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Shale-Oil Development Prospects: The Role of Shale-Gas in Developing Shale-Oil

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Abstract: Currently, most of the world's shale-oil is coming from the United States, but more may be needed from non-U.S. sources in order to keep the world price of oil from increasing, and yet a number of petroleum producing countries have yet to develop shale-oil resources. This article investigates why that may be. One reason for this may be the role that shale-gas development plays in the search for shale-oil. In the oil and natural gas industry over much of the 20th century, finding oil has usually been more valuable than finding natural gas because the gas has less energy density than oil, making each BTU (or Joule) of oil energy easier to store, transport and use for consumers. However, since shale source-rock often has both natural gas and oil, then it behooves a shale search process to start by looking for natural gas first rather than oil to enhance the profitability of the search process. The problem, then, is that a shale-oil only search strategy has the same problem that first plagued the oil and gas industry: What do you do with the natural gas? In this paper, we will examine how this "chicken and egg" exploration scenario has played out in the U.S. in order to draw lessons on how difficult shale-oil development will be for the rest of the world.

Keywords: shale-gas; shale-oil; sustainability; peak oil

1. Introduction

One of the most fascinating concepts in all of energy economics is how shale-gas and shale-oil extraction are compliments in production when it is primarily shale-gas that is being supplied, but they are substitutes in production when it is primarily shale-oil that is being supplied. Therefore, the article adds a number of explanations to try to explain the many intricate aspects of the U.S.' oil and gas industry in order to prove the confusing, yet opposing ideas of how the economics of petroleum extraction simultaneously has substitutes and compliments in production. The analysis here draws on the typical business environment of the oil and gas industry where underground petroleum reservoirs contain both oil (the liquid part of the petroleum) and natural gas (the gaseous part of the petroleum) and where the business of oil and gas development interacts with each other in complex ways. There are a lot of moving parts in the oil and natural gas businesses that are not easy to understand because the characteristics of the two energy types are substantially different. For example, oil and natural gas can be compliments or substitutes in the production process but also compliments or substitutes in consumption, a fact that is seldom written about in the academic energy literature, and where the business strategy of oil and natural gas are completely different even though they both can come out of the same reservoir (associated gas) or can come out of completely separate underground reservoirs (non-associated gas). The complexity and nuance of these interactions requires many notes to explain step by step how these interactions create costs, regulation problems and (sometimes but not always) opportunities that a number of readers will be unfamiliar with. These vagaries of the industry can cause misunderstandings of what is happening with shale resources. In essence the single idea presented here requires not just an article to explain it, but an entire textbook to get at the background information that supports the idea, otherwise readers may misunderstand some aspects.

Global warming issues notwithstanding, the world may still need to use petroleum resources for energy due to petroleum's valuable characteristics of energy density (GJ/m^3), of being in a liquid or gaseous state, and of its power density at the source (GJ/hectare), see Smil [1] and Reynolds [2]. See Reynolds [3] and Smil [4] to see how the history of the modern industrial era is a history of going from low characteristic valued energy resources to high characteristic valued resources, i.e., instead of neo-classical economic, free market exclusive institutions causing worldwide growth, energy characteristics also played a role. That is the inherent characteristics of energy resources are independent of technology, even though it takes certain technologies to extract and use high characteristic valued energy. For example since coal is a solid energy resource, it can only be used in external combustion engines like steam engines, but gasoline derived from oil, a liquid energy resource, can be used in internal combustion engines for a much better energy to engine weight performance. Being a liquid or a solid is independent of technology, but the technological value of going from a low grade characteristic coal resource to a high grade characteristic oil resource can cause a tremendous improvement of the economy. However, Reynolds [5] shows that conventional liquid petroleum (oil) from underground traps like that of the great Ghawar oil field in Saudi Arabia, East Texas oil field in the U.S. and the Western Siberian Samotlor oil field in Russia, have already begun to decline.

Note, the term conventional oil and unconventional oil is interesting. We can call oil from certain sand sources as either tar-sand or oil-sand. People call it tar-sands when they want to explain the high costs and the difficulty in obtaining oil from such a source. They call it oil-sands when they want investors to give money to companies in the hope that it is a good investment opportunity and to make investors believe that costs are low and revenues are high. We could call coal-to-liquids unconventional oil since it comes from a different geological structure than petroleum and has only been around for a mere 50 years. However, why not call shale-oil "unconventional" after all it too is from a different geological structure similar to oil-sands, basically a structure that is an order of magnitude older than conventional oil traps from a field like Prudhoe Bay, and also shale oil has only been done for about ten years, a lot less time than tar sands. The only difference between coal-to-liquids and shale-oil is that coal-to-liquids sounds dirty and shale oil sounds clean and that there is likely to be a lot of it. Investors will tend not to invest in coal-to liquids unless you are in a situation like Nazi Germany during the war or apartheid South Africa, but there are lots of investors for shale-oil. Nevertheless let us just call it "tight sands" recovery if that makes it more in line with the current understanding. Also note, the U.S. Energy Information Administration [6] actually keeps statistics of shale-oil production as a separate category from total U.S. oil production of all oils. If that is done then it means that shale-oil is not the same thing as all oil, i.e., there is a difference between the two, call it a cost difference or a technology difference. Nevertheless, seeing as the difference exists, the EIA shows that it is only in the last 10 years or so that shale-oil production has been going.

Therefore shale-oil must be separate from conventional oil of the last 100 years, which means worldwide shale-oil extraction is needed to keep oil prices low, otherwise as Hamilton [7,8] shows, high oil prices can adversely affect the world's economy. Also note, natural gas such as methane (c1), ethane (c2), propane (c3) and butane (c4) are considered natural gas liquids (NGLs), which is often categorized as oil, but can be categorized as a gas and is often transported by pipeline, and where its processing and distribution often requires a pipeline. Usually pentane (c5) and petroleum components with higher carbon content are considered crude oils, which can use pipelines, but can equally use tanker trucks, ships and trains to transport. These transportation physics create business problems for using natural gas as opposed to oil.

The usual idea on shale-oil development is that countries and regions will simply start looking for shale-oil, develop it and produce it just like they do with conventional petroleum reservoirs. The thing about shale-oil resources, though, is that there is often as much shale-gas as shale-oil, or even more shale-gas than shale-oil, in many source rock reservoirs. For example, Brick [9] shows how too much shale-gas in the shale-oil prolific Permian region (in West Texas and Eastern New Mexico in the U.S.) is limiting shale-oil production there. This is because the shale-gas cannot be sold as there are not enough natural gas pipelines to take the shale-gas to market. Since much shale-gas is produced while producing shale-oil, and you cannot sell shale-gas, then it inhibits the production of shale-oil unless you allow flaring, i.e., the burning up of the natural gas into the atmosphere. However, flaring brings up concerns about creating more carbon contributions into the atmosphere and adding to global warming. Plus with shale resources, if you find shale-gas with shale-oil then the natural gas can be a nuisance. In the early days of oil production, Singerman [10], the oil and natural gas would come out simultaneously with an oil well and where the natural gas often drifted into the air and caused explosions. So, the natural gas had to be flared for safety reasons. Now, if natural gas comes out with oil it is often not allowed to be flared for conservation or pollution reasons. However, you cannot produce the oil if the natural gas cannot be marketed, as you have to wait for new natural gas pipelines to be built to get your natural gas to market, and with shale-resources you cannot easily re-inject the natural gas into the shale rock.

Nevertheless, the initial search for shale-gas in the U.S. was due to important characteristics in the U.S. petroleum industry that lead to the general shale development. That is the U.S. followed an unusual "chicken and egg" difference in the petroleum exploration sequence: Instead of finding oil first and then developing natural gas later, as in the 20th century (see Yergin [11]), shale-gas was found first. As an example, Prudhoe Bay, Alaska has about as much natural gas as oil in terms of the BTUs of the field, but the natural gas has not been developed in 50 years. The original explorers were not looking for natural gas and they have had a hard time marketing it, but since they found it and could not market it, it has become stranded gas. This is a very typical situation around the world even in the Middle East where it took many years before liquefied natural gas (LNG) exports became prevalent. Therefore, the U.S. in the 21st century has first searched for shale-gas and developed it, and then in the process producers eventually found shale-oil and then developed it. Since shale-oil is in general more valuable than shale-gas then when you look for shale-gas and find shale-oil it becomes an added bonus value over and above the shale-gas development. That is finding shale-oil when you are looking for shale-gas creates a secondary profit stream, whereas the opposite is not true in most cases.

It is like looking for gold and silver in a very expensive underground mine location. If the costs are such that looking for sliver is lucrative then the search for silver that finds gold is very profitable. However, if the costs are such that looking for gold is just barely viable and you find silver you lost money on the search. However, while finding silver sounds like you have compensated your search process a little bit, that is not the case with shale-gas. When you find shale-gas the economics are much worse than finding silver when searching for gold because with shale-gas the natural gas is volatile. You must either flare the natural gas if you want to produce the shale-oil with it or not produce the shale resources at all. Therefore if you find any natural gas at all, you have to wait until a pipeline can be built to your location, which will not happen until natural gas prices are high in that region. Therefore the analogy should be this: While you are looking for gold, you instead find bottles of highly volatile nitroglycerin right next to the gold. Then the gold extraction will be expensive and dangerous to deal with, unless you can also economically extract the nitroglycerin as well. If you only find the nitroglycerin exclusively, and you were not looking for it or have no way of using it, then you lost money on your search. When you are looking for gold and you find nitroglycerin, it either becomes an impediment to gold extraction, in which case it has to be carefully gotten out of the way, or it has to be left in the ground, which means you cannot produce anything, or it has to have very specific infrastructure developed for its removal and marketing, which can take awhile. Note, unlike oil, natural gas cannot easily or cheaply be stored so the entire value chain has to be in place from wellhead to burner tip for shale-gas, and that value chain can slow down if the extraction is slowed down, i.e., you also have to slow down the associated oil production as well. Oil has some ability for storage at the well in a tanker at other locations and at the burner tip by customers and retailers, so that gives oil much better leeway for using its value while natural gas has much less leeway.

From an explorer's perspective, though, this sequence of development is interesting, if you find natural gas, and that is what you are looking for, then you have not lost money for your exploration and development efforts and you gain a profit. If you do not find good natural gas prospects at first then there can still be a possibility of good shale prospects nearby and you will often drill a few more wells just to make sure. Note, if you drill for petroleum, there are three outcomes: (1) Finding nothing, (2) finding natural gas or (3) finding oil. If you find nothing, that gives a slightly higher probability that the next well you drill will also find nothing, but there is still some probability of finding gas or oil, so you would normally try a few more wells. If you find natural gas, that gives it a high probability that nearby shales will also have mostly natural gas. Therefore if there is a 33% probability of each outcome at the beginning where you drill, and if nothing is found, then suddenly the probability of the outcomes of drilling nearby wells becomes something close to 50% for nothing, 25% for natural gas and 25% for oil. Therefore, your prospects are still about the same: 66% for something valuable in your pre-drill analysis, versus 50% for something valuable in your post-first drilling analysis for doing more drilling. Therefore, you still have a 50/50 shot at finding something valuable on the next well. If you find natural gas, then your probabilities change to 25% nothing, 50% natural gas and 25% oil, so suddenly oil and gas prospects go from 66% expected success rate to 75% rate, i.e., a very high probability of a gain if you drill more exploratory wells. If you are looking for oil exclusively, but you find natural gas, then you go from a 33% probability of discovery of oil to a 25% probability of discovery oil and it becomes a much lower expected outcome for finding shale-oil and it becomes hard to justify more drilling, so, finding natural gas when you are looking for oil is a complete loss. Crucially, though, if you find oil during natural gas exploration, then you obtain an even higher profit margin because of the inherent high value of oil and the ease of storing it, of transporting it and of selling it on the market. The fact that you are really looking for natural gas, and yet you find oil means you have not lost money in your search process, but have enhanced your profitability, i.e., your oil is a compliment in production.

However, if you start out by looking exclusively for shale-oil and you find shale-gas, then that implies you were not expecting to find shale-gas and so you would not normally have a way to market the natural gas or get it to market since a gas is less dense and harder to get to market than oil. Therefore, usually you do not have a profitable option to develop that gas and your initial search is unsuccessful and you have lost money. That is, in the search for oil exclusively, the natural gas becomes a substitute in production, and suddenly the whole search process is a loss. Oil and gas exploration costs are determined based on the size of what you find, as well as the expected probability of finding something as explained in Reynolds [12]. Therefore, as an example, when you look for conventional oil and gas that are in underground traps, a $100 million exploration program might find 100 million barrels of oil or 1 trillion cubic feet (TCF) of natural gas, i.e., $1/Bbl ($0.15/Giga Joule) cost to find the oil or a $0.1/mcf ($0.1/GJ) to find natural gas. However a search for shale resources might encounter a $100 million exploration cost to find only five million barrels of shale-oil or 200 billion cubic feet (BCF) of shale-gas. That is $20/Bbl ($3.3/GJ) for oil or $2/mcf ($2/GJ) for natural gas. As an example, Prudhoe Bay, Alaska had 17 million barrels of oil and about 10 TCF of estimated natural gas reserves found. For example, Great Bear on the North Slope expected to find shale resource fields that might have had millions of barrels of oil, but it has found shale-gas, and has been unsuccessful in finding commercial quantities of oil. Finding shale-gas will also imply that most nearby shale resources will also be shale-gas rather than shale-oil and you will quickly terminate the search. Then in that case, you may give up on the search for shale resources more quickly and therefore not search nearby formations as extensively. Since shale-oil and shale-gas are more expensive to produce than conventional oil and gas, the loss is large and it leads to much less exploration for shale-oil, where exploration costs for both are similar. In other words, a search for shale-gas that finds shale-oil is relatively speaking a gain, but a search for shale-oil that finds shale-gas is relatively speaking a loss especially when a present value analysis of the resources is conducted.

Note, if it takes ten years to finally develop a natural gas resource, because you need to wait for a pipeline to be financed, permitted and built, the present value of the benefit of the natural gas compared to the cost of exploration can be a net loss, e.g., $cost_0 > benefit_{10}/(1 + r)^{10}$. Therefore if you have a $1 million cost of exploration in year zero, and a $2 million net benefit of natural gas in year 10, the present value of the gas is a loss of about a quarter of a million dollars at a ten percent interest rate (which is a typical required return for risky prospects). Plus since there is often more gas than oil in shale formations, such as in the Permian Basin, then you have a harder time separating the shale-oil from the shale-gas unless you flare the gas, otherwise you will have to have extensive pipelines to carry the natural gas to market, which could take years to get in place. This suggests that the key to successfully search for shale-oil is to first search for shale-gas.

The historical precedent for how oil and gas exploration and development was conducted has always been organized by searching for oil first, and then if you find natural gas you would simply hold on to it until a pipeline came by. See for example Lerche and MacKay [13]. That is, the incentive for finding oil and the cost and value of obtaining oil was such that everyone wanted more oil rather than natural gas. Although, if you did find natural gas, and if, later on, the natural gas was found to be valuable, then eventually you would develop it, but only if you found natural gas in large enough quantities in that region to develop it and, even then, only if a natural gas pipeline was nearby or was soon coming by or if you had enough supply to build your own gas pipeline to a far away location but with a very large market. For example, also according to Yergin [11] Patillo Higgins of Spindle Top Fame found natural gas seeping up out of the ground, but did not develop that natural gas because there was no way to get it to the market at that time. Nevertheless, he used the natural gas evidence to look for oil by actually drilling into the ground, where the natural gas was coming out, and eventually he found the super giant spindle top oil field in 1901, and where as the oil was produced, the natural gas was flared. This might suggest that searching for shale-gas will lead to large quantities of oil, but conventional oil and gas typically have large reservoirs of petroleum under the ground, while shale resources do not. This is very typical of the 20th century where one first drills for oil not natural gas, but if natural gas is found, it is flared if it is associated gas, or left alone if it is non-associated gas and eventually, often years later, it will find a market and a use.

The next question in oil and gas exploration and development, though, was what came first, the natural gas pipeline or the natural gas source? The answer has traditionally been that it was the natural gas source that always came first and then, if it was a large enough supply, you would go ahead and build a pipeline to it that would be cost effective enough to create profitable development. You would never build a natural gas pipeline first in the hope of finding natural gas, since if you did not find that natural gas than you would lose money on the pipeline, rather you look for oil first and if you find gas then you think about building a natural gas pipeline later. Eventually, you do build a natural gas pipeline from the natural gas producing region to a consuming region, and then since a major hub exists at the supply source, and feeder gas lines exist there too, then you can at that point look for new natural gas resources exclusively as its own commodity but only near (within about 50 to 100 miles) the existing feeder lines. Still, even then you are more apt to look for oil first, and then if you find natural gas, you are forced to connect it to the natural gas pipeline system later. This has been the convention in the oil and gas industry for most of the 20th century, see Busby [14].

Interestingly, though, this idea of the oil first and natural gas second sequence of exploration and development has been flipped with shale. The first development of shale in the U.S. was not as a source of shale-oil, but as a source of shale-gas, which is different than the traditional oil first, gas second way of developing conventional oil and gas. This switch of the chicken and egg solution to the oil and natural gas exploration process happened for three reasons. First, shale-gas was more abundant than shale-oil (this is because, as EIA [15] shows, oil wells often include 25% natural gas by BTU extraction, but natural gas wells only include 6% oil by BTU extraction), and therefore shale-gas was the resource with the higher expected probability of discovery. Second, the entire shale phenomenon started in the United States and Canada when natural gas hub prices were twice as high as oil prices per BTU in the crucial year of 2005, just before oil prices shot up. Third and importantly, the U.S. had many natural gas feeder pipelines crisscrossing the major shale-gas regions, such that when shale-gas exploration occurred, there were ready-made pipelines already available and relatively nearby to take away the product.

Note, what does searching entail? A search process. Where will I look? I will look at the best place. What place is that? It depends on what information I have. For example, why did it take so long before gold miners went looking for gold in Alaska? There was no information about Alaska until the 1890s. How did that information come about? It happened when someone in Dawson, Canada suddenly found some gold. As soon as that was announced everyone went to Dawson, Canada. Then someone had the idea that if Dawson, Canada has gold, maybe so does Alaska. However, what were the chances? There was information: Gold existed in Canada, maybe it would exist in Alaska, but based on the information in the early 1890s, the probability that gold existed in Alaska was maybe only 10%. Later gold was found in Alaska, so at that point, after the first discovery, suddenly the probability that gold was in Alaska became 100%. Do you see how probability changes as information increases. Yet there were many places in Alaska to look. Each new place had some sort of expectation, before the search, of what might happen. This is exactly how the process of exploration for oil and gas works, you do not know 100% if you will find oil or gas ahead of your drilling. However, you drill in the location with your best knowledge that something might be there, just like after Dawson, Canada gold was found, prospectors decided that maybe the same could also happen in Alaska. The probability of something being found is not the probability of it actually being there, which we now know is 100%, but the probability before exploring for gold that one may or may not find the gold, which is a subjective probability based on information available at the time.

Therefore, how does subjective probability affect costs? If I believe that there is a 25% chance of finding something it is as if I need to drill four wells, or even have four exploration drilling projects, to find one good reservoir. If my expected probability is 10%, I need to have ten such exploration projects. Therefore the lower the probability of expected results, the higher the costs I expect to have, which inhibits my willingness, and indeed my ability to convince investors, to explore. In a way, what is needed is the set of explorers' subjective probabilities and ideas about what they are looking for, then do a probability distribution of what they thought during the time when they found a resource to prove what is going on. However, explorers cannot reveal their probabilities and subjective probabilities because others will steal that information from them and get to the oil first. Therefore what we need to do to prove the point is to observe the probable amount of information, which we do by watching actual production, i.e., where a high probability of discovery reduces the costs of exploration.

What has to be remembered is that unlike oil, natural gas prices are highly regionally dependent even with the extensive liquefied natural gas (LNG) trade that exists worldwide. For example, even if LNG can arrive at China's industrial east coast at $10/mcf ($10/GJ) on land, that does not necessarily mean China's western shale-gas producers will receive the same price. Natural gas has very skewed prices due to the high transportation costs per mcf or per Giga Joule. Therefore depending on the size of a pipeline, and how much it is filled over the course of seasonal needs, China's western shale-gas producers may only receive $1/mcf even when Eastern consumers pay $10/mcf at the city gate for landed supplies. Therefore the incentive to find shale-gas in western China can be very low. Logically, China can simply build pipelines to make the shale-gas more lucrative, but building pipelines in China, even when the needs of the country outweigh the needs of local regions, can still take a long time to plan, permit and secure contracts to make sure that a natural gas pipeline stays full and covers its costs of construction. If there are delays in construction then the cost of the pipeline can go up making for higher tariffs and a lower wellhead price. Any regulator in China will have to take into account all of these factors. Any small increase in the delivered price of natural gas can suddenly cause consumers to want to use cheap coal instead.

Additionally, note that according to Tussing and Tippee [16] 24% of America's energy was from natural gas and every region in the U.S. used natural gas from Seattle to Miami either for electric power production or for residential heating. Most of the supplies also came from Texas, Louisiana, New Mexico, Colorado, Wyoming and some from Alberta, Canada, which is to say there were pipelines from all the producing states in the central part of the U.S. to all the consuming states across the U.S. and on the coasts, which means as natural gas prices increased after the year 2000, then all the shale-gas regions as shown in the EIA [15] were within 100 miles of an existing natural gas pipeline. Since U.S. oil and natural gas prices in the 21st century have both been close to three times more expensive in inflation adjusted terms BP [17] then they were for conventional oil and gas during most of the 20th century, then a close inspection of exploration costs show them to be higher for shale resources than for conventional resources, which means there was incentive to find shale due to the high natural gas prices, due to the property right incentives to produce the shale gas and due to the access to existing natural gas pipelines to be able to get the shale-gas to market once it was found and developed. The U.S. had all three characteristics for shale-gas.

Therefore, the exploration process for shale resources became that natural gas pipelines came first, owing to the existence of many gas pipelines throughout the U.S. and Canada, due to previous conventional oil and gas exploration and development in the 20th century that created the vast network of natural gas pipelines. Then, after the natural gas pipelines existed, the natural gas prices shot up high creating the incentive for natural gas only, in the form of shale-gas, exploration. Therefore, much of the original shale-gas exploration was mostly done near the existing natural gas pipelines, or near large consuming regions where incoming pipelines already had been built. It was only after the shale-gas industry was developed that finally a shale-oil industry came along, completely opposite of the oil first natural gas second sequence of development that happened during much of the world's conventional oil and gas development scenario for the 20th century.

Consider shale resources. If 100 countries do not produce shale-oil in great amounts, but one country does produce a lot of shale-oil, what logic could you use to find out the reason for this? Well what is the nature of a shale resource to begin with? It is not gold, not iron and not molybdenum, but shale-oil, shale-gas or nothing of value, i.e., three things. What is the probability of those three things are occurring? Well, if you know a shale-resource in detail, then you know 100% what it has in it: Either shale-oil or shale-gas or nothing. It is when you do not know what there is, or where it occurs, that you want to consider what the subjective probability of its existence is: Whether it be shale-gas or shale-oil or nothing in any given small area. As explained, you can not get that data because you can not ask the explorer what his thinking is because if they release that information, it will help their competitors find the shale-resource before he does. Therefore you are left with asking what logical difference exists between countries that are producing shale-oil and those that are not. What would normally cause a higher or lower subject probability for a region to be so busy exploring and another region not exploring. Clearly information is the key. Getting more information about locations of shale-resources will increase the subjective probability of knowing if there is shale-oil, shale-gas or nothing and the new information will logically result in more shale-oil or even more shale-gas production. However, what would cause this information to increase? Clearly doing more exploration gives more knowledge about underground resources. However, what could be causing this extra exploration in the U.S. that is not happening in 100 other countries? Well, the U.S. is a large oil and gas region with private property rights not government controlled property rights. It also has had since about 2003 a tight natural gas market relatively speaking of about a 10 to 1 ratio of years of reserves to yearly production or less. If any natural gas is also found, it is not more than 50 or 100 miles from an existing pipeline so that the natural gas can be marketed. This gives explorers a greater incentive to go out and find shale-gas and also if you happen to find shale-oil, no problem that is valuable too, so the high price of natural gas, which is regionally priced due to the high cost per energy unit to transport the natural gas relative to oil, gives the U.S. an incentive to look for shale-gas.

Crucially, then, the shale-gas and shale-oil sequence of development is opposite to the conventional oil and gas sequence: First shale-gas has to be looked for and developed, and then if you find shale-oil, you would go ahead and develop it. However, the exploring companies were not explicitly looking for shale-oil at first, but rather were looking for shale-gas near existing natural gas pipelines instead. Thus, the best way to develop shale-oil is to have an opposite sequence of exploration effort: First look for shale-gas near existing natural gas pipelines and then if you are lucky, you might find shale-oil. That is look for gas first if you want to find oil, then you do not lose money when you find shale-gas as you were already looking for it. On the other hand, if you look exclusively for shale-oil you will more readily lose money because much of the shale source rock has shale-gas and not shale-oil.

If we carry the lesson learned in North America more broadly, then only countries that look for shale-gas primarily will more readily find shale-oil, because you do not lose the profitability of the shale-gas side. Countries that engage primarily in shale-oil exploration and development without the shale-gas industry beside it will encounter low probabilities of success and therefore low profitability. In which case, there will be much less if any exploration for shale-oil exclusively until the price of oil increases much higher than it has been over the last part of the teen's decade. In this article, then, we are going to look at the development of shale-oil in the U.S., then we will look at the role shale-gas played in the development of shale-oil in the U.S., then we are going to look at other countries around the world to see if they are naturally inclined toward developing shale-gas resources and if not, then it will be highly unlikely that they will soon be developing shale-oil resources.

2. Shale Resource Characteristics

Many oil producing regions are mature including Saudi Arabia's Ghwar oil field, Simons [18], and Russia's Western Siberia region, Gustafson [19], all of which could soon go into oil production decline. One ray of hope for new oil production, though, is shale-oil resources such as those in Bakken, Eagle Ford and others in the United States, which should theoretically also occur in these other countries.

Shale is a category of sedimentary rocks, known for its role as a source rock for most petroleum basins. Shale contains organic matter that has existed under high pressures and temperatures for millions of years and is buried sufficiently deep enough to transform into kerogen and then into petroleum oil and or gas. Shales are known for low permeability, or limited ability to allow fluid flow through them. They are not the only low permeability rocks that exist, so this category of rocks is referred to as tight rocks. Examples of other tight rocks are fine-grained sandstones, carbonates, mudstones and siltstones. Rock permeability refers to the ability of rocks to allow fluid to flow through them and tight rocks are characteristically of low permeability. Compared to conventional rock formations that range from 5 millidarcies to over 1000 millidarcies, tight oil formations are typically below 0.1 millidarcy and could go as low as a few hundred nanodarcies (100×10^{-9}; Slatt, 2006). As a result of their low permeabilities, tight rocks require enhanced techniques to improve rates of oil or gas production and ultimately increase the quantity of petroleum oil or gas contained in the accessed formations.

The wide scale application of new horizontal drilling techniques derives from the use of better technology to position wells within thin layers of formation thousands of feet under the ground with greater precision, and the ability to drill for longer distances, oftentimes over 2 miles, horizontally within the rock. Hydraulic fracturing breakthroughs have enabled oil exploration and production companies to open up tight rocks that have been previously ignored due to difficulties in drilling within the layers or the very low and uneconomic production rates that result when these rocks are drilled. Low permeability rocks are considered tight because they do not allow oil and gas to flow at rates that could quickly provide a revenue base and make the business venture worthwhile. The ability to open these rocks further (stimulate the rocks) through hydraulic fracturing has increased production rates by several folds leading to greater profitability.

Tight formations have always existed in the U.S. and other places in the world. These formations, often referred to as plays, are rocks like fine-grained sandstone, siltstone and shale. These rocks are considered tight because of their characteristic low permeability, which enable them to serve as barriers to oil and gas flow and constituting development targets for oil and gas explorers. Shale makes up a significant share of tight rocks and is considered a source of rock for all petroleum systems. In the presence of adjacent conventional or more permeable formations, hydrocarbon oil and gas migrate naturally until meeting some barrier, where it aggregates within this trap system and becomes a petroleum reservoir target for exploration. In tight formations, these resources do not migrate at all or far enough and are still very much associated with the shale rock in which they formed or in other tight rocks closely associated with shale. Tight formations exist in several other nations across the world. The U.S. has 48 billion barrels of technically recoverable shale-oil resources and alongside China, Argentina, Algeria, Canada and Mexico make up over 65% of globally available technically recoverable shale-gas resources (U.S. Energy Information Administration/ARI [20,21]). In 2015 the U.S. produced 4.9 million barrels of tight oil daily, and in the same year exceeded 13 trillion cubic feet of tight gas production [6]).

Tight oil development is different from previous oil development waves in that previously, oil development occurred in conventional rocks. Among other characteristics of these 'conventional' rocks these are more permeable and do not require extensive stimulation to enable them to produce economically. As a result of this, the number of associated business activities stimulated by conventional resource development were less compared to tight oil development. Due to the resource intensive nature of tight oil development, other businesses involved in the logistics of sand and water supply are required to sustain the massive completion activities necessary for each tight oil well. Tight oil and gas development, because of hydraulic fracturing operations, require vast amounts of water during the completion stage of the well. A typical hydraulic fracturing operation requires between 2 to 6 million gallons of water and thousands of gallons of chemicals (Fracfocus, [22]). This water requirement leads to logistical challenges that include truck transportation of water among the other necessary activities that constitute drilling operations. This resource spread, energy involvement and operational footprint has drawn criticism from environmental activists and the public.

Tight oil and gas wells typically experience a faster decline especially in the first few years of production. Maugeri [23] observed decline rates as high as 50% in the first year of production compared to the rate of production during the first month. The second and third years also see another annual rate decline of approximately 30% [23]. As a result, maintaining a healthy production from any asset requires continually drilling new wells. This is different from conventional oil and gas development where, after the initial capital outlay in wells and facilities, relatively minor capital and operating expenditures are required to maintain production over a 20 to 30-year field life. Since typical well costs are historically higher for tight resource wells than conventional wells, while production is more sustained in conventional wells, the economics of tight oil and gas wells relies on a smaller margin, shorter cycle projects with more turn over to stay profitable.

For the last half a century, shale rocks have been the rocks to avoid by drilling engineers while pursuing conventional targets. This is as a result of the huge instability of the rocks and the potential of losing the entire drilled wellbore upon an unplanned encounter with shale rocks down hole during drilling operations. In placing a range on porosity and permeability, the science of petroleum engineering considers porosity levels in the single digits and permeabilities of ~0.01 millidarcies as poor (Slatt, [24]). These characteristics have become almost axiomatic in the development of oil for almost a century. However, following progressive changes in the technology of oil and gas development, this is the first period in the life of the oil and gas industry where these forgotten resources have been targeted systematically with astounding results.

As an example of how shale resources can help, consider the United States. Oil and gas production in the United States has increased significantly due to petroleum resource development in shale and other tight plays. U.S. oil production recorded an 88% increase from 2008 through to 2015, and from 2005 through to 2015, natural gas production increased by over 50% (IOGCC, [25]). Tight oil production has become a backbone of U.S. oil production and now contributes 52% of U.S. total crude oil production (EIA, [21]). From 2011 to 2012 the U.S. recorded an annual crude oil and lease condensate reserve increase of 4.5 billion barrels, the largest yearly increase in oil reserves in over 35 years (EIA, [26]). Petroleum reserves refer to those quantities of petroleum resources that can be produced with current technology and are economical to produce (PRMS, [27]). The level and mix of U.S. crude import has also been affected. In 2014 domestic oil production broke a 20-year record by exceeding imported crude [25]. While geologic understanding and engineering leaps have contributed to the tight oil revolution, the economic and regulatory dimensions of the tight oil experience have been no less contributory to the success of the phenomenon.

In October 1970, the U.S. produced over 10 million barrels of oil per day. By the year 2000 the local production had dropped to five million barrels of oil per day with a majority of that coming from over 400,000 marginal wells struggling at production rates of less than 20 barrels of oil a day around the country (IOGCC, [28]; EIA, [15,29]). Following almost half a decade of successful shale-gas development, by 2012 a new chapter was being written in the renaissance of oil production in many shale and other U.S. tight oil plays. By 2015, U.S. oil production contributed by tight oil development reached 50% of U.S. output [29]. While tight oil development has seen some pilot projects and limited successes in places like Canada and China, only the U.S. has sustained a production momentum reaching up to 4.9 million barrels of oil per day from these tight rocks [29].

The rise of U.S. oil production has had global ramifications on global oil markets and trade around the world. The U.S. constitutes a significant share of global crude oil consumption. Over the last 20 years, the U.S. consumed over 20% of global crude oil supply (BP, [17]). For the last decade, U.S. oil production has grown to cover a larger fraction of U.S. consumption. Due to tight oil production, the U.S. ranks first in gas production since 2011 and crude oil liquids production from 2013 through 2015 (EIA, [30]). Crude oil and condensate production growth in the U.S. from 2010 through 2015 constituted over 75% of the net new barrels added into global oil production, [25]. Crude oil and refined petroleum products imported into the U.S. from 2000 to 2012 amounted to over 2.8 trillion dollars in American trade deficits (Lawrence, [31]). The rebound in U.S. oil production translates into a reduction of imported crude oil, and therefore a reduction in national trade deficits going to overseas oil producing nations and thus creating a major rebalancing of foreign trade.

The implications of successful tight oil and gas production have been vast for the U.S. this past decade. From 2005 to 2011, with shale development leading the oil and gas industry expansion, upstream oil and gas jobs grew by over 120,000 (Brown and Yucel, [32]). This excludes the support industries that have spun from activities powered by the upstream sector of the oil industry. The oil and gas industry contributes approximately 2.7% of non-farm employment in a state like Texas (TX State Government, [33]). In 2011, due to the shale boom, the U.S. oil and gas industry contributed 1.6% to the U.S. GDP [32]. Several nations around the world with similar resource capacities would benefit from a similar reinvigoration of their economies, especially nations with high energy-intensive economies. Since several nations possess these same resources, the natural question follows as to what key lessons the U.S. experience can provide for tight oil development in other countries.

Tight oil development in the last decade has been powered mainly by technological leaps in two areas: Horizontal well drilling and hydraulic fracturing (Maugeri, [23]; FT, [34]). Horizontal drilling refers to a practice of drilling wells that target petroleum resources vertically into the ground until a specified depth and then deviating and continuing to drill horizontally within the rock formation, mostly a 90 degrees angle from the vertical direction. Hydraulic fracturing, on the other hand, is a well completion technique whereby water or other fluids containing chemicals and solid proppants are injected at high pressures down a well and into rocks, to fracture and extend fractures encountered within the zone a well has drilled through. Hydraulic fracturing is crucial to the development of oil because of the nature of the rocks that have powered this new era of U.S. production. The goal of the hydraulic fracturing technique is to allow the sand particles to fit into fractures and 'prop' open, and keep the rock spaces open, to allow for the flow of petroleum liquids or gas from the rock formation into the well. That is why the solids mixed in hydraulic fracturing fluid are referred to as proppants. The rocks being fracture stimulated are referred to as tight rocks because of their low permeability, and a good example of this category of rocks is shale.

Tight oil and gas development has also led to a surge of capital in the U.S. oil and gas industry. The EIA [35] reported that 73 deals in shale-oil and gas plays, from 2008 through to 2012, injected over $130 billion into tight resource development. In 2014 alone, over 40,000 wells were drilled and $120 billion invested in oil and gas production in the U.S. (Dale, [36]). These investments mean organic and inorganic growth of companies, wealth for shareholders, benefits to support industry and revenue to state and local governments in major oil and gas regions of the country.

3. The Sequence of Shale Development in the U.S.

As explained, an often overlooked aspect of the U.S. shale-oil revolution was the fact that it was shale-gas that was developed first, and then shale-oil. While the developments in shale-oil and shale-gas sound relatively unrelated, the two developments one before the other has tremendous implications for how the search process occurs for shale resources in general and shale-oil in particular. First, you have to find the shale rock that has good prospects for producing oil, then you need to determine how good that source rock is and how easy it will be to extract oil resources, and finally you need to drill a number of shale-oil wells in order to prove and develop the shale-oil potential. Since there was a massive search for U.S. shale-gas before looking for U.S. shale-oil then the shale-gas exploration dynamics are important to consider, because by searching for shale-gas U.S. companies found shale-oil in significant quantities as well.

According to Reynolds [37] there are two important effects that determine the extraction of an underground non-renewable natural resource: The information effect and the depletion effect. Considering the information effect aspect of the search process, it is very likely that the U.S. experience shows that an intense search for shale-gas may have lead to a significant information effect for the discovery of shale-oil resources. Indeed, upon close inspection, the United States was the only place in the world where several things were happening at the same time in regards to natural gas:

(1) In 2005, there was a shortage of conventional natural gas in the U.S. such that the regional natural gas prices increased to roughly twice the price of oil on a BTU basis. This was also because there was a lack of imported natural gas into North America, as the U.S. and Canada had always been self-sufficient in natural gas, and so they were in effect a closed natural gas market.

(2) There was a lot of oil and gas research in the U.S., including privately funded research, to find new ways to extract oil and gas in general and shale-oil and shale-gas in particular. This lead to greater innovation such as how George Mitchell and his company Mitchell Energy and Development Company came up with shale-gas fracking methods in order to extract the shale-gas. It is interesting to note, that George Mitchell had an obligation to fill his natural gas contracts, which might mean he discovered shale gas not because of high natural gas prices, but because of other business considerations. However, proven reserves of natural gas resources existed and were already discovered and could have been used such as those natural gas resources on the north slope of Alaska. Therefore why did not George Mitchell go get his obligations for natural gas filled by obtaining natural gas from Alaska? Well, the cost of transporting those reserves thousands of miles through pipelines would have been expensive. You can argue that Alaskan natural gas did not exist in the Lower 48, but if prices would have been higher, a simple contract could have been executed to get Alaskan natural gas to market within a few years. Therefore it is a price issue not a complex business issue that caused George Mitchell to find shale-gas. Granted, a long Alaskan pipeline would have made the gas expensive in the Lower 48, which is why George Mitchell did not "fill" his obligation with Alaskan natural gas or build a natural gas pipeline to Alaska. No, he needed gas near his existing pipeline to keep the costs reasonable. Likewise, he did not build an LNG import facility quickly, which was also an option. He needed something close to existing pipelines to reduce costs. If price was no object, Canada and the U.S. already had an agreement in place that could have started building a pipeline from Alaska all the way to the lower 48 states, although granted at high costs. Clearly price was an object.

(3) There were plenty of feeder pipelines, distribution pipelines and interstate pipelines available for natural gas all across the continental U.S. This means that throughout much of the U.S. Lower 48 states if you found shale-gas, you were never more than 50 to 100 miles away from a pipeline that you could use to get your natural gas product to market, even if some upgrading of the pipe were necessary.
(4) The U.S. natural gas pipeline system was deregulated, which meant it was relatively quick and cost effective to permit and build new pipelines and connect pipelines to the shale-gas regions or the shale-oil regions that also had shale-gas comingled in the shale-oil.
(5) Much of the U.S. shale-gas resources were privately owned mineral rights, which meant less government hesitation and more incentives to develop those resources faster.
(6) There were hundreds of private, independent oil and gas companies including drilling companies, rig manufacturers, trucking companies, etc., which were in competition with each other to find, extract and bring to market the shale-gas.
(7) Based on Reynolds [38] information and depletion effects, the exploration probabilities for the discovery of shale resources took time to gain momentum, but the intense exploration efforts soon enough overcame the lack of information about where the best shale resources were. The usual idea for explaining how coal, petroleum and metals extraction development occurs is to emphasize technology as in Barnett and Morse [39], Maugari [40] and Lynch [41]. However, clearly there is a search process as Reynolds [42], Bardi [43–45], Hubbert [46,47] and Jakobsson et al. [48] show and it is this search process theory that very few in the economics profession understand. However, what happened in the U.S. was a search process that commenced for natural gas in the form of shale-gas exploration that simultaneously revealed information about where shale-oil could be located, and this accelerated the exploration search process for shale-oil.
(8) There was a well developed private financial services sector in the U.S. including property right law institutions, contract law institutions, private investors and stock and bond markets that could innovatively finance ventures.
(9) There were also important financial products available in the U.S. such as hedging, futures and insurance contracts that would mitigate the risks inherent in any given project. These risk mitigation contracts allowed much greater risk taking in the industry so that more wells could be drilled faster and in more places.
(10) Since there were a number of large, economically vibrant cities across the continental U.S. then that induced a more geographically robust search for shale-gas as the value of the shale-gas increased the closer the wellhead was to the large cities owing to the variation in city-gate natural gas prices compared to many wellhead prices due to transportation costs.

All of these factors in the U.S. shale-gas market meant that there was a heightened race to find the cheapest and best shale-gas resources. However, shale-gas and shale-oil resources are often close to each other in geographic terms and depth terms. Therefore by looking for shale-gas you naturally will be able to find at least some shale-oil. While shale-oil is more valuable than shale-gas per BTU now, nevertheless the price of oil relative to the costs of the exploration process, including the expected probability of finding shale-oil, plus costs of fracking and extracting relatively smaller quantities of shale-oil in comparison to conventional oil, make shale-oil costs close to or below the breakeven point of a profitable exploration endeavor. Whereas the price of shale-gas relative to its costs can often be better than for oil, not because of the relative prices per BTU, which favors oil, but because of the probability of finding what you are looking for is higher, where the tight rock resources often have within them more natural gas than oil creating a better probability of success. As explained, if the probability of finding something valuable, like shale-oil and shale-gas together is 50%, then it takes two wells to find it. If the probability of finding something valuable, such as shale-oil alone, is 20% then it takes five wells to find it. That is the costs of more exploratory wells increases the costs of the shale-oil versus the shale-gas.

However, even when a region has mostly shale-oil and little shale-gas, the shale-gas piece of the puzzle still exists. For example the Bakken oil play got started due to the efforts of Mike Johnson and the Company EOG Resources looking for oil near the town of Parshall, in Mountrail County, North Dakota in the year 2006, just after the price of natural gas had reached twice the price of oil. Crucially, Parshall, North Dakota is less than 100 miles from the Alliance natural gas pipeline in Towner North Dakota, thus Johnson knew if he found natural gas in the Parshall field, he would still make money. Therefore, as North Dakota shale-oil continued to expand, there was always the knowledge that if major natural gas plays were found, it would still be possible to make money on the natural gas, and that knowledge enhanced the exploration process. However, since the shale-gas in North Dakota was not extensive enough yet to build a natural gas pipeline, the shale-gas portion of reserves have been flared.

Nevertheless, with high natural gas prices and lots of natural gas pipeline infrastructure onshore, especially in Texas, this allowed the U.S. search for shale-gas to commence. As the shale-gas was found, there was more often than not easy access to nearby pipelines. This meant there was no chicken and egg problem: What comes first, a high natural gas price, a natural gas reservoir or a pipeline to connect the natural gas resource? In the U.S., the first two had already happened. The U.S. in 2005 had very high natural gas prices. Then, if you found a natural gas field, there was always a nearby pipeline that you could hook into to sell your natural gas too. That is not the case in most oil and gas regions around the world where there is still plenty of conventional natural gas reserves for most producing regions with no need to find more natural gas. Often in these countries, natural gas consumption comes from a single long pipeline that is from a faraway producing region and so the country as a whole has very few pipelines going across it from many different regions to more central regions the way it was in the U.S. so there are often few pipelines to hook into, should local shale-gas be found. In those situations you have a chicken and egg problem if you want to develop shale-gas: Do you look for shale-gas first to assure that you have a market to sell to before you build a natural gas pipeline, or do you build a natural gas pipeline first before you start looking for shale-gas. Either prospect is expensive and would inhibit any search for shale-gas and since that problem inhibits the search for shale-gas, it also inhibits the search for shale-oil. Other potential shale-gas producing countries will have other problems such as concerns for earthquakes (The Netherlands) or top soil degradation (France), and therefore the lack of shale-gas development in general will inhibit shale-oil development.

4. Regional Issues Associated with Developing Shale-Gas

While we might expect that any given country with shale resources should want to develop shale-gas, the reality is that the incentive is often not there. Upon close inspection of each potential shale-gas and shale-oil producing country, (EIA [49]) there is often no incentive to look for shale-gas either due to having a high amount of natural gas reserves or due to nearby natural gas reserves. This suggests that the supply of shale-gas will not soon be developed and therefore there will be low exploration levels for shale-oil from these potential shale countries, unless oil prices increase substantially.

In Table 1 is shown all of the largest natural gas producing countries of the world with other statistics such as reserves to production ratios (high natural gas reserves where if those reserve exceed 40 years, then there is no reason to look for shale-gas), offshore or onshore production (where offshore production makes shale resource production too expensive per BTU or GJ) and nearby countries that have supplies of natural gas (if a nearby country has natural gas, there is no need to develop your own shale-gas). This explains which countries would have an incentive to explore for and develop shale-gas and which would not. Those countries with no incentives to develop shale-gas, such as having too much natural gas reserves, too little natural gas consumption or a lack of natural gas feeder pipelines have shaded boxes for each of the various reasons why they will not tend to develop shale-gas.

Table 1. Country natural gas production, reserves, reserve locations and nearby natural gas producers. (* means that this statistic indicates that there is no incentive in that country to find shale-gas)

	Country	2017 Production (TCM)	Reserves to Production Ratio (Years)	2017 Consumption (TCM)	Onshore or Offshore	Nearby Country with Natural Gas Reserves
1	USA	734.5	11.9	739.5	both	
2	Russia	635.6	*55.0	424.8	both	
3	Iran	223.9	*148.4	214.4	both	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
4	Canada	176.3	10.7	115.7	onshore	
5	Qatar	175.7	*141.8	*47.4	*offshore	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
6	China	149.2	36.7	*240.4	both	*Russia, Kazakhstan, Turkmenistan
7	Norway	123.2	13.9	*4.5	*offshore	
8	Australia	113.5	32.0	*41.9	both	
9	Saudi Arabia	111.4	*72.1	111.4	both	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
10	Algeria	91.2	*47.5	*38.9	onshore	
11	Malaysia	78.4	34.9	*42.8	both	
12	Indonesia	68.0	*42.9	*39.2	both	
13	Turkmenistan	62.0	*314.1	*28.4	both	
14	UAE	60.4	*98.2	72.2	both	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
15	Uzbekistan	53.4	22.7	41.6	onshore	*Turkmenistan
16	Egypt	49.0	*36.3	*56.0	*offshore	*Libya, Saudi Arabia
17	Nigeria	47.2	*110.2	*22.4	both	
18	United Kingdom	41.9	4.4	*78.8	*offshore	*Norway, Netherlands, Russia
19	Mexico	40.7	4.8	*87.6	both	*USA
20	Thailand	38.7	5.2	*50.1	*offshore	
21	Venezuela	37.4	*170.2	37.6	onshore	
22	Argentina	37.1	8.8	*48.5	both	
23	Netherlands	36.6	17.9	36.1	*offshore	
24	Pakistan	34.7	11.0	*40.7	onshore	*Turkmenistan, Iran
25	Trinidad & Tobago	33.8	7.7	*18.5	*offshore	
26	Oman	32.3	20.6	23.3	*offshore	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
27	India	28.5	*43.6	*54.2	both	*Turkmenistan, Iran
28	Brazil	27.5	13.8	*38.3	both	
29	Kazakhstan	27.1	*42.2	*16.3	onshore	*Turkmenistan
30	Azerbaijan	17.7	*74.4	*10.6	both	
31	Kuwait	17.4	*97.6	*22.2	both	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
32	Bahrain	15.1	10.3		both	*Qatar, Saudi Arabia, Iraq, Iran, Kuwait
33	Iraq	10.4	*148.4	12.0	onshore	

Russia:

Russia has extensive and unused natural gas reserves that can easily expand should there be more pipelines. Russia does not need to look for natural gas as it has it in spades, so there will not be the extensive search for shale-gas that occurred in the U.S., and Russia's major internal gas demand localities all have access to either natural gas or coal or both so there is no need to search for shale-gas near the major metropolitan areas, nor look for shale-gas near the existing conventional natural gas regions.

Iran:

They have so much natural gas they cannot get rid of it all, so, they will not soon be searching for shale-gas.

Canada:

Canada is a large producer of natural gas. It is onshore and its reserves-to-production ratio is a normal 14 years, so, all indications suggest that at least in Canada there could be lots of shale-gas production. However, a large portion of Canada's natural gas is produced in Western Canada and is exported to the United States or sent by long distance pipelines to Eastern Canada. What that means is Canada has to have enough large and long distance pipelines to be able to sell its natural gas. It becomes a chicken and egg problem. There is no use looking for natural gas unless you have pipeline capacity to sell it all, but there is no use building the pipeline capacity unless there is a lot of natural gas to sell, so building a new capacity of pipelines will not happen unless substantial new supplies are discovered and proven to exist. However, new large reserves will not be explored for, unless there is substantial pipeline capacity, so, while western Canadian feeder supply pipelines may be extensive, if there are any bottlenecks in the long distance pipelines, then that will reduce prices in the AECO (Alberta Energy Company) hub so that natural gas prices there are lower than U.S. hub prices. Such low prices can reduce the incentives for shale-gas exploration and inhibit the search for shale-gas, and the possibility of finding shale-oil.

Qatar:

Qatar has ample supplies of natural gas, which is mostly offshore. There is no need for it to develop shale-gas until it can export more LNG.

China:

China actually can use its coal and nuclear power for much of its energy needs. Currently, though, China imports natural gas, which suggests it can get much of what it needs by importation rather than internal development. While China can also use more natural gas, it does not have a lot of natural gas feeder lines. What it is developing is far-away, large natural gas projects piped from Russia and Central Asia, such that if shale-gas is found, it has little chance of finding a pipeline to hook into. Nevertheless, China's state run gas company may engage in a search for shale-gas no matter the cost as a way to find a cheap alternatives to using coal, although clean coal technologies could work just as easily as natural gas for much of China's pollution problems. Note: Alternative energy such as nuclear power or solar energy is about electricity, whereas here, we are only looking at a liquid fuel that is storable. The substitution of electrified systems with liquid and natural gas systems is interesting. Such substitutions though may require not just changes in infrastructure, technologies, and entire life styles, but changes in entire economic systems. China has many advantages along these lines as it can organize its economy quickly and already has a lot of infrastructure that can use electricity types of transport systems.

Norway:

Norway has both hydro power and extensive natural gas supplies. It can use the natural gas or sell it through long pipelines or use the hydro-power or sell it via long power lines. Plus, Norway has a lot of oil and gas experience, a lot of property right law, markets, institutions, etc. that should allow it to develop shale-gas. However, there is not much need to find more natural gas. Plus, the major oil and gas reserves of Norway are offshore reserves, which is not as amenable to looking for shale-gas. The costs of undersea shale-gas would be quite high compared to other natural gas sources, such as their own or Russia's conventional natural gas supply.

Norway may have some onshore shale-gas reserves, but their pipelines are direct from offshore production regions to onshore consuming regions without a lot of onshore feeder lines. Thus, if you find shale-gas, you cannot easily hook it into a pipeline. This is a similar situation as for the Netherlands and the United Kingdom. Thus, it is unlikely that Western Europe will soon develop shale-gas, and use that as a catapult to finding and developing shale-oil if it exists. There is just not the same extensive natural gas infrastructure as in the U.S. that can help induce a shale-gas industry and that would lead to a shale-oil industry.

Australia:

Australia has extensive natural gas reserves that are being developed for export. It also has an onshore natural gas pipeline network for consumption. All of this would entail the possibility of extensive shale-gas exploration and development. However since Australia can export much of its natural gas in the form of LNG, then more effort will go into exports than domestic consumption. Already there exist enough reserves for export for the next few decades so it is unlikely that shale-gas will be needed. Coal bed methane will continue to be developed too.

Saudi Arabia:

Since much of Saudi Arabia's existing oil and gas fields have untapped natural gas production potential, there is no need to search for shale-gas.

Libya and Algeria:

They have plenty of gas and can simply develop existing resources, so they will not be looking for shale-gas any time soon.

Malaysia, Indonesia, Thailand:

While Malaysia could use some more natural gas, Indonesia has plenty, so in general it would be easier for Malaysia to get its supply of natural gas from Indonesia than to develop its own shale-gas.

Central Asia:

Given the high reserves of natural gas in Turkmenistan, Azerbaijan and Kazakhstan, then Uzbekistan and Tajikistan as well as the rest of Central Asia do not need to look for natural gas as it would be cheaper to just add to the pipeline system connecting the region.

Kazakhstan already has enough natural gas for its own needs and uses coal extensively, so there is not any need to find more natural gas. Plus while there are a few long natural gas pipelines in Kazakhstan, the pipeline infrastructure throughout the country is not extensive. Plus, Kazakhstan can buy natural gas from Turkmenistan if it needs or it can expand the use of coal. Kazakhstani cities, as many former Soviet cities throughout Central Asia, have also centralized heating, which can use coal.

U.A.E.:

Some of the U.A.E.'s reserves of oil and gas are onshore and since there is the potential for U.A.E. to expand its natural gas exports in the form of LNG, then that could incentivize finding more natural gas. However, U.A.E.'s reserves are already substantial and so there is no need to develop shale-gas.

Egypt:

Most of Egypt's discovered natural gas fields are offshore. Offshore shale-gas would be too costly to develop.

U.K.:

The U.K. still has plenty of natural gas, and most of it is offshore, so there is less incentive to search for shale-gas. Onshore, there is not an extensive natural gas supply feeder chain of pipelines that would be amenable to new shale-gas resources being marketed. While any new natural gas resources that they develop can be exported to Germany, nevertheless, Germany wants more gas from Russia since it would be cheaper than shale-gas from the U.K.

Nigeria:

Nigeria could have good onshore natural gas prospects for shale-gas, however, Nigeria's current reserves to production ratio is over 100 years. As such there is no need to look for more natural gas. There is rather a need only to export more of the natural gas that already is proven reserves, but that depends on putting in place large pipelines and large LNG facilities and depend on world LNG prices. As such, Nigeria will not need to look for shale-gas and that will inhibit its search for shale-oil.

Mexico:

For example, while Mexico has recently opened up to outside oil and gas companies, the process to be able to explore and develop oil and gas is long and involved. It is not yet clear how this process will work in practice. In the near term, Mexico is still under a single oil and gas firm, PEMEX, which reduces the competitive incentives to explore for shale-gas.

Moreover, Mexico is a net importer of natural gas and it does not have a large natural gas pipeline infrastructure either at producing regions or consuming regions. This will make searching for shale-gas a challenge.

Venezuela:

While Venezuelan shale-oil and gas potential can eventually expand and add more natural gas production, the more likely expansion efforts will go into tar sands development once the price of oil increases.

Brazil:

Much of Brazil's natural gas is offshore, which could not be conducive to shale-gas exploration and development. Between Argentina and Brazil, there are also plenty of natural gas reserves and again that makes the need for shale-gas very limited.

Argentina:

Argentina does have a lot of natural gas production and this may have helped it in its development of the Vaca Muerta shale-oil field, so, while Argentina did have large reserves of natural gas, its extensive natural gas pipelines may have helped it in its search for shale resources and the development of shale-oil.

The Netherlands:

The Netherlands has some of its natural gas resources onshore and a substantial amount of pipeline infrastructure. Not only that, but the Netherlands is a hub for natural gas sales, which suggests it is a good region for trying to explore for and develop shale-gas and subsequently if found, shale-oil. However, the Netherlands has reduced the amount of natural gas production from its onshore Groningen field because of concerns that production from that field has induced seismic activity in the region. The earthquakes around the Groningen field were 3.4 on the Richter scale and could cause damage to many buildings. Shale-gas is also thought to induce seismic activity including earthquakes, which have happened in the U.S. shale-gas regions. This suggests that the Netherlands will not allow much if any shale-gas exploration and development until it can be proven that seismic activity can be reduced or circumvented for regions around the shale-gas fields. There is also natural gas offshore, but there is less incentive to search for shale-gas there as offshore shale gas would be too costly. While the Netherlands can export shale-gas to Germany, Germany can still get more gas from Russia and for a lower price.

Pakistan and India:

Pakistan and India can still use coal resources for energy and they do, so there is no need to search for more natural gas as a cheaper source of natural gas would be pipelines from Iran or Turkmenistan or even LNG from Qatar.

Trinidad and Tobago:

They already export LNG and have plenty of resources. Much of their reserves are offshore, which is too costly for shale-gas exploring and development.

Kuwait, Bahrain and Oman and Iraq:

While there could be substantial shale-gas resources in these countries, it is cheaper to use Iranian or Qatari natural gas or their own natural gas resources than to develop unconventional gas, so any new shale-gas development would be at a competitive disadvantage.

Poland:

Poland would like to use more natural gas, although it has plenty of coal, coal infrastructure and urban district heating based on coal, so there is not as much need for natural gas. It does have some natural gas pipelines but extensive feeder pipelines from many different supply locations does not exist. There are only a few pass-through natural gas lines that would be able to carry much natural gas. Poland did try to find shale-gas but experiments proved unsuccessful due to having clay within the shale source rock. Plus it has much district heating, which can use coal.

France:

France has the potential for shale-gas, but due to its important wine and agricultural industries, it will not develop it. Plus, France has put more emphasis on developing its nuclear industry rather than its natural gas industry.

5. Conclusions

To suggest that the world will soon be awash in vast resources of shale-oil because the U.S. has been able to develop and produce much shale-oil, obfuscates the way in which the U.S. shale-oil industry actually developed, which was through extensive shale-gas exploration and development as a precursor to shale-oil development. The way to logically analyze how the search process goes is to say what are the subjective probabilities of the explorers? Such probabilities are not published anywhere, since they are kept secret, so that you cannot easily do a statistical analysis, but by using logic, we can explain the one thing we do observe, which is that it is mostly, and indeed almost only, the United States that is producing shale-oil.

During the search process, there are three mutually exclusive outcomes: (1) Finding nothing, (2) finding mostly shale-oil or (3) finding mostly shale-gas. Suppose a thorough search of an area requires a $100 million? What are the respective values of the outcomes? Using the example from above and adding numbers shows gas to be less valuable than oil, and in most countries it is not valuable at all because (A) they have natural gas resources already, and/or (B) they do not have a lot of natural gas pipelines at or near the location where the search would happen, therefore it makes the value of exclusively searching for oil low. Thus, in a county like that where natural gas is not valuable and assuming a 33% chance of finding nothing, a 33% chance of finding gas (which is tantamount to finding nothing) and a 33% chance of finding oil, and where the shale-oil discoveries will be drained quickly so that the shale-oil is only worth $300 million if you find it, will you explore? Well in such a situation, it would take an average of three exploration efforts costing a total of $300 million to find $300 million worth of product. That is only a break-even proposition so you would need a higher price of oil before you would search.

What if you were looking for gas? If you find gas it is only worth $200 million but you can still extract and sell oil if you should find it. Therefore the minimum value is $200 million but you now have a 76% chance of finding something valuable. Basically three exploration efforts totaling $300 million will find you $500 million worth of gas or oil, so its profitable to undertake such exploration if gas is valuable, but for gas to be valuable you must have low reserves of natural gas in the region or else plenty of natural gas pipelines available where you can transport the product to consumers, i.e., in general you would have ten years or less of your proven reserves to production ratio, like the U.S. has, and you also need nearby pipelines that your gas can be taken away by, like the U.S. has. If you do not have nearby pipelines, then if you find gas, it can take 5 or 10 years to get a new pipeline put in place to your area and so the present value, in business terms where you need a 10% or 15% return on investment, means finding natural gas is a present value loss. If other regions cannot develop an extensive shale-gas industry first then they probably will not develop an extensive shale-oil industry any time soon, unless the price of oil reaches very profitable heights probably much higher than a mere $100 per barrel in 2018 dollars. This further suggests that the world's second Hubbert cycle peak in oil production, the first being in about 2005, is about to commence once the U.S. shale-oil industry reaches its height.

As Smil [1,4,50–52] and Vettese [53] suggest, having less oil means having less economic vibrancy because alternatives to oil are much less valuable in physical/engineering terms and therefore less potent in an economic sense. Here, we saw that the way shale-oil is developed has a lot to do with how shale-gas is developed, where the key element of shale-oil development in the U.S. was having a shale-oil/shale-gas interaction. Since the U.S. depended on its need for shale-gas to get shale-oil exploration going, then other countries around the world will have a more difficult time developing their shale-oil resources. We could have worldwide peak oil with limited shale-oil exploration and production outside of the U.S. soon.

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