# Unconventional Gas in the U.S.

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While production of the easy-to-recover petroleum and natural gas declines worldwide, several adjustments will be made: (1) The rich countries will continue to limit their total energy consumption; (2) the United States in particular will have to cut its primary energy consumption by a factor of two to the level of the most affluent West European countries; (3) the poor countries will be helped to produce and deploy passive solar devices for cooking and heating, and will gain access to the clean burning, locally produced biofuels for local transportation and other local uses; (4) all other countries will have to limit their reliance on coal for most of modernization; (5) several alternative energy systems that rely on the sun will be developed and deployed; and (6) electricity generation by nuclear fission will grow as old coal-fired power stations are decommissioned. The world will have three other environmentally unfriendly alternatives: (1) Produce massive amounts of biofuels; (2) recover, process and burn more ultra heavy oil or tar; and (3) burn more coal. For the next several decades the world will have only one environmentally acceptable option to fuel a majority of the required changes: clean natural gas. Natural gas will come from conventional deposits and, increasingly, from unconventional tight sands, shales, and coal seams. The United States of America is endowed with the huge unconventional gas – and oil – resources. In 2009, the technically recoverable unconventional gas is energy-equivalent to producible oil in 5 – 10 Prudhoe Bays or 1 – 2 Ghawars. The Prudhoe Bay in Alaska is the largest oil field in North America. The Ghawar giant in Saudi Arabia is the largest oil field on the Earth. Major unconventional gas resources in Texas and the U.S. are discussed. Comments are made on the major technical, environmental and political difficulties of producing these resources.

**Keywords:** Fossil fuels, greenhouse gas emissions, natural gas, unconventional

## 1 Problem Statement

The only perhaps meaningful alternatives to fossil fuels and nuclear energy are wind turbines, solar thermal systems, and solar photovoltaic cells – all equipped with efficient batteries and/or closed-cycle chemical energy storage systems, see, e.g., (Patzek, 2007b; Patzek, 2008a).

Based on the fundamental physics of the planet Earth, it can be shown that the sustained industrial-scale production of biofuels of whatever generation from whichever source is impossible, see **Figure 1** for an example. Production of biofuels on a global-scale is causing untold damage to the largest ecosystems on the Earth, and the recent tropical forest fires alone have emitted as much greenhouse gases as all other human activities. Massive production of biofuels

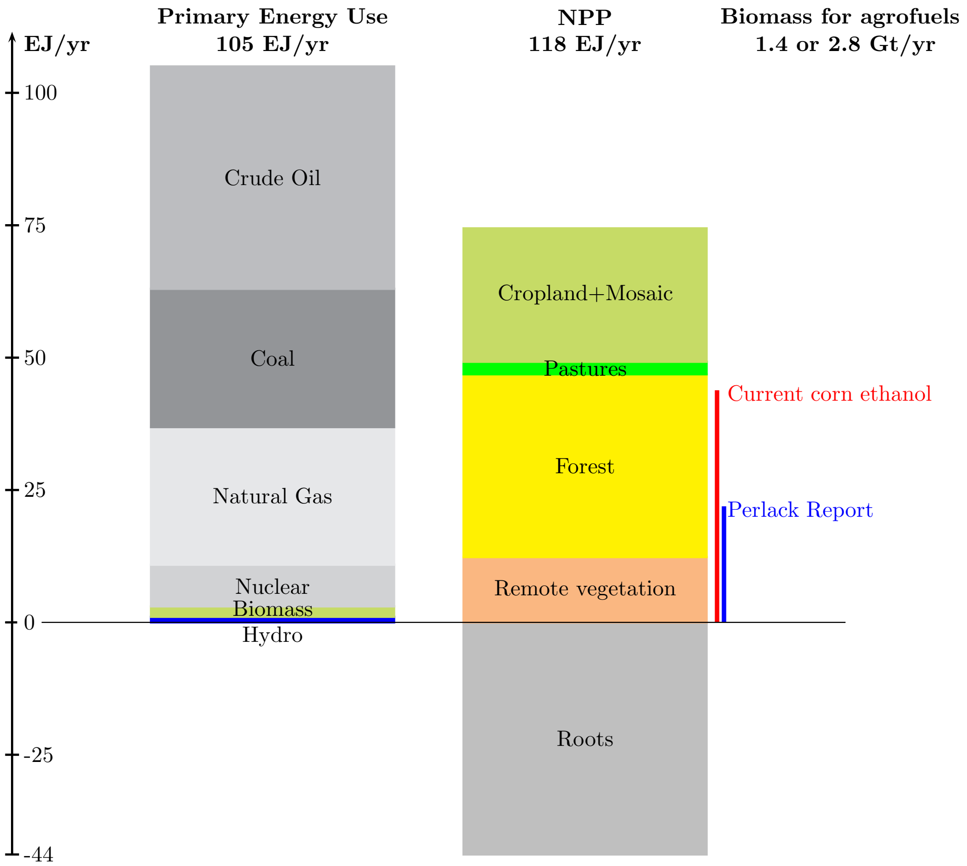

Figure 1: The U.S. uses more primary energy each year than the quantity of heat that might be obtained by burning all annual growth of all living above-ground plants on its territory. The 2003 primary energy consumption in the U.S. is shown on the left and the corresponding net primary productivity (NPP) on the right. For comparison, the annual growth of all biomass in the 48 contiguous states plus the District of Columbia, estimated from the MODIS satellite images of plant infrared emissions spectra, has been translated from gigatonnes per year to the higher heating value of this biomass growth in exajoules per year. Only roughly 75 EJ/y is produced annually as above-ground biomass. The remainder, 44 EJ/y, goes to growth of plant root systems. The mosaic landscape consists of grasses and bushes dotted with trees. The USDA/DOE proposal (Perlack et al., 2005) to produce 130 billion gallons of ethanol per year from 1.4 billion tonnes of biomass would consume 32% of above-ground NPP in the U.S. at a 52% conversion efficiency (the blue bar), or 64% at the current efficiency of the corn-ethanol cycle (the red bar). Of course an implementation of this proposal would be madness. Source: Patzek (2007b; 2008a)

is particularly harmful today, as the world is nearing the peak of coal production (Patzek and Croft, 2010), and $CO_2$ sequestration by the tropical forests is more important than ever.

Sadly, the photovoltaic (PV) – and wind turbine – solution is far away from satisfying even a tiny fraction of our current energy needs and will remain so for the next $20-30$ years, see **Table 1**, regardless of the heroic efforts of so many outstanding researchers and companies. In fact, at the end of 2006 (the latest quality-controlled data), the total peak electrical power from the PV cells installed in the U.S. was 500 $\mathrm{MW}_e$ (Pedigo et al., 2007), or $\sim 500/5 = 100$ $\mathrm{MW}_e$ of continuous power[1], equal to that of *one* small conventional electricity generator powered most likely by coal. Usually there is an equivalent of $10-20$ such generators in a single electric power

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[1] The EIA accounting for electricity actually produced from photovoltaics in 2007 was 70 $\mathrm{MW}_e$ of continuous power, www.eia.doe.gov/cneaf/solar.renewables/page/wind/wind.html, Table 1.11.

plant. In summary, photovoltaics delivered roughly 0.006 EJ of primary energy in 2007, or 6 parts in 100,000 of primary energy needs in the U.S.

In 2007, electricity generation by wind turbines was much more substantial, amounting to 3,900 $MW_e$ of continuous power, equivalent to 4 baseload power stations. Wind turbines produced 0.35 EJ of primary energy or 3 parts in 1000 of primary energy needs in the U.S.

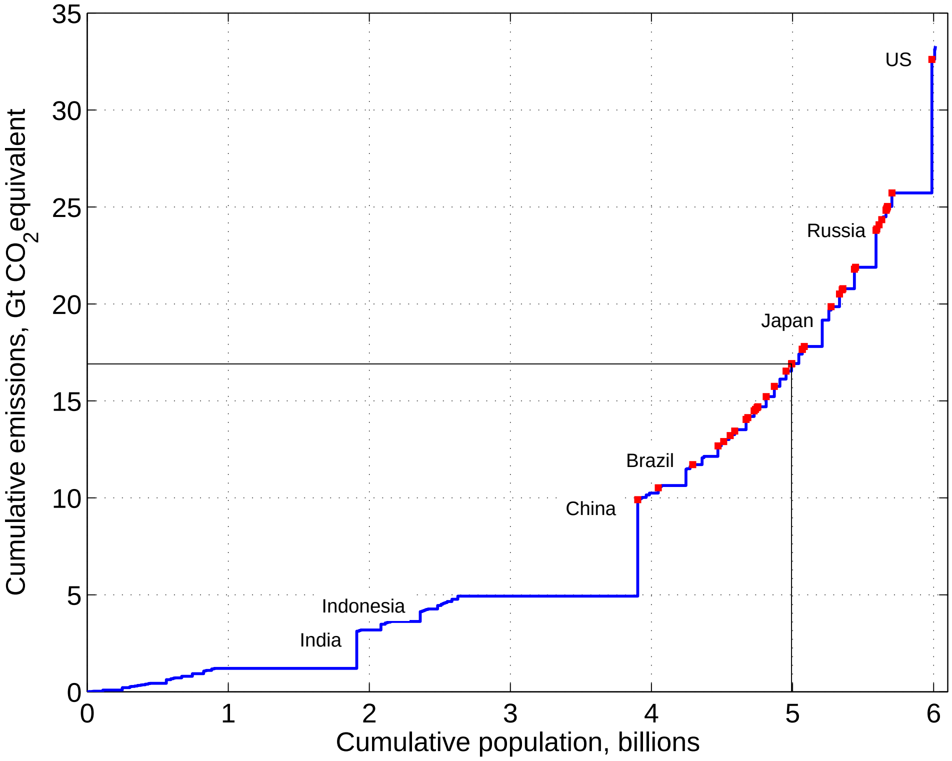

Figure 2: Cumulative emissions of greenhouse gases (GHG), expressed as gigatons of equivalent carbon dioxide, versus the cumulative human population responsible for these emissions. This plot is based on the data for carbon dioxide, methane, nitrous oxide, perfluorocarbon, hydrofluorocarbon and sulfur hexafluoride emissions in the year 2000, compiled by the World Resources Institute (WRI) from several sources, including the US Department of Energy's Carbon Dioxide Information Analysis Center (CDIAC) and the US Environmental Protection Agency. Bunker-fuel emissions are not included. The likely understated (Patzek, 2007b) estimates of emissions caused by land-use change, mostly deforestation of the tropics, are incorporated. The red dots are the GHG emissions from the "developed" or Annex 1 countries. Note that the cumulative emissions from the countries inhabited by 5 billion poorest people were equal on the average to those of the remaining 1 billion people. Seventeen percent of the world's population generated 50 percent of GHG emissions, and twenty percent of the world's population was responsible for 70 percent of the emissions. The carbon dioxide emissions from the deforestation of Indonesia, Brazil, and equatorial Africa are habitually underestimated.

Combustion of fossil fuels produces carbon dioxide and other greenhouse gases. The amount of carbon recycled every year by the biosphere and the oceans is some 20 times larger[2] than the recent anthropogenic carbon emissions in **Figure 2**. But this comparison is misleading. The ever-accelerating flow of anthropogenic carbon *into* the atmosphere began a mere 200 years ago, but a compensating flow of carbon *out* of the atmosphere has not materialized in the ensuing years. At equilibrium, these two additional carbon flows would cancel each other

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[2] Through fossil fuel burning and deforestation, humans emit about 10 Gt C/yr, and the carbon flow rates over land are about 120 Gt/yr, while those over ocean are about 90 Gt/yr. Source: (Anonymous, 2007).

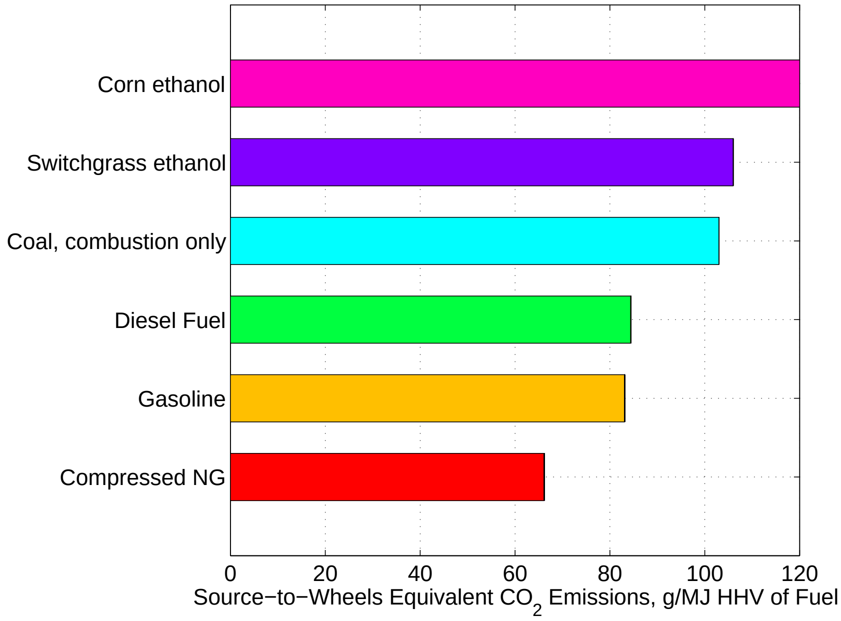

Figure 3: Fuel source-to-wheel equivalent $CO_2$ emissions from automotive transportation fuels. The units are grams of $CO_2$ equivalent per megajoule of the higher heating value (HHV) of fuel. Emissions from combustion of bituminous coal are shown only for comparison. Conversion of that coal to electricity to charge car batteries would triple the emissions. Compressed natural gas fuel is charged with additional 9.7 g/MJ of emissions for recovery, separation, transport, compression, and storage (López et al., 2009). The gasoline and diesel fuel emissions are from a well-to-wheel analysis based on the 2005 crude sources and refining (NETL). The corn ethanol cycle emissions are from Patzek (2004). The switchgrass ethanol cycle emissions are from Patzek (2010a).

Table 1: Role of renewables in the 2007 U.S. primary energy sources. Data source: US DOE EIA.

| Source | Energy Delivered, EJ |
|---|---|
| Wind Energy | 0.35[c] |
| Solar[a]/PV[b] Energy | 0.07[c] |
| Geothermal Energy | 0.34 |
| Hydroelectric Power | 2.58 |
| All Biomass | 3.81 |
| **Total Renewables** | 7.18 |

[a] Mostly solar thermal collectors.
[b] In 2007, all installed photovoltaic (PV) cells were providing $<1$ part in 10,000 of primary energy equivalents.
[c] Electricity is converted to primary energy by division through an average efficiency of 0.35.

exactly. Instead, anthropogenic carbon has been accumulating in the atmosphere helping to warm the Earth.

Compressed natural gas generates less greenhouse gas emissions than all other liquid transportation fuels: 22% less than gasoline and diesel fuel, 15% less than switchgrass ethanol, and 45% less than corn ethanol. See **Figure 3**. Patzek recently compared the differences in greenhouse gas emissions, water contamination, and solid waste generation from electric power generation in the U.S. that uses coal and natural gas as fuels (2010b). The differences in emissions are staggering in favor of natural gas. Some of the reasons for the low greenhouse gas emissions from a life cycle of natural gas are listed in **Tables 2** and **3**.

Table 2: Net Carbon Dioxide Emissions

| Activity | Natural Gas | Oil/gasoline |
|---|---|---|
| Production | No pumping | Pumping energy, steam generation, EOR[a] |
| Refining[b] | Low if no $CO_2$ | Hydrogen production |
| Transportation | Burned for Compression, LNG | Low |
| Consumption | About 55% of energy from C | 80% of energy from C |

[a] EOR = Enhanced Oil Recovery

[b] Note that $CO_2$ streams from refining oil or gas are nearly pure, suitable for EOR.

Table 3: Net Energy Inputs

| Activity | Natural Gas | Oil/gasoline |
|---|---|---|
| Production | No pumping | Pumping water and oil |
| Injection | None | Water, high if steam EOR |
| Well Fixed Energy | Big frac job, gathering lines | Pump, water handling equipment |
| Refining | Low if no $N_2$ or $CO_2$ | Uses about 1/10-1/6 of oil energy |
| Transportation | 1-2% by pipe, 25% by LNG | Low |
| Consumption | Compression if domestic gas | Some VOC loss |
| Car Fixed Energy | About same as gasoline | About same as gas |

**Remark 1** Natural gas is the least polluting fuel available; it is also present in gigantic quantities across much of the territory of the U.S.A. The strategic plan for the Department of Petroleum and Geosystems Engineering at the University of Texas in Austin is in part about helping to provide the State of Texas and United States with the cleanest fossil energy possible: natural gas and natural gas liquids, while causing the least amount of environmental damage. The two new competing technologies – wind turbines and photovoltaic cells – provide, respectively, 3 parts in 1,000 and roughly 1 part in 10,000 of the current primary energy needs in the U.S. Even if significance of these two technologies increased continuously by 25% per year for the next 10 years, they would grow by a factor of 10 each. If the remainder of energy uses in the U.S. did not change in the next 10 years, these two new technologies together would still be supplying less than 3% of primary energy equivalents. □

## 2 Natural Gas

Paraphrasing a prescient NYT article by Dan Neil, dated October 20, 1999: What if there was a fuel that was cheap, almost limitless and clean-burning? A fuel whose supply and price were strategically secure, free from the caprice of oil-producing nations? A fuel whose use relied on engineering fundamentally no more esoteric than that of a restaurant stove or a car engine?

This abundant fuel is natural gas, now produced in the U.S. mostly from unconventional deposits: tight gas sands, gas shales, and coal seams with areas that span entire counties or states. The United States imports almost 70% of crude oil and oil products Americans consume at the cost of $700 billion in 2008. The United Sates can replace most of its oil imports with domestically produced natural gas, but this is no small task. Unconventional natural gas and the associated liquids also happen to be the most important source of clean energy in the State of Texas.

Importance of natural gas in the global energy market is growing faster than that of any other fossil fuel and will continue to grow over the next two decades, as both oil and coal production rates peak (Patzek, 2007a; Patzek, 2008b; Patzek and Croft, 2010). In parallel, state ownership of natural resources is also rapidly growing. In the world of insufficient hydrocarbon production, oil exports will suffer first at the expense of increasing domestic energy demand in most of the producing countries; Indonesia and Mexico are good examples. Parenthetically, the same restrictions will appear soon with coal production. China produces almost 3 billion tons of coal per year. When China's coal production peaks, possibly in 2011, the global coal production may be insufficient to satisfy even today's needs (Patzek and Croft, 2010).

The looming decrease of oil exports will put more pressure on the domestic recovery of natural gas. Today, the United States produces $27 \times 10^{18}$ J = 27 EJ/year as natural gas and condensate, see **Figure 4**, and 12 EJ/year as crude oil, see **Figure 5**. In terms of energy, the current ratio of domestic gas to oil production, 2.25, is expected to grow to 3 – 4 over the next decade. In other words, soon, natural gas produced in the U.S. will be delivering at least 3 - 4 times more energy each year than domestic crude oil. Today, most of natural gas in the U.S. is produced from gigantic unconventional deposits.

The importance of unconventional resources will only increase in the future. Currently, it is estimated the technically recoverable unconventional gas in gas shales, tight gas sands, and coal deposits is energy-equivalent to 10 times the recoverable oil from Prudhoe Bay, the largest oil field in North America, see **Figure 6**. This amount of energy is contained in 1,600 years of production of ethanol at 6 billion gallons per year.

Today, natural gas and natural gas liquid production in Texas is almost 8 EJ/year, compared with 2 EJ/year as crude oil, see **Figure 7**. In fact, the energy produced as natural gas liquids alone is as large as the energy produced as crude oil. Texas is currently producing about 20% of domestic crude oil and 25% of natural gas[3], see **Figure 8**. **Tables 4** and **5** underscore importance of the giant unconventional gas fields of Texas.

## 2.1 Value of Science and Technology

As shown in **Figure 9**, the difference between the actual oil production in the United States and the cumulative oil produced from the fundamental Hubbert cycle (Patzek, 2008b; Patzek and Croft, 2010) is at least 200 EJ, or two years of primary energy consumption in the U.S.[4] This incremental oil has been – and will continue to be – produced mostly because of progress in well drilling and completion technologies (better and faster drilling methods, directional wells, horizontal wells, multilateral wells, smart multi-interval wells, etc.), fracturing technology, waterflood and polymer-enhanced waterflood, and enhanced oil recovery methods, mostly steam injection, $CO_2$ injection, and surfactant/polymer flooding. At 50 USD per barrel of oil, the value of incremental oil production in the U.S. will be 1.5 trillions of the 2008 USD.

In natural gas production, the impact of new technology to access unconventional gas resources has been even more dramatic, more than doubling the ultimate recovery, see **Figure 10**. The difference between the cumulative gas production in 2060 and the fundamental gas cycle is 1000 EJ, or 10 years of primary energy consumption in the U.S. In the United States, the impacts of accessing new gas resources and creating new gas well completions are at least 5 times larger than the impacts of new oil recovery technologies.[5] More importantly, most of new gas is produced by the relatively small independent companies, while – thus far – the major

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[3] Natural gas liquids are not accounted for because of somewhat different numbers from O&GJ and EIA.

[4] The ultimate difference will be at least 400 EJ.

[5] This statement accounts only for the produced primary energy and disregards the large premium we put on liquid hydrocarbons.

oil companies have shown little public interest.[6] Therefore, gas producers will need extensive research performed by academia. At 5 USD per 1000 scf of natural gas, the value of incremental gas production in the U.S. will be 4.5 trillions of the 2008 USD. Of course the real price of natural gas will continue to climb; in March 2009, the price of natural gas corresponded to 24 USD per barrel of oil. With time and demand this price will have to double.

**Remark 2** A cautious estimate of the value of research and technology development applied to oil and gas production is 1.5 and 4.5 trillions of the 2008 USD, respectively, almost 50% of the 2008 GDP of the United States. On an energy basis, production of natural gas and natural gas liquids in Texas is about 4 times more important than production of crude oil. This ratio will continue to increase with time. □

## 2.2 Problems with Producing Natural Gas in the U.S.

Natural gas production in the U.S. is a perfect example of two different populations of gas-producing reservoirs. Between 1990 and 2007 gas production was 28% higher, see Figure 4, than the peak oil production between 1970 and 1983, see Figure 5. The early natural gas was associated with petroleum production and peaked in 1972, see the left main Hubbert cycle in Figure 4. This gas was mostly flared and the accounting of its volume was inadequate at best. More recently, offshore gas/condensate reservoirs in the Gulf of Mexico and unconventional gas deposits have dominated gas production in America, and are probably peaking in 2008, see the right main Hubbert cycle in Figure 4 and the smaller cycles. The second peak and the smaller Hubbert cycles have the ever-increasing contributions from tight gas sands and gas shales in the interior of the United States, and coal-bed methane, see **Figure 11**. The second peak of gas production in the U.S. has been flattened by a heroic drilling program, with 80% of all active rigs in the U.S. drilling for gas, see **Figure 12**, and most gas rigs drilling the unconventional deposits at an exponentially increasing cost, see **Figure 13**. The exponentially growing well costs and feet drilled per year, see **Figure 14**, translate currently into an annual cost of 70 billion USD per year for drilling and completing gas wells in the U.S. It is obvious that major new research and technology development are needed to arrest the rate of decline of average gas well productivity in the U.S., and in Texas in particular, see **Figure 16**.

## 2.3 Water and Proppant Management

Drilling and hydrofracturing an unconventional gas well is resource-intensive. For example, a typical well in the Barnett shale requires 3.5 million gallons of distilled water (13,400 tons of water) to drill and complete. In addition, some 325,000 lbs (160 tons) of proppant are needed per hydrofracture stage. With 10-20 fracture stages per well, this requirement translates into 1,600 – 3,200 tons or more of proppant per well. In the Barnett shale, chloride content in produced water begins near zero, then it rises to 40-50,000 ppm; 20-30% of the volume pumped during fracturing is recovered in first 2 – 3 weeks following the fracturing, necessitating large water purification facilities. It seems, therefore, that water and proppant requirements, in addition to well-feet drilled, will limit expansion of production of unconventional gas in many arid regions of the United States.

## 2.4 Summary of Problems and Hopes

**Remark 3** The current drilling effort in the U.S. cannot be sustained without major new advances to increase the productivity of tight gas formations. Therefore, one of the top areas of research & development in the U.S. should be drilling, completions, and water management for unconventional natural gas. □

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[6] With a notable exception of Exxon Mobil, BP, and Statoil Hydro. However, to my knowledge, all major companies now have unconventional hydrocarbon recovery departments headed by managers at the VP or GM rank.

The actual future course of U.S. natural gas production will be the sum of the known Hubbert cycles, shown here, and the future Hubbert cycles (Patzek, 2008b; Patzek and Croft, 2010). The area under one future Hubbert cycle for natural gas is known today: Alaska. Published North Slope reserves of >35 Tcf (trillion standard cubic feet) $\approx 10^{12}$ $\mathsf{sm}^3$ are proven[7] in well-studied oil fields (Prudhoe Bay and Point Thompson), so the actual resource is larger. Unfortunately, as Figure 4 attests, the drawing down of gas caps at Prudhoe Bay and Point Thompson will have a relatively small impact on the overall availability of natural gas in the United States. According to the analysis here, the remaining producible gas in the United States was 600 Tcf in 2007 and 700 Tcf in 2002, compared with 1100 – 1400 Tcf of technically recoverable gas estimated elsewhere[8] in 2002. The other estimates include the yet-untapped volume of producible natural gas equal to 30 - 40 times the known gas volume at Prudhoe Bay and Point Thompson. Fifty percent of that hypothetical producible gas volume has not yet been included in the current analysis.

**Remark 4** Given the size of domestic natural gas resources, The United States can count on decades of uninterrupted production, provided that there exist a stable demand for (i) a substantial natural gas-powered peak electricity generation capacity and (ii) a compressed natural gas infrastructure for automobile transportation. Both will support a stable price of natural gas, and multi- -5 to 10 - year gas supply contracts. □

# 3 A Few Aspects of Problem Scope and Solution

## 3.1 Characteristics of Unconventional Plays

The large areas of low permeability hydrocarbon-charged sandstones and/or shales are called "plays." These are geologically complex structures with generally unconfined source rock overlain by stratigraphic and structural traps or their combinations (Shanley et al., 2004). For a lack of a better term, a compact volume of unconventional rock that produces gas (and/or oil) will be called a "reservoir." Here are some of the common characteristics of "unconventional reservoirs:"

- Unconventional reservoirs have low to very low permeability.
- Most unconventional reservoirs are self-sourced, i.e., natural gas and, possibly, oil are not yet expelled from the kerogen-rich source rock.
- Because hydrocarbons cannot be expelled, structural trapping may be unnecessary.
- Because structural trapping is not necessary, unconventional reservoirs tend to be regional in extent (but their best parts may be defined by traps).
- Because unconventional reservoirs are regional in extent, they contain enormous volumes of hydrocarbons in place and are exceedingly complex geologically.
- Only a small fraction of the hydrocarbons-in-place will ever be produced, and how to produce them in an optimal fashion is still an open research question.

**Remark 5** There exist enormous domestic sources of high-quality hydrocarbons (natural gas, gas liquids, and conventional petroleum), but these sources are very difficult to produce, and the current recovery factors are low (less than one to a few percent of the fluid hydrocarbons-in-place). Essentially new, non-reductionist and interdisciplinary science and engineering are

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[7] *In Need of Access: Alaska's Known and Potential Gas Resources*, DAVID HOUSEKNECHT, Research Geologist, U.S. Geological Survey, MARK MYERS, Director, Division of Oil and Gas, Dept. of Natural Resources, July 28, 2004, lba.legis.state.ak.us/sga/0407281000.htm.

[8] See www.naturalgas.org/business/analysis.asp.

needed to unlock the unconventional reservoirs to the highest degree possible and provide the U.S. with a measure of real energy security. Texas has some of the largest unconventional reservoirs in the U.S., see **Figure 17**, and the Barnett Shale there has been developed at an incredible rate, see **Figure 18**, which is coming to a halt in the year 2009, because of the overproduction of natural gas in the U.S. and its collapsing price, see **Figure 15**. □

### 3.2 Role of The University of Texas (UT) at Austin

The Cockrell School on Engineering at UT Austin has identified five strategic research priority areas for interdisciplinary research and education programs to address major societal-scale problems:

1. Sustainable Energy
2. Engineering Human Health and Health Care Delivery
3. Design and Manufacturing for High Value Products, Systems, and Structures
4. Sustainable and Secure Infrastructure Systems and Networks
5. Space and Earth Engineering

Geosciences, and the Department of Petroleum and Geosystems Engineering in particular, will play a key role in Areas 1 and 5, and participate in Areas 3 and 4. In this paper, however, the focus has been on unconventional resources.

## 4 Summary and Conclusions

As shown in this paper, the fundamental and applied research on the enhanced methods of accessing and recovering natural gas and natural gas liquids from unconventional deposits warrants utmost attention by the leading scientists and policy makers. Given its strategic importance to the energy security of the United States, research in these areas is imminent; the opportunity presented here is to make Texas – and UT Austin – the origin of this research innovation. Therefore the Department of Petroleum and Geosystems Engineering at UT Austin proposes to create the following:

1. The Texas Center for Drilling, Completions and Production, focused mostly on unconventional resources, and including sufficient collaborative space, funding for startup packages, and endowments to support research of new faculty.
2. A graduate program in unconventional resources, followed by the creation of an unconventional resources specialization in the undergraduate program. The new graduate program will house about 30 Ph.D. students.
3. Facilities that encourage and foster collaboration with the industry.
4. A K-12 Outreach program resulting in middle and high school curricula for the Science, Technology, Engineering, and Mathematics (STEM) courses that includes instructional material for STEM teachers outlining innovations in energy technology, recovery, and related career opportunities.
5. Venues of educating the society at large about our activities and achievements.

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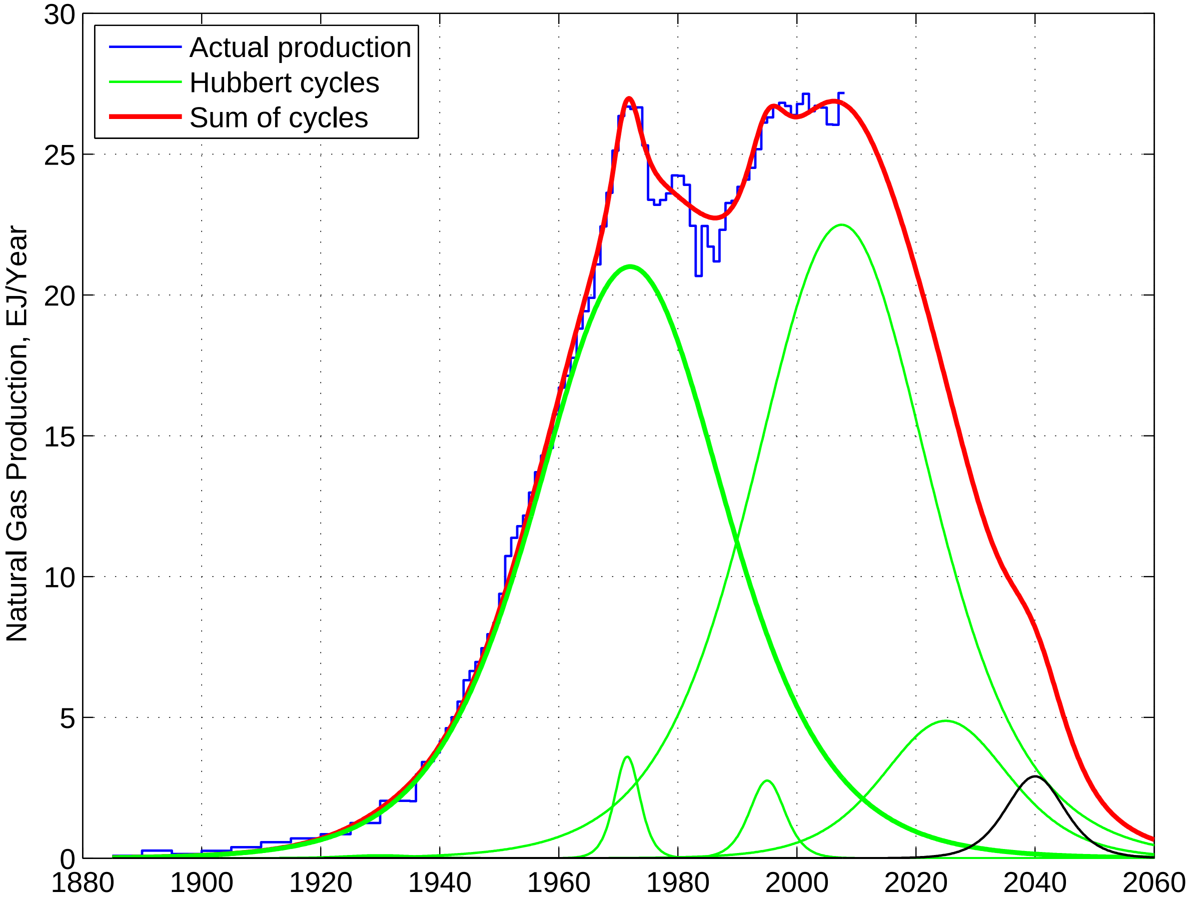

Figure 4: The Hubbert cycle analysis of natural gas endowment in the U.S. There are two main cycles. The original Hubbert cycle for conventional natural gas peaked in 1972. The second comparable cycle, mostly from the Gulf of Mexico gas fields and unconventional gas fields, saw the highest drilling activity in 1981 and is peaking as of this writing. Since 1981, the majority of drilling for gas has occurred on land, more recently in unconventional gas deposits in Texas, Colorado, New Mexico, Oklahoma, etc. Note that the production rate of natural gas in the U.S. will soon be declining at 10-15% per year. The gas produced from the second main Hubbert cycle and the smaller cycles will be exhausted in the next 50 years. The rightmost small cycle is a hypothetical drawdown of the Prudhoe Bay and Thompson Point gas caps ($10^{12}$ $\mathrm{sm}^3$ of natural gas) with the peak production rate in 2040. Data sources: US DOE EIA, USGS, State of Alaska.

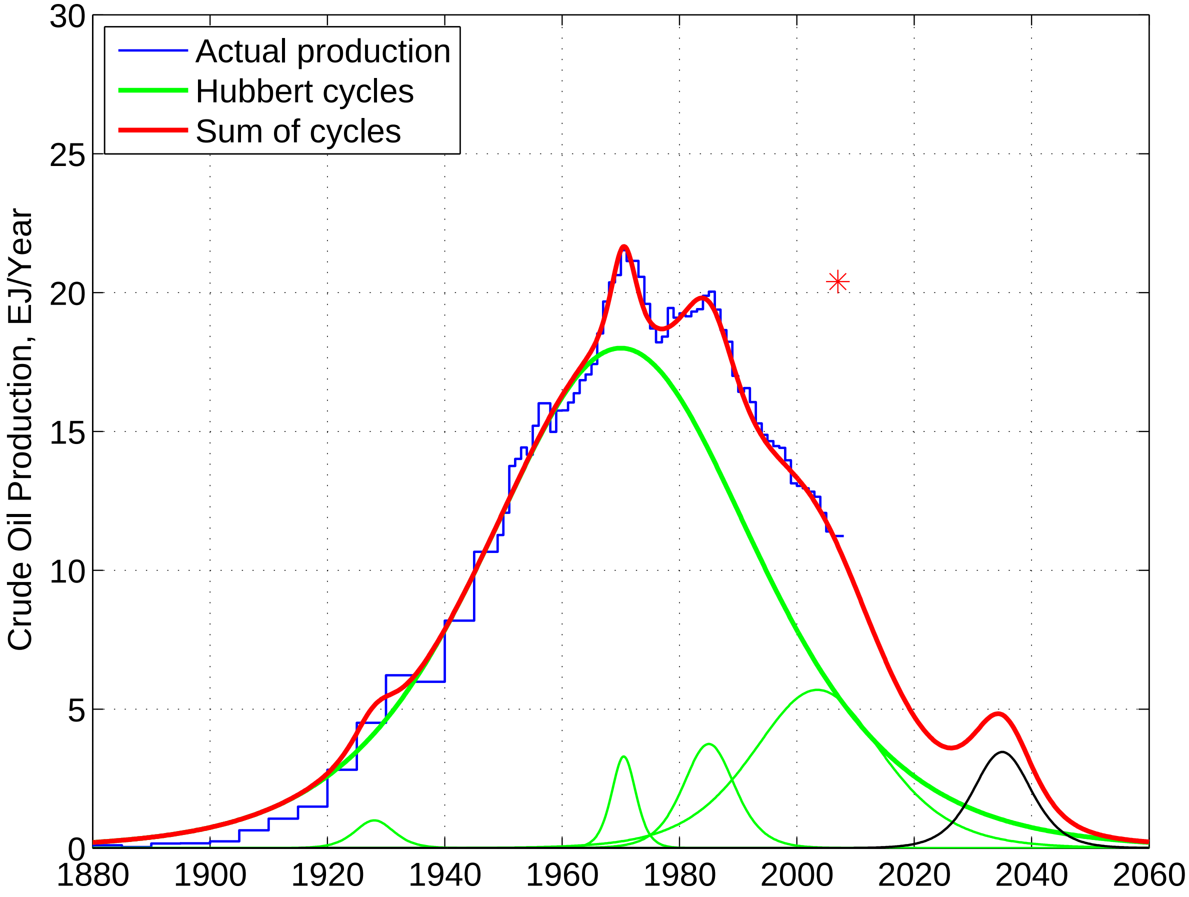

Figure 5: The HUBBERT cycle analysis of U.S. crude oil/condensate endowment. The Main Cycle gives the original HUBBERT estimate of ultimate oil recovery of 200 billion bbl. The smaller cycles describe the new populations of oil reservoirs (Alaska, Gulf of Mexico, Austin Chalk, California Diatomites, etc.) and new recovery processes (waterflood, enhanced oil recovery, horizontal wells). Note that the total rate of production of all oil resources in the U.S. goes through a peak, and *cannot* continue growing exponentially. In fact, in 2003, the total U.S. oil production decreased all the way down to the 1950 level. The star shows the higher heating value of automotive gasoline burned in the U.S. in 2007. The Hubbert cycles shown here were fixed in 2001, and continued to predict the U.S. oil production for another 7 years. Also shown, as the rightmost small Hubbert cycle, is a hypothetical production of the undiscovered, technically producible 7.7 billion barrels of oil from Area 1002 of the Arctic National Wildlife Refuge, Alaska, (ANWR) that peaks in 2035. Data sources: US DOE EIA, USGS, State of Alaska.

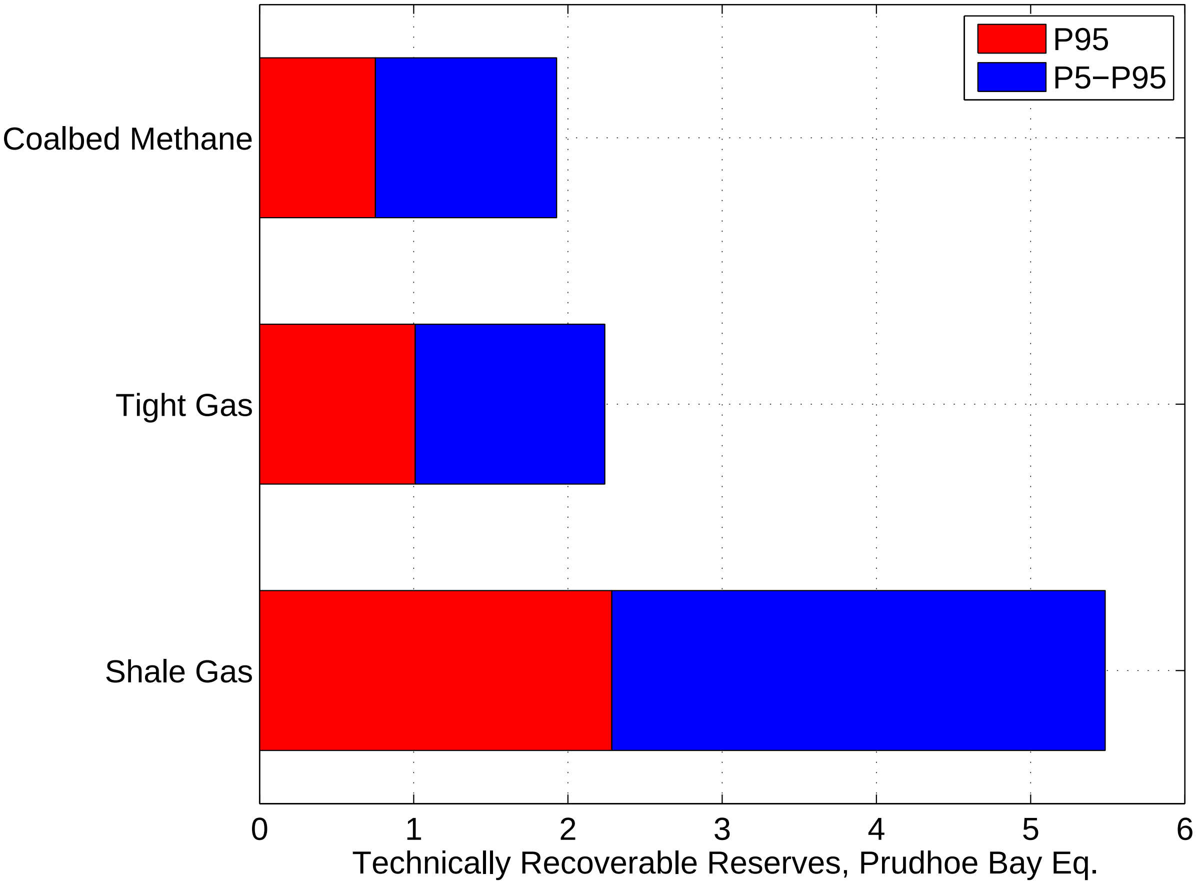

Figure 6: A current estimate of technically recoverable unconventional natural gas in the US. The unit of measurement is total recoverable oil from Prudhoe Bay, 12 billion barrels of oil. The higher heating value of natural gas is converted to that of equivalent oil. Source: Navigant Consulting, Inc., 2008.

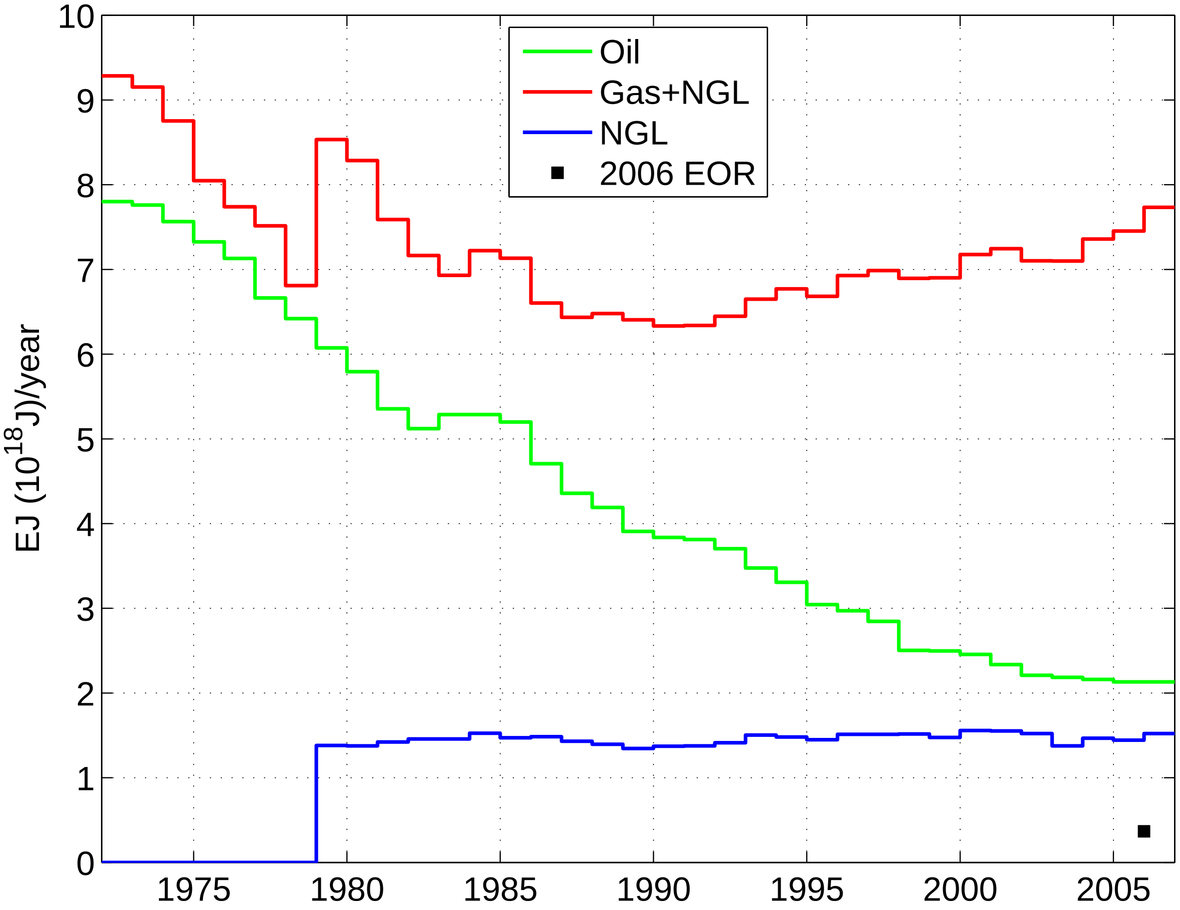

Figure 7: Today, on an energy basis, natural gas and natural gas liquids produced in Texas are about 4 times more important than all oil and 21 times more important than enhanced oil recovery (EOR) here. Note that the natural gas liquids in Texas are as important as the total oil production. Data sources: Oil & Gas Journal, US DOE EIA, and Texas Railroad Commission.

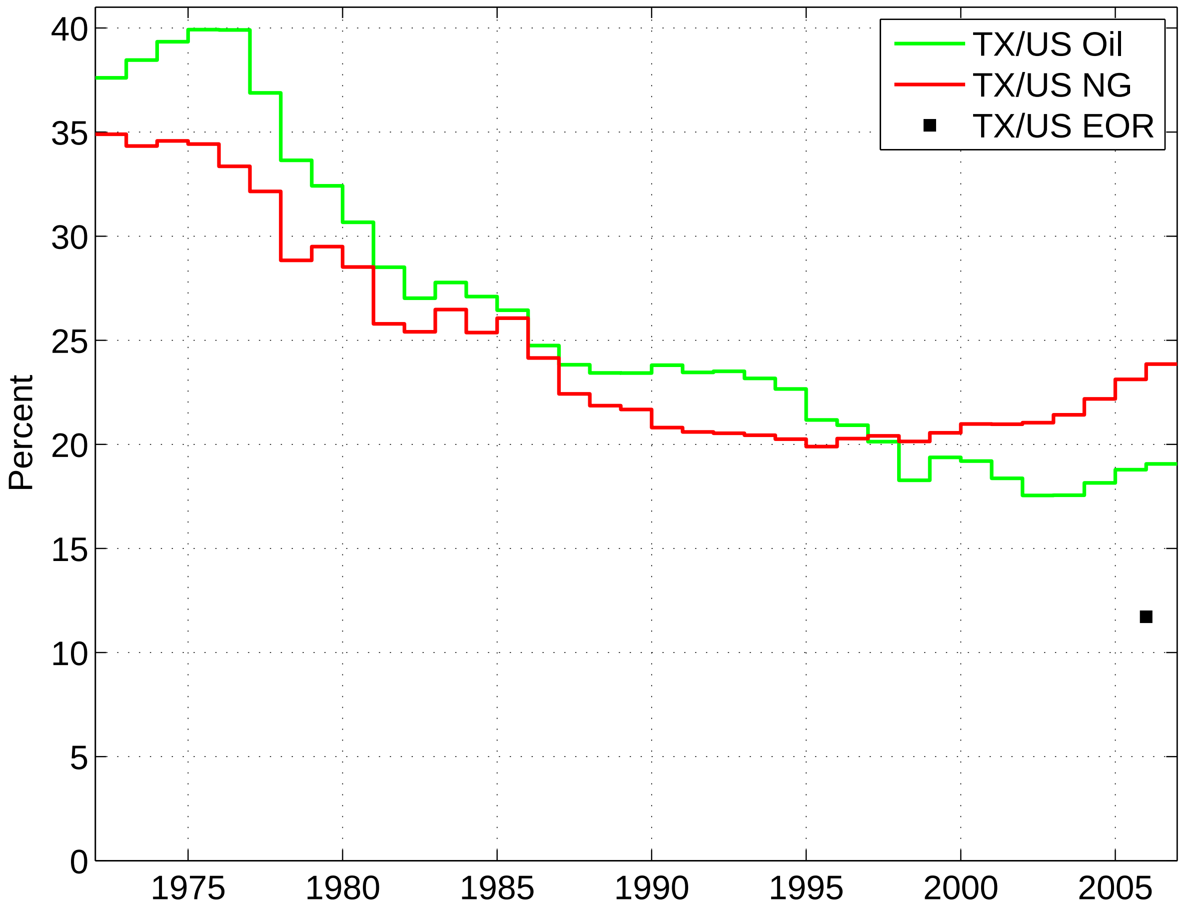

Figure 8: Today, Texas produces roughly 20% of U.S. oil and 25% of natural gas. Texas' share of enhanced oil recovery (EOR) in the U.S. is 12%. Data sources: US DOE EIA, Texas Railroad Commission.

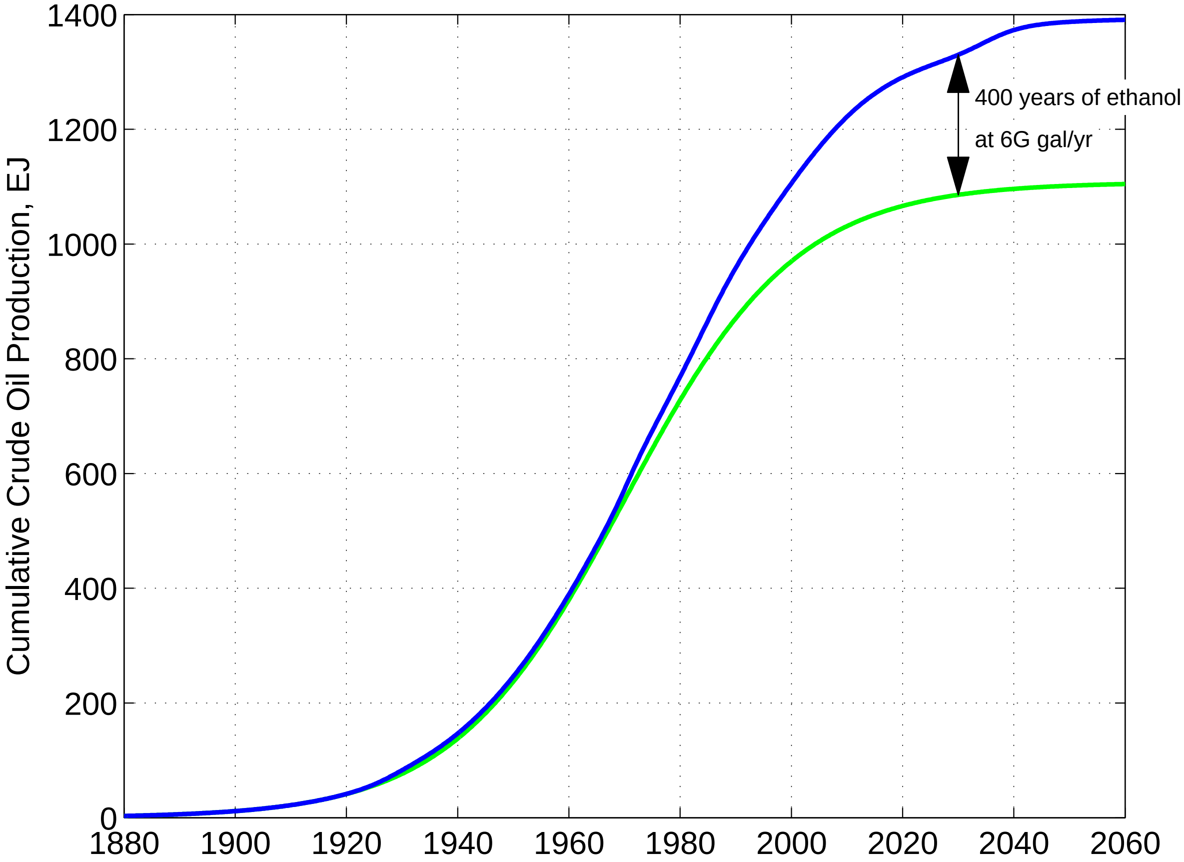

Figure 9: The cumulative oil production in the U.S. cannot continue growing forever. The increment between the main HUBBERT cycle and the total recovery is equal to twice the total U.S. energy consumption in 2003. This difference is a contribution of new technology and research in the oil industry. Coincidentally, this difference is equal to 400 years of pure ethanol production at 6 billion gallons per year, equal to the global record set in the U.S. in 2007. The small increase of the total recovery curve after 2030 is caused by a hypothetical production of 7.7 billion barrels of oil from the Arctic National Wildlife Refuge (ANWR) in Alaska.

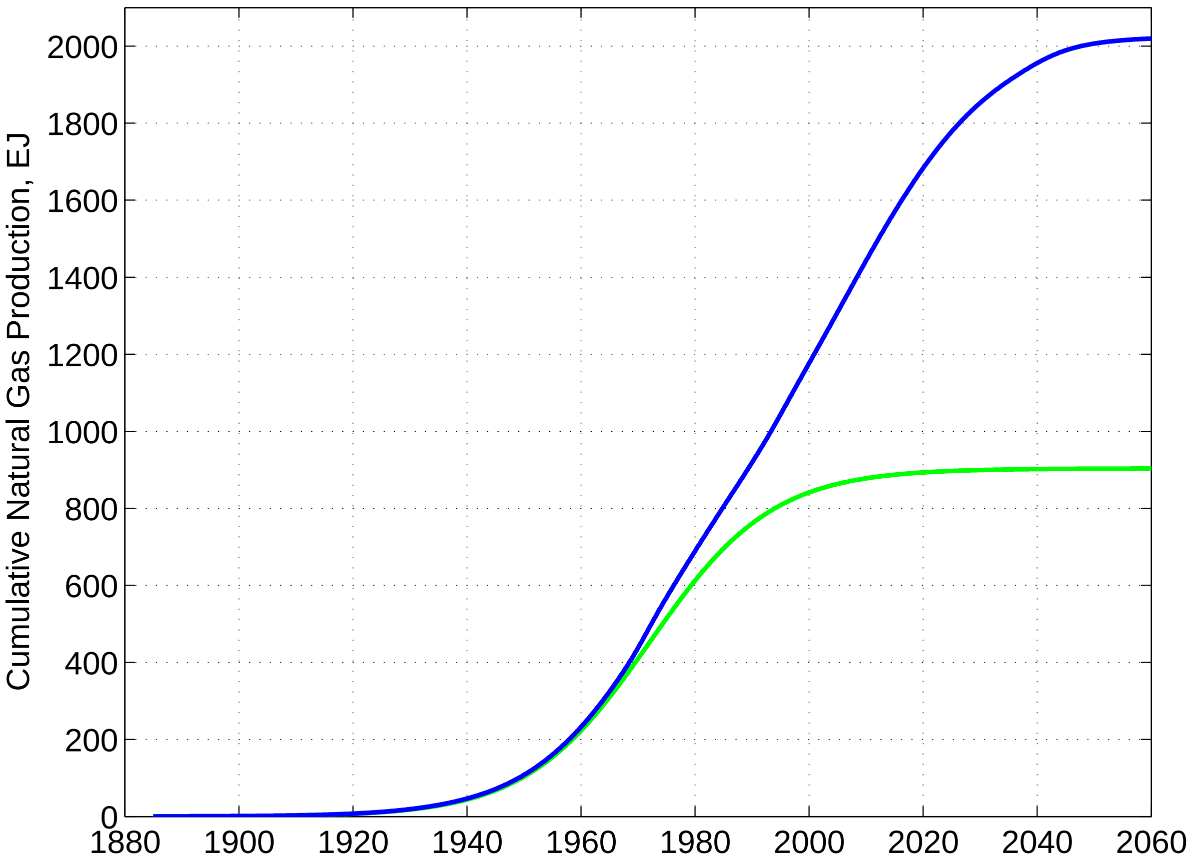

Figure 10: The increment between the main HUBBERT cycle of natural gas production and its ultimate total recovery is equal to 10 times the total U.S. energy consumption in 2003. This difference is a contribution of new technology and research in the gas industry.

Figure 11: How is gas production kept relatively constant in the U.S.? By drilling a myriad of deep expensive gas wells, some of which were photographed by Patzek when he was flying over Colorado in the summer of 2007. In 2006, ∼3,800 wells/month were drilled in the U.S., most of them for gas. Many of the new gas wells decline initially at 33% per year in the first 1 – 2 years, switching to the low production regime later. Image source: T. W. Patzek.

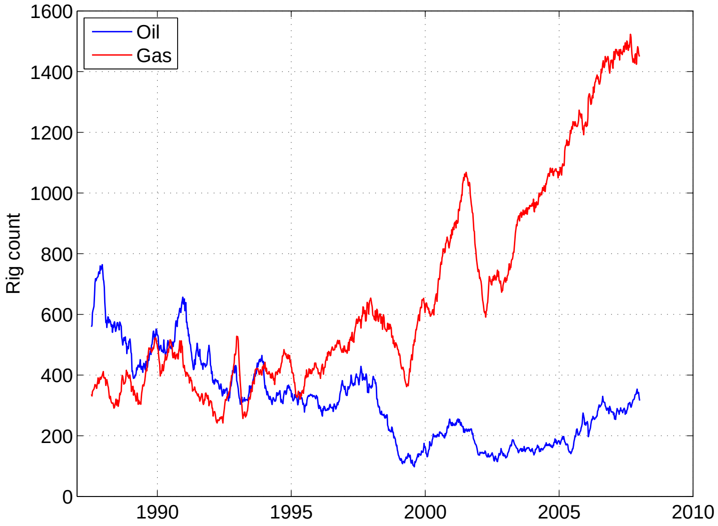

Figure 12: The July 1987 – January 2008 count of U.S. gas and oil rigs. Note that since 1999 about 80% of all active rigs have drilled for gas. Data source: Baker-Hughes.

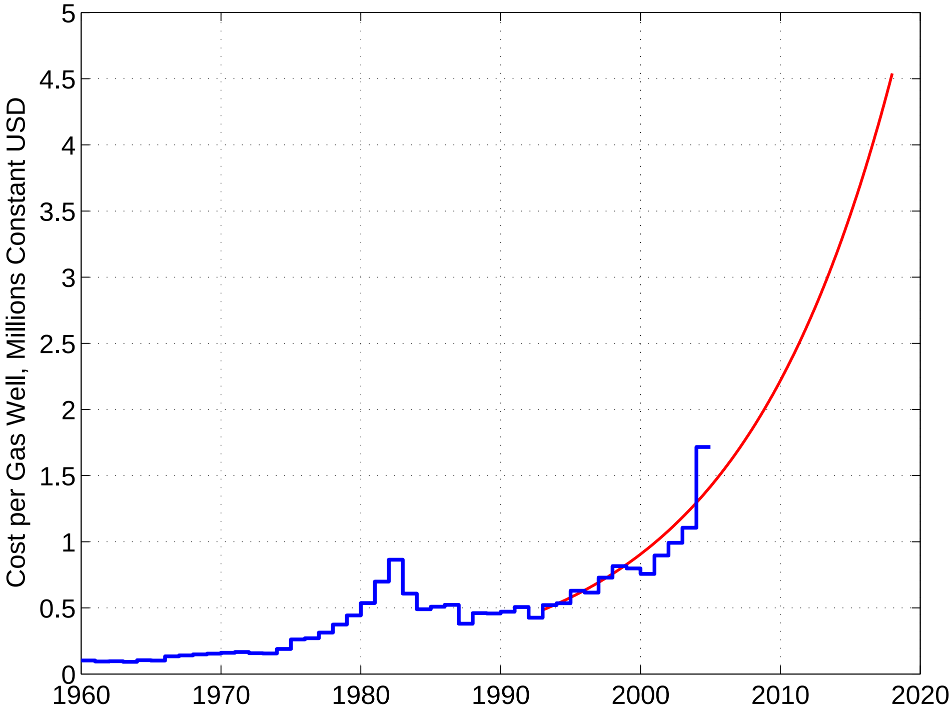

Figure 13: Growth of well costs in constant dollars. The recent escalation of well costs is more than exponential. Data source: US DOE EIA.

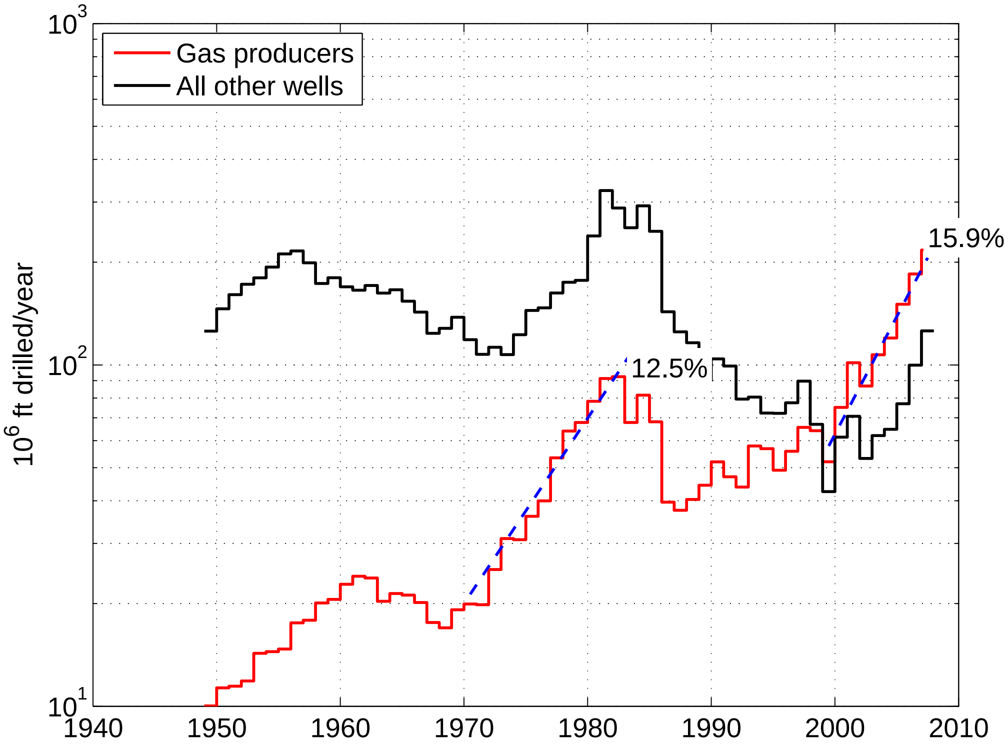

Figure 14: The millions of feet drilled in the U.S. for gas and oil wells each year. The recent annual rate of drilling for gas is increasing at an unsustainable rate of 16% per year. An average oil well cost is \$400/ft and that of a gas well is \$350/ft. These costs translate into 70 billion dollars *each* spent in 2008 in the U.S. on the drilling and completing gas and oil wells. Sources: US DOE and EIA.

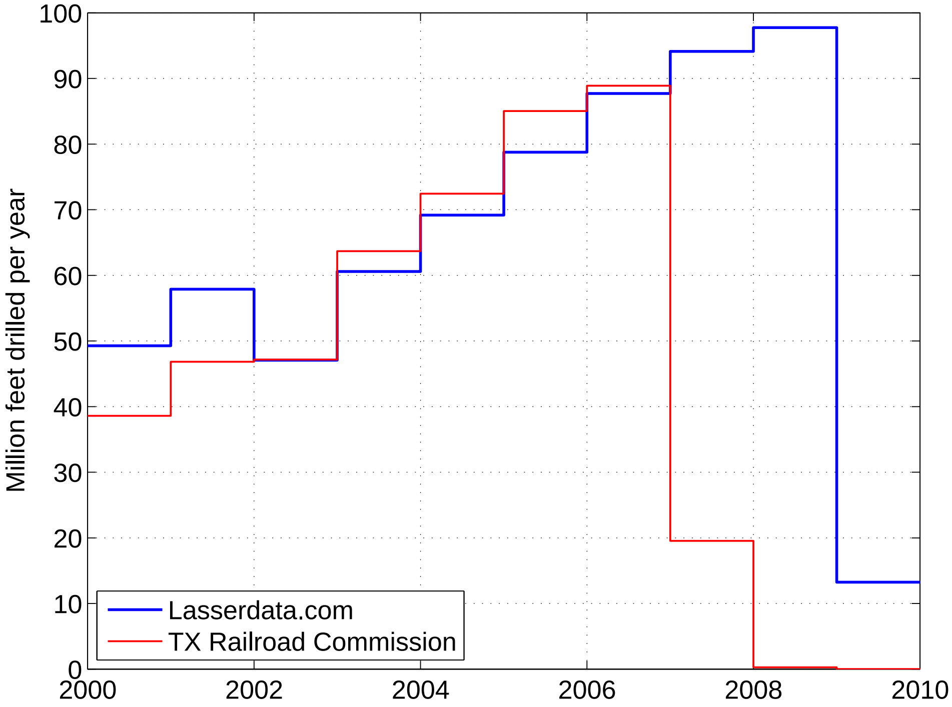

Figure 15: The millions of feet drilled in Texas for gas wells each year. Note the collapse of drilling in 2009, caused by the historically low gas price. The Texas Railroad Commission data are updated less frequently that those of a private data provider, LasserData. Sources: Terry D. Payne, President, Platt, Sparks and Associates, TX Railroad Commission.

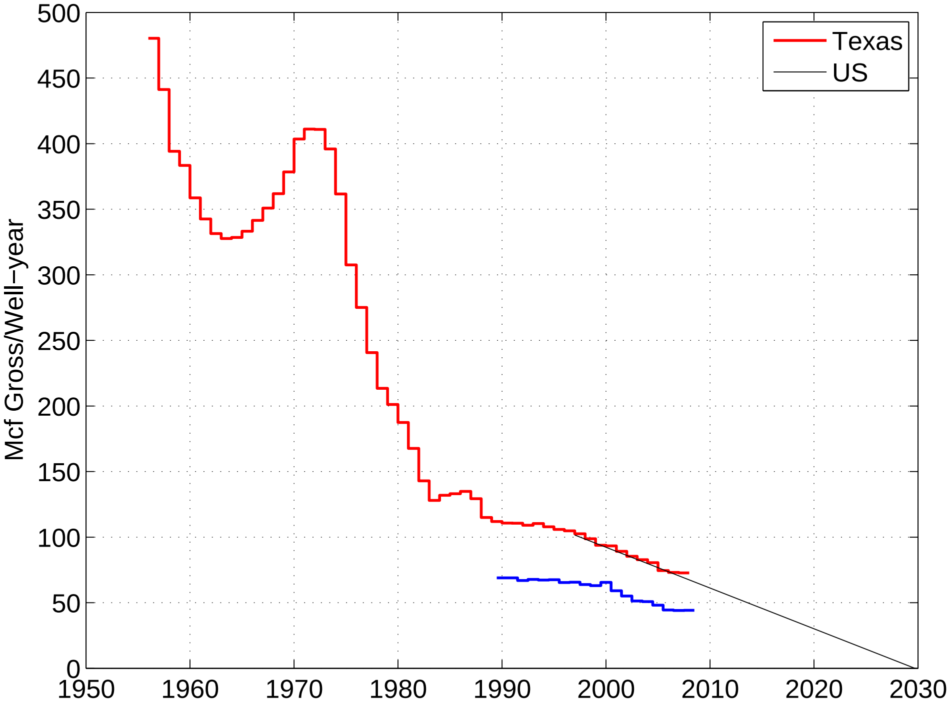

Figure 16: Average productivity of a population of gas wells each year. As conventional gas deposits decline and are replaced by unconventional ones, the average well productivity declines and the relative well cost increases. In fact, if the current trend of decline of well productivity is not slowed down, an average gas well in the U.S. will stop producing in 20 years. The current rate of decline of gas well productivity reveals that vigorous research and development of new technology are absolutely essential to the energy security of the United States. Sources: Texas Railroad Commission, EIA.

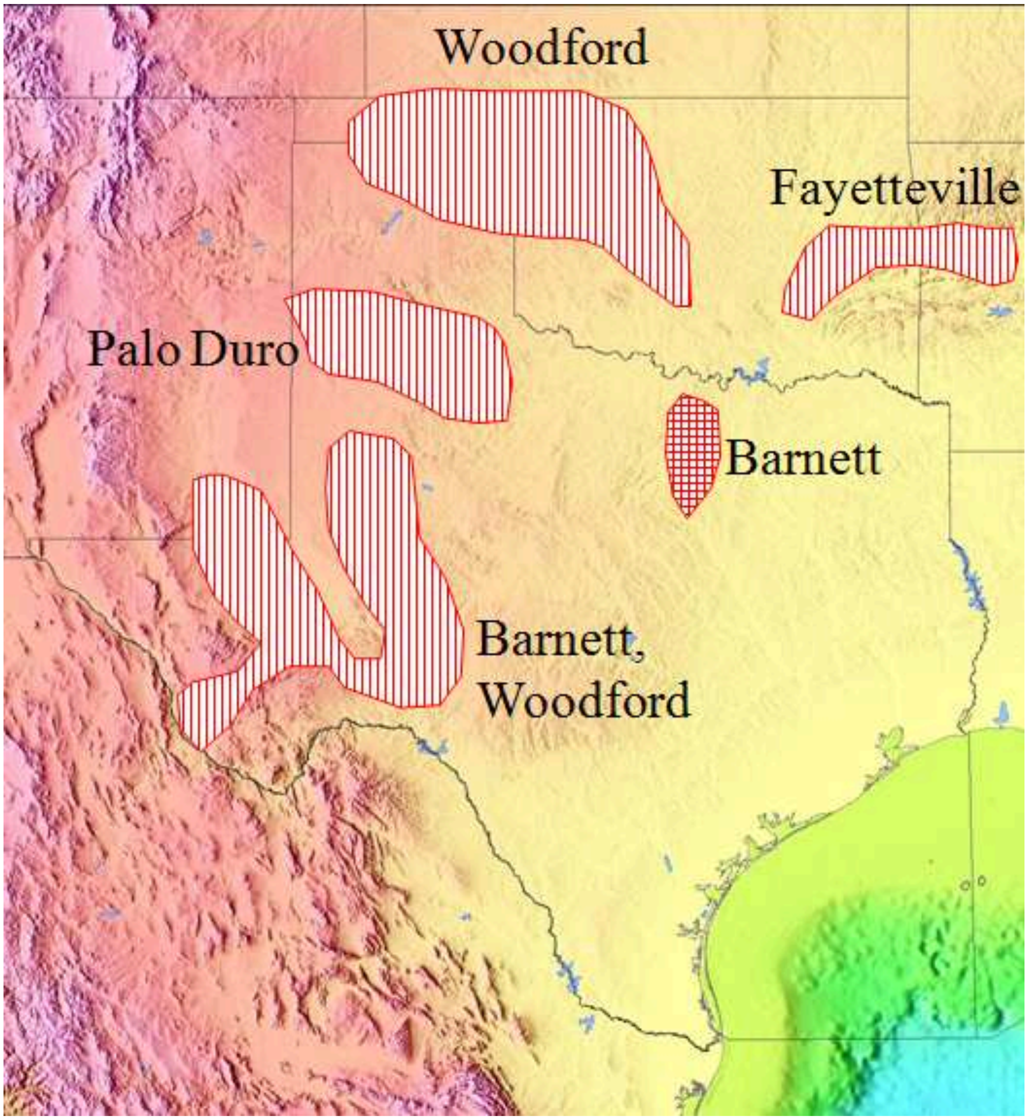

Figure 17: Some of the unconventional gas areas in Texas. Data source: US DOE EIA, USGS, Greg Croft, Inc.

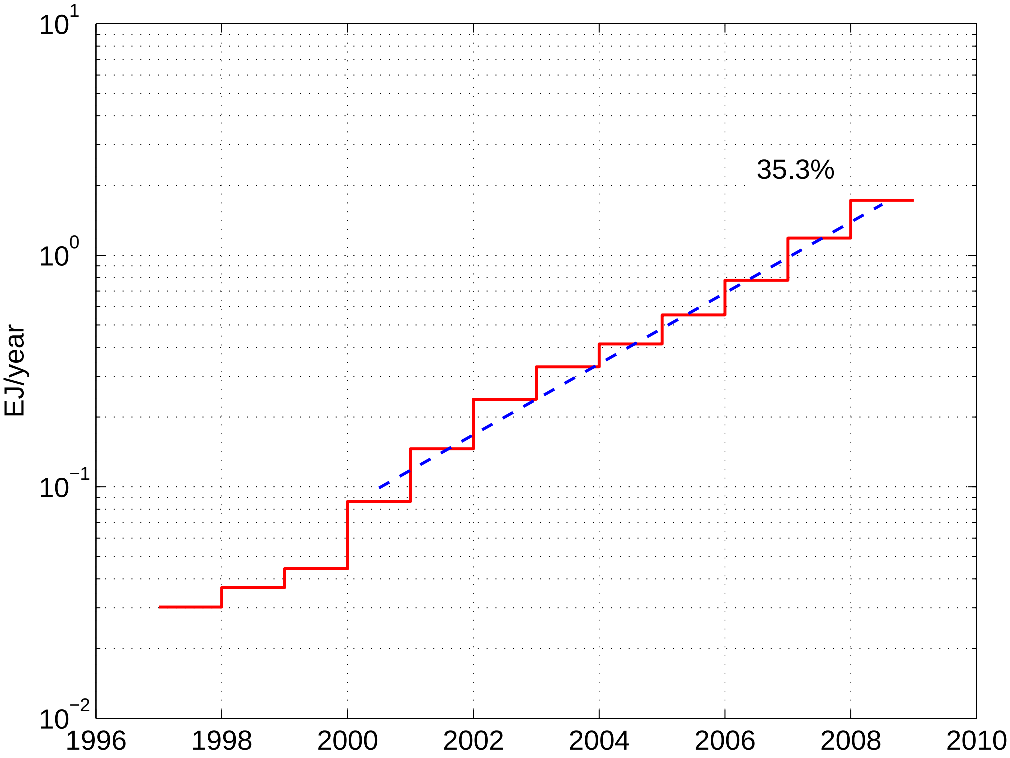

Figure 18: The Barnet Shale in Texas has been developed faster than almost any other large-scale natural resource worldwide. Source: Texas Railroad Commission.

Table 4: Most largest gas fields are in Texas. Data source: US DOE EIA.

| Rank | Field Name | Location State | Year Discovered | 2005 Production Volume, bcf[a] |
|---|---|---|---|---|
| 1 | SAN JUAN BASIN GAS AREA | CO & NM | 1927 | 1397.0 |
| 2 | PINEDALE | WY | 1955 | 457.3 |
| 3 | NEWARK EAST | TX | 2002 | 496.5 |
| 4 | HUGOTON GAS AREA | KS&OK & TX | 1922 | 480.7 |
| 5 | PRUDHOE BAY | AK | 1967 | 193.0 |
| 6 | JONAH | WY | 1977 | 273.1 |
| 7 | WATTENBERG | CO | 1970 | 179.1 |
| 8 | MADDEN | WY | 1968 | 163.7 |
| 9 | ANTRIM | MI | 1965 | 164.9 |
| 10 | CARTHAGE | TX | 1981 | 214.1 |
| 11 | RATON BASIN GAS AREA | CO & NM | 1998 | 120.9 |
| 12 | NATURAL BUTTES | UT | 1940 | 133.6 |
| 13 | PRB COALBED | WY | 1992 | 336.1 |
| 16 | SPRABERRY TREND AREA | TX | 1952 | 78.7 |
| 17 | SAWYER | TX | 1960 | 75.1 |
| 26 | OAK HILL | TX | 1958 | 97.9 |
| 27 | WASSON | TX | 1954 | 78.1 |
| 31 | BALD PRAIRIE | TX | 1976 | 54.5 |
| 32 | FARRAR | TX | 2002 | 53.2 |
| 34 | HALEY | TX | 1983 | 43.2 |
| 37 | OAKS | TX | 1975 | 36.5 |
| 38 | FREESTONE | TX | 1949 | 80.9 |
| 40 | MOCANE-LAVERNE GAS AREA | KS&OK&TX | 1946 | 64.0 |
| 43 | GIDDINGS | TX | 1960 | 106.0 |
| 45 | BUFFALO WALLOW | TX | 1969 | 51.5 |
| 47 | OVERTON | TX | 1973 | 49.0 |
| 50 | PINON | TX | 1982 | 14.4 |

[a] 1 bcf = 1 billion standard cubic feet of natural gas. Standard conditions are 1 atm and $15.5^0$C ($60^0$F).

Table 5: Large gas fields are among the largest hydrocarbon producers in U.S.

| Field | Gas Bcf/yr | Liquids MBbl/yr | OEG[a] MBbl/yr | Type | Discovery Year |
|---|---|---|---|---|---|
| San Juan Basin, CO&NM | 1397 | | 233 | Unc. Gas | 1927 |
| Prudhoe, AL | 193 | 119 | 151 | Oil | 1967 |
| Newark East, TX | 497 | | 83 | Unc. Gas | 2002 |
| Mars/Ursa, LA | 93 | 67 | 82 | Oil | 1989 |
| Hugoton, KS&OK&TX | 481 | | 80 | Conv. Gas | 1922 |
| Pinedale, WY | 457 | 4 | 80 | Unc. Gas | 1955 |
| Wasson, TX | 78 | 56 | 69 | Oil | 1954 |
| PRB Coalbed, WY | 336 | | 56 | Unc. Gas | 1992 |
| Jonah, WY | 273 | 3 | 48 | Unc. Gas | 1977 |
| Kuparuk, AL | | 48 | 48 | Oil | 1969 |
| Midway-Sunset, CA | | 42 | 42 | Oil | 1901 |
| Carthage, TX | 214 | | 36 | Unc. Gas | 1981 |

[a] OEG = oil-equivalent gas, an energy equivalent of gas production expressed as millions of barrels (Mbbl) of oil equivalent produced per year.