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Accepted manuscript doi: 10.1680/jener.22.00020

Submitted: 04 March 2022
Published online in ‘accepted manuscript’ format: 08 March 2022

Manuscript title: The modern global oil market under stress - system dynamics and scenarios

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Abstract

Modelling techniques developed 40 years ago to gain insight into the issues of energy supply security remain powerful even as the focus of energy technology policy analysis has shifted to consider new problems and research methods more closely linked to pressing environmental challenges. Dynamic modelling continues to be of merit and indeed it has the potential to provide helpful perspectives on contemporary problems such as climate change and the Net Zero transition. This work seeks to help revive system dynamics modelling of the global oil market. The SD-based analysis used in this paper facilitates a rational representation of physical stocks and flows as well as causal linkages that drive decision-making in the global oil system. The use of SD provides insights (intuitive and counter-intuitive) into the macro-level non-linear dynamics of global oil exchanges and permits assessment of the potential impacts of future changes in system behaviour. The model exhibits damped oscillations in oil prices, broadly consistent with real market behaviours. The results further illustrate the resilience of market dynamics in the phase of extreme supply side shocks and reveal the ability of System Dynamics to simulate and model such effects even beyond the point of market failure.

Keywords: Oil price; oil price volatility; oil demand; shale oil production; scenario analysis; system dynamics
Section 1: Introduction

Ever since its first discovery in Pennsylvania in 1859 and the discovery of a large petroleum reserve in Texas in the early 20th century, oil has reinforced its role and retained its significance as a global commodity and a strategic fuel. The past century has witnessed systemic changes in the world economy and political order. The rules of the game are rapidly changing with the rise of new demand centres-mainly China (and to a lesser extent India), expansion in unconventional oil production and mounting concerns over a rapidly changing world climate. These factors combine to affect the security of supply and economics of oil. Despite this, oil still remains at the centre of foreign and energy policy narratives across the world in the twenty-first century, much as it did throughout a good part of the twentieth century. The Twentieth Century saw key events, such as the Suez Crisis in 1956, the 1973 Arab oil embargo, the Iran-Iraq war in 1980, and the 1991 and 2003 Gulf wars. It also saw the formation of Organisation of the Petroleum Exporting Countries (OPEC) and in response, the International Energy Agency (IEA). For approximately 100 years oil has impacted and determined the very principles and fundamentals of energy governance (Betts, et al., 2006). Despite the urgent need to decarbonise, and the goal of an end to the age of oil being increasingly plausible, simple realism requires one to acknowledge that oil remains central to any contemporary considerations of energy policy and energy governance given its role in influencing energy markets, economic shifts and global geopolitics. For example, in 2019, oil contributed towards 33.1% of total energy consumed. Despite the manifest threat posed by climate change, oil demand in 2017 was forecast to remain strong reaching 105 Mb/d (million barrels per day) by 2040 (International Energy Agency, 2017). The IEA prediction from 2017 is broadly consistent with a more recent assessment from BP of 100 Mb/d, presented in Figure 1 (Looney, 2020).

Oil price shocks have historically been linked to macroeconomic performances of various economies seriously impacting policy choices (Barsky & Kilian, 2004); (Hamilton, 2003); (Allsopp & Fattouh, 2016)). Oil price movements since the 1970s have triggered many changes in the world order and led to economic recession, inflation, and sometimes to a concentration of wealth in OPEC nations, but more typically to volatile cycles of boom and bust across the oil industry (Morecroft & van der Heijden, 1992). It is sometimes said that oil is the only genuine market commodity in energy. Coal, natural gas and electricity lack transparent liquid markets and are overly shaped by location and network effects. As an energy-dense and easily-transported fluid, oil is as good as it gets in energy markets. As the world seeks to decarbonise and to eliminate most uses of petroleum, what will happen to energy markets? Some might celebrate the elimination of supply and demand volatility and the direct consequences of price spikes and crashes, but these things are a sign of market price formation, and they represent market signals for investment. The oil industry has been built around such realities and the industry works well despite, arguably indeed, because of, the price volatility. Things, however, can go too far and it was in direct response to oil price shocks that the first major structural changes to global energy governance were instituted including the formation of the IEA and the setting-up of oil-surplus quotas (Samii & Teekasap, 2010). Figure 2 charts the historical trajectory of the oil price. The very wide time frame of Figure 2 shows well the volatility of oil prices, especially in what historians may one day call the beginning (1860-1920) and the end (1970-2040) of the industry. These two sixty-year periods are extremely volatile compared to the middle 50 years (1920-1970). In examining Figure 2 it is important to remember that the global oil industry grew by 17,000% in the hundred years of the Twentieth Century (rising from 20 Mt in 1900 to 3.4 Gt in 2000 (Smil, 2000)).
Such volatility, however, is not the same as oil market oscillation. Volatility can be dominated by repeated external shocks distinct from oscillatory market adjustments ringing after passed shocks.

Oil market oscillation is a known phenomenon and previous work has attributed the observation to multiple causes including currency fluctuations and sometimes consequential impacts on national budgets (Manasseh, et al., 2019). In the 1970s and the 1980s there was much academic attention given to understanding and anticipating one of the great challenges of those times – the security of fossil fuel supplies (Naill,1977; 1992; Choucri, 1974; 1979; 1980; 1981; Morecroft & Marsh, 1997). Methods deployed included System Dynamics, as first developed by Jay Forrester and colleagues at MIT in the 1950s. One of the authors of this paper has previously used SD techniques to explore the supply and demand dynamics of natural resources including fuels for electricity generation (Chi, et al., 2009, and Rooney, et al., 2015). There has, however, been relatively little academic modelling of such behaviours in recent years. The work of Hosseini and colleagues is a notable exception (Hosseini, et al., 2016). Hosseini and colleagues seek to provide insight into the separate roles played by, for example, the existence of futures markets and political factors in oil price oscillation. Hosseini and co-workers caution that: “local analysis of the entire system with complex interrelations cannot explain the phenomena of price fluctuations well and an integrated model is missing”.

Given its role in destabilising economies, causing inflationary pressures, and signalling global imbalances, understanding oil price behaviour remains vital for understanding national and industrial planning and the management of risks associated with possible future disruptions. Uncertainties influence several key aspects, including oil reserves, transit routes, trading mechanisms, demand centres and prices. The importance of non-linearities and multiple feedback loops between numerous actors and decision centres is characteristic of world oil markets. To understand the global future of our climate it is essential to have insight into Twenty-First Century oil dynamics. Given the complex interactions between these constituents and their combined impact on oil prices, the structural models can be deemed to be better suited than analytical methods for explaining both the price formation of oil as well as for analysing the system-wide impact of changes in specific parts of the system on key macroeconomic indicators.

The system dynamics modelling methodology is a well-established method to study various aspects of oil exchange related to production, distribution and capacity expansion as well as other strategic aspects related to global oil markets and the geopolitics of oil. Little such modelling of oil dynamics has been done in recent decades and a holistic model representing the exchanges that characterise and capture the new drivers of global exchange across a number of crucial emerging scenarios was not found. This paper presents a System Dynamics (SD) model covering a period of 50 years from 2014 and capturing the feedbacks that influence the endogenous oil price formation and its impact on observed real-world oil trends. This study aims to provide a system wide perspective of exchanges in global oil and assess its wider implications for emerging energy pathways by developing and testing a dynamic hypothesis for oscillatory oil price behaviour. The work presented here deliberately seeks to take a high-level view and to establish whether a model of the modern global oil industry can be developed that is simultaneously capable of reproducing oil price volatility and real-world complexities while also being simple enough as to provide fundamental insights. The authors posit that SD oil researchers using models of different scope and specificity can mutually inform each other and further hope prompt renewed interest in questions that have largely
been dormant for several decades. These questions now face a very different context – the pressing need for global decarbonisation.

Section 2: Literature Review

2.1 Global Oil Markets and Price Formation

Oil is a political commodity (Penrose, 1976) and has been central to a number of key global economic and political decisions over many decades. Crude oil, together with its refined products, is the most widely traded commodity both by volume and by value (Stevens, 2005) and it has the highest energy content of all the fossil fuels. Despite some reduction in the last two decades, oil continues to be largest source of primary energy globally (34 percent in 2018), followed by coal (27 percent), natural gas (24 percent), hydro (7 percent), nuclear (4 percent) and renewables (4 percent) (BPSR, 2019). This section provides a review of the global oil market focusing on its fundamental characteristics and the principles of oil price formation.

2.1.1: Global Oil Outlook

Oil prices impact all the economies of the world in a characteristically unique way. From an oil producer’s perspective, revenue from oil exports remains vital to their economic development and growth rendering them vulnerable to price volatilities. Consumer countries benefit from oil price drops, but get impacted by fluctuations in the quantities of oil supplied by exporting countries, thus impacting their economic and political stability (Allsopp and Fattoh, 2013). Oil price fluctuations have, therefore, justifiably drawn much attention from governments, financial institutions and the energy industry.

The demand-supply paradigms that have historically underpinned the oil markets have undergone structural shifts since the heyday of interest in oil industry SD modelling in the 1970s and early 1980s. Since those times there has been explosive demand growth in developing countries in the east, led by China, and on the supply side there has been the shale oil revolution in the US. Furthermore, global supply and demand patterns responded sharply to the economic slowdown arising from the COVID-19 global pandemic. The U.S. Energy Information Administration (EIA) has reported that the global consumption of oil stood at 92.2 million barrels per day in 2020, declining by 9 percent or, 9.0 million barrels per day compared to 2019. EIA’s Short Term Economic Outlook (2021) reports that the combined effect of reduced oil demand, as a result of the global pandemic (notably from reduced jet fuel consumption), and an easing of geopolitical tensions caused Brent crude oil spot prices to crash from around $67 in early January 2020 to $18.38 in April of the same year. However, as consumption increased in the latter half of 2020, coupled with reduced production from OPEC and partner countries (OPEC+) and U.S. crude, inventories fell and oil price recovered to a monthly average of $50 per barrel. An upsurge in global growth, driven by collective global recovery from the aftermaths of the global pandemic, is expected to drive a robust increase in oil demand and to re-balance the global oil inventory levels adding significantly to upward oil price pressures. The EIA expects that Brent prices are likely to experience downward price pressures over the next two years and the prices may average $59 per barrel, depending, among other factors, on future production decisions by OPEC+, the responsiveness of U.S. shale production to higher oil prices, and rate of oil demand growth (EIA, 2021). The model presented here seeks to emulate such behaviours. Depending on the pace of economic growth and strategic decisions by major players guided by longer-term drivers of growth, the global demand for oil is expected to grow at an average annual rate of 1.2 million barrels per day, reaching 104.1 million barrels per day by 2026, up 4.4 million barrels per day from 2019 levels (International Energy Agency, 2021). Emerging
and developing economies, led by China and India, underpinned by their increasing population and income growth are predicted to be the strongest drivers of global oil demand growth. Whether there will be enough supply from producers to meet the rising demand would have been a major consideration in the past. But the upsurge in oil supplies with the discovery of tight oil in US has shifted the narrative away from resource scarcity towards resource abundance. These uncertainties in the supply-demand dynamics can, as a direct consequence, create widespread speculation and fluctuations in oil prices. Table 1 shows the top crude oil producers and consumers of the world.

Unlike other traded commodities, market mechanisms do not solely determine oil prices, as highlighted above. According to Fattouh (2010), expectations from, or perceptions of, future market fundamentals have a key role in oil price formation, an price bubbles may result as a consequence of changes in supply-demand dynamics away from their basic essential values (Fattouh, 2010). A closer appreciation of the basic principles of oil price formation helps to better understand the trajectory of oil price movements and such ideas are described in the following section, and again, the model presented in this study is developed so as to mimic these realities.

2.2 Fundamentals of oil price formation

Details on the modern-day mechanisms of oil price formation can be found in the work by many experts, notably, Fattouh (2009, 2011, 2016, 2018), Energy Charter Secretariat (2011) and Barsky (2014). These studies, besides providing an understanding into the oil market structure and an insight into the dynamics behind global oil exchanges, also highlight the significant changes that have occurred in oil markets since 1980. The modern-day exchanges, characterised by financial instruments such as forward markets, swaps, futures and options, differs markedly from those that existed in the 1970s and the first half of the 1980s. The aim of this study is to develop a model that helps to analyse the modern-day exchanges in global oil markets anchored around oil prices.

2.2.1 Crude Oil, Benchmarks and Transactions

Crude oil is a global commodity, traded since the inception of modern oil industry in the 1860s (ECS, 2011). An understanding of the unique nature of crude oil is crucial to understanding oil pricing mechanisms, which is determined by a range of factors influencing oil supply-demand dynamics, such as by the government policies, geopolitical conflicts, global and economics and strategic influences by stakeholders.

Crude oil is the commercial term for raw petroleum, as extracted from the ground. It is a naturally occurring unrefined liquid comprising hydrocarbons with different chemical compositions. It is found in sedimentary rock deposits and basins within the earth’s crust. Petroleum (literally ‘rock oil’) has formed from the decomposition of aquatic animals and plants buried at high pressure for hundreds of millions of years (Everett and Crabbe, 2012). The presence of geological traps preventing the lateral migration of the petroleum away from the reservoir is an essential prerequisite for the accumulation of crude oil reserves (Everett and Crabbe, 2012: 214).

Over a hundred crude grades are traded in markets around the world. The total value of the crude is determined on the basis of the total value of the products processed from crude, also sometime referred to as the gross product worth (or GPW). While GPW may be believed to define the upper limit of crude prices and interact with the prices of products, it does not necessarily set the price of crude oil (ECS, 2011). Benchmark crudes act as points of reference for other crudes of similar grades.
West Texas Intermediate (WTI) and Brent crude replaced Arabian Lights in the late 1980s, acting as the two globally dominant benchmark prices. There are, however, significant differences between WTI and Brent crudes and the two are often seen trending at significantly different prices. A possible explanation can be their perceived role in their respective markets. North Sea Brent is produced by several producers yielding it a higher degree of security of supply, greater diversity of sellers and broader acceptance by consumers. Owing to higher volumes of production from across multiple oil fields, there is greater market trading liquidity for Brent. WTI, in contrast, is produced in lower quantities, has a landlocked delivery system and is located unsuitably from various international trading markets for a benchmark grade. Nonetheless, WTI has been a huge commercial success since it was selected for the launch of crude oil futures on the New York Mercantile Exchange (NYMEX). It has since become the leading US benchmark price. It is essential to highlight that WTI has the advantage of faster response and an almost immediate reaction to market volatility. However, given the linkages between Brent and physical markets, arguably Brent crude reveals better the supply-demand dynamics of the market (ECS, 2011).

Saudi Arabian crude is not traded in the spot market but directly under long-term contracts. Dubai and Oman together play the role of a Middle East benchmark price and play an important role in retroactive pricing formula by large producers of the region such as Saudi Arabia, Iran and Kuwait. Urals grade crude comprises of crude from oil fields from Russia and neighbouring region, which are mixed and transported by Transneft’s pipelines. The East Siberia-Pacific Ocean (ESPO) Oil Pipeline was laid by Russia to transport its crude for market trading into newer markets (ECS, 2011; Gyagri et al., 2017).

While most of the crudes are marketed via ports, some inland markets also exist. Crude oils on the North American continent are traded via inland markets. Some popular regional crudes include Malaysia’s Tapis, Indonesia’s Minas, Nigeria’s Bonny Light and the twelve OPEC crude grades that make up the OPEC Basket (ECS, 2011).

2.2.2 Crude Oil Pricing Mechanism

The emergence of a market-related pricing system in the 1980s was a response to the supply disruptions from the oil crises of the 1970s (the 1973 oil crisis occurred as a result of unilateral price increase by OPEC from $3 to $12 per barrel following the Yom Kippur War, and the one in 1979 took place after the Iranian revolution, when the oil prices shot up from $12 to $30 per barrel). The 1980s saw a new chapter in the history of oil price formation. The disruption brought about by the two oil crises had created widespread nervousness among crude oil buyers, who were ready to pay higher spot prices than the official prices to secure the desired stock of oil supply. This signalled a shift away from OPEC-administered pricing system and the emergence of market-based oil pricing governed by the dynamics of supply and demand fundamentals (Fattouh, 2011; ECS, 2011). Crude oil, in more recent times, has been said to have acquired the traits of a financial asset attaining a complex-market structure that comprises spots together with physical forwards, futures, options and other derivative markets referred to as paper markets (ibid). However, crude oil (unlike pure financial assets) also has a physical aspect to it as it can be consumed, stored, and traded in physical quantities at agreed prices between various transacting parties. The spot prices reflect the supply-demand dynamics of markets and serve as an anchoring point for prices in the futures market (Fattouh, 2010). It is important to note that physical realities and psychological concerns both play important roles in oil market price formation. The model developed in this paper includes both price drivers.
While the oil markets have in recent decades seen the emergence of a number of financial layers such as forward markets and financial instruments such as: swaps, futures, and options, unlike other pure financial assets, the physical dimension of crude oil market lends an anchoring point for expectations of market fundamentals. Consequently, in principle, through the process of arbitrage the future market prices must converge to the spot prices that underlie the physical supply agreements. In the context of physical delivery of oil, contracts are negotiated bilaterally with price agreements determined by formula pricing becoming the basis for price determination (Fattouh, 2010). Fattouh (2011) provides a detailed review of the anatomy of oil pricing system detailing out various specific components. The formula pricing system allows for crude oils to be price-indexed to benchmark crudes adjusted by a discount or a premium based on quality and relative demand-supply conditions. Fattouh (2010) specifies that for a crude oil of variety x, the formula pricing can be determined as \( P_x = P_R \pm D \), where, \( P_R \) is the benchmark crude price, and D is the value of the price differential. Fattouh’s formalism aligns with the view that, aside from fixed offsets specific to each variant benchmark, there is indeed a single global oil price. The model in this paper has been constructed consistent with that well established assumption.

The global oil market has both financial and physical layers, and it can be difficult to isolate the two. It can also be observed that while the spot price of oil can reflect market dynamics, the true fundamentals of the market are determined by the interaction between various participating players involved in the overall global exchange of oil at various levels impacting its production, processing, transportation and the existing social, economic and political landscape impacting its uptake in consuming markets.

2.3 Overview of the System Dynamics Approach and Oil Market Models

Volatility in oil prices, together with uncertainty over its availability and escalating tensions over its transit routes, dominated energy policy scholarship over much of the Twentieth Century (Barsky & Kilian, 2004). The complexity of oil markets has become even more profound with the urgency to reduce carbon emissions. Change has been mandated in the way the world produces, consumes and trades all forms of energy, but most significantly oil. These concerns, past and present, have led to model-based efforts to analyse energy-systems linked to various policy choices (Hoffman & Wood, 1976; Samii & Teekasap, 2010). The system dynamics modelling approach is well suited for modelling and simulating complex physical and nonlinear decision-based systems, such as those existing in oil markets (Choucri, 1974; Mutingi, et al., 2017, Hosseini et al., 2016).

System Dynamics is grounded in the principles of nonlinear dynamics and feedback control as originally developed in mathematics, physics and engineering. The approach involves simultaneous linear and non-linear equations which represent functional relationship between variables, and enables representation through stocks and flows and analysis of feedback relationships (Hoffman & Wood, 1976). System dynamics helps in studying the long-term dynamic behaviour of complex systems. It represents a theory of system structure and has been used for identifying, describing and analysing multi-loop feedback relationships for many decades (Choucri, 1979). These system structures are represented in system dynamics models as stocks and flows, with causal mechanisms controlling their rates of change and feedback loops expressing various causalities. Complex real-world systems comprise several interconnected feedback loops together with interactions between the physical and decision-making structures (Forrester, 1970). The macro-level dynamics that emerge in complex systems can be mapped by enabling representation of interactions of both physical and decision-making processes used by the dominant actors in the system along with the delays and other constraints. It, therefore, applies extremely well to the analysis of dynamic effects.
of policy choices (Sterman, 1980:57-58). Sterman (2000) explains that by mapping the stock and flow structures and their careful integration with feedback loops the dynamics of the structure can be analysed. He posits, that in simpler feedback systems, positive feedback yields exponential growth and negative feedback processes result in goal adjusting behaviour (Sterman, 2000). Stocks, or the state of a system, create delays, capture the memory and inertia, and are responsible for the disequilibrium dynamics of the system (ibid: 229). The dynamics of stocks and flows yield useful insights into problems (ibid: 262). A schematic of modelling process using system dynamics method is shown in Figure 3, where the solid arrows represent the main steps involved in the modelling and the arrows with dotted lines represent the iterative processes that support the model building process.

As an analysis tool, system dynamics allows one to both describe the relationship between variables and to represent a practical problem in software (Sterman, 2000). Inputs in a system dynamics model are generated from feedback relations within the system, and the outputs of one period feed in as inputs for next. Because the inputs are generated endogenously, their behaviour is state determined. Delays in a system represent lags, which can influence the stability of the system and usually explains why it often takes significant time for the effect of policy decisions to be felt. They determine the severity of ‘shocks’ and are responsible for the ‘overshoot and collapse’ behaviour demonstrated by many systems and lie at the heart of oscillatory dynamics (ibid). Furthermore, SD models can also be used as a tool to investigate, analyse and assess the behaviour of complex systems. In addition, they can be helpful for designing policies through computer-aided modelling and simulation of complex situations (Hosseini and Shakouri, 2005).

Some of the early applications of system dynamics in energy modelling include Roger Naill’s FOSSIL-2, an integrated model of U.S. energy supply and demand used to inform its policies in the 1970s and 1980s (Naill, 1992). Naill’s early work was based on the life cycle theory of oil and gas discovery and production put forth by petroleum geologist M. King Hubbert (System Dynamics Society). The method has proved particularly significant in studies that include cross-cutting implications from socio-economic, political, management, market and environmental domains (Chouchri, et al., 2007). Many notable contributions of system dynamics can be found in the literature which includes its application to a wide range of key energy-policy issues through contributions by many notable experts in the field such as by Forrester, et al. (1976), Chouchri (1980), Sterman (1982), Morecroft & van der Heijden (1992) to name a few. System dynamics modelling has facilitated evidence-based strategic energy planning studies in critical areas including in climate change vulnerability assessment (Sterman, et al., 2012; Fiddaman, 2002).

Price movements are central to determining dynamic behaviour of resources and have been the basis of most global oil models. The dramatic oil price movements of the past have caused major structural changes such as economic recession, the transfer of capital from consumers to producers, and booms and bust in the production and exploration sector (Morecroft & Marsh, 1997). A number of different approaches have been used to model oil. Some models are based on the estimation of price elasticity and the income elasticity of oil demand, examples include Adelman’s (1982) model-based analysis (Psacharopoulos, 1987) and econometric models by the IEA and IMF. Many others have based their price determination work on the pioneering work by British economist Harold Hotelling, based around the assumption that oil is an exhaustible resource, and it could, therefore, be treated as a financial asset commanding a premium over and above its immediate value, which increases overtime with intensified perceptions of its scarcity (Hotelling, 1931). However, in an era of supply abundance ushered by shale oil revolution, the assumption that oil is a
The authors of this paper tend to the opinion that the end of the age of oil is likely to be accompanied by an abundance of oil and consequently low oil market prices will be seen by those few buyers that remain, although prices may be held up in some territories by ever more substantial taxation or levies. Hotelling’s logic and its subsequent analogue ‘peak oil’ (Hubbert, 1956) would appear to have the situation backwards. The end of oil will not be driven by the passing of a peak in supply, but rather from the sector’s transition through a peak in demand. Many detailed reviews of oil models can be found in the literature (Al-Qahtani, et al., 2008), (Morecroft & van der Heijden, 1992), (Samii & Teekasap, 2010)).

System dynamics enables a more dynamic representation of the reality of interactions between price, supply and demand compared to classical econometric models, which do little to indicate timescales or the process through which economic equilibrium is reached. Choucri (1979, 1980), laid the foundation of the principles for model-based determination of demand, supply and price specification of the oil markets. Many researchers, including Choucri (1979, 1980), Morecroft (1997) and Samii & Teekasap (2010) propose that price determination is the central element for analysing the costs and benefits of policy choices and must, therefore, be endogenously determined. Any valid long-term analysis of resources must be based on endogenous interactions between producers, consumers and market forces that regulate and manage the flow of these resources (through price control mechanisms mediated by markets players, government regulation or midstream operations) and must consider the political and economic costs to individual actors. A dynamic model that incorporates these interactions together with associated sources of conflict has the potential to be instrumental in analysing impacts of policies for both the producers and consumers. Furthermore, given that the production, flow and transit of resources transcend borders, any analysis must therefore incorporate a global perspective. The model developed in this study is guided by these central ideas that are key to oil market exchanges. Uncertainties in markets (through price-demand-supply movements), time delays, non-linear causal relationships and various concurrent interactions between various oil sub-systems are all incorporated to generate the system dynamics. These are subsequently used to assess the impact of various likely scenarios, providing evidence-based insights to enable policymakers to make informed decisions.

Section 3. Conceptualising a System Dynamics based representation of oil market fundamentals

This study uses an SD-based analysis to facilitate a rational representation of physical stocks and flows as well as nonlinear causal linkages that drive decision-making in the global oil system. The essential aggregate features in a global oil exchange are supply, demand, and price relationships. These aggregate dynamics are further determined by extremely complex feedbacks between various social, economic, and political factors, which, for the sake of simplicity, have been excluded, other than at a high level of generality, from this study. It has been further established in the section on oil price mechanism that the structure of oil markets stays in a constant state of flux, and the process of price determination constantly adjusts to the changing dynamics of supply and demand. This study endogenously models oil price volatility and analyses the macro-dynamics of oil exchange without attempting to make predictions.

A simple causal-loop diagram developed to highlight the relationship between supply, demand, price and market perceptions is shown in Figure S1 (available in the online supplementary material). The relationships and exchanges shown in the figure determine the feedbacks that guide the model-based analysis undertaken in this work to illustrate the modern-day market fundamentals. The importance of ‘market perceptions’ is stressed as this
will be one way in which the model presented in this paper seeks to reflect the complex realities described above. For example, ‘perceived oil balance’, shown in Figure S1 (available in the online supplementary material), is a psychological reality grounded in, but distinct from, a physical reality.

Price formation in the model occurs via a process established by Sterman (2000) called ‘hill climbing’. Implicit agents in the model find the optimal operating point, or price in this study, that can achieve the desired outcomes through a series of floating goals in a behaviourally realistic way. Hill-climbing optimisation applies well to situations where decision-maker strives to optimise a system but lacks the knowledge needed to identify the optimal operating point. In a hill-climbing structure, the desired state of a system is anchored on the current state, which is in turn adjusted by various external pressures. The heuristic advanced by the hill-climbing model closely resembles the oil price adjustment process. In stable conditions, or in market equilibrium, price is at a level that can principally balance supply and demand. But supply and demand of a commodity like oil is also impacted by expectation of future outcomes and volatilities. As supply and demand dynamics change, the price of oil adjusts to an indicated price over an interval given by Price Adjustment Time. If demand exceeds supply, the indicated price rises, and with it the actual price. Conversely, price falls when supply exceeds demand. The balancing Price Adjustment loop adjusts price to the indicated level, which in turn is based on the current price. Indicated price adjusts through the reinforcing price discovery loop. The partial feedback structure of price formation via hill-climbing method is presented in Figure S2 (available in the online supplementary material).

Based on the causal loop diagram shown in Figure S1 (available in the online supplementary material) and the partial hill-climbing price determination structure shown in Figure S2 (available in the online supplementary material), a model comprising of feedbacks between aggregate supply, demand and price components in the markets is developed as presented in Figure S3 (available in the online supplementary material). Each term in the SD causal loop diagram is determined by its previous value and mathematical links to other terms that influence it (as denoted by incoming arrows). The mathematical links are functions of the states of the terms of influence. These algebraic functions can individually be non-linear or be relatively simple and straightforward. In either case, with the numerous feedback loops and the possibility of delays, the consequence is that the model, taken as a whole, can be expected to manifest highly non-linear behaviours which may be sensitive to external stimuli such as emerging geopolitical dynamics. As such very different future scenarios can emerge sensitive to such stimuli or initial conditions. The oil demand/supply coverage variable in the model represents the supply chain of the oil markets and remains constant under stable market conditions indicating that there are no fluctuations in the oil production, processing and transportation systems. For simplicity, perceived coverage is modelled with a first order smoothing and a delay formulation is introduced to factor in the delay in time to form expectations and make required adjustments. The supply side feedbacks of the oil model consist of conventional and shale oil supplies from oil producing countries, demand side dynamics are dominated by US, China, India and Rest of the World (ROW) countries’ demand and the price dynamics consist of the impact of market sensitivities and the impact of oil balance perceptions and inventory coverage on oil prices. Table functions are used to establish relationships between supply, demand and the correlation between oil price and other key variables. These table functions are based on estimated correlation between selected variables. On demand side, a country’s GDP and oil prices are used as indicators to determine the amount of oil imported. The model uses China and India as relatable cases to
represent developing countries’ demand growth, as together they are likely to account for the biggest share of global demand growth. However, there will be a host of other countries which are also likely to follow similar patterns of low-cost economic growth with an impact on oil dynamics.

The price dynamics component of the model, shown in Figure S2 (available in the online supplementary material), forms the core structure of the model and is simulated to run a partial model test to assess the intended rationality of the price setting process and determine the robustness of the structure. The oil demand/supply coverage variable in the model representing the supply chain of the oil markets remains constant under stable market conditions indicating that there are no fluctuations in the oil production, processing and transportation systems. Since the financial crisis in 2009, oil prices remained on an upward trajectory until 2013, which marked the point of inflection in this trend. Prices have since stayed volatile, exacerbated by many commercial and geopolitical developments. The goal of this structure is to provide a solid foundation to model price setting consistent with the relevant information available to and behavioural decision process of actors involved in price-setting process.

The full model structure showing various exchanges is presented in Figure S3 (available in the online supplementary material). The model was initiated with the Brent price of $108 per barrel, as reported for 2013 by the BP Statistical review. The maximum time horizon considered is 50 years. According to BP’s annual statistical review of world energy, based on the world proved oil reserves of 1687.9 billion barrels in 2013, an estimated 53.3 years of oil is left at the current rate of production. Consideration of long-term upstream resource depletion is excluded from this modelling. It is further noted that the historical predictions of looming geological resource depletion have proven to be pessimistic.

Within the scope of this model the impact of price on levels of production and consumption for various dominant producers and consumers can be analysed. The model also helps assess the effect on oil market dynamics of interactions between the oil price and key macro-economic parameters. One such parameter is the level of economic growth. An input variable has been included in the model to introduce demand disruptions enabling study of emerging model behaviours and the impact of demand disruption on other key variables.

Section 4 Analysis of model behaviour and simulation results

The model is initiated in an equilibrium state by assigning constant values to parameters such as initial oil stock, factors of production and consumption. Figure 4 shows a gentle and straightforward convergence towards equilibrium from nearby initial conditions. It shows system stability in the absence of external shocks or disturbances. But, noting long-term considerations, such as geological resource depletion which are not accounted for in this modelling, such a state is only likely to exist in simulated conditions such as during a model run with disruptions blocked.

To analyse the impact of various feedbacks on oil market dynamics the impact of delays on oil price behaviour will be assessed and different scenarios will be introduced, relating to different forced model inputs as might emerge as a consequence of external shocks such as market disputes, technical failures, wars or international public policy push.

Oil Price Dynamics: Price changes affect both the amount of oil demanded and the quantity supplied, which in turn impacts on price. On the supply side there are delays associated with adjustments to ramp the production levels up or down, based on demand signals. Demand adjustments occur relatively more easily than supply adjustments, which usually take longer to materialise as they involve lasting changes to the entire supply chain. Neither of these
adjustments, however, are instantaneous and both involve significant time lags. Somewhat
simplistically, price at a given time \(t_1\) leads to a specified quantity of oil demanded, which
through signals and interactions and over various decisions by agents based on available
information and perceptions lead to changes in the amount supplied. This amount is
constrained by previous demand patterns and prevalent factors of production involving key
components such as labour, capital and resources.

The modelled oil price trajectory responding to adjustment delays is shown in Figure S4
(available in the online supplementary material). Oil price in the model shows significant
sensitivity to various adjustment times. The SD model developed here has three fundamental
adjustment time parameters: Price Adjustment Time; Demand Adjustment Time; and Oil
Balance Perception Time. Of these the shortest is the Price Adjustment Time and in modern
markets with high levels of market automation this step could in principle be close to
instantaneous for a single market player. Nevertheless, it is posited that such an adjustment
actually takes some time to take hold at a global level. Furthermore, as the SD modelling here
is intended to explore long-term trends as such markets with monthly time steps and a 50-
year range are considered. In such a framing the price adjustment time is set to 6 months (0.5
years). Here it is important to remember that the modelling presented in this paper is an
aggregate model of global oil dynamics and that the minute-by-minute variation of the Brent
Crude or WTI benchmark as observed on electronic exchanges, rather the equilibrated price
globally is modelled. In some of the test modelling (see Figure S4, available in the online
supplementary material) this parameter is set to a value two months, i.e., rapid in terms of the
50-year timeframe of the model. The next time parameter is the Demand Adjustment Time,
which has been set at 1 year in this modelling. This is a measure of the physical oil demand
situation. It involves supply chain considerations and in real life demand can be slow to
adjust to new price realities. It can, for example, take some time for drivers to adjust their
driving habits in response to the latest price signals, but the slower issues relate to the global
supply chain between refining and retail sales. This involves tankers, pipelines and storage.
These demand side considerations also cascade up to affect supply chain steps upstream of
refining concerning resource extraction and even exploration. Noting these various supply
chain steps the impact of refined product demand on upstream crude oil demand can be
slower to adjust than crude oil prices. Finally, there is the oil balance perception time – this
parameter has its basis in human psychology. It relates to the time it takes for data-driven
fears to transform into demand response decisions. It is a quicker process than the supply
chain issues shaping the Demand Adjustment Time, and, in this modelling, typically set at 6
months (0.5 years).

Figure S4 (available in the online supplementary material) illustrates the characteristic
damped oil market oscillations that are seen throughout the modelling when hit by a severe
shock (see next section for discussion of the effects of specific shocks). Each figure shows
the current oil price and the indicated oil price, which is key to the oil model’s price
formation process. These prices are shown per barrel in USD with a significant y-axis offset.
The third curve, change in oil price, relates to the other two but it has different dimensions as
it represents the flow of change in price, and it is shown much magnified and on a scale that
spans negative and positive values. In Figure S4B one can see that the frequency of the
oscillations in price and price change are not the same. The only difference between Figure
S4A and S4B is that the Oil Price Perception time is very different, six times slower in the
case of Figure S4B. While this change dramatically slows the oscillation frequency that
frequency is not simply the same as the Oil Price Perception Time. When the Oil Price
Perception Time is 2 months the oscillation period is roughly 3.5 years and when it is 18
months the oscillation period is roughly 13 years. The damping rate is far slower and appears unaffected by this parameter.

With an awareness that the model tends to manifest a damped oscillation SD archetype, a pair of supply demand shock scenarios relating to different forced model inputs as might emerge as a consequence of external shocks such as market disputes, technical failures, wars or international public policy push are considered. These scenarios are designed to analyse the impact of various feedbacks on oil market dynamics. Scenario 1 considers a set of supply-side shocks. Scenario 2 explores the possible consequences of growing pressures of decarbonization, especially those affecting demand effectively in OECD countries. In each case the focus is on the consequences for global oil prices and aggregate global demand with an intention to examine the consequences of relatively simple supply and demand side pressures in scenarios where, for example, China and India remain outside an aggressive global policy and governance framework, a perfectly plausible scenario, as seen during COP 26 negotiations in Glasgow. The purpose of this modelling is not to predict future oil prices or levels of production or consumption, rather it is to use SD in order to assess the types (termed ‘archetypes’ in SD discourse) of market dynamics that might be expected to occur in markets under stress and to consider the resilience of markets and the SD modelling technique. (Systems archetypes are a class of tools offered by Systems Thinking methodology for diagnosing problems and to capture ‘common stories’ or dynamic phenomenon occurring repeatedly in diverse settings, for details see (Kim, 1992)). The SD model is sufficiently robust and seen to function well into a scenario space of market failure.

**Scenario 1: Oil Production Shock**

**Scenario Description:** This scenario explores the changes in oil market behaviour when the production rate of a set of dominant aggregate producers, in this case OPEC members, suddenly decreases. For example, it is asserted that events in the Middle East are strongly correlated to political and economic events globally through their effect on the price of oil, which is influenced by varying the production and supply of oil (Barsky and Killian, 2004). The state of oil-market directly impacts the economies of countries reliant on petrodollar (or, any U.S. dollar paid to oil-exporting countries in exchange for oil; the term has been loosely used to indicate reliance on oil trade). An oversupply-driven-low-oil-price regime is not conducive to OPEC producers, who may find it increasingly difficult to sustain their economies in the age of competitive oil, even forced to run large fiscal deficits and cut back on essential welfare provisions, which would have ripple effects of global oil production and prices. For the purposes of a test of the model a ‘STEP’ input is introduced in year 20 with supply restoration over two years. In the model the OPEC production is reduced in this way by 10%, 20% and even 50%.

**Scenario Analysis:** The Figure S5 (available in the online supplementary material) illustrates the response of the global oil system to supply-side shortfall shocks of differing magnitudes lasting two years (in years 20 and 21). In the case of a 10% reduction in OPEC supply a demand reduction consistent with normal price elasticity behaviours is seen. By 20%, however, archetypal oscillatory effects start to manifest themselves and these endure far beyond the initial 2-year shock. In the 50% case a massive reduction in demand is immediately triggered. At the risk of exaggerating and, at the risk of overly humanising the model, panic steps in... prices skyrocket and demand collapses. Stocks in the system are drained and non-OPEC and US Shale production adjusts in response to price signals. Figure S5 shows how demand falls precipitously until around year 24, it discontinuously falls no further.
It is interesting that the demand curve shows a discontinuous trend when the actual upstream supply shock is already over, and full OPEC production is enabled once again. This flat demand feature in the 50% case is attributed to a sharply increasing oil price during this period. A properly functioning market might intuitively be expected to exhibit smoother behaviours without exhibiting such discontinuities, but the realities of agent decision making in real markets can give rise to market failure. The 50% case demand profile is identified here as being a type of market failure, at least for the market as implemented in the model. The model lacks a futures market that is known to be extremely important to the functioning of the modern oil supply system. However, the absence of this aspect does not fundamentally undermine the approach adopted in this study. As stated previously, physical realities play an important role in oil markets. They serve as an anchoring point for prices in the futures market. The core information on which a futures market would depend arise from physical realities, as captured by the model.

Sensitivity testing of the behaviours revealed in Figure S5 confirms that the length of time where total oil demand is flat in the 50% case is determined by one key parameter – the Demand Adjustment Time. The longer that time is, the longer the extent of the flat feature seen in Figure S5. That said, the duration of flat demand is not the same as Demand Adjustment Time. The Demand Adjustment Time determines the flat demand period, but the flat demand lasts longer than the Demand Adjustment Time. In the case where the Demand Adjustment Time is set at un-realistically low, essentially instantaneous, level then the discontinuities and flat feature entirely disappears. In that case the market would appear to operate effectively, but it is not a realistic situation. The authors posit that the existence of a futures market in the real world mitigates the risk of market failure arising from the time need for demand adjustment.

Figure S6 (available in the online supplementary material) shows the associated behaviour of the oil price in each case, corresponding to Figure S5 and despite the anomalies in the demand profile in the case of the 50% supply-reduction-shock, only smooth price behaviours is seen. The SD model appears to run well even in such a highly stressed scenario. Indeed, to produce the archetypal damped oscillations seen in Figure S5 it must be noted that the system was severely shocked.

With a restoration of full supply pent up demand returns (after delays) and there is a strong increase in demand before oscillatory behaviours is seen, as seen cleanly in the 20% case. Long term effects on equilibrium levels of demand with reference to Figure S6 will be considered.

Figure S6 shows that with a 10% supply shortfall shock, prices rise as part of the price demand elasticity discussed in connection with Figure S5. Oscillations mirroring those seen in demand are also visible in oil prices over the relevant timescales in each case (more marked in 20% and 50% reduction). Table functions have been used in the model to establish the correlation between oil production and price. In Scenario 1, since oil price starts to increase as soon as the supply-side shock input steps in, the OPEC Production rate increases accordingly. Both conventional and unconventional oil production rates are impacted by sustained increase in oil prices, and therefore demand remains depressed in response to the supply shock. In the case of the 50% shock, even though the demand response indicates a discontinuous inability to match supply with demand (abrupt dynamic responses) the model indicates a smooth evolution in price. As also illustrated in Figure S5, with a 50% supply side shock the oscillatory effects rumble on for nearly 20 years. It is also interesting to see the impact of the shock on long-term demand. In every case long-term equilibrium demand
reduces, significantly in the case of a 20% or 50% shock. It is suggested that this is consistent with a real-world market where, as a result of an extreme two-year shock, end-users could be expected to fuel switch away from expensive and insecure oil and also that they might act to improve energy use efficiency measures. Some physical adjustments of global oil infrastructure can take decades and may therefore result in lasting changes. Once the crisis is over the global oil market is smaller and a new supply-demand equilibrium is established at a new price point.

The following section will consider a particular form of oil demand decrease scenario. Here the focus will move away from a short sharp shock, although the SD modelling could handle such a scenario without difficulty, rather the study will focus on an enduring shift – an energy transition.

**Scenario 2 The Climate Response**

A gedanken experiment is presented here, one that considers the impact of a future climate response on emerging oil dynamics. There is consensus that immediate action is needed to mitigate the harmful effects of climate change, which includes, among other things, a significant reduction in fossil fuel emissions. Any number of pathways to achieve the desired level of CO$_2$ emission reductions may unfold depending on the level of feasible demand reductions, and the local political and economic context, prevalent at the time, within various countries. Within the scope of this study it is assumed, based on the current political and economic rhetoric, that some oil will continue to remain in the energy mix of almost all countries. This study uses China and India as relatable cases to represent developing countries’ demand growth, as together they are likely to account for the biggest share of global demand growth. However, there will be a host of other countries too that are likely to follow similar patterns of low-cost economic growth. Furthermore, the growth in oil consumption by India and China in response to low oil prices is a likely future possibility suggested by many oil industry analyses (BP; IEA; EIA). Such a future pathway is extremely concerning to a climate-conscious global community.

This scenario is assessed, not because it is believed to represent a realistic case, but rather because SD modelling reveals a somewhat counter-intuitive consequence of the proposition. One of the valuable attributes of SD modelling is its ability to reveal system effects that, although readily understood once revealed, are not what one might have expected ab-initio.

The central proposition for the following modelling is as follows. In this scenario the world is divided into three aggregate downstream oil consumers, China as a new major source of oil demand, India as a growing source of oil demand and the Rest of the World as dominated by the OECD demand centres and with a history of seeking to regard oil as a globally traded market commodity. Table functions are used in the model to represent the correlation between oil demand and oil price and average GDP growth rate. In case of India and China, faster economic growth rate would result in a higher demand of oil, even at higher oil prices, reflecting inelasticity of demand. The model enables to force down demand in any, or all of these global regions. Ab-initio it was expected that such step would reduce global oil demand significantly and indeed it does eventually, as can be seen in Figure S7 (available in the online supplementary material) in the case of a forced reduction.

**Scenario Analysis:** The model starts at time zero in a suppressed but equilibrated level as determined by test modelling. In the case of Figure S7, ROW demand is forced down by 90% and in this, admittedly exaggerated, scenario it is suggested that such a step might arise from a strong political desire to mitigate climate change causing emissions. The model is allowed to run from the suppressed state (e.g. ROW 90% demand suppression) whereby the ROW demand remains held down artificially. The model clearly shows a direct price response, and
as prices fall demand in India and China rises fast. The level of that non-ROW response is remarkable. It prompts whole system oscillation such that four years in total global demand touches levels similar to those seen without ROW demand suppression. Of course, this is simply market oscillation but it appears that the magnitude of such effects might be enormous.

The simulation results showcase that following an almost 90 percent reduction in oil demand by the ROW countries, the total demand at long term equilibrium drops from 28 Billion barrels per year to 20 Billion. The global enduring shortfall falls short of what one might expect given the original importance of ROW countries to total demand because of dynamic response by India and China and the global oil system finding a new normal.

A scenario in which China acts to strongly (90%) suppress its demand by fiat with significantly weaker (60%) forced suppression in the ROW is also modelled. In this scenario India remains almost entirely unconstrained with only 10% demand reduction. This is arguably a somewhat more realistic scenario than the one underlying Figure S7. The results when the model is allowed to run from such a dis-equilibrium starting state are shown in Figure S8 (available in the online supplementary material).

The impact of the steep demand reduction in China is significant, Figure S8. The simulation result shows that a similar reduction in total demand from 28 Billion barrels per year to 20 Billion as in the earlier ROW 90% scenario can be achieved. Again, powerful oscillations are seen, in this case dominated by the Indian response. Figure S8 and the SD modelling presented in this paper more generally reveals the established importance of Chinese demand in global oil dynamics – sufficient to shift overall equilibrated demand levels almost as much as the OECD/ROW. Second the arrival of India as a large unconstrained growth market has the power to generate whole system oscillation dynamics. The cheap-oil induced GDP growth is likely to further inflate the demand of oil. This increased demand growth may help the oil prices to recover to some extent, and it may become profitable for some non-OPEC producers to become marginal suppliers of oil. Experts believe that the crash in prices could potentially trigger the so-called ‘rebound effect’, in which falling prices stimulate higher demand (Dale and Fattouh, 2018). The outcomes of rebound effect on China and India’s demand as a response to emerging oil dynamics are very likely to manifest very differently based on the specific policy choices in these countries. Of course, this model may not capture these truths in their entirety or provide quantitative guidance on the actual magnitudes of change. What it does do is suggest fundamental truths regarding the importance of various global actors and the extent to which oil market dynamics becomes a concern when thinking about climate change motivated demand side actions.

6. Conclusions

This paper presents a system dynamics-based analysis of the fundamental dynamics and exchanges underpinning the global oil markets. The paper argues that with the commoditisation of oil, the regular interactions between financial instruments of commodity markets and physical layers of oil supply-demand dynamics determine and account for various trends and behaviour patterns observed in oil markets. The SD model presented in this paper is found to operate smoothly in a range of highly-stressed global oil market scenarios. As such it mirrors the known ability of markets to accommodate system shocks. Markets are largely resilient and so is the modelling tool presented here. In a future where the age of oil may be coming to an end the world must be careful not to lose the resilience and flexibility of markets, albeit with the fact that sometimes market volatility can be very painful. Sometimes this painful short-term volatility is not just a consequence of current
market fundamentals, but it is merely an oscillatory response to past shocks, not resolved, but still causing enduring harm.

The modelling reveals an archetypical SD behaviour: damped oscillation of long duration. The principle that the structure of a system generates this behaviour mimics in some ways the much-observed volatility in oil prices and the associated supply and demand dynamics.

Two sets of scenarios have been considered using an SD model. The first set considers a brief but serious supply side shortfall in OPEC crude oil production. The second examines the extended effects of a strategic global or OECD move away from oil as a fuel as might occur for climate change reasons. Simulation results reveal just how much the world has changed since the golden age of SD oil market modelling in the 1980s. Today global oil market dynamics must consider China and India, both because China alone can shift long-term oil demand and oil prices, but also because the existence of large flexible and unconstrained players like India can drive oil market oscillations very significantly. Any policy makers contemplating the much-needed reduction in OECD oil use should pause to reflect on possible global consequences arising purely from market dynamics and without geopolitical interventions.

[The authors would like to thank Dr Sally Caird, Professor John Hatchard and Professor Jeff Johnson for useful discussions and The Open University for funding this research. Responsibility for the content of this paper rests with the authors alone.]

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Accepted manuscript doi: 10.1680/jener.22.00020


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Table 1 Top 10 Crude Oil Producers and Consumers in 2018

<table>
<thead>
<tr>
<th>Country</th>
<th>Million barrels per day</th>
<th>Share of world total</th>
<th>Country</th>
<th>Million barrels per day</th>
<th>Share of world total</th>
</tr>
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<tr>
<td>United States</td>
<td>17.87</td>
<td>18%</td>
<td>United States</td>
<td>19.69</td>
<td>20%</td>
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<td>12%</td>
<td>China</td>
<td>12.79</td>
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<tr>
<td>Russia</td>
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<td>11%</td>
<td>India</td>
<td>4.44</td>
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<tr>
<td>Canada</td>
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<td>Japan</td>
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<tr>
<td>China</td>
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<td>5%</td>
<td>Russia</td>
<td>3.63</td>
<td>4%</td>
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<td>Iraq</td>
<td>4.62</td>
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<td>Saudi Arabia</td>
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<td>Iran</td>
<td>4.47</td>
<td>4%</td>
<td>Brazil</td>
<td>2.98</td>
<td>3%</td>
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<tr>
<td>United Arab Emirates</td>
<td>3.79</td>
<td>4%</td>
<td>South Korea</td>
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<td>3%</td>
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<tr>
<td>Brazil</td>
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<td>3%</td>
<td>Canada</td>
<td>2.47</td>
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<tr>
<td>Kuwait</td>
<td>2.87</td>
<td>3%</td>
<td>Germany</td>
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<td>Total top 10</td>
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<td>70%</td>
<td>Total top 10</td>
<td>58.31</td>
<td>60%</td>
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<tr>
<td>World total</td>
<td>100.66</td>
<td>100%</td>
<td>World total</td>
<td>96.92</td>
<td>100%</td>
</tr>
</tbody>
</table>

Source: U.S. Energy Information Administration, 2019

Figure captions

Figure 1 Oil’s Share in global primary energy mix in 2019 Source: (Looney, 2020)
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Figure 02
Figure 03
Accepted manuscript doi:
10.1680/jener.22.00020

Figure 04