EON Geothermal Workshop

Transformative Economics

May 7, 2019

LucidCatalyst

EON's Mission and Vision

- EON's mission is to multiply and accelerate the real zero-carbon energy technology options available for large-scale, affordable, market-based decarbonization of the global economy over a wide range of future scenarios. (health and prosperity)
- We do this by conducting credible research and analysis on promising innovative technologies and identifying the full range of global strategies – government policy, new investment and business models, etc. to move zero carbon energy technologies from "promising" to commercial available.

Each element of this mission statement deserves explanation

- **Multiply and accelerate**: Because we cannot reliably predict future energy demand or the amount and timing of associated CO_2 emissions reduction that may be needed, we must rapidly develop a more robust set of zero-carbon energy technology solutions than is currently available to cover the broad and uncertain cloud of possible futures.

- **Real energy technology options:** Large-scale change cannot occur unless the solutions are real possibilities that are functionally adequate and demonstrated.

- **Available:** The solutions must be ready to be broadly implemented, at commercial scale, commercial risk levels, and commercially financeable.

- **Large-scale:** The global economy might grow by as much as a factor of four by 2050, and global energy demand could potentially grow by a factor of 10 this century. We need energy solutions that can be deployed faster, and at a larger scale, than any energy technology has been in history.

- **Affordable**: No solution will ultimately be able to achieve the necessary scale unless it is affordable. Solutions need to be either economically competitive with carbon-emitting alternatives or have sufficiently small incremental costs to make the policy drivers needed to deploy them politically feasible. Even if there were a consensus around policy backed by real political will, we would still need to use the power of the market to make changes of the necessary scope. Targeted policies can support this process, but it would be unacceptably risky to rely solely on policy as the primary driver of large-scale deployment for the foreseeable future.

Each element of this mission statement deserves explanation

- **Decarbonization:** To stabilize climate at moderate levels of warming, global CO2 emissions will need to eventually drop to virtually zero, at the same time as there is massive growth in the world economy and concomitant energy demand.

- **Global:** Solutions must be available for the many different contexts beyond today's developed world. Nearly all population growth and at least three-quarters of energy demand growth this century will occur in developing countries. Political, cultural, economic, and energy resource contexts will vary widely across those regions, requiring energy technology solutions appropriate to diverse contexts.

- **Economy:** Massive growth of the global economy, lifting billions from poverty, may well be a precondition for population stabilization, as has been suggested in recent research. The sooner this wealth is generated, the lower the global peak population number and associated energy demand is likely to be.

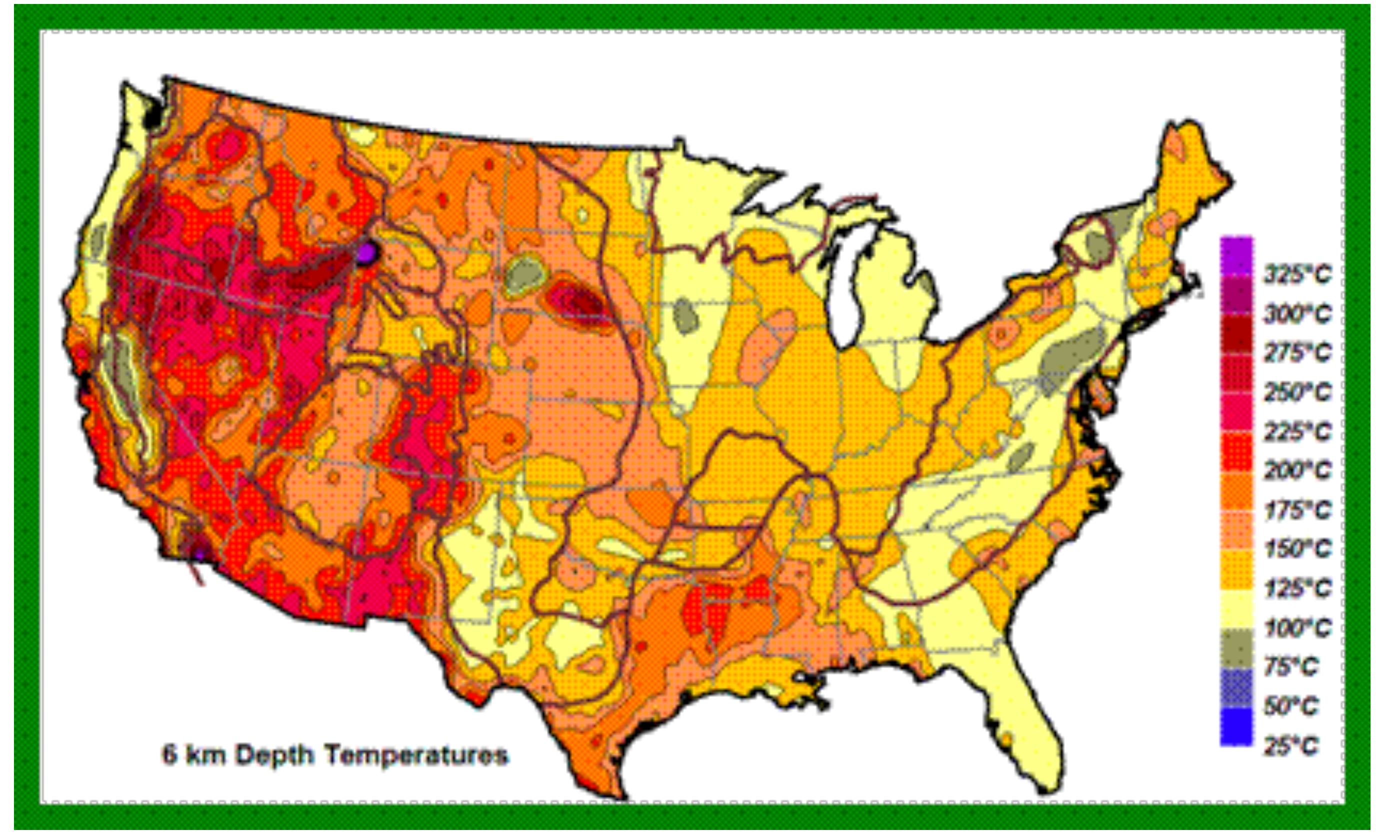
- **Wide range of future scenarios:** The many climate science uncertainties today preclude reliable predictions of global impacts resulting from significantly increased GHG (greenhouse gas) emissions. Large uncertainties exist about future energy demand due to variables such as population and economic growth, increases in per capita energy consumption, and other factors. These combined uncertainties suggest that the sensible approach is to quickly develop a set of affordable energy technology solutions that can solve the problem over the full range of future scenarios: high to low population growth, fast to slow economic growth, high to low energy intensity, slower or faster decarbonization, severe to moderate climate forcing, and moderate to severe climate effects. In summary, we need to plan for the worst, while hoping for the best.

SEGS could be one of the most effective climate solutions we have seen

- Large scale
- Global
- Low cost
- Rapid deployment
- Conversion of existing fossil power plants
- Decarbonization beyond electricity

Large Scale

- Map and sizing from Tester
- MIT report estimates 6,000x US energy consumption (check)
- Properly constructed projects will have a long life, reducing the requirement for rebuilding

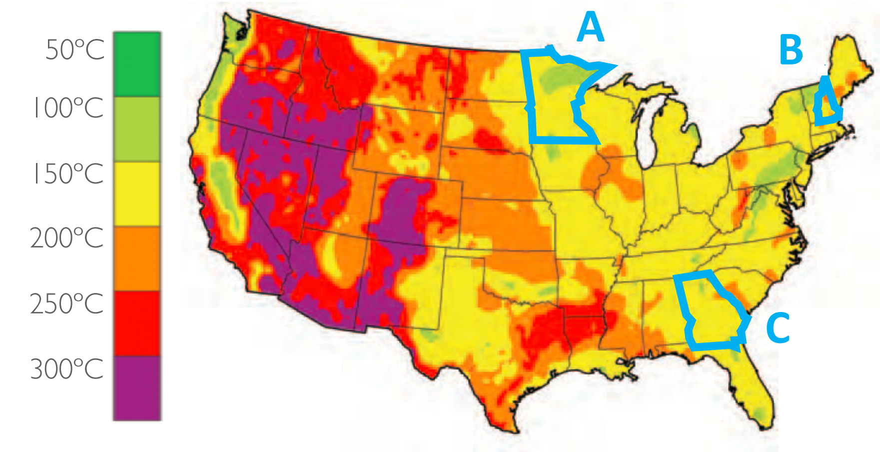


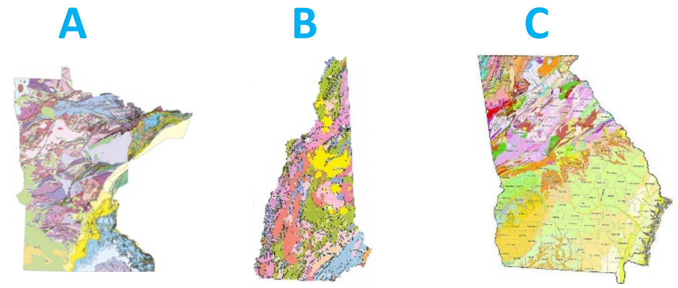
Geographic Applicability of Supercritical Steam

Supercritical geothermal applications require crystalline rock of a specific thermal gradient and density

- Geothermal gradients are affected by crust thickness and radioactive decay in minerals within the crystalline structure. For example, granitic rock outcrops may be heated by the presence of radioactive isotopes as opposed to proximity to the mantle
  - Where granite reaches the surface, the geothermal gradient is usually high, typically 40 C/km or more.
- On average around the world, the thermal gradient on dry land is around 25 C/km, however there are many local differences depending on the exact geology in a location
- In almost any country places with 40 C/km can be found, sometimes 50 C/km or higher (Iceland, Japan, Italy, Turkey, Philippines, etc.)

Est. Temperatures at 10km





Although the US map above suggests low temperatures at depth (10km) in the states highlighted, there are a number of crystalline rock outcroppings that have thermal gradients high enough for SCS geothermal projects

Global

- Global resource (map)
- Transferable to or developable in most countries
  - Particularly useful in countries planning large coal plant builds (India)
- No more complicated than O&G and Existing geothermal (to operate) which are all over the world.
- Operating characteristics are excellent for emerging grids and mature grids
- Heat can supply industrial processes,

Low Cost due to dramatically better power density wells

- ~5-10x improvement in well output for a ~2-4x increase in cost
  - Traditional geothermal well is 5MWe
  - Supercritical well can be 25-50MWe
- Supercritical Steam enables other cost reduction in project performance compared to traditional geothermal
  - Improved conversion efficiency from higher temp fluid (1.2-1.5x)
  - Reduced pumping load reduces capex and parasitic load compared to EG 1.2-1.3x
  - Higher energy density/flow rate of supercritical fluid reduces # of production wells per unit of power output (1.5-3x)
- BOP cost is $2-3,000/kW for <50MWe with low temperature and

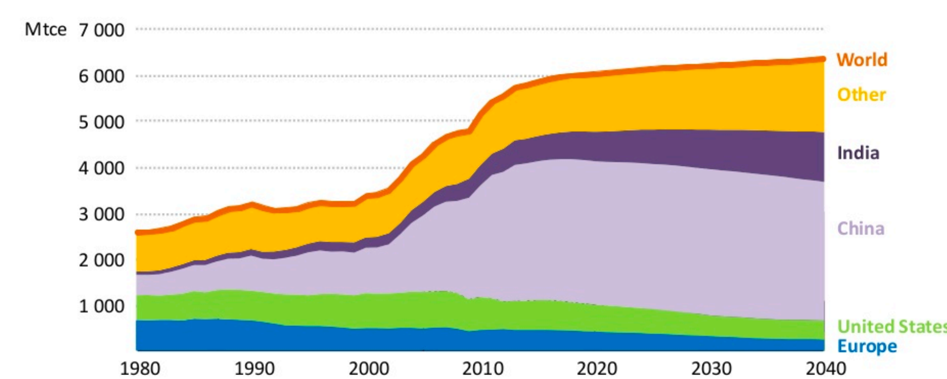
Low Cost due to larger projects driving lower balance of plant costs

- Traditional geothermal projects are small (e.g. Geysers-largest in the world at ~1,000-1,500MW consists of 22 plants = ~60MW each)
- For traditional geothermal plants BOP cost is $2-3,000/kW for <50MWe driven by:
  - Wet steam/low temperature
  - Small size
- BOP for 500MW and supercritical conditions is $350-700/kW, this alone can result in a 40-50% reduction in cost/kW
- Higher power density wells, higher conversion efficiency, and larger equipment all drive large reductions in operating cost/MWh as well.

Conversion of existing fossil power plants is essential

- We need technologies to convert existing coal plants (especially the newer ones in the developing world
- Repowering coal plants is the fastest way to decarbonize the electricity system
  - Repowering with SG lowers the generation cost
  - Steam turbine, grid connection, staff, can all be reused/retained
  - Expensive parts, fuel, pollution control, maintenance of boiler, etc. are eliminated
- Very important for developing countries that have made recent investments in coal generating capacity

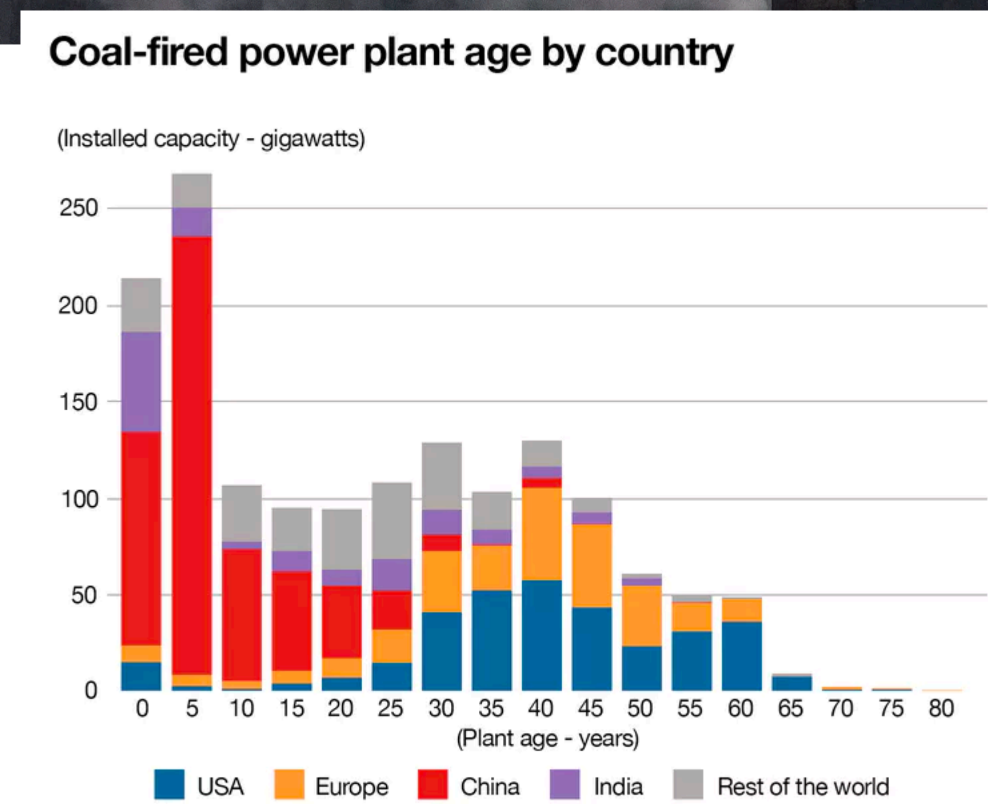
Global coal demand by key region



Global coal demand growth slows rapidly due to more stringent environmental policies, underlining the importance of high-efficiency plant & CCS to coal's future

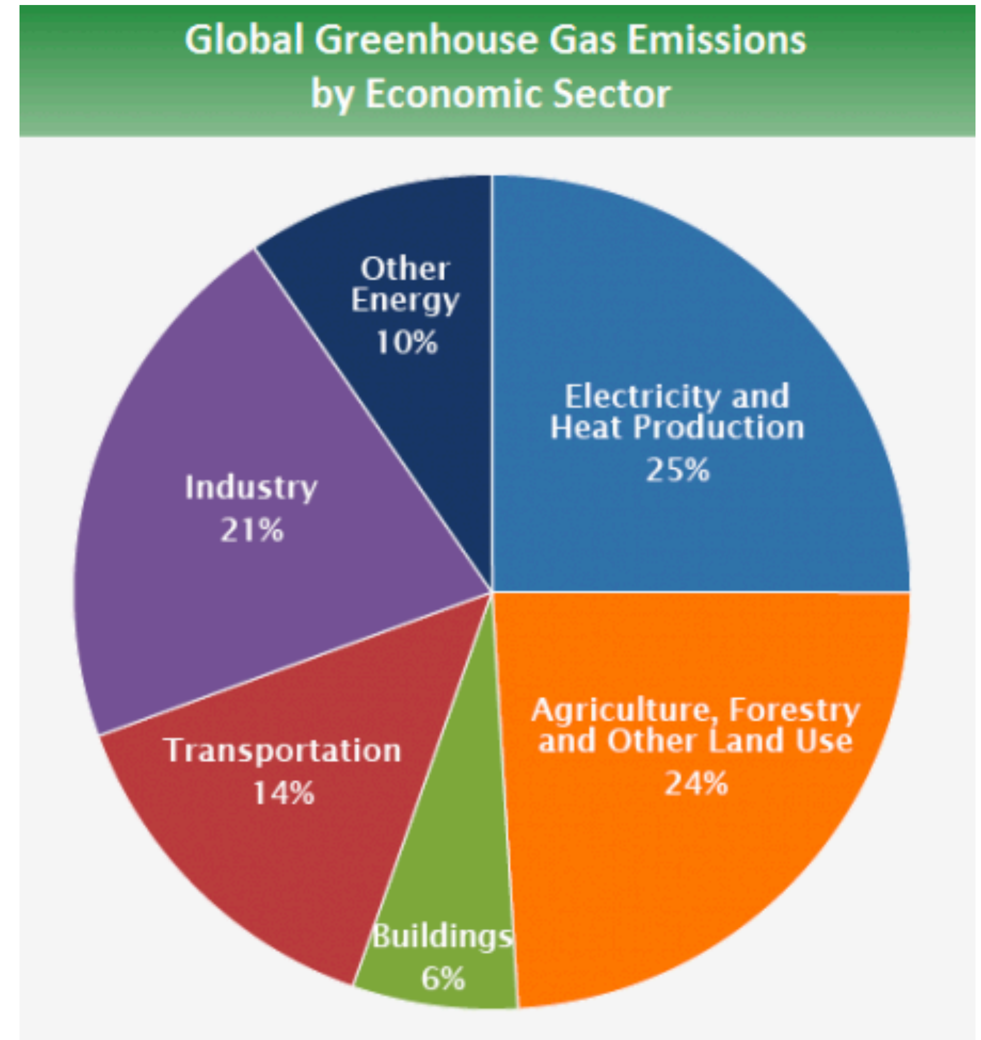
Conversion of existing fossil power plants is essential

- Near term achievable costs:
  - 15 production wells (45 wells total) for $1Bn to convert an existing depreciated 500MWe coal plant in the US would have a cost of energy of less than $30/MWh
  - Similar to a fully depreciated coal plant with $2/MMBTU fuel cost
  - Drilling costs would be lower in China and India
  - Conversion would **lower** the cost of energy for coal plants in China and India
    where coal prices are higher



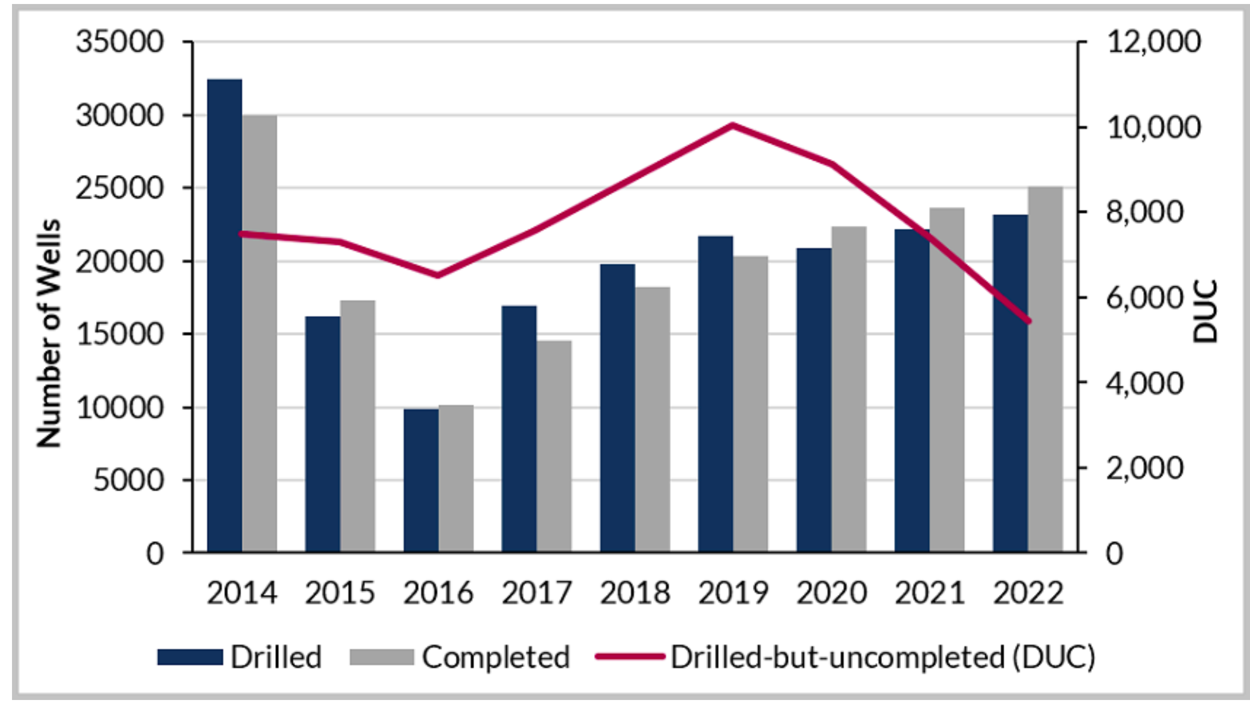
Decarbonization beyond electricity

- Electricity is 20% of emissions
- Large amounts of carbon-free hydrogen and syngas from captured carbon would enable decarbonization of other key sectors:
  - Industrial energy
  - Synthetic fuels for transportation
  - Chemicals and plastics
- Thermochemical cycles, currently being developed for nuclear and solar thermal, would enable direct conversion of heat to hydrogen at approximately 2x the efficiency of electrolysis--$6-7/GJ H2
- This is lower cost than natural gas in many countries and lower cost than H2 from Methane in the US.
- These costs would enable carbon-neutral synthetic fuels competitive with wholesale gasoline prices in the US. (~$2/gal-$16/GJ)



Rapid deployment

- Global drilling capacity and thermal power available per well or pair/triplet of wells
- 80-120GWe of new capacity/conversion per year in the US
- US fully has converted electrical sector with headroom for electrification, in 10 years



- Typical well is 18k feet (~5km)
- Assume 3x slower in hard rock
- Assume 2 injection wells for every production well
- Assume 35MWe per production well
- @21k wells (shale) rate per year (2019 rate)

Cost reduction potential

- Industrialization of the process

- https://seekingalpha.com/article/4034075-oil-economics-much-oil-gas-well-cost

What SEGS requires—very different from traditional geothermal

- Shale drilling technology revolution
- Industrialization of the drilling program
- Large size of projects
- Learning by doing
- Chevron Indonesia example
  - 100 wells
  - Last well cost 70% less than first well

Attractive to different partners

- Large oil and gas
- Large investments-similar to large oil and gas projects
- Used to managing geologic risks and solving drilling issues