Electricity markets
GEOS 24705/ ENST 24705
U.S. energy use is almost entirely from fossil fuels

U.S. energy use, 2005

Estimated Future U.S. Energy Requirements $\approx 96.8$ Quads)

= $3 \times 10^{12}$ W / 300M people = 10,000 W/person

from LLNL, in quads/yr : 1 Q / yr $\sim 10^{18}$ J / yr $\sim 30$ GW

Projection Year 2005
From Year 2005
Efficiency Year 2005
Energy Distribution Year 2005
Electrical grid operation: basic questions

• Why so many different voltages?

Note also different layout in E. and W.
Electrical grid operation: basic questions

• What controls how much power flows, and where?

Nothing except the balance of generation and demand – an entire interconnected grid is a single complex circuit. Imagine a plumbing system with interconnected pipes but no “valves” that control the flow of current. You can’t control what power flows where except by tinkering with inputs and outputs.

The U.S. grid is broken into 3 weakly connected regions, and not much power flows in between. But the regions are connected to Canada (strongly) & Mexico (weakly).

Texas is its own grid!
And its own regulatory entity.

Electrical grid operation: basic questions

• How big is the grid?

Total U.S. network: ~ 300,000 km

Most of this is high-voltage
  (> 250,000 km are > 230 kV)

Cost of high-voltage on average $1M/km

_Total value of the distribution part of the grid is of order $300 billion dollars._
Electrical grid: Who owns and manages what?

Color Key:
- Black: Generation
- Blue: Transmission
- Green: Distribution

Generating Station

Transmission lines 765, 500, 345, 230, and 138 kV

Substation Step Down Transformer

Subtransmission Customer 26kV and 69kV

Primary Customer 13kV and 4kV

Secondary Customer 120V and 240V

Generating Step Up Transformer

Transmission Customer 138kV or 230kV

For most of the 20th century, one entity owned all components in the chain. Now typically owned by 2 or 3 different entities, managed by another, and the market can be managed by an outside broker—up to 5 players in the game.

- Generator
- Transmitter (long-dist. wires)
- Grid operator (wires operator)
- Utility for distribution (local wires)
- Load-serving entity (seller to consumer)
Electrical grid: major regulatory shifts

1. UNIFYING AND CENTRALIZING GRID
2. INTRODUCING MARKET FORCES
3. DECENTRALIZING GENERATION
Electrical grid: major regulatory shifts

1. **UNIFYING AND CENTRALIZING GRID**: shift from disconnected organizations and transmission to unified transmission (3 grid regions), gradually more centralized authority

- Federal Power Act (1920, 1935, etc. amended), led to Federal Electricity Regulatory Commission (FERC) in 1977 to regulate rates (+ license hydro)
- Post-1964 blackout – more communication between utilities on voluntary basis to ensure reliability
- Voluntary reliability council (NERC) replaced by “Electric Reliability Organization” with actual enforcement authority in 2005
2. **INTRODUCING MARKET FORCES:** Transition from vertically integrated regional monopolies (one utility owns generation, transmission, distribution) to competitive systems

- 1992 Energy Policy Act: FERC can order a company to carry power for someone else
- FERC orders through 1996 encourage formation of Regional Transmission Organizations (RTOs)
- In most places now: utility or load-serving entity buys from multiple independent generators, with a market for power and hourly pricing
- Possibly in the works: proposals for market system on retail side too (req. hourly pricing)
- Still problematic: competitive distribution
3. **DECENTRALIZING GENERATION**: Encouragement of distributed power:

- Small (2-10 MW) operators can sell at market rate by Federal law
- Demand-side management, or DSM (pay for “negawatt” generation) is now an option in some markets, areas
Electrical grid organization and management: basic questions

- Who owns what? (generation, transmission, distribution)

High-voltage transmission: generally owned by utilities, managed by RTOs (regional transmission organizations), themselves owned by groups of utilities.

**Definition: Regional Transmission Organization**

"An entity that is independent from all generation and power marketing interests and has exclusive responsibility for grid operations, short-term reliability, and transmission service within a region.”
**Definition: Regional Transmission Organization**

An RTO is an entity created to balance generation across a regional footprint regardless of ownership of generation. Invented to promote competition and hopefully efficiency.

RTOs eliminate the need for generators to contract with separate utilities to sell and transmit power, and prevent integrated utilities to favor their own generation and block transmission of competitors. The goal is to create a transparent market to incentivize more optimal building and dispatching of generation.
Electrical grid organization and management: basic questions

- Who owns what? (generation, transmission, distribution)

RTOs as of 2010 (ISO/RTO Council)

Note: Chicago area is part of PJM, not of MISO
Electrical grid organization and management: basic questions

- Who owns what? (generation, transmission, distribution)

**RTO exceptions:**

**Arizona:** from electricity standpoint is essentially a colony of California – its generation not managed by RTO, but independent generators make long-term contracts with California, sell into California markets.

**Texas:** The only state where a single agency regulates both the generation/transmission side (wholesale prices) and demand side (retail rates). Texas is its own RTO, full state-wide authority. Makes planning much easier to have one central power.

**SE U.S.** is traditional utility ownership and operation on big scales (e.g. TVA, The Southern Company) so no need for RTOs

**Rocky Mtn. corridor** doesn’t have much transmission
Electrical grid organization and management: basic questions

- **Who owns what?** (generation, transmission, distribution)

**Distribution:** owned by utilities: 3170 total in U.S. (75% of customers served by 239 investor-owned; remainder public, co-op, Federal)

The primary job of utilities (like ComEd) is to maintain a distribution network and to sell power to residential, commercial, and industrial customers.

Many utilities still generate much of the power they carry, but some generate none. The businesses of generating and selling are becoming decoupled. You can even bypass the utility for your electricity purchase and ONLY pay them for the distribution service. Very analogous to phone system after deregulation.
Electrical grid organization and management: basic questions

• Who owns what? (generation, transmission, distribution)

**Generation:** can be owned by utilities but also by independent power producers who sell on the open market

Example: Exelon, who own Dresden nuclear generating station, is not a utility. It is mostly a power company that owns power plants and sells their output to utilities or RTOs.

Exelon **owns** ComEd – the utility is a subsidiary of Exelon, not the other way around. When the lights go out, the guys (or gals) who come fix it will wear ComEd hardhats, not Exelon hardhats.
Electrical grid organization and management: basic questions

• Who owns what? (generation, transmission, distribution)

Summary of ownership

Utilities are “wires” companies. They own the lines, repair the lines, process the billing, take payment from retail customers.

RTOs are managers: (for most people, though not everywhere): manage the market (buy and sell, set clearing prices), exercise minute-by-minute control of generation and congestion management (call to get plants turned on or off)

Anyone can be a generator: in market system power production is open to all
Electrical grid organization and management: basic questions

- 3 markets for electricity generation

For electrical power itself

- **Day-ahead market** payment made under contract to provide power if needed at market-clearing price
- **Real-time market** emergency purchases of power as needed minute by minute at pre-set rates

For electrical capacity

- **Capacity markets** payments made to all generators in RTO simply for existing to provide backup (ca. 2% of elect. price)
Electrical grid organization and management: basic questions

• Who pays, and to who?

**RTO:** Every day the RTO buys all the power that will be used and sells all that power.

Each day the RTO forecasts power demand for next day. Each day the generators all send in “bids” stating how much they’ll be willing to sell their power for. The RTO then buys all the power it thinks will be needed, at the *marginal price*. I.e. everyone gets the price of the highest-priced seller whose power is bought.

But, the RTO doesn’t actually write a check to those generators til the power is used. If power isn’t needed after all, no $ change hands. Only if power is generated does the RTO writes a check to generators.

The RTO then turns around and sells all that power to utilities, who then sell it to their customers. The utilities write a check to the RTO.
Electrical grid organization and management: basic questions

- **Who pays, and to who?**

**RTO:** Every day the RTO buys all the power that will be used and sells all that power.

**Utilities:** The utilities pay the RTO.

Utilities can also make “bilateral contracts” with particular generators, to lock in that power for the utility at a given price. If so, the utility then pays the generator just the difference between the market price and the contract price. This is a hedging strategy to minimize risk.
Electrical grid organization and management: basic questions

- **Who pays, and to who?**

**RTO:** Every day the RTO buys all the power that will be used and sells all that power.

**Utilities:** The utilities pay the RTO.

**Generators:** Sell to RTOs. Also get $ from contracts with utilities.

Generators can also sell directly to customers IF on private land and if the distribution network can be bypassed.

And, generators are also paid not for power but simply for existing, to provide power if necessary. ("Capacity" market)
Electrical grid organization and management: basic questions

• Who pays, and to who?

**RTO:** Every day the RTO buys all the power that will be used and sells all that power.

**Utilities:** The utilities pay the RTO.

**Generators:** Sell to RTOs.

**Residential power customers:** pay $ to the utilities
Electrical grid organization and management: basic questions

• Who pays, and to who?

**RTO:** Every day the RTO buys all the power that will be used and sells all that power.

**Utilities:** The utilities pay the RTO.

**Generators:** Sell to RTOs.

**Residential power customers:** pay $ to the utilities

**Transmission owners:** receive payment from the RTO, but just for recovering costs – fixed return on investment. (Need permission to build, though).

*Note:* If transmission owners are also generators they have insufficient incentive to build more transmission, since get more money for generation if it must be local because of congestion. (Even 15% return w/ no risk from building transmission won’t outweigh the profit from generation).
Electrical grid organization and management: basic questions

• Who sets the amounts that people pay?

   \textit{In the old days}

The utilities owned everything, and would charge customers enough to recover their costs. The state utilities commission would approve the rates.

   \textit{Nowadays}

\textbf{Generator price set by the day-ahead market:} Sets the hour by hour price that generators receive for power or for capacity.

\textbf{Wholesale price set by market and by FERC:} Sets the markup that the RTO can charge over market. Sets the transmission rates.

\textbf{Retail price set by state utilities commissions:} Determines the rates that the utilities can charge their customers. Flat rates – no hourly changes.
Usefulness of electricity market driven by 1) diurnal demand curve

High Summer demand day

High Winter demand day

Image: World Nuclear Org.
Usefulness of electricity market driven by different operating cost for different generation technologies

Market clearing means that everyone receives the price bid by the last (most expensive) generator whose bid is accepted. (Hourly bids).

Nuclear will bid zero because it wants to be on always and its operating costs are tiny. Oil is expensive so will bid high – will only turn on if price > operating costs.
Expensive peakers are turned on only during max load

Baseload power stays on all the time. High-marginal-cost power is purchased only during times of day when demand is highest.

During those times, the baseload providers also get peak prices – so some gaming of the system is possible (e.g. Enron)

Figure 11: Generation source for a typical daily demand profile. Courtesy of NGC 2007
(CCGT: Combined Cycle Gas Turbines).
Peakers vs. baseload:
Conveniently, the expensive marginal cost generation is fast to turn on and off, so these can be used as peakers.

<table>
<thead>
<tr>
<th>Generation Type</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumped Storage</td>
<td>10 seconds</td>
</tr>
<tr>
<td>Gas Turbines</td>
<td>2 minutes</td>
</tr>
<tr>
<td>Combined Cycle Gas Turbine</td>
<td>6 hours</td>
</tr>
<tr>
<td>Oil Fired</td>
<td>8 hours</td>
</tr>
<tr>
<td>Small Coal</td>
<td>12 hours</td>
</tr>
<tr>
<td>Large Coal</td>
<td>24 hours</td>
</tr>
<tr>
<td>Nuclear</td>
<td>48 hours</td>
</tr>
</tbody>
</table>

Table 4: Typical Response Times of various forms of Power Generation
(National Grid Company, 2007).
**Peaker vs. baseload allows market for generation**
Generators are turned on when their bid is below market-clearing price

Generators bid their marginal costs ... then each generator receives the market-clearing price when it is turned on.

Should in theory result in incentives for building more efficient generating capacity, also for clever peak-shaving strategies (demand reduction, storage, etc.)

Note: the new market system does not guarantee that the user will get a lower price than in the old monopoly system. He now pays the **marginal** cost of electricity generation rather than the **average** cost. And the marginal cost is always higher than the average cost. The theory is that eventually retail prices will drop – but immediately on adoption of the market they will rise.
Electricity strategies driven by the diurnal cycle

**Peakers:** buy high cost but fast turn-on generation that can come on just for the peak energy demand period

**Peak-shaving:** buy electricity when it’s cheap and store it, then sell it back to the grid when it’s expensive

**Demand-side management:** sign contracts with customers forcing them to turn off if demand is too high

**Demand-side management:** introduce time-variable pricing for customers to incentivize less use at peak periods, more off-peak

**Load-dumping:** since baseload power can’t turn off, sometimes just have to dump it if have too much
Forms of fossil fuels

- **Solid:** coal, peat

- **Liquid:** crude oil

- **Gas:** natural gas

In use throughout history – coal in Britain already main fuel in 1500s, getting scarce in 1600s

Significant use only in 1800s

Significant use only after 1900

**Why?** Extracting liquid or gas required more technology than mining a solid – and first use of coal was from surface exposure
Forms of fossil fuels

Early 1800s alternatives for lighting

- **Liquid:**

- **Gas:**
Forms of fossil fuels

Early 1800s alternatives for lighting

- **Liquid:** whale oil
- **Gas:** coal gas
“Peak whale oil” was hit around 1850 with expected corresponding rise in prices.
Natural oil seeps were used from antiquity

Natural seeps of crude oil and asphalt were used early. Words for asphalt exist in ancient Sumerian, Sanskrit, Assyrian, Greek, etc. Native Americans collected oil seeps on rivers by skimming with blankets. Asphalt used to caulk boats by 3800 B.C., paved Baghdad in 8th century. Uses: glue, sealing boats and baths, mixed with sand etc. for mortar, medicine, lamps, mummification, warfare (“Greek fire”, liquid that ignited on contact with water), paintings.

Tarwater Creek, Santa Cruz Mountains, CA.

Photo: USGS
Natural oil seeps were used from antiquity

Genesis 6:14

\textit{Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch}

Exodus 2:3

\textit{And when she could not longer hide him, she took for him an ark of bulrushes, and daubed it with slime and pitch, and put the child therein ...}

\textbf{Hand-dug oil wells at Bibi-Eibat, Azerbaijan, mid-1800s?}
\textit{From: San Joaquin Geological Society.}

\textbf{Temple of the Fire Worshipers at Ateshkah, Azerbaijan, natural gas seeps continually burning for millennia. From: San Joaquin Geological Society.}
Distillation of crude oil also has long history

Distillation = separation of components by boiling point

Distillation used by Arab chemists by ~ year 0 to produce petroleum products

Commercial petroleum distilling by 1270s in Persia (described by Marco Polo)

Early Industrial Revolution: distilled naphtha and kerosene
Oil production then takes off
Modern era begins with first well in Titusville, 1859

Site is long known “Oil Creek”, oil was nuisance. Purposeful drilling for oil instigated by businessmen looking for lighting alternative
Oil production boomed by x 1500 in 4 yrs, x 5000 in 15 years

Phillips and Woodford wells on Oil Creek, PA, 1861

From Pennsylvania Historical & Museum Commission,
Drake Well Museum Collection, Titusville, PA
Oil production then takes off
Modern era begins with first well in Titusville, 1859

Refineries and pipelines by 1870s (Rockefeller’s Standard Oil founded 1870) – for kerosene, gasoline was waste product – too volatile and flammable for use for lighting

1878: Edison’s lightbulb reduces kerosene demand, causes oil industry slump
1886: invention of car provides market for gasoline

By WWI U.S. is dominant oil producer (Texas, California) and exporter, followed by Russia

Oil barrels (1860s?)
Titusville.

As much as 50% of oil was lost to spillage in production & transport (Paleontological Research Assn.)
Petroleum refining output: 100 x as much gasoline as kerosene

<table>
<thead>
<tr>
<th>Crude Oil Hydrocarbons</th>
<th>Symbol</th>
<th>Name</th>
<th>Phase</th>
<th>Products</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH₄</td>
<td>Methane</td>
<td>Gas</td>
<td>Petroleum Gas</td>
</tr>
<tr>
<td></td>
<td>C₂H₆</td>
<td>Ethane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₃H₈</td>
<td>Propane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₄H₁₀</td>
<td>Butane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₅H₁₂</td>
<td>Pentane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₆H₁₄</td>
<td>Hexane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₇H₁₆</td>
<td>Heptane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₈H₁₈</td>
<td>Octane</td>
<td>Liquid</td>
<td>Gasoline</td>
</tr>
<tr>
<td></td>
<td>C₉H₂₀</td>
<td>Nonane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₀H₂₂</td>
<td>Decane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₁H₂₄</td>
<td>Undecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₂H₂₆</td>
<td>Dodecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₃H₂₈</td>
<td>Tridecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₄H₃₀</td>
<td>Tetradecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₅H₃₂</td>
<td>Pentadecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₆H₃₄</td>
<td>Hexadecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₇H₃₆</td>
<td>Heptadecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₈H₃₈</td>
<td>Octadecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₁₉H₄₀</td>
<td>Nonadecane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₀H₄₂</td>
<td>Eicosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₁H₄₄</td>
<td>Heneicosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₂H₄₆</td>
<td>Docosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₃H₄₈</td>
<td>Tricosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₄H₅₀</td>
<td>Tetracosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₅H₅₂</td>
<td>Pentacosane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C₂₆+H₅₆+</td>
<td>---</td>
<td>Solid</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lubricating Oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heating Oil</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Kerosene</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jet Fuel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gasoline</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Petroleum Gas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In 42 gal Barrel:

- 20 gal
- 0.2 gal
- 4 gal
- 9 gal
- 0.5 gal
- 2 gal
- 6 gal other

From: Clean Coal Technology of Texas
Crude oil is mixture of many different components

Long-chain hydrocarbons make it viscous (thick and sticky)

Canadian crude has viscosity similar to molasses, can get 10 x more viscous

Soldiers from the South Korean army clean up crude-oil spills over Mallipo Beach after an accident involving a Hong Kong-registered tanker in Taean, about 106 miles southwest of Seoul, on December 10, 2007.
Crude oil is a mixture of many different components.

Refining = separating crude oil into components, also altering the chemistry of those components.

1. Distillation – separating components of crude oil
2. Catalytic cracking – breaking down components
3. Reforming – combining constituents

Paraffins

Naphthenes

Aromatics
Petroleum refining: separation of useful components of crude
“nose to tail” use of output – waste nothing

From: California Energy Commission,
orig. from American Petroleum Institute
Petroleum refining:
Distillation = separating components of crude oil according to boiling points. In practice separates by weight of molecules.

Different vapor pressures of different constituents allow separation by distillation – the heaviest components condense out first (near bottom of column).

From: Institute of Petroleum
Petroleum refining:

Distillation

Distillation requires vertical length, so distillation towers are easy to spot at a refinery.
Petroleum refining:
Cracking = chemical breaking of molecules into smaller parts

Cracking can be done via catalyst or via steam; most now is catalytic. Techniques as old as 1855, first commercial catalytic 1930s.

Shukhov thermal cracking plant, Baku USSR 1934 (Wikipedia)
Petroleum refining:
Cracking

Cracking can be done via catalyst or via steam; most now is catalytic. Techniques as old as 1855, first commercial catalytic 1937.

Modern catalytic cracker. From: Corbis
Petroleum refining:
Reforming = chemical alteration

1. Dehydrogenation

2. Isomerization

3. Aromatization

4. Hydrocracking

From: Citizendium
Petroleum refining:
Reforming

From: Citizendium
Middle east modern oil industry has roots just as long

First drilled oil well in Baku, Azerbaijan in 1848 (before Titusville)

Nobel oil field in Balakhani, Azerbaijan, 1890s – Swedish-owned by Nobel brothers, one of whom goes on to invent dynamite and found a famous prize…From: San Joaquin Geological Society
High-pressure oil, no need for pumps – derricks only

R: Baku, Azerbaijan, 1890, building levees to try to save oil from gusher. Image from: San Joaquin Geological Society

L: The famous 1901 Lucas gusher in Spindletop dome, Texas, gushing more oil than the rest of the country’s production together. Image from: American Petroleum Institute
No more gushers: lower-pressure oil requires a pump
“Nodding donkeys”: beam pump to pump liquids from ground

Not a true beam engine. Typically use diesel engines, but reciprocating cylinders -> rotary motion motion and then -> linear motion of larger beam.

Can’t use linear motion of diesel engine cylinders since are too short and move too quickly.

Image: Tony Waltham

Gearbox
http://www.youtube.com/watch?v=FU0dYV3LvAk&feature=related

Sucker rod pump:
http://www.youtube.com/watch?v=SFJFiyXTOa0
Exhaustion of “easy” U.S. oil means increasing complexity of extraction and transport distance

First offshore platform off Louisiana in 1938 (100 foot depth)
After WWII oil in Arabian Middle East developed
1973 OPEC embargo prompted construction of Trans-Alaska pipeline (1977)

Now
Enhanced oil recovery (gas or CO$_2$ injection, steam heat) squeezes oil from marginal fields
Major production from oil sands began ~ 2003
Oil produced from deeper and deeper waters: BP “Deepwater Horizon” is 5000 ft (1500 m)
Industry projected extraction from 8000 ft water depths ... and wells to > 35,000 ft.

Petrobras P-51 oil and gas platform off the Brazilian coast: 180,000 barrels oil and 6M cubic meters gas per day.

Photo: Petrobras
Floating oil platforms allow deepwater production

Wells drilled from drill rigs, then replaced by production platforms. One platform can serve many slant wells, processing to separate oil from mud, gas, water, etc.

Generally wells need pumping. No rod pumps though! Too deep for them.

Blowout prevention system (BOP) seals well if back pressure detected.

Hibernia platform, world’s largest oil platform, N. Atlantic off Canada, gravity base structure, 50 wells drilled