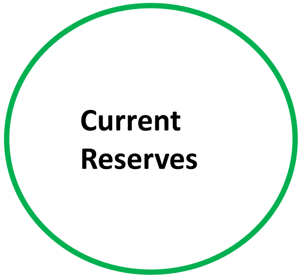
Optimal Extraction of an Exhaustible Resource

- *Three classifications of exhaustible resources:*
  - <u>current reserves</u> -- known reserves that can be profitably extracted at current prices. Also known as proved reserves.



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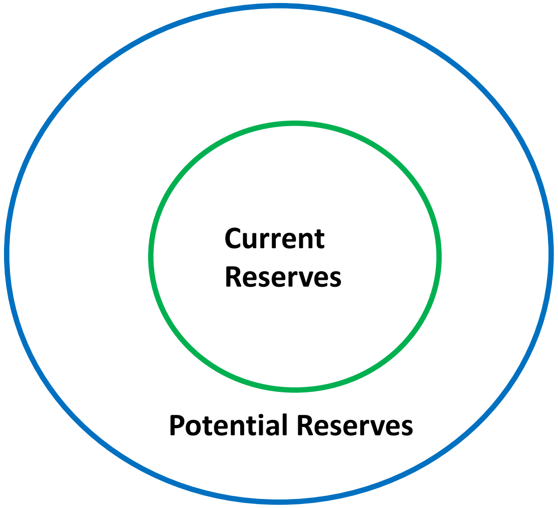

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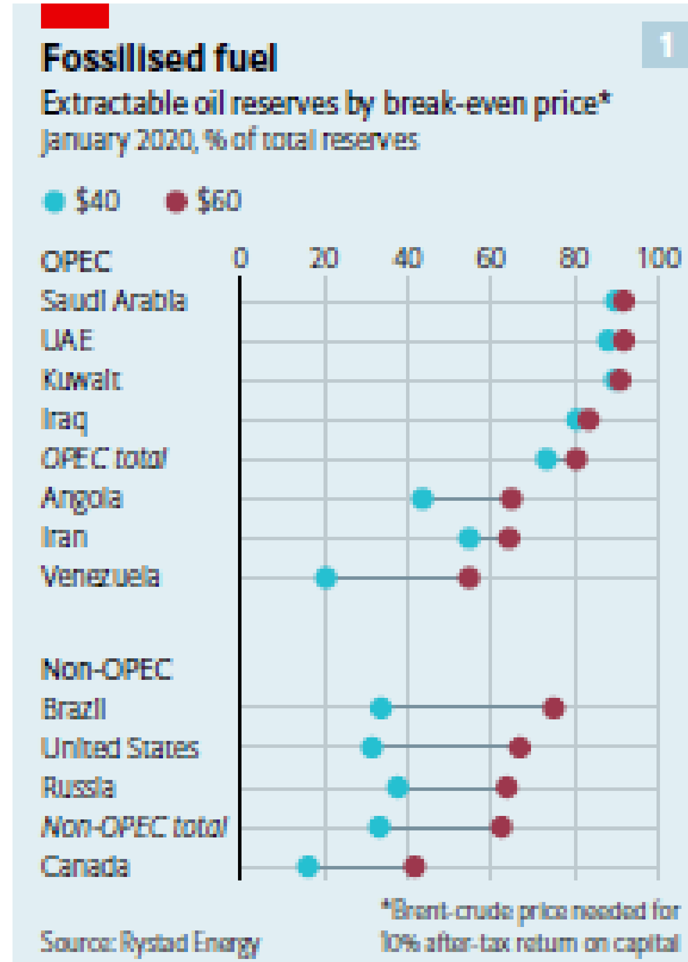

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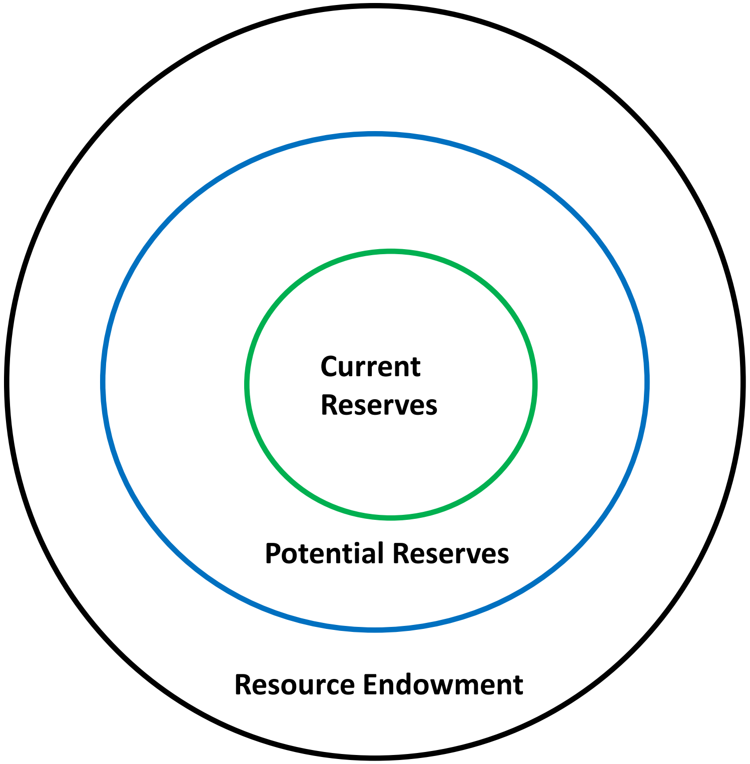
  - <u>potential reserves</u> -- reserves that could be recovered at higher prices.
  - <u>resource endowment</u> -- the entire geological supply of resources (including those not yet discovered).



Optimal Extraction of an Exhaustible Resource

- Decisions to use exhaustible resources are dynamic decisions, because future availability of the resource depends on what is used today.

- Thus, exhaustible resources should be treated as an asset.

The Costs of Extraction

- There are two costs to using a resource, such as oil, today:
  - Extraction cost
    - How much does it cost to obtain the resource?
    - At a minimum, can only sell if P >= MEC (marginal extraction cost)

The Costs of Extraction

- There are two costs to using a resource, such as oil, today:
  - Extraction cost
    - How much does it cost to obtain the resource?
    - At a minimum, can only sell if P >= MEC (marginal extraction cost)
  - User cost -- the opportunity cost of not having the resource to sell in the future
    - As a result, the price of the resource will be greater than the MEC.

The Costs of Extraction

- The owner of a resource, such as oil, has two options to make money for next year:
  - Sell all the oil now, and invest the profits at interest rate i
  - Wait and sell the oil next year

- How much is sold this year depends on expectations of future profits
  - Is it more valuable to sell now or to wait?

The Costs of Extraction

- Case A: Expected profit next year rises less than the rate of interest:
  - Present value of marginal profits next year is less than current value this year:

$$P_1 - MEC > \frac{P_2 - MEC}{1 + i}$$

  - What should the owner of the resource do?

The Costs of Extraction

- Case A: Expected profit next year rises less than the rate of interest:
  - Present value of marginal profits next year is less than current value this year:

$$P_1 - MEC > \frac{P_2 - MEC}{1 + i}$$

  - The owner of the oil is better off selling the oil now and investing it.
  - Leads to lower prices now (greater supply) and higher prices next year (lower supply).

The Costs of Extraction

- Case B: Expected profit next year rises faster than the rate of interest:
  - Present value of marginal profits next year is greater than current value this year:

$$P_1 - MEC < \frac{P_2 - MEC}{1 + i}$$

  - What should the owner of the resource do?

The Costs of Extraction

- Case B: Expected profit next year rises faster than the rate of interest:
  - Present value of marginal profits next year is greater than current value this year:
  $$P_1 - MEC < \frac{P_2 - MEC}{1 + i}$$
  - The owner of the oil is better off waiting to sell the oil next year.
  - Leads to higher prices now (lower supply) and lower prices next year (higher supply).

The Costs of Extraction

- Equilibrium
  - Prices adjust whenever one option (case A or B) looks better
  - Equilibrium is reached when the expected profit from the sale of the oil rises at the rate of interest

$$P_1 - MEC = \frac{P_2 - MEC}{1 + i}$$

$$(1 + i)(P_1 - MEC) = P_2 - MEC$$

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  - With a constant marginal extraction cost, this simplifies to:

$$P_1 + iP_1 - MEC - iMEC = P_2 - MEC$$

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$$P_2 - P_1 = iP_1 - iMEC$$

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$$P_2 - P_1 = iP_1 - iMEC$$

$$P_2 - P_1 = \Delta P = i(P_1 - MEC)$$

    - *Intuition*: with constant extract costs, prices adjust so that the profit received from extracting the resource rises at the rate of interest

The Costs of Extraction

- Marginal user cost (MUC) -- the present value of the opportunity cost of the *last unit of oil* used not being available in the next period.

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PV of expected profits is the PV of opportunity cost

The Costs of Extraction

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$$P_1 = \frac{P_2 - MEC}{1+i} + MEC$$

  – More generally:

$$P_t = MUC_t + MEC_t$$

The Costs of Extraction

- <u>Marginal user cost (MUC)</u> -- the present value of the opportunity cost of the *last unit of oil* used not being available in the next period.

$$P_t = MUC_t + MEC_t$$

  - If marginal extraction costs are constant, the marginal user cost rises at the rate of interest.
  - This implies that the present value of marginal user cost remains the same!
    - *Intuition:* Maximizing welfare over time on the last unit of oil sold.

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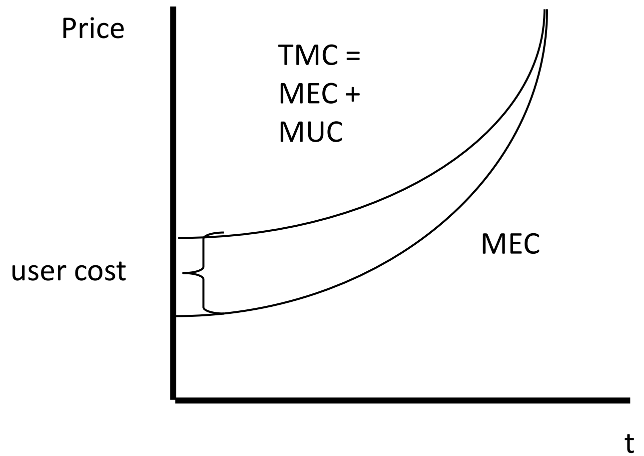
  - This implies that the present value of marginal user cost remains the same!
    - *Intuition:* Maximizing welfare over time on the last unit of oil sold.
  - Note that the price of a resource is greater than the MEC. Thus, higher prices are not, by themselves, evidence of abuse of market power.
    - Rather, they simply represent economic rent due to scarcity.

The Costs of Extraction

- Changes in the marginal extraction cost
  - Up to now, we have assumed the MEC is constant.
  - If marginal extraction costs rise over time, the marginal user cost will fall.
    - Intuition: MUC represents the opportunity cost of using the resource now. If it will be more costly to use the resource in the future, the opportunity cost is not as high.

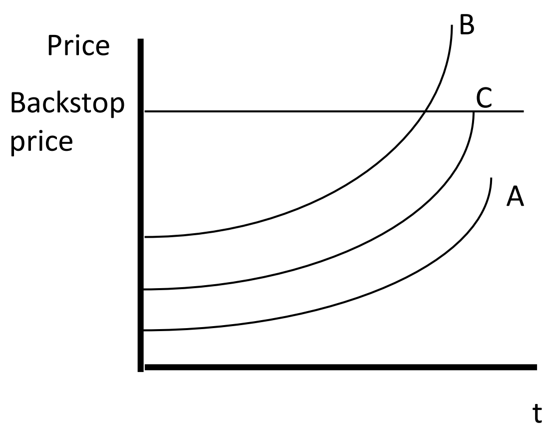


Backstop Technologies

- This theory describes how the price should change over time. But what price should we start at?
  - We want to run out of the resource at the highest price that people are willing to pay.
  - This is the backstop price. It is determined by a backstop technology.
  - A <u>backstop technology</u> is a technology that is available in vast quantities at the backstop price.
    - E.g.: solar energy
    - Note that the backstop price is constant, since the backstop technology is not exhaustible.

Backstop Technologies

- This theory describes how the price should change over time. But what price should we start at?
  - A: starts too low. As we approach the end, the price will jump, as people will hoard. Thus, should have started higher.
  - B: starts too high. Some of the resource remains in the ground at the backstop price, and must be sold at that price, which is lower than desired.
  - C: just right



Backstop Technologies

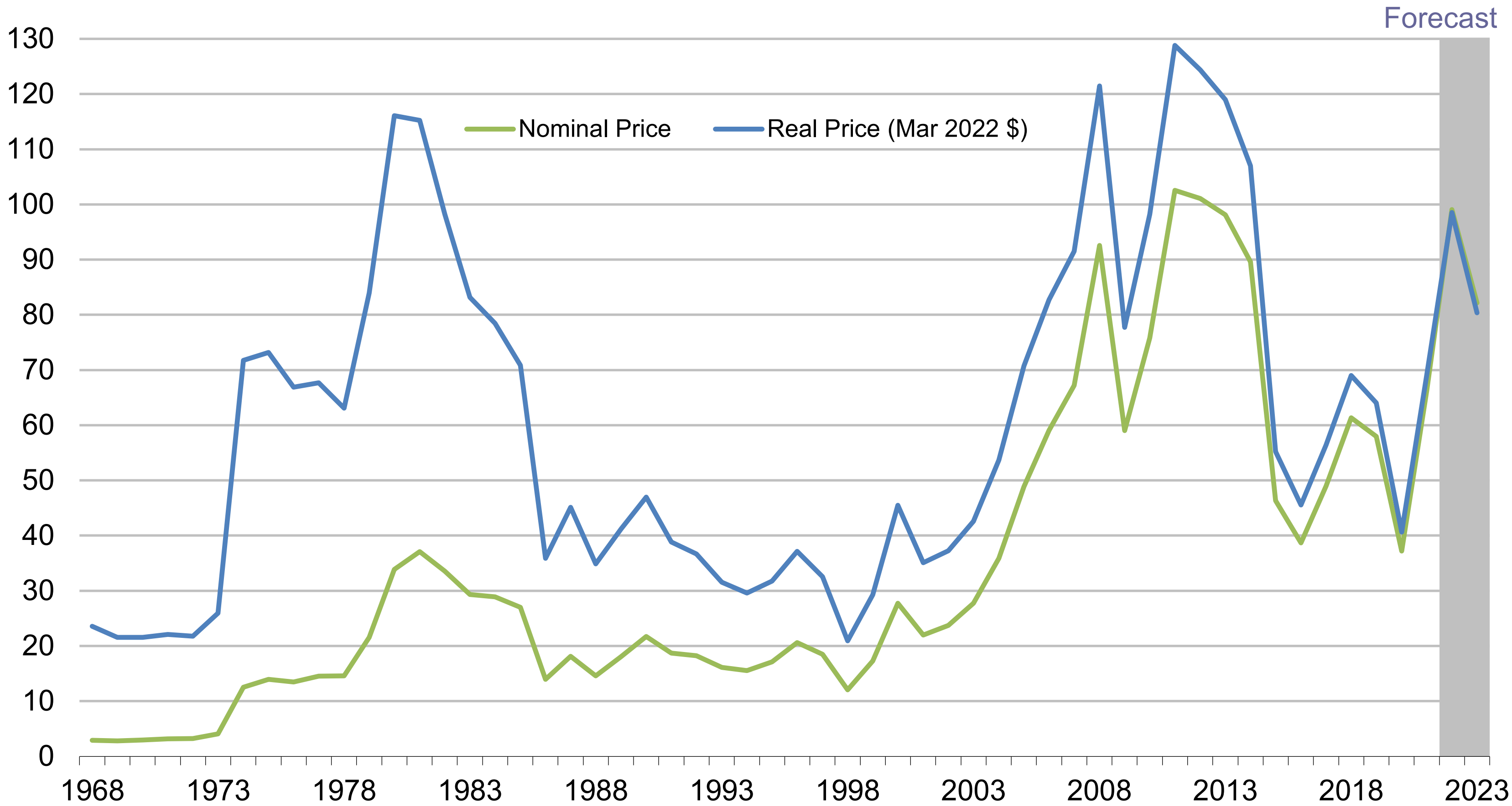
- This theory describes how the price should change over time. But what price should we start at?
  – Note that, if several fuels are available, we will begin by using the one with the cheapest extraction cost, and continue, using up each fuel, until the backstop technology is reached.
    - Note that, if these prices do not account for negative externalities, such as pollution, all of the dirty fuel supplies are used up!
  – Technological innovation on the backstop technology could lower its price and speed the transition.
    - However, if the backstop won't be usable for many years, markets might not support this research.

Energy Prices Over Time

- Theory predicts that energy prices should rise over time. That has not happened.

Annual Imported Crude Oil Price

dollars per barrel



EIA Short-Term Energy Outlook, March 2022

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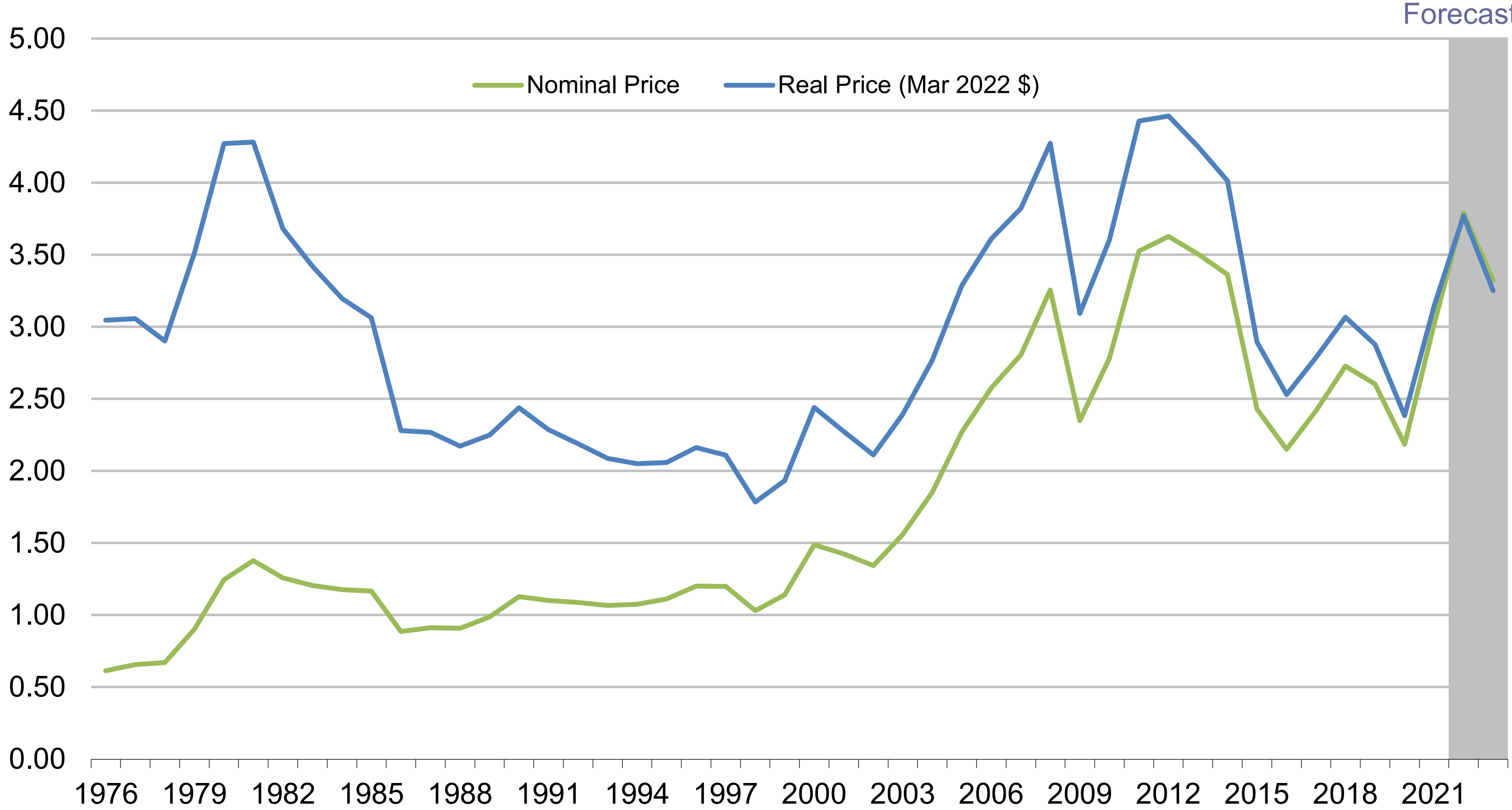
Annual Motor Gasoline Regular Grade Retail Price

dollars per gallon



EIA Short-Term Energy Outlook, March 2022

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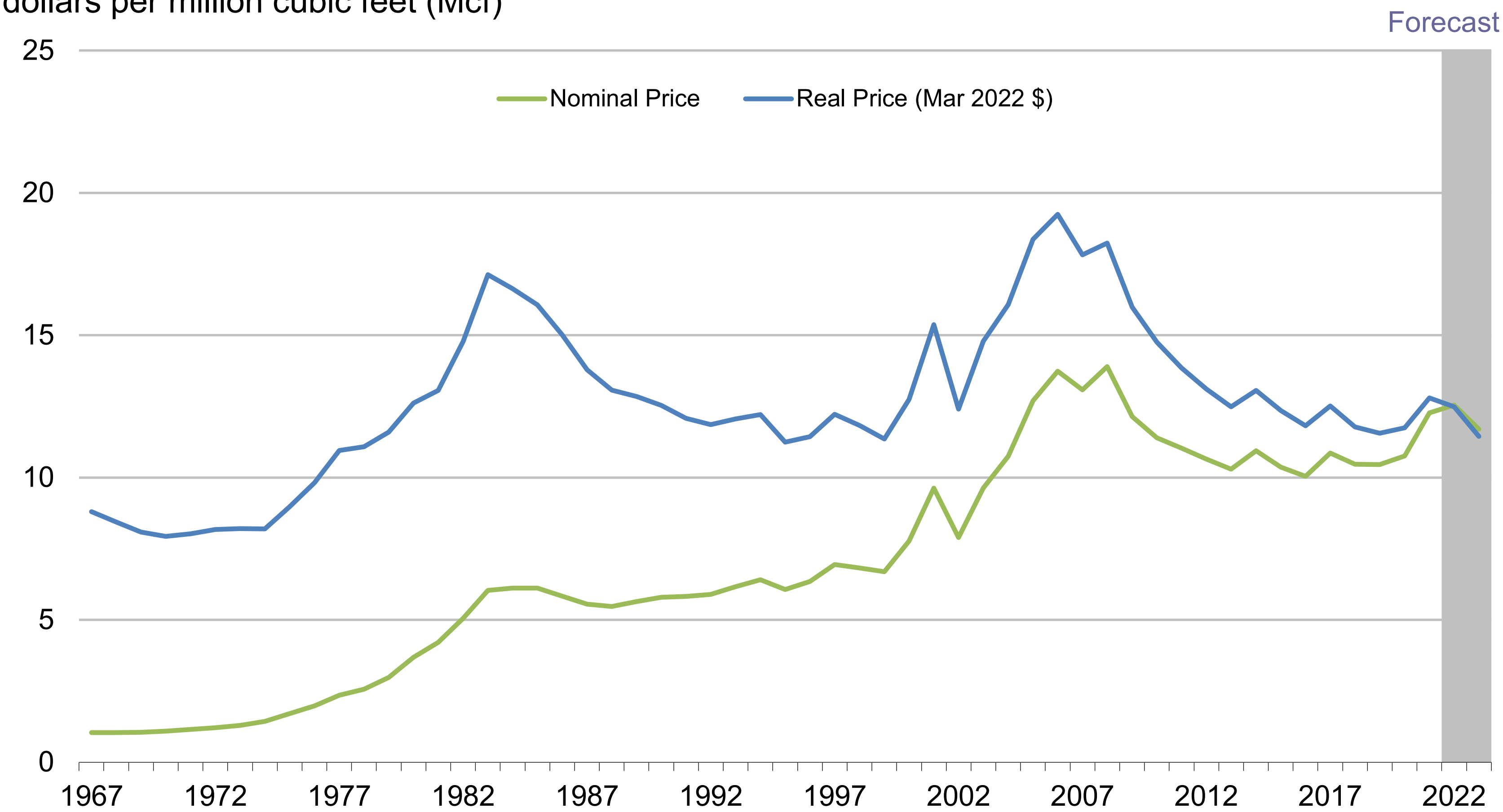
Annual Residential Natural Gas Price

dollars per million cubic feet (Mcf)



EIA Short-Term Energy Outlook, March 2022

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Energy Prices Over Time

- Theory predicts that energy prices should rise over time. That has not happened.

- Why haven't prices risen over time? What factors affect energy prices?

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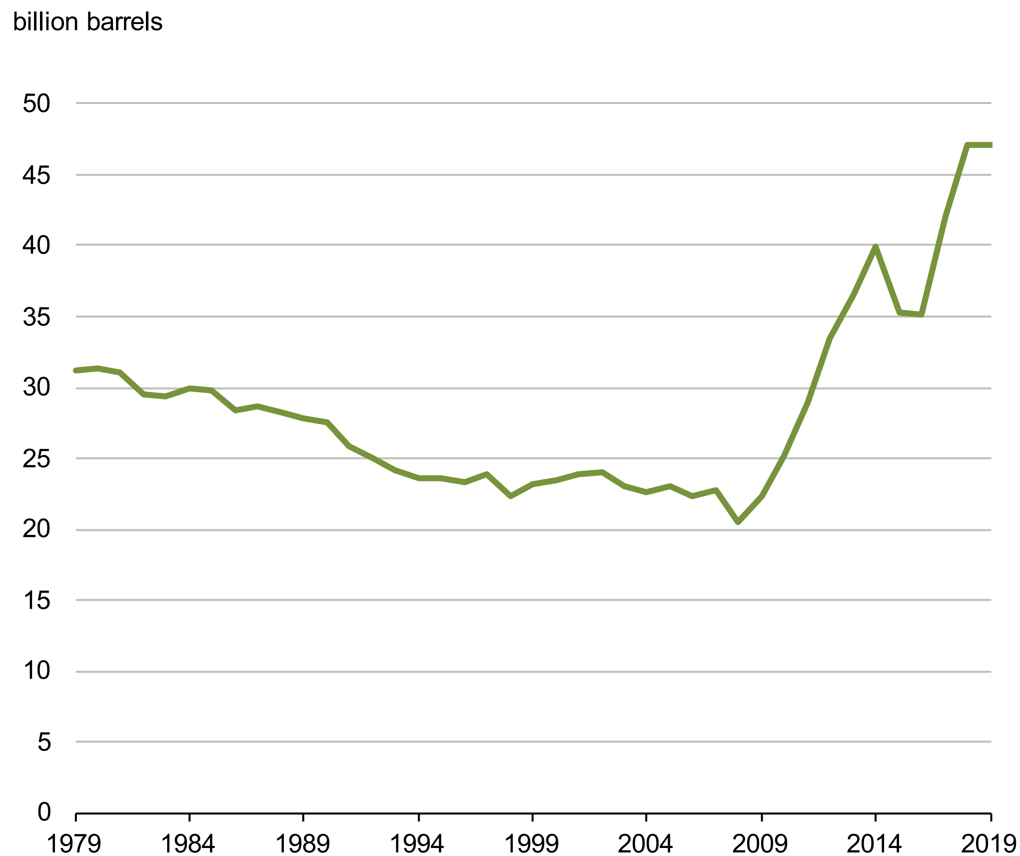
Energy Prices Over Time

- Factors leading to higher prices
  - Higher demand, particularly in emerging economies
  - Risk premium
    - Concerns over security and corruption in oil producing nations raise the risks of future shortages.
  - Lack of refining capacity
    - Even if more oil comes into the U.S., additional capacity needed to refine it into gasoline more quickly.
    - Price volatility reduces investment

Energy Prices Over Time

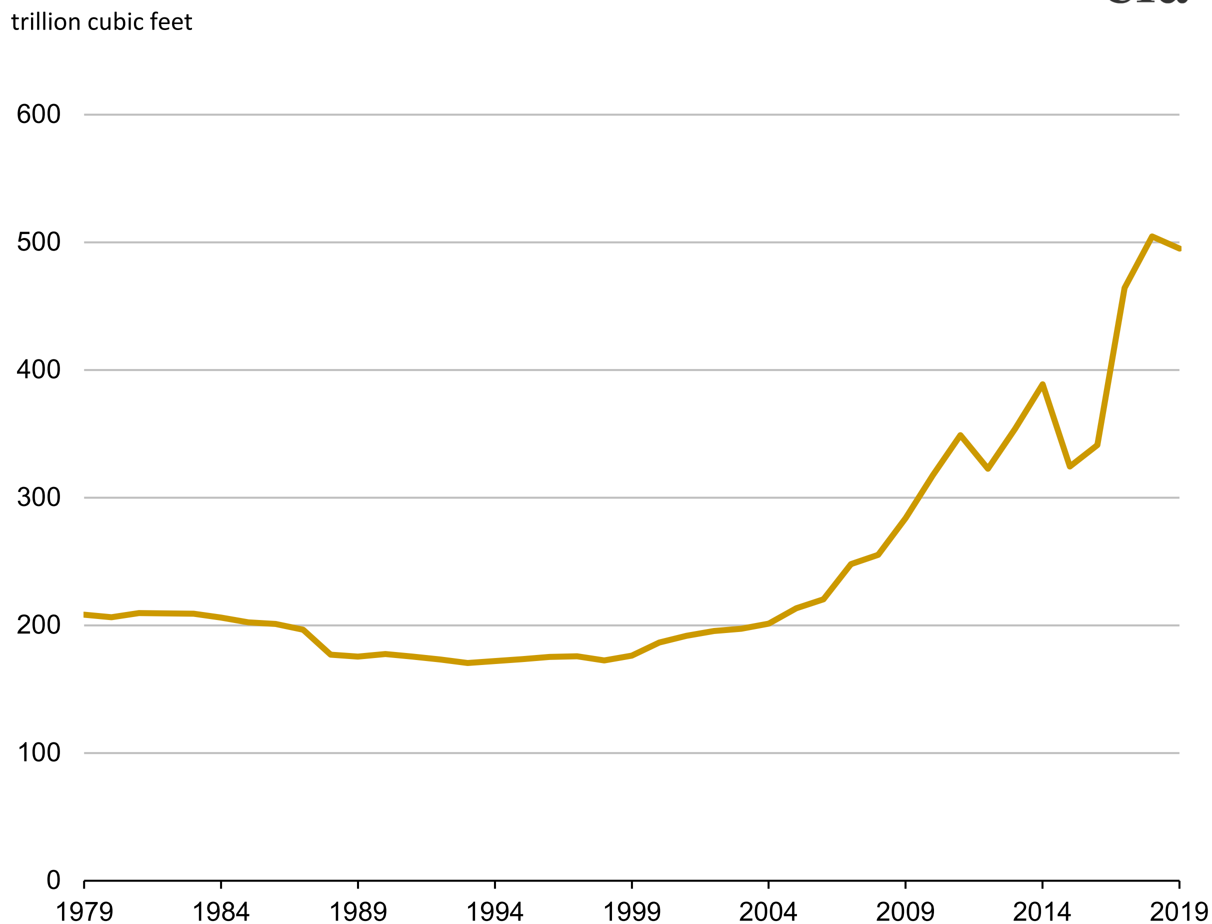
- Factors leading to lower prices
  - Demand for oil and gasoline in many richer countries is falling, as more consumers use hybrid and electric vehicles
  - Resource scarcity
    - If a resource is not scarce, the user cost is near zero, so the price is set at the marginal costs of extraction.
      - Scarcity rents become a factor as demand increases, leading to slowly rising prices.
    - Concerns about peak oil were first raised during World War I
      - US crude oil proved reserves grew from 22 billion barrels in 2000 to 36.3 billion in 2014
      - New discoveries have limited the importance of scarcity in oil prices.
        - » Current reserves in our model at the beginning of class change with market conditions
        - » Exploration increases when energy prices are higher

U.S. crude oil and lease condensate proved reserves



Sources: U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves, 1979–2019

U.S. total natural gas proved reserves



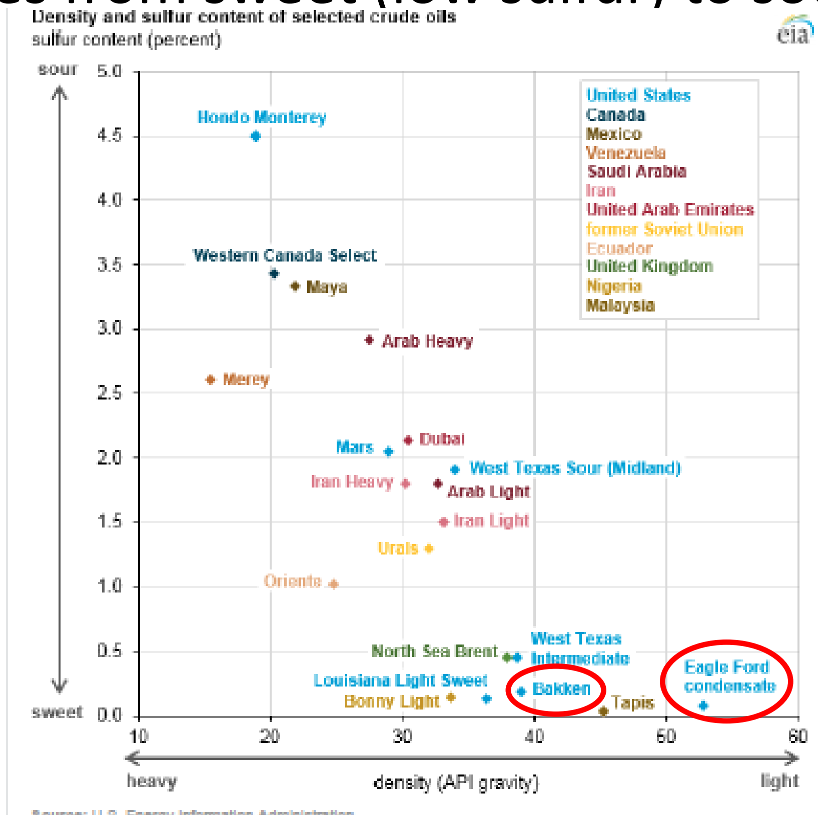
Sources: U.S. Energy Information Administration, Form EIA-23L, Annual Report of Domestic Oil and Gas Reserves, 1979–2019

Energy Prices Over Time

- Factors leading to lower prices
  - Competitive markets
    - Changes in the role of OPEC play a key role in oil prices. The supply of non-OPEC oil has increased
    - Complexity of oil markets leads to boom and bust cycles
      - Effective spare capacity, both upstream (exploration/drilling) and downstream (refining) matters
        - » Prices rise when spare capacity is low, because any shock will leave the market unable to react
          - Note how, like in our basic pricing model, concerns about the future of the market matter
  - The quality of oil also matters. This has caused complications for energy markets.

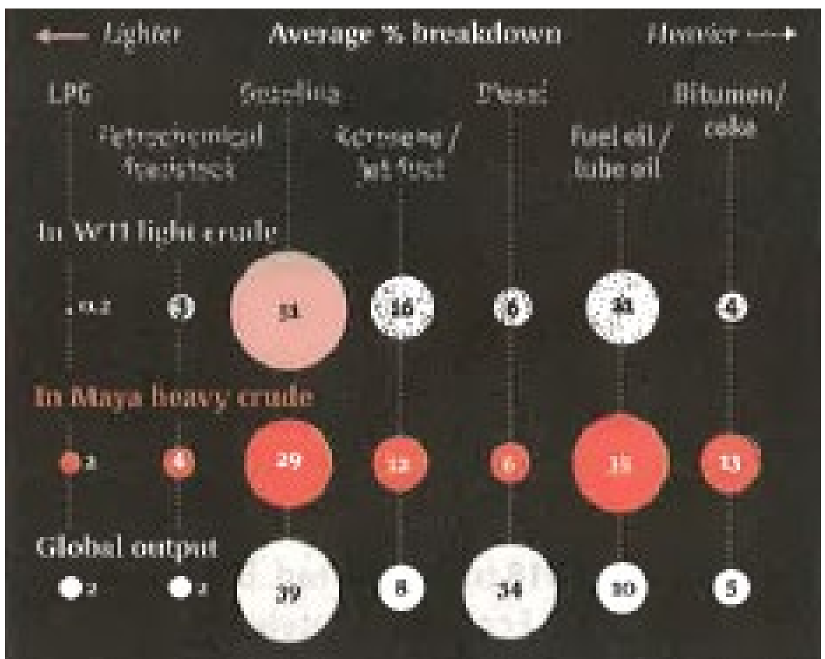
Quality of Oil Matters

- Two dimensions of oil quality
  - Density: ranges from light to heavy
    - Measured using American Petroleum Institute (API) gravity formula
  - Sulfur content: ranges from sweet (low sulfur) to sour (high sulfur)



Quality of Oil Matters

- Two dimensions of oil quality
  - Light sweet crudes used for gasoline
  - Heavier and sourer crudes best suited for diesel fuel and heavy fuel oils
    - It is costlier to refine heavier crude oil into gasoline



David Popp

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Quality of Oil Matters

- Two dimensions of oil quality
  - Conventional US oil is generally light sweet crude with API less than 40.
  - Shale oil has even higher API, and is thus even lighter
    - Thus, not always a perfect substitute for conventional oil, as these differences can affect the quality of refined products.
      - » But, it is well-suited for gasoline.

Quality of Oil Matters

- However, increase in shale oil supply caught refiners off guard
  - Because light sweet crude was becoming rarer, refineries were investing in technology to use with heavier and sourer crude oils
  - Also, pipeline infrastructure wasn't sufficient to transport oil from the central U.S to the east coast for refining
    - East coast refineries were best able to take on extra capacity
    - As a result, after 2011 US oil prices (West Texas Intermediate, or WTI) fell below world oil prices.
    - The gap began to shrink with the opening of new pipelines in 2014, including part of the Keystone XL pipeline.

Energy Prices Over Time

- Factors leading to lower prices
  - The model assumes constant marginal costs
    - Over time, technical progress has reduced the marginal cost of many resources.
    - Technological change has lowered extraction costs.
      - Lower extraction costs increase economic reserves => lower MUC as well.
    - Higher prices in recent years have made it feasible to extract energy from places with higher extraction costs.

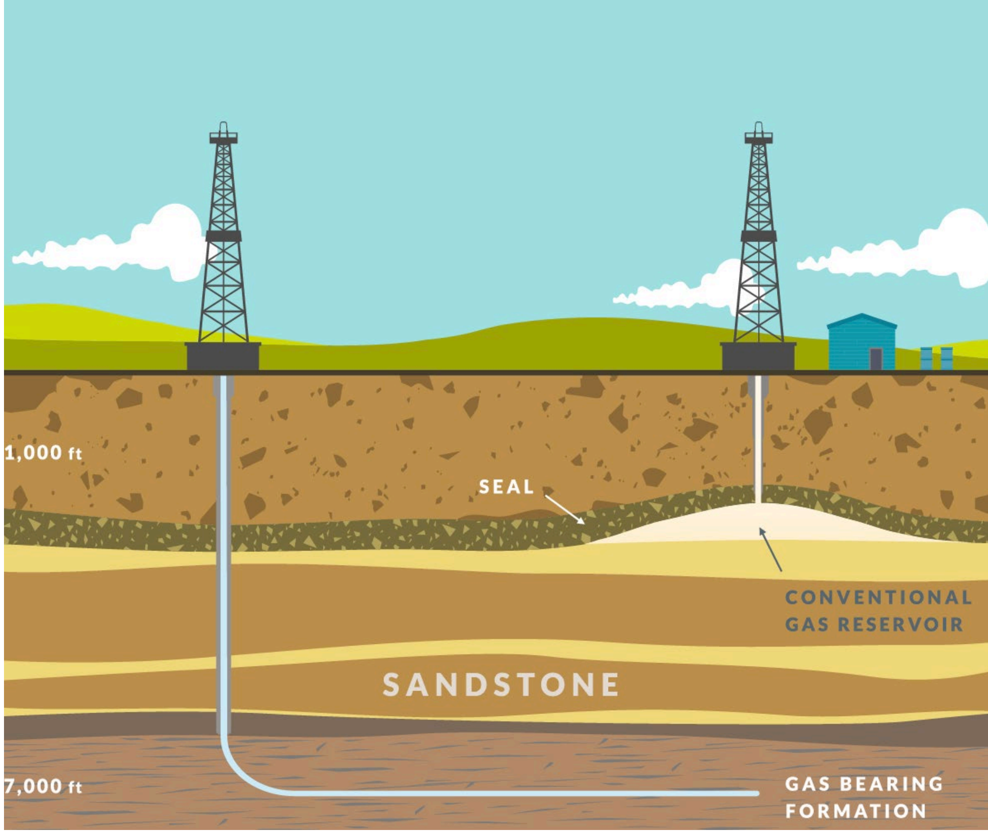
Hydraulic fracturing

- Hydraulic fracturing of shale oil is an example of technological change
  - Shale oil depends on three technological advances:
    - horizontal drilling
    - microseismic imaging
    - hydraulic fracturing

Hydraulic fracturing

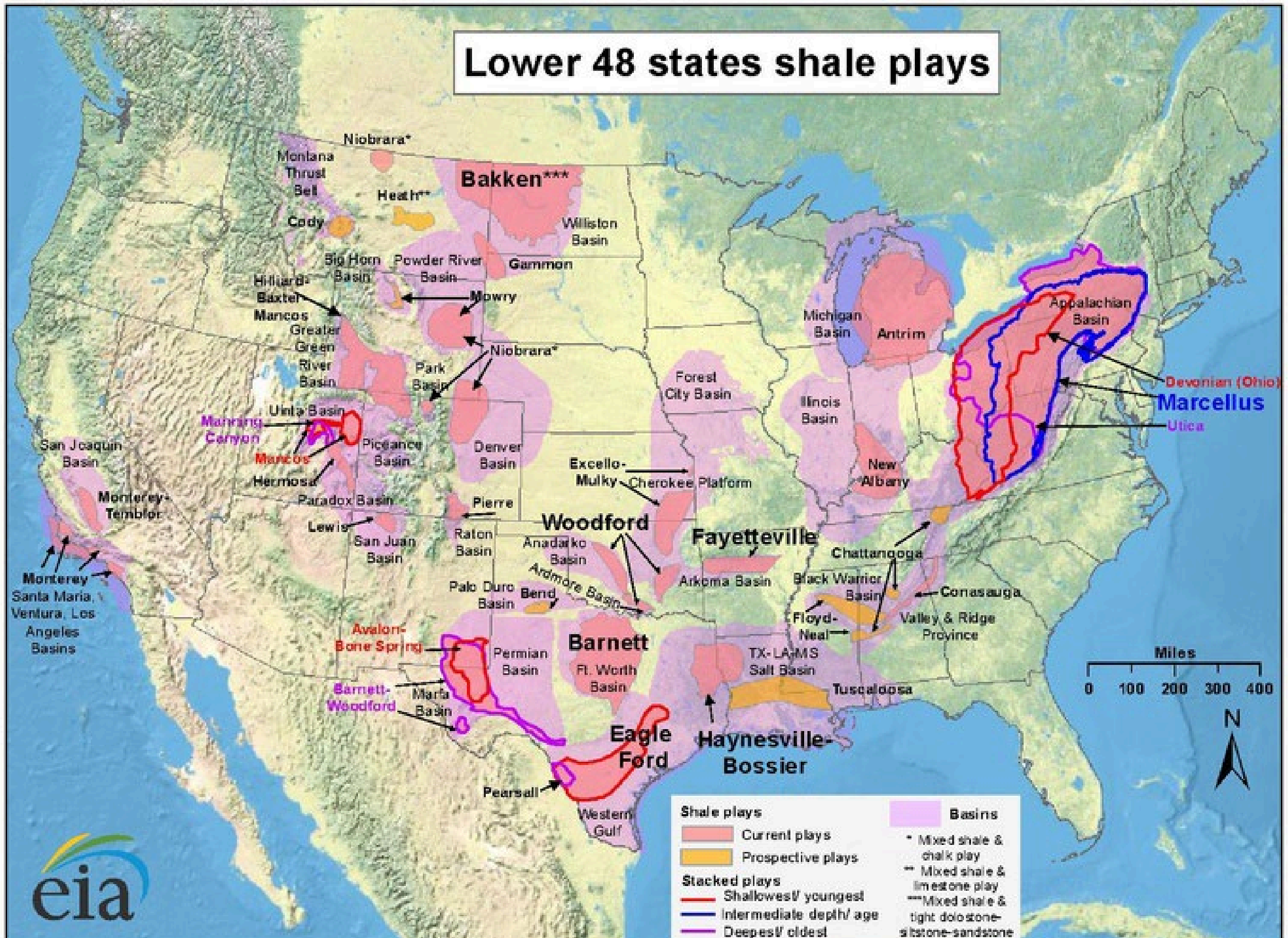
What is unconventional drilling?

- A large stock of natural gas that requires unconventional method, i.e. horizontal drilling and high-volume hydraulic fracturing (aka fracking) to extract
- Horizontal and directional wells drilled to extract shale gas are often referred as **unconventional wells** as opposed to conventional vertical wells
- Causes cracks and fissures in the rock formation that allow crude oil to escape



Hydraulic fracturing

Where are shale plays?



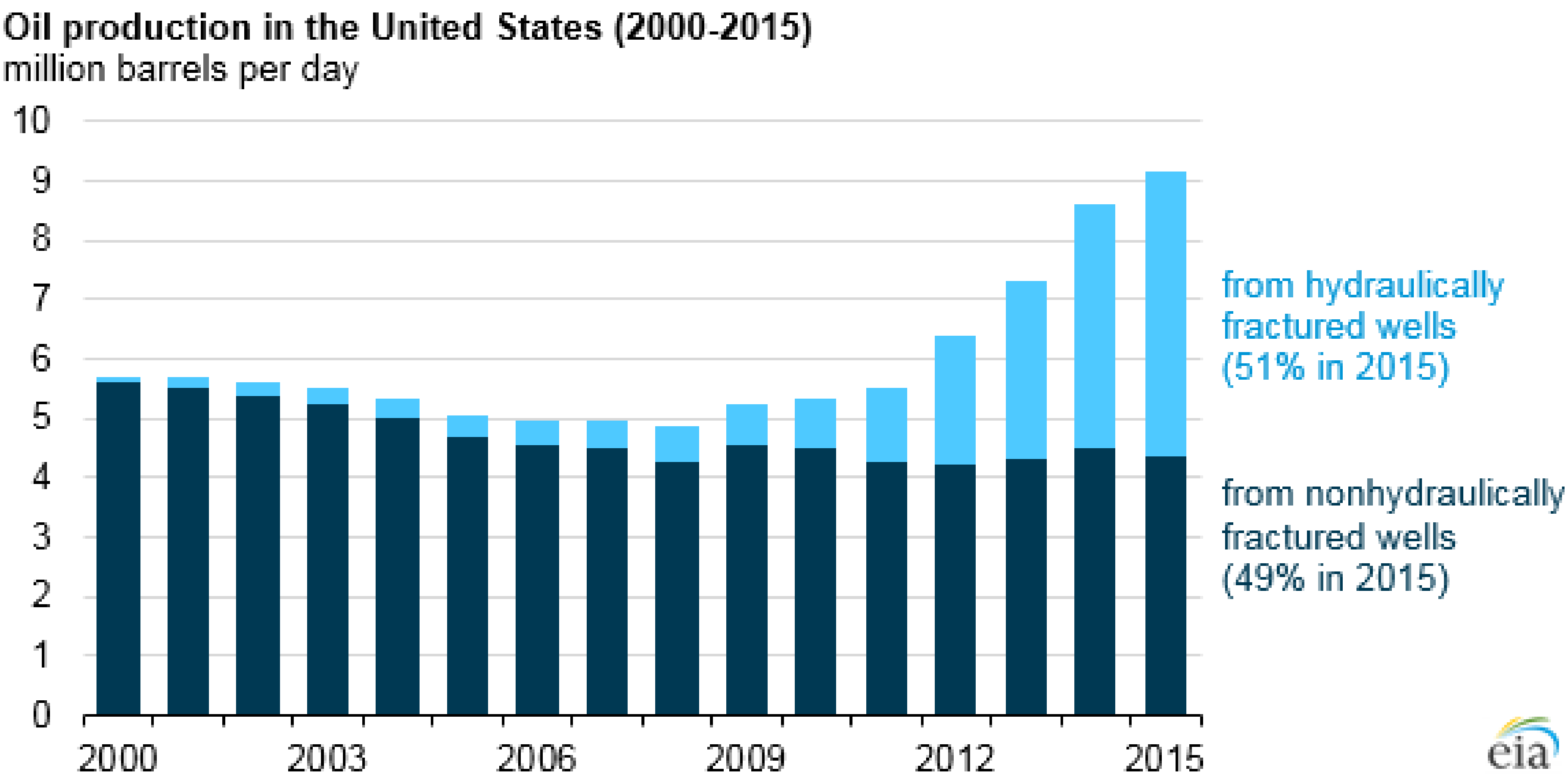
Source: Energy Information Administration based on data from various published studies.
Updated: May 9, 2011

Hydraulic fracturing

- Possible costs of fracking
  - Water resource impacts
    - Water used could reduce flows of rivers and streams
      - Quantities of surface water used are small
      - But most water usage concentrated during the fracturing process
        - If this occurs when water is scarcer (e.g. summer), may have an impact
    - Surface water pollution
      - These costs may be significant
    - Groundwater pollution
      - Determining causal effects often difficult.
    - Groundwater depletion not an issue in eastern U.S., but could be an issue in semi-arid areas
      - Little data on this yet
  - Increased seismic activity

Hydraulic fracturing

- Surge in fracking stimulated by high oil prices after 2003, which made the technology competitive
  - Since then, the cost of the technology has fallen
  - Energy companies become more efficient as gain experience and drill more wells
    - Advances include extending horizontal section farther
      - Requires more water and sand, but makes wells more productive
- Projected continued growth in US oil production comes entirely from shale oil



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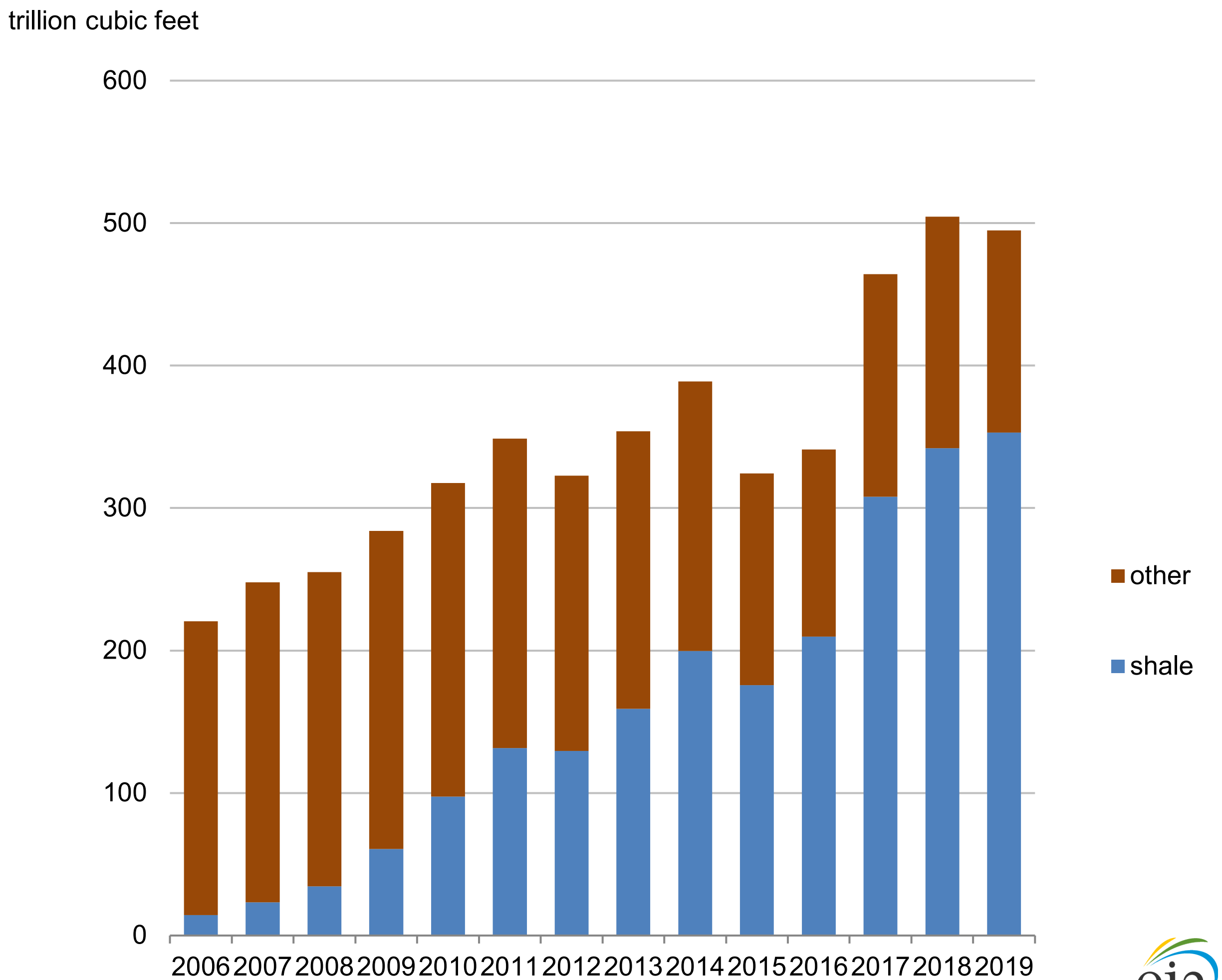
U.S. total natural gas proved reserves (shale and other sources), 2006–19



Source: U.S. Energy Information Administration, Form EIA-23L, *Annual Report of Domestic Oil and Gas Reserves, 2006–19*

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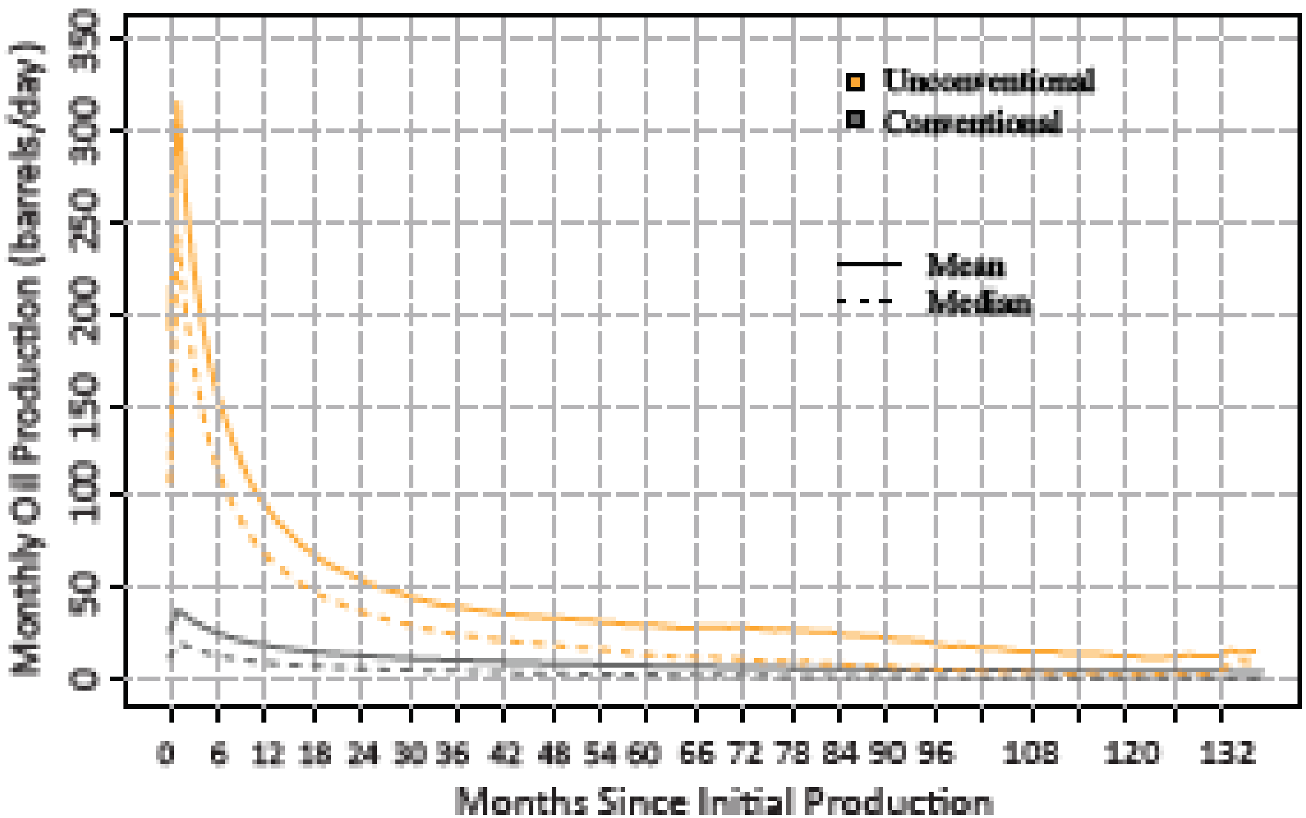
Hydraulic fracturing

- How has shale oil and gas affected prices?
  - Reduced US oil imports
  - Increased US exports of refined products
  - Building infrastructure to export natural gas
    - More pipelines (e.g. to Mexico)
    - Facilities for liquefied natural gas
  - Reduces volatility
    - Shale wells take longer to drill and reach production
    - But they produce more per well and have less variation in production
    - Thus shale oil and gas is more responsive to market prices
      - More so for natural gas, for which the market is primarily North America, rather than global

Figure 5. Mean and Median Profile of Monthly Oil Production, Oil Wells



Source: Newell & Prest, RFF Issue Brief 17-11

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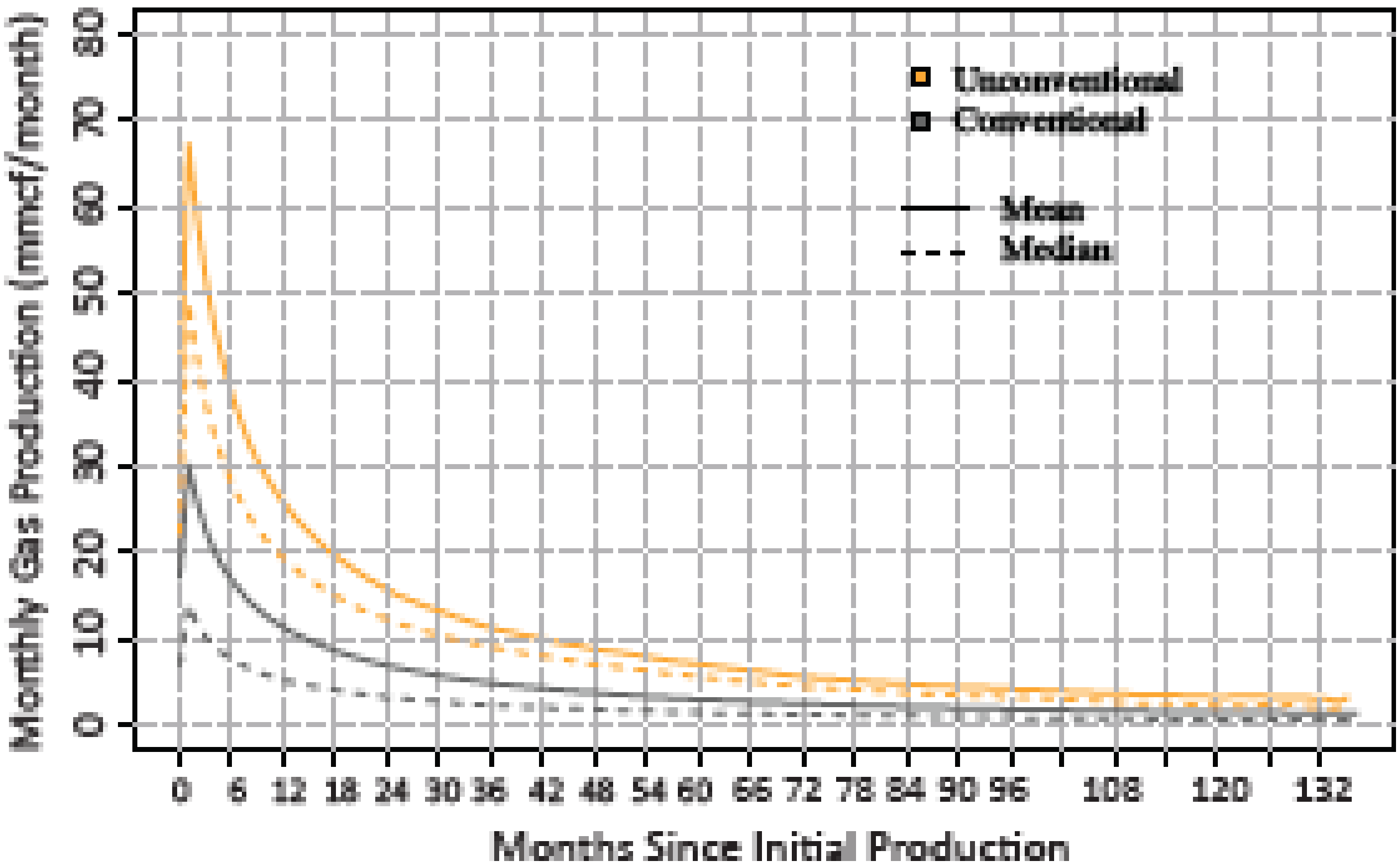
Figure 6. Mean and Median Profile of Monthly Gas Production, Gas Wells



Source: Newell & Prest, RFF Issue Brief 17-11

Figure 7a. Change in Oil Wells Beginning Production, following a 10% Price Shock

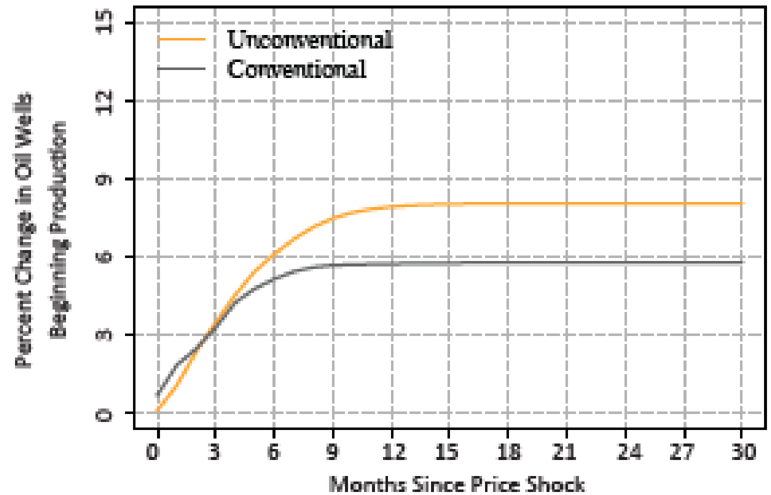
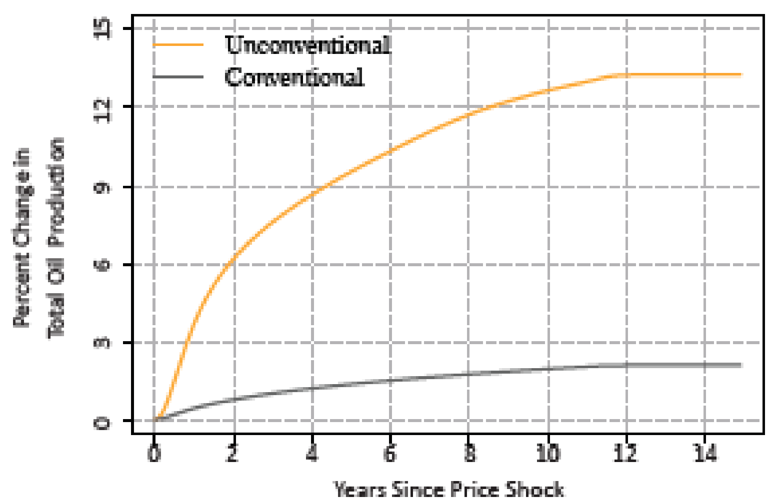


Figure 7b. Change in Oil Production from Oil Wells, following a 10% Price Shock



Source: Newell & Prest, RFF Issue Brief 17-11

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Figure 8a. Change in Gas Wells Beginning Production, following a 10% Price Shock

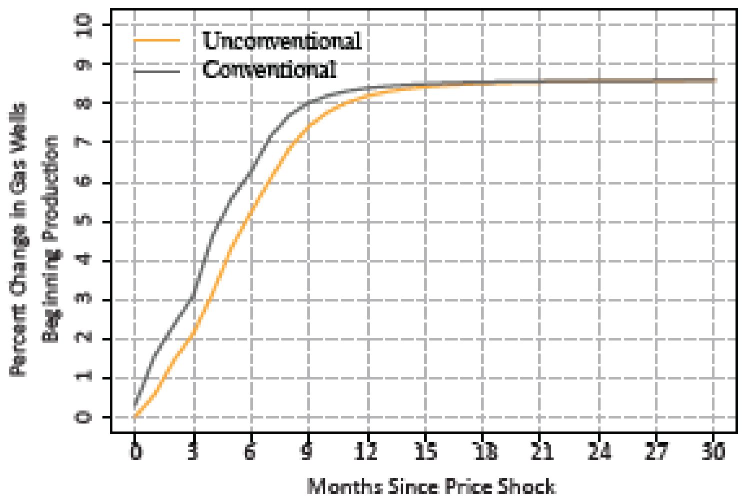
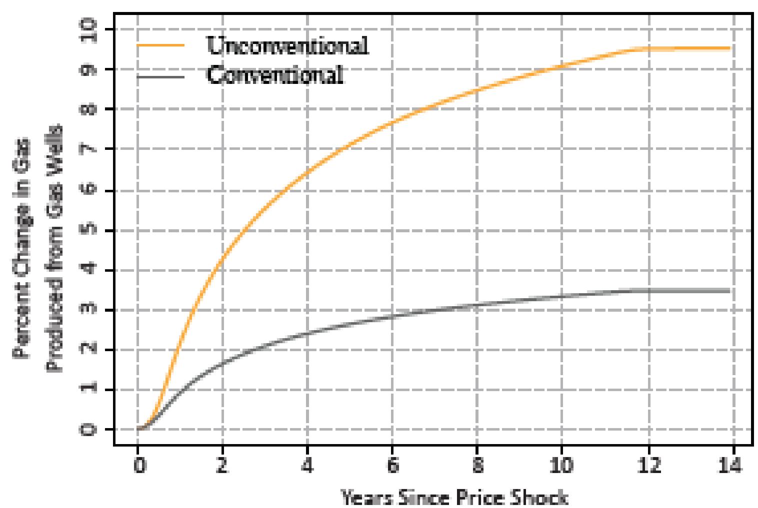


Figure 8b. Change in Gas Production from Gas Wells, following a 10% Price Shock



Source: Newell & Prest, RFF Issue Brief 17-11

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U.S. Power Plant Annual Emissions

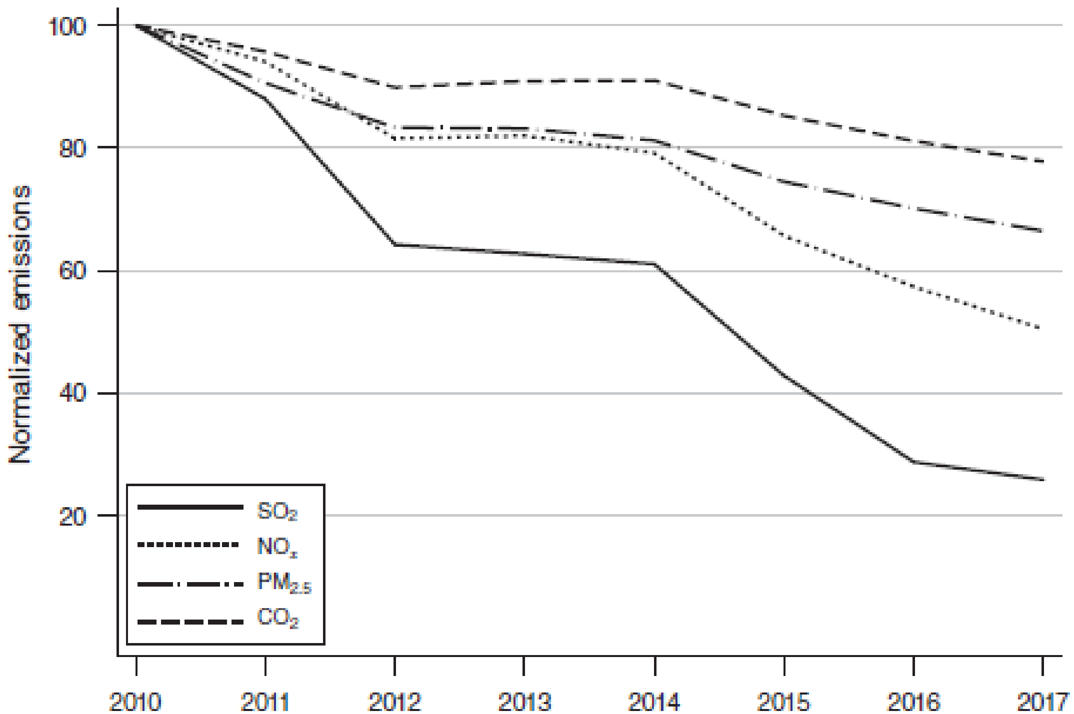

FIGURE 1. POWER PLANT EMISSIONS OF FOUR POLLUTANTS, 2010–2017

Note: This figure is normalized such that emissions in 2010 equal 100.

Source: EPA's Continuous Emissions Monitoring System (EPA 2010–2017)

Source: Holland et al. (*American Economic Journal: Economic Policy*, 2020)

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