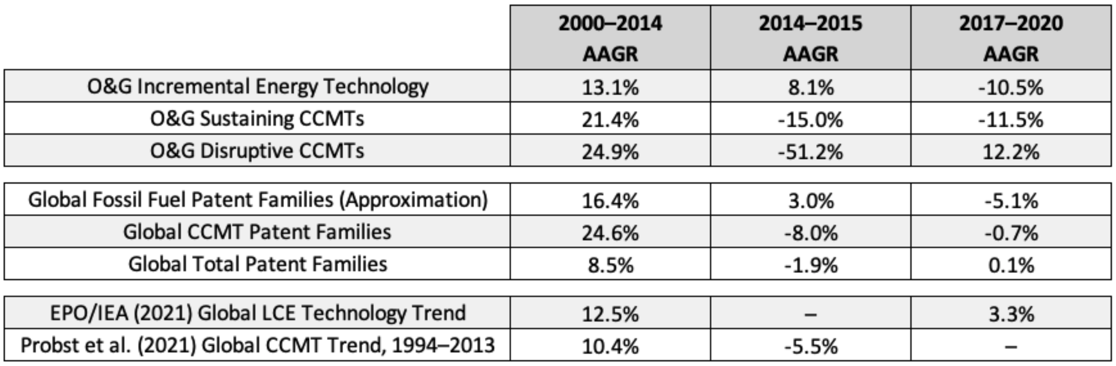
Figure 6.4: Results of Espacenet Search for Comparison with EPO/IEA and Energy Transition, 2000–2020. Source: Based on EIA and EPO/USPTO data.

6.3 Results

The results for comparing the Oil & Gas industry with the broader, global technology trends are included below. In total, there are two figures and one table presenting the results.

Figure 6.5 is a duplication of the EPO/IEA's bar graph that was presented in the previous subsection, but with the addition of O&G Disruptive CCMTs (Red) and O&G Sustaining CCMTs (Teal-Green). The only change made to this graph was the adjustment of the scale on the primary axis in order to accommodate the higher range of O&G Disruptive CCMTs. Figure 6.6 portrays the exact same data as Figure 6.5, but has changed the chart type from a bar chart to a line graph. Thus, Figure 6.6 allows for easier comparison and analysis of the changing trends.

Table 6.1 presents the calculated Average Annual Growth Rate (AAGR) for the Oil & Gas industry and the global technology landscape. Additionally, this table presents the published AAGR from both EPO/IEA (2021) and Probst et al. (2021). Average annual growth rate is calculated as the growth rate between the two dates, following the apparent method captured by the EPO/IEA (2021) and Probst et al. (2021). It should be noted that since the methodology on how the EPO/IEA sorted patents for Fossil Fuels is unknown, the values in the table are graphical approximations from Figure 6.1.



	2000–2014 AAGR	2014–2015 AAGR	2017–2020 AAGR
O&G Incremental Energy Technology	13.1%	8.1%	-10.5%
O&G Sustaining CCMTs	21.4%	-15.0%	-11.5%
O&G Disruptive CCMTs	24.9%	-51.2%	12.2%
Global Fossil Fuel Patent Families (Approximation)	16.4%	3.0%	-5.1%
Global CCMT Patent Families	24.6%	-8.0%	-0.7%
Global Total Patent Families	8.5%	-1.9%	0.1%
EPO/IEA (2021) Global LCE Technology Trend	12.5%	–	3.3%
Probst et al. (2021) Global CCMT Trend, 1994–2013	10.4%	-5.5%	–

Table 6.1: Comparison of Average Annual Growth Rates (AAGRs) for Global and O&G Patenting Trends in the Energy Transition, 2000–2020. The table shows the calculated non-compounded, average annual growth rate for comparative patent classes over the time intervals of 2000–2014, 2014–2015, and 2017–2020. Source: Based on EIA and EPO/USPTO data, (EPO/IEA, 2021) and Probst et al. (2021).

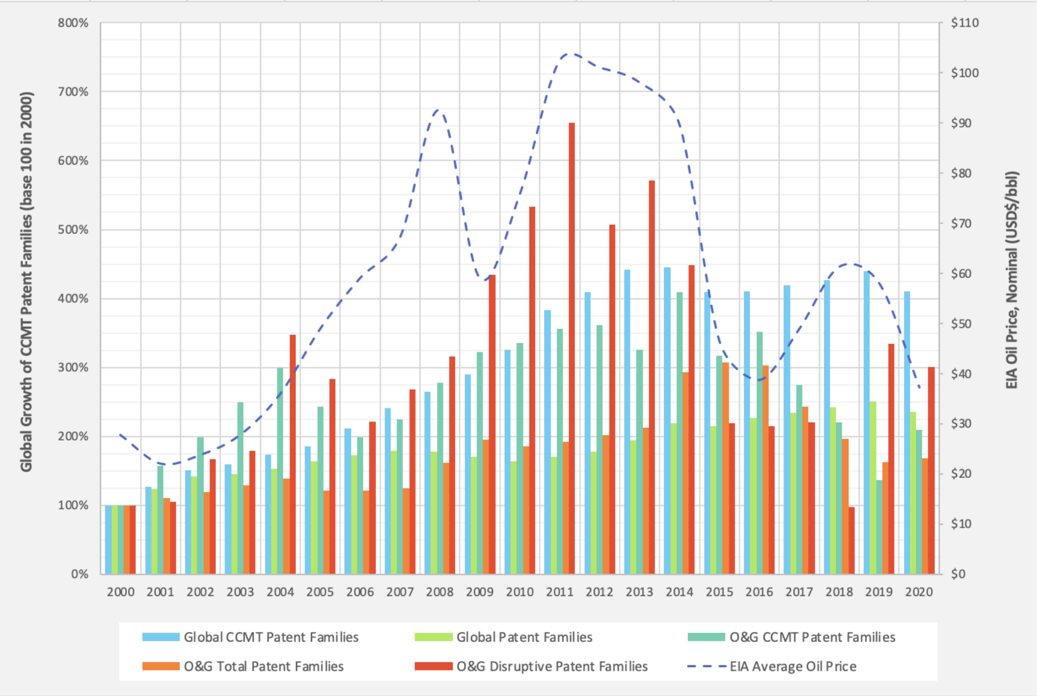


Figure 6.5: Global and O&G Patent Activity with Reference to the Energy Transition and Oil Price, 2000–2020 (1 of 2). The graph normalizes the patent data to base 100 in Year 2000, following EPO/IEA (2021) and Probst et al. (2021). EIA oil data is shown on the secondary axis and is non-normalized. Source: Based on EIA, and EPO/USPTO data.

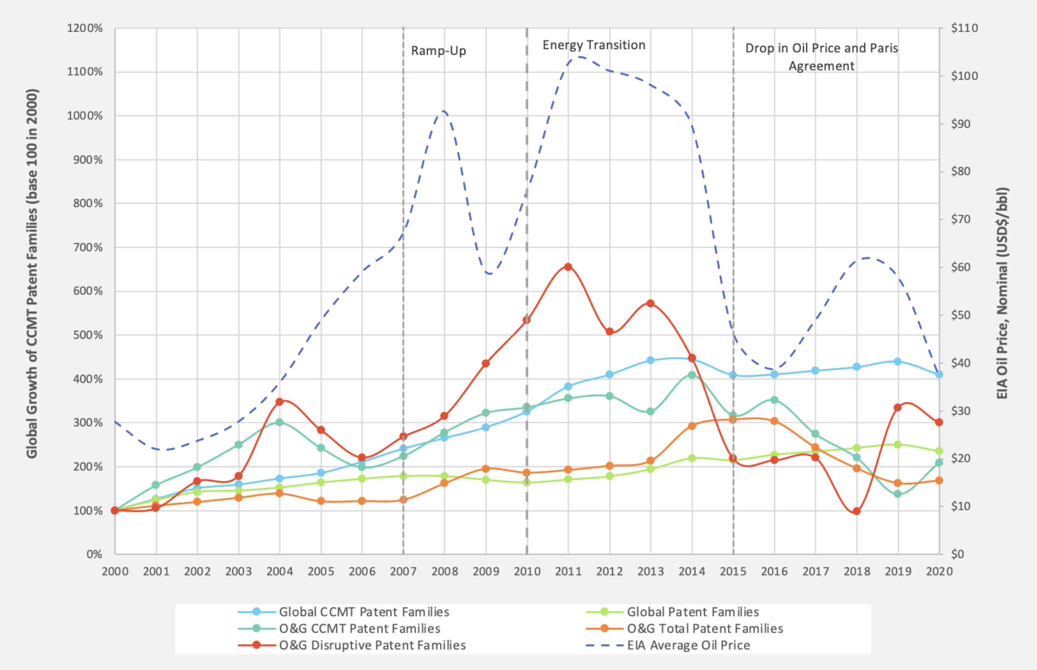


Figure 6.6: Global and O&G Patent Activity with Reference to the Energy Transition and Oil Price, 2000–2020 (2 of 2). The graph normalizes the patent data to base 100 in Year 2000, following EPO/IEA (2021) and Probst et al. (2021). EIA oil data is shown on the secondary axis and is non-normalized. Source: Based on EIA and EPO/USPTO data.

6.4 Analysis

The data show a surprising amount of parity between the Oil & Gas industry and the global trend in patenting CCMTs and LCE technologies from 2000 through 2016. Both Figure 6.5 and Figure 6.6 graphically exhibit the similar growth rates of Global CCMT Patent Families (Light Blue) and O&G Sustaining CCMT (Teal Green). The period of 2006–2010 is exceptional for the degree of coupling between the Oil & Gas industry and the broader growth of technologies during the Energy Transition. It appears that the drop in oil price between 2008–2009 from $90/bbl to under $60/bbl resulted in a readjustment for the Oil & Gas industry that took nearly five years, between 2010 and 2014, to regain the similar trajectory of the Global CCMT Patent Families. It is interesting to highlight that it does not appear that the broader R&D technological development of Global CCMT Patent Families was affected by the 2008–2009 drop in oil price. The two curves regain a similar normalized growth rate between 2014 and 2016, with both exhibiting total growth of nearly 400%. As recorded in Table 6.1, O&G Sustaining CCMTs achieved an AAGR of 21.4% between 2000–2014, while Global CCMT Patent Families had a near identical rate of 24.6%.

During this same time period of 2000 to 2013/2014, the yearly growth of O&G Incremental Energy Tech (Orange) was, likewise, very similar to the overall growth of Global Patent Families (Light Green). The similar growth rates between these two curves through the years 2008–2013 is noteworthy. As recorded in Table 6.1, O&G Incremental Energy Technology had an AAGR of 13.1% while Global Total Patent Families registered an AAGR of 8.5% and these number would be closer if the time period were calculated only to 2013, and not 2014.

However, the truly impressive curve, over this time period of 2000–2013/2014, is the O&G Disruptive CCMTs (Red). Here, O&G Disruptive CCMTs relatively traced the broader growth of both O&G Sustaining CCMTs and Global Total Patent Families from 2000 to 2008. But as oil prices continued to increase well above $80/bbl in 2008, the growth rate of published international families for O&G Disruptive CCMTs greatly increased. The combined growth for O&G Disruptive CCMTs increased from 300% in 2008 to over 600% in

2011, just three years later. This curve reached a peak of nearly 650% combined growth in 2011 as oil prices broke the $100/bbl threshold. Overall, O&G Disruptive CCMTs recorded an AAGR of 24.9% over the time period of 2000-2014, which shows strong alignment with the 24.6% of the Global CCMT Patent Families.

These normalized results lead to the new finding that the Oil & Gas industry was producing Climate Change Mitigation Technology (CCMT) on par with the broader global marketplace during the years 2000 to 2014. Overall, the growth of CCMT innovations mirrored the global growth of CCMTs. During increasing oil prices, O&G Disruptive CCMTs grew at a faster rate than both O&G Sustaining CCMTs and Global CCMT Patent Families. At the same time, the Global CCMT Patent Families appear to increase with rising oil prices, but do not show a noticeable downturn during the reduction in oil price in 2009.

The dramatic drop in oil price between 2014–2016 significantly challenges the parity between the O&G and Global curves. In this drop, oil prices fell from above $100/bbl in 2011 to under $40/bbl in 2016. Importantly, the Global CCMT Patent Families curve shows a decrease in growth between 2014 and 2015, as does Global Patent Families. As shown in Table 6.1, Global CCMT Patent Families dropped -8.0% and Global Patent Families dropped collectively as -1.9%. This highlights a finding in Probst et al. (2021) and EPO/IEA (2021) that all energy-related Climate Change Mitigation Technology (CCMT) are affected by changes in oil price. Referencing both Popp (2006) and Popp (2001) for their work, Probst et al. (2021) claim: "Existing research confirms a causal and not merely correlational relationship: CCMT inventors respond rapidly to changes in fossil fuel prices."

At the same time, the Oil & Gas industry had more dramatic drops in growth rates. Between 2014 and 2015, O&G Sustaining CCMTs dropped by -15.0% and Oil & Gas Disruptive CCMTs plummeted by -51.2%. On the other hand, O&G Incremental Energy Technology continued to increase, but this result is likely the ongoing publishing of innovations already in the pipeline as the growth rate does not begin to drop until 2016/2017.

Here, we can summarize that Global CCMT Patent Families are more impacted by decreases in oil price than Global Patent Families, but that this decrease is minor compared to the large-scale effect that changes can have on technology management in the Oil &

Gas industry. The evidence indicates that O&G Disruptive CCMTs are the first to be cut during periods of deflated prices, followed by O&G Sustaining CCMTs and, finally, O&G Incremental Energy Tech.

It is not entirely clear in the data whether overall activity in Global CCMT Patenting or the Oil & Gas industry has recovered from the 2014–2015 drop in oil price, a point highlighted in the literature (Probst et al., 2021; EPO/IEA, 2021). As noted by EPO/IEA (2021), the annual growth rate for Global CCMT Patent Families has been muted since 2015, showing a calculated value in Table 6.1 of -0.7% between 2017 and 2020. The EPO and IEA have noted that: "Overall, the current growth rate remains below that witnessed before 2013, and an acceleration in activity would be needed to make up for the lost years" (EPO/IEA, 2021, p. 10). Likewise, the growth rate for Global Total Patent Families is effectively zero at 0.1%.

A central premise in the EPO/IEA report, "Patents and the Energy Transition: Global Trends in Clean Energy Technology Innovation", is that the drop in the publication of patent families for Fossil Fuels since 2014/2015 is a broad indication of the Energy Transition at work (EPO/IEA, 2021). This premise may prove to be true, however it is not possible to completely differentiate between the lagged recovery from the 2014/2015 drop in oil prices and any strategic or structural changes to how Oil & Gas companies are pursuing R&D and patenting activity. Between 2017 and 2020, O&G Sustaining CCMTs have dropped by -11.5% and this is a greater percent change than the estimated amount by the EPO/EIA of -5.1%. This drop in O&G Sustaining CCMTs is closely mirrored by the similar decrease in O&G Incremental Energy Technology by -10.5%. There is the possibility that this decrease reflects not just the drop in oil price and subsequent recovery but a shift in technology management. While oil prices did increase to above $60/bbl in 2018–2019, the positive response in growth rates is muted, if any.

But perhaps there is some indication of the Energy Transition and shifts in technology management. Here, the O&G Disruptive CCMTs show an increase of 12.2% that may point toward expanding technology priorities. However, these numbers must be treated with caution due to the lower number of Disruptive CCMTs for the twelve companies: Small yearly changes can make a large percentage change.

In summary, the period following 2014–2015 is complicated for both global trends and those in the Oil & Gas industry. As expected, a decrease an oil price has a larger influence on Oil & Gas companies than on the technology landscape as a whole, and the recovery time appears to be longer. As argued by the EPO/EIA, there has been a decrease in O&G Sustaining CCMTs and O&G Incremental Energy Technology since 2015, however this claim cannot be differentiated from overall oil price. Despite the small yearly count of twelve companies in this study, the growth rate of Oil & Gas Disruptive CCMTs highlights potential shifts that could occur in the coming years.

6.5 Key Takeaways

1. The Oil & Gas industry has developed Climate Change Mitigation Technology (CCMT) on par with annual growth rates for global development of climate-forward technologies, specifically from 2000 to 2014.
2. Between 2000 and 2014, there was close alignment in the AAGR between O&G Sustaining CCMTs at 21.4% and Global CCMT Patent Families at 24.6%. Moreover, O&G Disruptive CCMTs had an AAGR of 24.9%. O&G Incremental Energy Technology shared a similar AAGR with Global Patent Families, at 13.1% and 8.5%, respectively.
3. The AAGR of O&G Disruptive CCMT patenting was affected first by the decrease of oil prices in 2014–2015, with subsequent impact on O&G Sustaining CCMTs and O&G Incremental Energy Tech. The wider Global CCMT Patent activity had a one-year drop of -8.0% due to changes in oil price.
4. The years since the 2014–2015 decrease in oil price are complex. The overall, and lingering, impact of the decrease seems to be reflected in both the overall R&D development of Oil & Gas patenting as well as global trends. Since 2014–2015, Global CCMT Patent Families have achieved a lower yearly growth rate of -0.7%. The cause of this could be the ongoing impacts of oil price, the higher hurdle to successfully patent CCMTs, impacts from the financial crisis, or market signals for increased governmental regulation (Probst et al., 2021, pp. 4–6).

Chapter 7

Conclusions and Practical Recommendations

This thesis, "Quantifying Technology Management in the Energy Transition: Evidence from the the Oil & Gas Industry", has utilized quantitative R&D data to explore how Oil & Gas companies are adapting their technology management during the Energy Transition.

7.1 R&D Metrics and Technology Management

Research Question #1 examined whether classical R&D benchmarking metrics are sufficiently descriptive to quantify how Oil & Gas companies have expanded their technology efforts during the Energy Transition (see Chapter 2).

- This study calculated R&D Intensity and confirmed values previously reported in the literature. The mean R&D Intensity for all O&G Producers is 0.373% (σ = 0.078%), while for O&G Service Providers this jumps to 2.338% (σ = 0.239%). On average, European Producers have a higher R&D Intensity than American Producers.

- This study provided evidence that R&D Productivity—defined as the total R&D expenditure per employee—is a more stable metric to track R&D commitment in the Oil & Gas industry due to the cyclical nature of oil prices and year-to-year fluctuations in net sales. Both European Producers and American Producers have nearly identical R&D Productivity at €8,055/employee and €8,099/employee, respectively. This metric for China is significantly lower at €2,130 due to an increased headcount. O&G Service Providers have a mean R&D Productivity of €5,235/employee.

- Overall, traditional R&D metrics provide a high-level snapshot of commitment to technology management over time. However, these metrics alone are not sufficient to indicate repositioning of technology strategies. This is due partly to the masking effect of oil price on net sales, profit, and overall R&D budgeting.

7.2 CCMT Patenting and Technology Focus Areas

Research Question #2 examined how much high-value innovation is classified as Climate Change Mitigation Technology (CCMT), and which technology focus areas are being researched and developed in the Oil & Gas industry (see Chapter 3).

- This study provided evidence that published international patent families are an ideal proxy for quantifying high-quality technological innovation because they provide for a normalized comparison between companies, industries and countries. The CPC's Y02–Y04S classification system is a powerful tool for R&D trends in Climate Change Mitigating Technologies and for improved technology management benchmarking.
- There is wide variability in the distribution of CCMT patenting activity between individual companies, sectors and regions. Overall, the Oil & Gas industry is producing near 11% of total technology patenting on Climate Change Mitigating Technologies. Nearly 19% of all yearly technological innovation by O&G Producers is Climate Change Mitigating Technology (CCMT). In contrast, O&G Service Providers are patenting just under 3% as CCMTs.
- The top three prevalent Y02–Y04 tags for CCMTs are Y02P 20/00: Technologies relating to chemical industry (32% of total CCMTs), Y02P 30/00: Technologies relating to oil refining and petrochemical industry (20%), and Y02C 20/00: Capture or disposal of greenhouse gases (11%). Enabling Technology is the fourth most common CCMT Focus Area at 7%, indicating technology that can fast-track future innovation. This finding mirrors broader global patenting trends in CCMT and enabling technologies.
- This study highlights a potential opportunity in technology management. Whereas O&G Producers have long relied on O&G Service Providers for innovation and product development, this trend is not present for CCMTs. Based on the current data, O&G Producers will need to either identify and outsource to new Service Providers or will need to increase in-house output of CCMT innovations.
- Finally, this study highlighted the potential value for benchmarking CCMT data between industry peers and competitors. This level of information can provide further insight on Technology Focus Areas and Revealed Technological Advantage. Additionally, this information can provide a framework for the current state of the art and opportunities to expand Absorptive Capacity in the company.

7.3 Disruptive and Sustaining Technologies

Research Question #3 investigated how companies are apportioning their R&D portfolios between Incremental Energy Technology, and both Sustaining and Disruptive Climate Change Mitigation Technology (CCMT). To explore this research question, a novel qualitative method was developed to further sub-classify the Climate Change Mitigating Technologies (CCMT) into either Sustaining CCMTs or Disruptive CCMTs. This method was based on using the detailed definitions in the CPC's Y02-Y04S schema to sort groups of technologies on whether they broadly supported, or "sustained", existing base businesses and value chains (see Chapter 3.

- A key finding of this study calculated that the twelve O&G companies exhibit an average of 89.4% Incremental Energy Technology, 8.3% Sustaining CCMT, and 2.3% Disruptive CCMT. These percentages shift toward Climate Change Mitigating Technologies when the O&G Service Providers are removed, resulting in 82.7% Incremental Energy Tech, 14.7% Sustaining CCMT, and 2.6% Disruptive CCMT.
- Regionally, this method highlighted that there is less variation between European O&G Producers and American O&G Producers. On average, American Producers publish more Incremental Energy Technology and Sustaining CCMT, while Europeans Producers have a higher percentage of Disruptive CCMTs and Sustaining CCMTs, although only slightly.
- O&G Service Providers are publishing a low percentage of both total Disruptive CCMT patents and total Sustaining CCMT patents.

7.4 Correlation Between Incremental, Sustaining, and Disruptive Technologies

As the first of the three research questions in Chapter 5, Research Question #4 examined if there is positive correlation between the in-house organizational capability to produce Incremental Energy Technology and either Sustaining CCMTs or Disruptive CCMTs.

- This study shows that, on average, there is a moderately strong positive correlation between Disruptive CCMT Patents and both Sustainable CCMT Patents and Incremental Energy Tech Patents (see Figure 5.6). This finding indicates a degree of shared organizational capacity and portfolio management across the research groups for the industry as a whole. Here, it is theorized that a higher positive correlation between Incremental Energy Technology and either Sustaining CCMT or Disrupting CCMT indicates more established or centralized organizational R&D capabilities.

- However, this finding does not hold for all of the individual companies. Several companies show non-correlation between all patenting activity, indicating that innovation may occur in silos or in a R&D portfolio management system that does not differentiate funding between types of innovation (see Appendix I).

7.5 Association Between Patenting and R&D Metrics

Research Question #5 addressed the question of how R&D Spend, R&D Intensity and R&D Productivity are linked to the innovation of high-value Climate Change Mitigating Technology. Additionally, it explored the question of whether time lag needs to be included in correlation studies between R&D patents and R&D expenditure.

- Time-lag analysis indicates that the "lag" of R&D Expenditure to overall R&D patenting activity is complex. In general, R&D Expenditure lags from zero to one year in the past, with 5 months in the past as the average (Trajtenberg, 1990; Griliches, 1998). Time-lag analysis exhibits the counter-intuitive finding that R&D Expenditure frequently lags into the future, indicating that successful R&D innovation can further enable increased future R&D and/or funding (Griliches, 1998).
- This study provides evidence that R&D Expenditure does positively lag Disruptive innovation, here represented as Disruptive CCMT Patents. This general finding is presented in Figure 5.3, as well as the Appendices H.3 and H.6, suggesting the correlation is likely due to the decreased number of Disruptive innovations.
- Results of the correlation analysis showed that R&D Productivity provides more explanatory power than R&D Intensity, due to the strong dependence of R&D Intensity on fluctuating Net Sales (Helfat, 1994). R&D Productivity shows moderate same-year positive correlations with Disruptive CCMT Patents, Sustaining CCMT Patents, and Incremental Energy Patents. As shown by Morbey & Reithner (1990), there is a moderately strong positive association between R&D Productivity and same-year Sales per Employee (see Figure 5.6).
- On average, European Producers exhibit a stronger positive correlation between Disruptive CCMT Patents with both Sustaining CCMT Patents and Incremental Energy Patents, while US Producers demonstrate higher association among Sustaining CCMT Patents and overall patenting, and greater positive correlation between the R&D Expenditure and Total R&D Patenting. Both show similar strong positive correlation between Net Sales and same-year patenting (see Figures 5.9 and 5.10).

7.6 R&D Activity, Net Sales and Oil Price

As the last research question explored in Chapter 5, Research Question #6 examined how significantly an organization's overall R&D effort and R&D innovation capability are correlated with year-to-year fluctuations in net sales and oil price.

- Oil Price exhibits only weak correlation to same-year patenting or R&D Expenditure. Oil price has low correlation with same-year Net Sales.
- Spearman correlation results give support to previous findings that there is a strong "asymmetric response" between R&D Expenditure and Oil Price, indicating that R&D expenditure rises slowly during periods of increase in oil price, but decrease quickly when oil prices fall.

7.7 Global Trends and the Energy Transition

As outlined in Chapter 6, Research Question #7 explored how the Oil & Gas industry's R&D focus on CCMTs compares with the broader, global technology trends driving the Energy Transition.

- The Oil & Gas industry has developed Climate Change Mitigation Technology (CCMT) on par with annual growth rates for global development of climate-forward technologies, specifically from 2000 to 2014.
- Between 2000 and 2014, there was close alignment in the annual growth rates between O&G Sustaining CCMTs at 21.4% and Global CCMT Patent Families at 24.6%. Moreover, O&G Disruptive CCMTs had a near identical AAGR of 24.9%. O&G Incremental Energy Technology shared a similar growth rate with Global Patent Families, at 13.1% and 8.5%, respectively.
- The AAGR of O&G Disruptive CCMT patenting was affected first by the decrease of oil prices in 2014–2015, with subsequent impact on O&G Sustaining CCMTs and O&G Incremental Energy Tech. The wider Global CCMT Patent activity had a one-year drop of -8.0% due to changes in oil price.
- The years since the 2014–2015 decrease in oil price are complex. The overall, and lingering, impact of the decrease seems to be reflected in both the overall R&D development of Oil & Gas patenting as well as global trends. Since 2014–2015, Global CCMT Patent Families have achieved a lower yearly growth rate of -0.7%. The cause of this could be the ongoing impacts of oil price, the higher hurdle to successfully patent CCMTs, impacts from the financial crisis, or market signals for increased governmental regulation (Probst et al., 2021, pp. 4–6).

7.8 Practical Recommendations

The findings of this research result in several practical recommendations for technology managers, particularly those in the Oil & Gas industry.

- ***R&D Productivity.*** Findings suggest an expanded role for R&D Productivity for competitive benchmarking and, ideally, both capital allocation and yearly budgeting. This metric presents a more stable measure of R&D commitment than either R&D Intensity or R&D Expenditure. Benchmarking could include a target Average Annual Growth Rate for R&D Productivity. Additionally, companies may examine how R&D Productivity relates to attracting and retaining top talent.
- ***Y02-Y04 Tracking and Revealed Technological Advantage.*** Organizations should develop an in-house system for tracking and monitoring Y02-Y04 patenting activity for sharpening business intelligence and growing organizational capability.
- ***Innovating CCMTs.*** Organizations should examine how new innovations can be adapted to qualify for CCMT tagging through increased efficiency and mitigation.
- ***Percent CCMT for Benchmarking and Portfolio Management.*** Findings suggest adopting Percent CCMT (% CCMT) as an additional technology benchmark for tracking competitors and in-house focus areas. Ideally, R&D portfolio management could set target percentages for Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT. It is recommended that project selection and funding should occur within each separated category, independent of the other two categories.
- ***R&D Effort as a Proxy for Absorptive Capacity.*** The R&D organization of the future may be as focused on synthesizing knowledge from outside the organization as on creating new knowledge inside the organization (Cohen & Levinthal, 1990). This is particularly true for companies and industries that are typically defined as "fast followers". The expansion of Y02-Y04 CCMTs presents a practical opportunity for corporations to evaluate how absorptive capacity is occurring within R&D efforts, and the preferred channels for capturing and cascading organizational learning.
- ***Service Companies and the Energy Transition.*** The CCMT patenting trends of O&G Service Providers may be a mid-term to long-term technology concern for O&G Producers. As Oil & Gas companies continue to pivot into expanded markets opened up by the Energy Transition, it is not evident from the current data that Service Providers will have the in-house competencies to develop innovation in areas tangential or outside of hydrocarbons. Oil & Gas Producers will likely need to increase in-house R&D in the area of CCMTs or develop relationships with additional service providers with expertise in Climate Change Mitigating Technologies.
- ***Strategic Technology Roadmapping.*** The above recommendations and findings support the development and maintenance of integrated technology roadmaps to be used as drivers of strategic planning, particularly for critical areas of Sustaining CCMTs and Disruptive CCMTs (de Weck, 2022; Phaal et al., 2013).

Chapter 8

Recommendations for Future Work

This final chapter presents three broad research areas that are fertile ground for future exploration. Several of the recommendations are for methods or topics that have been introduced in this thesis but that could be expanded. Other recommendations are aimed at potential next-steps for advancing how quantitative methods and data analytics can be used in the evaluation of technology management strategies. The overarching goal of these inquiries is to better understand and model how companies, communities and governments can best shape technology-management plans in the face of uncertainty.

8.1 Patent Landscaping

As detailed in Chapter 3, a significant focus of this thesis explored how Climate Change Mitigating Technologies can be searched, extracted from the public patent data, and analyzed to gain additional technological insight.

- ***Patent Data Collection***. An improved search method for collecting CCMT data from the Y02–Y04S tagging scheme is needed. Specifically, a method to access or download data sets is necessary to conduct more complex research studies in CCMT patenting trends, perhaps with more companies or for cross-industry studies. This thesis relied on the EPO's Espacenet patent search engine and a large amount of manual searching and data handling. Access to the EPO's PATSTAT data base could facilitate large-scale data downloads. As noted in Chapter 3, MIT provides free-access to both PatSnap and PatenScout, however these patent search engines have paywalls for other users.

- ***Quantitative Analysis with Patent Citations and Network Theory***. This research did not utilize the rich data provided by patent citations. The current academic literature provides numerous examples of applying clustering and networking algorithms to establish the connection between patents (Svensson, 2022; Scherer, 1992; Fischer & Leidinger, 2014; Trajtenberg, 1990). There is opportunity to utilize forward patent citations—defined as the network of future patents that specifically cite the original patent—on top of the methods presented in this thesis on CCMT patenting (Svensson, 2022; Harhoff, Scherer, & Vopel, 2003; Fischer & Leidinger, 2014). This could improve the differentiation between "Disruptive" and "Sustaining" technologies through the introduction of the patent concepts of "radicalness" and "originality" (Popp et al., 2020; Trajtenberg, 1990; Trajtenberg et al., 1997). Here, "radicalness" evaluates how individual patents have absorbed ideas from outside of their primary technology area, while "originality" evaluates that degree of different fields that an individual patent relies on (Popp et al., 2020, p. 27). For example, are patents labeled as "Disruptive" linked to other "Sustaining" technologies developed by a company and/or industry, or are the connections more widespread? Building on the clustering algorithms: How are "Disruptive" technologies clustered compared to other technology? These are rich areas for future research on the Energy Transition.

- ***Qualitative Classification of Sustaining and Disruptive Technologies***. Future research could expand the proposed method for sorting patents as Sustaining and Disruptive, particularly through the application of qualitative methods. Specifically, the Delphi method could be used to anonymously poll subject-matter experts to better establish the boundaries for Sustaining and Disruptive technologies. In addition to the Delphi method, additional qualitative tools could be applied (Nightingale & Rhodes, 2015).

- ***Patent Timing***. Building on the research methods used by other patent landscape studies, this thesis used the first instance of the Publication Date of the International Patent Family. And due to the limitations with the collection of patent data from Espacenet, the First Filing date was not recorded for this study. Future studies could use both the First Filing date and the Publication Date to better understand the "turnaround time" or "time to market" for technology development and patenting processing time. Moreover, this information could be used to improve the Time-Lag Analysis between R&D Expenditure and time to patents. As will be discussed below, this could improve the overall correlation model.

- ***Collaboration Analysis***. A relatively new trend in patent landscape studies is to analyze the amount of connection or collaboration which exists between the patent filer and those that license or cooperate through collaborative models (Perrons, 2014). Here, future studies could examine the degree of technology transfer between companies, industries and/or geographic regions Ghafele & Gibert (2011). Perrons (2014) includes a rather comprehensive literature review on current work on collaborative R&D endeavors in the Oil & Gas industry.

8.2 Correlation Analysis

- ***Corporate Venture Capital***. This research relied heavily on differentiated patent data to build a case for trends in technology management and potential strategic repositioning to meet outside change (Perrons, 2014; Daneshy, 2004, 2003). Future work could incorporate the publicly available data for Corporate Venture Capital (CVC), perhaps from a source like CrunchBase (Popp et al., 2020, p. 36). Several intriguing areas of pursuit open up with the addition of CVC data. Is there technology alignment between CCMT Patents or Disruptive Patents and Corporate Venture Capital? Do investment trends support or contradict findings of a Revealed Technological Advantage? Here, the research could explore whether internal R&D is aligned with external acquisition of technology, potentially still using the Y02–Y04S schema to align the data sets. Perrons (2014) provides a partial bibliographic list of the role of CVC in the Oil & Gas industry.

8.3 R&D Benchmarking Metrics

This research attempted to explore several metrics that are useful for evaluating R&D technology programs. Several potential metrics were discussed or mentioned in this study that could provide a springboard for future inquiry.

- ***Percent CCMT Patents***. This research proposed a potential R&D metric of Percent CCMT Patents as a measure of the amount of technologies broadly associated with the Energy Transition. Future work could examine the relationship of Percent CCMT Patents and R&D Intensity across multiple industries. Whereas it is common for studies to present average R&D Intensities per industry, there could be added value in establishing an average Percent CCMT Patents across sectors. This could advance the work presented in Chapter 6, which attempted to connect technological development in the Oil & Gas industry with broader, global trends.

- ***Approximating R&D Portfolio Budgets***. The work in this thesis resulted in the separation of R&D patenting into three main groups: Incremental Energy Technology, Sustaining CCMT, and Disruptive CCMT. Importantly, these groups, constructed as percentages, could be utilized as a proxy for the overall distribution of R&D effort in a company. Using this division, future work could explore the development of weighting factors to estimate how R&D Expenditure is approximately being appropriated between different portfolio groups.

- ***Absorptive Capacity***. Following the landmark paper by Cohen & Levinthal (1990), the expanding role of how corporate R&D departments can expand the overall "absorptive capacity" of the company remains a rich area of inquiry. Here, several approaches could be used to estimate how companies are benefiting from the development of CCMTs by neighboring competitors, including the analytical "technology proximity" models forwarded by A. B. Jaffe (1989). Here, there are rich opportunities to adapt the Jaffe equations for large-scale data analytics.

Glossary

Absorptive Capacity "The ability of an organization to recognize, assimilate, and utilize new knowledge" (Schilling, 2020, p. 29).

Alternate Technology "An alternate technology is one of several technologies that exist or can be developed within the time frame required to meet one or more targets for a technology roadmap. In some cases, two technologies are pure alternatives in that the target can be reached using either technology X or Y. In other cases, they may be complementary, in that X and Y together may allow a target to be obtained" (Bray & Garcia, 1997).

Applied Research "Research targeted at increasing knowledge for a specific application or need" (Schilling, 2020, p. 27).

Architectural Innovation "An innovation that changes the overall design of a system or the way its components interact with each other" (Schilling, 2020, p. 49).

Basic Research "Research targeted at increasing scientific knowledge for its own sake. It may or may not have any long-term commercial application" (Schilling, 2020, p. 27).

Capital Rationing "The allocation of a finite quantity of resources over different possible uses" (Schilling, 2020, p. 146).

Competence-destroying Innovation "A competence-destroying innovation renders existing knowledge and skills obsolete. An innovation can be competence enhancing to one firm, while competence destroying for another" (Schilling, 2020, p. 48).

Competence-enhancing Innovation "A competence-enhancing innovation builds on existing knowledge and skills" (Schilling, 2020, p. 48).

Complex System "A system with components and interconnections, interactions, or interdependencies that are difficult to describe, understand, predict, manage, design, or change. (This implies nonrandom and nonsimple structure)" (de Weck et al., 2011).

Cooperative Patent Classification A patent classification system developed in partnership between the USPTO and the EPO. It is an extension of the International Patent Classification (IPC) system which further classifies patent documents into specialised categories and is used by more than 45 patent offices. More specifically, the CPC consists of all IPC symbols; a "main trunk" of CPC symbols; plus a Y section for tagging emerging technologies or technologies spanning several sections of the CPC. The CPC is subject to ongoing revision by both offices, and documents are reclassified accordingly (Source: https://www.epo.org/searching-for-patents/technical/espacenet.html)..

Critical System Requirement "A critical system requirement (CSR) is an essential product characteristic. It is derived from product needs by assessing customer requirements, product technologies, and process technologies that are essential in delivering the product in the future" (Bray & Garcia, 1997).

Development "Activities that apply knowledge to produce useful devices, materials, or processes" (Schilling, 2020, p. 28).

Discontinuous Innovation "A technology that fulfills a similar market need by building on an entirely new knowledge base" (Schilling, 2020, p. 53).

Disruptive Technology "A disruptive technology is one that falls short of satisfying one or more current customer requirements, but which has such a rapid projected improvement that it will soon overcome this problem. In most cases the disruptive technology overtakes the existing sustaining technology and replaces it" (Bray & Garcia, 1997).

Dominant Design "A product design that is adopted by the majority of producers, typically creating a stable architecture on which the industry can focus its efforts" (Schilling, 2020, p. 60).

Emergent Properties "Properties or behaviors of a system that are discovered (i.e. properties that were there but latent), those that emerge spontaneously over time or space, and those that arise in response to behavior of other systems and environments; in a hierarchical view of systems, emergent properties show up at one level of the hierarchy, but not at lower levels" (de Weck et al., 2011).

Emerging Technology "An emerging technology is a new, potentially promising technology perhaps demonstrated in the lab, but not developed enough to clearly identify all of its uses and benefits. Investments in emerging technologies tend to be more positioning than ROI (return-on-investment) decisions. An emerging technology may appear in either a product technology roadmap or an emerging technology roadmap" (Bray & Garcia, 1997).

Enabling Technology "Component technologies that are necessary for the performance or desirability of a given innovation" (Schilling, 2020, p. 101).

Engineering System "A system designed/evolved by humans having some purpose; large-scale and complex engineering systems will have a management or social dimension as well as a technical one" (de Weck et al., 2011).

Era of Incremental Change A period of stable dominant designs characterized by focus on process improvement and efficiency Anderson & Tushman (1990). Schilling notes that during the Era of Incremental Change, companies may "cease to invest in learning about alternative design architectures and instead invest in refining their competencies related to the dominant design" (Schilling, 2020, p. 61).

Era of Ferment A period of "turbulence and uncertainty" brought on by a technological discontinuity that disrupts the previously stable dominant design and introduces competition between alternative design concepts (Schilling, 2020; Anderson & Tushman, 1990, pp. 60–61).

Espacenet Espacenet is the EPO's free, public patent search engine. It is updated daily and contains over 130 million global patents (European Patent Office, n.d.-c) .

Incremental Innovation "An innovation that makes a relatively minor change from (or adjustment to) existing practices" (Schilling, 2020, p. 47).

Incumbent Inertia "The tendency for incumbents to be slow to respond to changes in the industry environment due to their large size, established routines, or prior strategic commitments to existing suppliers and customers" (Schilling, 2020, p. 101).

Innovation "The practical implementation of an idea into a new device or process" (Schilling, 2020, p. 19).

International Patent Family Each IPF covers a single invention and includes patent applications filed and published at several patent offices. It is a reliable proxy for inventive activity because it provides a degree of control for patent quality by only representing inventions for which the inventor considers the value sufficient to seek protection internationally.

International Patent Classification Almost all patent applications are classified in this internationally recognised classification system. It is maintained by the World Intellectual Property Organization (WIPO) and is used in more than 100 countries worldwide. The IPC has a hierarchical structure and is subdivided into sections, classes, subclasses, groups and subgroups. One of the most precise classification systems available, the IPC currently divides technology into around 70,000 areas (World Intellectural Property Organization, n.d.).

Learning Organization "An organization that systematically reviews its experience with its internal and external environments and acquires knowledge in order to improve its functioning" (de Weck et al., 2011).

Metric "A metric is a variable that can be quantified and may be used to define a target for either the product or the technology" (Bray & Garcia, 1997).

Milestone "Milestones reflect the technology progress along a timeline necessary for achieving the performance targets" (Bray & Garcia, 1997).

Modular Innovation "An innovation to one or more components that does not significantly affect the overall configuration of the system. Also called "Component Innovation" (Schilling, 2020, p. 49).

Radical Innovation "An innovation that is very new and different from prior solutions" (Schilling, 2020, p. 47).

Scenario-Based Planning "This is a planning methodology that explicitly addresses uncertainty about the future. This methodology allows planners to explicitly identify several alternate future states or scenarios. One can then consider prerequisites for or consequences of each alternative. In the technology roadmapping context, this approach provides a mechanism to deal with uncertainty in either product needs or technological developments" (Bray & Garcia, 1997).

Sociotechnical Systems "Broadly, systems in which both human and nonhuman elements interact, and where the social or management dimensions tend to be significant" (de Weck et al., 2011).

Strategic Business Development "Strategic business development (SBD) is planning for, and implementation of, certain aspects of the strategic plan, specifically those involving the development of new products and services and/or new lines of business" (Bray & Garcia, 1997).

Strategic Planning "Strategic planning is the generation of high-level business goals and directions for the company; given a corporate vision, it involves decisions that identify and link at a high level the customer/market needs a company wants to address and the products and services to satisfy those needs" (Bray & Garcia, 1997).

Systems Point of View "A conviction that system behaviors are qualitatively different from the behaviors of a system's components, that system design requires doing more than designing the components, and that special effort is required to understand systems and their behavior over and above what is required to understand any individual component" (de Weck et al., 2011).

Target "A target is the quantitative value that the technology driver must achieve by a certain date" (Bray & Garcia, 1997).

Technological Spillovers "A positive externality from R&D resulting from the spread of knowledge across organizational or regional boundaries" (Schilling, 2020, p. 37).

Technology "The application of science to solve the problems of development capability, in the context of the marketplace, competition and historical performance" (Willyard & McClees, 1987). "Technology is a use of science- and engineering-based knowledge to meet a need" (Bray & Garcia, 1997).

Technology Roadmap "A technology roadmap is the output of the technology roadmapping process at either the corporate or the industry level. It identified (for a set of product needs) the critical system requirements, the product and process performance targets, and the technology alternatives and milestones for meeting those targets" (Bray & Garcia, 1997).

Technology Planning "Technology planning is the process for identifying, selecting, and investing in the technologies that are required to support those product and service requirements identified in a company's strategic plan. Technology roadmapping is only one of many forms of technology planning" (Bray & Garcia, 1997).

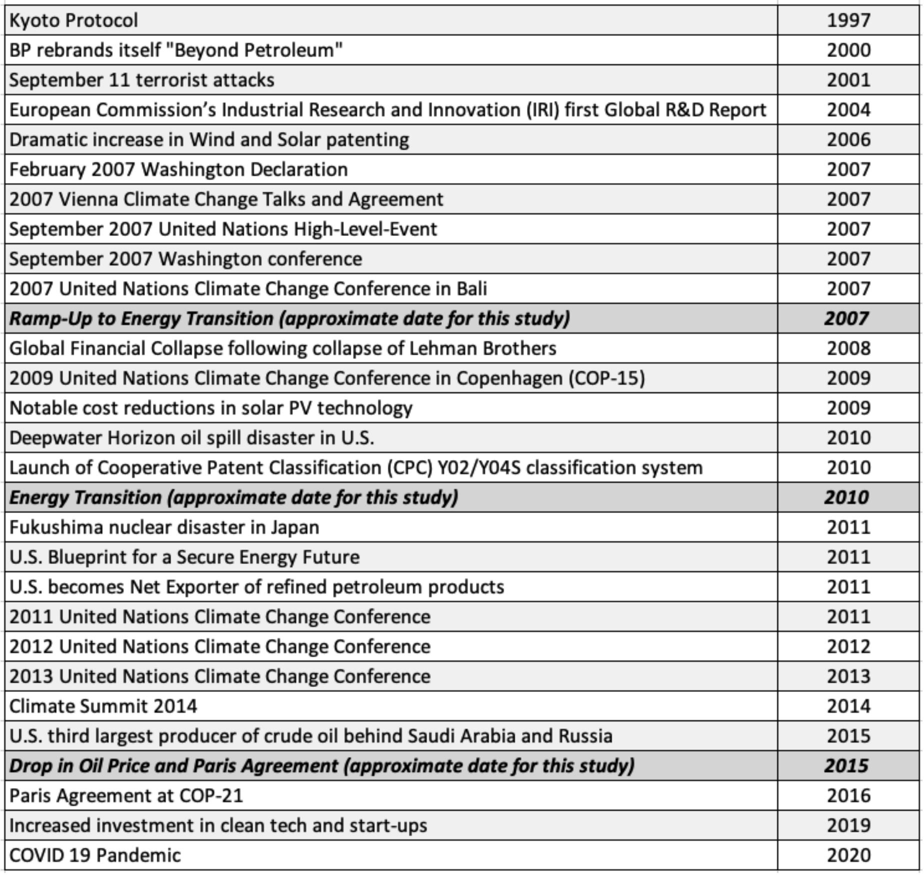
Technology Management "Technology management addresses the effective identification, selection, acquisition, development, exploitation and protection of technologies (product, process and infrastructural) needed to maintain a market position and business performance" (Nimmo, 2013).

Technology Driver "The technology drivers are the critical variables that determine which technology alternatives will be pursued. They are dependent on the technology areas, but relate to how the technology addresses the critical system requirements" (Bray & Garcia, 1997).

World International Patent Organization Agency of the United Nations responsible for promoting the protection of intellectual property throughout the world by encouraging co-operation between nations. WIPO is responsible for: the promotion of the protection of intellectual property throughout the world through co-operation among states; the administration of various multilateral treaties dealing with the legal and administrative aspects of intellectual property; the administration of the Patent Cooperation Treaty and PCT patent applications (World Intellectural Property Organization, n.d.).

Appendix A

Timeline of the Energy Transition



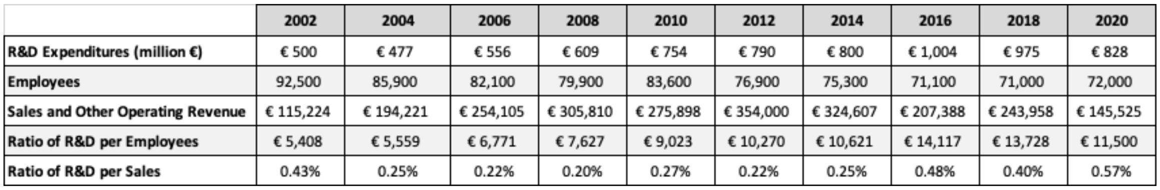
Kyoto Protocol	1997
BP rebrands itself "Beyond Petroleum"	2000
September 11 terrorist attacks	2001
European Commission’s Industrial Research and Innovation (IRI) first Global R&D Report	2004
Dramatic increase in Wind and Solar patenting	2006
February 2007 Washington Declaration	2007
2007 Vienna Climate Change Talks and Agreement	2007
September 2007 United Nations High-Level-Event	2007
September 2007 Washington conference	2007
2007 United Nations Climate Change Conference in Bali	2007
Ramp-Up to Energy Transition (approximate date for this study)	***2007***
Global Financial Collapse following collapse of Lehman Brothers	2008
2009 United Nations Climate Change Conference in Copenhagen (COP-15)	2009
Notable cost reductions in solar PV technology	2009
Deepwater Horizon oil spill disaster in U.S.	2010
Launch of Cooperative Patent Classification (CPC) Y02/Y04S classification system	2010
Energy Transition (approximate date for this study)	***2010***
Fukushima nuclear disaster in Japan	2011
U.S. Blueprint for a Secure Energy Future	2011
U.S. becomes Net Exporter of refined petroleum products	2011
2011 United Nations Climate Change Conference	2011
2012 United Nations Climate Change Conference	2012
2013 United Nations Climate Change Conference	2013
Climate Summit 2014	2014
U.S. third largest producer of crude oil behind Saudi Arabia and Russia	2015
Drop in Oil Price and Paris Agreement (approximate date for this study)	***2015***
Paris Agreement at COP-21	2016
Increased investment in clean tech and start-ups	2019
COVID 19 Pandemic	2020

Table A.1: Rough Timeline of Events Related to the Energy Transition, 1997–2020. While there are no exact dates or timeline for what is broadly called the Energy Transition (Markard, 2018), it is helpful to contextualize the Energy Transition in a broader landscape of world events. The table includes three generalized time periods used in this study to evaluate changes in technology management: Ramp-Up (∼2007), Energy Transition (∼2010), and Drop in Oil Price and Paris Agreement (∼2015). Source: Based on data from IEA (2020), Markard (2018), and Wikipedia.

Appendix B

Quality Check of IRI R&D Data with SEC 10-K

	2002	2004	2006	2008	2010	2012	2014	2016	2018	2020
R&D Expenditures (million US $)	$631	$649	$733	$847	$1,012	$1,042	$971	$1,058	$1,116	$1,016
Employees	92,500	85,900	82,100	79,900	83,600	76,900	75,300	71,100	71,000	72,000
Sales and Other Operating Revenue	$200,949	$291,252	$365,467	$459,579	$370,125	$451,509	$394,105	$218,608	$279,332	$178,574
Ratio of R&D per Employees	$6,822	$7,555	$8,928	$10,601	$12,105	$13,550	$12,895	$14,880	$15,718	$14,111
Ratio of R&D per Sales	0.31%	0.22%	0.20%	0.18%	0.27%	0.23%	0.25%	0.48%	0.40%	0.57%

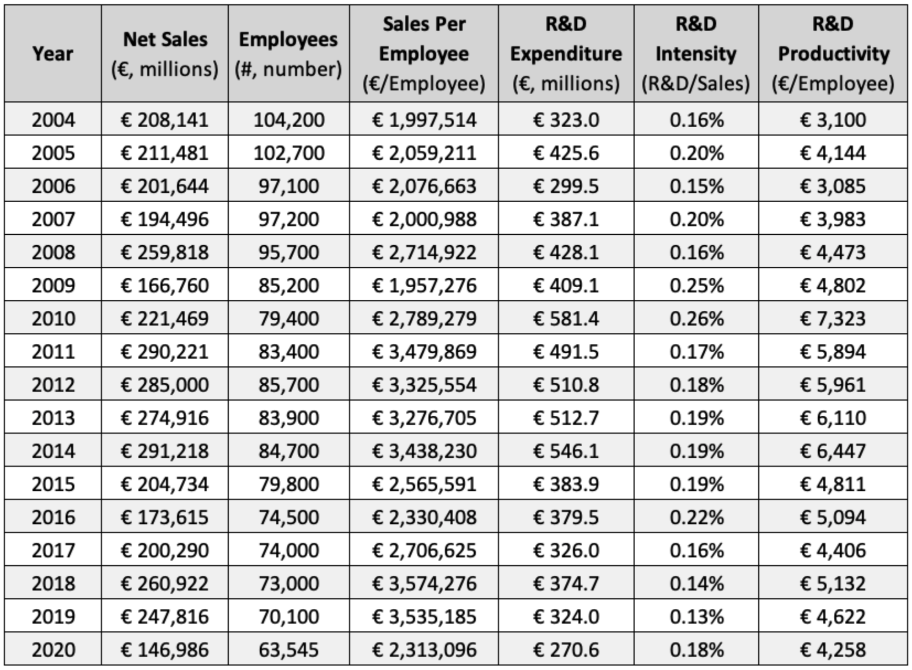


	2002	2004	2006	2008	2010	2012	2014	2016	2018	2020
R&D Expenditures (million €)	€ 500	€ 477	€ 556	€ 609	€ 754	€ 790	€ 800	€ 1,004	€ 975	€ 828
Employees	92,500	85,900	82,100	79,900	83,600	76,900	75,300	71,100	71,000	72,000
Sales and Other Operating Revenue	€ 115,224	€ 194,221	€ 254,105	€ 305,810	€ 275,898	€ 354,000	€ 324,607	€ 207,388	€ 243,958	€ 145,525
Ratio of R&D per Employees	€ 5,408	€ 5,559	€ 6,771	€ 7,627	€ 9,023	€ 10,270	€ 10,621	€ 14,117	€ 13,728	€ 11,500
Ratio of R&D per Sales	0.43%	0.25%	0.22%	0.20%	0.27%	0.22%	0.25%	0.48%	0.40%	0.57%

Table B.1: Comparison of ExxonMobil's SEC 10-K and IRI Data to Ensure Accuracy, 2002–2020. The IRI data shows consistency with official 10-K filings accounting for currency adjustment of U.S. Dollar to Euro. Note strong consistency between the calculated metric of Ratio of R&D per Sales (%). Source: Based on data from ExxonMobil's SEC 10-K filings.

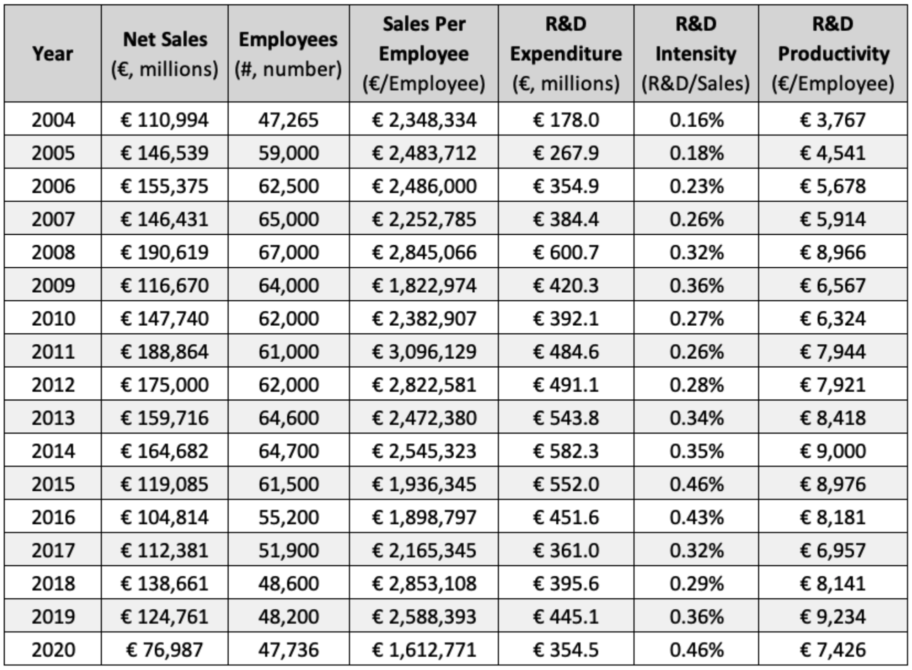
Appendix C

R&D Metrics: Collected IRI Data and Calculated Results



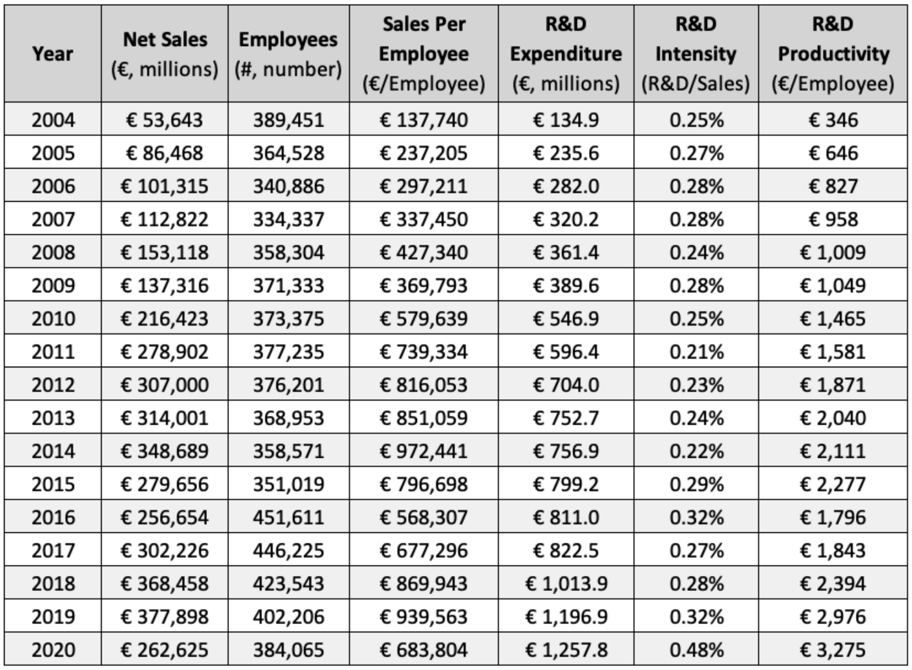
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 208,141	104,200	€ 1,997,514	€ 323.0	0.16%	€ 3,100
2005	€ 211,481	102,700	€ 2,059,211	€ 425.6	0.20%	€ 4,144
2006	€ 201,644	97,100	€ 2,076,663	€ 299.5	0.15%	€ 3,085
2007	€ 194,496	97,200	€ 2,000,988	€ 387.1	0.20%	€ 3,983
2008	€ 259,818	95,700	€ 2,714,922	€ 428.1	0.16%	€ 4,473
2009	€ 166,760	85,200	€ 1,957,276	€ 409.1	0.25%	€ 4,802
2010	€ 221,469	79,400	€ 2,789,279	€ 581.4	0.26%	€ 7,323
2011	€ 290,221	83,400	€ 3,479,869	€ 491.5	0.17%	€ 5,894
2012	€ 285,000	85,700	€ 3,325,554	€ 510.8	0.18%	€ 5,961
2013	€ 274,916	83,900	€ 3,276,705	€ 512.7	0.19%	€ 6,110
2014	€ 291,218	84,700	€ 3,438,230	€ 546.1	0.19%	€ 6,447
2015	€ 204,734	79,800	€ 2,565,591	€ 383.9	0.19%	€ 4,811
2016	€ 173,615	74,500	€ 2,330,408	€ 379.5	0.22%	€ 5,094
2017	€ 200,290	74,000	€ 2,706,625	€ 326.0	0.16%	€ 4,406
2018	€ 260,922	73,000	€ 3,574,276	€ 374.7	0.14%	€ 5,132
2019	€ 247,816	70,100	€ 3,535,185	€ 324.0	0.13%	€ 4,622
2020	€ 146,986	63,545	€ 2,313,096	€ 270.6	0.18%	€ 4,258

Table C.1: R&D Metrics for BP, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



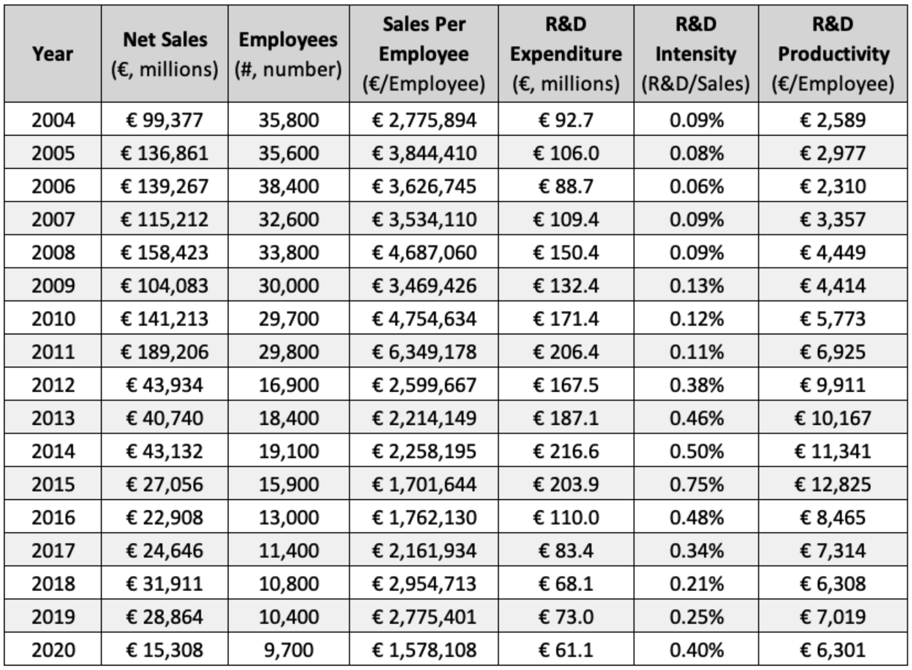
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 110,994	47,265	€ 2,348,334	€ 178.0	0.16%	€ 3,767
2005	€ 146,539	59,000	€ 2,483,712	€ 267.9	0.18%	€ 4,541
2006	€ 155,375	62,500	€ 2,486,000	€ 354.9	0.23%	€ 5,678
2007	€ 146,431	65,000	€ 2,252,785	€ 384.4	0.26%	€ 5,914
2008	€ 190,619	67,000	€ 2,845,066	€ 600.7	0.32%	€ 8,966
2009	€ 116,670	64,000	€ 1,822,974	€ 420.3	0.36%	€ 6,567
2010	€ 147,740	62,000	€ 2,382,907	€ 392.1	0.27%	€ 6,324
2011	€ 188,864	61,000	€ 3,096,129	€ 484.6	0.26%	€ 7,944
2012	€ 175,000	62,000	€ 2,822,581	€ 491.1	0.28%	€ 7,921
2013	€ 159,716	64,600	€ 2,472,380	€ 543.8	0.34%	€ 8,418
2014	€ 164,682	64,700	€ 2,545,323	€ 582.3	0.35%	€ 9,000
2015	€ 119,085	61,500	€ 1,936,345	€ 552.0	0.46%	€ 8,976
2016	€ 104,814	55,200	€ 1,898,797	€ 451.6	0.43%	€ 8,181
2017	€ 112,381	51,900	€ 2,165,345	€ 361.0	0.32%	€ 6,957
2018	€ 138,661	48,600	€ 2,853,108	€ 395.6	0.29%	€ 8,141
2019	€ 124,761	48,200	€ 2,588,393	€ 445.1	0.36%	€ 9,234
2020	€ 76,987	47,736	€ 1,612,771	€ 354.5	0.46%	€ 7,426

Table C.2: R&D Metrics for Chevron, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



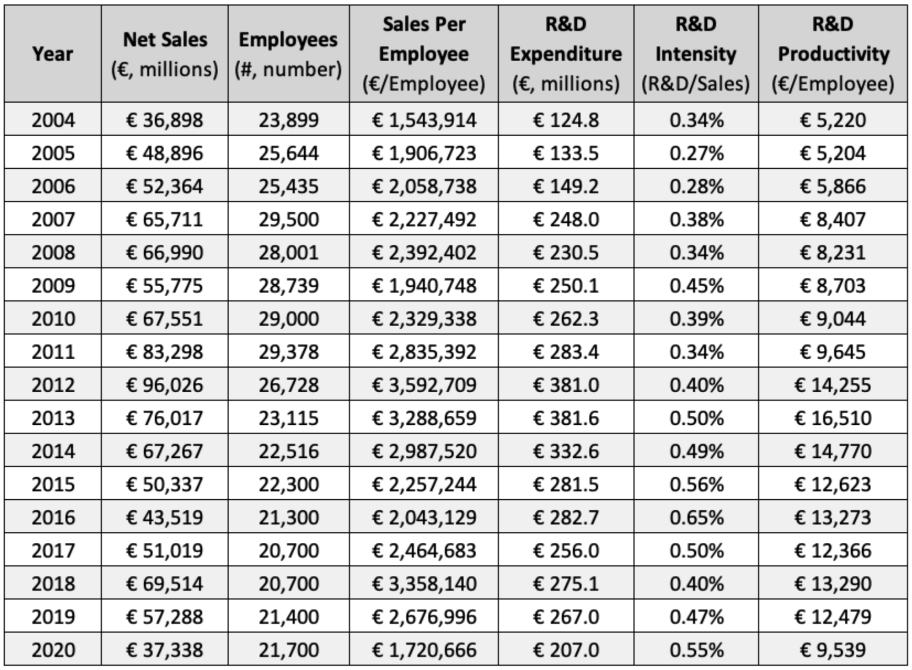
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 53,643	389,451	€ 137,740	€ 134.9	0.25%	€ 346
2005	€ 86,468	364,528	€ 237,205	€ 235.6	0.27%	€ 646
2006	€ 101,315	340,886	€ 297,211	€ 282.0	0.28%	€ 827
2007	€ 112,822	334,337	€ 337,450	€ 320.2	0.28%	€ 958
2008	€ 153,118	358,304	€ 427,340	€ 361.4	0.24%	€ 1,009
2009	€ 137,316	371,333	€ 369,793	€ 389.6	0.28%	€ 1,049
2010	€ 216,423	373,375	€ 579,639	€ 546.9	0.25%	€ 1,465
2011	€ 278,902	377,235	€ 739,334	€ 596.4	0.21%	€ 1,581
2012	€ 307,000	376,201	€ 816,053	€ 704.0	0.23%	€ 1,871
2013	€ 314,001	368,953	€ 851,059	€ 752.7	0.24%	€ 2,040
2014	€ 348,689	358,571	€ 972,441	€ 756.9	0.22%	€ 2,111
2015	€ 279,656	351,019	€ 796,698	€ 799.2	0.29%	€ 2,277
2016	€ 256,654	451,611	€ 568,307	€ 811.0	0.32%	€ 1,796
2017	€ 302,226	446,225	€ 677,296	€ 822.5	0.27%	€ 1,843
2018	€ 368,458	423,543	€ 869,943	€ 1,013.9	0.28%	€ 2,394
2019	€ 377,898	402,206	€ 939,563	€ 1,196.9	0.32%	€ 2,976
2020	€ 262,625	384,065	€ 683,804	€ 1,257.8	0.48%	€ 3,275

Table C.3: R&D Metrics for China Petroleum, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



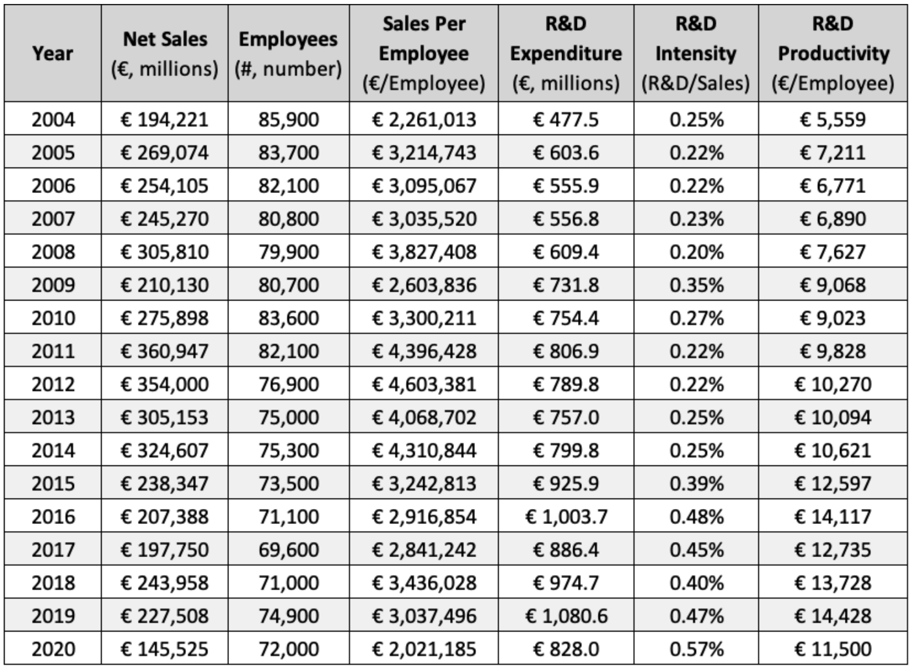
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 99,377	35,800	€ 2,775,894	€ 92.7	0.09%	€ 2,589
2005	€ 136,861	35,600	€ 3,844,410	€ 106.0	0.08%	€ 2,977
2006	€ 139,267	38,400	€ 3,626,745	€ 88.7	0.06%	€ 2,310
2007	€ 115,212	32,600	€ 3,534,110	€ 109.4	0.09%	€ 3,357
2008	€ 158,423	33,800	€ 4,687,060	€ 150.4	0.09%	€ 4,449
2009	€ 104,083	30,000	€ 3,469,426	€ 132.4	0.13%	€ 4,414
2010	€ 141,213	29,700	€ 4,754,634	€ 171.4	0.12%	€ 5,773
2011	€ 189,206	29,800	€ 6,349,178	€ 206.4	0.11%	€ 6,925
2012	€ 43,934	16,900	€ 2,599,667	€ 167.5	0.38%	€ 9,911
2013	€ 40,740	18,400	€ 2,214,149	€ 187.1	0.46%	€ 10,167
2014	€ 43,132	19,100	€ 2,258,195	€ 216.6	0.50%	€ 11,341
2015	€ 27,056	15,900	€ 1,701,644	€ 203.9	0.75%	€ 12,825
2016	€ 22,908	13,000	€ 1,762,130	€ 110.0	0.48%	€ 8,465
2017	€ 24,646	11,400	€ 2,161,934	€ 83.4	0.34%	€ 7,314
2018	€ 31,911	10,800	€ 2,954,713	€ 68.1	0.21%	€ 6,308
2019	€ 28,864	10,400	€ 2,775,401	€ 73.0	0.25%	€ 7,019
2020	€ 15,308	9,700	€ 1,578,108	€ 61.1	0.40%	€ 6,301

Table C.4: R&D Metrics for Conoco, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



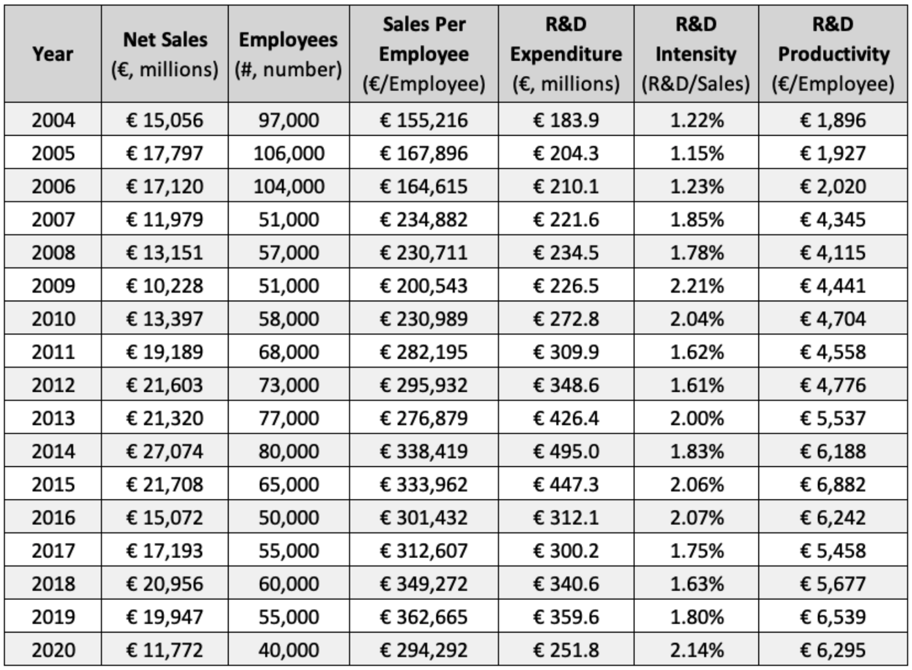
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 36,898	23,899	€ 1,543,914	€ 124.8	0.34%	€ 5,220
2005	€ 48,896	25,644	€ 1,906,723	€ 133.5	0.27%	€ 5,204
2006	€ 52,364	25,435	€ 2,058,738	€ 149.2	0.28%	€ 5,866
2007	€ 65,711	29,500	€ 2,227,492	€ 248.0	0.38%	€ 8,407
2008	€ 66,990	28,001	€ 2,392,402	€ 230.5	0.34%	€ 8,231
2009	€ 55,775	28,739	€ 1,940,748	€ 250.1	0.45%	€ 8,703
2010	€ 67,551	29,000	€ 2,329,338	€ 262.3	0.39%	€ 9,044
2011	€ 83,298	29,378	€ 2,835,392	€ 283.4	0.34%	€ 9,645
2012	€ 96,026	26,728	€ 3,592,709	€ 381.0	0.40%	€ 14,255
2013	€ 76,017	23,115	€ 3,288,659	€ 381.6	0.50%	€ 16,510
2014	€ 67,267	22,516	€ 2,987,520	€ 332.6	0.49%	€ 14,770
2015	€ 50,337	22,300	€ 2,257,244	€ 281.5	0.56%	€ 12,623
2016	€ 43,519	21,300	€ 2,043,129	€ 282.7	0.65%	€ 13,273
2017	€ 51,019	20,700	€ 2,464,683	€ 256.0	0.50%	€ 12,366
2018	€ 69,514	20,700	€ 3,358,140	€ 275.1	0.40%	€ 13,290
2019	€ 57,288	21,400	€ 2,676,996	€ 267.0	0.47%	€ 12,479
2020	€ 37,338	21,700	€ 1,720,666	€ 207.0	0.55%	€ 9,539

Table C.5: R&D Metrics for Equinor, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



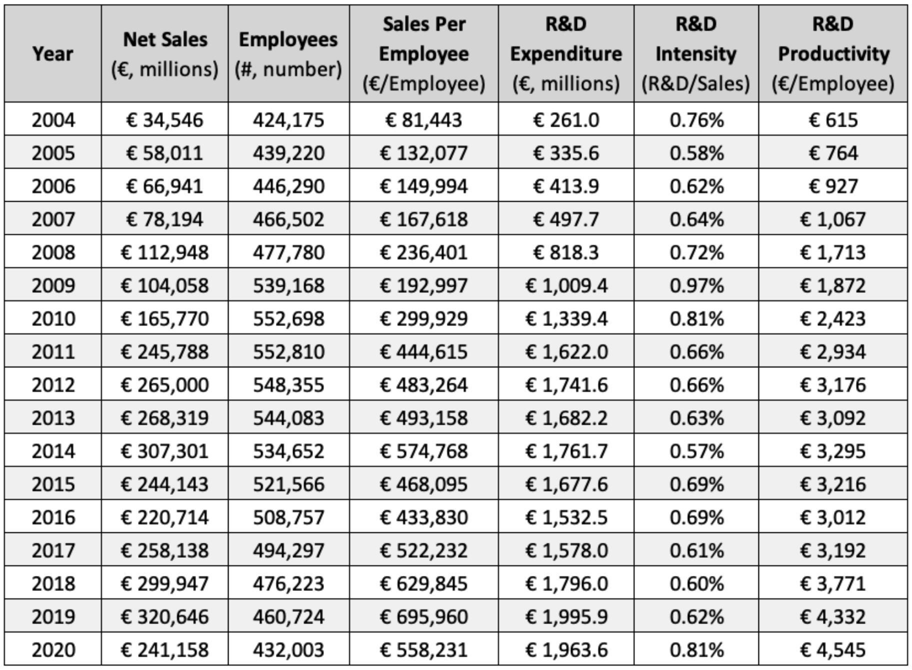
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 194,221	85,900	€ 2,261,013	€ 477.5	0.25%	€ 5,559
2005	€ 269,074	83,700	€ 3,214,743	€ 603.6	0.22%	€ 7,211
2006	€ 254,105	82,100	€ 3,095,067	€ 555.9	0.22%	€ 6,771
2007	€ 245,270	80,800	€ 3,035,520	€ 556.8	0.23%	€ 6,890
2008	€ 305,810	79,900	€ 3,827,408	€ 609.4	0.20%	€ 7,627
2009	€ 210,130	80,700	€ 2,603,836	€ 731.8	0.35%	€ 9,068
2010	€ 275,898	83,600	€ 3,300,211	€ 754.4	0.27%	€ 9,023
2011	€ 360,947	82,100	€ 4,396,428	€ 806.9	0.22%	€ 9,828
2012	€ 354,000	76,900	€ 4,603,381	€ 789.8	0.22%	€ 10,270
2013	€ 305,153	75,000	€ 4,068,702	€ 757.0	0.25%	€ 10,094
2014	€ 324,607	75,300	€ 4,310,844	€ 799.8	0.25%	€ 10,621
2015	€ 238,347	73,500	€ 3,242,813	€ 925.9	0.39%	€ 12,597
2016	€ 207,388	71,100	€ 2,916,854	€ 1,003.7	0.48%	€ 14,117
2017	€ 197,750	69,600	€ 2,841,242	€ 886.4	0.45%	€ 12,735
2018	€ 243,958	71,000	€ 3,436,028	€ 974.7	0.40%	€ 13,728
2019	€ 227,508	74,900	€ 3,037,496	€ 1,080.6	0.47%	€ 14,428
2020	€ 145,525	72,000	€ 2,021,185	€ 828.0	0.57%	€ 11,500

Table C.6: R&D Metrics for Exxon, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



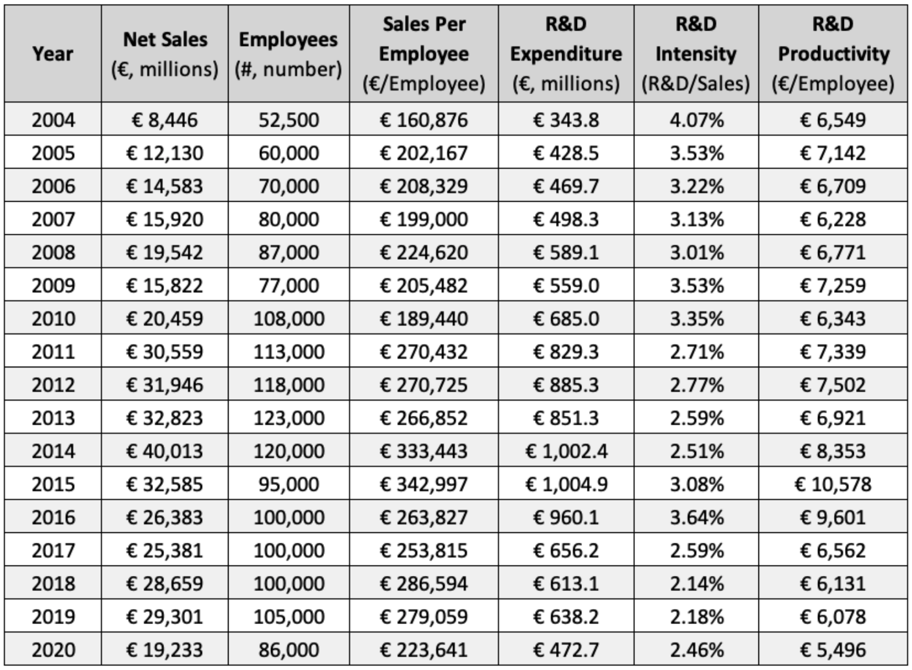
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 15,056	97,000	€ 155,216	€ 183.9	1.22%	€ 1,896
2005	€ 17,797	106,000	€ 167,896	€ 204.3	1.15%	€ 1,927
2006	€ 17,120	104,000	€ 164,615	€ 210.1	1.23%	€ 2,020
2007	€ 11,979	51,000	€ 234,882	€ 221.6	1.85%	€ 4,345
2008	€ 13,151	57,000	€ 230,711	€ 234.5	1.78%	€ 4,115
2009	€ 10,228	51,000	€ 200,543	€ 226.5	2.21%	€ 4,441
2010	€ 13,397	58,000	€ 230,989	€ 272.8	2.04%	€ 4,704
2011	€ 19,189	68,000	€ 282,195	€ 309.9	1.62%	€ 4,558
2012	€ 21,603	73,000	€ 295,932	€ 348.6	1.61%	€ 4,776
2013	€ 21,320	77,000	€ 276,879	€ 426.4	2.00%	€ 5,537
2014	€ 27,074	80,000	€ 338,419	€ 495.0	1.83%	€ 6,188
2015	€ 21,708	65,000	€ 333,962	€ 447.3	2.06%	€ 6,882
2016	€ 15,072	50,000	€ 301,432	€ 312.1	2.07%	€ 6,242
2017	€ 17,193	55,000	€ 312,607	€ 300.2	1.75%	€ 5,458
2018	€ 20,956	60,000	€ 349,272	€ 340.6	1.63%	€ 5,677
2019	€ 19,947	55,000	€ 362,665	€ 359.6	1.80%	€ 6,539
2020	€ 11,772	40,000	€ 294,292	€ 251.8	2.14%	€ 6,295

Table C.7: R&D Metrics for Halliburton, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in millions. Source: Based on IRI data.



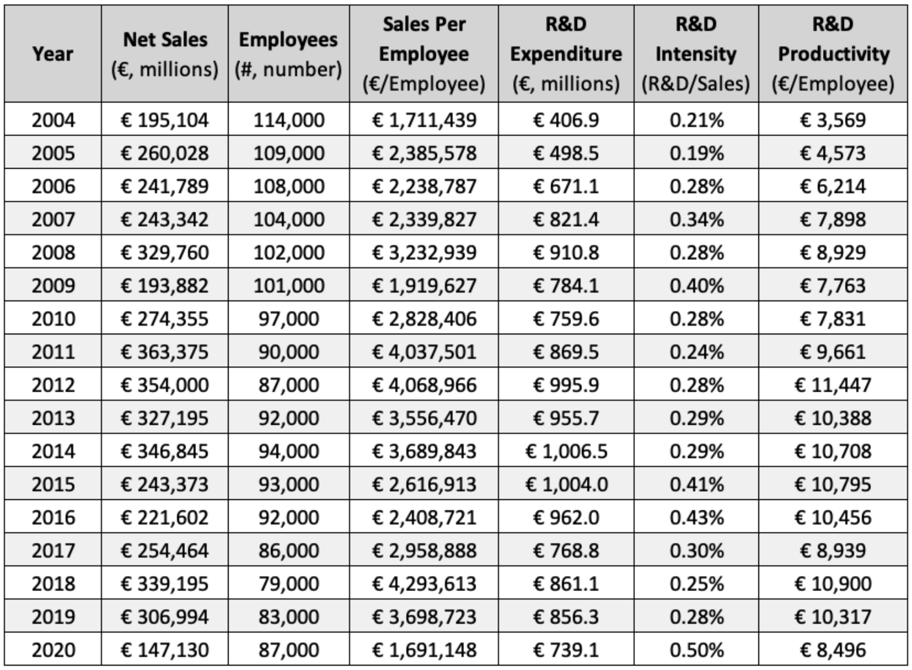
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 34,546	424,175	€ 81,443	€ 261.0	0.76%	€ 615
2005	€ 58,011	439,220	€ 132,077	€ 335.6	0.58%	€ 764
2006	€ 66,941	446,290	€ 149,994	€ 413.9	0.62%	€ 927
2007	€ 78,194	466,502	€ 167,618	€ 497.7	0.64%	€ 1,067
2008	€ 112,948	477,780	€ 236,401	€ 818.3	0.72%	€ 1,713
2009	€ 104,058	539,168	€ 192,997	€ 1,009.4	0.97%	€ 1,872
2010	€ 165,770	552,698	€ 299,929	€ 1,339.4	0.81%	€ 2,423
2011	€ 245,788	552,810	€ 444,615	€ 1,622.0	0.66%	€ 2,934
2012	€ 265,000	548,355	€ 483,264	€ 1,741.6	0.66%	€ 3,176
2013	€ 268,319	544,083	€ 493,158	€ 1,682.2	0.63%	€ 3,092
2014	€ 307,301	534,652	€ 574,768	€ 1,761.7	0.57%	€ 3,295
2015	€ 244,143	521,566	€ 468,095	€ 1,677.6	0.69%	€ 3,216
2016	€ 220,714	508,757	€ 433,830	€ 1,532.5	0.69%	€ 3,012
2017	€ 258,138	494,297	€ 522,232	€ 1,578.0	0.61%	€ 3,192
2018	€ 299,947	476,223	€ 629,845	€ 1,796.0	0.60%	€ 3,771
2019	€ 320,646	460,724	€ 695,960	€ 1,995.9	0.62%	€ 4,332
2020	€ 241,158	432,003	€ 558,231	€ 1,963.6	0.81%	€ 4,545

Table C.8: R&D Metrics for PetroChina, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in millions. Source: Based on IRI data.



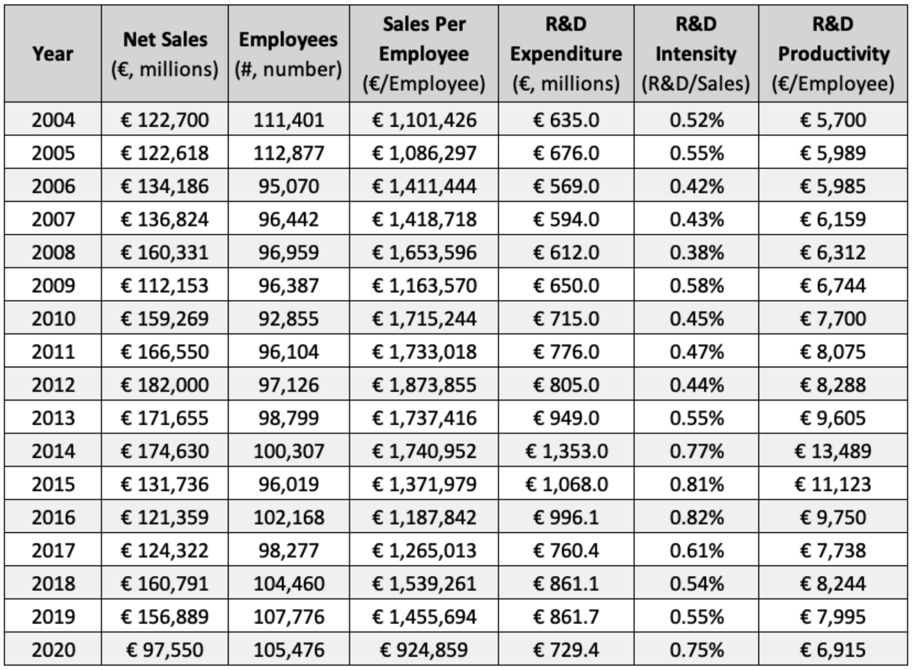
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 8,446	52,500	€ 160,876	€ 343.8	4.07%	€ 6,549
2005	€ 12,130	60,000	€ 202,167	€ 428.5	3.53%	€ 7,142
2006	€ 14,583	70,000	€ 208,329	€ 469.7	3.22%	€ 6,709
2007	€ 15,920	80,000	€ 199,000	€ 498.3	3.13%	€ 6,228
2008	€ 19,542	87,000	€ 224,620	€ 589.1	3.01%	€ 6,771
2009	€ 15,822	77,000	€ 205,482	€ 559.0	3.53%	€ 7,259
2010	€ 20,459	108,000	€ 189,440	€ 685.0	3.35%	€ 6,343
2011	€ 30,559	113,000	€ 270,432	€ 829.3	2.71%	€ 7,339
2012	€ 31,946	118,000	€ 270,725	€ 885.3	2.77%	€ 7,502
2013	€ 32,823	123,000	€ 266,852	€ 851.3	2.59%	€ 6,921
2014	€ 40,013	120,000	€ 333,443	€ 1,002.4	2.51%	€ 8,353
2015	€ 32,585	95,000	€ 342,997	€ 1,004.9	3.08%	€ 10,578
2016	€ 26,383	100,000	€ 263,827	€ 960.1	3.64%	€ 9,601
2017	€ 25,381	100,000	€ 253,815	€ 656.2	2.59%	€ 6,562
2018	€ 28,659	100,000	€ 286,594	€ 613.1	2.14%	€ 6,131
2019	€ 29,301	105,000	€ 279,059	€ 638.2	2.18%	€ 6,078
2020	€ 19,233	86,000	€ 223,641	€ 472.7	2.46%	€ 5,496

Table C.9: R&D Metrics for Schlumberger, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



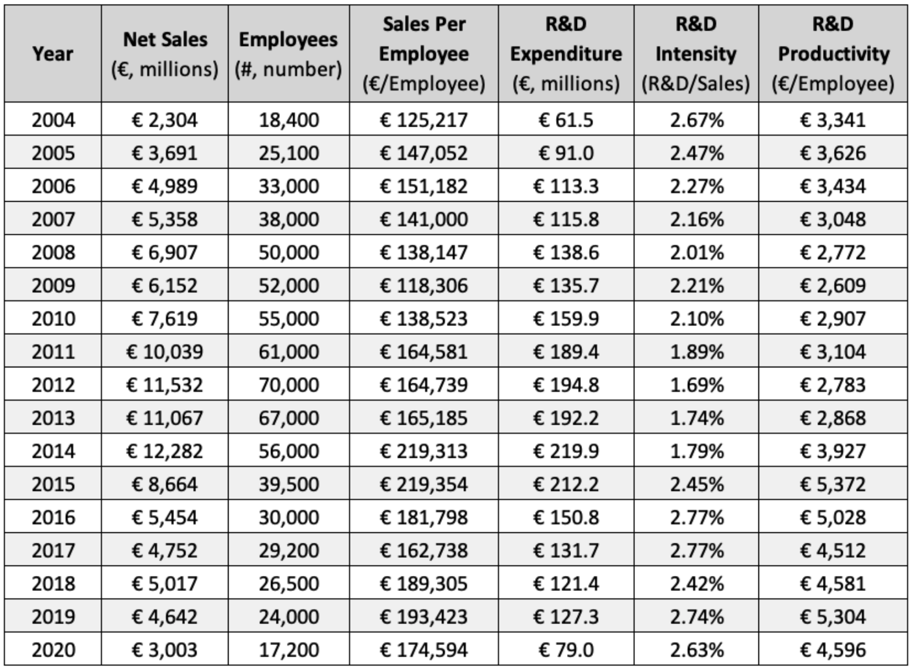
Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 195,104	114,000	€ 1,711,439	€ 406.9	0.21%	€ 3,569
2005	€ 260,028	109,000	€ 2,385,578	€ 498.5	0.19%	€ 4,573
2006	€ 241,789	108,000	€ 2,238,787	€ 671.1	0.28%	€ 6,214
2007	€ 243,342	104,000	€ 2,339,827	€ 821.4	0.34%	€ 7,898
2008	€ 329,760	102,000	€ 3,232,939	€ 910.8	0.28%	€ 8,929
2009	€ 193,882	101,000	€ 1,919,627	€ 784.1	0.40%	€ 7,763
2010	€ 274,355	97,000	€ 2,828,406	€ 759.6	0.28%	€ 7,831
2011	€ 363,375	90,000	€ 4,037,501	€ 869.5	0.24%	€ 9,661
2012	€ 354,000	87,000	€ 4,068,966	€ 995.9	0.28%	€ 11,447
2013	€ 327,195	92,000	€ 3,556,470	€ 955.7	0.29%	€ 10,388
2014	€ 346,845	94,000	€ 3,689,843	€ 1,006.5	0.29%	€ 10,708
2015	€ 243,373	93,000	€ 2,616,913	€ 1,004.0	0.41%	€ 10,795
2016	€ 221,602	92,000	€ 2,408,721	€ 962.0	0.43%	€ 10,456
2017	€ 254,464	86,000	€ 2,958,888	€ 768.8	0.30%	€ 8,939
2018	€ 339,195	79,000	€ 4,293,613	€ 861.1	0.25%	€ 10,900
2019	€ 306,994	83,000	€ 3,698,723	€ 856.3	0.28%	€ 10,317
2020	€ 147,130	87,000	€ 1,691,148	€ 739.1	0.50%	€ 8,496

Table C.10: R&D Metrics for Shell, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.



Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 122,700	111,401	€ 1,101,426	€ 635.0	0.52%	€ 5,700
2005	€ 122,618	112,877	€ 1,086,297	€ 676.0	0.55%	€ 5,989
2006	€ 134,186	95,070	€ 1,411,444	€ 569.0	0.42%	€ 5,985
2007	€ 136,824	96,442	€ 1,418,718	€ 594.0	0.43%	€ 6,159
2008	€ 160,331	96,959	€ 1,653,596	€ 612.0	0.38%	€ 6,312
2009	€ 112,153	96,387	€ 1,163,570	€ 650.0	0.58%	€ 6,744
2010	€ 159,269	92,855	€ 1,715,244	€ 715.0	0.45%	€ 7,700
2011	€ 166,550	96,104	€ 1,733,018	€ 776.0	0.47%	€ 8,075
2012	€ 182,000	97,126	€ 1,873,855	€ 805.0	0.44%	€ 8,288
2013	€ 171,655	98,799	€ 1,737,416	€ 949.0	0.55%	€ 9,605
2014	€ 174,630	100,307	€ 1,740,952	€ 1,353.0	0.77%	€ 13,489
2015	€ 131,736	96,019	€ 1,371,979	€ 1,068.0	0.81%	€ 11,123
2016	€ 121,359	102,168	€ 1,187,842	€ 996.1	0.82%	€ 9,750
2017	€ 124,322	98,277	€ 1,265,013	€ 760.4	0.61%	€ 7,738
2018	€ 160,791	104,460	€ 1,539,261	€ 861.1	0.54%	€ 8,244
2019	€ 156,889	107,776	€ 1,455,694	€ 861.7	0.55%	€ 7,995
2020	€ 97,550	105,476	€ 924,859	€ 729.4	0.75%	€ 6,915

Table C.11: R&D Metrics for Total, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.

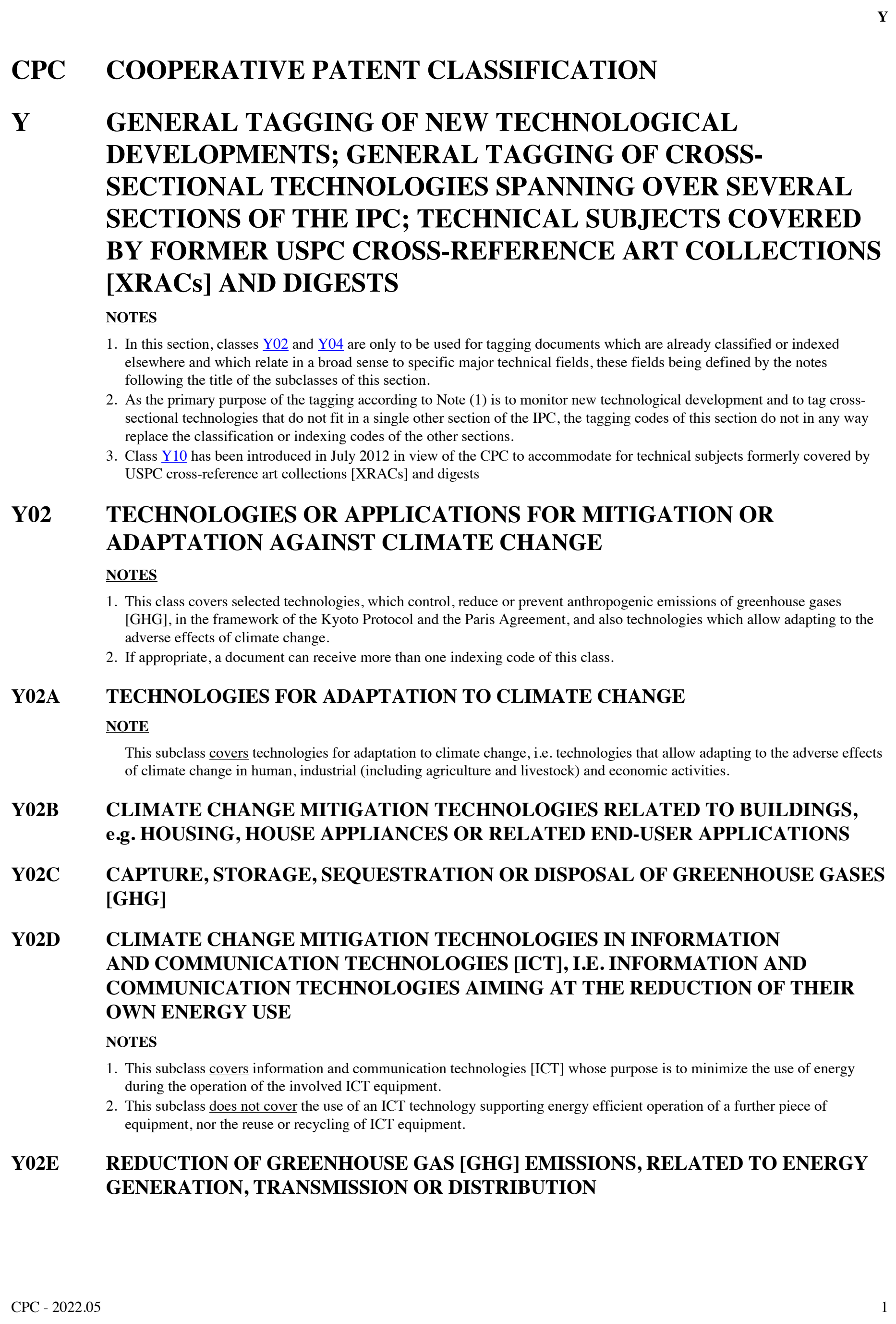


Year	Net Sales (€, millions)	Employees (#, number)	Sales Per Employee (€/Employee)	R&D Expenditure (€, millions)	R&D Intensity (R&D/Sales)	R&D Productivity (€/Employee)
2004	€ 2,304	18,400	€ 125,217	€ 61.5	2.67%	€ 3,341
2005	€ 3,691	25,100	€ 147,052	€ 91.0	2.47%	€ 3,626
2006	€ 4,989	33,000	€ 151,182	€ 113.3	2.27%	€ 3,434
2007	€ 5,358	38,000	€ 141,000	€ 115.8	2.16%	€ 3,048
2008	€ 6,907	50,000	€ 138,147	€ 138.6	2.01%	€ 2,772
2009	€ 6,152	52,000	€ 118,306	€ 135.7	2.21%	€ 2,609
2010	€ 7,619	55,000	€ 138,523	€ 159.9	2.10%	€ 2,907
2011	€ 10,039	61,000	€ 164,581	€ 189.4	1.89%	€ 3,104
2012	€ 11,532	70,000	€ 164,739	€ 194.8	1.69%	€ 2,783
2013	€ 11,067	67,000	€ 165,185	€ 192.2	1.74%	€ 2,868
2014	€ 12,282	56,000	€ 219,313	€ 219.9	1.79%	€ 3,927
2015	€ 8,664	39,500	€ 219,354	€ 212.2	2.45%	€ 5,372
2016	€ 5,454	30,000	€ 181,798	€ 150.8	2.77%	€ 5,028
2017	€ 4,752	29,200	€ 162,738	€ 131.7	2.77%	€ 4,512
2018	€ 5,017	26,500	€ 189,305	€ 121.4	2.42%	€ 4,581
2019	€ 4,642	24,000	€ 193,423	€ 127.3	2.74%	€ 5,304
2020	€ 3,003	17,200	€ 174,594	€ 79.0	2.63%	€ 4,596

Table C.12: R&D Metrics for Weatherford, 2004–2020. IRI data for Net Sales, Employees, and R&D Expenditure used to calculate R&D Intensity, R&D Productivity, and Sales Per Employee. Net Sales and R&D Expenditure are in units of millions. Source: Based on IRI data.

Appendix D

Cooperative Patent Classification: Documentation of Y02–Y04 Schema



Y

CPC COOPERATIVE PATENT CLASSIFICATION

Y GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS; GENERAL TAGGING OF CROSS-SECTIONAL TECHNOLOGIES SPANNING OVER SEVERAL SECTIONS OF THE IPC; TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS

NOTES

1. In this section, classes Y02 and Y04 are only to be used for tagging documents which are already classified or indexed elsewhere and which relate in a broad sense to specific major technical fields, these fields being defined by the notes following the title of the subclasses of this section.
2. As the primary purpose of the tagging according to Note (1) is to monitor new technological development and to tag cross-sectional technologies that do not fit in a single other section of the IPC, the tagging codes of this section do not in any way replace the classification or indexing codes of the other sections.
3. Class Y10 has been introduced in July 2012 in view of the CPC to accommodate for technical subjects formerly covered by USPC cross-reference art collections [XRACs] and digests

Y02 TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE

NOTES

1. This class covers selected technologies, which control, reduce or prevent anthropogenic emissions of greenhouse gases [GHG], in the framework of the Kyoto Protocol and the Paris Agreement, and also technologies which allow adapting to the adverse effects of climate change.
2. If appropriate, a document can receive more than one indexing code of this class.

Y02A TECHNOLOGIES FOR ADAPTATION TO CLIMATE CHANGE

NOTE

This subclass covers technologies for adaptation to climate change, i.e. technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities.

Y02B CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO BUILDINGS, e.g. HOUSING, HOUSE APPLIANCES OR RELATED END-USER APPLICATIONS

Y02C CAPTURE, STORAGE, SEQUESTRATION OR DISPOSAL OF GREENHOUSE GASES [GHG]

Y02D CLIMATE CHANGE MITIGATION TECHNOLOGIES IN INFORMATION AND COMMUNICATION TECHNOLOGIES [ICT], I.E. INFORMATION AND COMMUNICATION TECHNOLOGIES AIMING AT THE REDUCTION OF THEIR OWN ENERGY USE

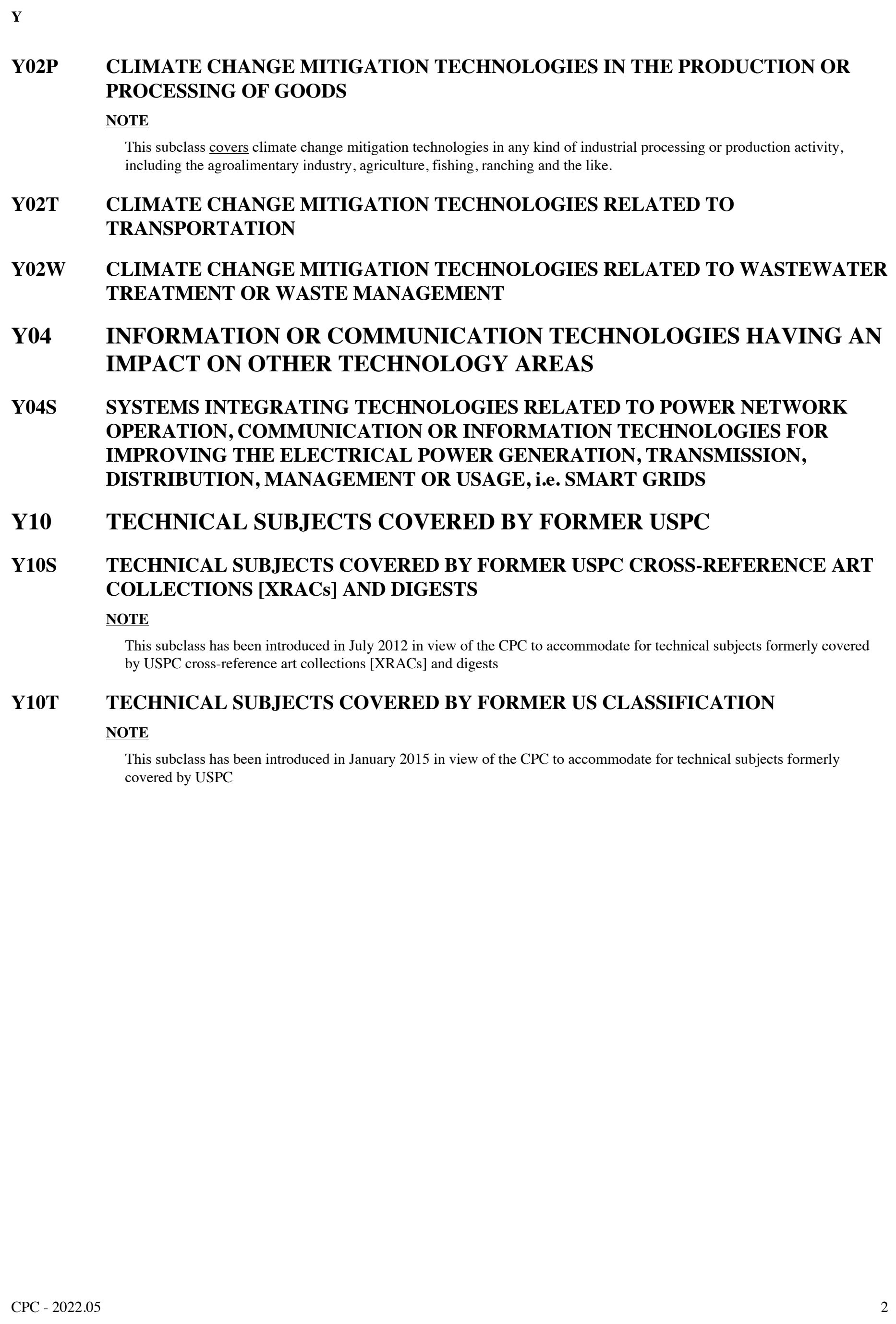
NOTES

1. This subclass covers information and communication technologies [ICT] whose purpose is to minimize the use of energy during the operation of the involved ICT equipment.
2. This subclass does not cover the use of an ICT technology supporting energy efficient operation of a further piece of equipment, nor the reuse or recycling of ICT equipment.

Y02E REDUCTION OF GREENHOUSE GAS [GHG] EMISSIONS, RELATED TO ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION

CPC - 2022.05 1

Figure D.1: Formal Documentation for Cooperative Patent Classification (CPC) (1 of 2). This shared document between the USPTO and the EPO defines the formal definitions for the CPC's Y02–Y04 tagging schema. Importantly, this document (1) defines Y02–Y04S tags to be applied in parallel with existing CPC technology classifications; (2) states that multiple Y02–Y04 tags can be applied to the same technology; and (3) introduces the terminology of Climate Change Mitigation Technology (CCMT). Source: U.S. Patent and Trademark Office (Cooperative Patent Classification, 2022).



Y

Y02P **CLIMATE CHANGE MITIGATION TECHNOLOGIES IN THE PRODUCTION OR PROCESSING OF GOODS**

NOTE

This subclass covers climate change mitigation technologies in any kind of industrial processing or production activity, including the agroalimentary industry, agriculture, fishing, ranching and the like.

Y02T **CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO TRANSPORTATION**

Y02W **CLIMATE CHANGE MITIGATION TECHNOLOGIES RELATED TO WASTEWATER TREATMENT OR WASTE MANAGEMENT**

Y04 **INFORMATION OR COMMUNICATION TECHNOLOGIES HAVING AN IMPACT ON OTHER TECHNOLOGY AREAS**

Y04S **SYSTEMS INTEGRATING TECHNOLOGIES RELATED TO POWER NETWORK OPERATION, COMMUNICATION OR INFORMATION TECHNOLOGIES FOR IMPROVING THE ELECTRICAL POWER GENERATION, TRANSMISSION, DISTRIBUTION, MANAGEMENT OR USAGE, i.e. SMART GRIDS**

Y10 **TECHNICAL SUBJECTS COVERED BY FORMER USPC**

Y10S **TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS**

NOTE

This subclass has been introduced in July 2012 in view of the CPC to accommodate for technical subjects formerly covered by USPC cross-reference art collections [XRACs] and digests

Y10T **TECHNICAL SUBJECTS COVERED BY FORMER US CLASSIFICATION**

NOTE

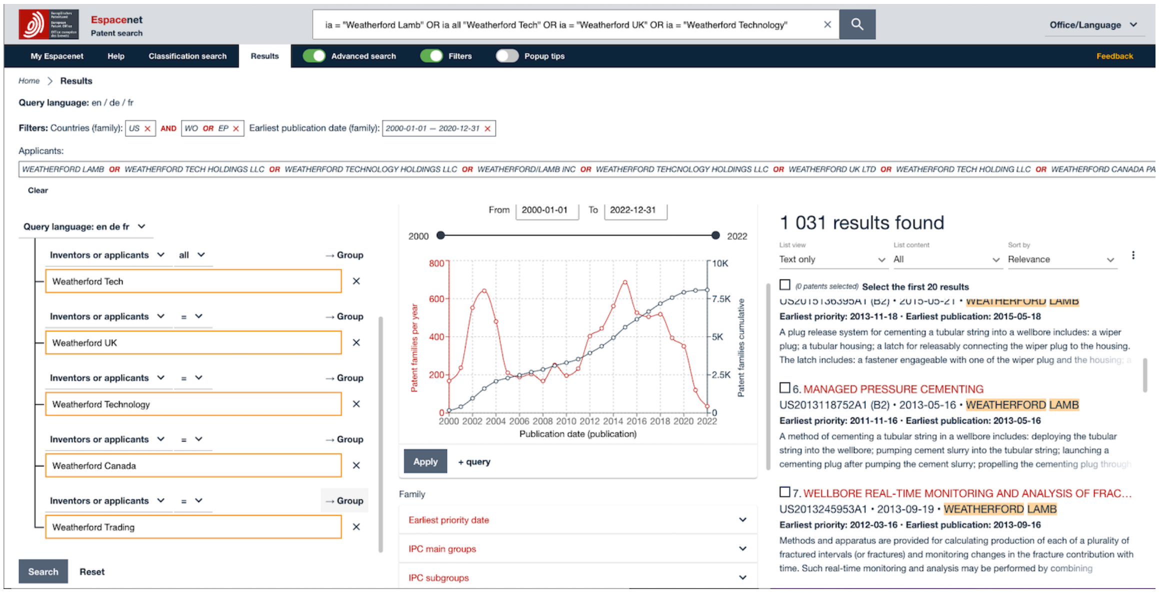
This subclass has been introduced in January 2015 in view of the CPC to accommodate for technical subjects formerly covered by USPC

CPC - 2022.05 2

Figure D.2: Formal Documentation for Cooperative Patent Classification (CPC) (2 of 2). This shared document between the USPTO and the EPO defines the formal definitions for the CPC's Y02–Y04 tagging schema. Importantly, this document (1) defines Y02–Y04S tags to be applied in parallel with existing CPC technology classifications; (2) states that multiple Y02–Y04 tags can be applied to the same technology; and (3) introduces the terminology of Climate Change Mitigation Technology (CCMT). Source: U.S. Patent and Trademark Office (Cooperative Patent Classification, 2022).

Appendix E

Research Design for Patent Searching in EPO's Espacenet Database



ia = "Weatherford Lamb" OR ia all "Weatherford Tech" OR ia = "Weatherford UK" OR ia = "Weatherford Technology"

Query language: en / de / fr

Filters: Countries (family): *US* **AND** *WO* ***OR*** *EP* Earliest publication date (family): *2000-01-01 — 2020-12-31*

Applicants:

WEATHERFORD LAMB ***OR*** *WEATHERFORD TECH HOLDINGS LLC* ***OR*** *WEATHERFORD TECHNOLOGY HOLDINGS LLC* ***OR*** *WEATHERFORD/LAMB INC* ***OR*** *WEATHERFORD TEHCNOLOGY HOLDINGS LLC* ***OR*** *WEATHERFORD UK LTD* ***OR*** *WEATHERFORD TECH HOLDING LLC* ***OR*** *WEATHERFORD CANADA PA*

Query language: en de fr

Inventors or applicants: all
Weatherford Tech

Inventors or applicants: =
Weatherford UK

Inventors or applicants: =
Weatherford Technology

Inventors or applicants: =
Weatherford Canada

Inventors or applicants: =
Weatherford Trading

From 2000-01-01 To 2022-12-31

1 031 results found

List view: Text only
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Sort by: Relevance

☐ *(0 patents selected)* **Select the first 20 results**

US2015136395A1 (B2) • 2015-05-21 • WEATHERFORD LAMB
Earliest priority: 2013-11-18 · Earliest publication: 2015-05-18
A plug release system for cementing a tubular string into a wellbore includes: a wiper plug; a tubular housing; a latch for releasably connecting the wiper plug to the housing. The latch includes: a fastener engageable with one of the wiper plug and the housing; a

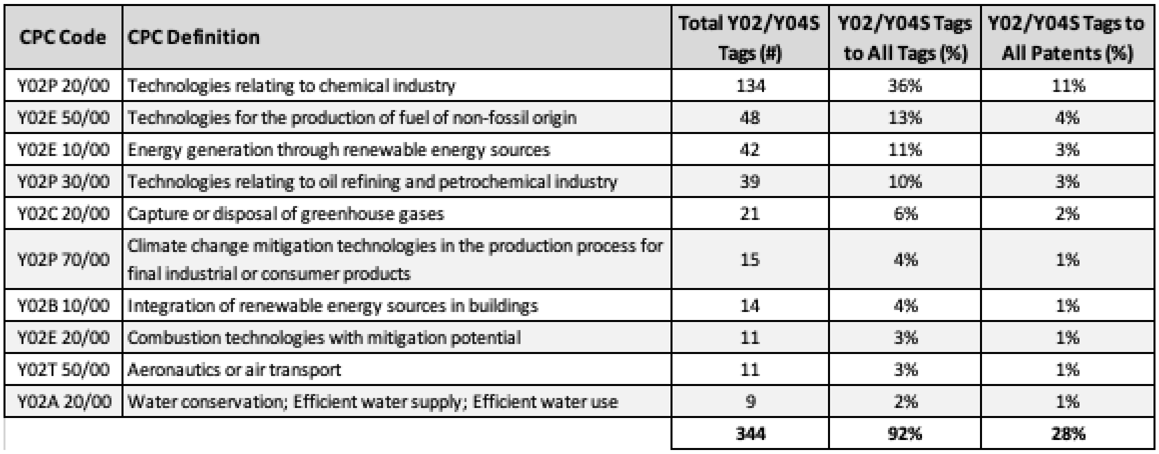
☐ 6. MANAGED PRESSURE CEMENTING
US2013118752A1 (B2) • 2013-05-16 • WEATHERFORD LAMB
Earliest priority: 2011-11-16 · Earliest publication: 2013-05-16
A method of cementing a tubular string in a wellbore includes: deploying the tubular string into the wellbore; pumping cement slurry into the tubular string; launching a cementing plug after pumping the cement slurry; propelling the cementing plug through

☐ 7. WELLBORE REAL-TIME MONITORING AND ANALYSIS OF FRAC…
US2013245953A1 • 2013-09-19 • WEATHERFORD LAMB
Earliest priority: 2012-03-16 · Earliest publication: 2013-09-16
Methods and apparatus are provided for calculating production of each of a plurality of fractured intervals (or fractures) and monitoring changes in the fracture contribution with time. Such real-time monitoring and analysis may be performed by combining

Figure E.1: Screenshot of Patent Search Parameters on EPO's Espacenet Database. This figure captures the primary search parameters for this research, including: Patent Families (US and EP or WO), Date Range (2000-01-01 to 2020-12-31), Languages (EN/DE/FR), and Company Names. Not shown are CPC Y02–Y04 tags. Source: Espacenet, https://worldwide.espacenet.com/patent/my-espacenet.

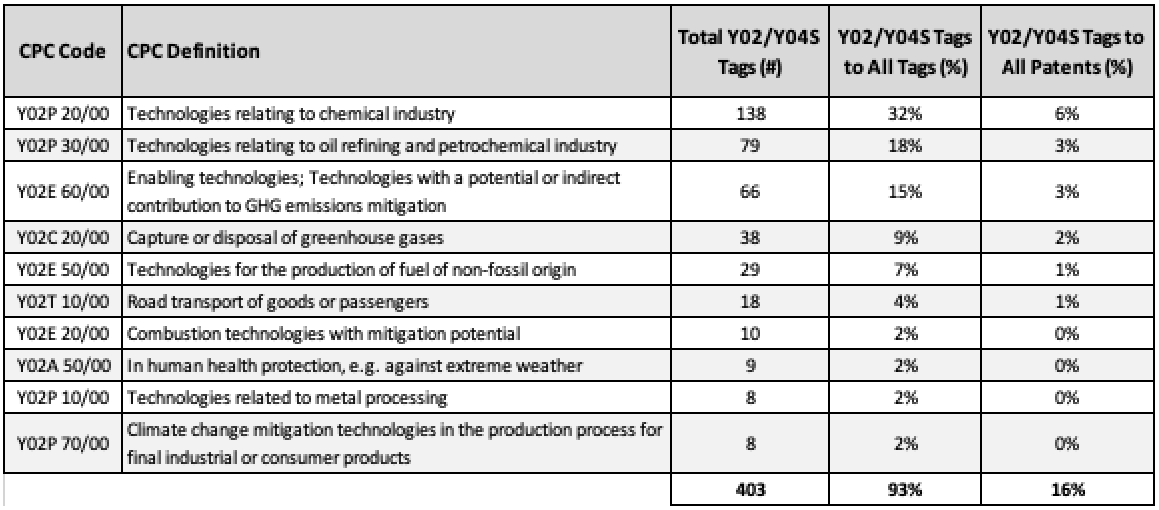
Appendix F

Climate Change Mitigating Technology Focus Areas by Company



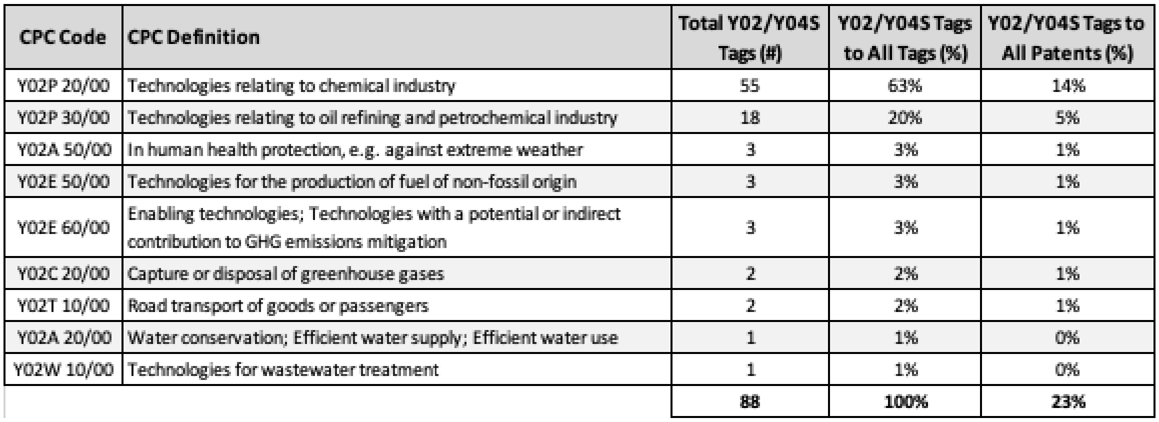
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	134	36%	11%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	48	13%	4%
Y02E 10/00	Energy generation through renewable energy sources	42	11%	3%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	39	10%	3%
Y02C 20/00	Capture or disposal of greenhouse gases	21	6%	2%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	15	4%	1%
Y02B 10/00	Integration of renewable energy sources in buildings	14	4%	1%
Y02E 20/00	Combustion technologies with mitigation potential	11	3%	1%
Y02T 50/00	Aeronautics or air transport	11	3%	1%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	9	2%	1%
		344	**92%**	**28%**

Table F.1: BP’s Top 10 Technology Focus Areas by Y02–Y04S Tags, 2000–2020. Source: Based on EPO and USPTO data from the Espacenet patent database.



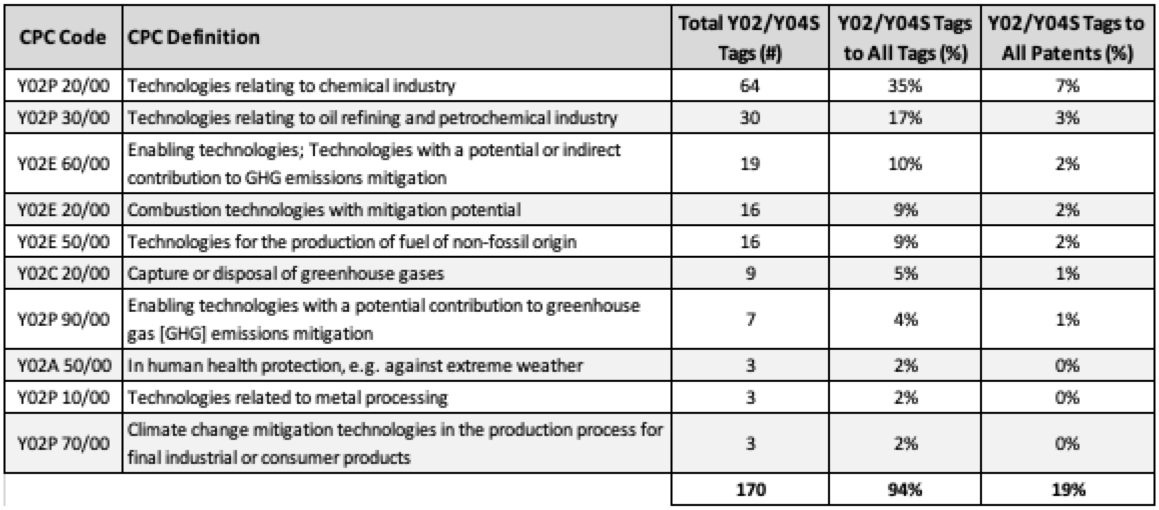
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	138	32%	6%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	79	18%	3%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	66	15%	3%
Y02C 20/00	Capture or disposal of greenhouse gases	38	9%	2%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	29	7%	1%
Y02T 10/00	Road transport of goods or passengers	18	4%	1%
Y02E 20/00	Combustion technologies with mitigation potential	10	2%	0%
Y02A 50/00	In human health protection, e.g. against extreme weather	9	2%	0%
Y02P 10/00	Technologies related to metal processing	8	2%	0%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	8	2%	0%
		403	**93%**	**16%**

Table F.2: Chevron’s Top 10 Technology Focus Areas by Y02–Y04S Tags, 2000–2020. Source: Based on EPO and USPTO data from the Espacenet patent database.



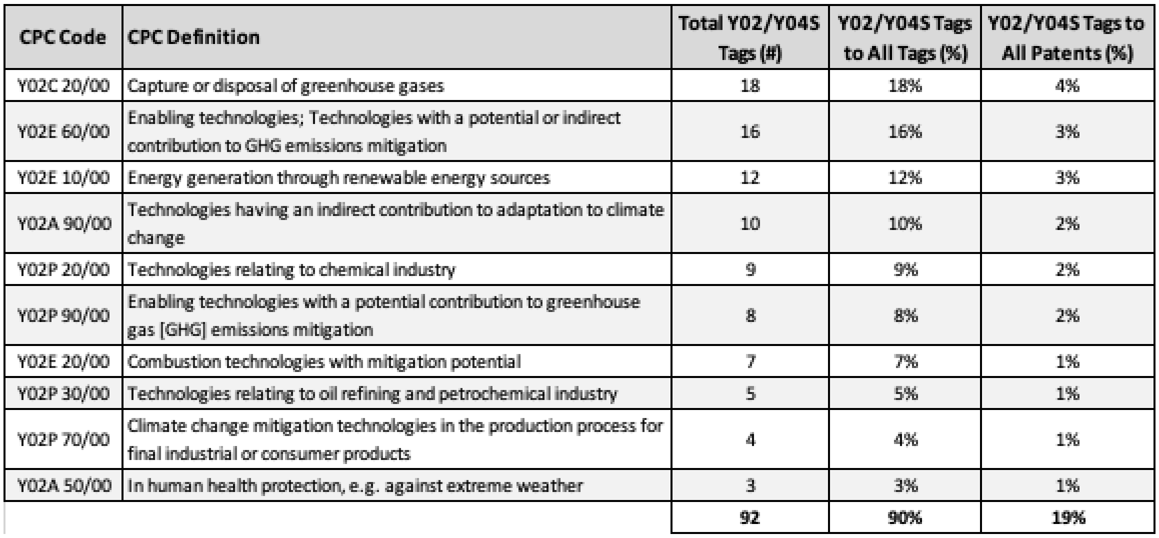
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	55	63%	14%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	18	20%	5%
Y02A 50/00	In human health protection, e.g. against extreme weather	3	3%	1%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	3	3%	1%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	3	3%	1%
Y02C 20/00	Capture or disposal of greenhouse gases	2	2%	1%
Y02T 10/00	Road transport of goods or passengers	2	2%	1%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	1	1%	0%
Y02W 10/00	Technologies for wastewater treatment	1	1%	0%
		88	**100%**	**23%**

Table F.3: China Petroleum's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



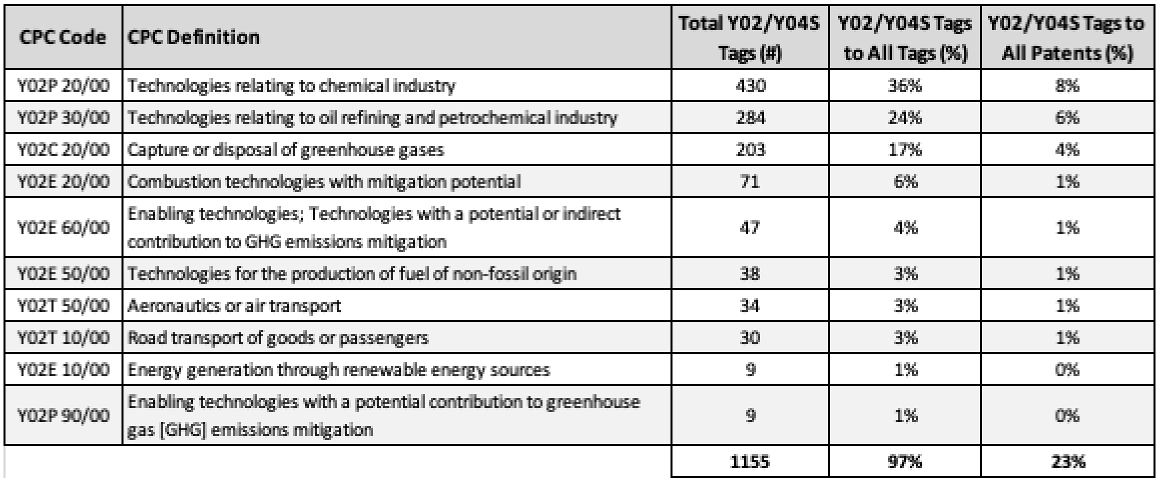
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	64	35%	7%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	30	17%	3%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	19	10%	2%
Y02E 20/00	Combustion technologies with mitigation potential	16	9%	2%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	16	9%	2%
Y02C 20/00	Capture or disposal of greenhouse gases	9	5%	1%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	7	4%	1%
Y02A 50/00	In human health protection, e.g. against extreme weather	3	2%	0%
Y02P 10/00	Technologies related to metal processing	3	2%	0%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	3	2%	0%
		170	**94%**	**19%**

Table F.4: Conoco's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



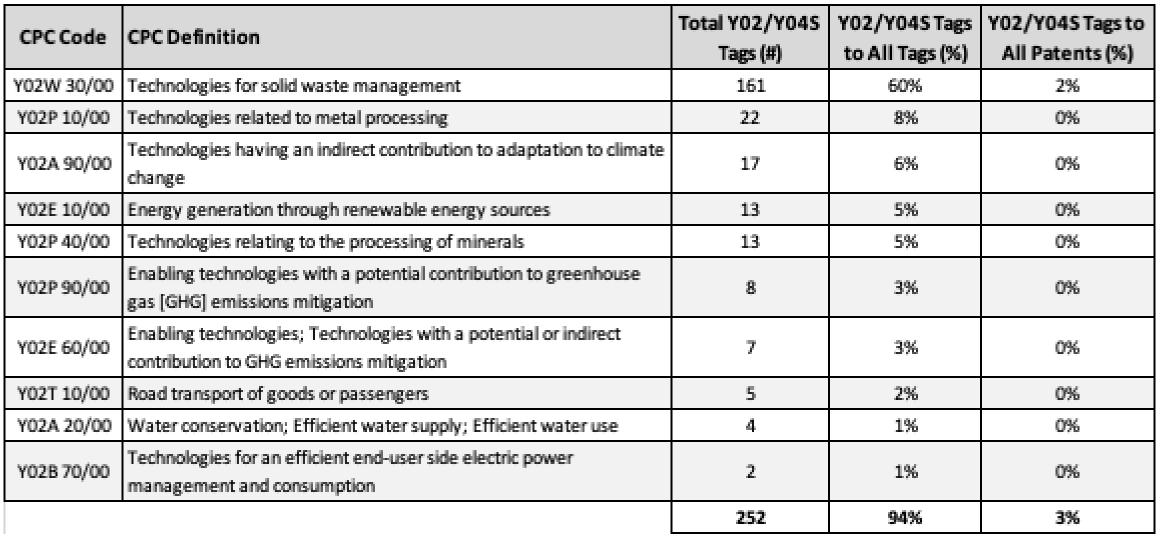
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02C 20/00	Capture or disposal of greenhouse gases	18	18%	4%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	16	16%	3%
Y02E 10/00	Energy generation through renewable energy sources	12	12%	3%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	10	10%	2%
Y02P 20/00	Technologies relating to chemical industry	9	9%	2%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	8	8%	2%
Y02E 20/00	Combustion technologies with mitigation potential	7	7%	1%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	5	5%	1%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	4	4%	1%
Y02A 50/00	In human health protection, e.g. against extreme weather	3	3%	1%
		92	**90%**	**19%**

Table F.5: Equinor's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



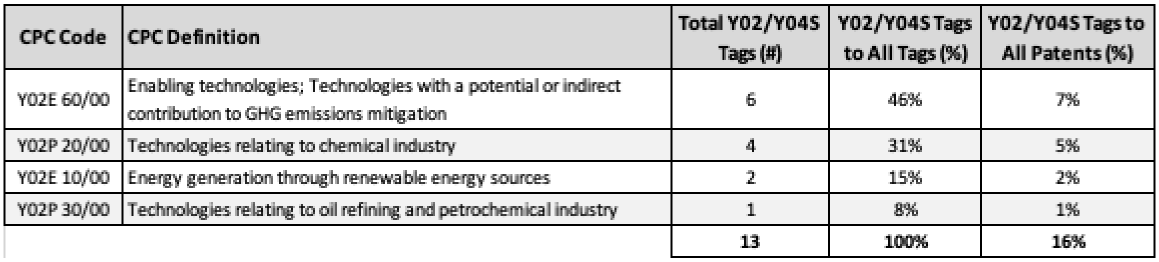
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	430	36%	8%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	284	24%	6%
Y02C 20/00	Capture or disposal of greenhouse gases	203	17%	4%
Y02E 20/00	Combustion technologies with mitigation potential	71	6%	1%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	47	4%	1%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	38	3%	1%
Y02T 50/00	Aeronautics or air transport	34	3%	1%
Y02T 10/00	Road transport of goods or passengers	30	3%	1%
Y02E 10/00	Energy generation through renewable energy sources	9	1%	0%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	9	1%	0%
		1155	**97%**	**23%**

Table F.6: Exxon's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



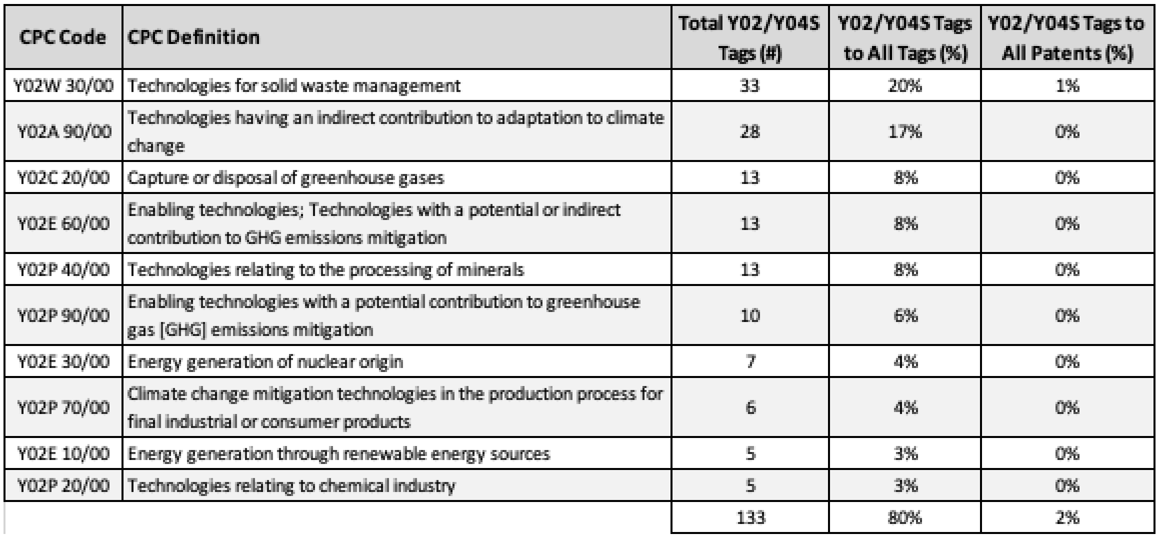
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02W 30/00	Technologies for solid waste management	161	60%	2%
Y02P 10/00	Technologies related to metal processing	22	8%	0%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	17	6%	0%
Y02E 10/00	Energy generation through renewable energy sources	13	5%	0%
Y02P 40/00	Technologies relating to the processing of minerals	13	5%	0%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	8	3%	0%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	7	3%	0%
Y02T 10/00	Road transport of goods or passengers	5	2%	0%
Y02A 20/00	Water conservation; Efficient water supply; Efficient water use	4	1%	0%
Y02B 70/00	Technologies for an efficient end-user side electric power management and consumption	2	1%	0%
		252	**94%**	**3%**

Table F.7: Halliburton's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



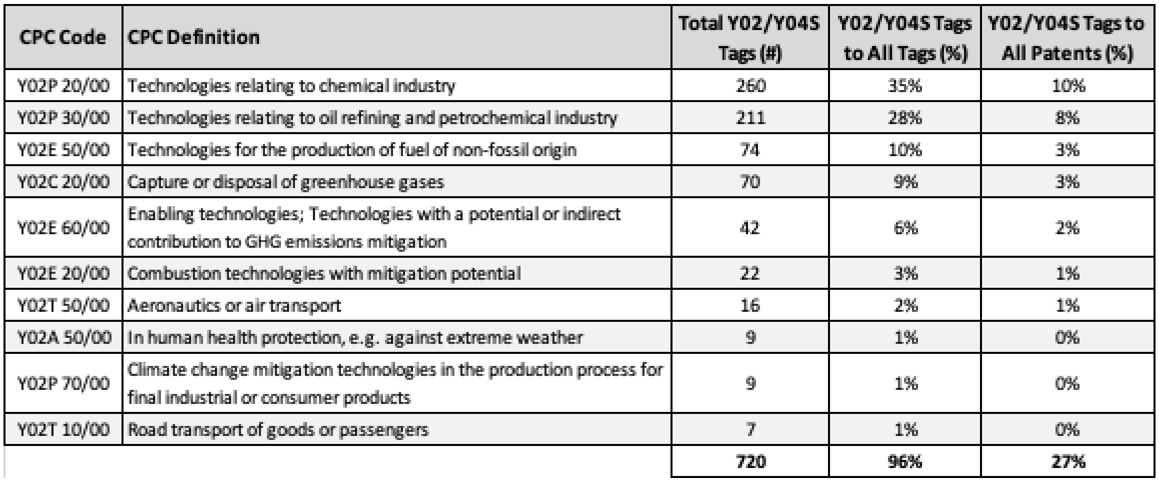
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	6	46%	7%
Y02P 20/00	Technologies relating to chemical industry	4	31%	5%
Y02E 10/00	Energy generation through renewable energy sources	2	15%	2%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	1	8%	1%
		13	**100%**	**16%**

Table F.8: PetroChina's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



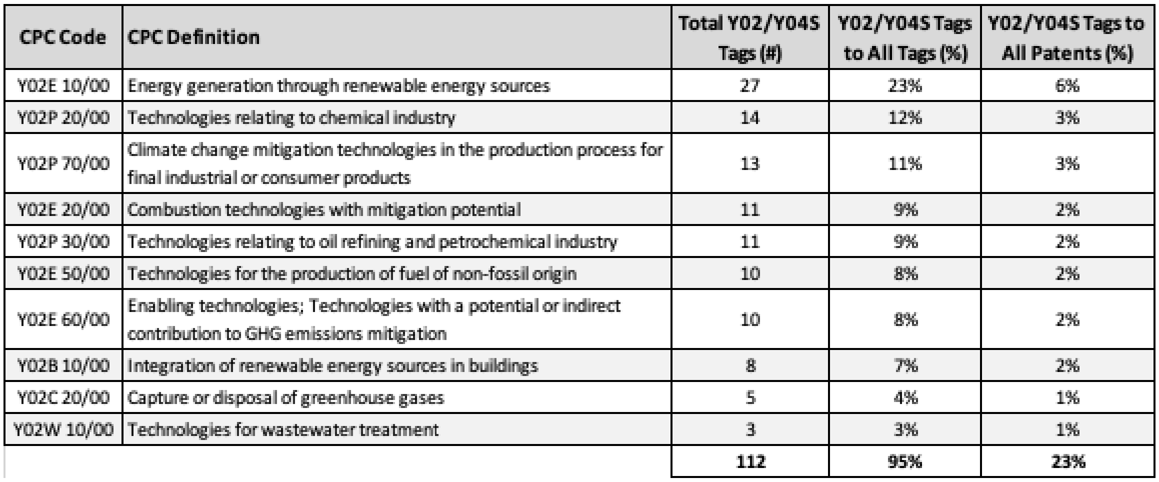
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02W 30/00	Technologies for solid waste management	33	20%	1%
Y02A 90/00	Technologies having an indirect contribution to adaptation to climate change	28	17%	0%
Y02C 20/00	Capture or disposal of greenhouse gases	13	8%	0%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	13	8%	0%
Y02P 40/00	Technologies relating to the processing of minerals	13	8%	0%
Y02P 90/00	Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	10	6%	0%
Y02E 30/00	Energy generation of nuclear origin	7	4%	0%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	6	4%	0%
Y02E 10/00	Energy generation through renewable energy sources	5	3%	0%
Y02P 20/00	Technologies relating to chemical industry	5	3%	0%
		133	80%	2%

Table F.9: Schlumberger's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



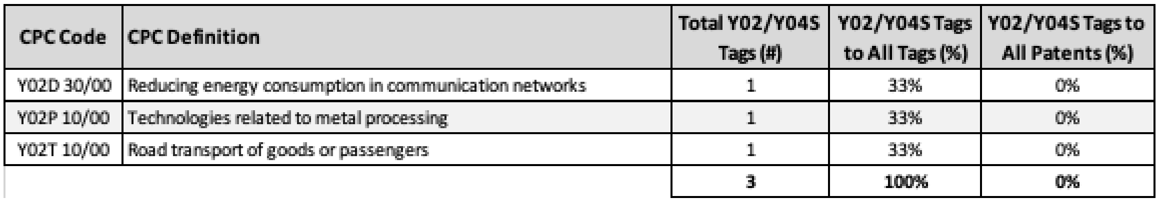
CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02P 20/00	Technologies relating to chemical industry	260	35%	10%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	211	28%	8%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	74	10%	3%
Y02C 20/00	Capture or disposal of greenhouse gases	70	9%	3%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	42	6%	2%
Y02E 20/00	Combustion technologies with mitigation potential	22	3%	1%
Y02T 50/00	Aeronautics or air transport	16	2%	1%
Y02A 50/00	In human health protection, e.g. against extreme weather	9	1%	0%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	9	1%	0%
Y02T 10/00	Road transport of goods or passengers	7	1%	0%
		720	**96%**	**27%**

Table F.10: Shell's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02E 10/00	Energy generation through renewable energy sources	27	23%	6%
Y02P 20/00	Technologies relating to chemical industry	14	12%	3%
Y02P 70/00	Climate change mitigation technologies in the production process for final industrial or consumer products	13	11%	3%
Y02E 20/00	Combustion technologies with mitigation potential	11	9%	2%
Y02P 30/00	Technologies relating to oil refining and petrochemical industry	11	9%	2%
Y02E 50/00	Technologies for the production of fuel of non-fossil origin	10	8%	2%
Y02E 60/00	Enabling technologies; Technologies with a potential or indirect contribution to GHG emissions mitigation	10	8%	2%
Y02B 10/00	Integration of renewable energy sources in buildings	8	7%	2%
Y02C 20/00	Capture or disposal of greenhouse gases	5	4%	1%
Y02W 10/00	Technologies for wastewater treatment	3	3%	1%
		112	**95%**	**23%**

Table F.11: Total's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.



CPC Code	CPC Definition	Total Y02/Y04S Tags (#)	Y02/Y04S Tags to All Tags (%)	Y02/Y04S Tags to All Patents (%)
Y02D 30/00	Reducing energy consumption in communication networks	1	33%	0%
Y02P 10/00	Technologies related to metal processing	1	33%	0%
Y02T 10/00	Road transport of goods or passengers	1	33%	0%
		3	**100%**	**0%**

Table F.12: Weatherford's Top 10 Technology Focus Areas by Y02–Y04S Tags. Source: Based on EPO and USPTO data from the Espacenet patent database.

Appendix G

Comparison of R&D Metrics to R&D Patenting Activity by Company

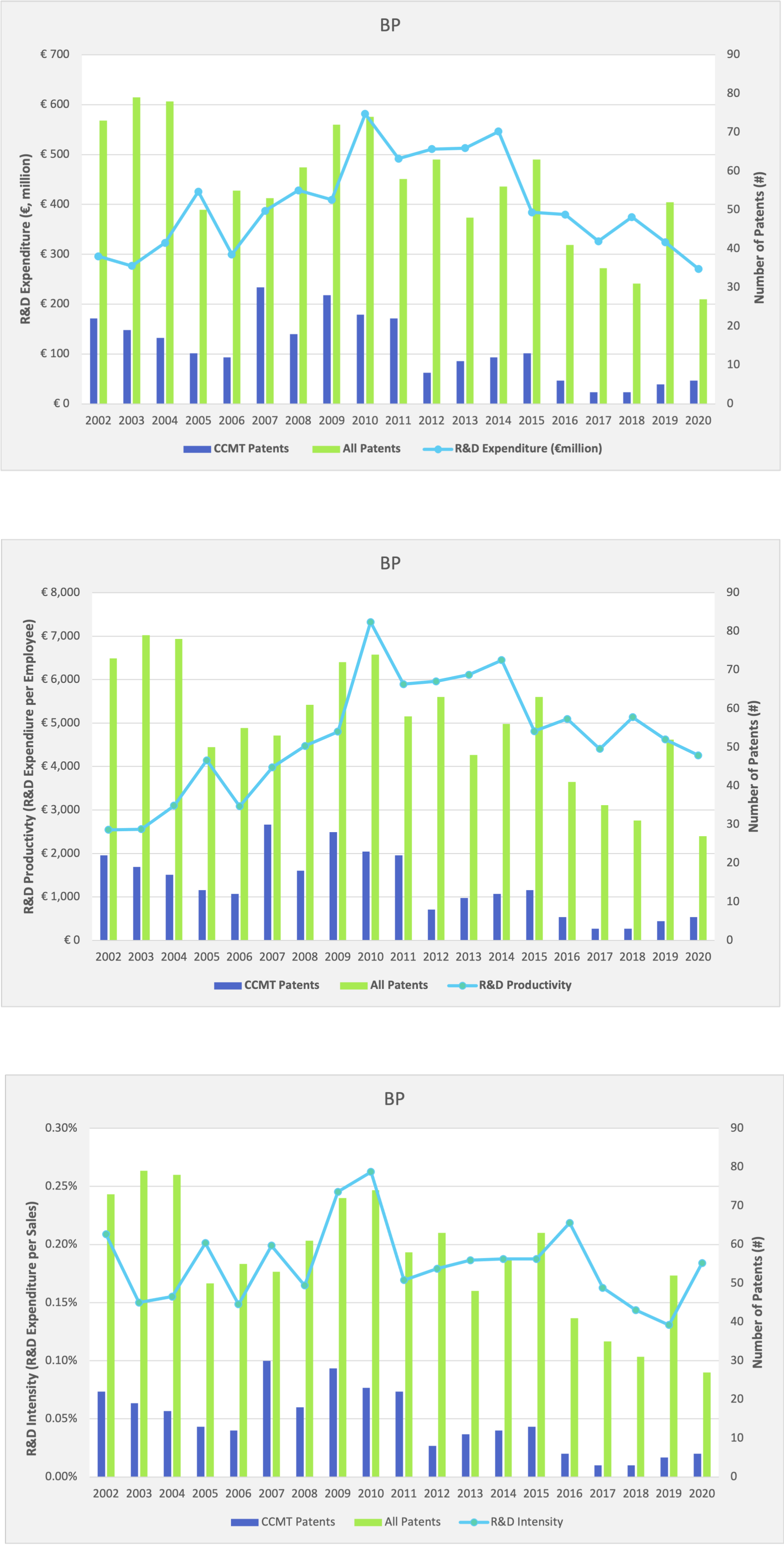
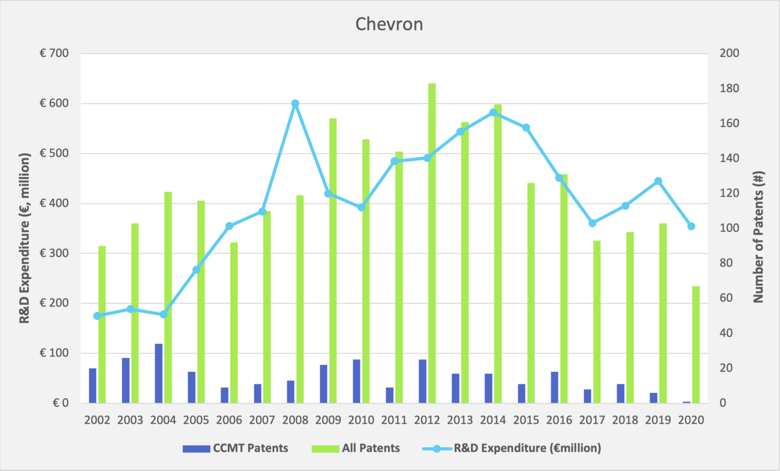
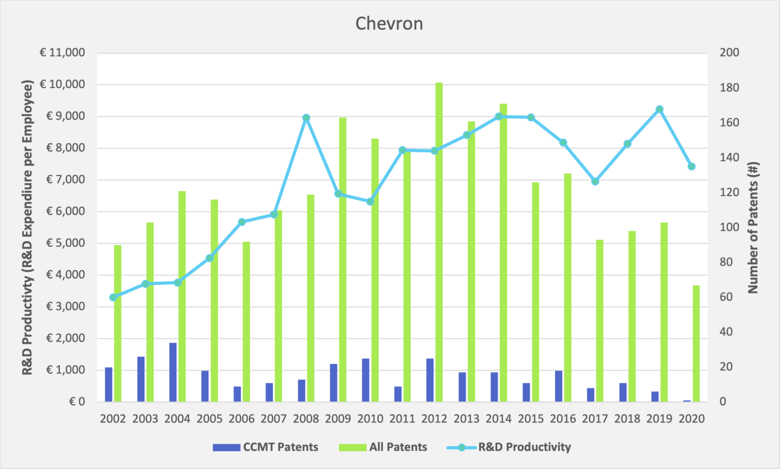


Figure G.1: Comparison of BP's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





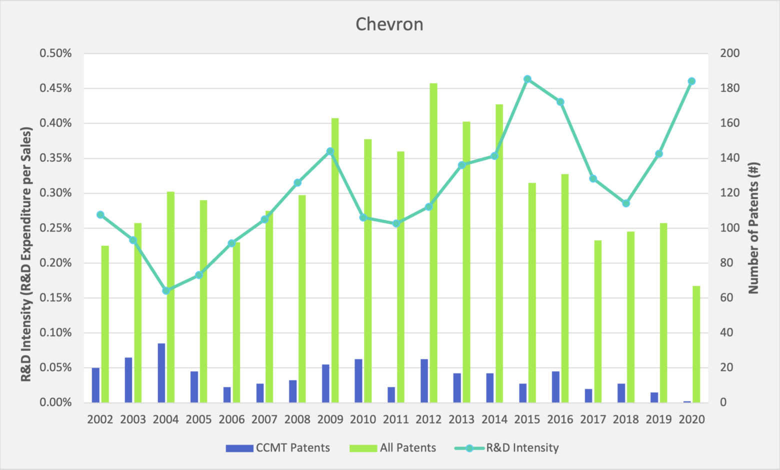
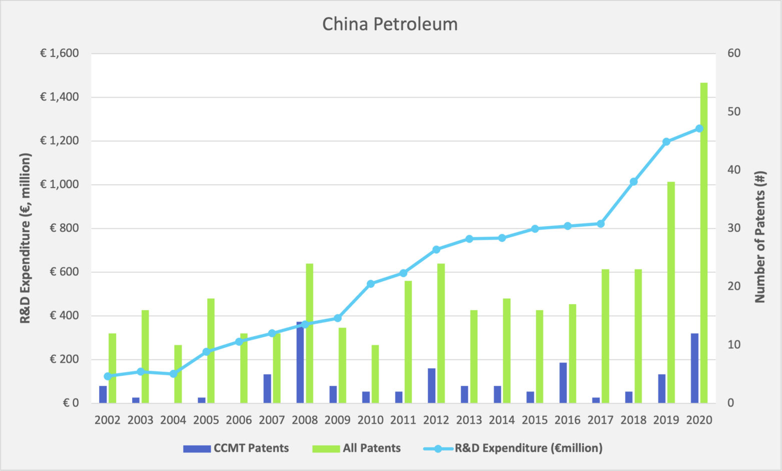
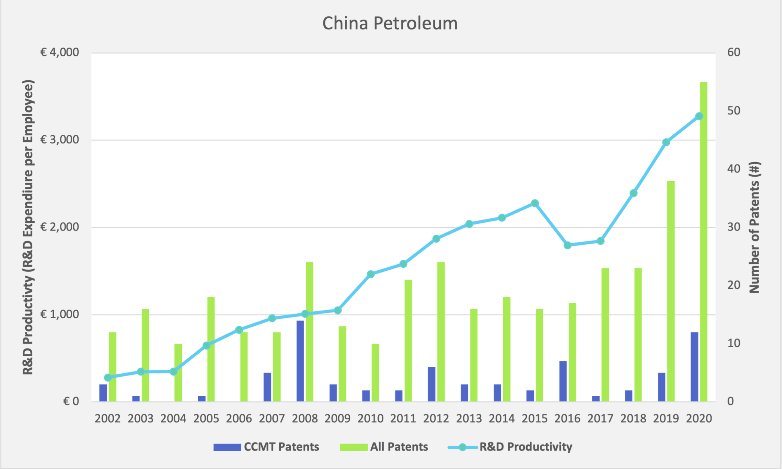


Figure G.2: Comparison of Chevron’s R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





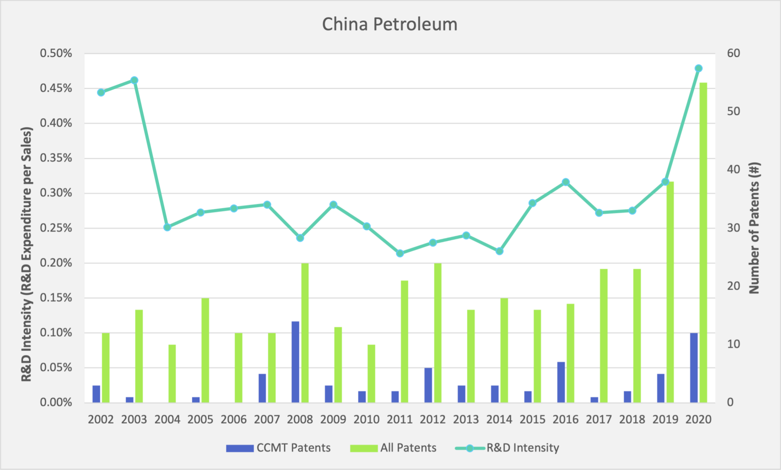
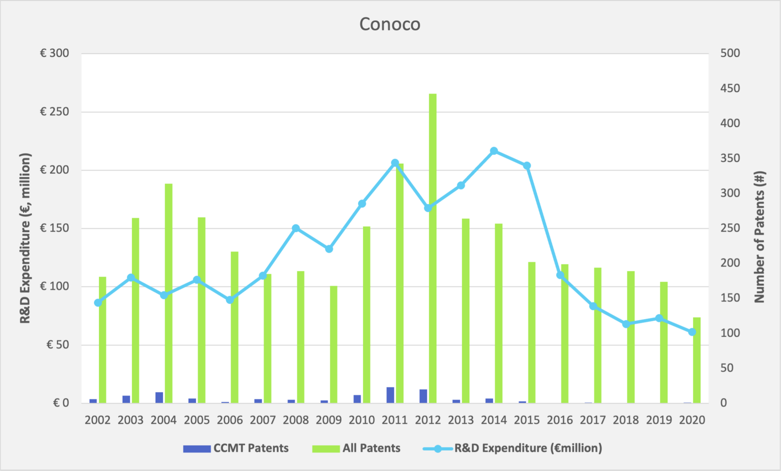
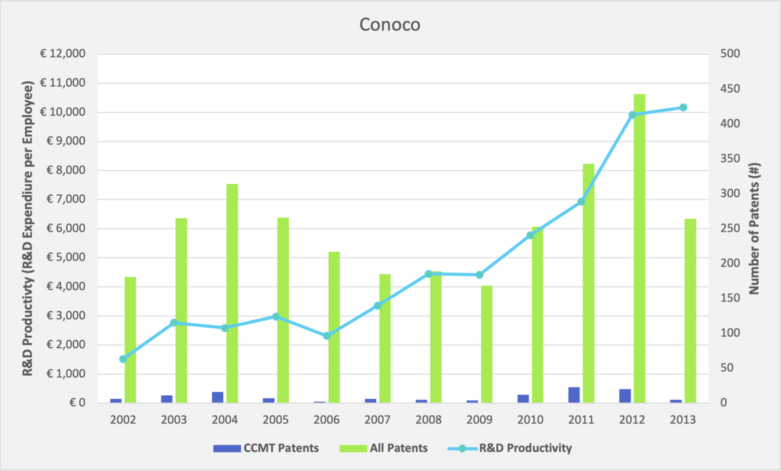


Figure G.3: Comparison of China Petroleum's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





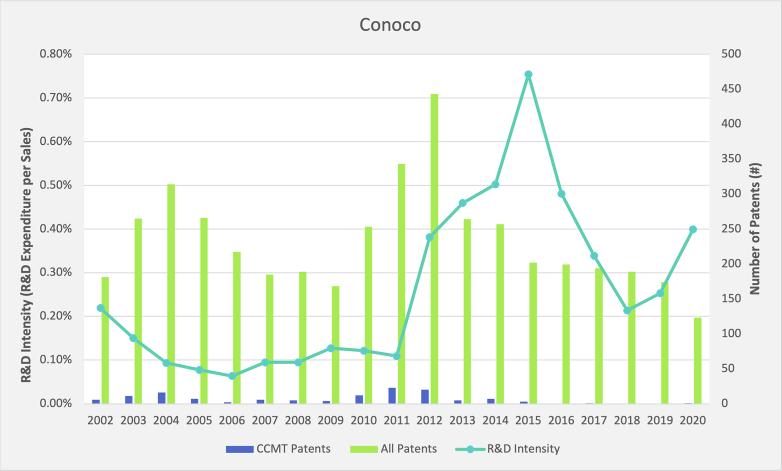


Figure G.4: Comparison of Conoco's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

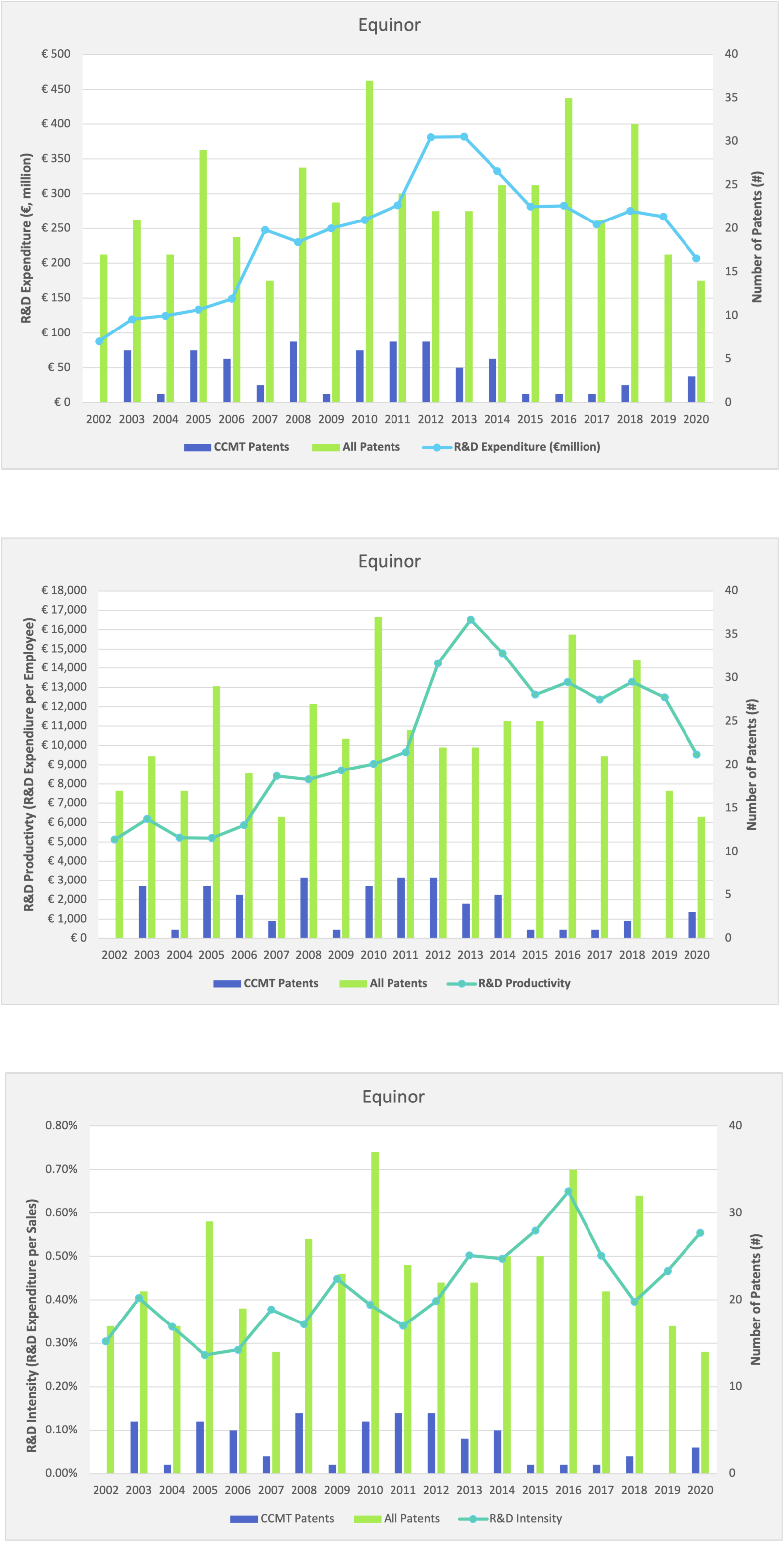
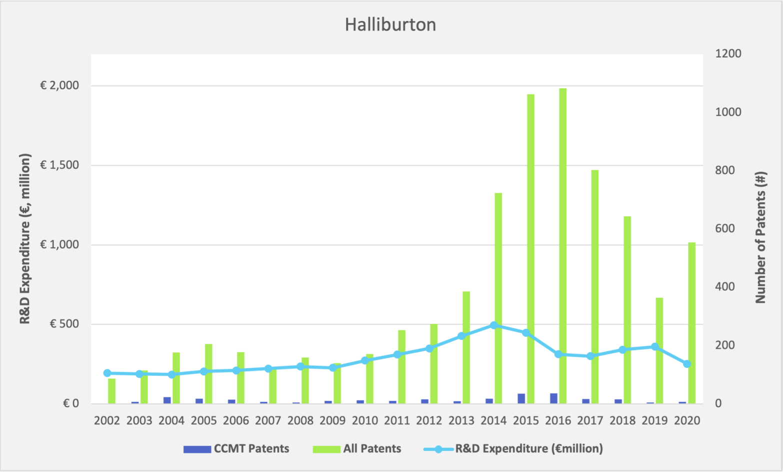
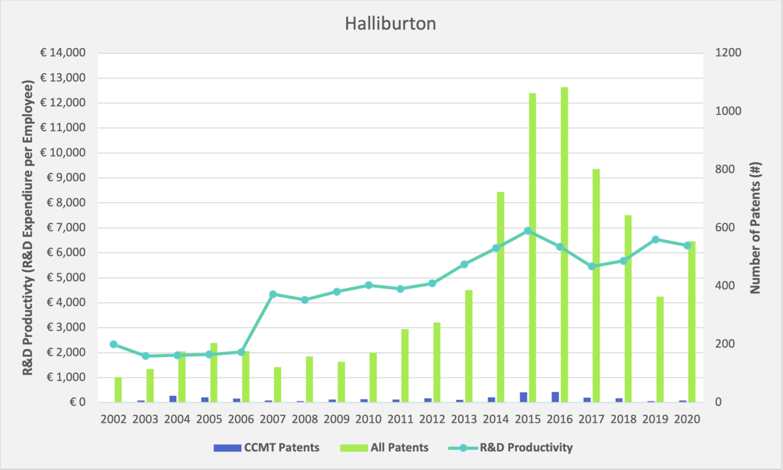


Figure G.5: Comparison of Equinor's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

Figure G.6: Comparison of Exxon's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





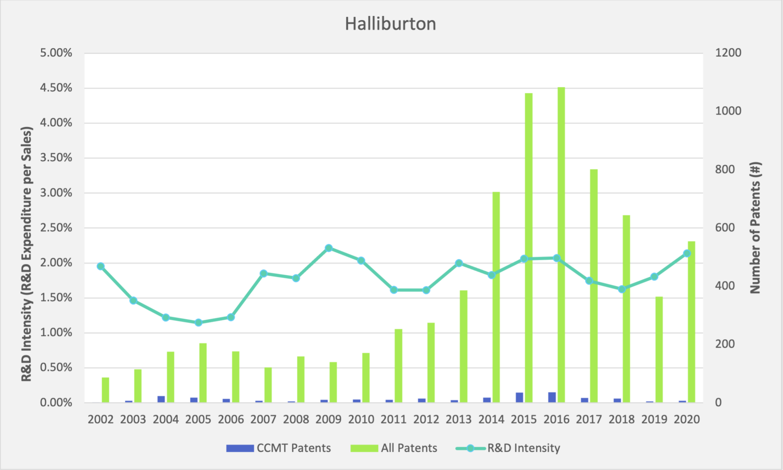


Figure G.7: Comparison of Halliburton’s R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

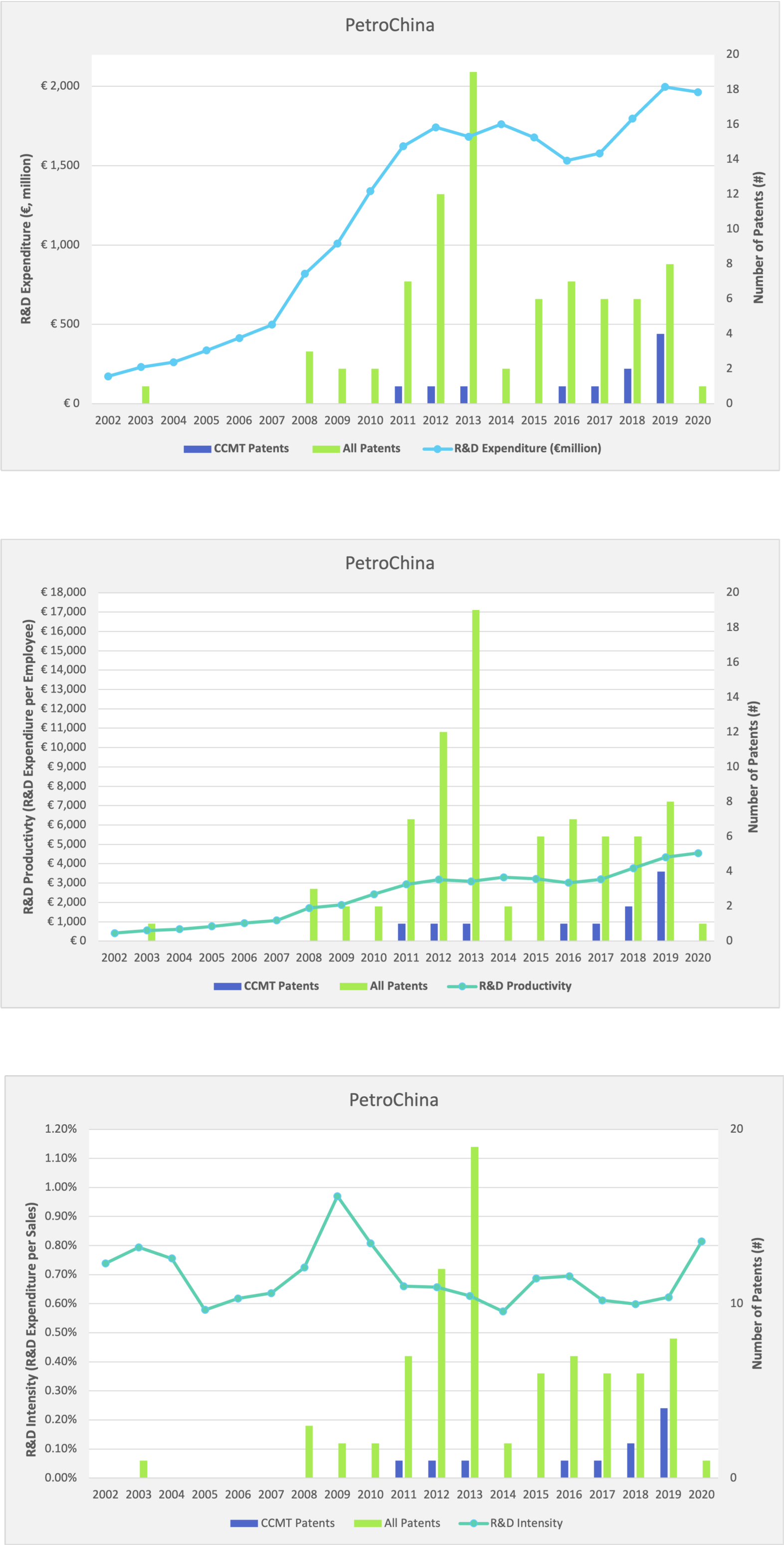
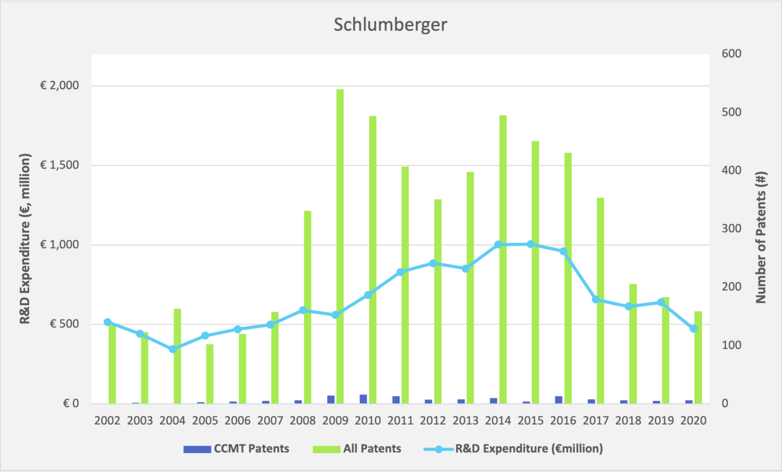
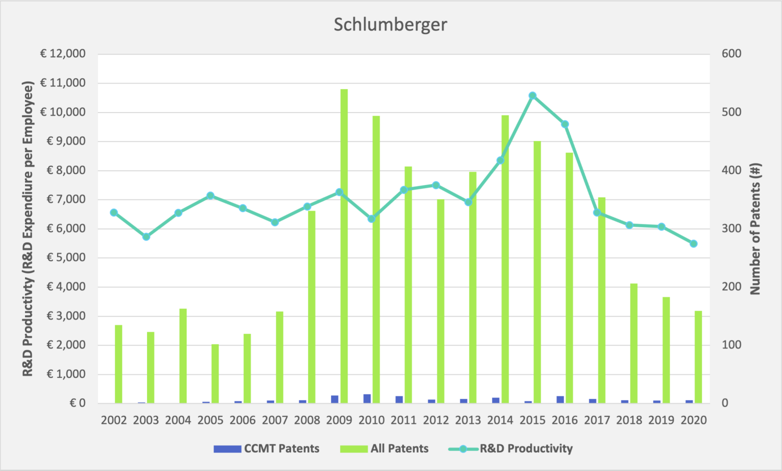


Figure G.8: Comparison of PetroChina's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





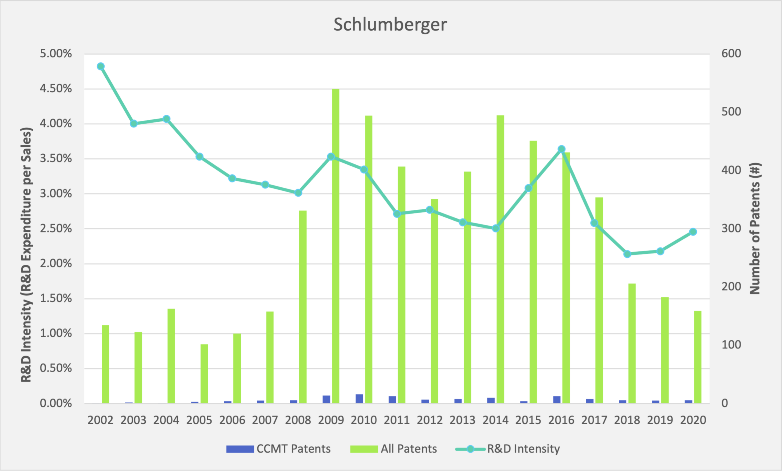
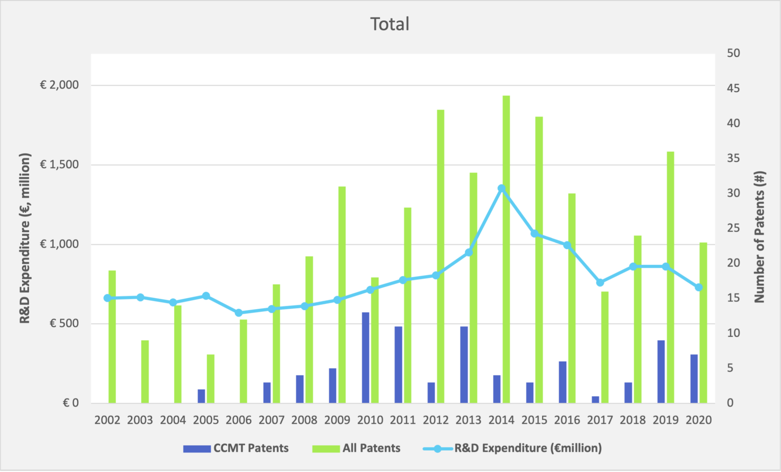
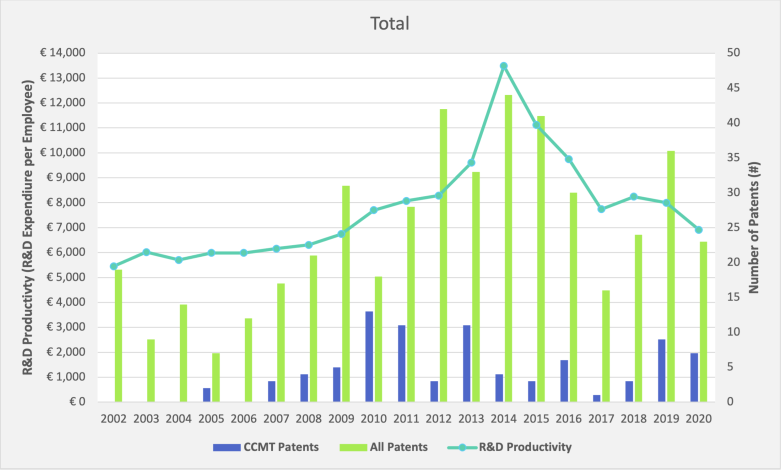


Figure G.9: Comparison of Schlumberger's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

Figure G.10: Comparison of Shell's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.





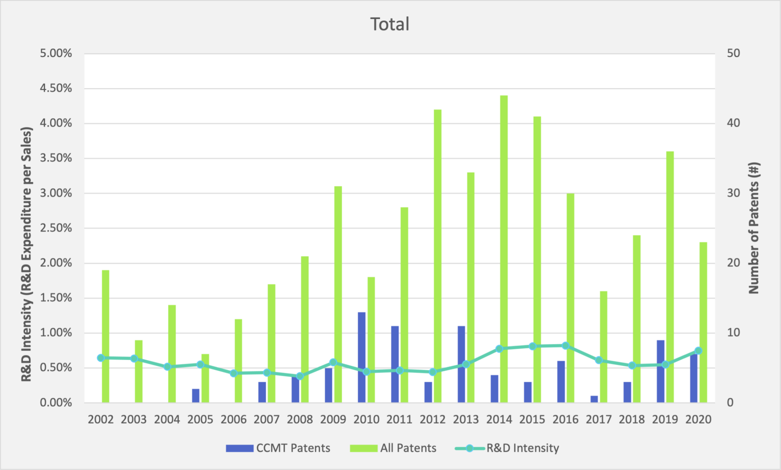


Figure G.11: Comparison of Total's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

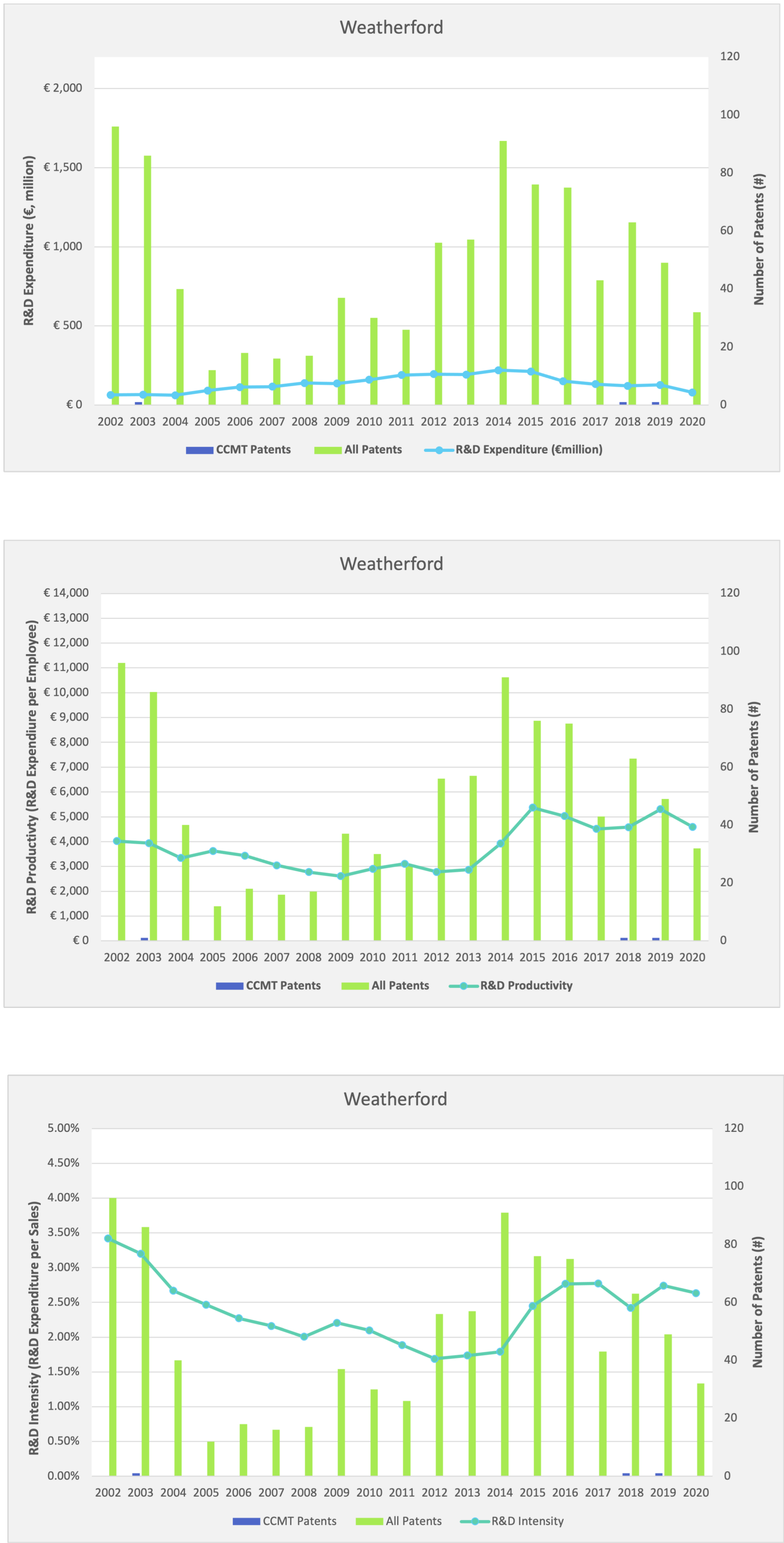


Figure G.12: Comparison of Weatherford's R&D Metrics to CCMT Patents, 2002–2020. These figures chart the yearly R&D Expenditure (top), R&D Productivity (middle), and R&D Intensity (bottom) on the primary axis (left). Yearly CCMT Patents and Total Patents are plotted on the secondary axis (right). Source: Based on IRI data and EPO/USPTO data.

Appendix H

Lag of R&D Expenditure to Sustaining, Disruptive and Total Patents

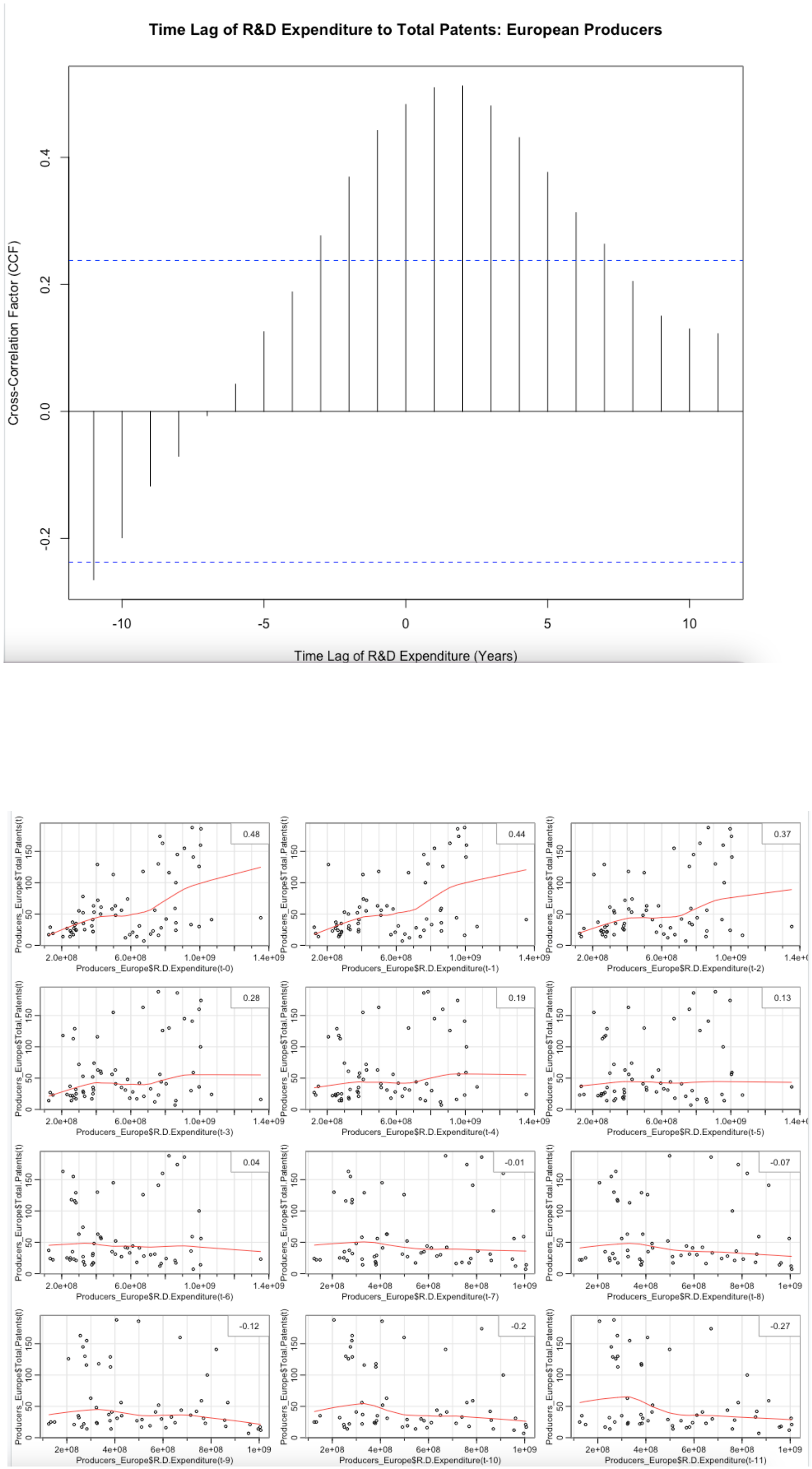


Figure H.1: Lag of R&D Expenditure to Total R&D Patenting Activity: European Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Total Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

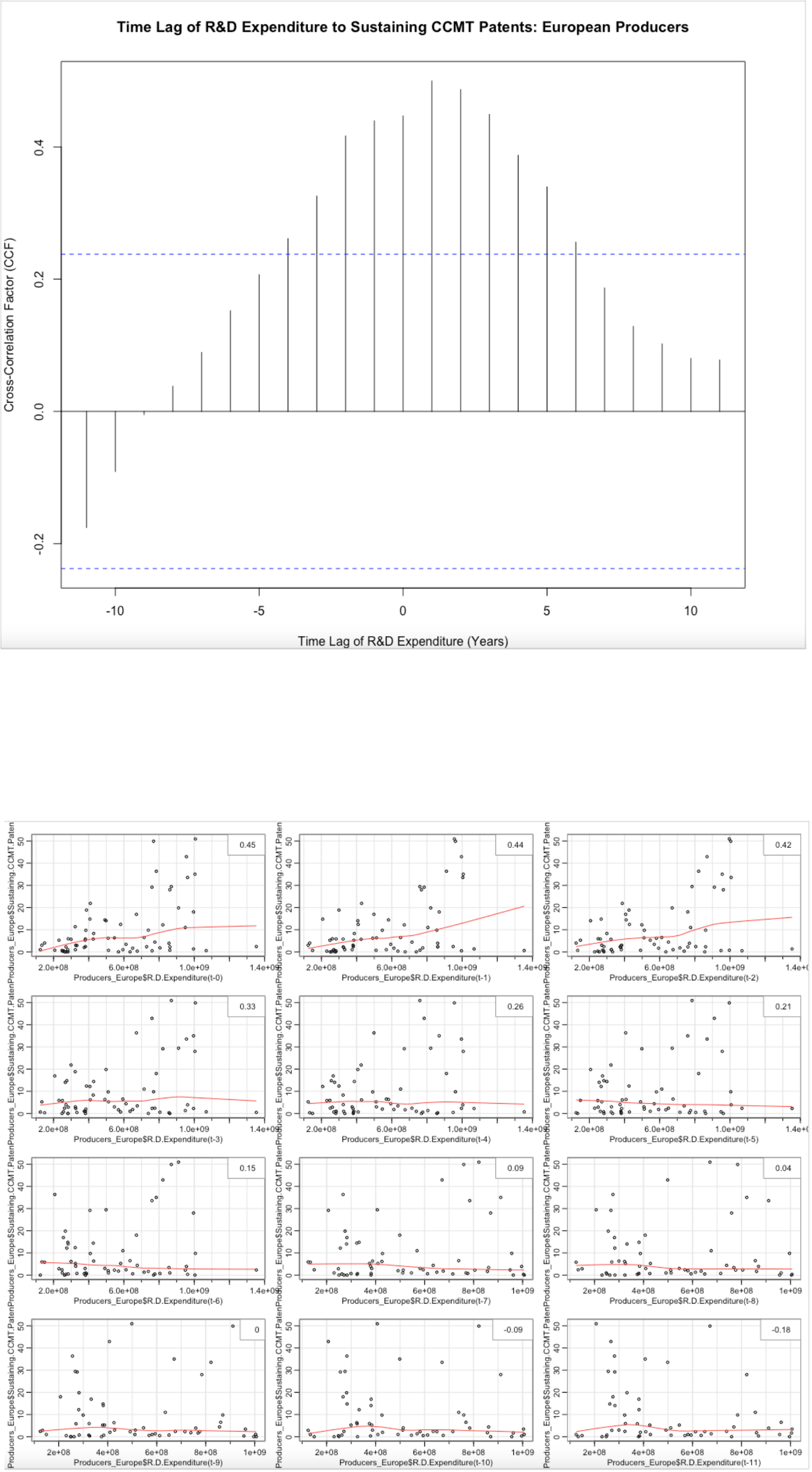


Figure H.2: Lag of R&D Expenditure to Sustaining CCMT Patenting Activity: European Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Sustaining Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

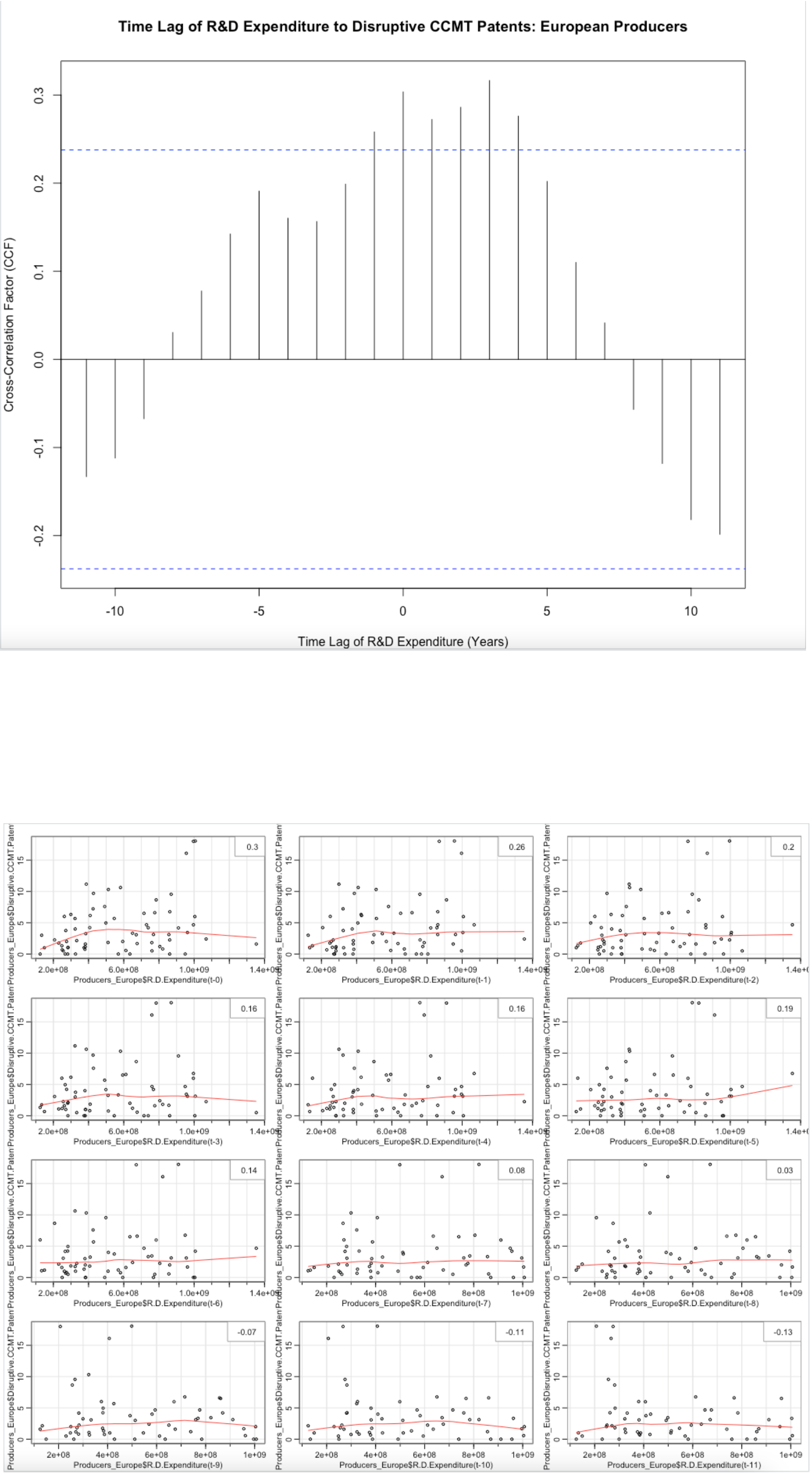


Figure H.3: Lag of R&D Expenditure to Disruptive CCMT Patenting Activity: European Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Disruptive Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

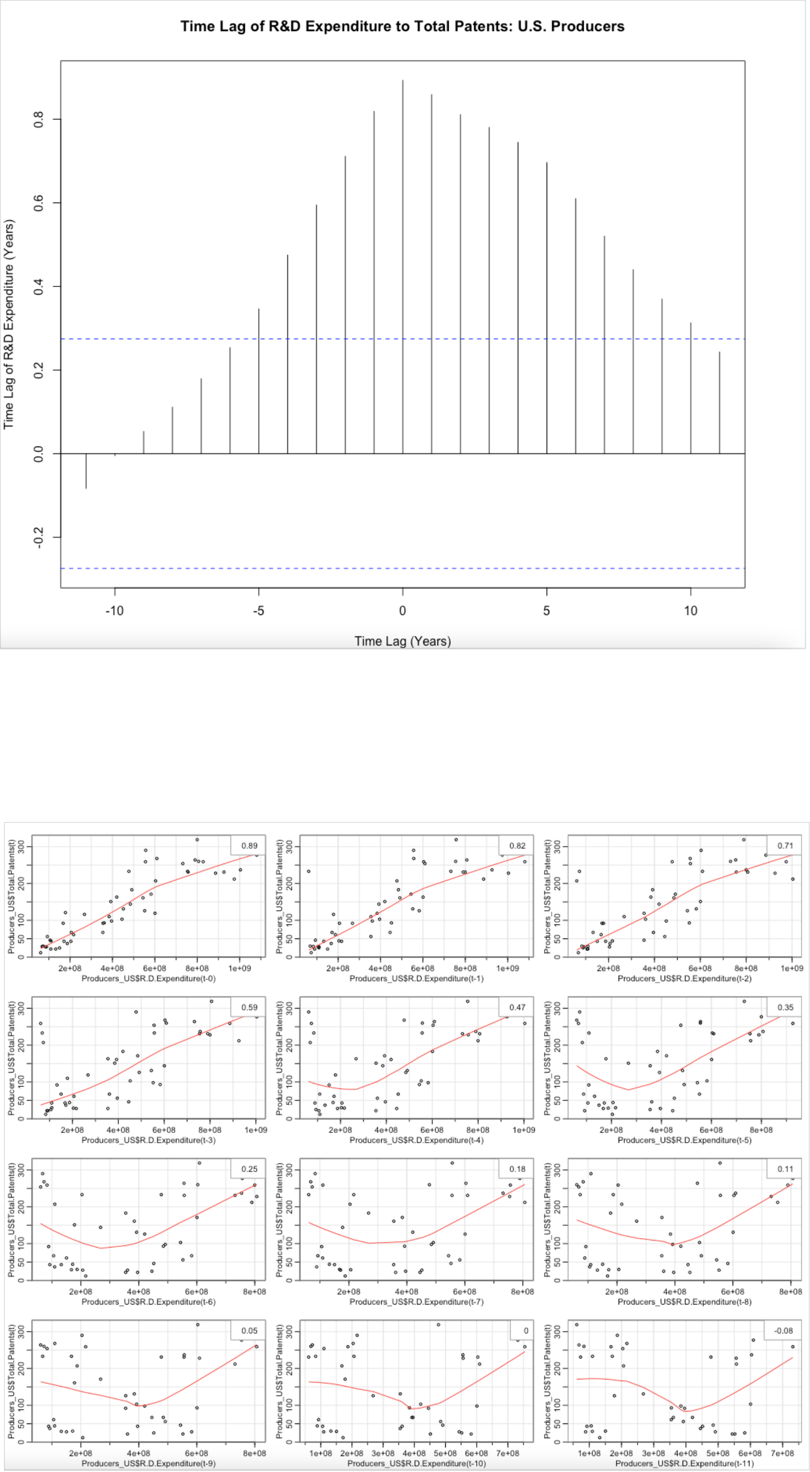


Figure H.4: Lag of R&D Expenditure to Total R&D Patenting Activity: U.S. Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Total Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

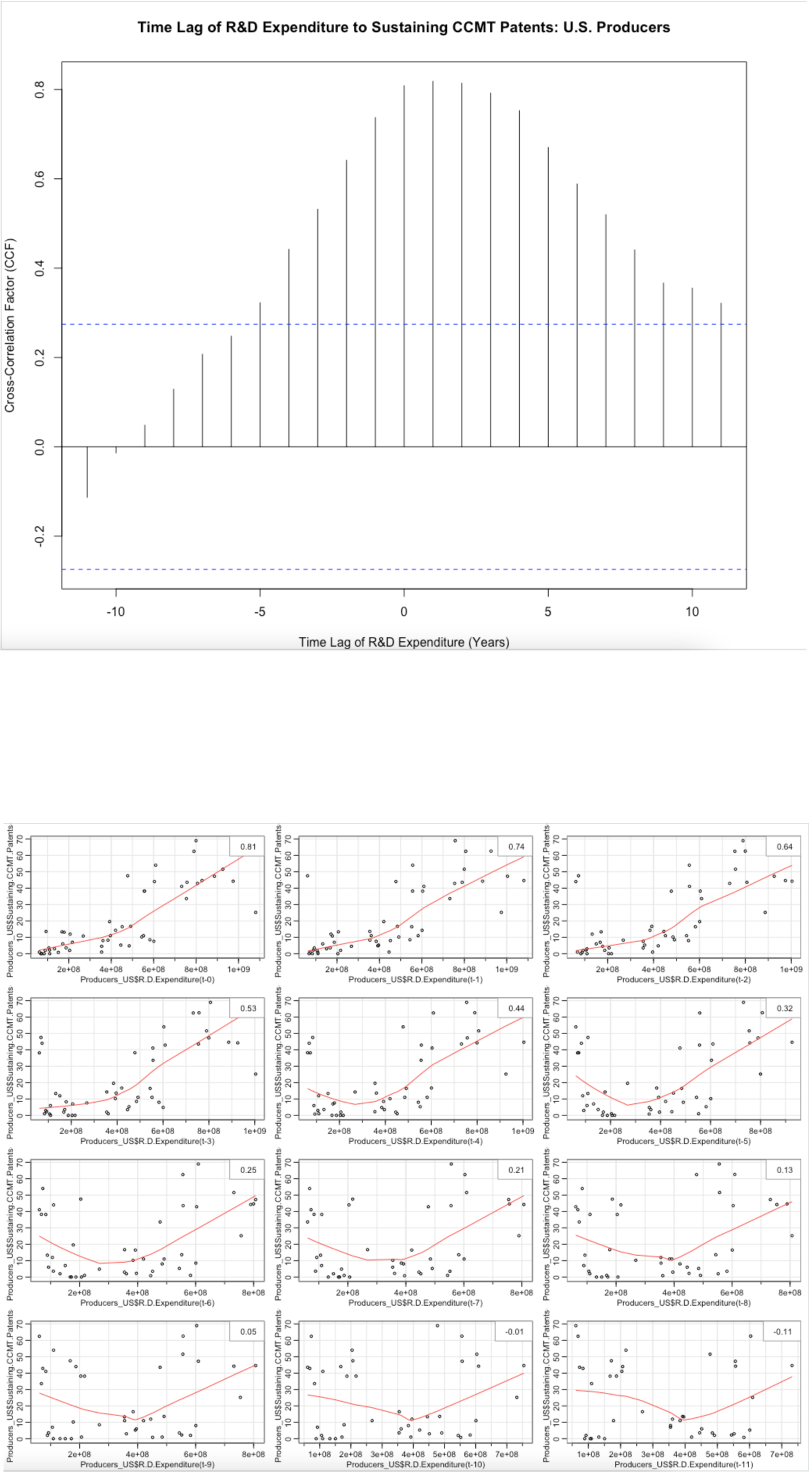


Figure H.5: Lag of R&D Expenditure to Sustaining CCMT Patenting Activity: U.S. Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Sustaining Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

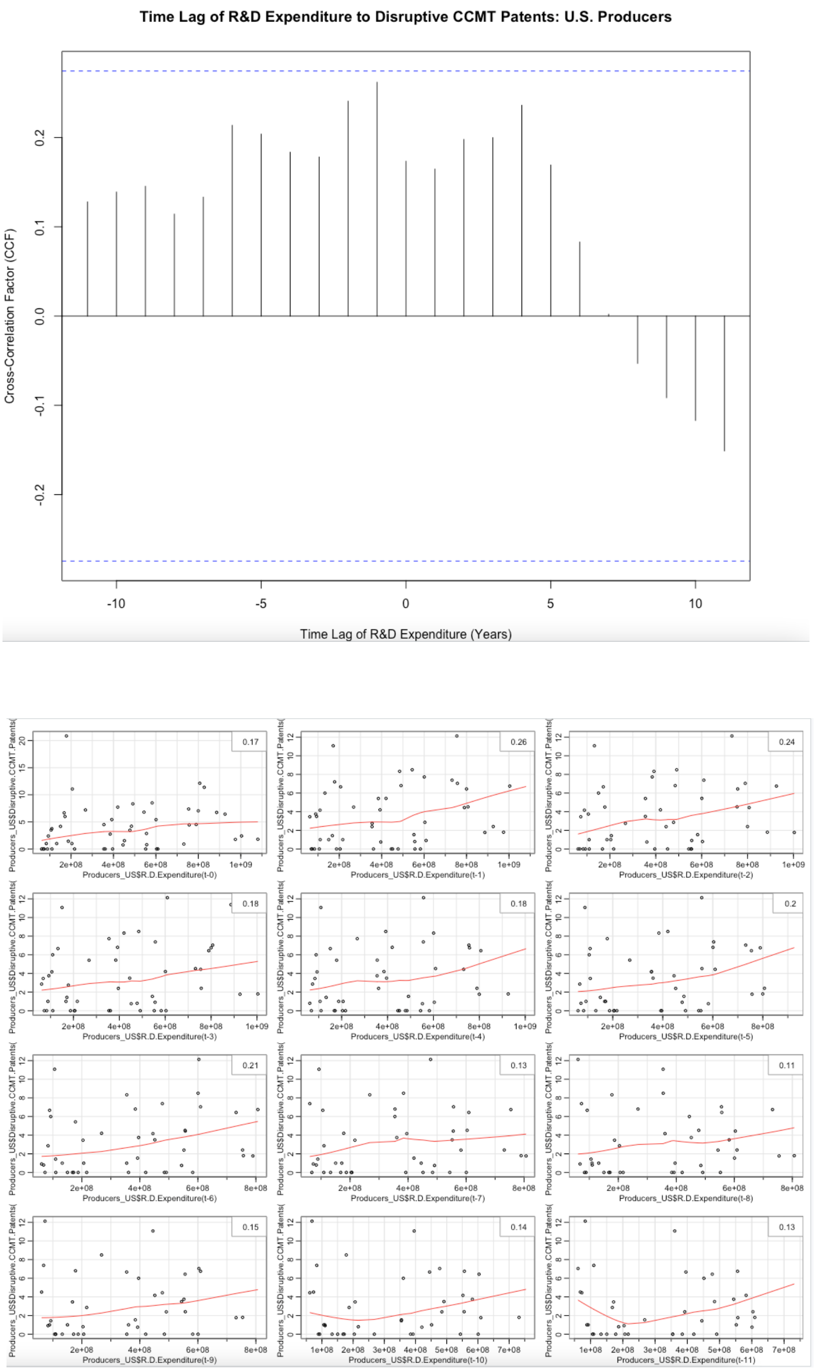


Figure H.6: Lag of R&D Expenditure to Disruptive CCMT Patenting Activity: U.S. Producers, 2000–2020. The top plot shows the time series cross-correlation function (CCF) between R&D Expenditure and Disruptive Patents, with R&D Expenditure as the lagged series and autocorrelation at time 0. The bottom plot shows past correlation distribution with R&D lagged. Note that CCF value on top plot aligns with values in top-right boxes on lower plot. Source: Based on IRI data and EPO/USPTO data.

Appendix I

Spearman Correlation of Patent Activity with R&D Metrics, Sales and Oil Price by Company

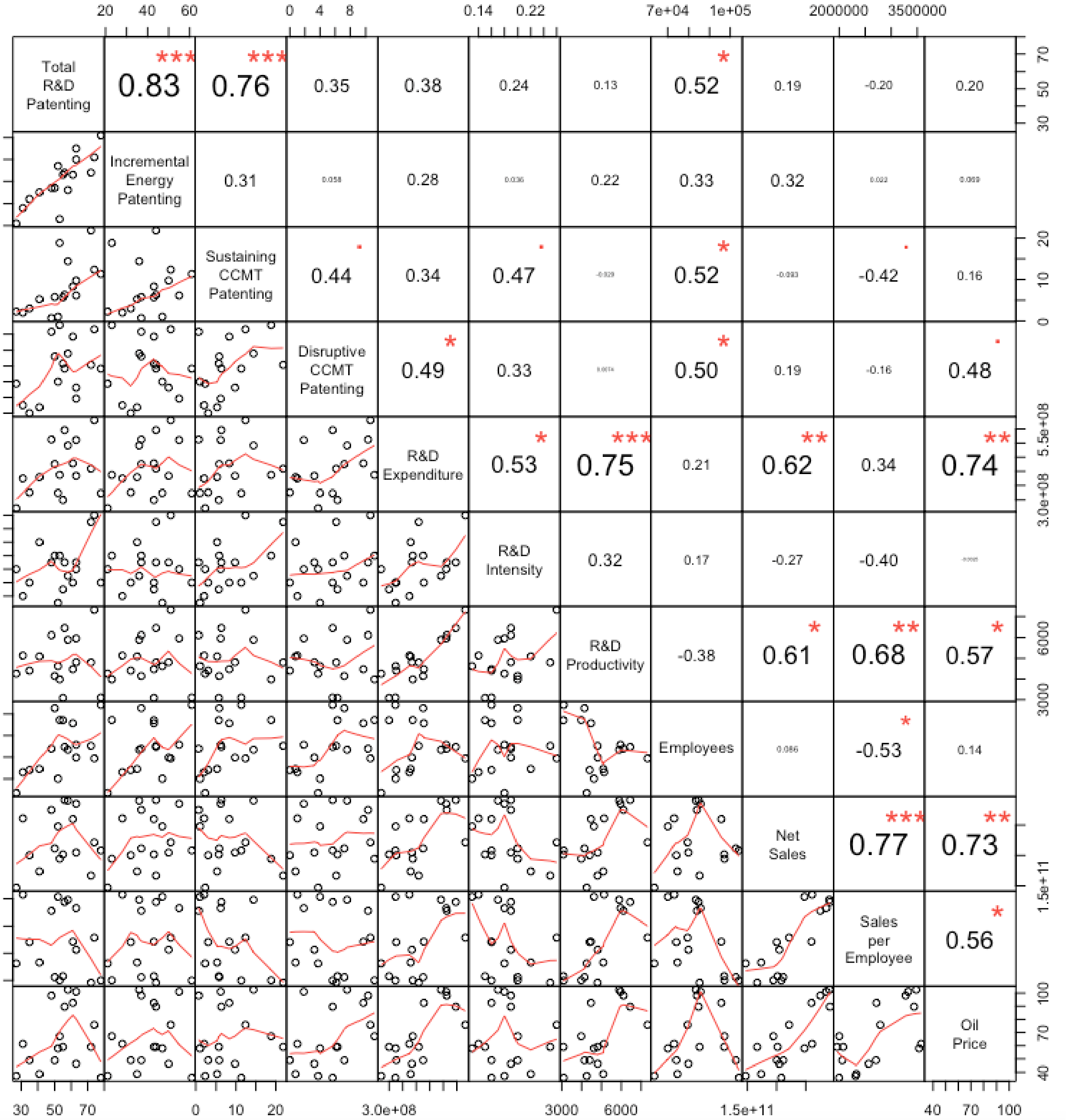


Figure I.1: Spearman Correlation of BP's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For BP, there is low positive correlation between Disruptive CCMT Patents and Sustaining CCMT Patents, with $r_s(15) = .44,\ p = < .1$, and a higher than normal correlation between R&D Expenditure and Oil price, with $r_s(15) = .74,\ p = < .01$. There is not same-year, non-lagged correlation between either R&D Expenditure or R&D Productivity with any patenting activity. Source: Based on IRI data and EPO/USPTO data.

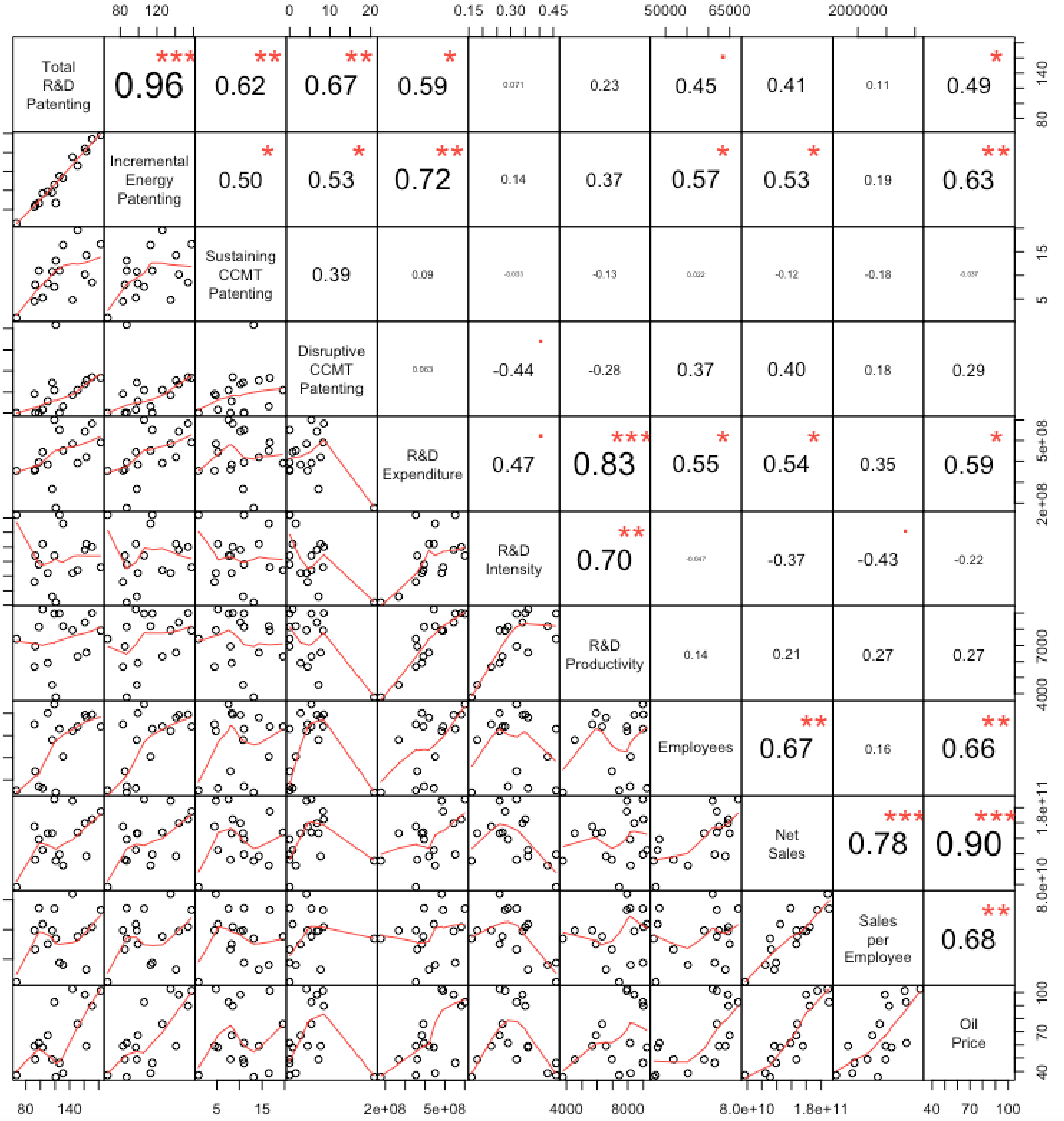


Figure I.2: Spearman Correlation of Chevron's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Chevron, there is weak positive correlation between Sustaining CCMT Patents and Disruptive Patents, with $r_s(15) = .39,\ p = < .1$, and a moderate correlation between Disruptive Patents and Total Patents, with $r_s(15) = .67,\ p = < .01$. There is less significant association between between same-year Total Patents and R&D Expenditure ($r_s(15) = .59,\ p = < .05$) and same-year Total Patents and Oil Price ($r_s(15) = .49,\ p = < .05$). Source: Based on IRI data and EPO/USPTO data.

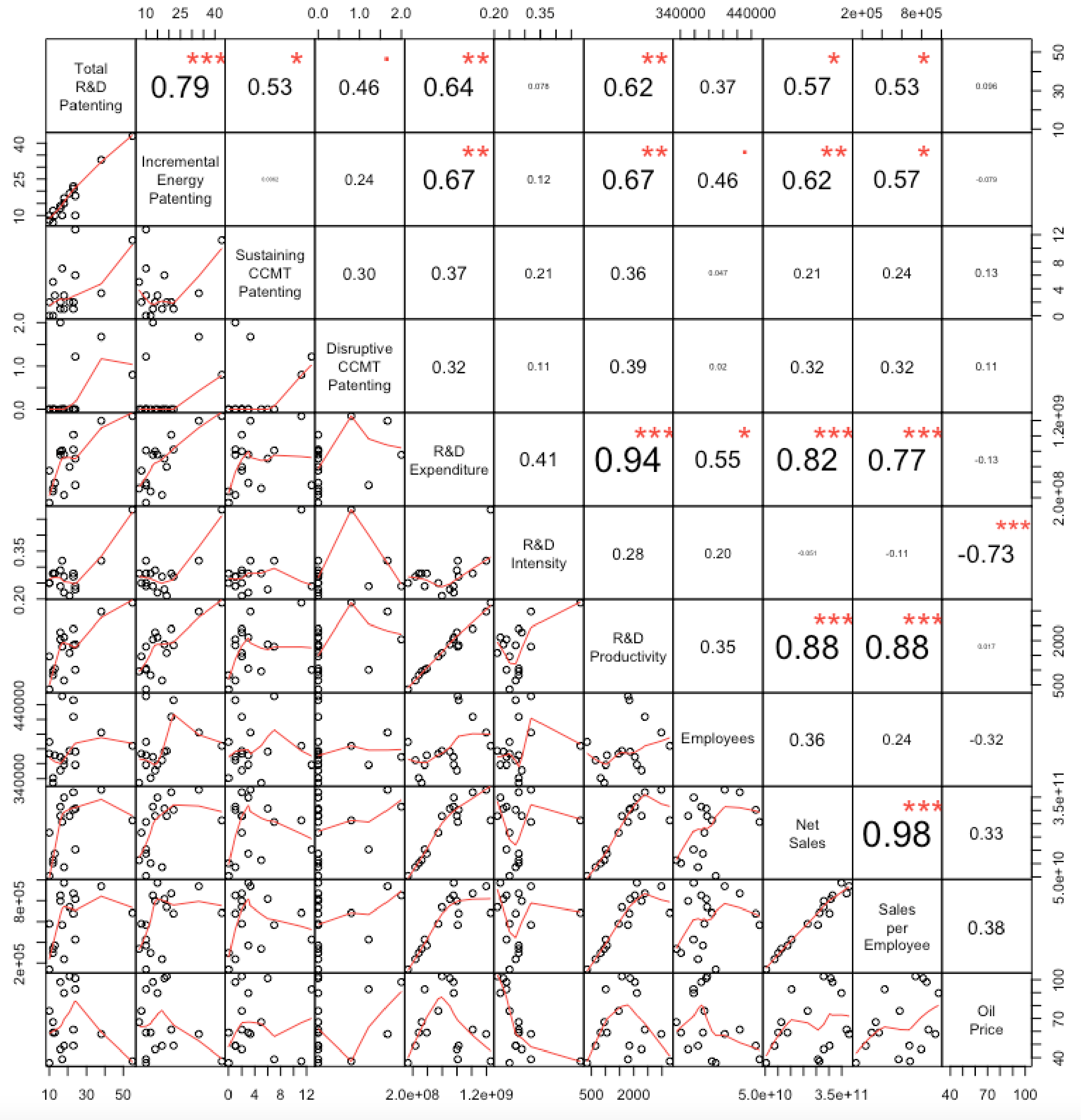


Figure I.3: Spearman Correlation of China Petroleum's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For China Petroleum, there is strong positive correlation between R&D Productivity and Sales Per Employee, with $r_s(15) = .88,\ p = < .001$, confirming analytical results forwarded by Morbey & Reithner (1990). There is moderate correlation between R&D Expenditure and Total Patents ($r_s(15) = .64,\ p = < .01$) but lower than average association between combined patenting activity. China Petroleum shows relatively no same-year association with Oil Price except for strong negative correlation between R&D Intensity and Oil Price, with $r_s(15) = -.73,\ p = < .001$. Source: Based on IRI data and EPO/USPTO data.

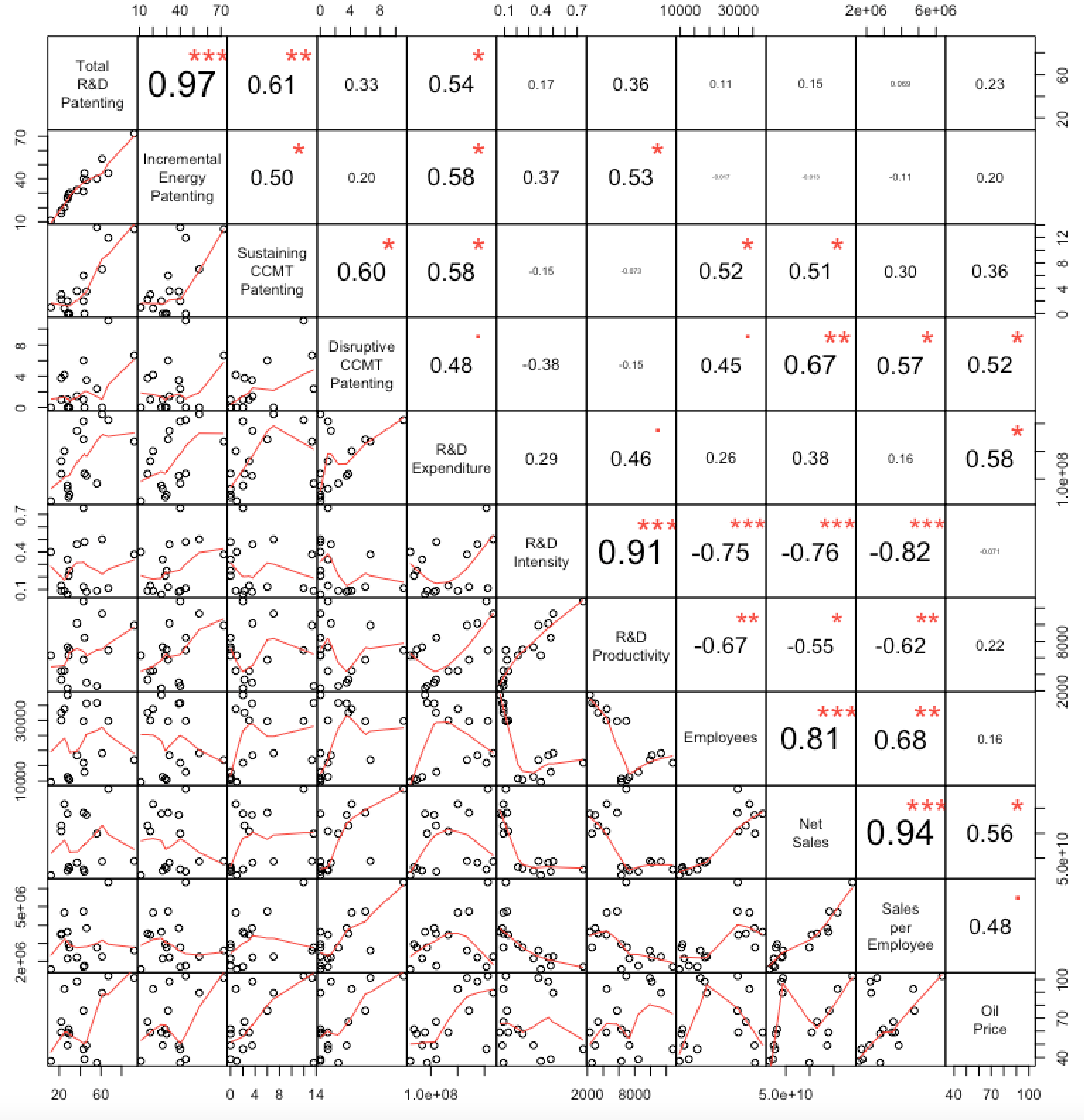


Figure I.4: Spearman Correlation of Conoco's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Conoco, there is moderate positive correlation between R&D Expenditure and same-year Sustaining CCMT Patents, with $r_s(15) = .58,\ p = < .05$, and positive correlation between same-year Sustaining CCMT Patents and Disruptive CCMT Patents, with $r_s(15) = .60,\ p = < .05$. Conoco displays higher same-year positive association between Net Sales and both Disruptive Patents, with $r_s(15) = .67,\ p = < .01$. R&D Expenditure has a higher than average weak correlation with Oil Price, at $r_s(15) = .58,\ p = < .05$. Source: Based on IRI data and EPO/USPTO data.

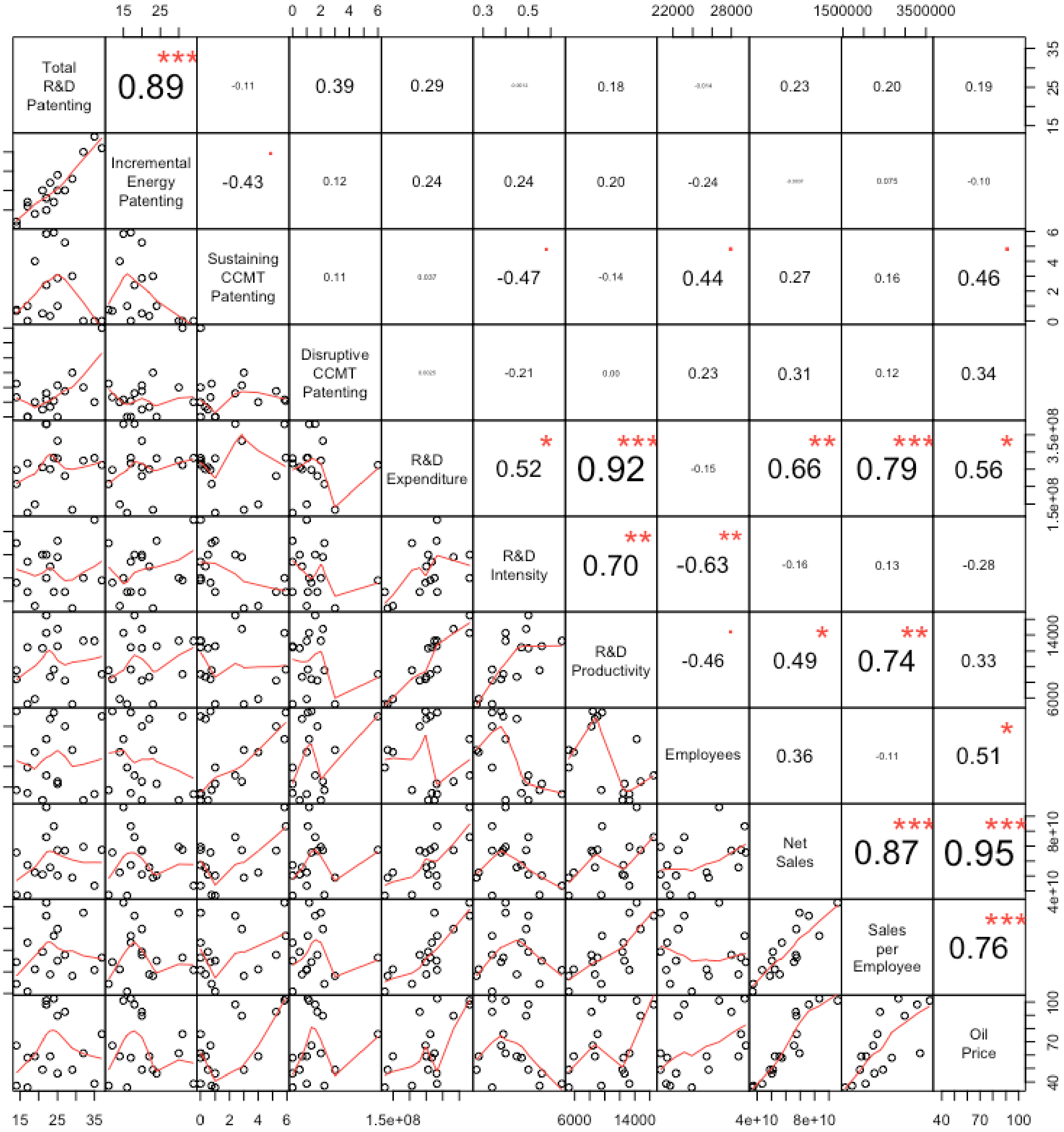


Figure I.5: Spearman Correlation of Equinor's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Equinor, there is the highest positive correlation between Net Sales and same-year Oil Price, with with $r_s(15) = .95,\ p = < .001$. Equinor exhibits lower association between all three types of patents than the combined companies and there is no associations between R&D Productivity and patenting activity. R&D Expenditure is moderately correlated with Net Sales, with $r_s(15) = .66,\ p = < .01$. Source: Based on IRI data and EPO/USPTO data.

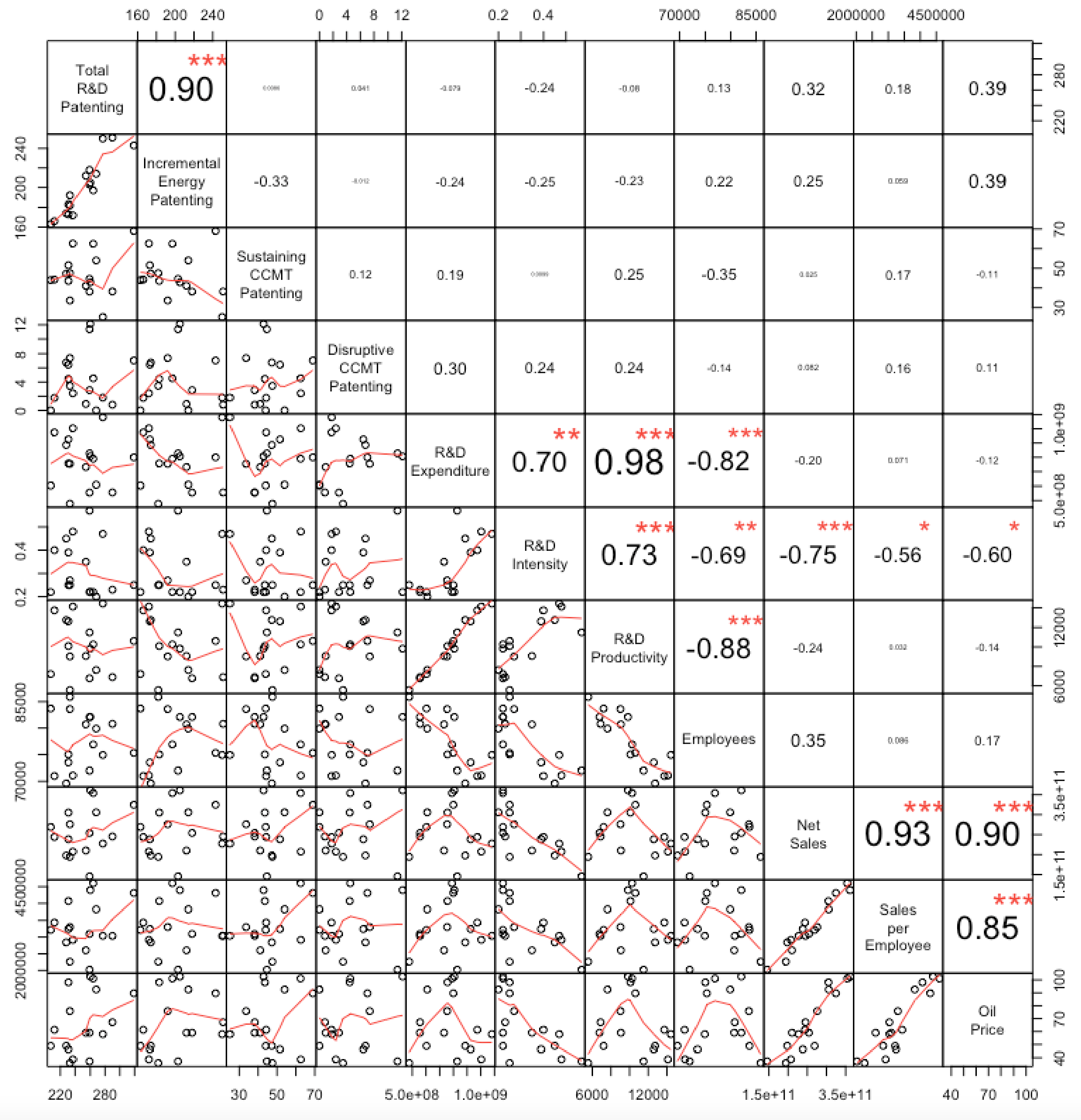


Figure I.6: Spearman Correlation of Exxon's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Exxon, the overall association is less pronounced than other companies or the aggregated groups of All Producers and U.S. Producers. Exxon exhibits no significant correlation between the patent groups, although there is insignificant positive correlation between Total Patents and Oil Price, with $r_s(15) = .39,\ p = < .1$. There is strong positive significant correlation between Net Sales and Oil Price, with $r_s(15) = .90,\ p = < .001$. Source: Based on IRI data and EPO/USPTO data.

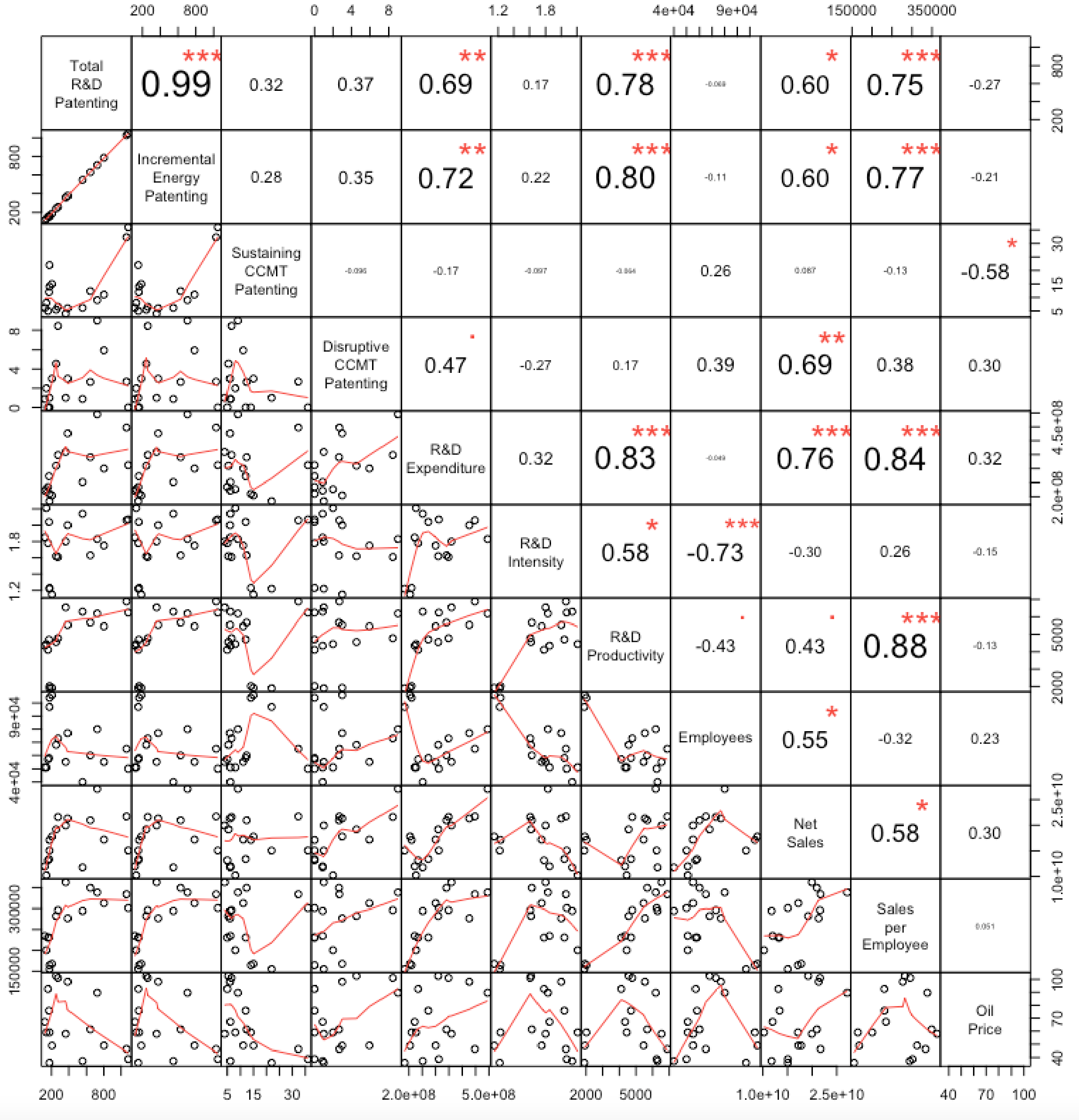


Figure I.7: Spearman Correlation of Halliburton's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Halliburton, there is a strong positive correlation between R&D Expenditure and Net Sales, with $r_s(15) = .76,\ p = < .001$, and likewise between same-year R&D Expenditure and Total Patents, with $r_s(15) = .69,\ p = < .01$. For Halliburton, Oil Price does not demonstrate any significant association between other variables. Finally, Halliburton's strongest association regarding patents is between same-year Total Patents and R&D Productivity, at $r_s(15) = .78,\ p = < .001$. Source: Based on IRI data and EPO/USPTO data.

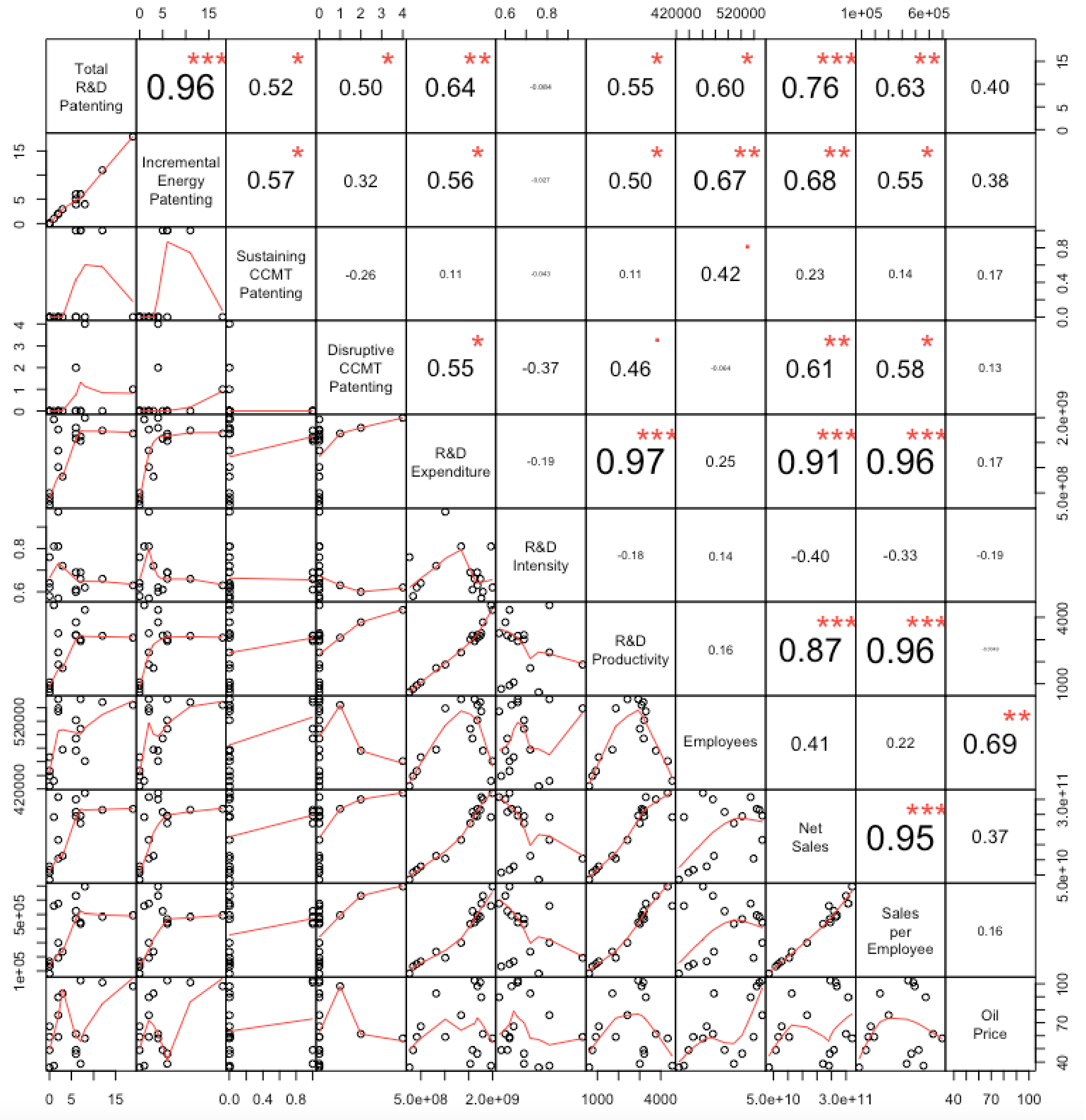


Figure I.8: Spearman Correlation of PetroChina's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For PetroChina, there is association across multiple technology variables. There is strong positive correlation between R&D Expenditure and Net Sales, with $r_s(15) = .91,\ p = < .001$. PetroChina has higher correlation in same-year pairing of patenting. There is a weak positive correlation between Total Patents and Sustaining CCMT Patents, with $r_s(15) = .52,\ p = < .05$, and also moderate correlation with Disruptive Patents, with $r_s(15) = .50,\ p = < .05$. Source: Based on IRI data and EPO/USPTO data.

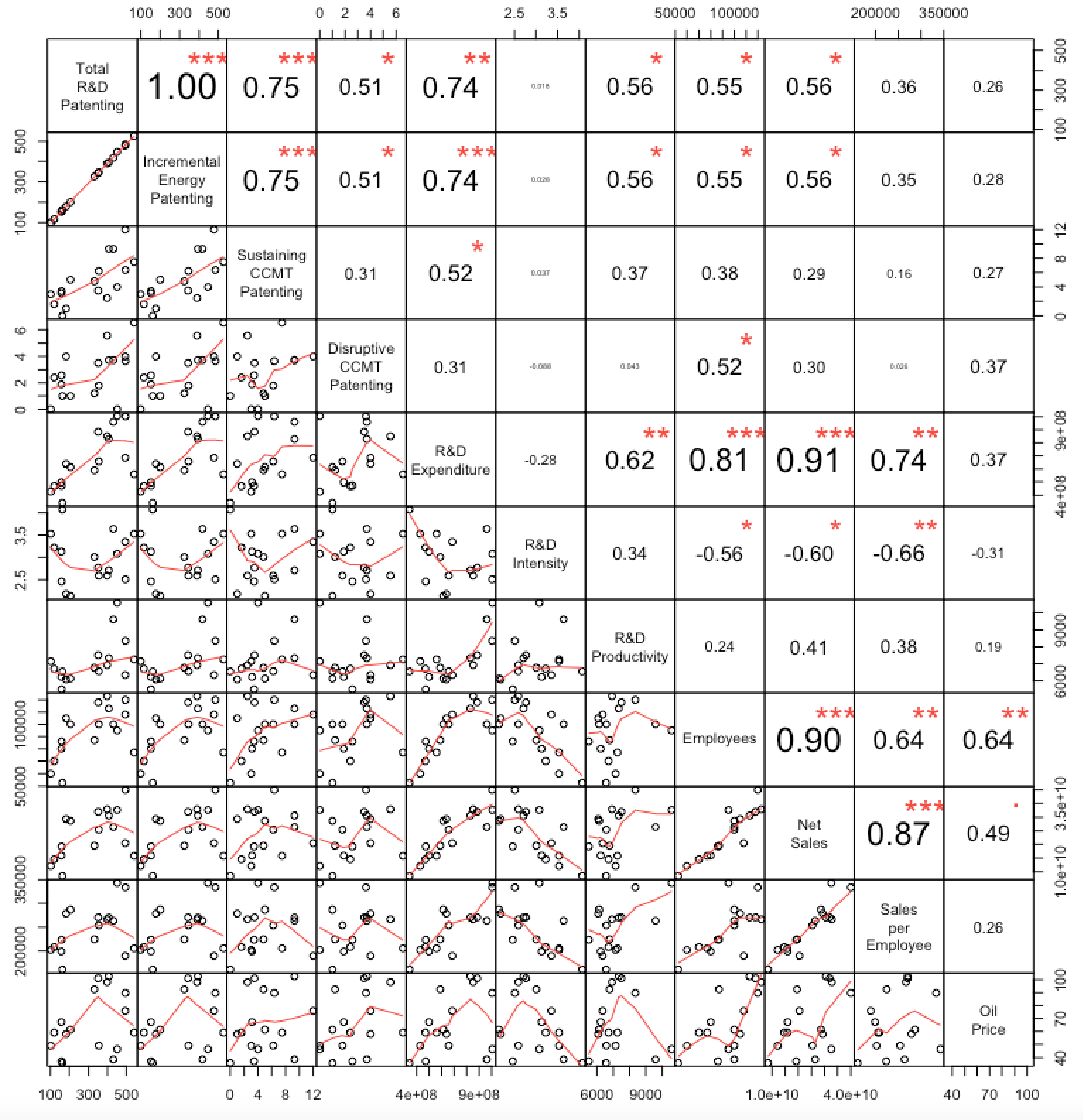


Figure I.9: Spearman Correlation of Schlumberger's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Schlumberger, there is a very strong positive correlation between R&D Expenditure and Net Sales, with $r_s(15) = .91,\ p = < .001$. Same-year Total Patents demonstrate strong association with Sustaining CCMT Patents ($r_s(15) = .75,\ p = < .001$) and moderate correlation with same-year R&D Expenditure ($r_s(15) = .74,\ p = < .01$). Interestingly, there is a moderate but lower significant association with Net Sales and Total Patents, with $r_s(15) = .56,\ p = < .05$. Source: Based on IRI data and EPO/USPTO data.

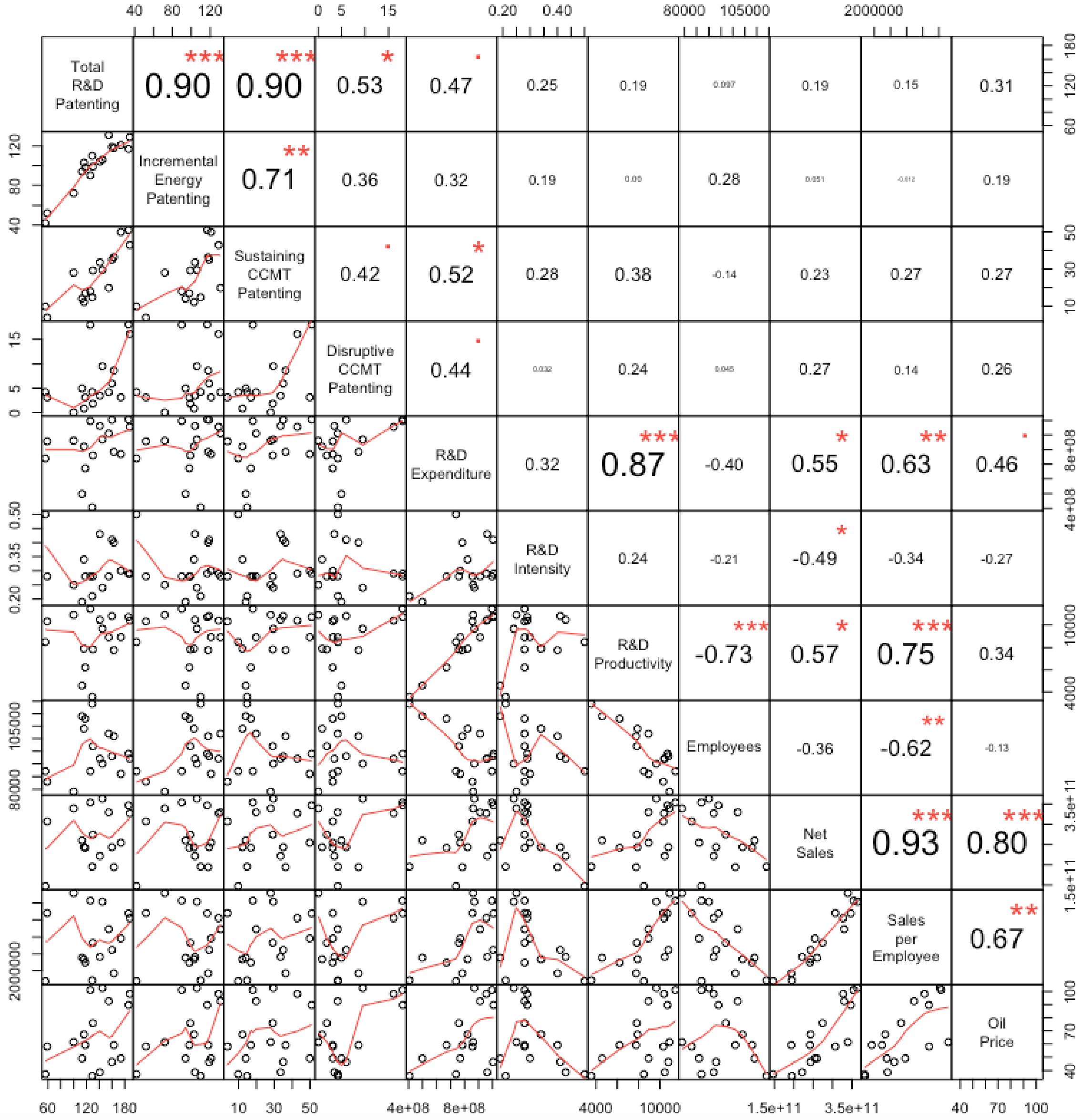


Figure I.10: Spearman Correlation of Shell's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Shell, there is a very strong positive correlation between Total R&D Patents and Sustaining CCMT Patents, with $r_s(15) = .90,\ p =< .001$. But Disruptive CCMT Patents are only loosely associated with CCMT Patents ($r_s(15) = .42,\ p =< .1$) and Total Patents ($r_s(15) = .53,\ p =< .05$). While Oil Price shows minimal correlation to R&D Expenditure, Oil Price is strongly correlated with Net Sales, with $r_s(15) = .80,\ p =< .001$. Source: Based on IRI data and EPO/USPTO data.

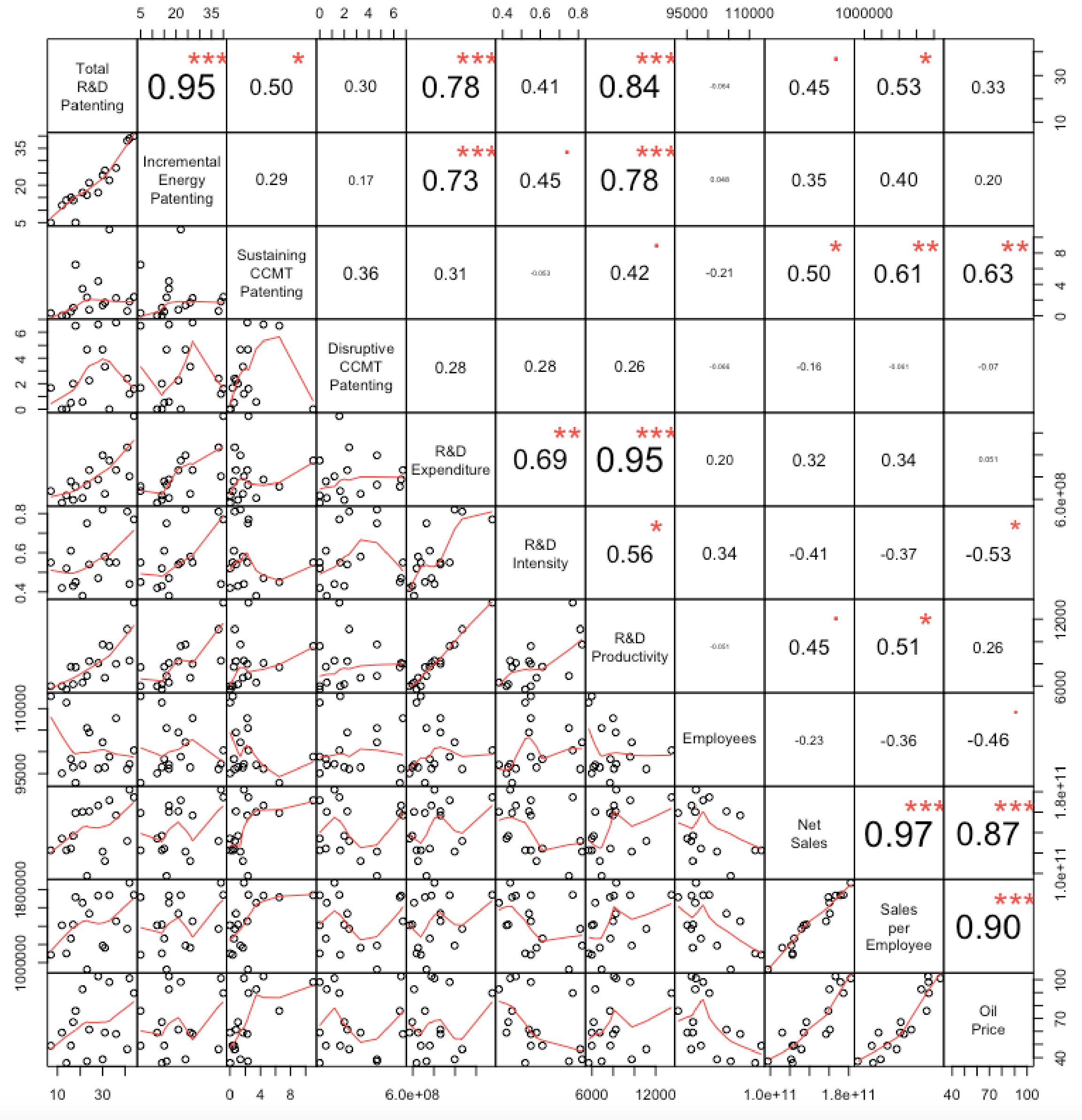


Figure I.11: Spearman Correlation of Total's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. For Total, there is less correlation among the technology variables than for other producers. However, same-year Total Patents are strongly correlated to R&D Productivity ($r_s(15) = .84,\ p = < .001$) and R&D Expenditure ($r_s(15) = .78,\ p = < .001$). Additionally, Total shows stronger correlation between Oil Price and Net Sales, with $r_s(15) = .87,\ p = < .001$. For CCMT, Total shows no significant association between CCMT Patents and Disruptive, indicating that research efforts may be siloed within the company. Source: Based on IRI data and EPO/USPTO data.

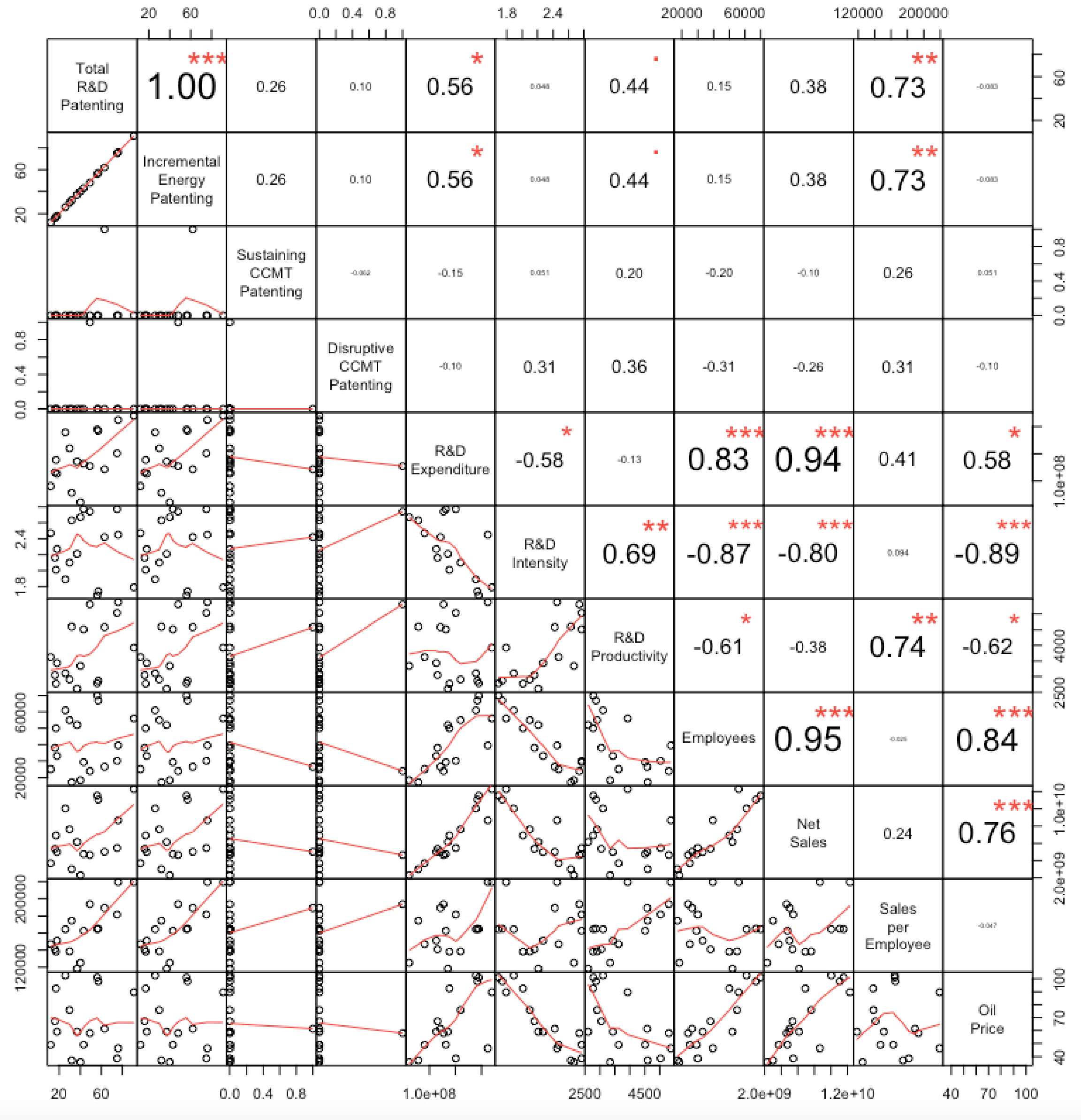


Figure I.12: Spearman Correlation of Weatherford's Patent Activity with R&D Metrics, Sales and Oil Price, 2004–2020. Figure is graphed with R package `PerformanceAnalytics` and displays significant same-year, non-lagged ranked Spearman associations between variable pairs as described in Chapter 5. Like the other two Oil & Gas service companies, Weatherford demonstrates strong positive correlation between R&D Expenditure and Net Sales, $r_s(15) = .94,\ p = < .001$, and an associated correlation between Oil Price and Net Sales, $r_s(15) = .76,\ p = < .001$. For Weatherford, there is low correlation between Total Patents and other markers, other than a weak association with R&D Expenditure ($r_s(15) = .56,\ p = < .05$). Source: Based on IRI data and EPO/USPTO data.

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