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Geothermal Transitioning

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Contents: Geothermal transitioning: A Personal View

- **PART A – The geothermal energy landscape**
  - The energy and climate premise
  - What are the geothermal commodities?
  - Core geothermal background – some basics
- **PART B – Technologies & workflows**
  - New geothermal technologies
  - Incremental advance of existing geothermal workflows & technology
  - Regional exploration and scalability
- **PART C – How does geothermal fit in/compare?**
  - Oil & gas versus geothermal – what is different?
  - Against surface renewables – how does geothermal compete?
  - Are nuclear and geothermal ever in competition? Will they ever be?
- **PART D – The customers**
  - Big single heat or power customers
  - Networked energy distribution – heat or power
  - Critical mineral users
- **PART E – Geothermal Direct Lithium Extraction (DLE)**
  - How to explore for and produce geothermal DLE Lithium

Today will be a fast-paced overview of geothermal in an energy transition context
~ 55 min

Grey = Not for today

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I'm a geoscientist of ~ 30 years experience and now direct my consultancy company

I've been looking at geothermal exploration in a number of capacities over the past 7 years

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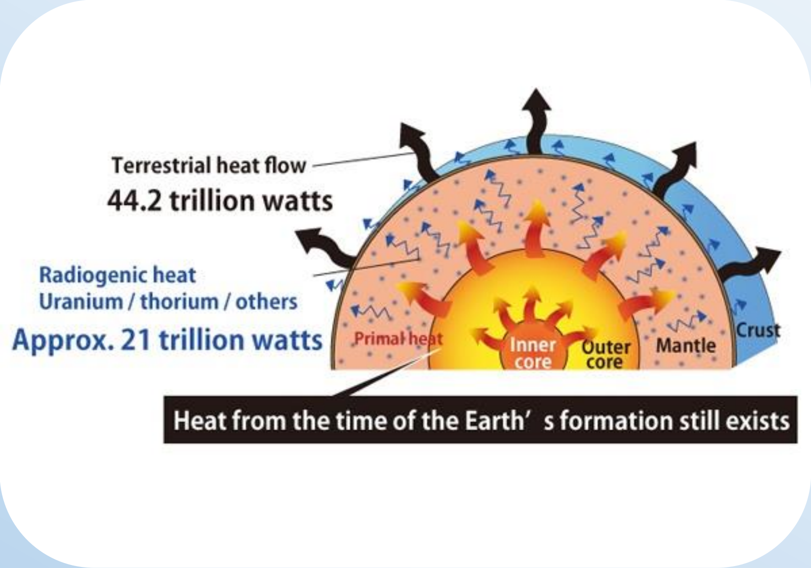
The energy & climate premise

Some comparisons

Three fundamental energy sources & a definition

1) The solar and cosmic radiation incident on our planet
2) The kinetic energy of early solar system bombardments converted to heat & lunar orbit
3) The heat of radioactive decay - both naturally in the crust, and stimulated in reactors

- *Geothermal energy drives from 2 & 3, roughly half and half*
- *It is heat derived from the earth*



The decarbonisation ticking clock – a competitive driver

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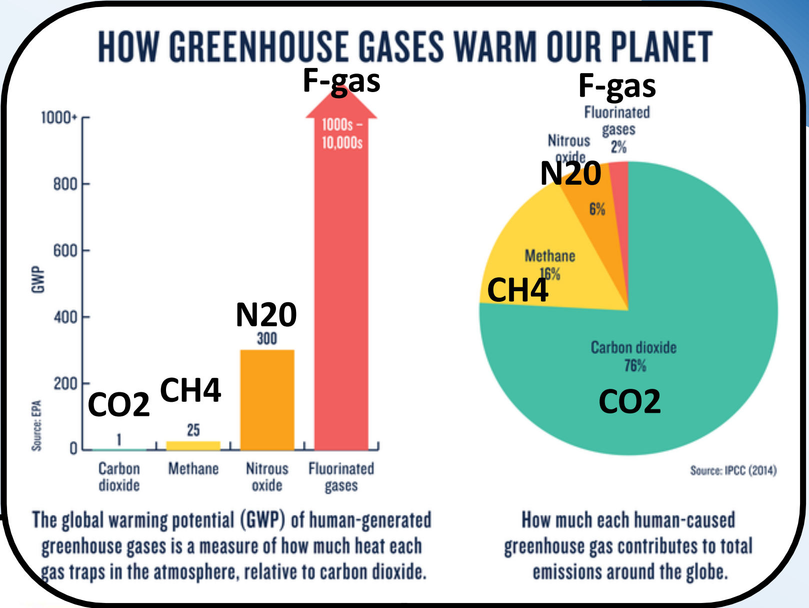
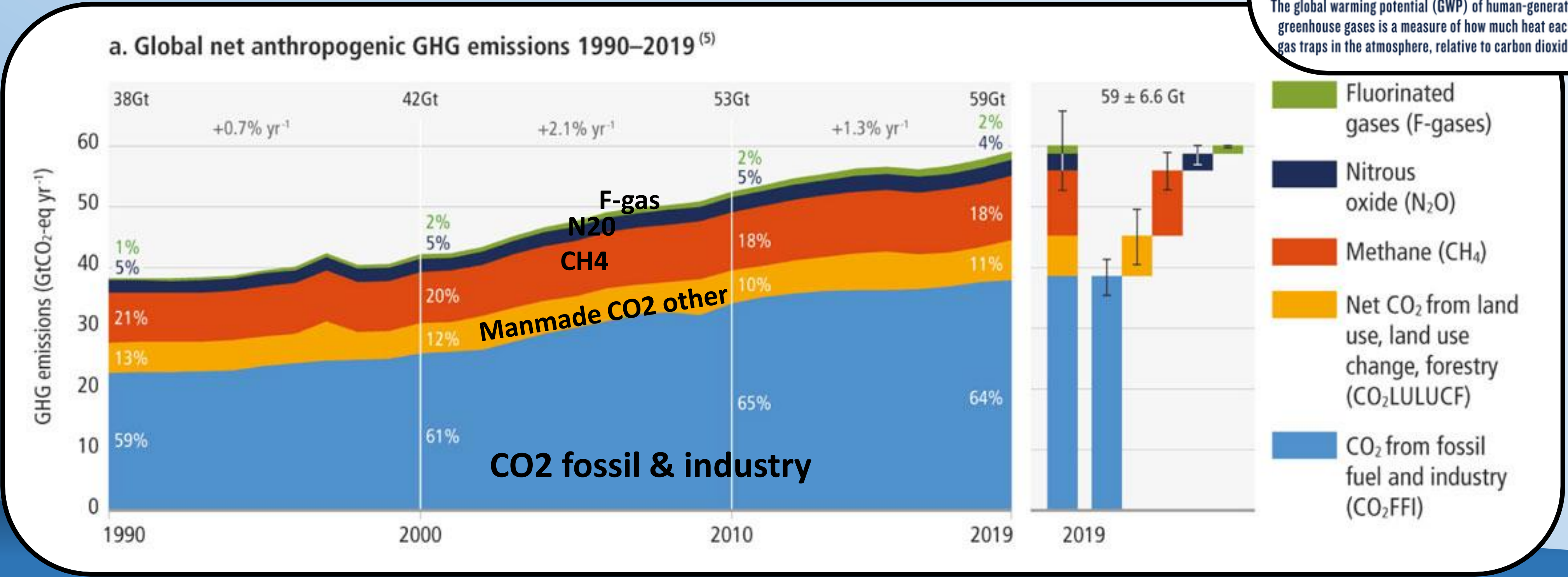
- Now at 419 ppm and ~ 2.4 ppm/a increase.
- 450 ppm => 2 deg C global temperature rise.
- 80% reduction in fossil fuel combustion to stop runaway warming
- Strong incentive to decarbonise
- Strong drive to better incorporate the true cost of emissions

Geothermal – what's new?
The drive to decarbonise has accelerated and the cost of carbon has been realised





- CO2 is not the only culprit
- It is by far the biggest anthropogenic one

The importance of decarbonising heat

- In UK, 50% of energy demand is heat related
- Two thirds is gas (69%), and nearly four fifths (79%) is oil or gas
- Typical of temperate advanced economies
- The size of the decarbonisation prize is big
- Geothermal is not the only option – but it has an important role to play

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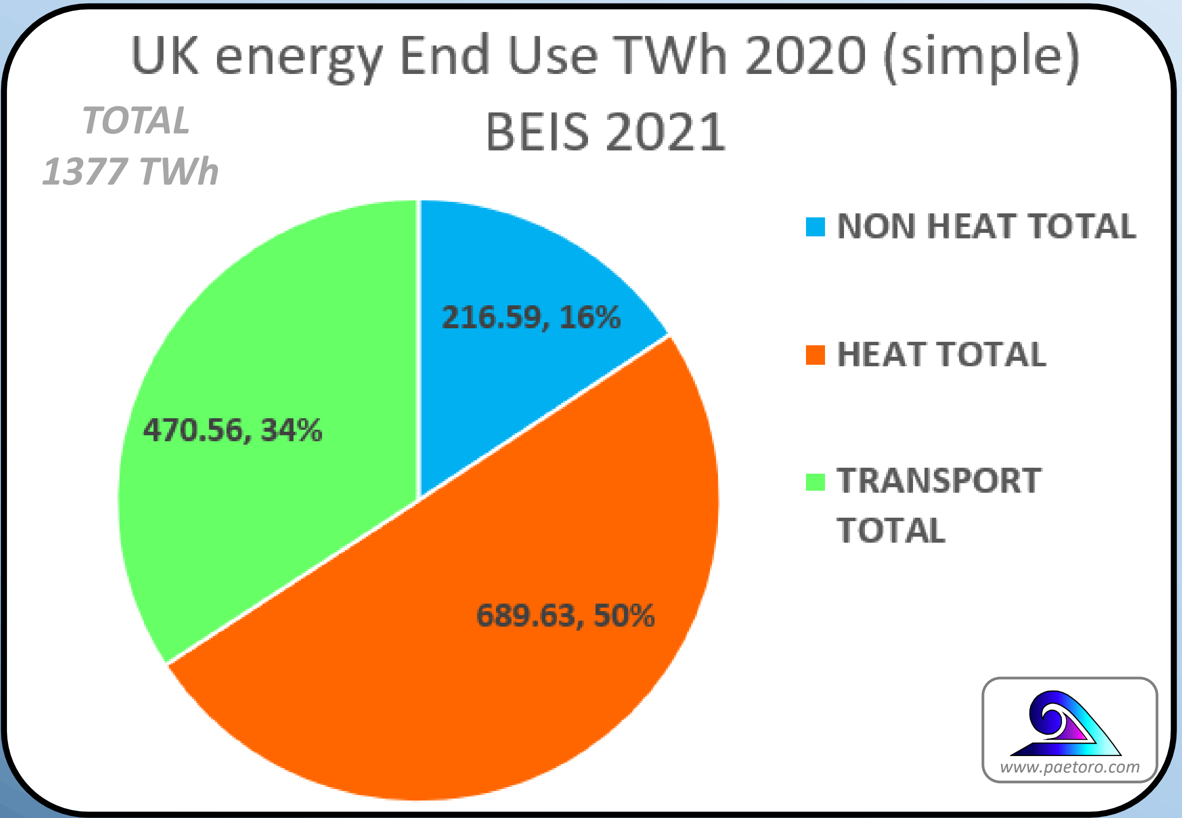
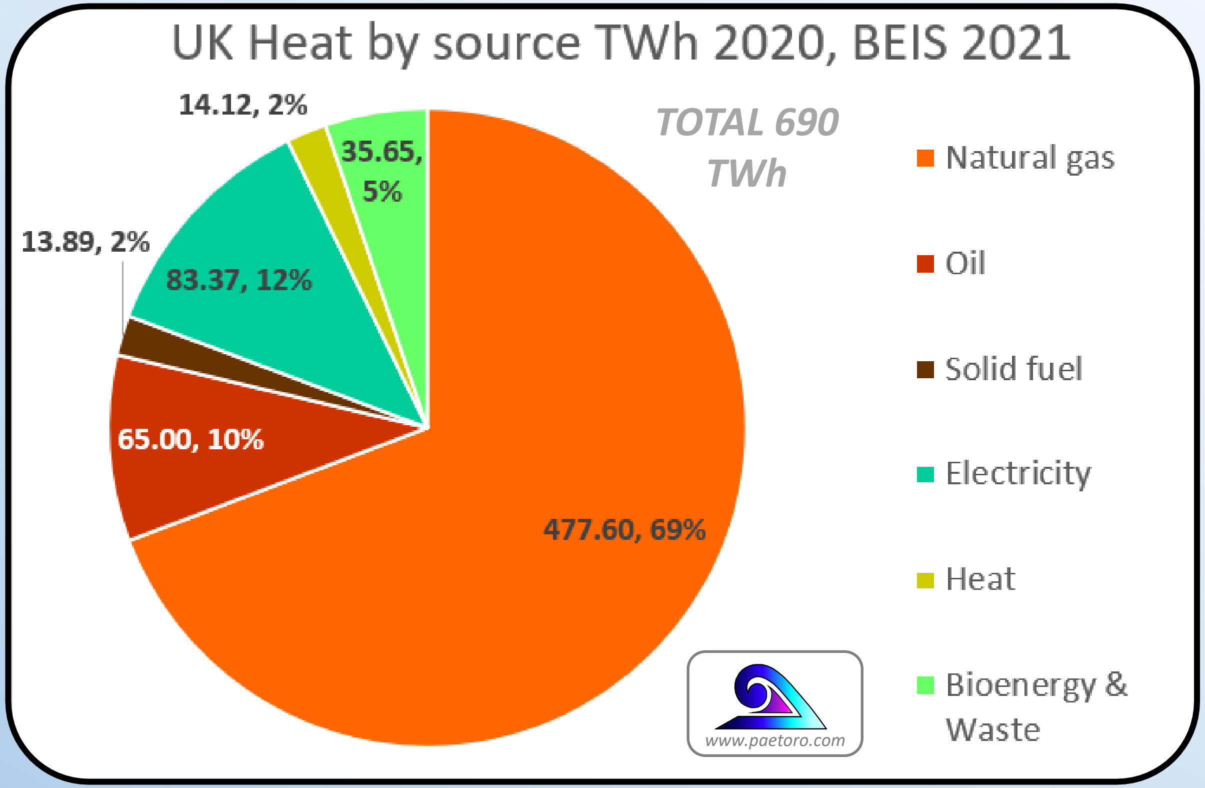
Major economies use as much as half of their primary energy on heat



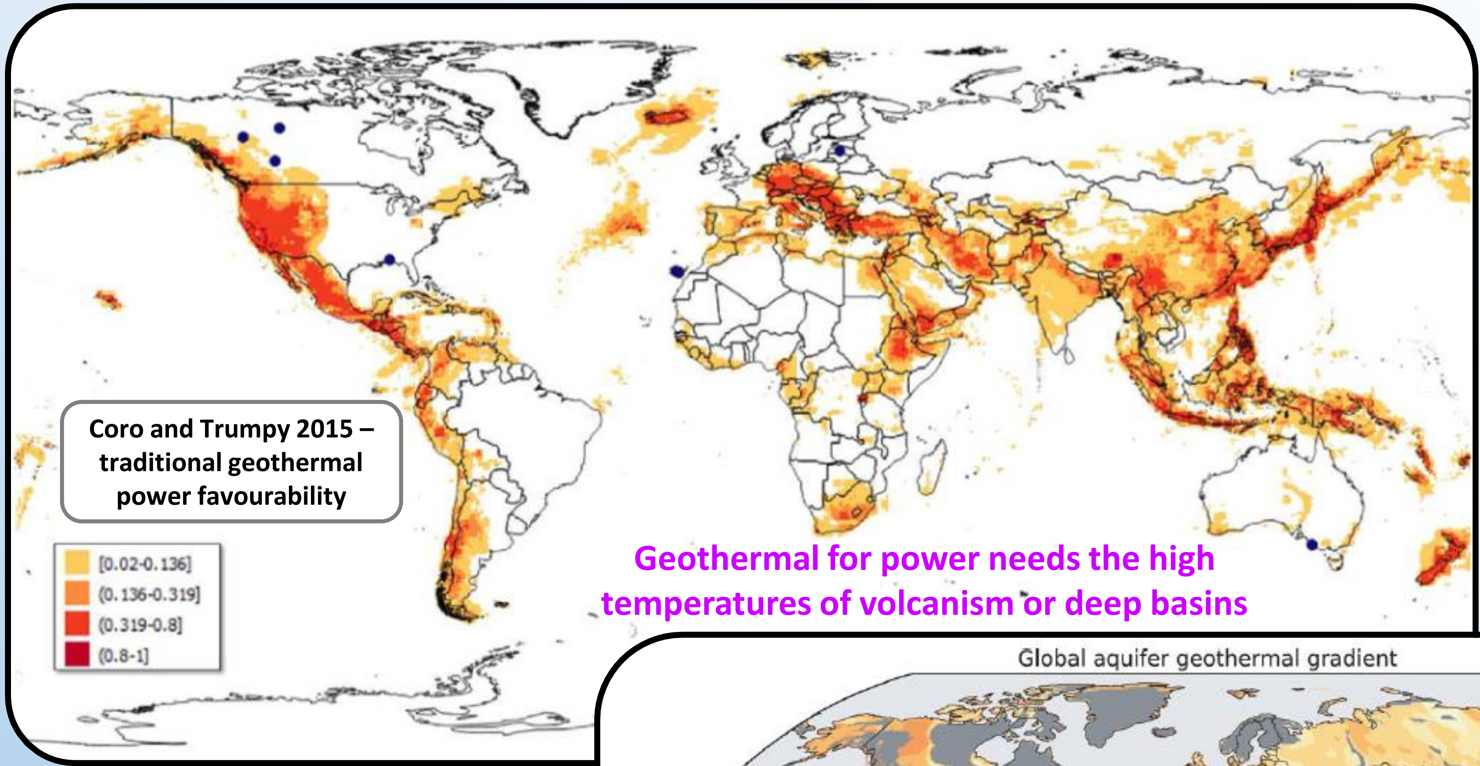


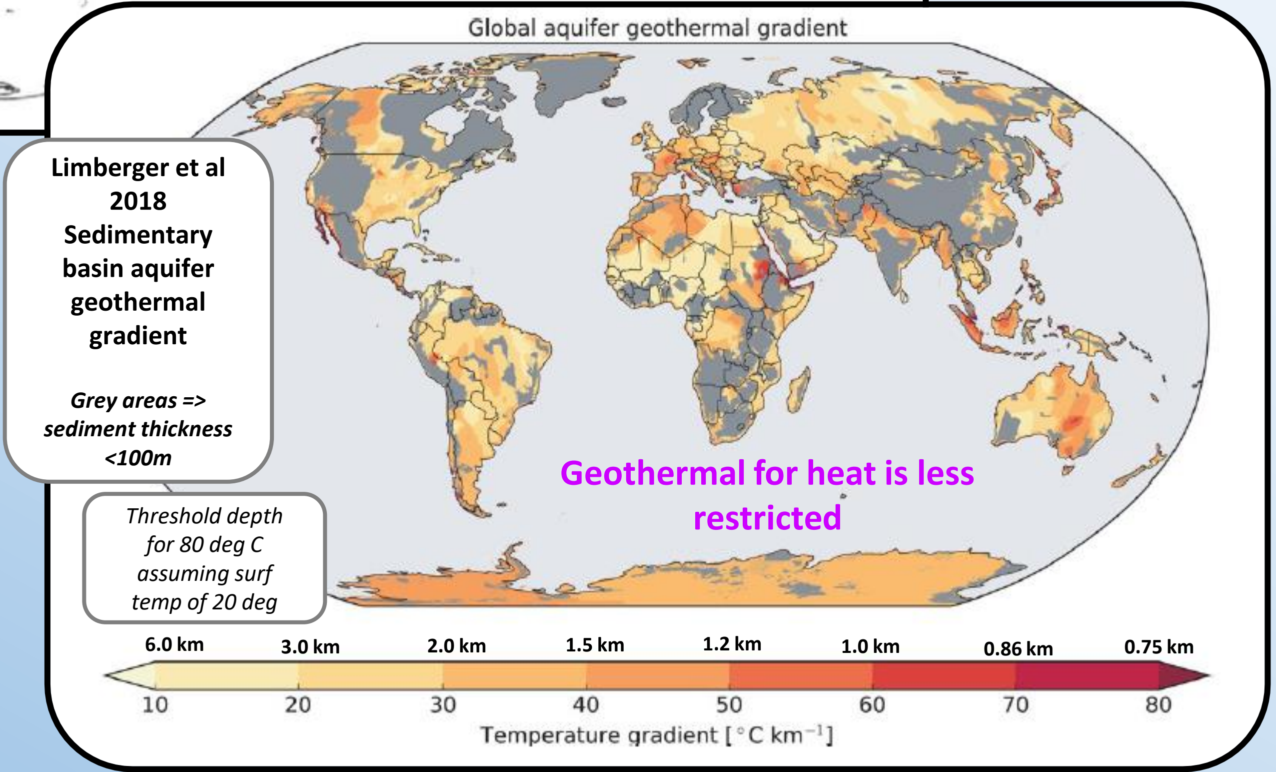
Geothermal Commodities

Heat, power, mineral

Heat & power

- Geothermal energy is not just about power, which needs higher temperatures
- Geothermal resource is *not* only where there is very high volcanic heat flow
- Sedimentary reservoirs and aquifers around the world provide many options for heat use

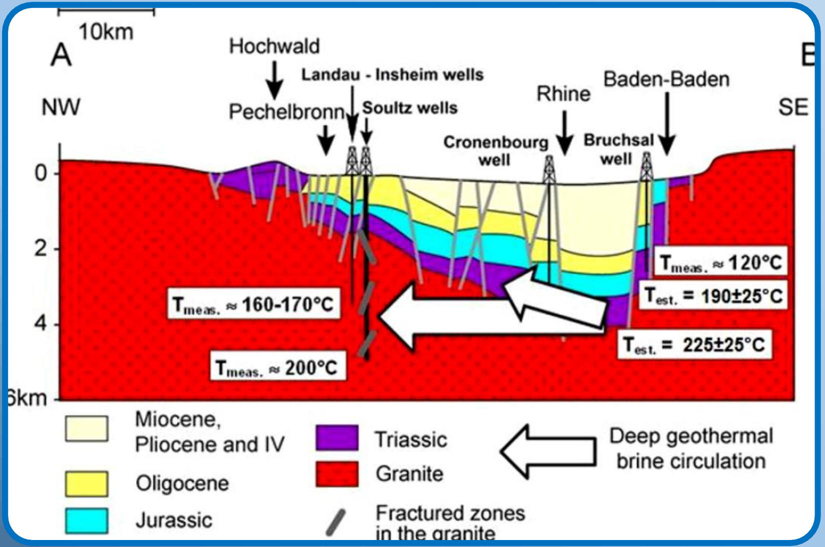




Geothermal DLE (Direct Lithium Extraction)

- Geothermal direct lithium extraction – all the rage, but full scale production lines are yet to come – the concept is still at pilot stage
- The best brine mineral concentrations – tend to come with high temp
- Li concentrations above 100 ppm are considered interesting, but it's about sustainable volume – not just the concentration
- We need longevity of producing concentrations – especially if injection is happening – that means long term testing to prove viability
- Understanding Li genesis and the fluid circulations is critical
- Both often uncertain, and vary widely from place to place – no one formula fits all

Some key factors:
Igneous source
+/- Alkali volcanism
Sedimentary reworking
Evaporative reworking
Active rift burial
High enthalpy heat supply
Hydrothermal reworking
Lacustrine hydrothermal



But not just lithium to go for...

Assessment of Mineral Resources in Geothermal Brines in the US

Ghanashyam Neupane and Daniel S Wendt
Idaho National Laboratory, Idaho Falls, ID 83415, USA
E-mail: Ghanashyam.neupane@inl.gov

Hot water is an excellent solvent
But heat does seem to be the key for brine minerals

That means aggressive fluids - scale and corrosion issues – comes with the package

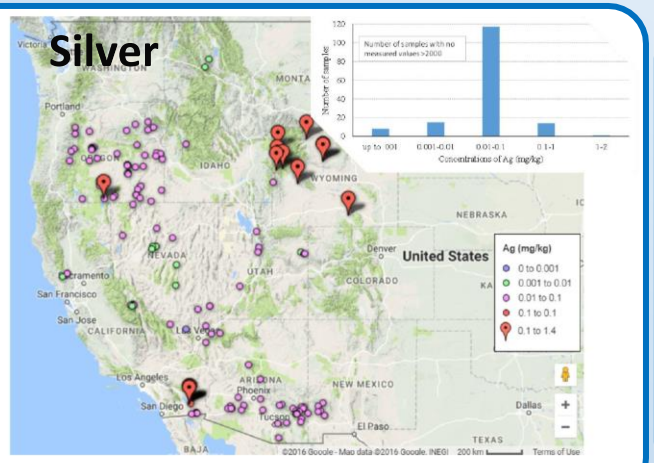
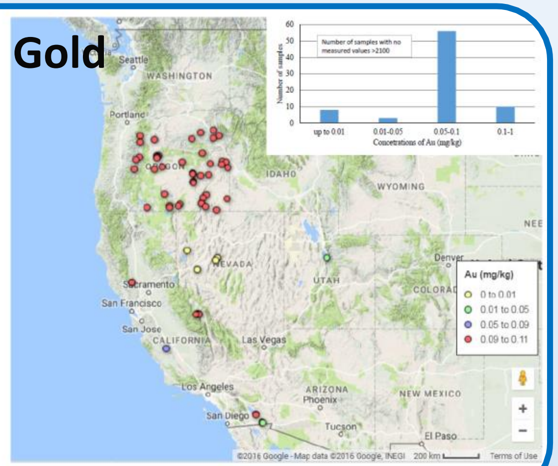


Figure 2. Distribution of geothermal brine samples with measured Ag concentrations.



ure 3. Distribution of geothermal brine samples with measured Au concentrations.

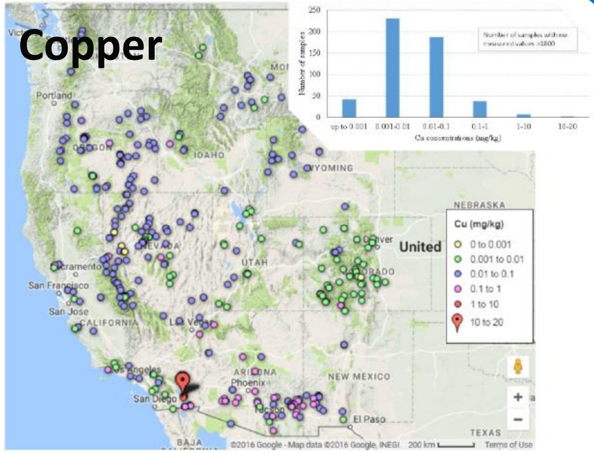
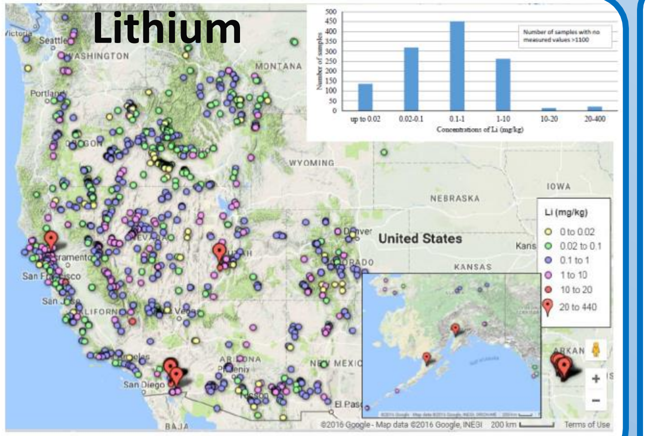


Figure 4. Distribution of geothermal brine samples with measured Cu concentrations



igure 5. Distribution of geothermal brine samples with measured Li concentrations.

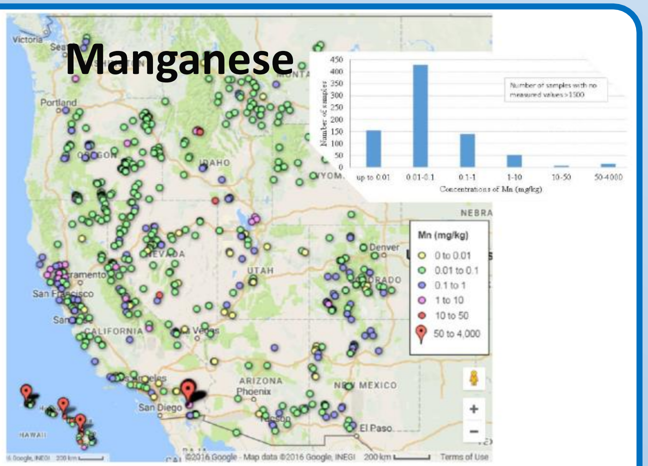


Figure 6. Distribution of geothermal brine samples with measured Mn concentrations.

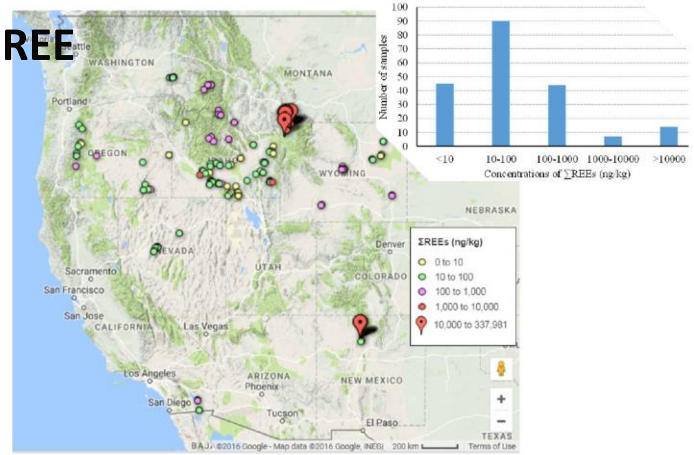


Figure 7. Distribution of geothermal brine samples with measured REEs (total REEs) concentrations.

Silica and potassium have potential too

High TDS = good for minerals

But costs for maintenance and processing

Impacts power side

The hybrid renewables proposition?

- Sometimes combined solar and geothermal plants are proposed – to "make the best of both"
- The approach is in its infancy and being tried out in some places – e.g. Nevada
- But hybrid typically means more complicated too – optimising one thing from an engineering and financing perspective is hard enough without having to juggle two – compromises both a little – the gain needs to be worth the extra hassle
- So while there is a definitely case for learning more – sometimes sticking with one and doing it well is best
- Investors like things to be commercial standalone and not depending on multiple things working

ENEL Stillwater Nevada triple hybrid power plant – Geothermal, Solar PV, Solar Thermal

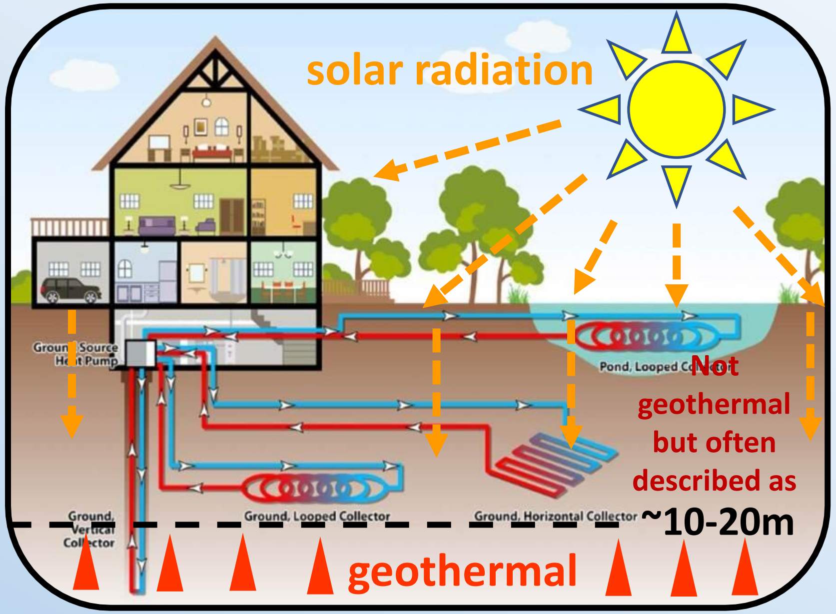
Geothermal & Solar..

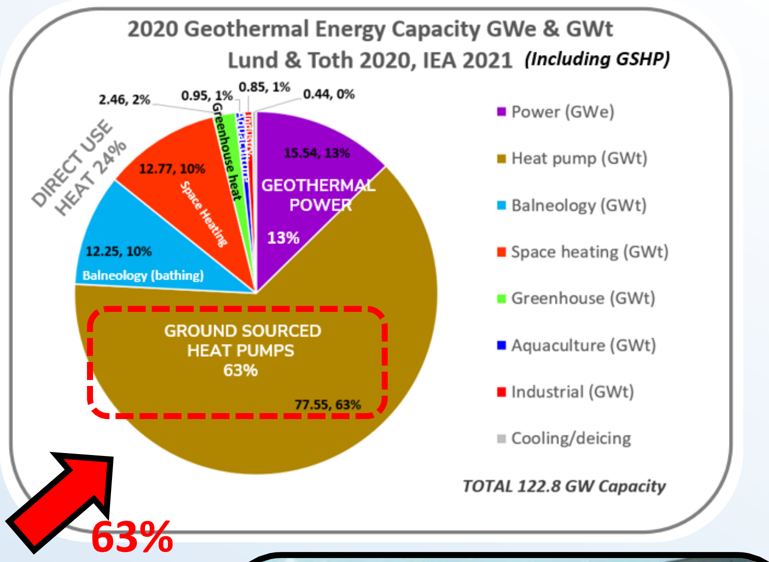
Two or even three things for the price of one, sounds good on paper...

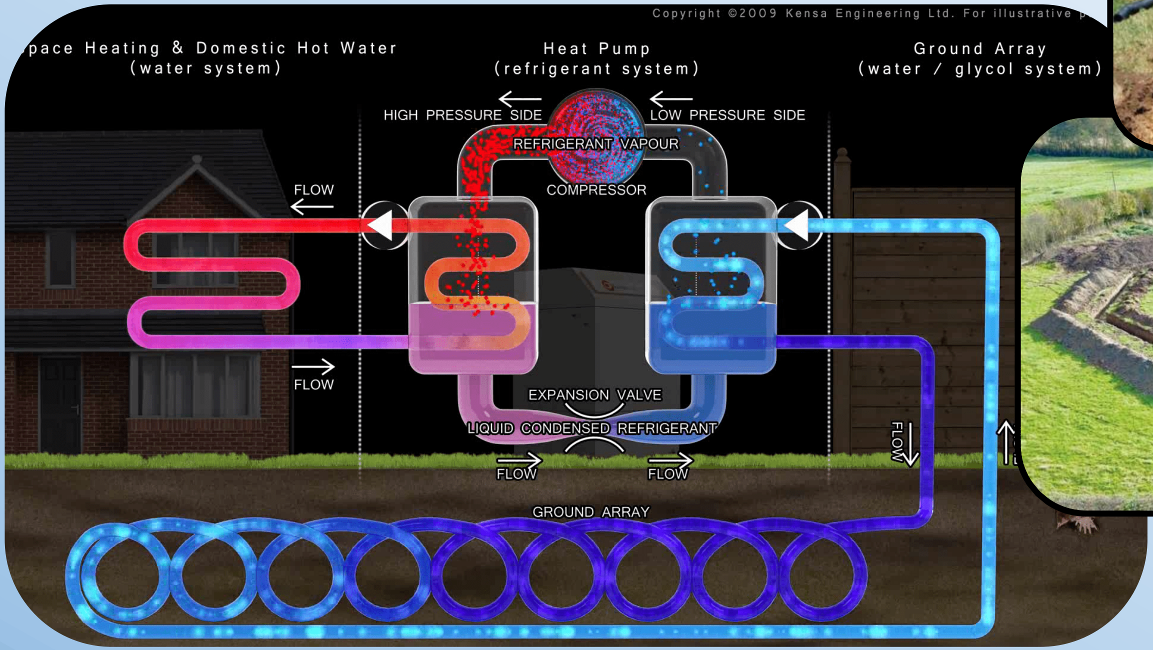
In practice it brings commercial and engineering complexity

GSHP: Geothermal vs subsurface thermal

- Ground sourced heat pumps (GSHP) are shallow circulating systems to conduct heat from the ground into a fluid and put it in a hotter one
- They are not harnessing true geothermal heat unless they go below the ~ 10-20m depth of solar influence
  - BUT they are often called so, especially in US
- They need some power to run compressors and pumps
- For a little energy in they get a lot out
  - Water bodies or the air can also be used as a heat source
  - They utilise daily and seasonal solar radiation fluctuations for coupled heat and cool
- Land area needed for meaningful heat supply can force going vertical and deep instead
- Of used subsurface heat resource, encompassing both ground sourced and 63% - nearly 2/3 is ground sourced

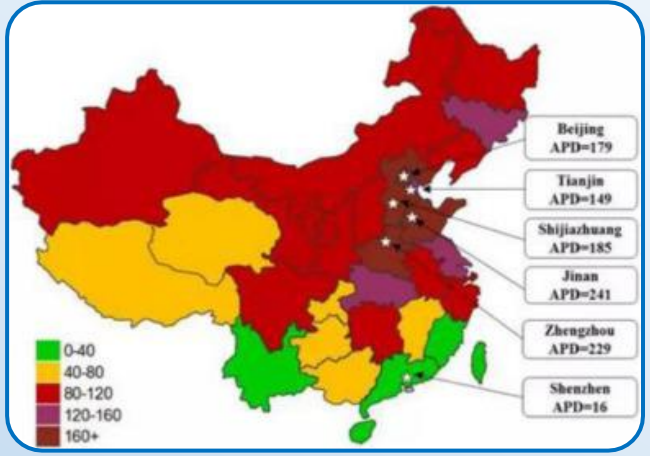




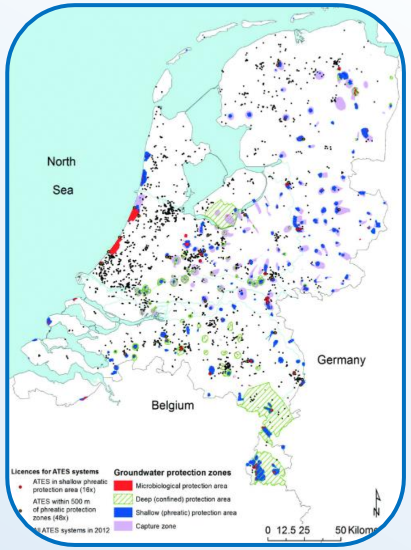


ATES: Heat & cool storage

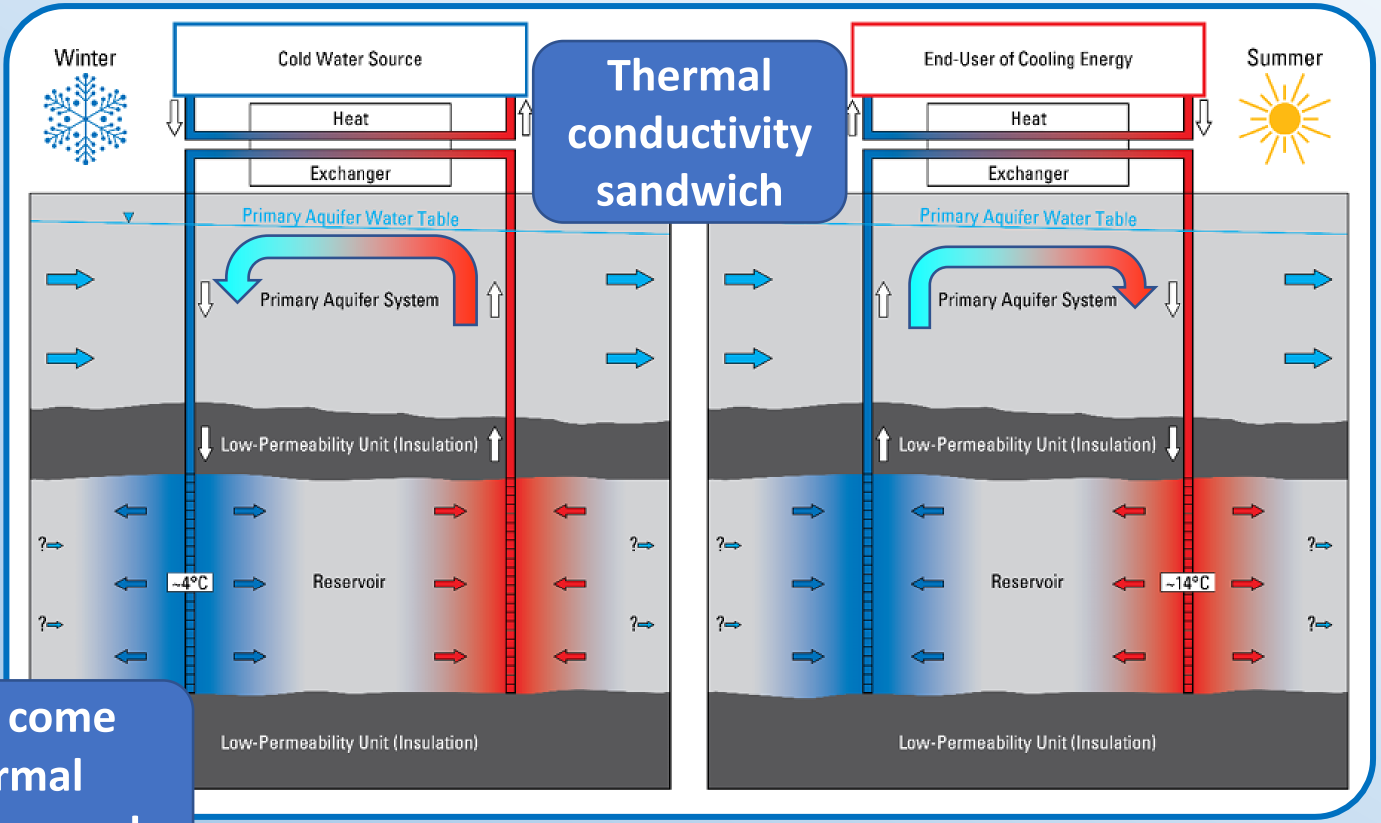
- ATES= Aquifer thermal energy storage
- It's NOT geothermal energy per se
- The stored energy can come from *any* source
- Discovered by accident in China in 60's during injection to stop subsidence
- Looking for a thermal conductivity sandwich – high conductivity between low conductivity
- To store seasonal and daily heat and cold
- Can work well – BUT thermal energy storage is never the most efficient means of storing energy..
  - ...but if the aquifer is shallow and cheap to reach
  - ...and the energy would be otherwise wasted
  - ...what's not to like
- Very big in China, Netherlands, and increasingly elsewhere
- Lots of potential for megacity cooling in the tropics if adjacent to deep water bodies
- If drilling for geothermal, worth tagging what you see on the way down



No. of ATES projects by province, China



ATES projects Netherlands



Thermal conductivity sandwich

ATES ≠ Geothermal per se – the heat (or cool) can come from anywhere, BUT you can use it *with* geothermal Storing daily or seasonal heat & cool in tune with demand

Core geothermal background

Some comparisons

Different types of geothermal

- A definition: Geothermal energy is heat that is *generated* within the Earth
  - *not* then ground sourced heating in the top 20m of the earth = solar
  - *not* thermal energy storage underground
- By commodity
  - Direct use heat or power (& brine mineral)
- By energy punch
  - Supercritical/High enthalpy/Low enthalpy
  - Enthalpy incorporates both temperature and pressure
- By working fluid(s)
  - Water/steam/supercritical CO_2/secondary organic fluids
- By depth
  - Shallow ~<800m; Deep > 800m
- By geothermal system
  - Volcanic, conductive, advective, convective
- By exploitation system
  - Open system doublets/closed loop/DBHE/EGS
- By customer type
  - Many and varied

Drilling for direct use heat between greenhouses, Netherlands

Geothermal energy is not one thing – it is many

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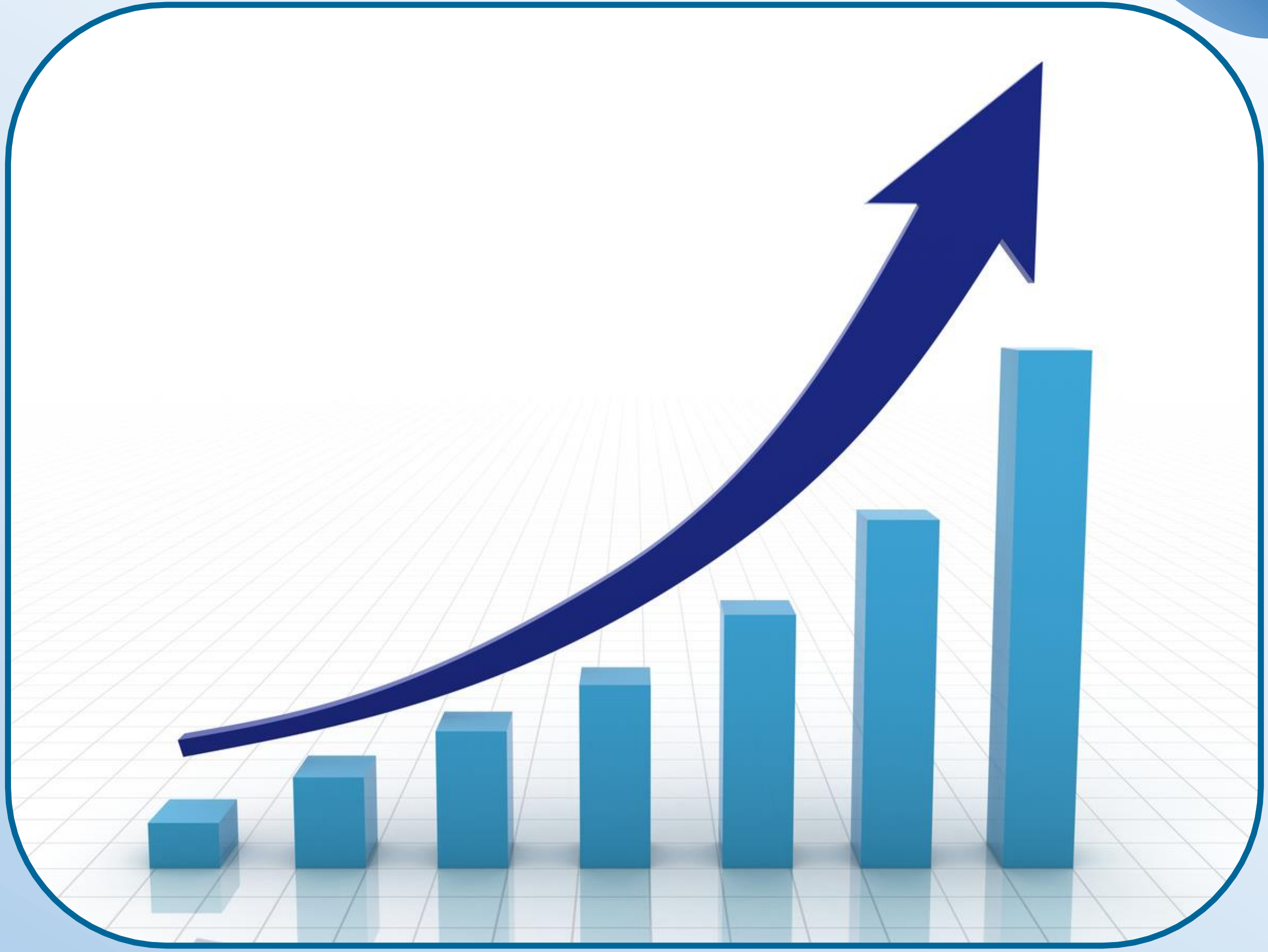
Scalability of investment

- For an investment in a project to be attractive
- It has to be scalable
- The investor has choice – it is not their role to do us favours because it's "green"
- Nobody wants to spend a lot of time and effort on something that can't be repeated
- Yet individual geothermal projects are very location specific – not just to the geoscience – but to the market
- That makes upscaling a challenge
- How do we apply widely the success of one project when it is so different to the next?



We need to be able to upscale and repeat
We need to meet customer requirements better than the competition

Complexity, Diversity, Locality

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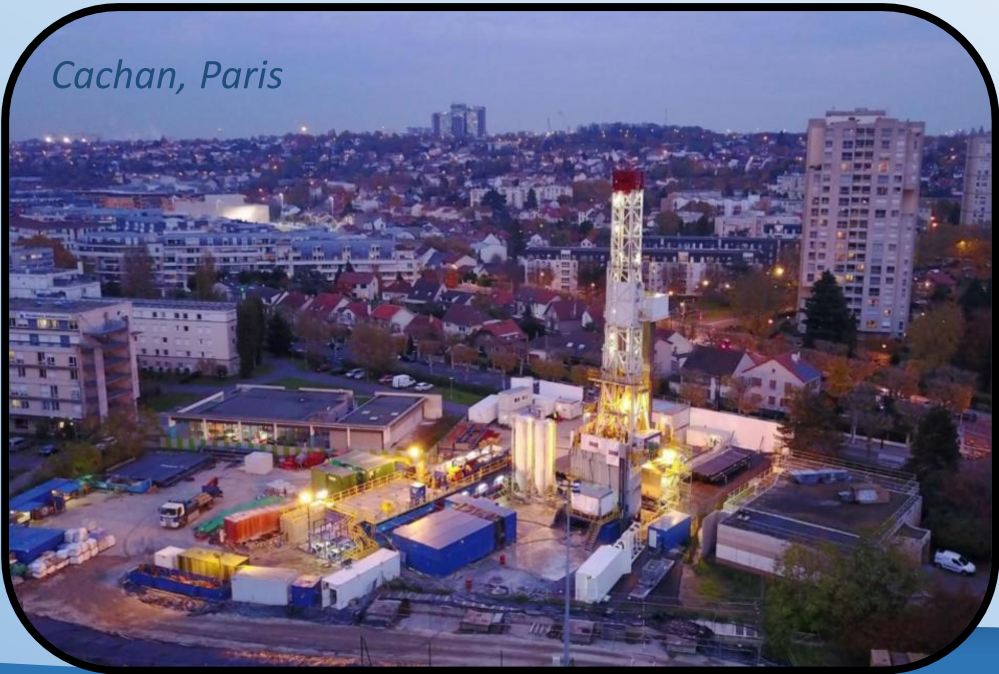
GEOTHERMAL COMPONENTS – a non exhaustive selection

- Commodity type
- Resource System
- Data Maturity
- Technology
- Hazard mitigation
- Customer & infrastructure
- Community & Competitor
- Finance
- Regulatory framework



Many things have to come together for geothermal success

Often the geoscience is the least of the issues

Geothermal system diversity

Diversity = opportunity

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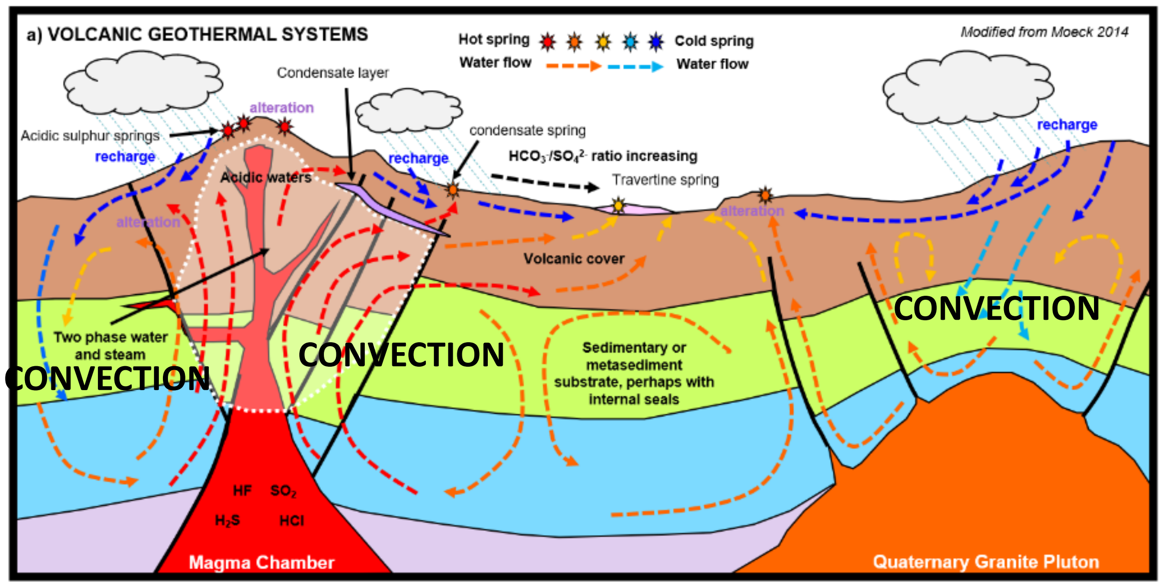
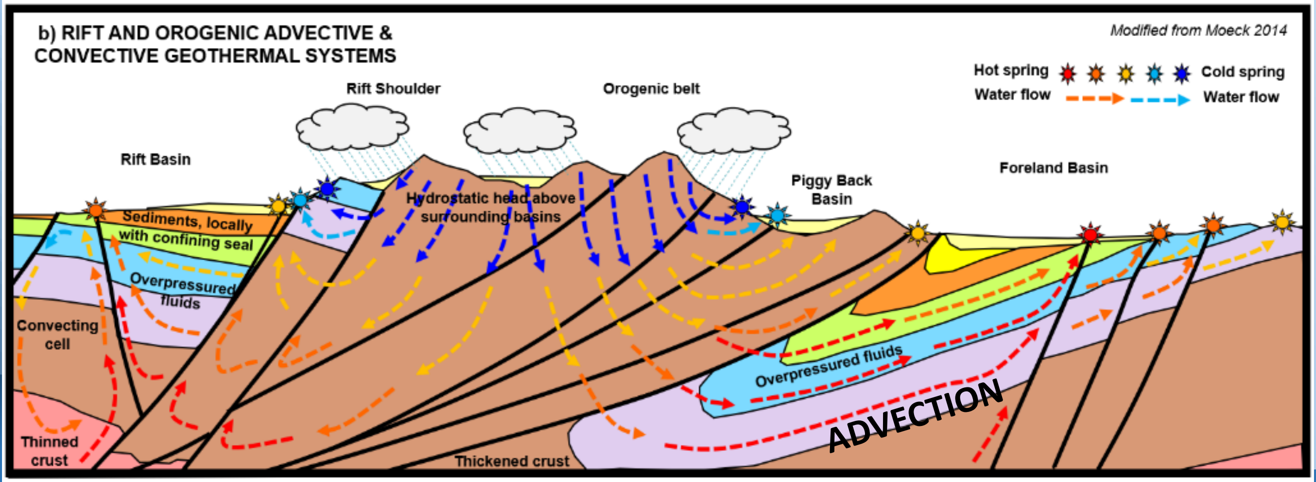
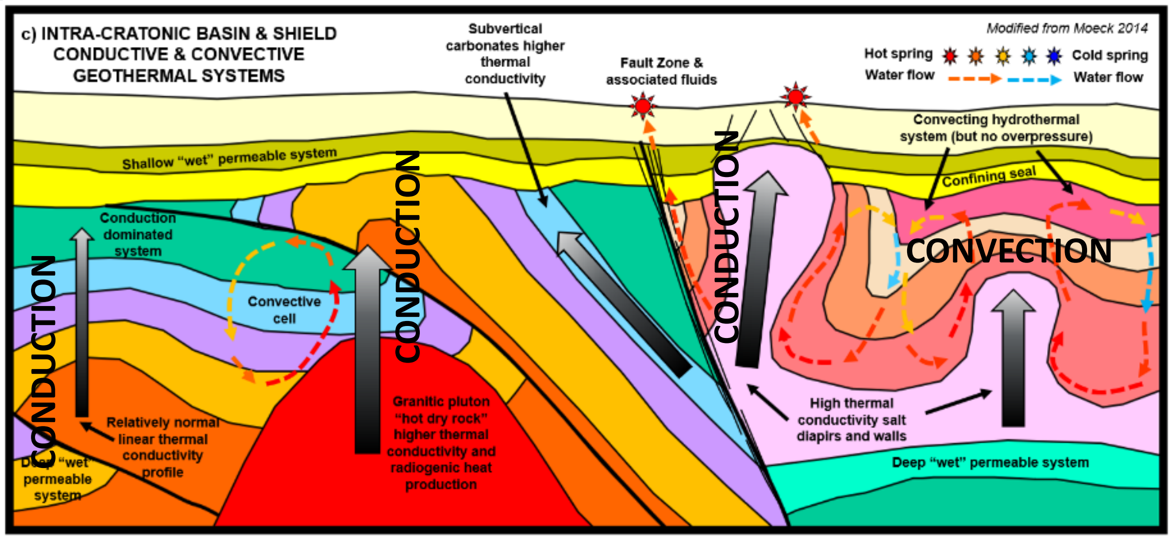
- Geothermal systems are diverse
  - Lithology and permeability architectures modify heat flows
  - Temperature and geochemical gradients modify fluid behaviour
  - Pressure-temperature-depth-phase relationships vary
  - These are all reasons why scaling geothermal up has been difficult
- Volcanic geothermal systems along active plate margins the ones we are most familiar with
  - Lots of heat and good for power
- Coupled Orogen-basin advective & convective geothermal systems
  - Mountain belt recharge drives overpressured circulation in adjacent basins
- Intra-Cratonic basin & shield conductive & convective geothermal systems
  - Conductive heat flow from the lower crust is modified by lithological and structural variations
- All these systems present geothermal opportunity worth assessing







Diversity of geothermal customer

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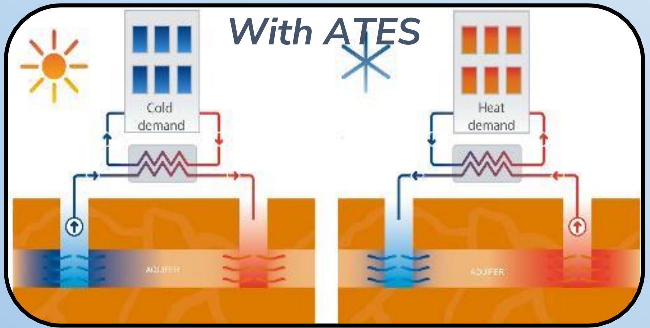
- Because the geothermal commodity – heat – is physically transient and can't be exported
- Geothermal commerciality is first and foremost about understanding the local market
- Many, many options, each with specific needs and efficiencies

Customer driven exploration



Geofood

- More than greenhouses
- Much food production requires heat
- Opportunity riding on COVID and transport cost drivers for more domestic food production

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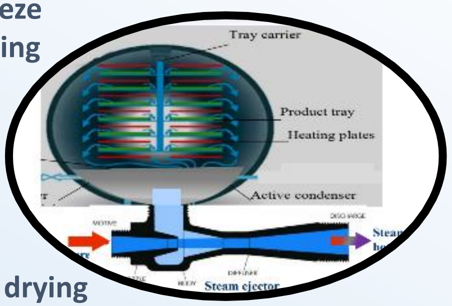
Livestock and equipment care

spirulina algal superfood

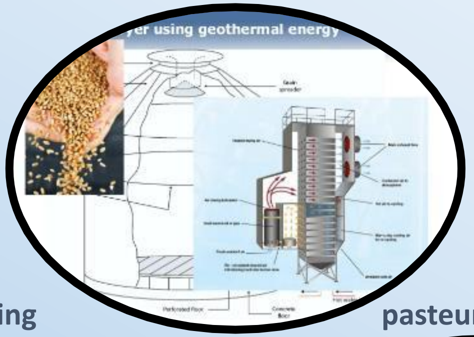
Freeze drying



greenhouses

aquaculture

grain drying



fruit drying

distillery

fish processing

fish drying

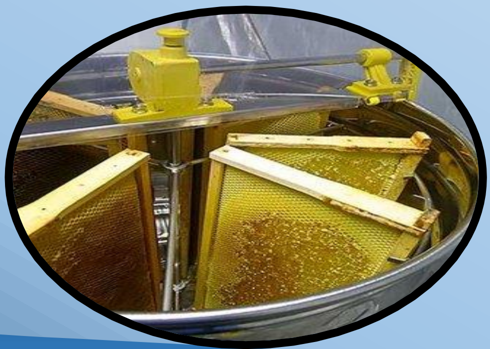
pasteurisation

brewery

Just a few.... Possibilities endless

meat processing

honey processing



edible (& fuel) oils

sterilisation

Cheese

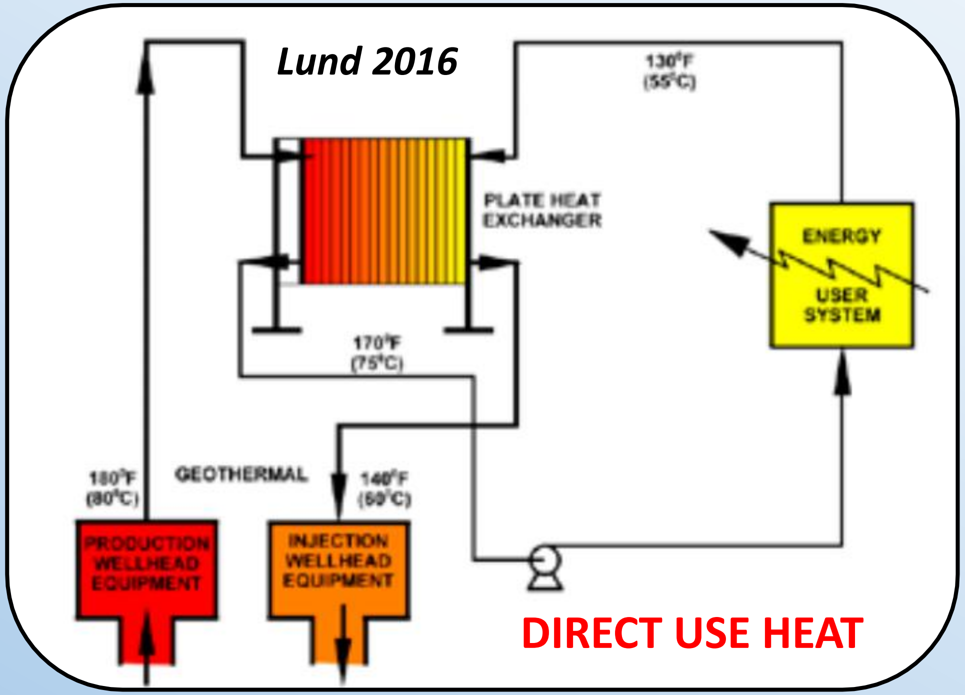
Just for starters...

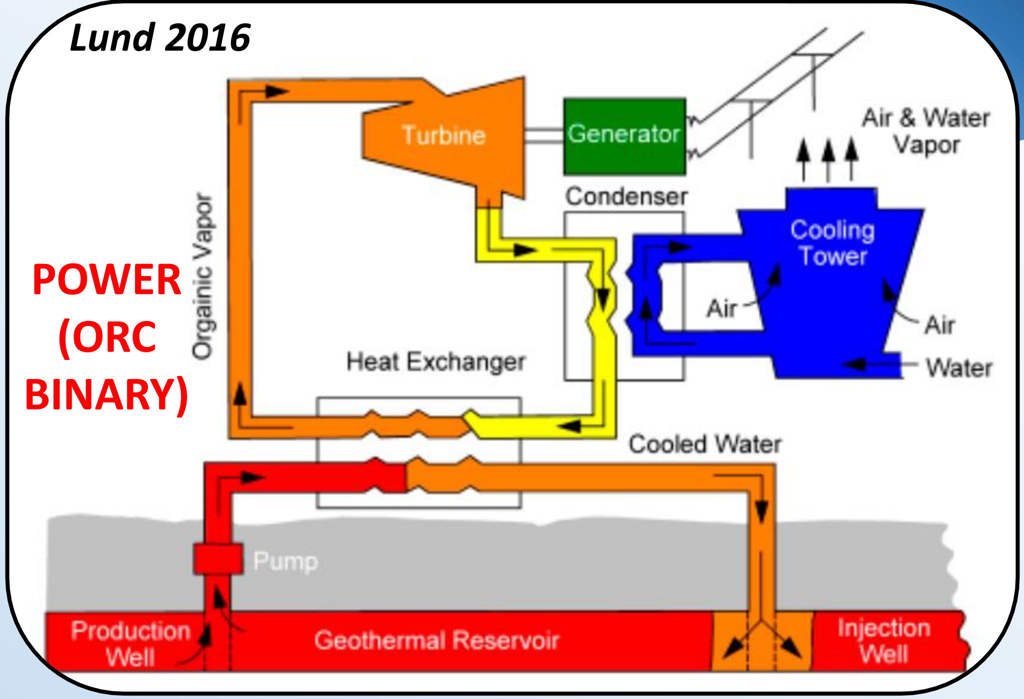
20

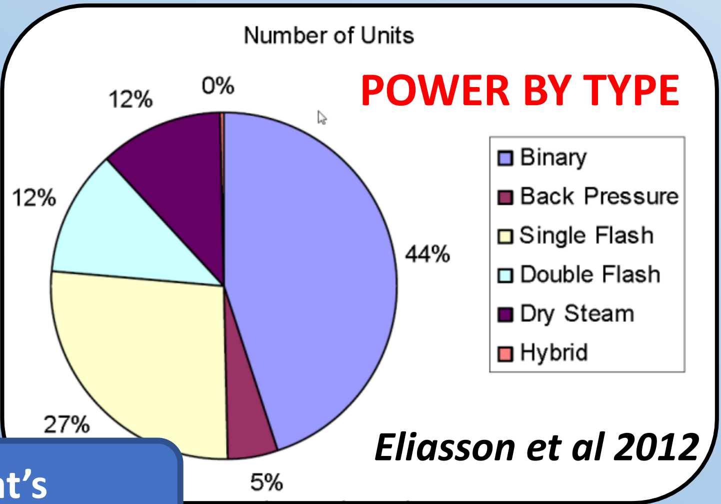
Harnessing geothermal heat – for direct use heat & power

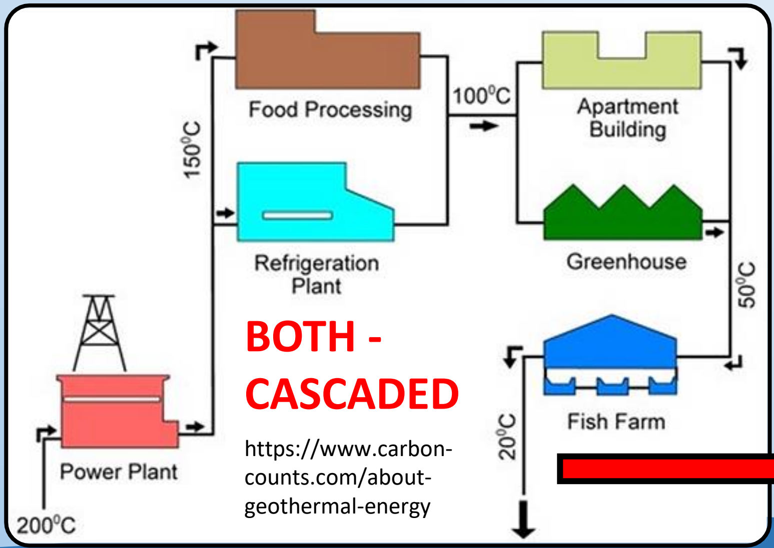
Heat is mostly straightforward to use directly as heat

- Organic Rankine Cycle (ORC) binary is the most common type of new power plant construction
- It uses two working fluids – one an organic one that is vapour at lower temperatures
- More efficient & accesses lower temperatures
- Dry steam, flash steam, dual flash steam are others but tend to be higher temp. affairs
- Commercial feasibility is a function of both flow rate and temperature
- ORC binary power is technically feasible to 90 deg C
- In practice ORC binary is rarely commercial below 140 deg C – it's possible but would need great flow rates
- Depending on how cool we can reinject into the reservoir, power's waste heat may have cascaded direct heat use options –the cooler we can go before injecting, the more the options







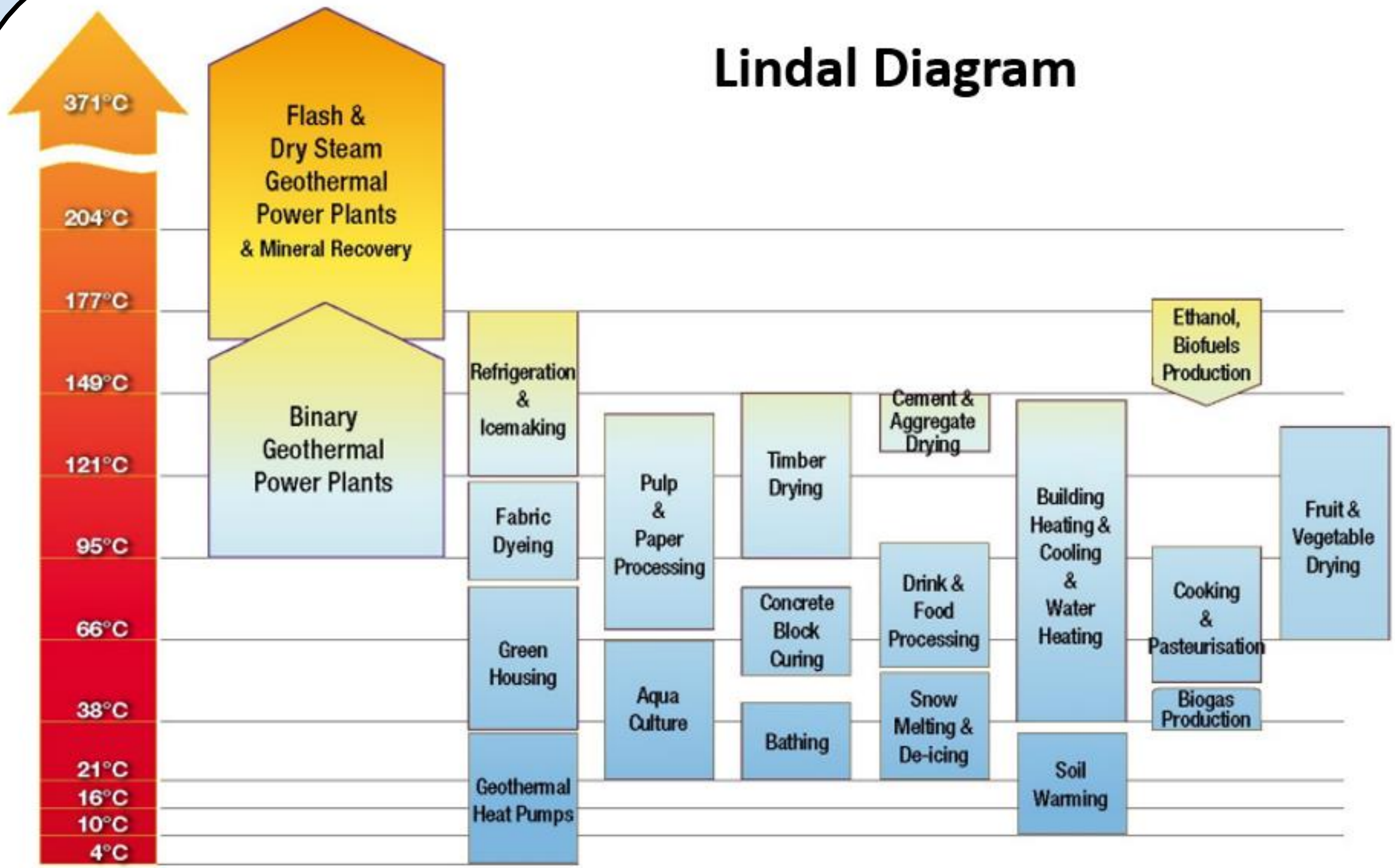


What's doable and what's commercial are very different things

The Lindal Diagram

- Different customers have very different temperature requirements

You don't need 140 deg C to grow cabbages or defrost a football pitch



Heat pumps also allow options of raising temperature by "concentrating" heat from a large cooler volume to a smaller hotter one

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What we want to know...

$$\Delta Q = mc\,\Delta T$$

USEABLE HEAT

Fluid mass

Flow rate * time

For a given surface flow rate: longer in reservoir = more heat

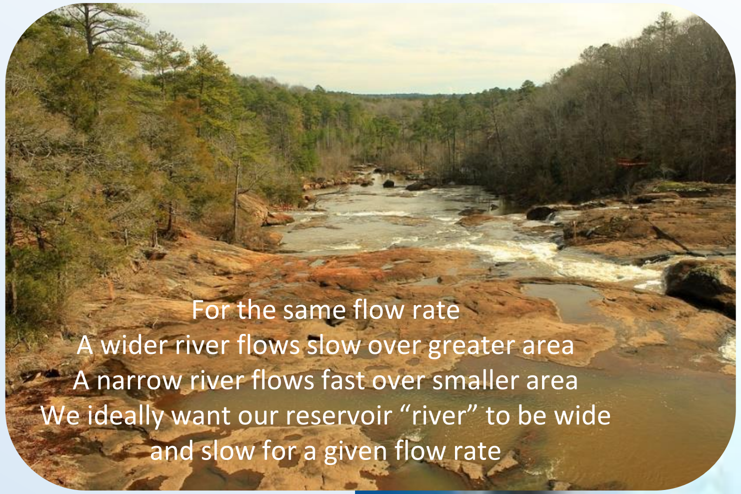
Heat flow = mW/m2 = MJ/s/m2 – function of both area and time

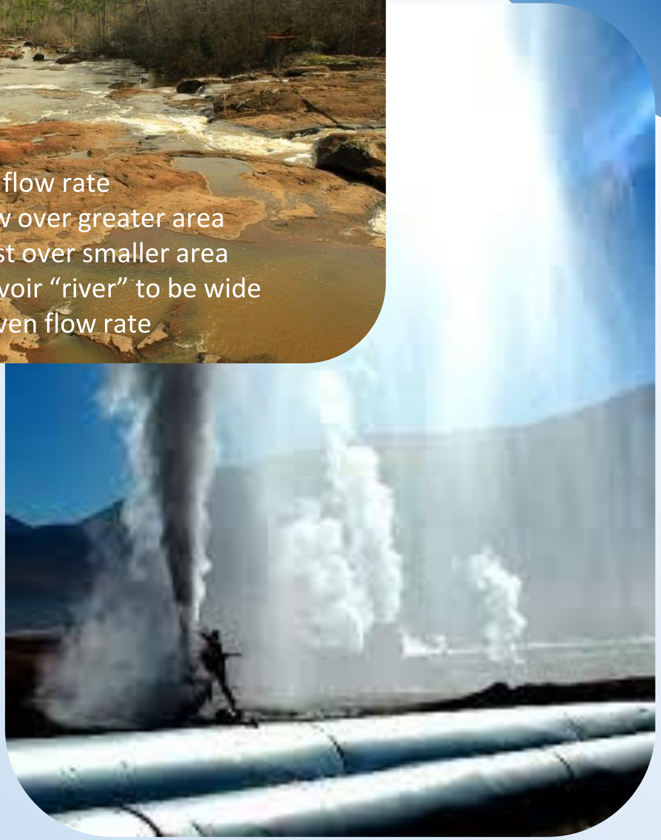
The more even the perm, the more distributed the flow, the greater the area, the slower the flow, the longer the time, the more heat collected

fluid constant – ability to carry heat

Production-injection temperature difference

The more we can cool to at surface, the more heat we can get out





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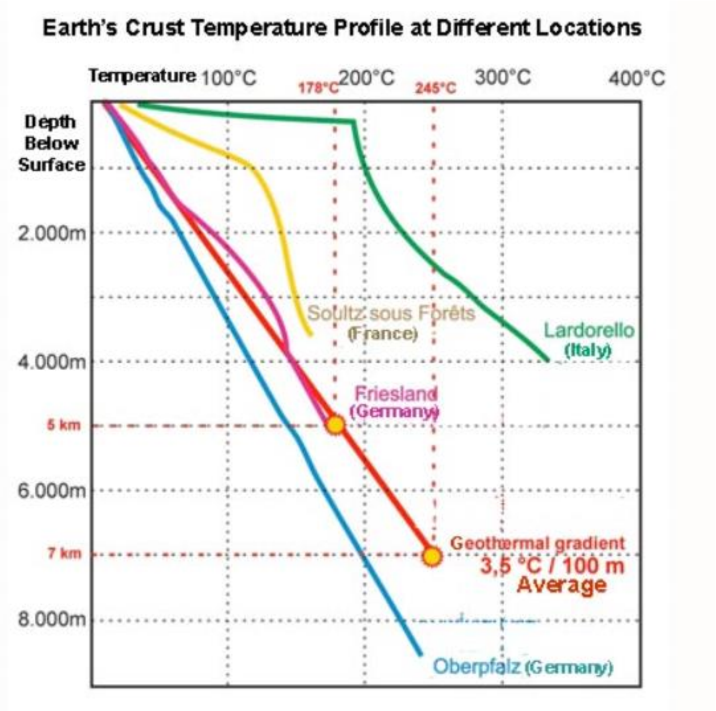
Flow rate is as important as temperature

And...
...how well production varies with time
...how quickly the reservoir cools with time
...how efficiently we can exchange heat
...how efficiently we can transform heat to power
Lower the temperature the lower the efficiency

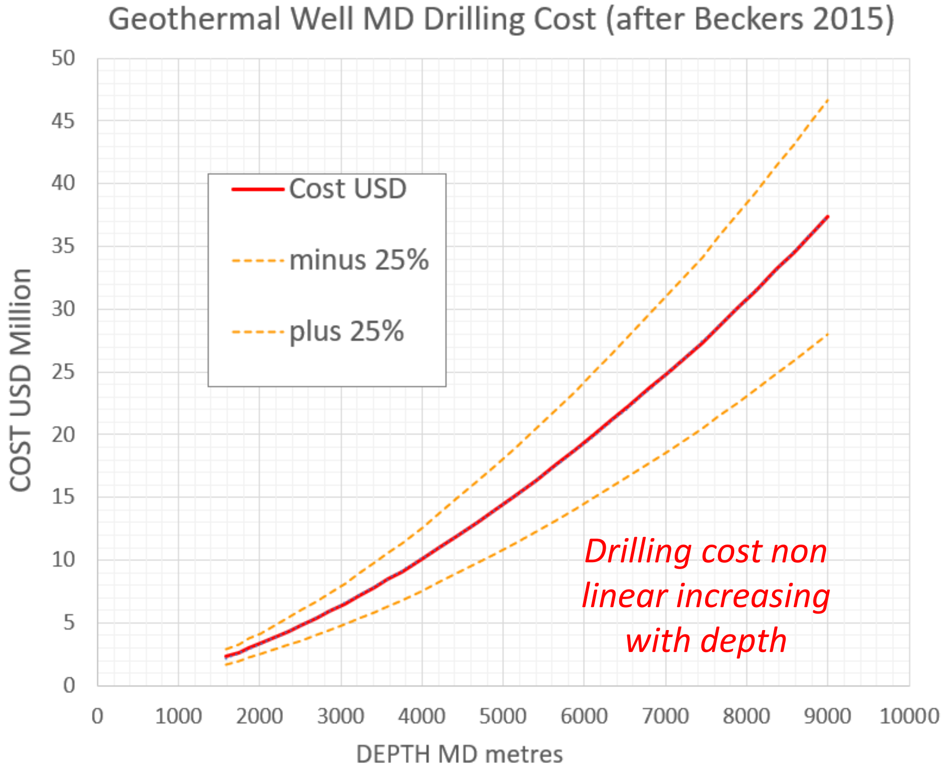
The beauty of shallow

Depending on customer, better flow rate shallower can be more attractive than better temperature deeper
For a price, heat pumps can also deliver temp. uplift

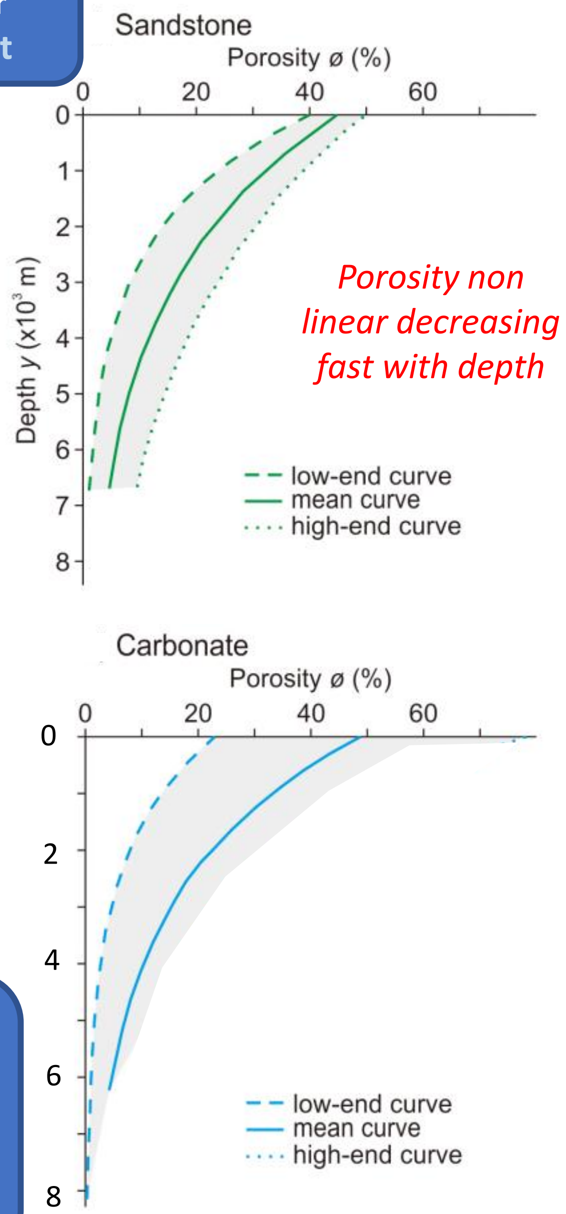
Temp generally approx. linear increasing with depth



Temperature



Drilling Cost



Porosity-Permeability

~ Flow rate ~ perm ~ porosity

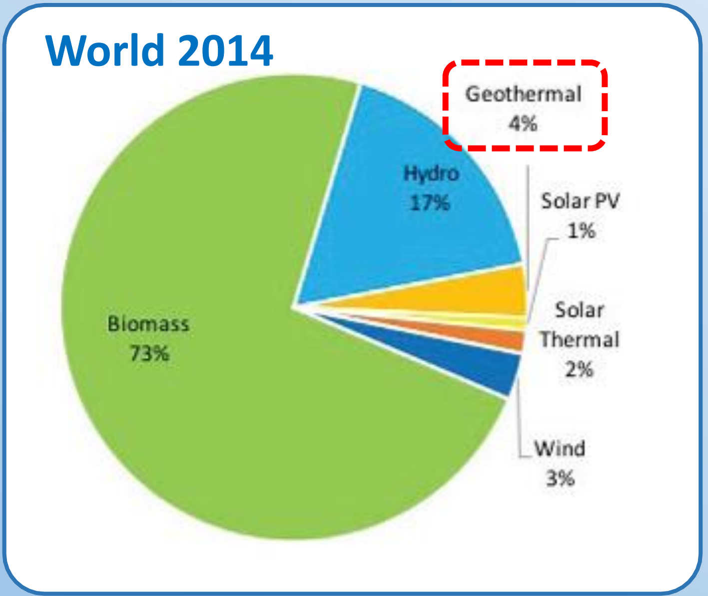
$$\Delta Q = mc\Delta T$$

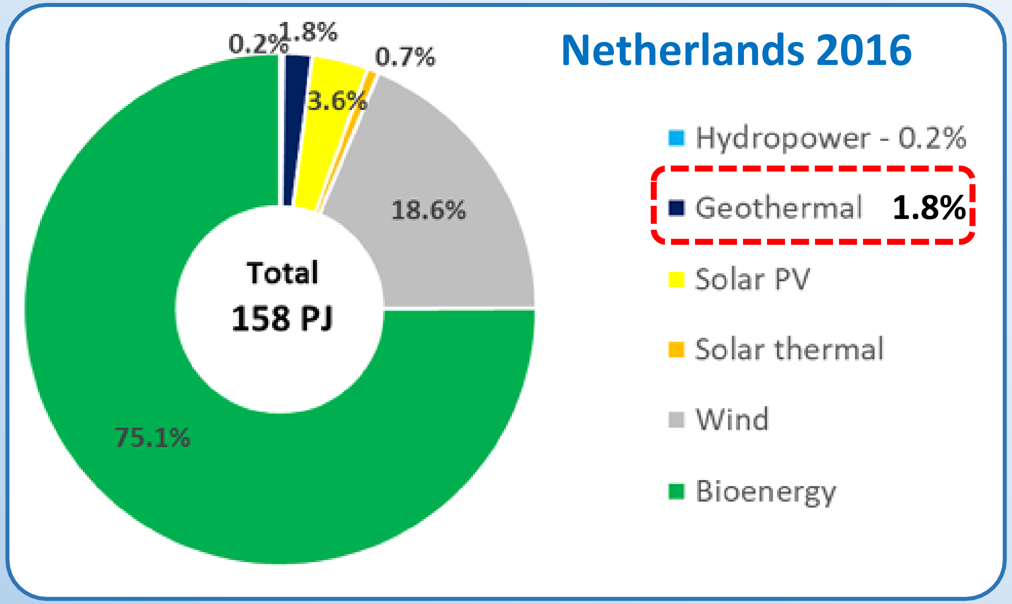
In general, porosity, permeability, flow rate, mass, gets better faster going up than temperature does going down, and heat pumps can beef up temperature with good flow rates cheaper than drilling deeper into tighter rocks can.

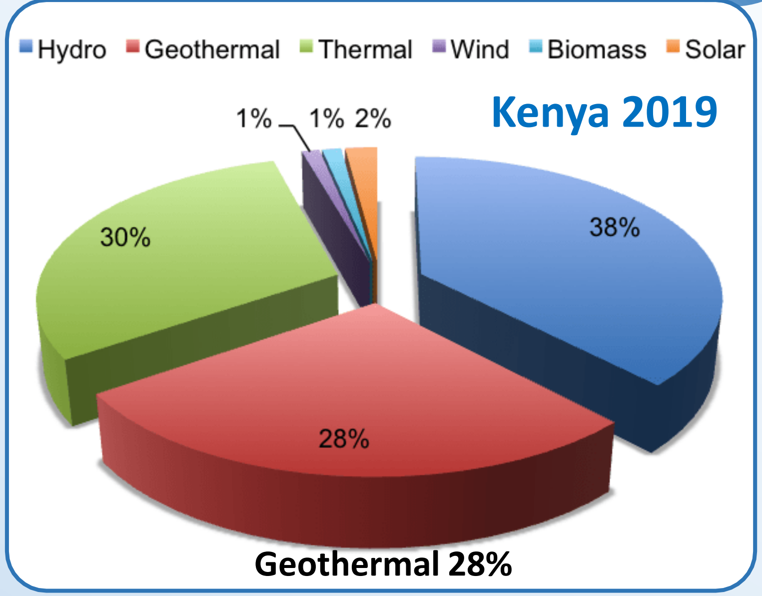
Temperature gets better going deep - linearly...
...Reservoir and costs get better going shallower - exponentially

What geothermal offers, realistically…

In an non-volcanic nation 5% *of total primary energy* is ambitious, 1% is doing OK
In a small to moderate sized volcanic nation 20 +/-10% can be doable







GLOBALLY 2014 - 4% of rnw
BUT renewables are only ~15% of whole => 0.6% whole

NETHERLANDS 2016 – 2% of rnw
BUT renewables are only 9% of whole => 0.2% whole

KENYA 2019 – 28% of rnw
Rnw 80% of whole => 22% whole

The % of renewable power ≠ % of total primary energy
We have to correct to get the true contribution

NZ ~ 22% of rnw
BUT renewables only 40% of whole => 9% whole

rnw = renewably sourced energy

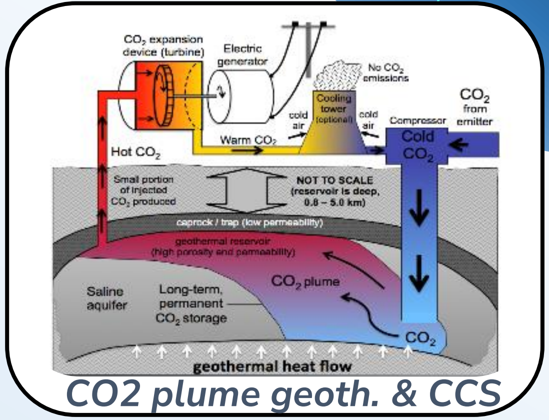
New geothermal technologies

The Great Technology Tease


Onshore seismic acquisition

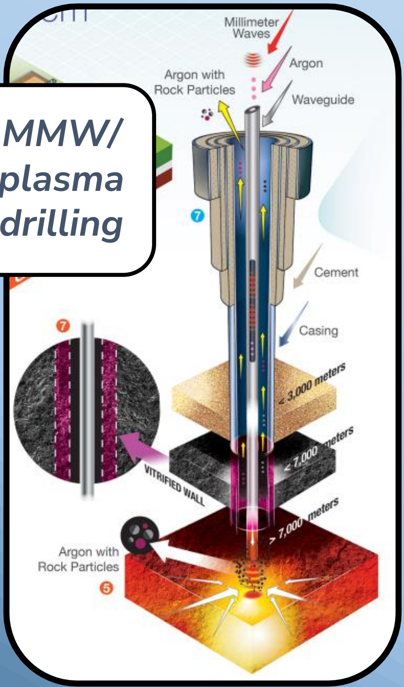

Drilling fast, deep, hard, slim


Supercritical geothermal

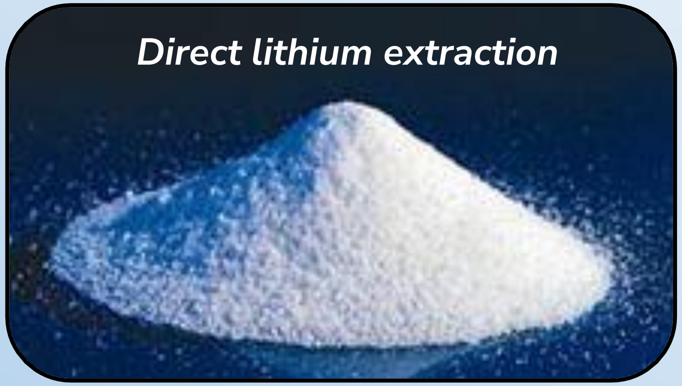


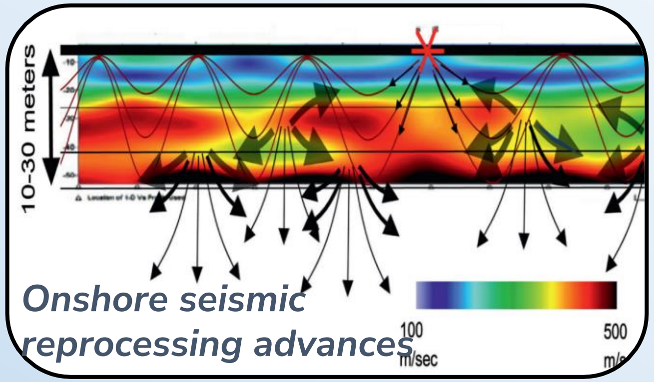
CO2 plume geoth. & CCS

MMW/ plasma drilling




Deep closed loop


Direct lithium extraction



Onshore seismic reprocessing advances

- Lots of things work already, but lots of new improvements are coming
- We don't need to know new technologies are certainly going to work…
- …To know and map where they are *most likely* to work if they do – and to get ready…
- BUT let's not forget all the stuff that works already and has lots of optimisation running room


EGS & Hot dry rock

New technologies in general – some key caveats

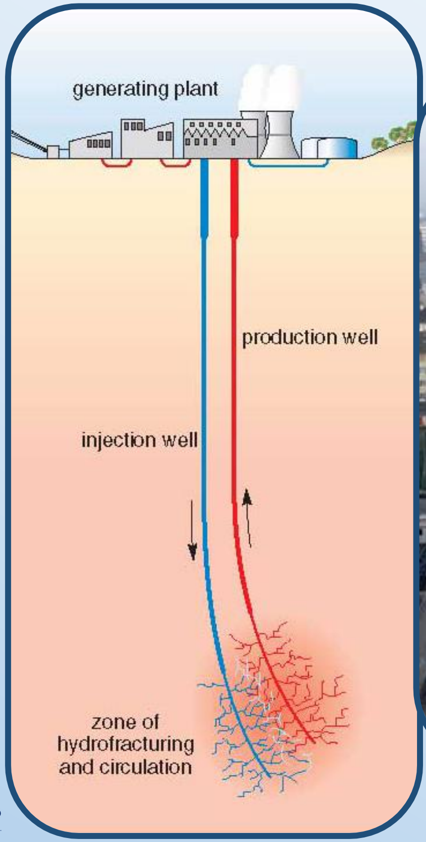
- **New tech R&D is undoubtedly of key importance**
- **But it's not whether new things can be done *technically*...**
  - It's whether they can be done **commercially better than the competition**
  - It's whether they can be deployed **on timescales that suit the customer**
- **And it's not about the size of resource**
  - Its about what can be ***recovered*** and at what cost and risk and speed, c.f. the competition
- **New technologies and supply chains can take a decade or even decades to develop and deploy at scale commercially**
- **Inherently risky – not all ideas work *commercially* – many fail**
- **With ultra-deep hot geothermal in particular**
  - it's not about getting there with drilling – that's the easier bit
  - it's about staying there and maintaining hole, heat, and flow rate
  - throughout decades of operational life of the facility – at manageable cost
- **That's harder**

Can it be done, versus can it sustainably pay its way...

Hard as it is to get there, staying there can be the even harder task...

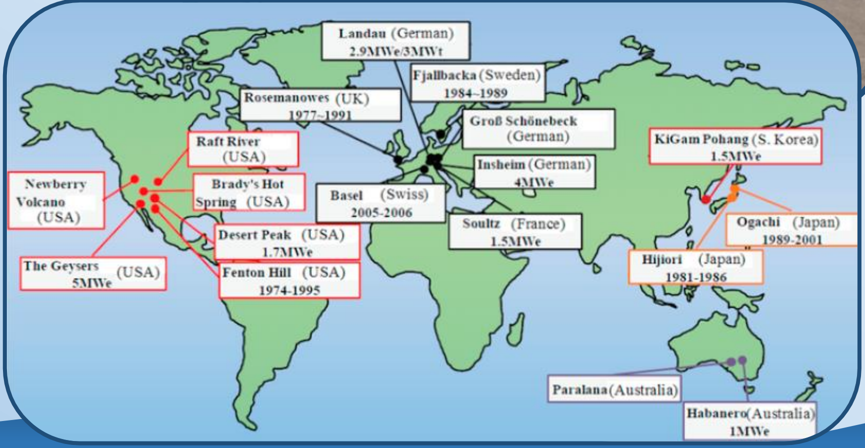
Deep hot dry rock & EGS (Enhanced Geothermal Systems)

- Might want to "enhance" natural fracture permeability by overpressuring to generate shear failure fractures
- Hot dry rock EGS does this, and introduces water circulation into deep hot rocks where it isn't present [much]
- Often looking for natural fracture systems to help
- A hot radiothermal granite component can help too
- Being tried in US, Australia, France & Switzerland, Scandinavia, China, UK
- Usually not quite fracking – that's different – induced tensile failure to pump in proppants and hold fractures open
- EGS is normally more "tickling" existing fractures – circa 2000 psi c.f. fracking 9000 psi
- *<u>But getting a commercially connected volume of fracture porosity is tricky</u>*
- Risk of induced seismicity –activating pre-stressed faults to prematurely release existing pent up tectonic stresses
- Social licence issues & monitoring costs



Greatly opens up the areas that can be considered for geothermal

But not a game for the risk averse - need to know your faults and fracture zones



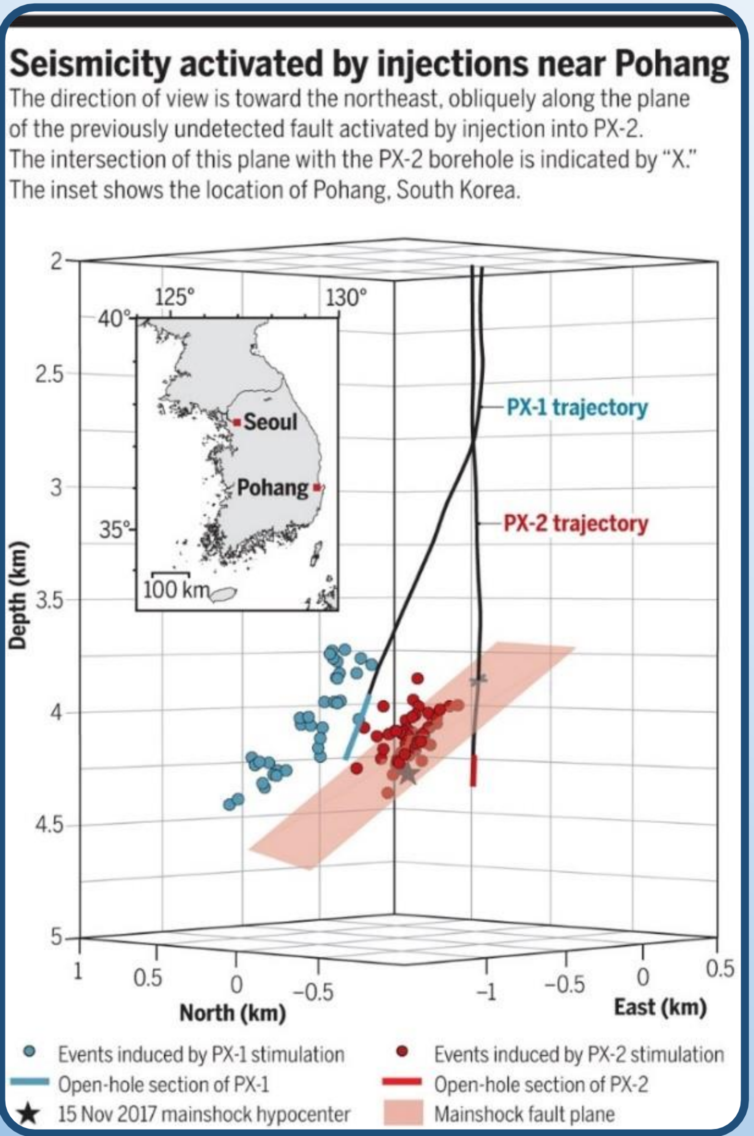
Deep hot dry rock & EGS (Enhanced Geothermal Systems)

- 2017
- 5.4 Pohang South Korea
- 82 injuries
- 9km deep, MMVI, 0.58g
- 5444 households damaged
- 1392 people displaced
- About $USD 50 million damage
- The fault was not identified pre drill & geothermal EGS operations activated
- A 3.4 EQ in Basel permanently stopped a project there
- => commercial risk even if there isn't a damaging event

Map & know your faults
& check your insurance policy...

Especially if near downtown

EGS geothermal wants to chase its market...not shake it up



Projects that don't elevate pressures, or inject water where is wasn't already

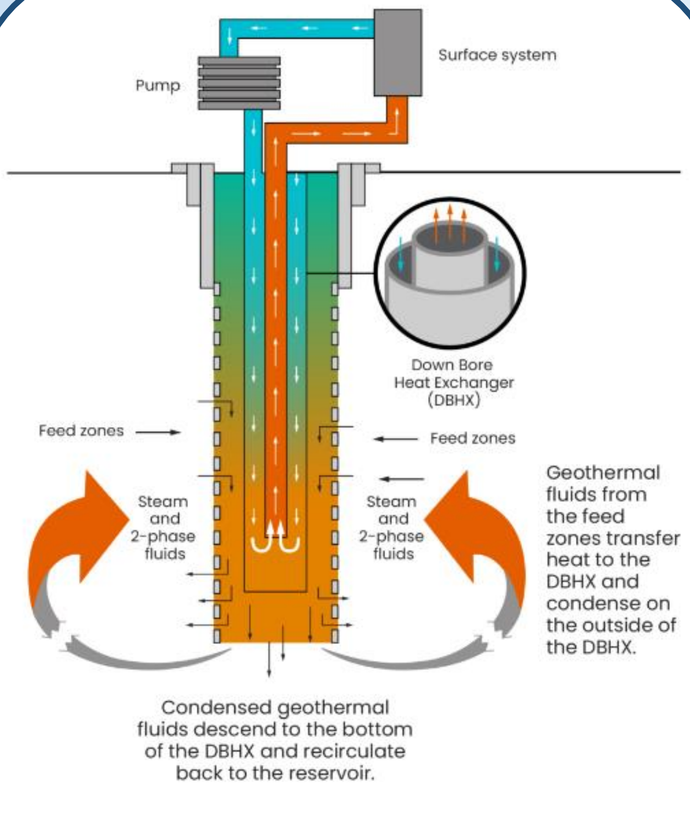
MOST GETOTHERMAL (especially for heat)

ARE MUCH LESS RISK

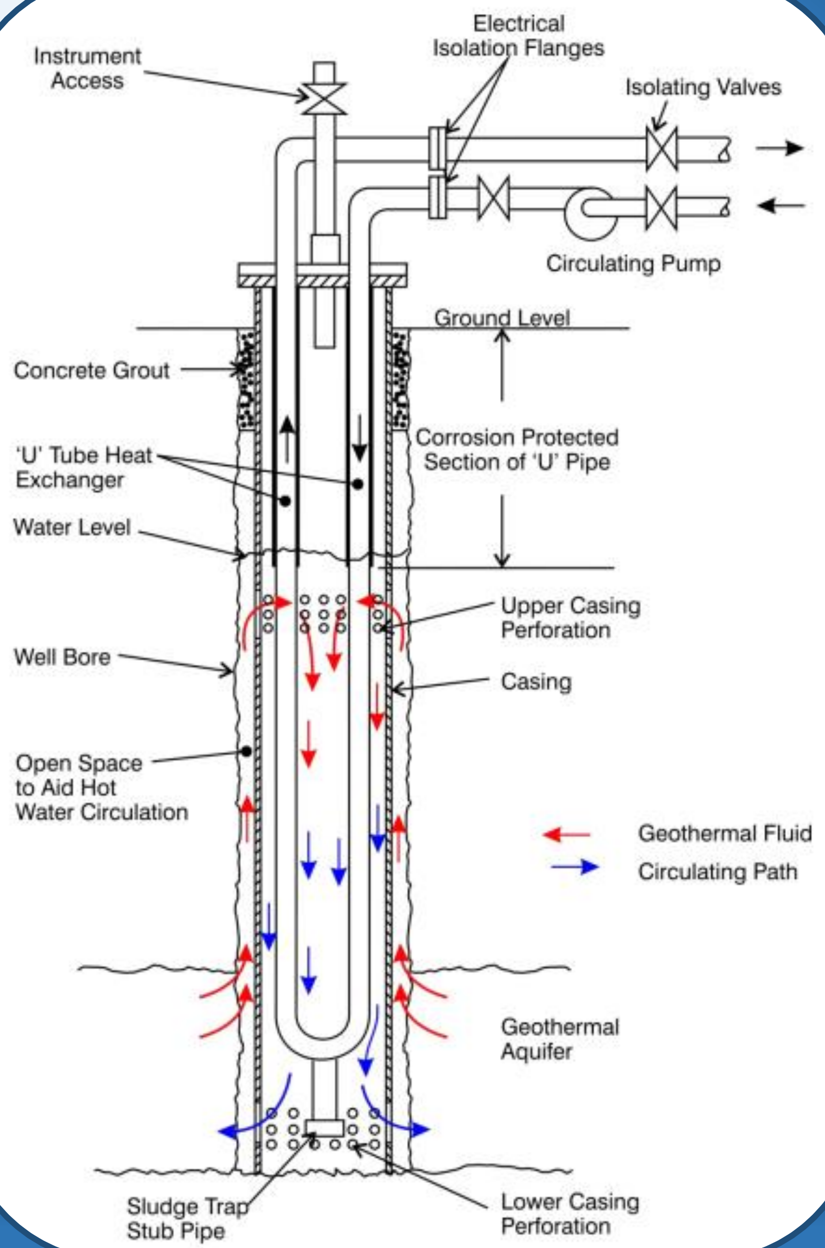
DBHE closed loop

- Deep borehole heat exchangers
- Close loop systems within a well bore applicable for heat or power
- Steam and/or water reservoirs
- Can experiment with working fluid inside loop – sCO_2
- Especially interesting repurposing old end of life geothermal or oil and gas wells
- But still might need to workover and create a bigger hole for the DBHE kit
- Lower energy punch than conventional open system so harder economically justifying totally new wells
- But all depends on precise customer needs

Great way to revitalise old existing wells
Economics for new more challenging



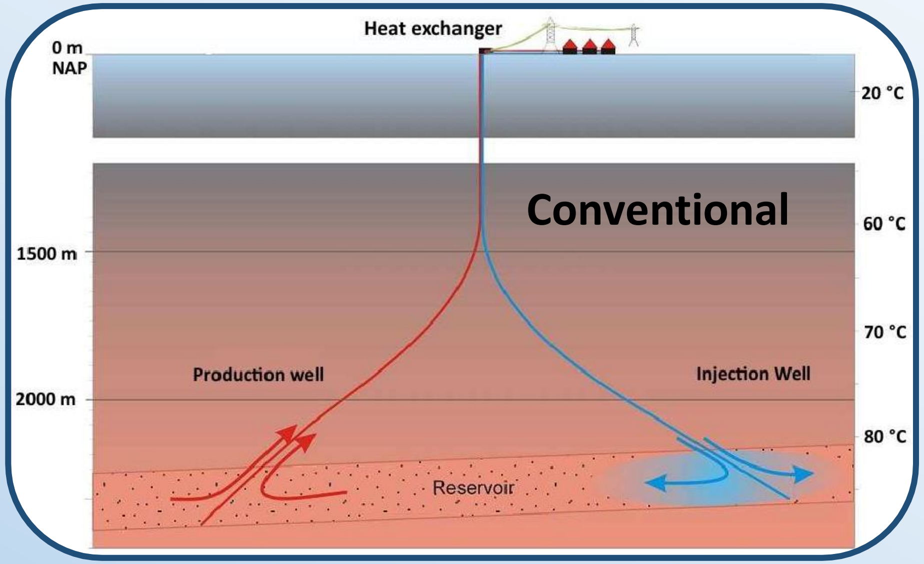
Steam GreenLoop and 2-Phase GreenLoop Designs

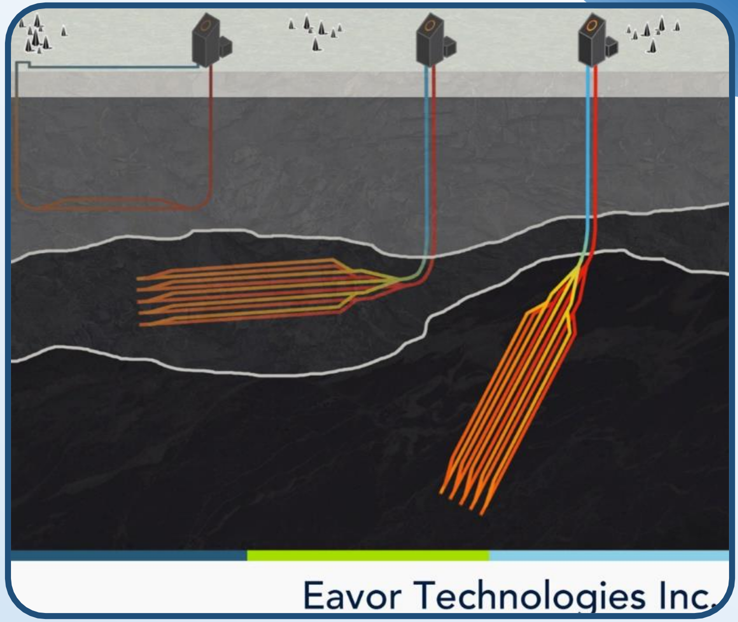


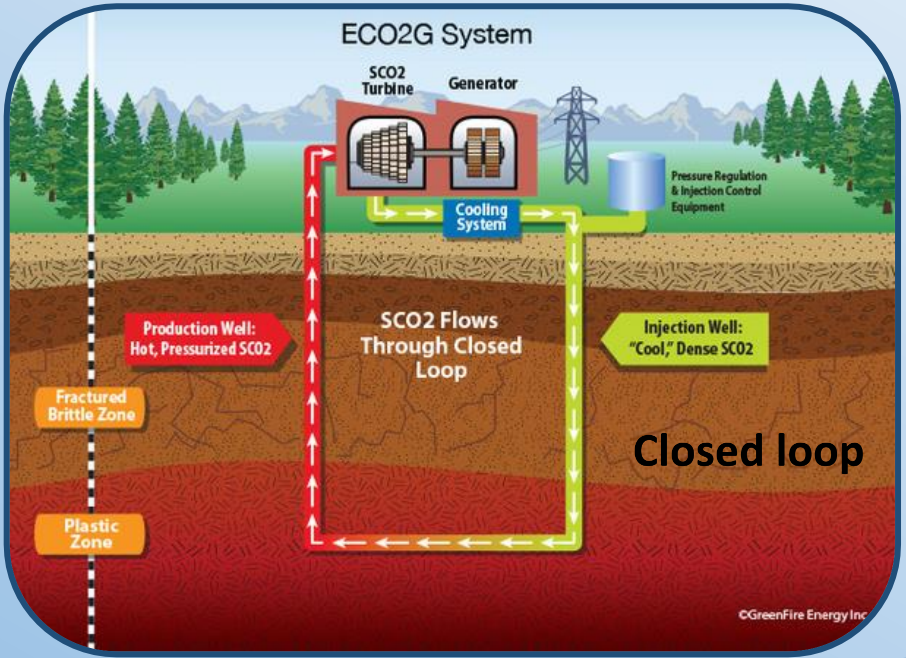
Deep closed loop

- **Longer closed loop with more complex drilling geometries – not just one single simple well – are another option**
- **A lot of drilling**
- **Can experiment with working fluids**
  - E.g. SCO2 = supercritical CO2
  - Additives to help conductivity
  - SCO2 has high thermal efficiencies
  - Great as long as it doesn't get wet, then very corrosive
- **BUT we need heat recharge into a much smaller area c.f. open systems to keep reheating the wellbore fluid**
  - We are cooling with injection the same rocks we extract heat from
- **Might be able to take advantage of any convection or advection within reservoir**
  - But that assumption introduces geological risk

Long term heat delivery & its economics is the key uncertainty

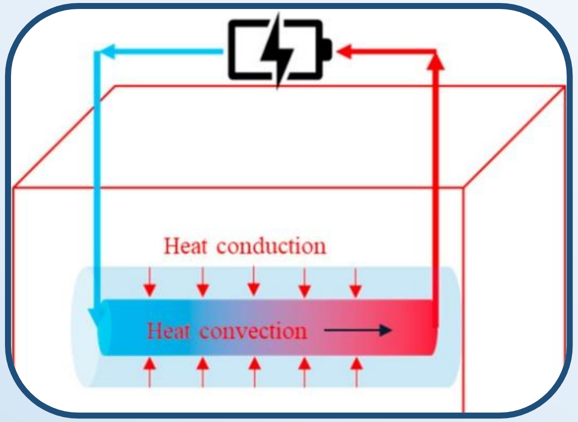




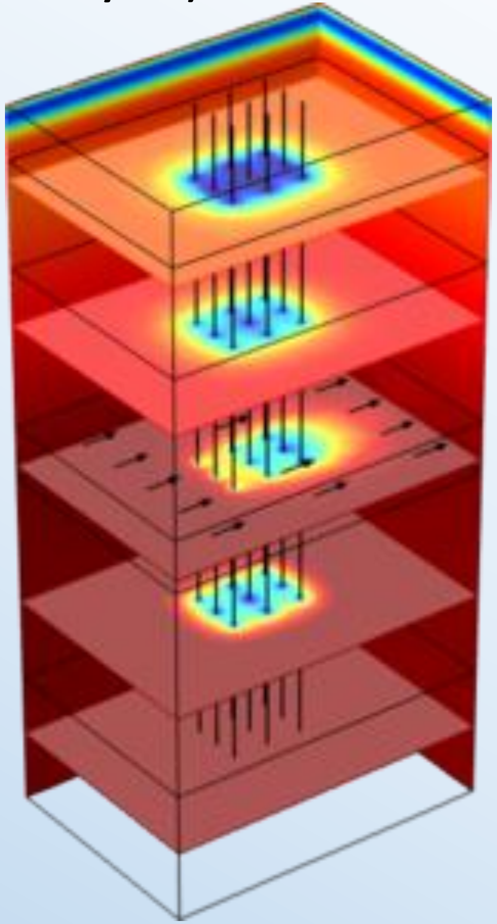


Open system versus closed loop – Close loop pros & cons

- Closed loop
  - Accesses heat conducted from around wellbore
  - Instead of heat advected from the reservoir's own fluids
  - Injection is cooling the same area
  - Heat can be order of magnitude less than a success case open system
    - A lot of drilling expense for less heat
    - Unless well exists already… repurposing
    - Typically of order 0.2-0.5 MW closed versus 2-3 MW open – but might be all customer wants
    - And might be higher for an end of life high enthalpy geothermal well
  - No dependency on reservoir permeability – less risk
  - No issues related to reservoir geochemistry
  - No risk of induced seismicity except during drilling
  - Less emissions risk c.f. dry steam or flash steam
  - **A trade off on drilling cost and heat delivery -**
  - Relatively few new projects commercial…so far
  - **Likely to expand, but how much is uncertain**



Closed loop – sucking heat through a 1D straw (or array of..)



Closed loop - gains on some risks but compromises on heat gained
That might be OK, or not, - depends on customer needs
Always a trade off of drilling cost and (risked) heat delivery

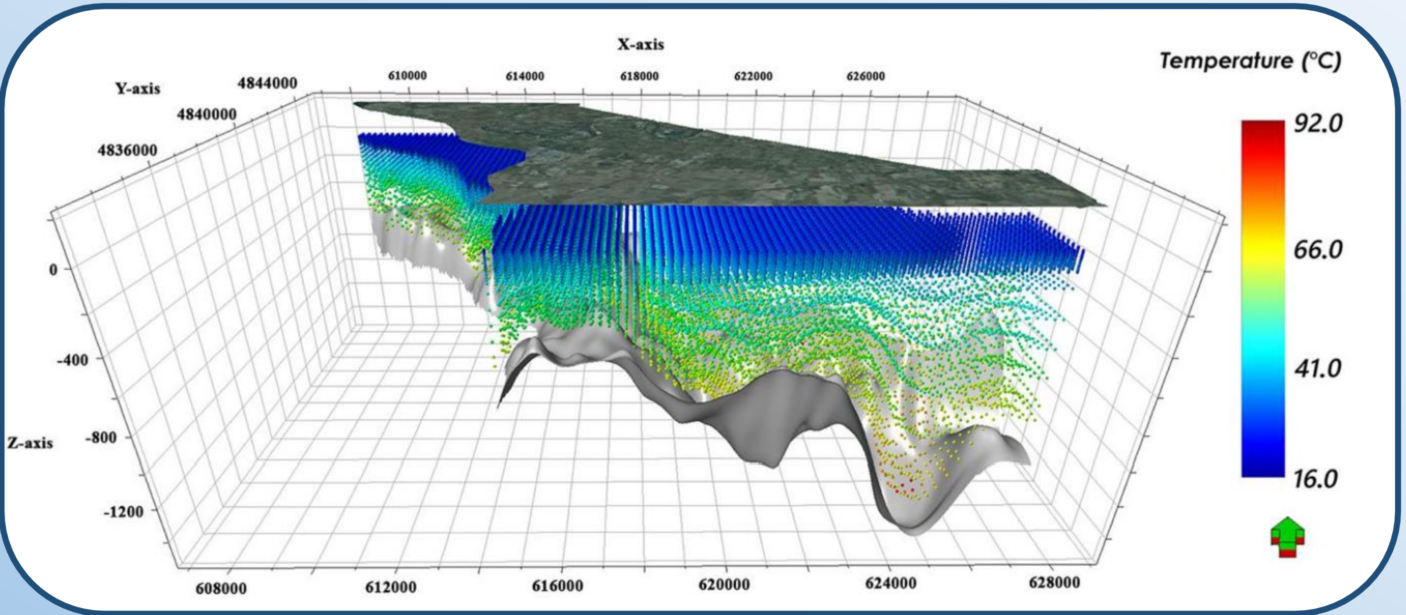
Oslo airport de-icing: A successful deep closed loop project

Open system versus closed loop – Open system pros & cons

- **Open systems advect the actual reservoir fluids with their heat to the surface**
  - **More risk on:**
    - Reservoir permeability
    - Fluid geochemistry corrosion & scale
    - If EGS - then induced seismicity risk
    - If hot dry steam or flash steam – then reservoir gas emissions might occasionally be an issue
  - **BUT**
    - Heat flow units are mW/m2
    - Function of area => more area, more heat
    - Watts = rate - energy per second = function of time => longer down there, the more heat collected
    - More a flow can spread out in a reservoir, slower it goes, more heat it can collect
    - Accessing a much larger area recharging heat catchment
    - Squeezing the heat of a much bigger 3D thermal sponge
    - **PROVEN in thousands of sites globally**
    - **And risk often isn't that bad for well known reservoirs and modern ORC binary plants or direct use heat**

Open systems more energy punch & commercially proven, but carry more geo-risk
Accesses a far greater heat catchment
Allows for greater heat recharge
Always a trade off of drilling cost and (risked) heat delivery

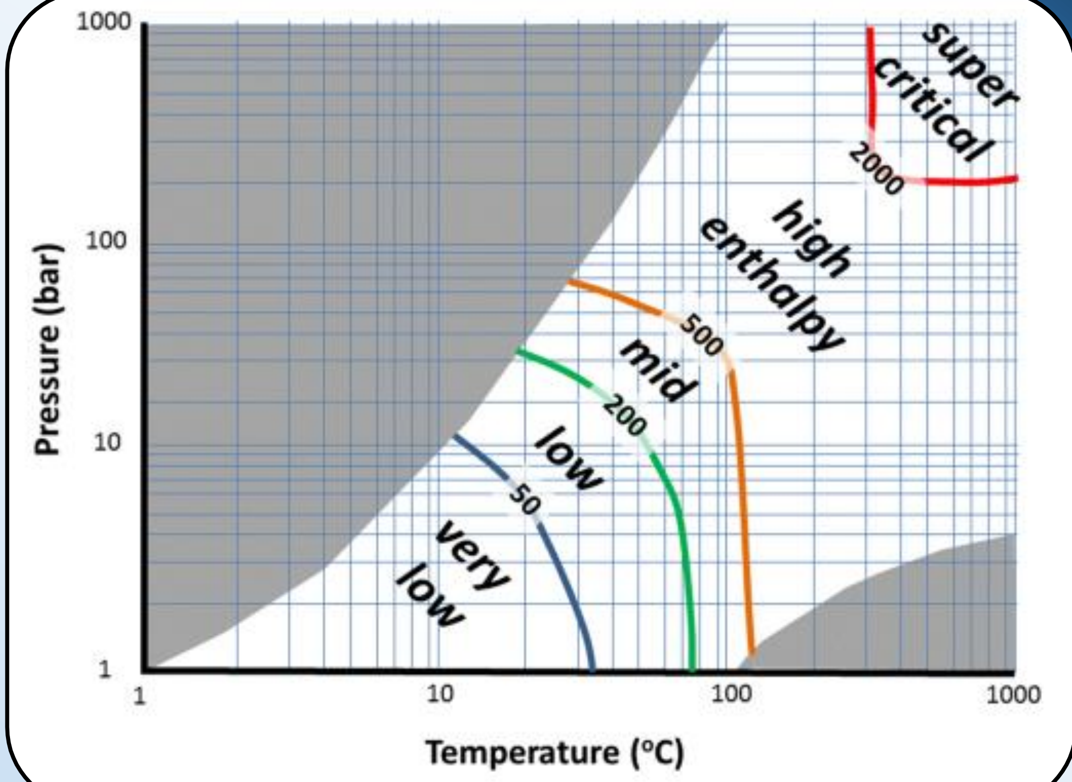
Open system:
Squeezing heat of a big 3D thermal sponge



Supercritical geothermal

- **Depths near or below the brittle-ductile transition**
- **Power plants can in theory obtain around ten times more useful energy from water that is supercritical**
- **Temps > 375 deg C and >220 bar (22 MPa, ~3200 psi)**
  - Up to 450 deg C so far from Iceland, and up to 500 deg C in Japan, and up to 1050 deg c above an intrusion in Hawaii
  - So far mostly low perm, but occasionally not bad, especially just above magma chambers
  - Ongoing R&D projects in Iceland, Mexico, New Zealand, Japan, Italy
- **~25 wells globally have encountered such conditions**
  - Italy, Western US, Hawaii, Iceland, Japan, Mexico, Kenya, New Zealand
  - Typically abandoned because of extreme conditions – but can we learn to handle?

Targets >375 deg C & 220 bar (or 22MPa ~ 3200psi)
Increased efficiencies
Up to ten times more useful energy obtainable
~2020, 25 wells globally had reached these conditions
Extreme conditions, low perm, hard to maintain



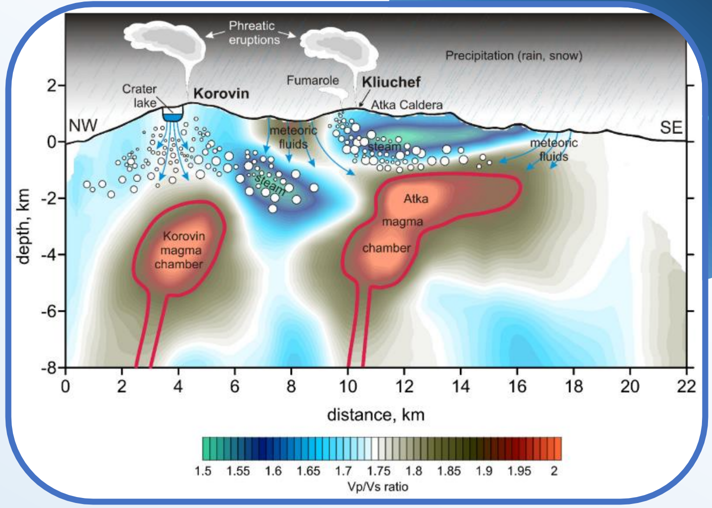
	CONVENTIONAL DRY STEAM WELL	IDDP WELL
Downhole temperature (°C)	235	430–550
Downhole pressure (bar)	30	230–260
Volumetric rate of inflow (m^3/s)	0.67	0.67
Electric power output (MW_e)	~ 5	~ 50

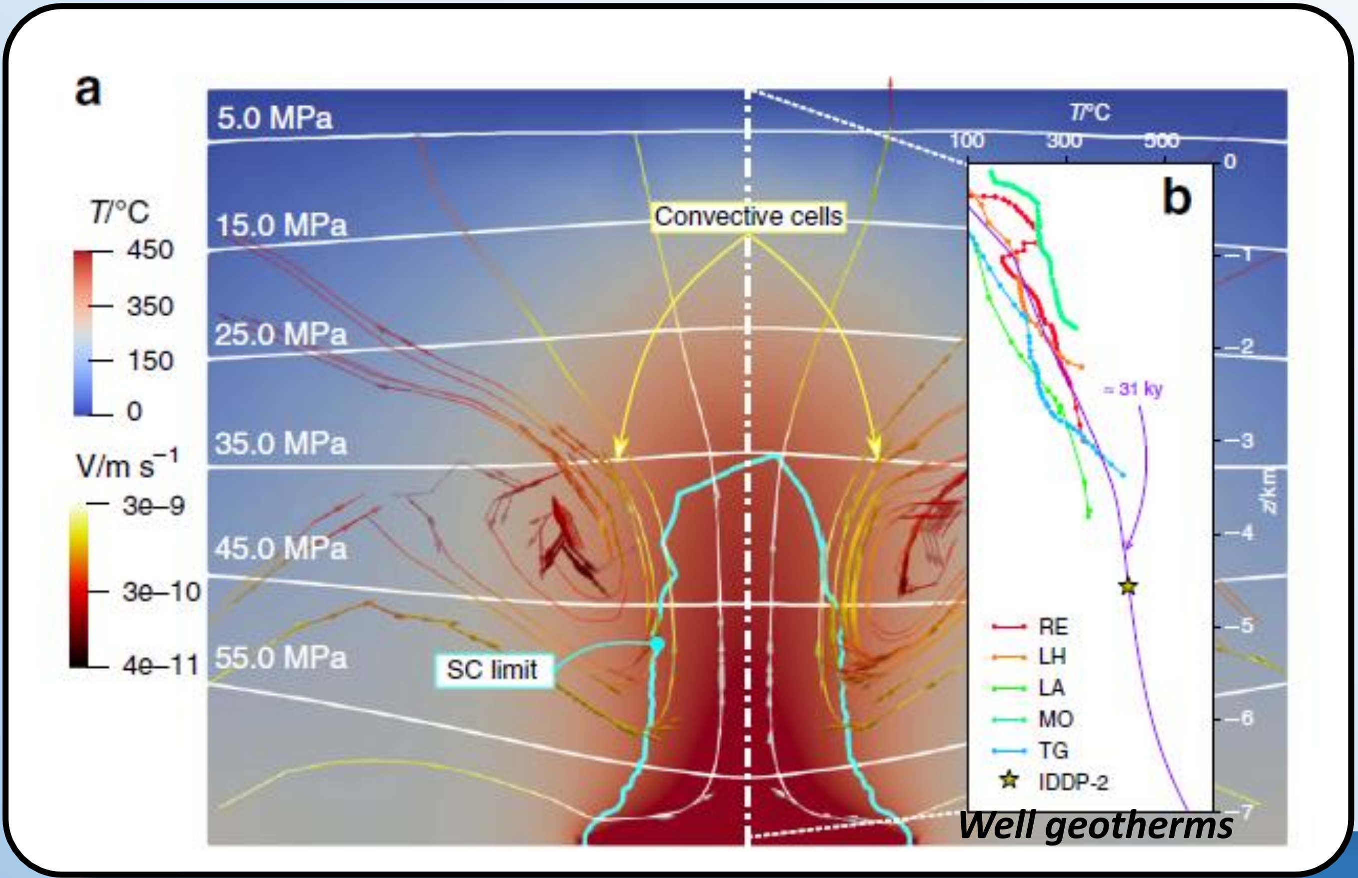
Table 1: Comparison of conventional and unconventional geothermal systems (Fridleifsson, 2011).

Supercritical geothermal

- **Projects to date have documented fluid entries, but can permeability be maintained?**
  - Is EGS in semi ductile rocks an option?
  - Large temperature contrasts with injected fluid also carries induced seismicity risk
- **Extreme corrosion, abrasion, and scale issues, and increased operational drilling risks**
  - Including dealing with magma –as has happened in Iceland
- **Logging a great challenge – one thing to drill there, another to make tool observations**
- **Supercritical usually requires either super deep well**
  - Drilling cost implication
- **Or shallower targets with but very effective insulating horizons**
- **Without it, in an unsealed hydrostatic hydrothermal system *already boiling near surface*, the depth threshold for supercritical occurs at around 3.6 km**

Big energy resource is not in doubt
Can we get there
Can we log there
Can we extract fluids there
Can we maintain operations over the life of a plant
Can we do so commercially given the costs and risks





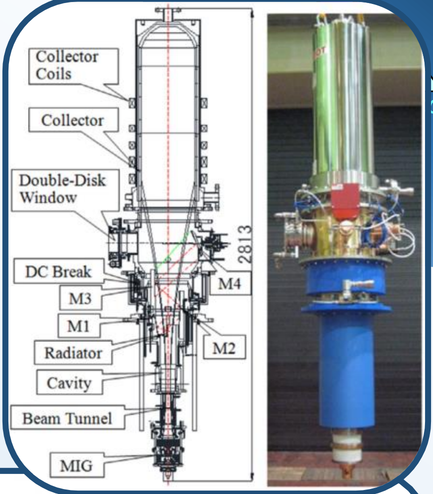
Supercrit. MMW Drilling (Quaise/AltaRock - US)

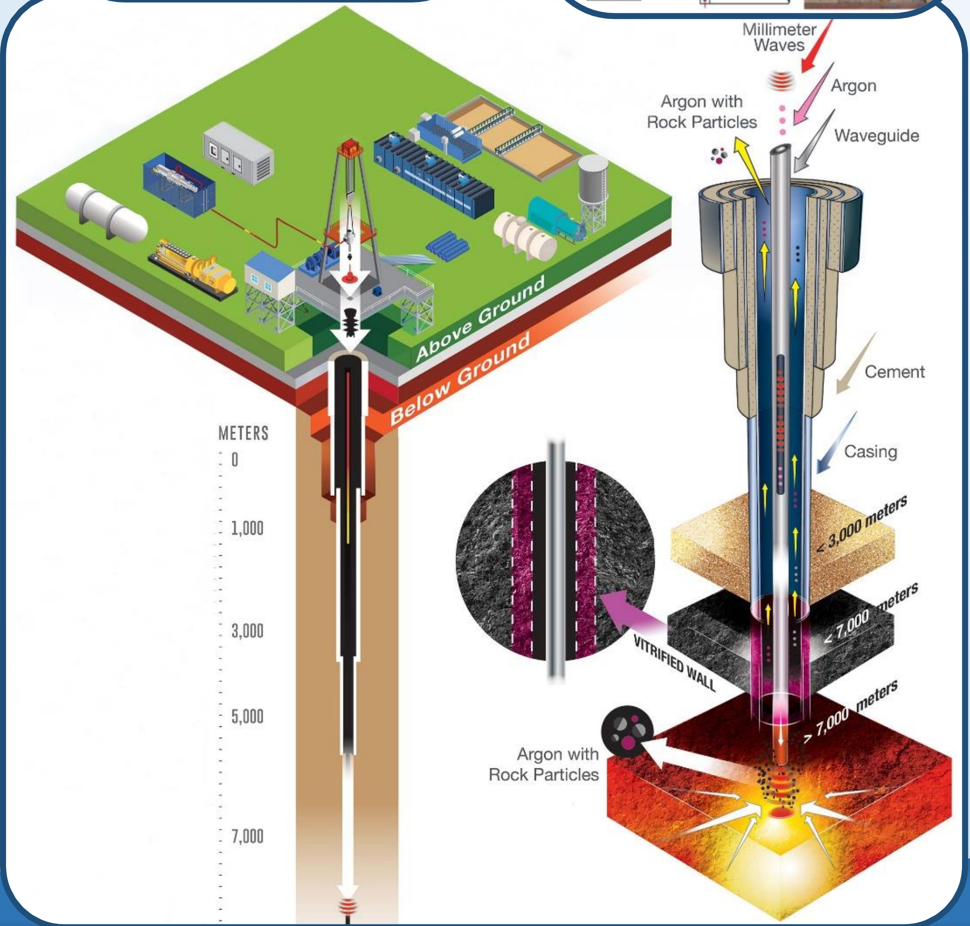
Electromagnetic millimetre wave drilling

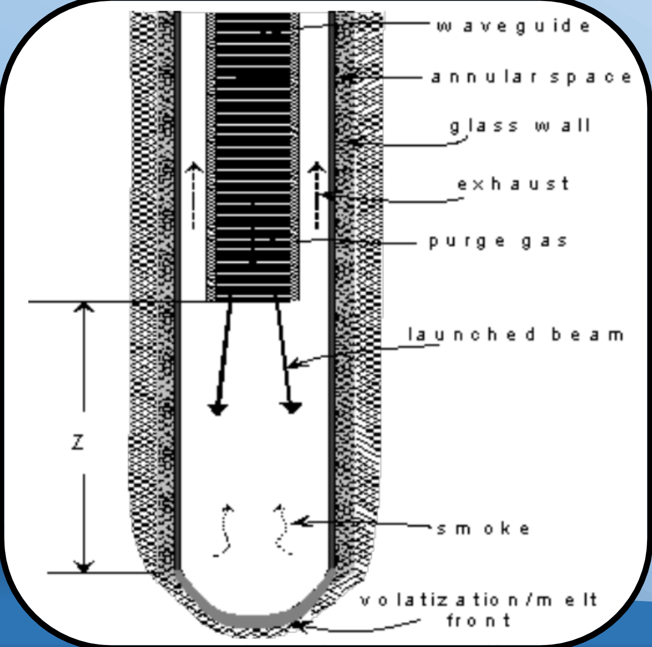
- Early R&D stage and the economics uncertain
- But development from players like MIT and ARPA-E, and ITER fusion project are in progress
- Uses Gyrotron electromagnetic rock destruction 30-300 Hz
- Vaporises the rock and evacuates it with argon
- Rock sides vitrified and sealed – at least during drilling
- How does a hole at near ductile conditions hold over time
- Getting there is not maintaining hole there

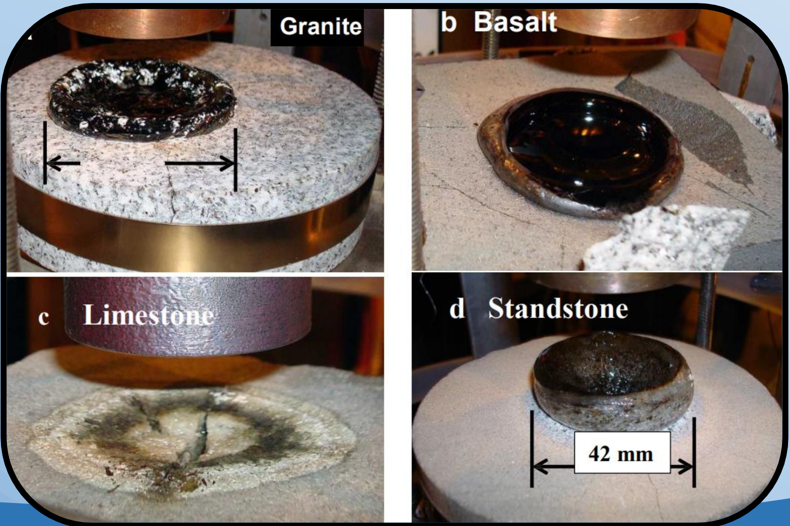
Ultra deep and ultra hot
Interesting but not here in deployment yet

10-20 KILOMETERS To supercritical conditions everywhere	100 DAYS To depth
1 MEGAWATT Gyrotron	1,000 TONS Rig capacity









Supercrit. Plasma torch drilling (GA Drilling Slovakia)

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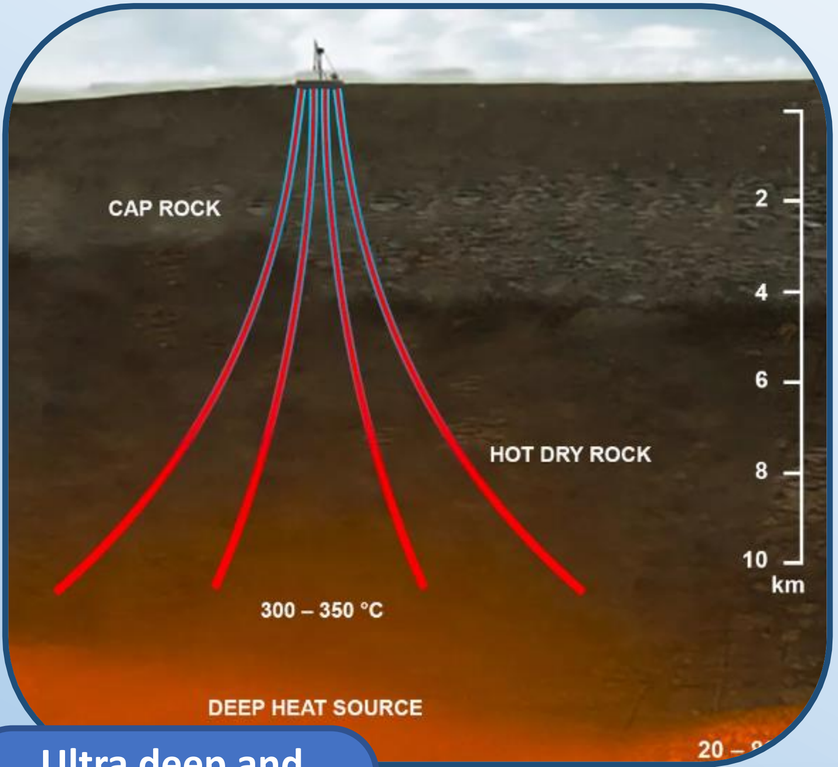
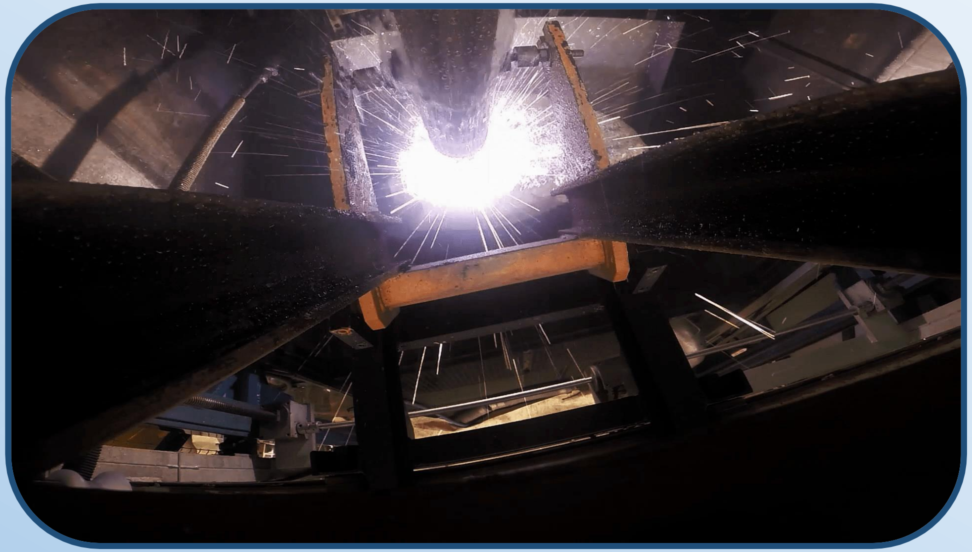
- Technology in R&D stage
- Plasma torch to blast rock
- Economics and energy intensity of protracted drilling to 10 km scale depths unclear
- But lab progress continues



Ultra deep and ultra hot
Interesting but not here in deployment yet



Incremental advance of conventional Geothermal Technologies & workflows

Slim hole exploration wells

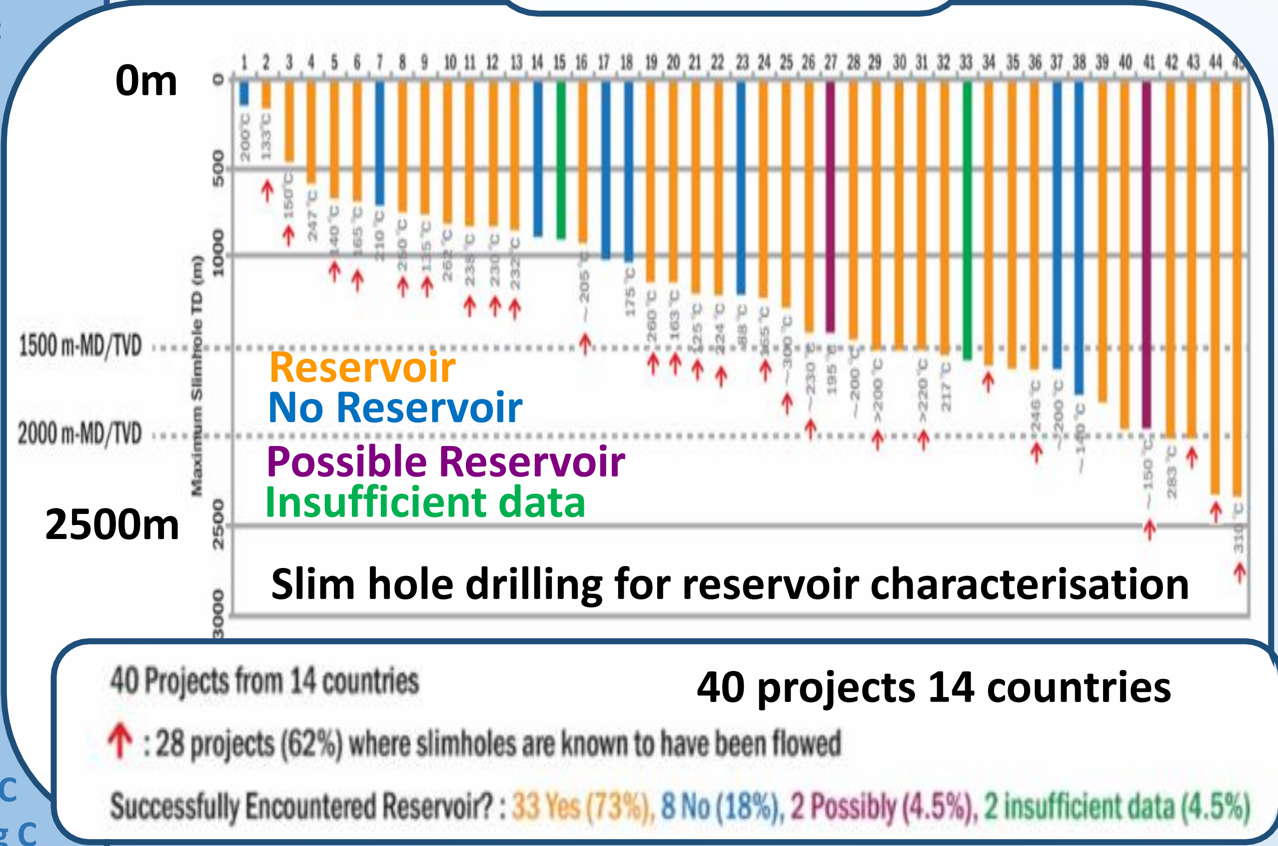
- 1920's-1950's tech…
  - <7" hole (~18 cm)
- GREAT…
  - When your key project critical risk is:
    - Reservoir quality or
    - Temperature or
    - Benign fluid chemistry
  - 20-25% cost of standard well
  - Full coring at reservoir possible
  - Helps when seismic or other remote geophysics isn't helping
- BUT…
  - But typically 2.5 km or less
  - Can't be used for production
  - Slower to drill
  - Deviation difficult
  - More Limited logging options

Review study:

45 wells from:
Guatemala
USA
Honduras
Chile
Iceland
Nicaragua
New Zealand
Indonesia
Argentina
Malaysia
Japan
Dominica
Japan

All < 2.4 km

One < 100 deg C
Five 100-150 deg C
Seven 150-200 deg C
Fifteen 200-250 deg C
Four 250-300 deg C
Two @ 300 deg C

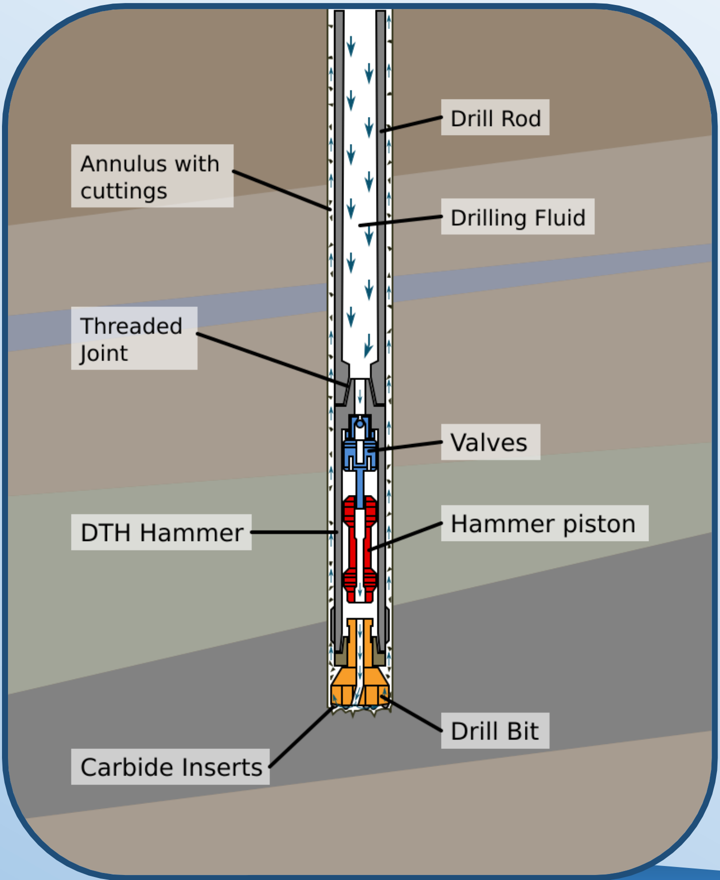


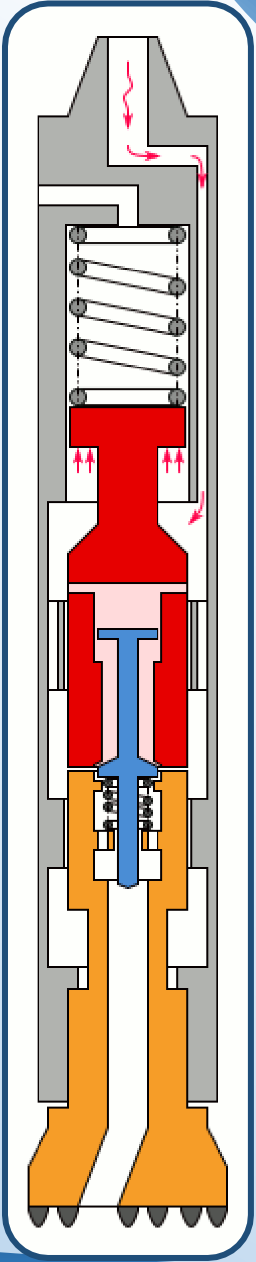
Value of information of a "quicklook"
Reservoir; Temp; Fluid chemistry

Down-the-hole (DTH) Hammer & fluid hammer percussion drilling

- Drilling deeper faster
- Water or air powered hammers
- Air loses effectiveness at depth and water better
- Trialled to 4.6km through granite, Finland
- Helps with hot dry rock & EGS applications

deep, fast, hard, safely, reliably, cheaply





Onshore seismic advance – critical

Onshore seismic will never be offshore seismic… But doesn't have to be - it can be good enough

- Where's the reservoir and what's the permeability architectu
- We don't need to find hydrocarbons with it…
- Unobtrusive techniques improving seismic in urban and commercial environments where the market is
- Nodal cable-free sensors changing paradigms
- AI, Computing power and processing advance is too.

Permeability architecture & dynamics

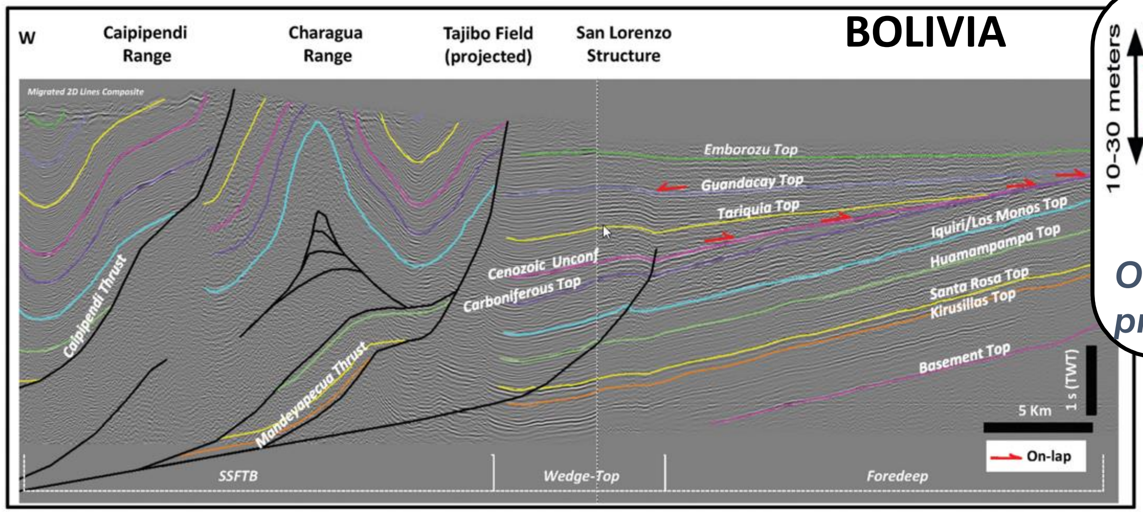
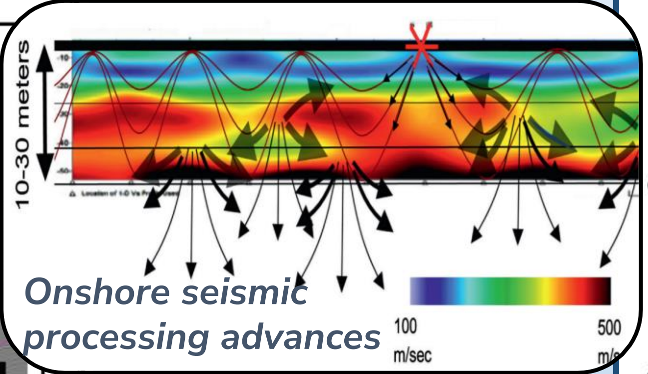


Figure 4. Regional interpreted 2-D seismic lines showing the relation between the SSFTB and the foreland basin system. The wedge-top is defined by a single main thrust at San Lorenzo structure location.

Andean Deformation and Its Control on Hydrocarbon Generation, Migration, and Charge in the Wedge-Top of Southern Bolivia – Pereira et al. 2019



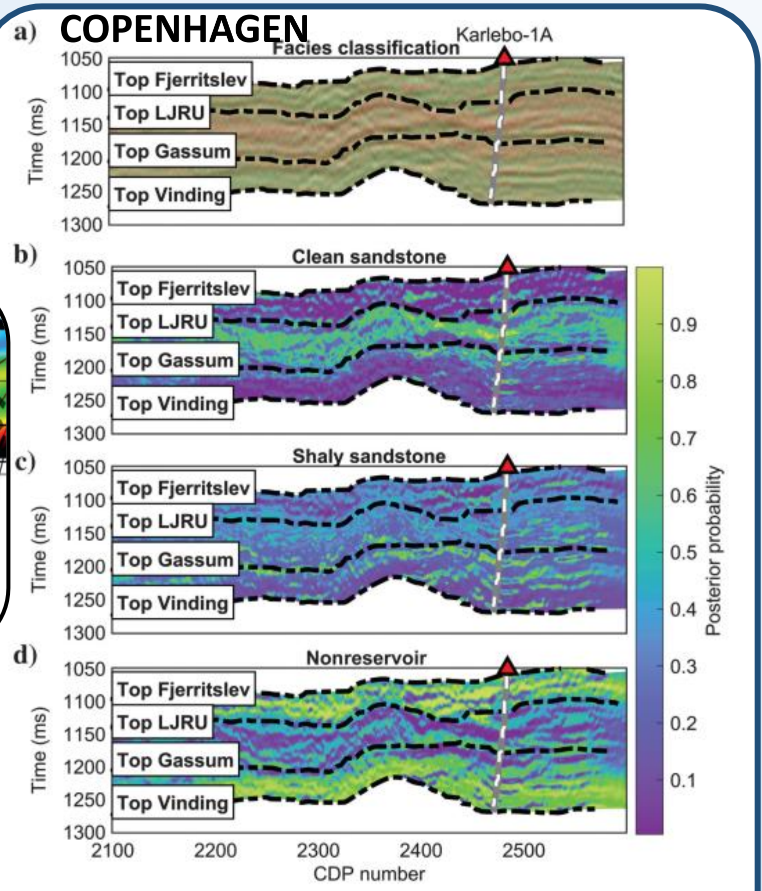


Figure 12. Seismic facies classification: (a) most probable facies superimposing a seismic backdrop and the posterior probabilities for (b) clean sandstone, (c) shaly sandstone, and (d) nonreservoir facies. The facies classification in (a) is red, yellow, and green for the clean sandstone, shaly sandstone, and nonreservoir, respectively.

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Plug & Play - Well and plant modularity

- A different approach – not how big is each resource and what bespoke design should we put on it…
- …here are the modules, how many of them could we put where?
- Good too for oil and gas well repurposing
- Also optimisation possible from multi-plant operational hubs
- Virtual plant control of the operations & heat/power distribution takes place remotely
- Paradigm change in approach, reduces costs
- Being tried in Kenya, Turkey, Iceland

Plug & Play Small ORC binary for oil and gas co-production

GEG & KenGen 5 MW Single Flash Olkaria Kenya

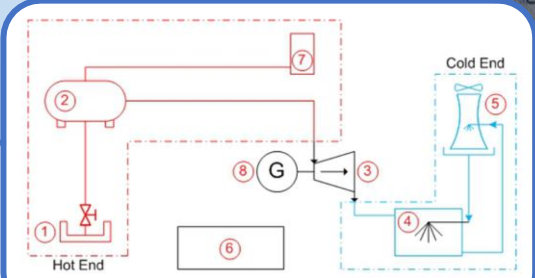
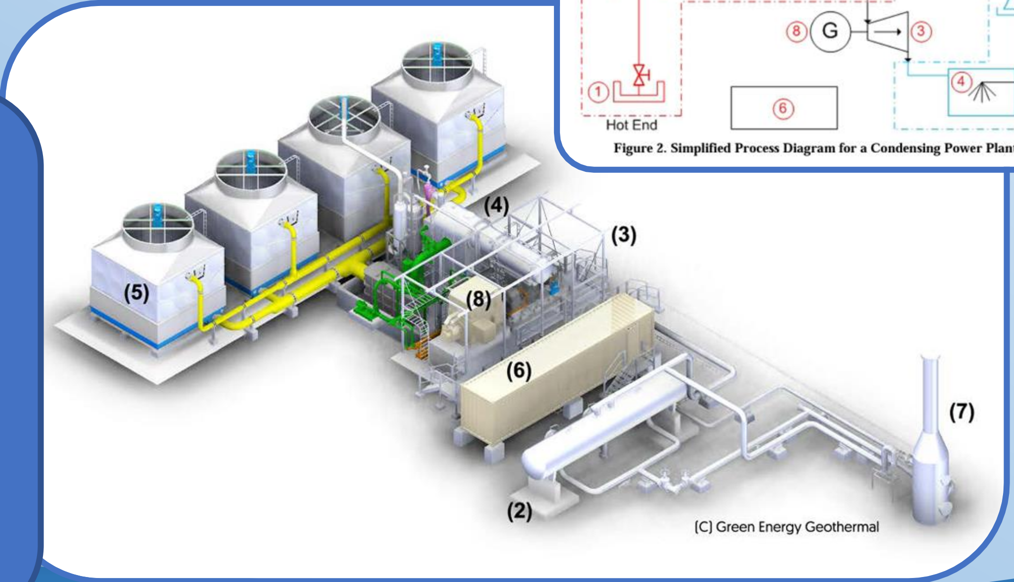


Figure 2. Simplified Process Diagram for a Condensing Power Plant



Similar resource is in lots of places

OPEX is the key for geothermal

⇒ Optimising the kit first is best way to optimise the resources

Virtual power plant monitoring Enel, Turkey

Planning & streamlining

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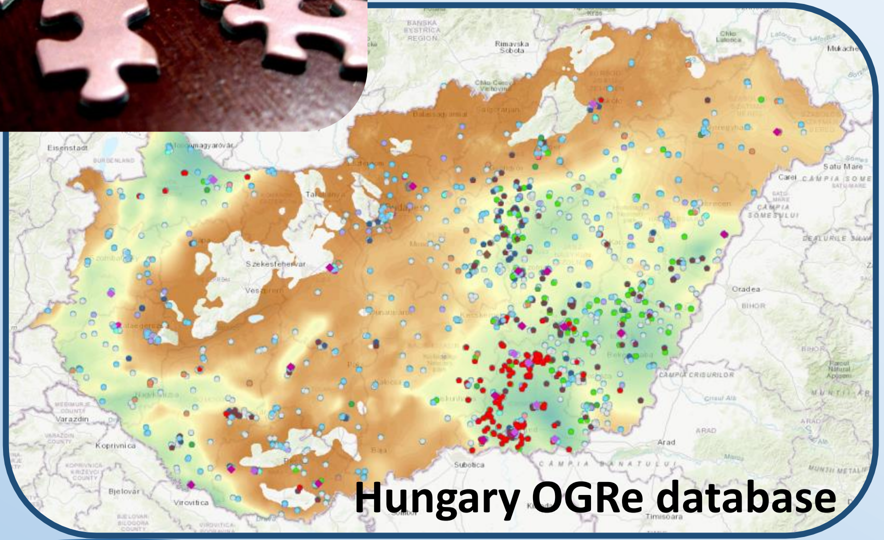
- Time to development is project critical to every customer
- Pre-emptively identifying exploration targets and planning permission protocols helps
- On the shelf ready to go when a customer turns up ready to run
- Knowing the regional potential and other players
- Back to back exploration and development and production co can be shared, including...
- Modular constructions
- Mobilisations
- Planning databases, regulatory frameworks, community consultations, business awareness
- So much progress is just about awareness and putting the jig-saw pieces together, and speed



Hungary OGRe database

Pre-emptive planning work is a key

Catch is... - it doesn't come for free

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Regional Exploration & scalability

Upscaling the opportunity

Scalability – A UK example

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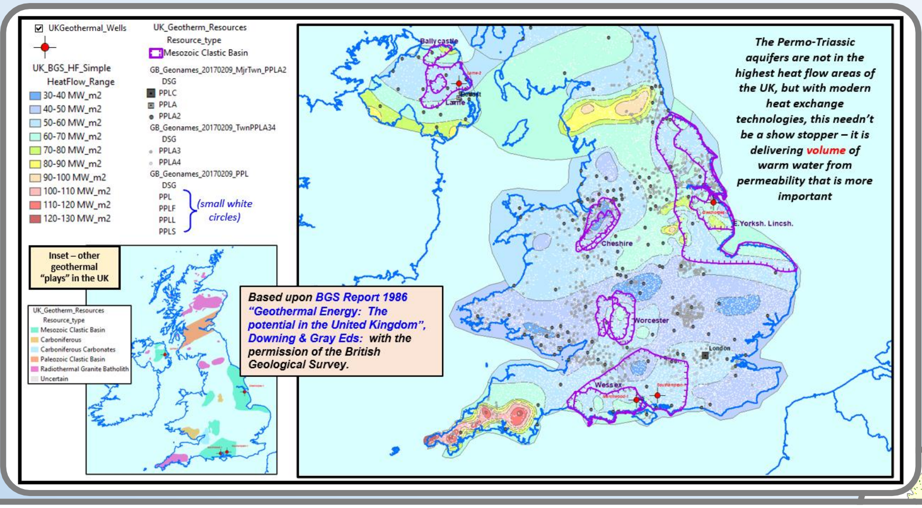
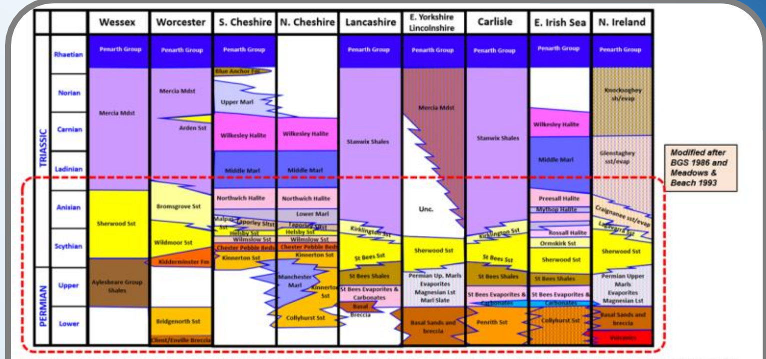
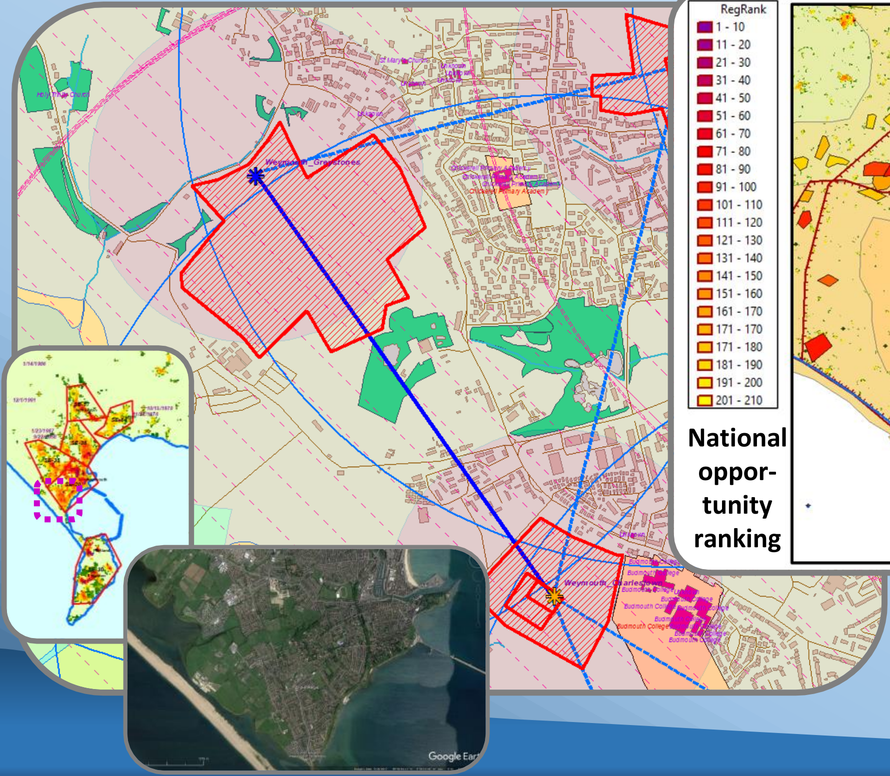
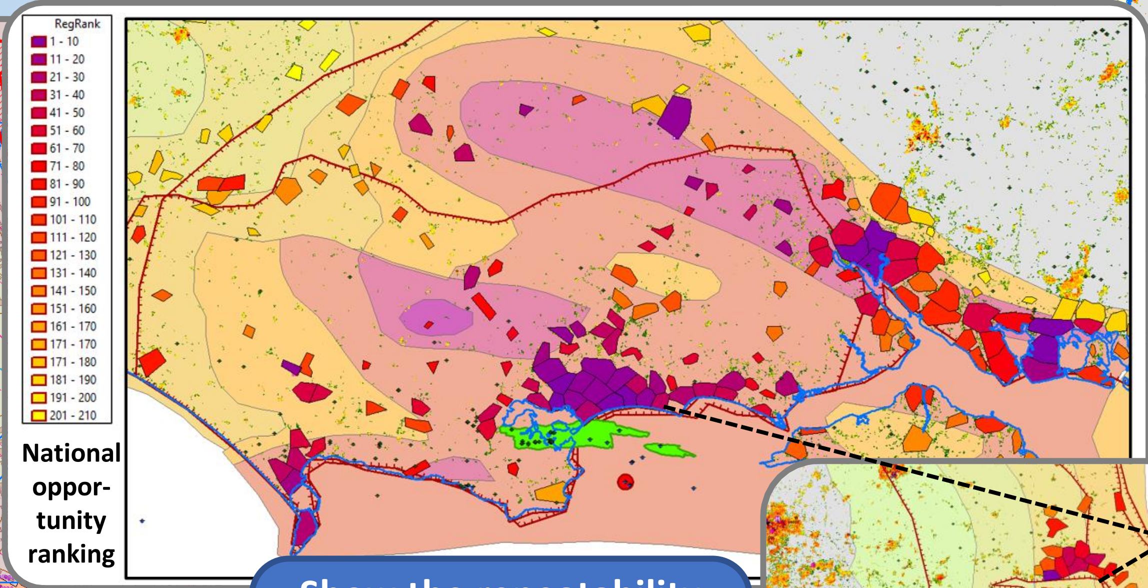
- Whichever flavour geothermal we want to deploy...
- Customer driven upscaling of local geothermal opportunity is investor empowering...
- ...to reveal a national potential – and in a location specific way that is much meatier than "concept"
- 200 opportunities catch more investor attention than 2





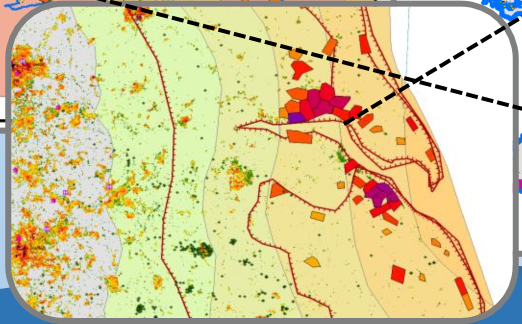
The oranges and browns are deeper hotter sands and breccias of the Permian, usually with more difficult and variable poroperm character – these are overlain by better permeability thick laterally extensive units of the Sherwood Sandstone Group (yellows), and finally, the purples pinks and lavenders of shales and evaporites in the Mercia Mudstone Group provide an efficient seal to the Permo-Triassic geothermal "play"

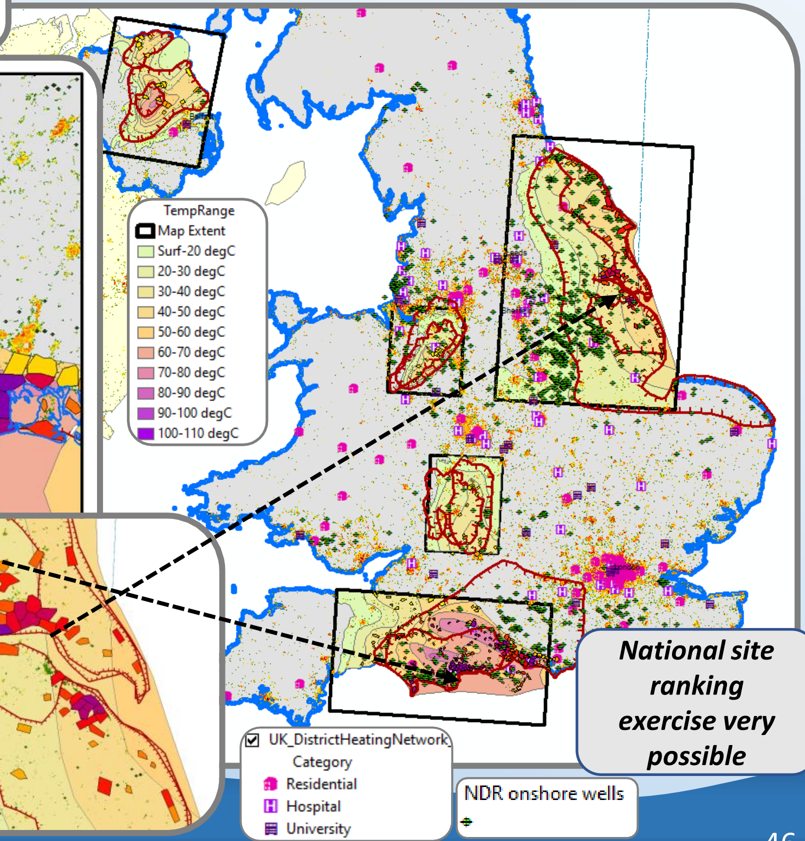




National opportunity ranking

Show the repeatability and the initial investment is much more attractive





National site ranking exercise very possible

ARGENTINA EXAMPLE – from my published work with Getech – Hungary the latest effort

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Favourability mapping

Translating data into quantitative favourability maps to recognise scalability:

Geophysics

Geology

Markets

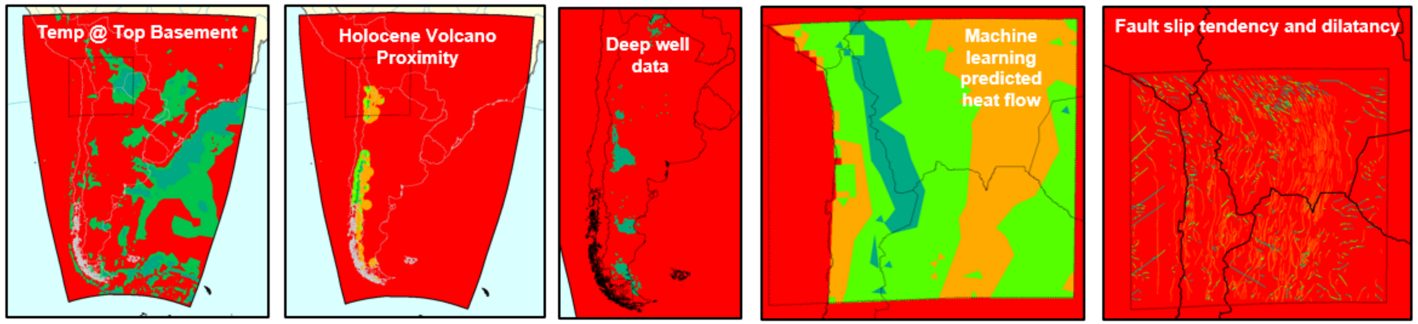
Infrastructure

Decarbonisation potential

Renewables - competition and collaboration

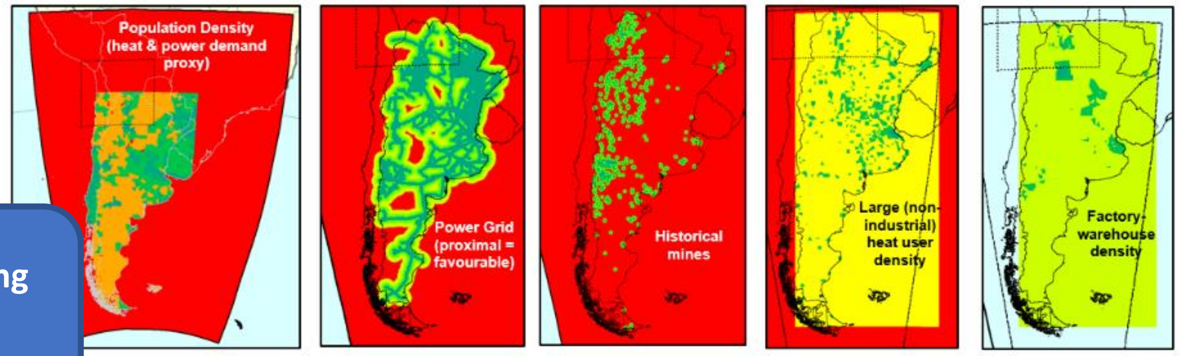
Geoscience

Basement Temperature | *Volcano Proximity* | *Deep well data* | *Machine learning Heat Flow* | *Fault slip tend. and dilatancy*



Customers and infrastructure

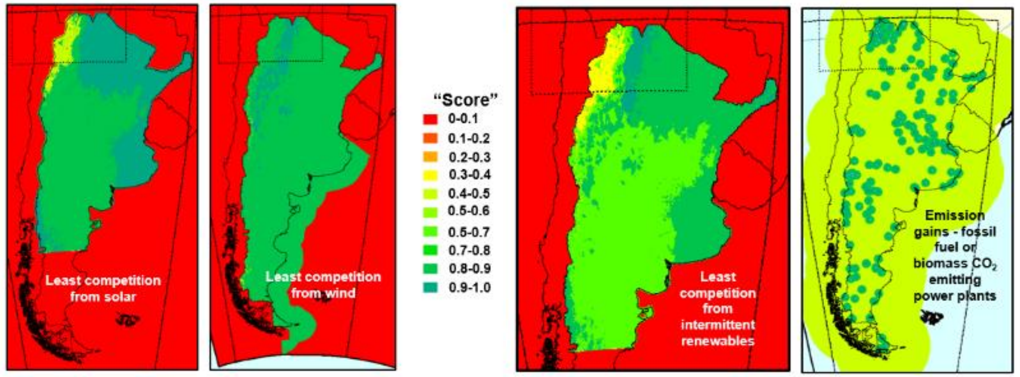
Pop. density | *Power Grid* | *Historical mines* | *Industrial heat users*



Waters et al 2021
Geothermal favourability mapping with technical and commercial integration
GRC Transactions, Vol. 45, 2021

Competing and collaborative resources for decarbonisation

Solar competition | *Wind competition* | *Wind & solar* | *Decarbonisation*



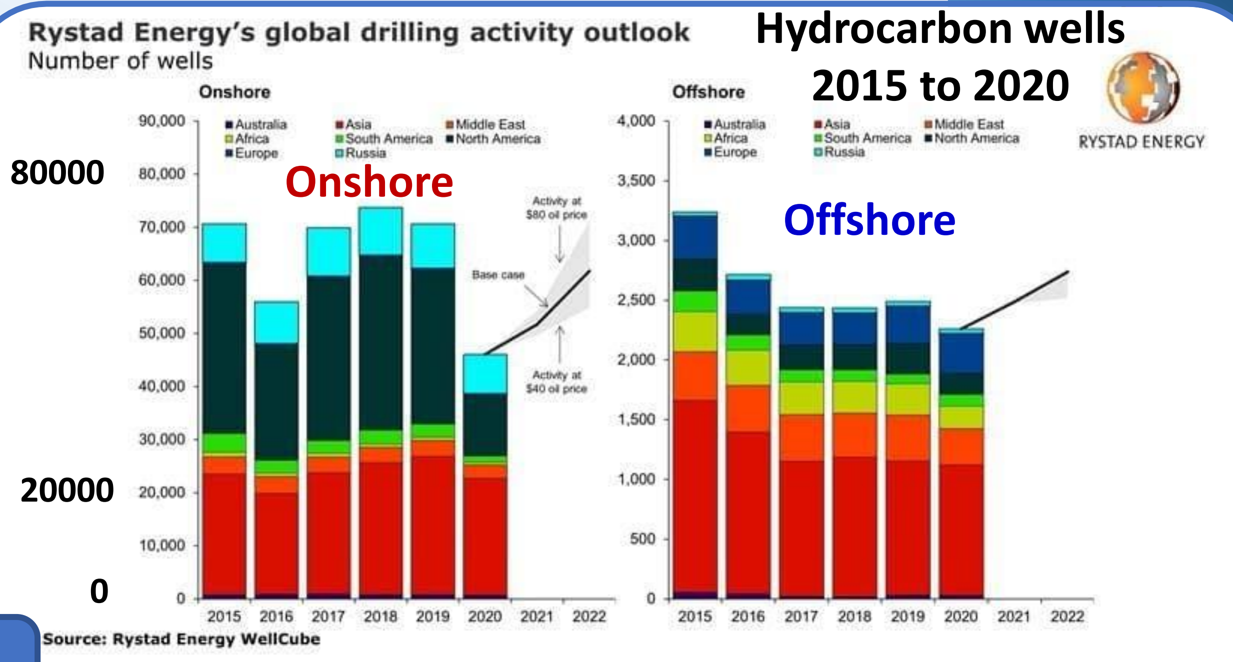
Different to "play mapping"
It's a relative favourability exercise,
Not an absolute chance of success
More subjective perhaps, but allows a much wider remit
No limit to what can be included
And combined geospatially

Oil & gas versus Geothermal

Some comparisons – What's different?

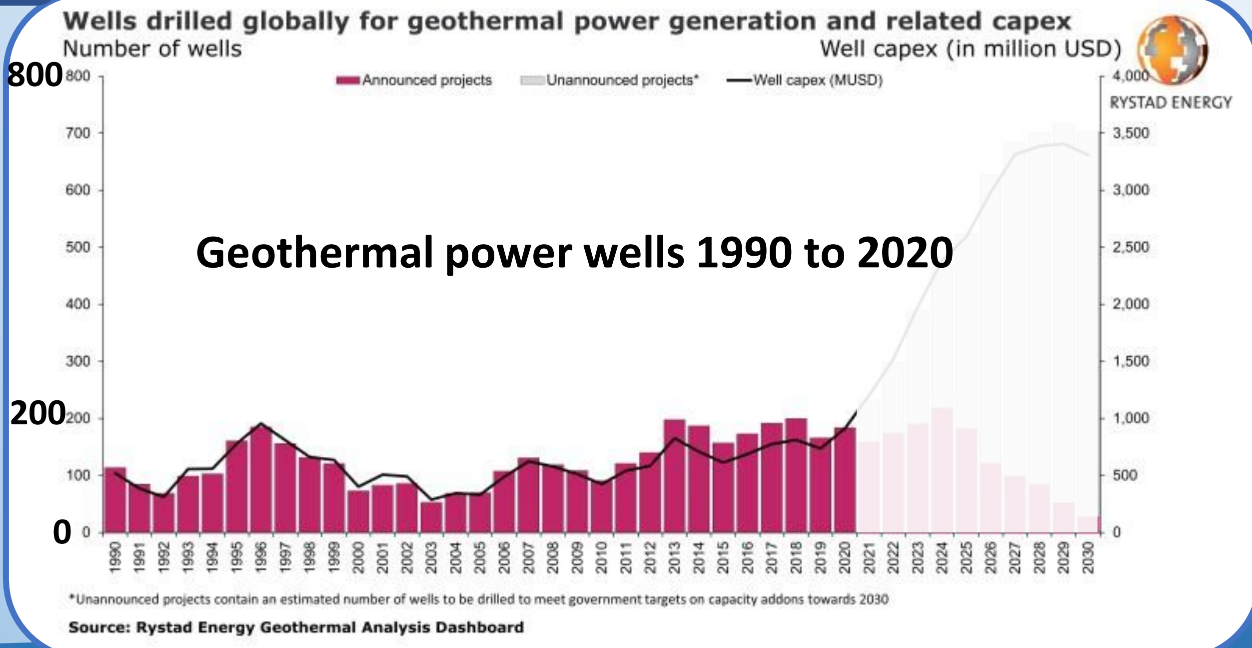
Activity scale

- **Oil & Gas**
  - Despite the sense that peak oil has happened – certainly for exploration
  - The number of wells drilled per year, globally, is still in the ballpark **of 50000 onshore and 2500 offshore**
  - That sticks two zeroes on the numbers c.f. geothermal



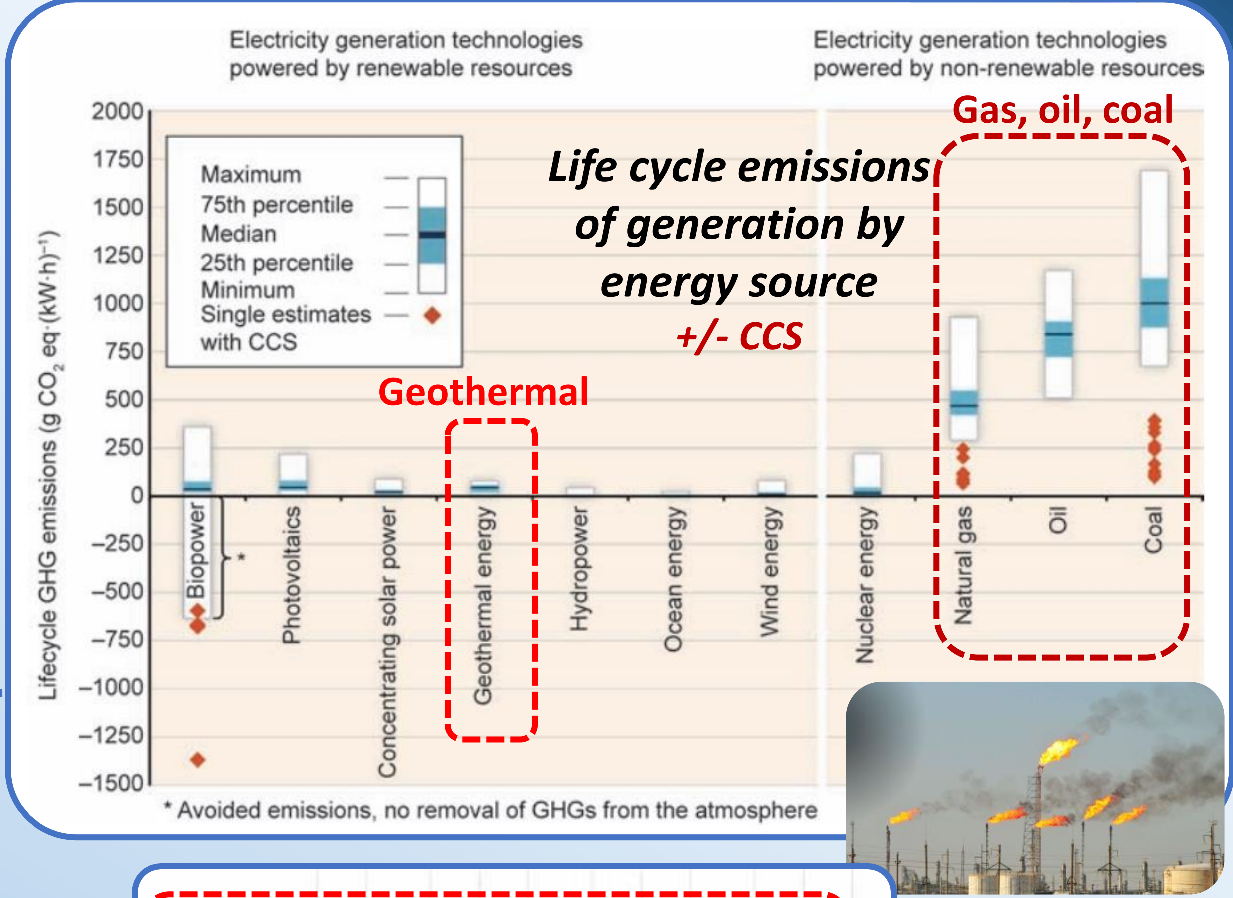
52500 versus 500?
It's growing, but not in the same league

- **Geothermal**
  - The number of deep geothermal wells drilled for power objectives, is not in the same league **~ 100-200 wells**
  - But **for geothermal heat,** the exact tally is far less available – deep > 800m it's probably similar to power, but between 20 and 800m may be much more
  - The number of true geothermal wells for earth derived heat is confused by usage of the term "geothermal" for ground source heat pumps – difficult to get reliable well counts that distinguish
  - Assertions of soon to be realised dramatic expansions – remain just assertions and project counts are real the currency of progress, not projections
  - Some increase seems likely – but steady incremental increase seems more likely than a paradigm change

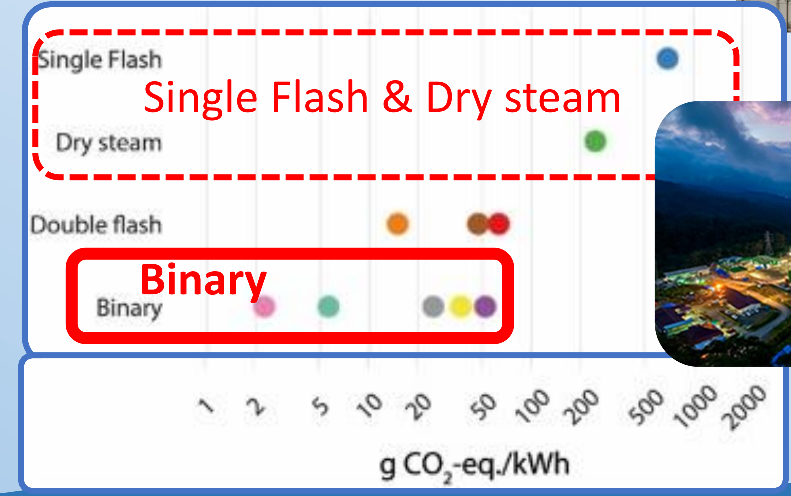


Carbon/GHG footprint

- **Oil & Gas emissions**
  - Combustion uses – dominate the total overall emissions
  - Production & transmission related emissions add – gas flaring, pipe leakage
  - Any use by facility of fossil sourced grid power does too
  - Construction & drilling related emissions – e.g. steel & hi temp steel alloy production
  - **Total ~ 300-1700 mgCO2e/kWh, gas typically ~ 500**



- **Geothermal emissions**
  - Any facility fossil sourced grid power
  - Construction & drilling related – e.g. steel & hi temp steel production
  - **Typically much better than O&G ~ 15-40 mgCO2e/kWh – (1-15%)**
  - Very occasionally high temp. geothermal CO2 & SO2 emissions
  - Dry steam and flash power rare worst case outliers ~ 500
  - ORC Binary power effectively doesn't have this problem



Geothermal is much better and any outliers are rare and specific to certain types of deployment

Mining and critical mineral footprint

- **Oil & Gas**
  - As much as 10% of global steel demand is related to oil and gas when all the infrastructure is included
  - Steel depends fundamentally on iron ore and metallurgical coal production – very big ticket mining items
  - Drilling requires high temperature resistant steel alloys
  - Chromium, Titanium, Nickel, Molybdenum, Tungsten, Tantalum
  - Electrical and motor driven components draw on Copper, Aluminium, Zinc, Nickel and REE

- **Geothermal**
  - Critical mineral drilling & facility needs essentially similar to oil and gas
  - Just not at the same scale
  - Offshore platform requirements not a thing for geothermal

The iron ore, coal, and critical mineral requirements of *any* high temperature drilling at scale are non-trivial

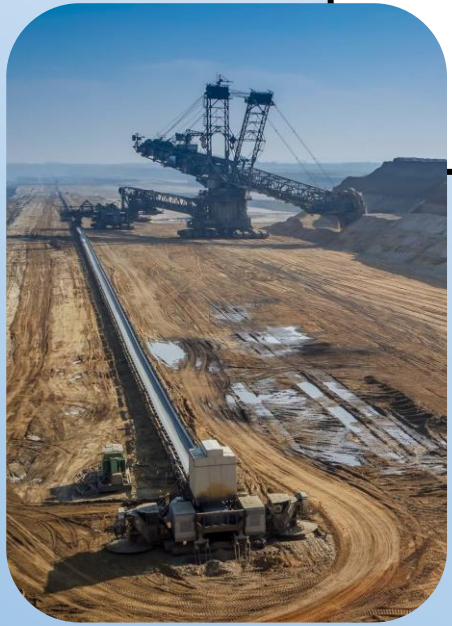
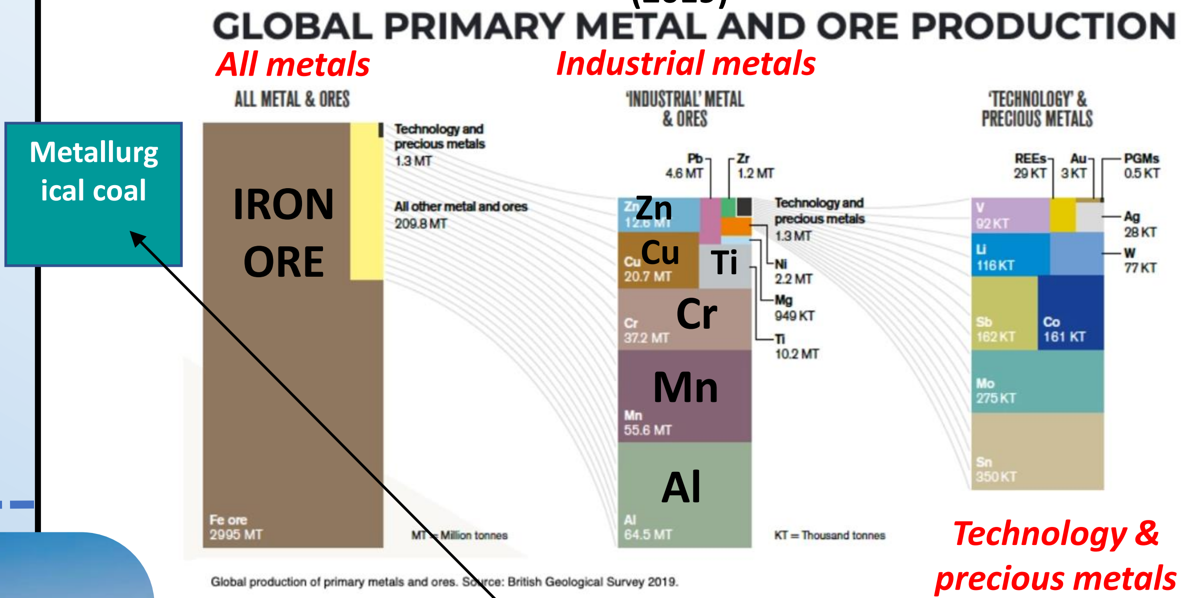


FIGURE 2: BGS/Mining.com Global metal and ore production (2019)

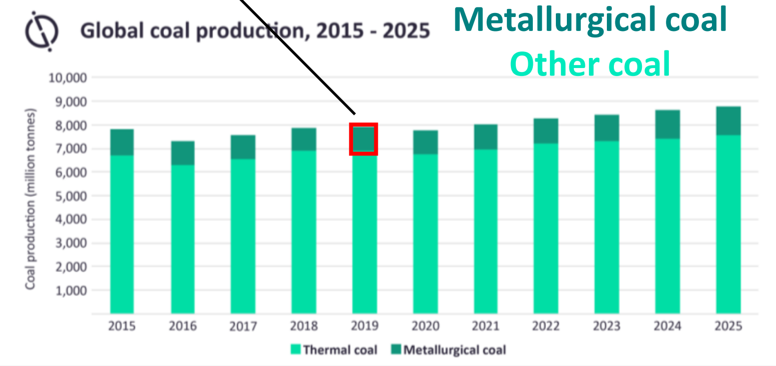


Global production of primary metals and ores. Source: British Geological Survey 2019.

*Excludes production of potash (~61mtpa) and phosphate rock (~157mtpa).

https://www.mining.com/graph-global-metal-and-ore-production-at-a-glance/

FIGURE 3: Thermal and metallurgical coal production



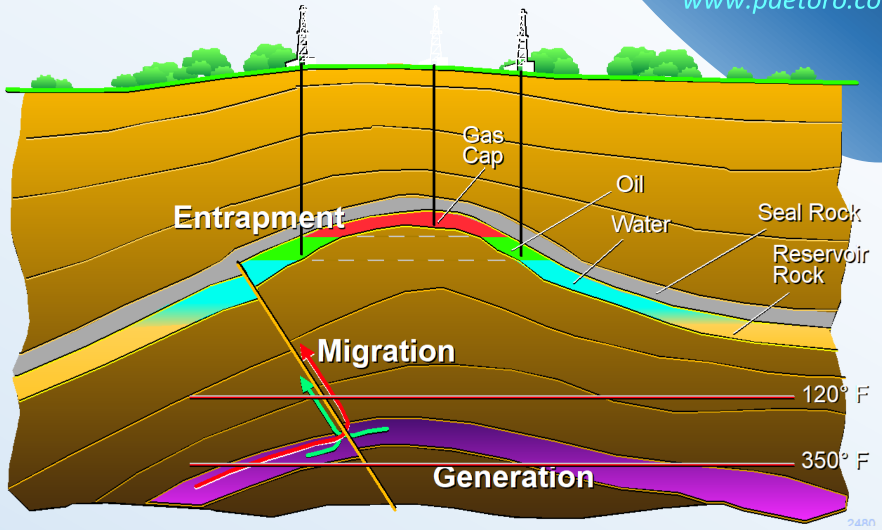
Source: GlobalData, Mining Intelligence Center

GlobalData.

https://www.globaldata.com/global-coal-production-expected-rise-3-5-2021-says-globaldata/

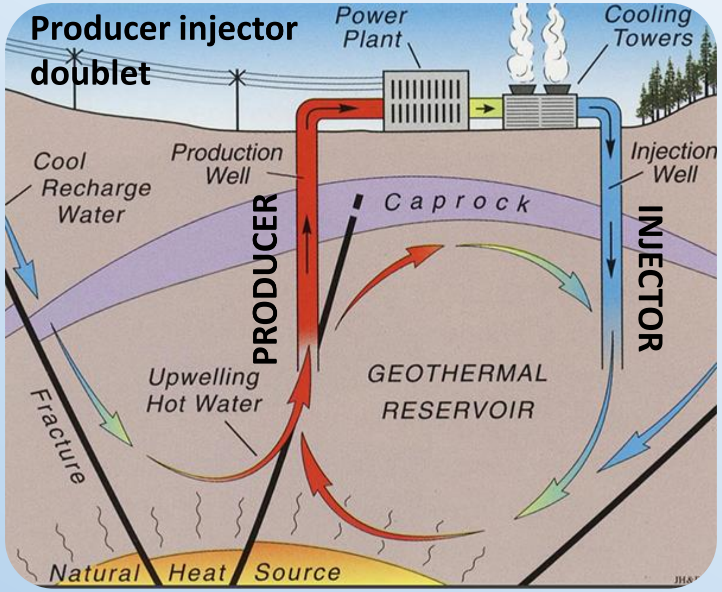
Resource geological play elements

- **Oil & Gas**
  - **Source presence, quality & maturity**
  - **Reservoir presence and quality** – sedimentary/fault & fracture/diagenetic
  - **Structure presence**
  - **Seal** – needs to prevent any leakage
  - **Migration to trap** - including appropriate timings



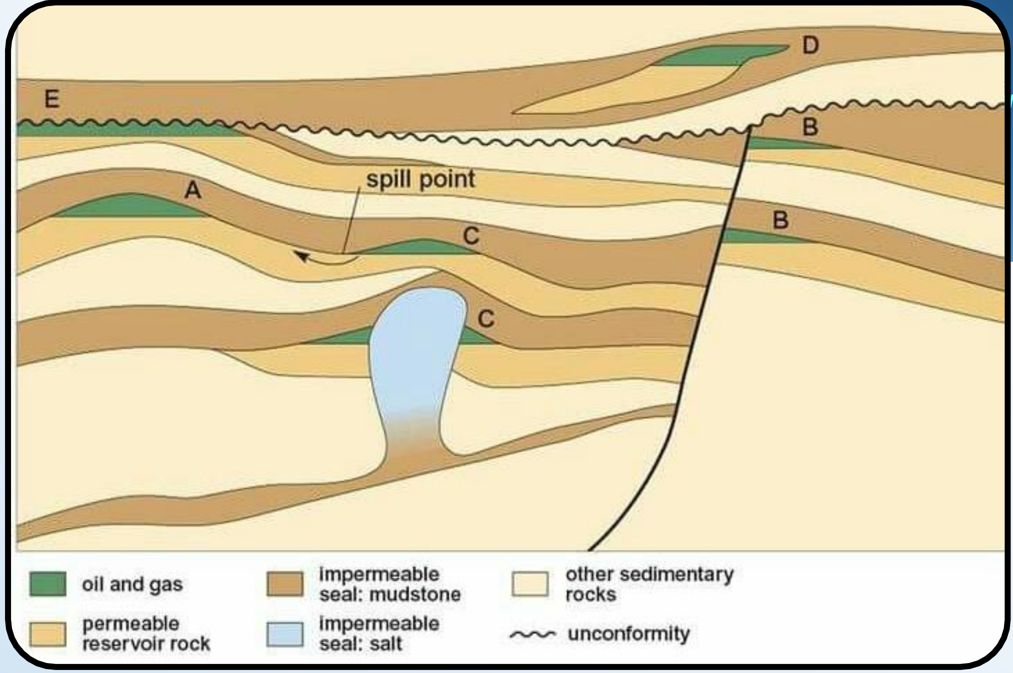
Geothermal has fewer geological play elements to find
But the ones it has have to work better to be commercial

- **Geothermal**
  - Open system
    - **Heat recharge** – convective, advective, conductive
    - **Reservoir presence and quality** – sedimentary/fault & fracture/diagenetic
    - **Fluid recharge** – meteoric or overpressured –water is there everywhere already but good recharge helps and saves costs
      - (may involve seal – but doesn't need to be perfect)
    - **Fluid geochemistry** – conducive to development and heat delivery
  - Closed loop
    - **Just need heat recharge – but has to conduct into the well bore**
    - **So, thermal conductivity to wellbore is also key**



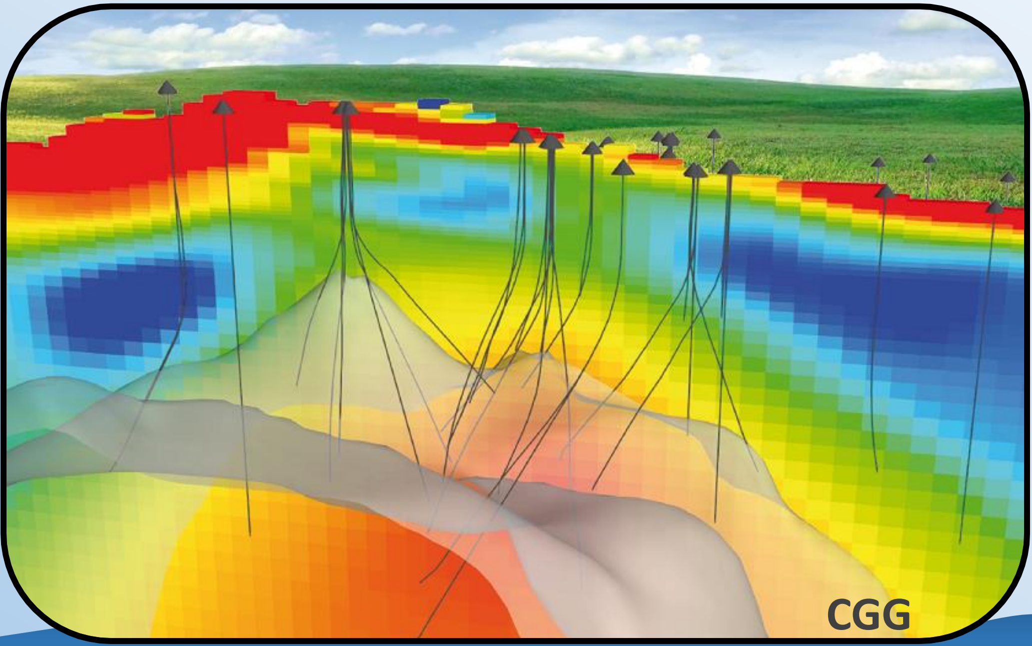
Target structure

- **Oil & Gas**
  - Exploit density difference with water
  - Hydrocarbon exploration chases buoyant fluids that migrate of their own accord to the tops of traps
  - Wells therefore target the top parts of structures
  - Buoyancy and various drive mechanisms typically keep driving fluids to the top of the reservoir even during production
  - So often the very top of the structure may be the only thing we need to target



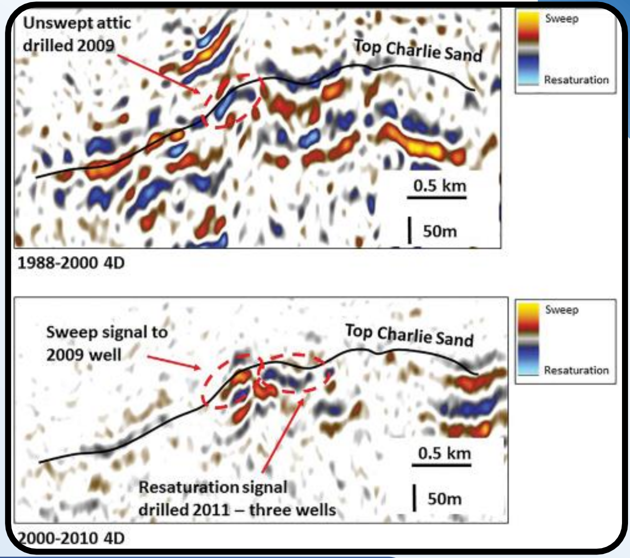
Geothermal production isn't restricted to the crest of a structure

- **Geothermal**
  - No big density difference driver for water alone
  - Except perhaps salinity and phase – i.e. water/steam
  - Water is everywhere in the reservoir
  - We can produce from all levels, wherever the permeability is best
  - We might want to target the top of a reservoir simply because the drilling cost is less
  - But if the temperature or permeability gets better deeper, it can be chased
  - We don't have to worry about finding a structure
  - That said, the geometry of a sealing unit can affect reservoir fluid flow and heat recharge, so we don't totally forget it either



Recharge

- **Oil & Gas recharge**
  - Hydrocarbons usually only recharge on very long geological timescales - longer than production time scales
    - Compaction and pressure depletions in very permeable reservoirs can accelerate in-field migrations & redistribution – e.g. time lapse Forties Field in the North Sea –
    - But these are oddities and minor in volume
  - As a rule – there's no effective recharge - we suck it out and then it's gone and then we go



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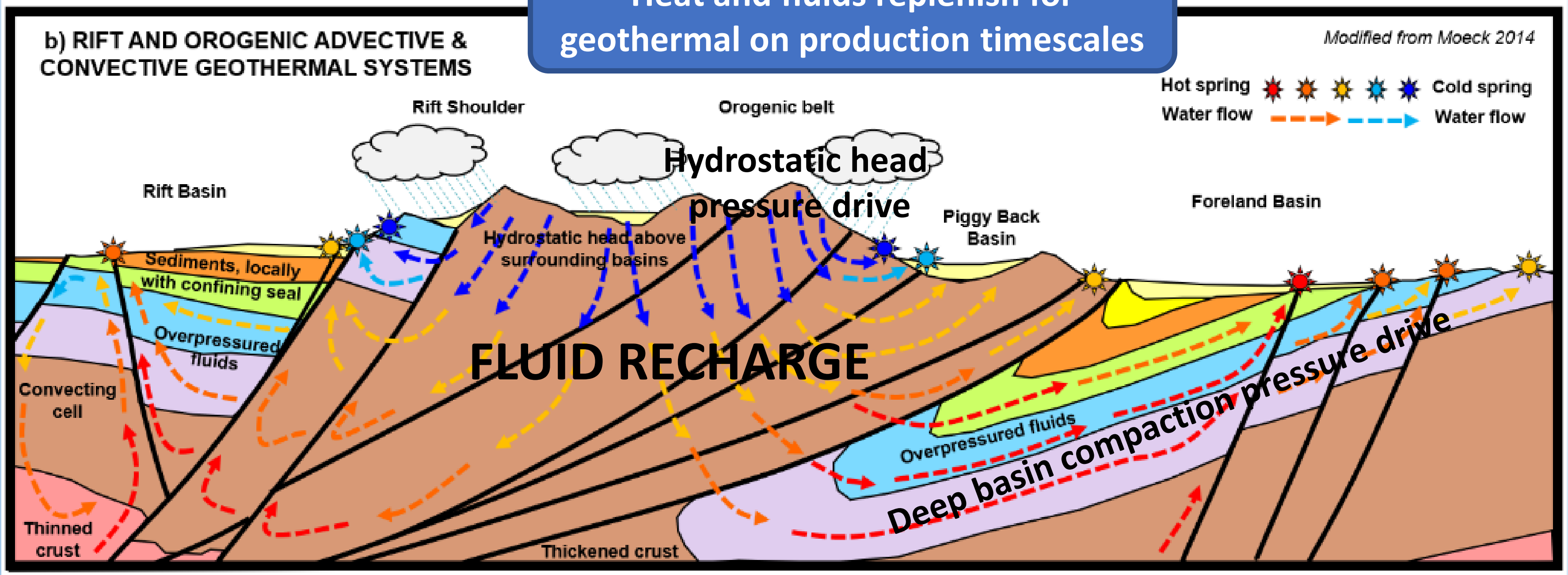
- **Geothermal recharge**
  - **Geothermal fluids can recharge** – either from overpressures or rainfall & hydrostatic head
  - If they don't injection is required to sustain pressures – but this also injects cool
  - **The geothermal heat is constantly recharging too**
  - However it is possible to suck the water out faster than it can warm up again
  - So We get geothermal heat resource depletion with time if not monitored and responded to

Heat and fluids replenish for geothermal on production timescales

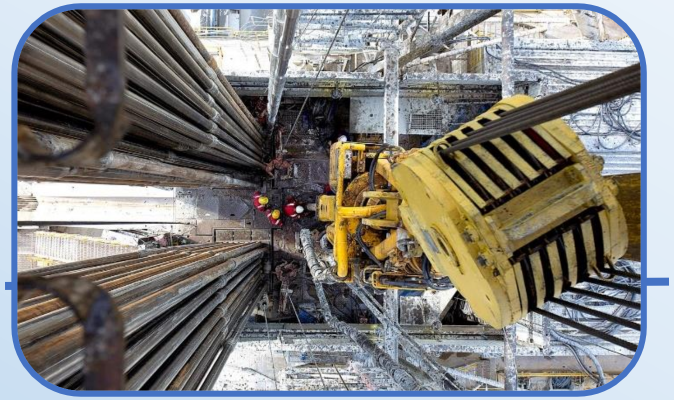


HEAT RECHARGE

Hazard

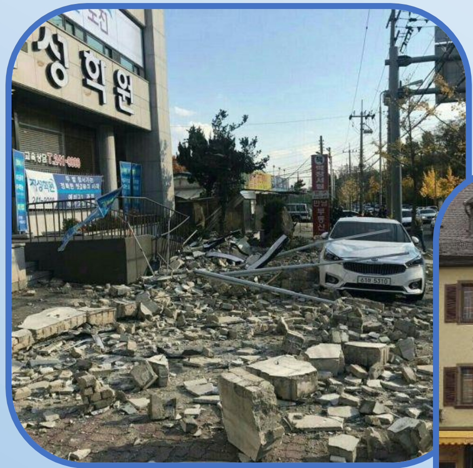
- **Oil & Gas**
  - **Ignition/Explosion**
  - **Spill**
  - **Production & usage emissions**

  - Blowout/well control loss – overpressure/shallow gas
  - Induced seismicity related to EGS & fracking
    - big topic in Texas & US Midwest
  - Subsidence
    - E.g. Groningen, Netherlands
  - Various drilling operational hazards incl. falling objects, H2S etc



Geothermal is not without hazard, but for the most part much less than for oil & gas

- **Geothermal**
  - Subsidence & heave – e.g. anhydrite hydration => gypsum
    - But easily mitigated if aware of the problem
  - Blowout/well control loss – overpressure/shallow gas
    - Less of an issue outside known hydrocarbon provinces
  - EGS related induced seismicity if it is used
    - at a lower level than fracking risk - but non zero
  - Various drilling operational hazards incl. falling objects, H2S etc
  - Emissions typically not a big problem
    - Some rare exceptions for high enthalpy dry steam/single flash



EQ, S Korea

Heave, Germany

Market deployment

- **Oil & Gas**
  - The commodity is a chemical entity – a hydrocarbon
  - Used for 1) fuels – combustion – which destroys the commodity
  - And used for 2) chemical feedstocks – which to an extent preserves the commodity, depending on recycling efficiencies
    - Latter includes plastics and metals refining and fertilisers via hydrogen production
  - The commodity can travel, be stored, and retains its value until used
  - The profit margins mean customer can be largely thought about post development

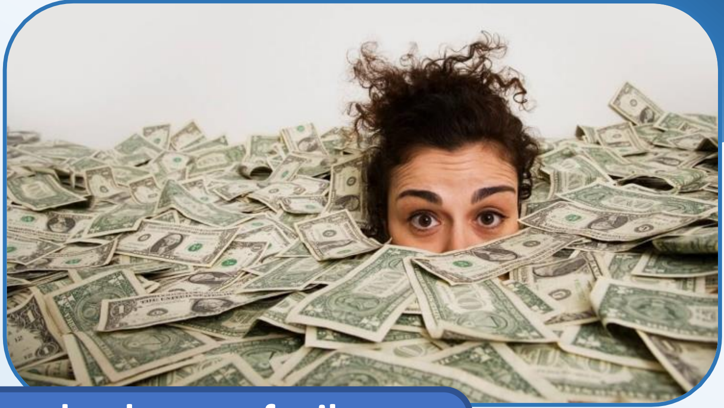
A good oil and gas resource will find a market
Even the best geothermal resource can fail if there is no local market

- **Geothermal**
  - The commodity is a physical entity – heat energy from ongoing deep heat flows
    - Except where dissolved solutes also have potential value – e.g. lithium, silver, potassium, manganese, REE – but these extractive processes still very much on the drawing board
  - A wide variety of users for heat, including power generation when hot enough
  - So the commodity is transient – it doesn't stay hot forever at surface
  - It can't really be exported distally – the market has to be proximal
  - The customer can get it elsewhere – there is lots of competition
  - The lower profit margins mean customer has to be thought about immediately from first exploration

Profit margins

- Oil & Gas
  - Depends on the commodity – oil, gas
  - If you find a big enough resource, don’t have to worry ***too*** much about market at the exploration stage
  - **US$ 80+/- 40 per barrel ~ US¢ 50 +/- 25 per litre**
  - Gas prices vary regionally from 0.01 to 42 ¢/kWh, international prices vary from around $1-6/MMbtu
  - At ~ 11 kWh/m3 (it varies) of gas, or 0.091 m3/kWh that equates to **0.0035 to 0.02 ¢/L**
  - Comparing profitability can be a challenge given the energy units labyrinth:
    - 1 boe ~ 58 therm; 1 therm ~ 29 kWh; 1 boe ~ 1680 kWh; 1 boe ~ 6Mcf; ¢/kWh = $/MWh; 1kWh ~ 11m3 gas; 1m3 gas = 35300 BTU

Whoops the global price went up



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~2 orders of magnitude difference in profit per produced volume c.f. oil
Not a show stopper – oil profits beat many things– but good to be aware
There is money to be made, BUT have to be more careful every step of the way

- **Geothermal**
  - Depends on the commodity – hot water, power, or brine mineral
  - Power prices and profits achievable vary enormously by country and by power/heat purchasing agreements between organisations
  - **Power price can vary by two orders of magnitude – in 2020 – 0.7¢ to 41¢ per kWh**
    - Libya min Somalia max
    - **Global average per kWh late 2022 - 16¢, Europe average - 30¢ , UK - 65¢, Egypt - 10¢**
  - Price of heat depends on origin – fossil fuels or power or biomass or waste heat etc
  - If we assume hot water is generated from power – **hot water then costs 0.05 to 3 US¢/l (av 0.75)**
  - **1-2 orders of magnitude difference on price per volume oil c.f. hot water**
  - **So the local market has to be understood from day one of a geothermal project**
  - **=> Need LOTs of volume to make money & justify cost of drilling and plant**

Geothermal can be profitable, but it takes careful audit every step of the way

(https://www.cable.co.uk/energy/worldwide-pricing/, https://www.globalpetrolprices.com/electricity_prices/)

Units

Oil & Gas

- Volume
  - Mmbbl, bcf, mmboe
  - M3, BCM
- Energy
  - Oil – Joule, MWh, kWh, 1 kWh = 3.6MJ
  - Gas – Joule, therm, btu, kWh; 1 therm = ~ 10000 btu
- Flow rate
  - Oil – bopd
  - Gas mmscf/d
- Capacity & Power (e.g oil & gas power plants)
  - Theoretical delivery per unit time = MW, GW of power
  - % of time operational = capacity factor

Geothermal

- Volume
  - Litres/m3
- Energy
  - MWh, kWh
  - Thermal & electric MWh_t MWh_e
- Flow rate
  - l/s;
  - 1 l/s = 543 bwpd
- Capacity & Power
  - Theoretical delivery per unit time = MW, GW of power
  - % of time operational = capacity factor

Understanding the units is one of the best value for effort exercises you can do if new to geothermal
1 l/s = 543 bwpd

FLOW RATE

1 (row) = X (col)

From row to column	scf/s	mmscf/d	scf/d	bbl/d	m3/d	m3/s	l/s (or kg.s @ 1kg/l)
scf/s	1	0.0864	86400	15388.495	2446.576	0.028316847	28.31685
mmscf/d	11.57407407	1	1000000	178107.585	28316.847	0.32774128	327.74128
scf/d	1.15741E-05	0.000001	1	0.178108	0.028317	3.27741E-07	0.000327741
bbl/d	6.49836E-05	5.61458E-06	5.614584	1	0.158987	13736.50396	0.001840131
m3/d	1.03316E-05	3.53147E-05	35.314667	6.289810	1	1.15741E-05	0.011574074
m3/s	35.314667	3.051187205	3051187.20	0.000073	86400	1	1000
l/s (or kg.s @ 1kg/l)	0.035314667	0.003051187	3051.1872	543.439584	86.4	0.001	1

Litres per s **bwpd**

l/s	Conversion	bbl/d	Conversion	l/d	l/bbl
1	543.440	543.4	86400	86400	158.987
2	543.440	1086.9	86400	172800	158.987
5	543.440	2717.2	86400	432000	158.987
10	543.440	5434.4	86400	864000	158.987
20	543.440	10868.8	86400	1728000	158.987
50	543.440	27172.0	86400	4320000	158.987
100	543.440	54344.0	86400	8640000	158.987
150	543.440	81515.9	86400	12960000	158.987
200	543.440	108687.9	86400	17280000	158.987
250	543.440	135859.9	86400	21600000	158.987
300	543.440	163031.9	86400	25920000	158.987
350	543.440	190203.9	86400	30240000	158.987

*The moment we **understand 50 l/s** is often a **rough onset of commercially interesting flow rates** for geothermal - and that this equals ~ **27000 bwpd** – and that **100 l/s is desirable (54000bwpd)** is the moment we understand a key home truth about geothermal:*

VOLUME IS KING AND THAT MEANS EXCELLENT RESERVOIR AND EXCELLENT HEAT RECHARGE

Flow rate & hole size

- **Oil & Gas**
  - **Offshore 2000 bopd** might be considered decent sustained flow rate
  - 5000 bopd good
  - **Onshore even 100 bopd** ticking away might be acceptable
  - **Lots of reservoir types can deliver these** kind of flow rates

Reservoir flow rate delivery an order of magnitude more than for a commercial oil and gas well

- **Geothermal**
  - **We might cope OK with lower than expected temperatures using heat pumps**
  - **But flow rates too low are a real killer**
  - It depends on the use, temperature and depth, but typical rules of thumb are:
    - 50 l/s = 27000 bwpd starts to look commercially interesting
    - **100 l/s = 54000 bwpd is starting to feel comfortable**
    - **This is an order of magnitude more than a good oil production well**
    - We would like **laterally extensive vertically communicating reservoir**
    - With – rule of thumb - circa **5000 mD.m permeability thickness or more**
      - 100 m of 50 mD; 50m of 100 mD; 20m of 250 mD; 10m of 500 mD, 5m of 1000 mD
  - **Big flow rate needs mean big holes are needed** – impacts for well management, drilling cost and risks, and ease of repurposing O&G wells

Fluid chemistry

- **Oil & Gas**
  - Hydrocarbons are a very chemically diverse family
  - But they are not soluble in water
  - That means they happily separate themselves out for us in the subsurface

Fluid chemistry can control geothermal plant OPEX and the heat delivery possible
It is not just an academic interest

- **Geothermal**
  - Geothermal deals with water
    - Water is one of the best solvents in the universe - especially hot
    - All sorts of stuff caught up in it - some good, some not so good
  - Changing equilibrium temperatures and pressure can makes stuff come in and out of solution - **Scale**
    - In the wellbore and in the reservoir
  - Injection temperatures into reservoir critical
    - In turn controls amounts of heat delivery at surface – $\Delta Q = mc\Delta T$
  - Hot aggressive fluids can corrode metals – **Corrosion**
  - Corrosion & Scale hits operations & maintenance costs - OPEX
  - Reservoir fluid geochemistry is then project critical
  - Some problems are bypassed if closed loop is used, but have to consider the compromise on heat

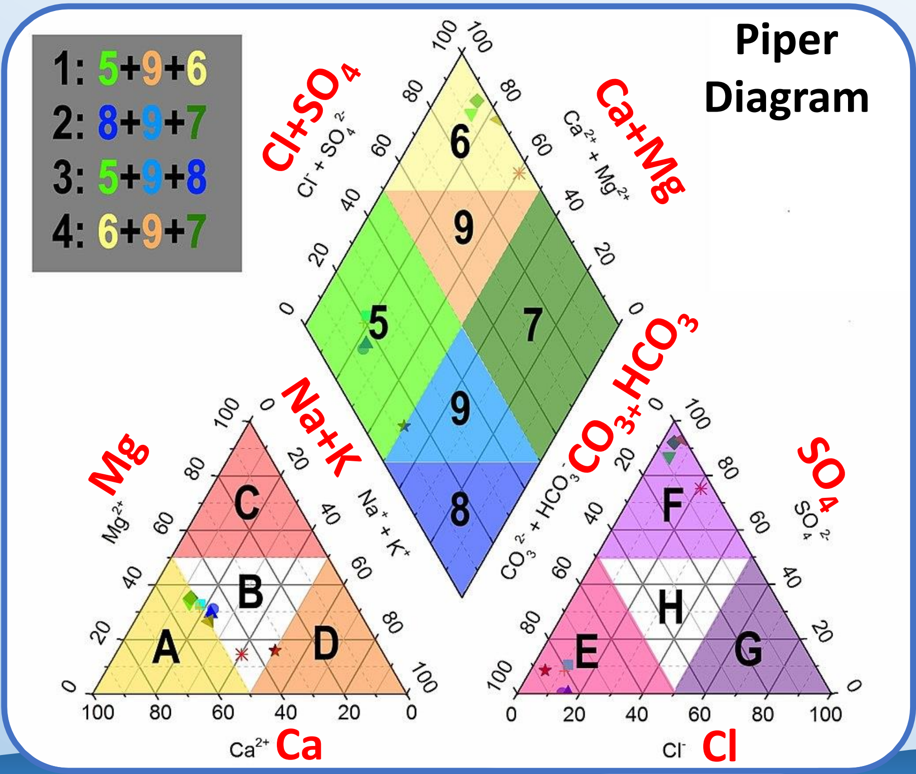
Piper diagram hydrochemical facies.

ABCD:
A: Calcium type; B: No dominant type; C: Magnesium type; D: Sodium and potassium type;

EFGH:
E: Bicarbonate type; F: Sulphate type; G: Chloride type; 1: Alkaline earths exceed alkalis;

1-4:
2: Alkalis exceed alkaline earths; 3: Weak acids exceed strong acids; 4: Strong acids exceed weak acids;

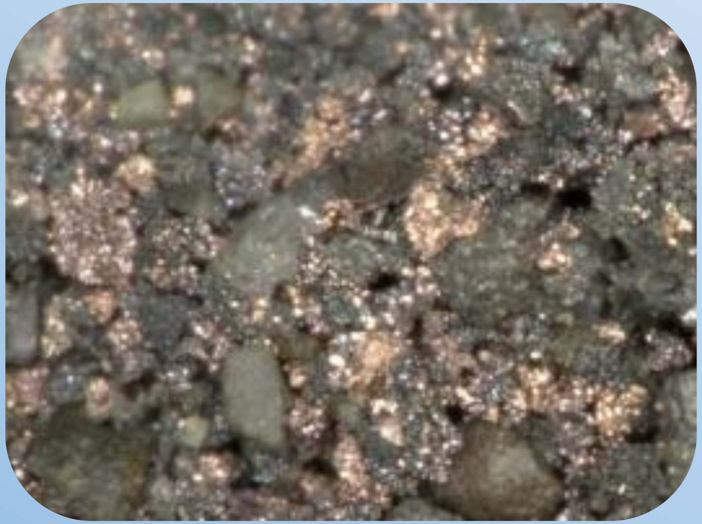
5-9:
5: Magnesium bicarbonate type; 6: Calcium chloride type; 7: Sodium chloride type; 8: Sodium bicarbonate type; 9: Mixed type



Fluid Geochem & Geothermal OPEX

These fluid chemistry effects can be project killers if not anticipated & planned for

Geothermal reservoir damage (German Rotliegend)



The sampled material filling the well is predominantly composed of native copper (Cu^0), barite ($BaSO_4$), magnetite (Fe_3O_4), and lead (Pb) bearing phases such as laurionite (PbOHCl), as well as minor amounts of calcite ($CaCO_3$), and an amorphous phase containing mainly Si, Fe, Ca, Pb, and Al.

Scale (often sulphides and carbonates)

Corrosion

Oil and gas well geothermal repurposing & co production

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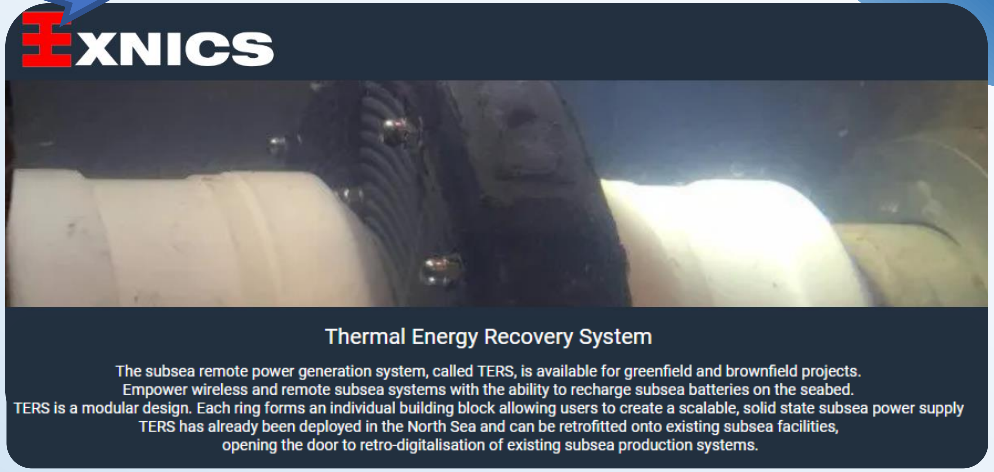
- **Simply utilising heat from pipework conduction…small bonus but easy…**
- **Geothermal co-production or repurposed end of life extension are bigger deals**
- **Delays abandonment costs & local field power requirements can be the market**
- **It can't be done everywhere there is an oil and gas well**
    - Fluid geochemistry; Reservoir permeability; Market; Larger volume/flow rate needed; bigger hole; - these reduce the viable subset
- **Costs of reworking a well in a non-optimal site may mean it's best to do a new well**
- **But thousands of wells with very good and well understood reservoir, close to market – that might have potential**
    - Can also drill deeper or off structure from same well pads to get better reservoir
    - Not limited to top of reservoir – but may be additional costs to access deeper
    - The infrastructure and access helps even if you need a new well
- **There is a window of opportunity while there are still producing holes down in the ground to activate geothermal**
    - A standing start is much harder once they are gone
    - Geothermal can perhaps carry on building out even after oil and gas has gone
- **Offshore looks hard unless the market is a local offshore one (i.e. platform or network of platforms)**
    - Offshore is always expensive
    - Cable laying is expensive
    - Platform space is a premium



Growing market

Surface renewables versus Geothermal

Some comparisons

Scale - CAPACITY

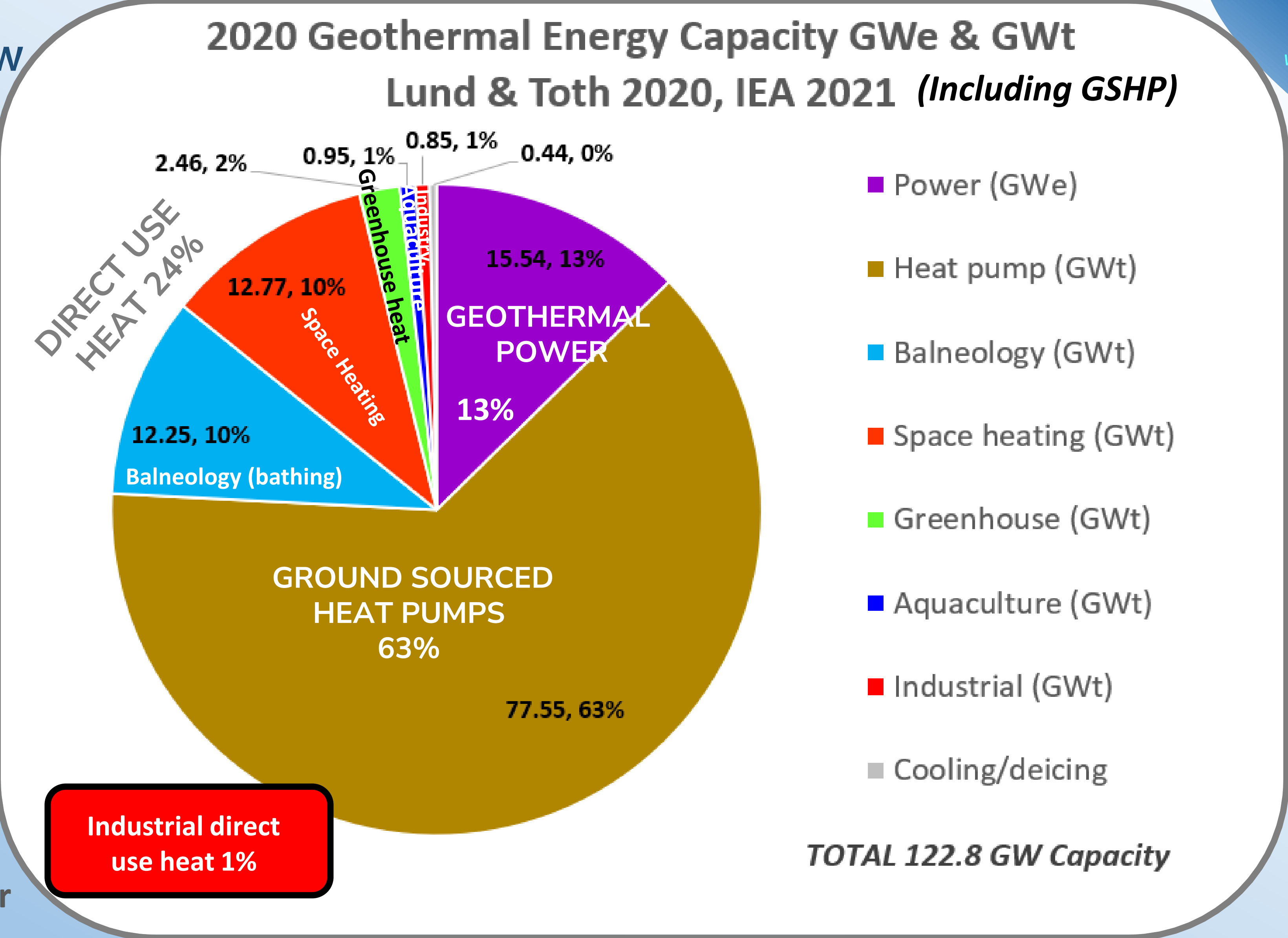
- Subsurface renewables 123 GW (GWt + GWe)
- Direct use heat for Industry – just 1% => huge scope for expansion

How many of the world's largest hydro, nuclear, wind sites, would it take to equal the global geothermal capacity contribution?

5x  hydro

6x  wind

15x  nuclear



Total ~ 123 GW Capacity

c.f. Nuclear 395 GW; Wind ~ 650 GW; Solar ~ 775 GW; Hydro ~1330 GW; Biomass 143 GW

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Scale - Generation

- Subsurface renewables 45 GW (GWt + GWe)
- Direct use heat for Industry – just 1% => huge scope for expansion

How many of the world's largest hydro, nuclear, wind sites, would it take to equal the global geothermal generation contribution?

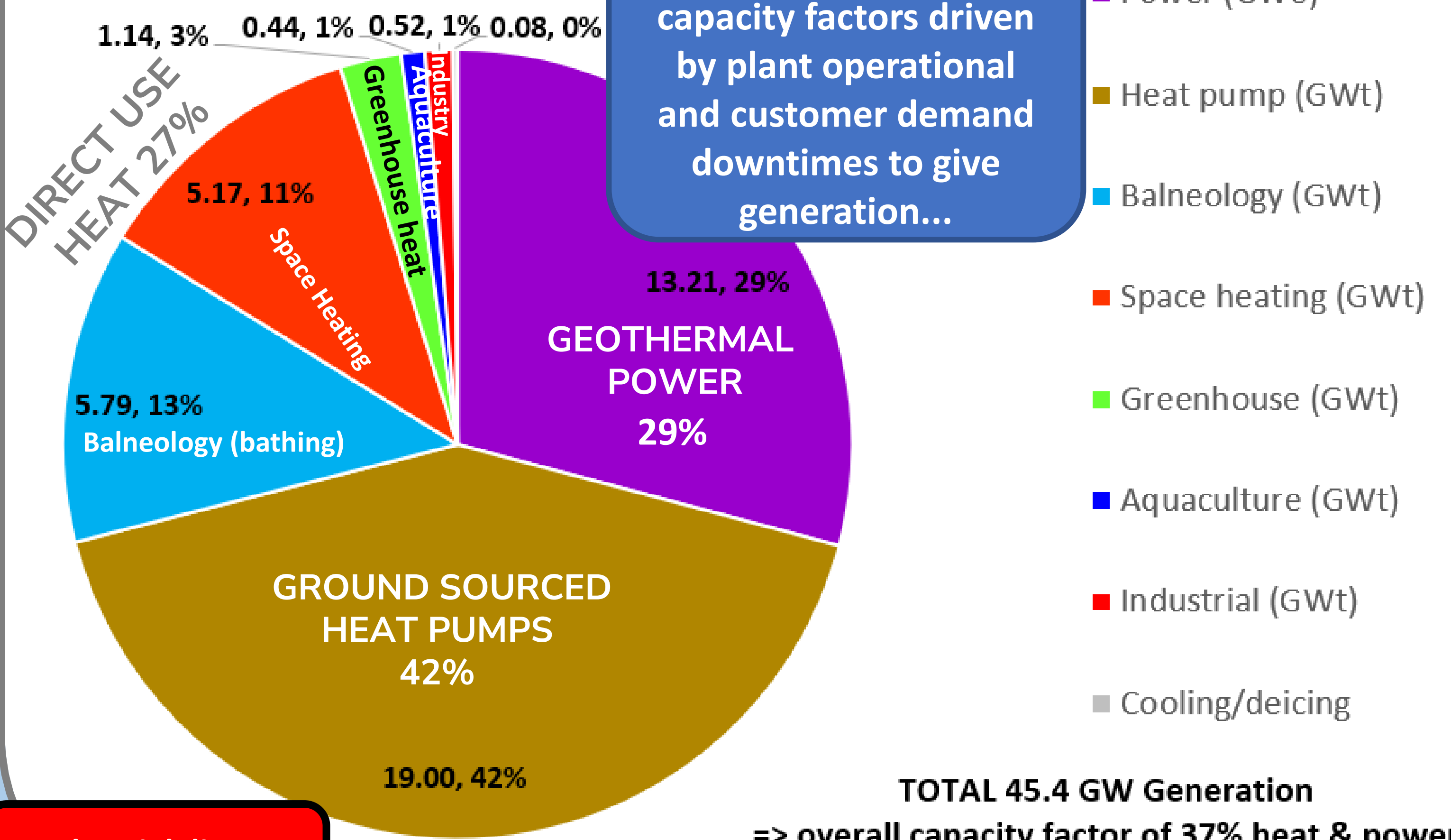
4x  hydro

7x  nuclear

9x  wind

2020 Geothermal Energy Generation GWe & GWt
Lund & Toth 2020, IEA 2021

(Including GSHP)



If we correct for capacity factors driven by plant operational and customer demand downtimes to give generation...

Industrial direct use heat 1%

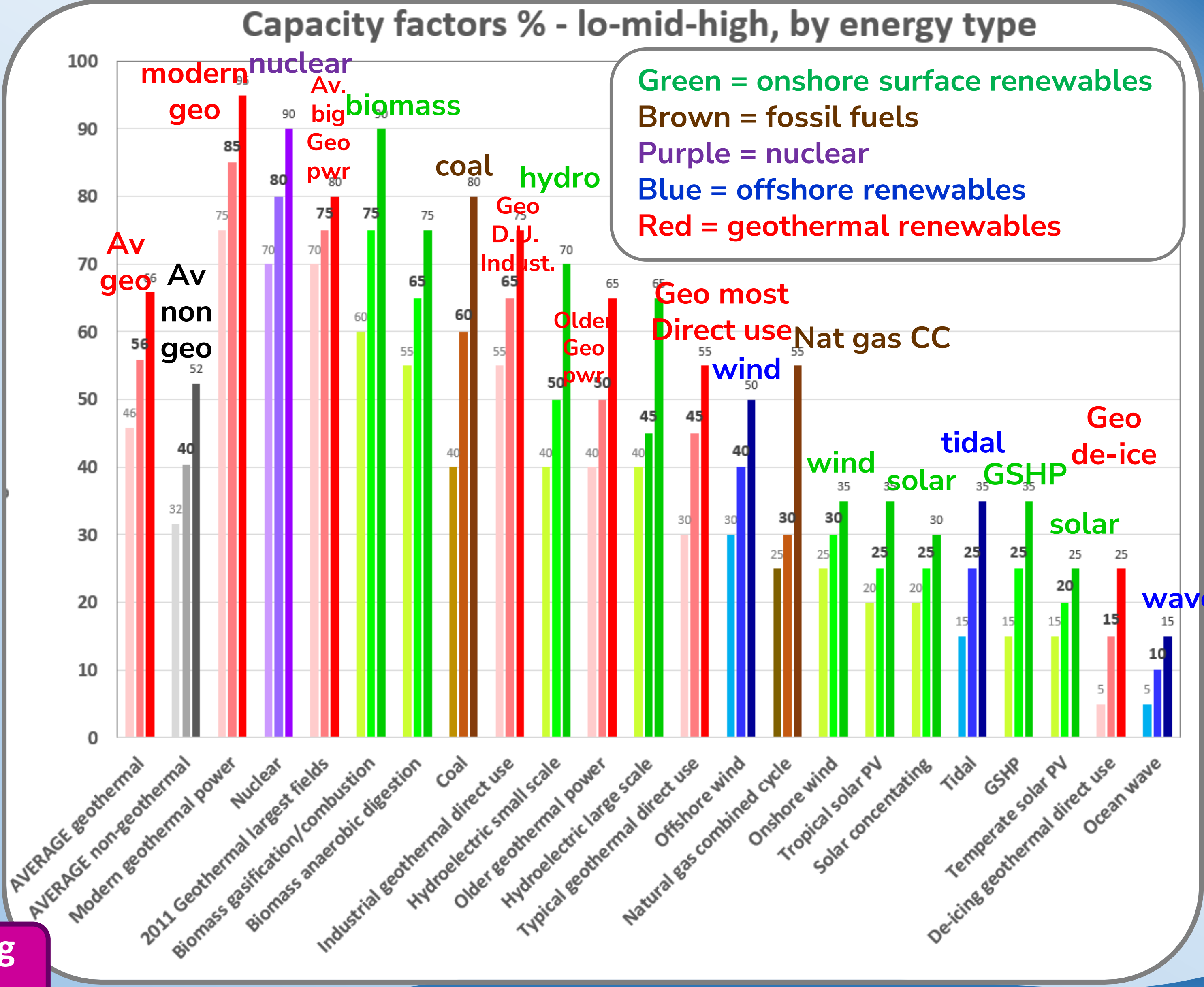
TOTAL 45.4 GW Generation
=> overall capacity factor of 37% heat & power
32% for direct use, & assuming 85% for power

Total ~ 45 GW Generation

c.f. estimated. Nuclear 316 GW; Wind ~ 163 GW; Solar ~ 194 GW; Hydro ~665 GW; Biomass 86 GW

Geothermal & Capacity Factors

- Energy supply capacity factor is about % operational time or "when is it selling?"
- Downtimes in plant operation OR customer demand affect that:
  - Rain, sun, wind, tide inactive
  - Down for O&M (operations & maintenance)
  - Customer doesn't always need it
- Capacity factor
  - For onshore wind, about 25%
  - (up to ~ 40% offshore)
  - For solar, about 20-30%
  - For nuclear ~90%
  - For hydro ~ 40-50%
  - For biomass ~ 60%
  - For GSHP - ~ 25%
- A global average of big geothermal fields in 2011 was ~75%
  - But modern plants are improving – 85-95%
  - Direct use heat varies by usage
    - ~ 65-70% industrial
    - ~ 45% typical space & water heating uses
    - ~15% de-icing



Capacity factor is a win for geothermal – long lived multidecade 24/7 energy price stability

Geothermal heat & power in context of other big power providers

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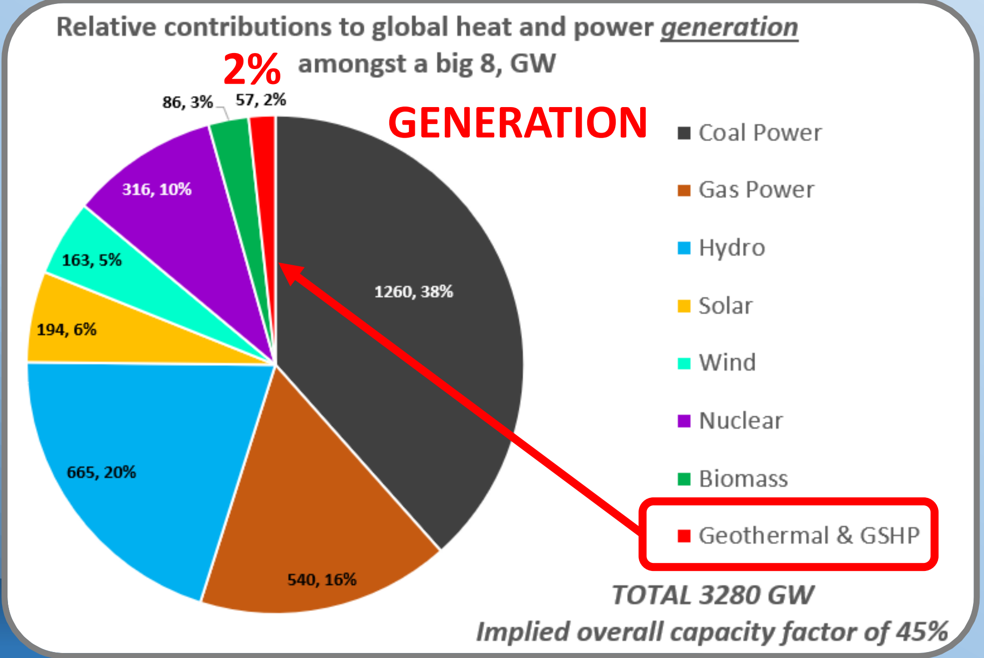
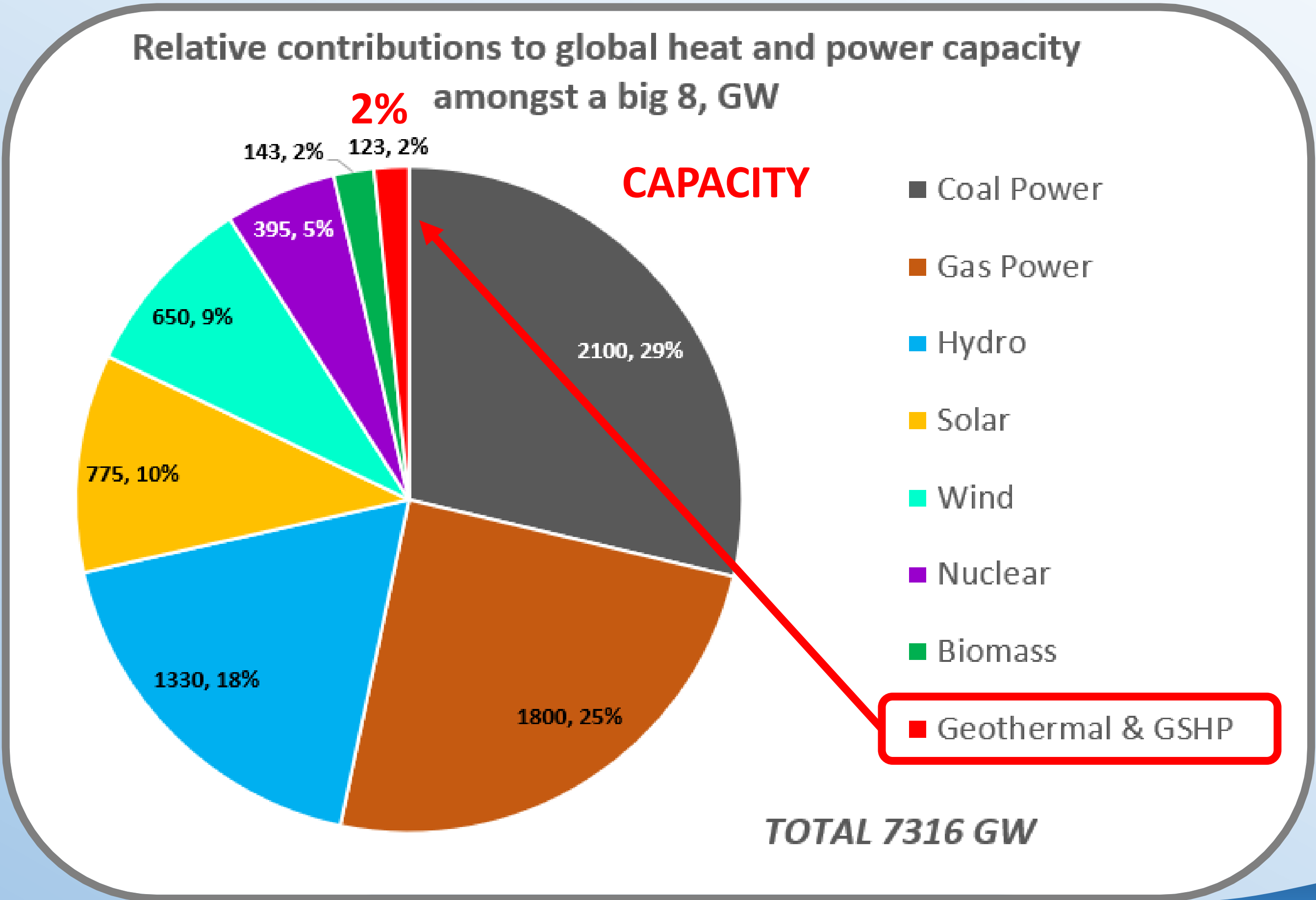
- **Comparison of 8 biggest contenders for future power:**
  - Geothermal heat & power
  - Wind, solar, hydro, biomass & nuclear power
  - Gas & coal power
- **If we move toward more electrification, electric efficiencies mean we don't have to replace the losses of combustive sources**
  - 75%+/-10% electric c.f. 20%+/-10% combustion
  - Big win on reduced losses
  - The hill to climb isn't quite as scary as it looks
- **But…the road is long & target setting needs to be realistic**

Geothermal heat and power's contribution 2% c.f. other big power providers
Both capacity and generation
Aiming for 5% is ambitious,
but probably a realistic target… for now



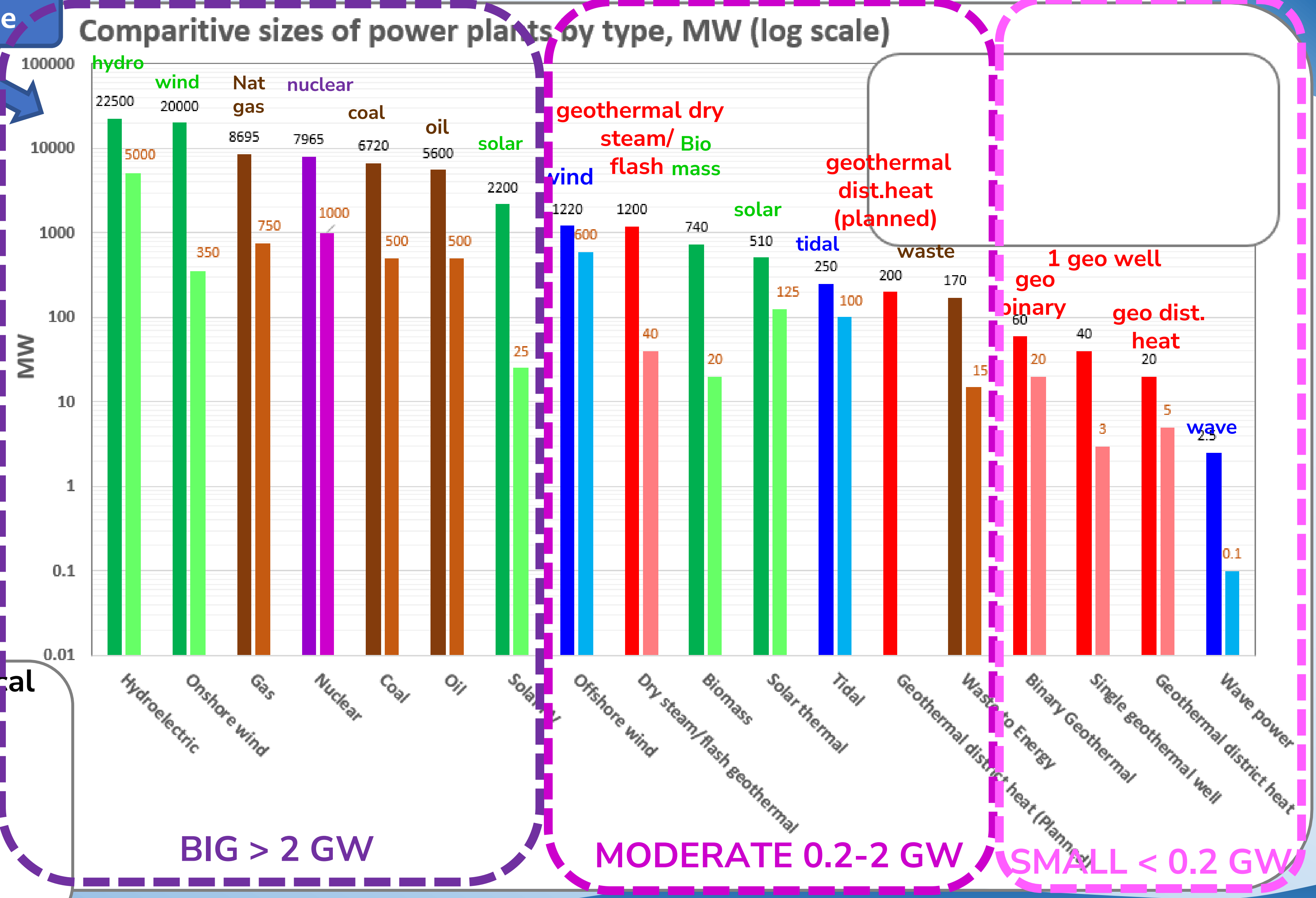


Scale for cost – the challenge

Geothermal is mostly in the 0.1 to 1 GW range
Not the biggest scales

- 1st bar = biggest
- 2nd bar = typical
- Up to 1.2 GW – biggest for geothermal
- Typical well more like 2-3 MW
- Binary Plants & District heating systems 20-200 MW
- Geothermal isn't today in the really big league > 2GW...
- But it doesn't have to be big to be useful

Log scale



1st bar = biggest, 2nd bar = typical
Green = onshore surface renewables
Brown = fossil fuels
Purple = nuclear
Blue = offshore renewables
Red = geothermal renewables

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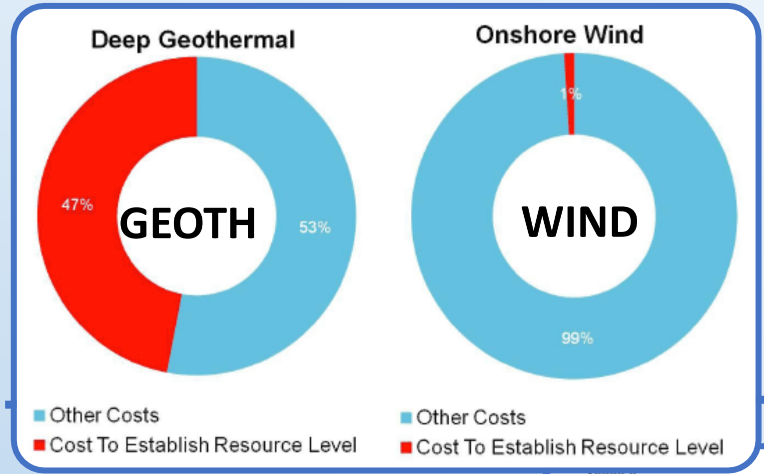
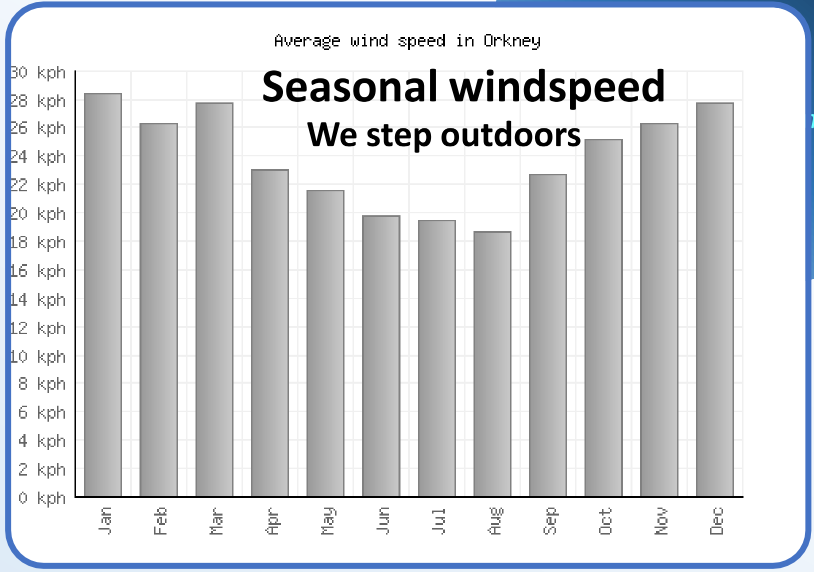
Technical & commercial risk

- **Surface Renewables**
  - It is relatively quick and cheap to quantify a surface resource
  - There is no expensive drilling involved
  - The capex costs are mostly easy to estimate
  - Less up front spend to assess the feasibility of a resource
  - The time to deployment is usually not too difficult to quantify

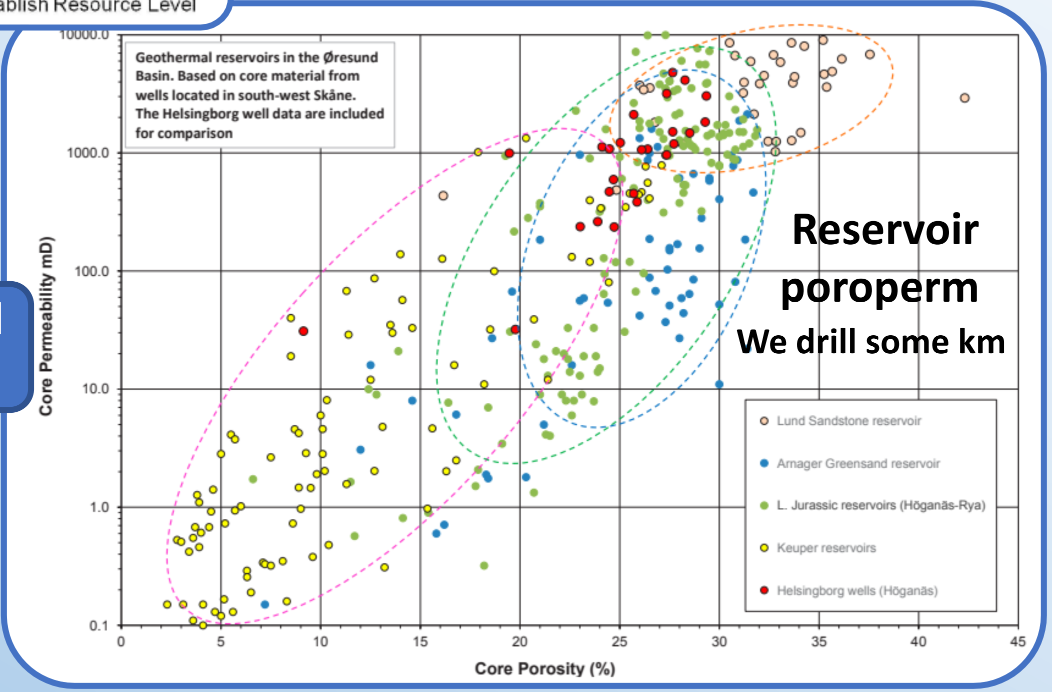
Resource estimation costs in red





- **Geothermal**
  - **Commercial risk** of geothermal staying best option for a nearby customer that wants the heat…it's a long term bet
  - **Planning risk** of poor regulation & delay to deployment
  - **If open system – we need** laterally extensive **good permeability and reservoir volume**
  - **And fluid chemistries** that are workable
  - If **power, temperatures** that are economic
  - **If closed system, thermal conductivities** and long term sustainable temperatures
  - **Drilling risks –** wells can fail for operational reasons
  - **Induced seismicity** if any EGS involved,
  - **Emissions** risk with some high temp. dry steam/single flash power plants

It's riskier so the reward has to be worth it



A customer fit to size, flavour, duration, local resource, & risk

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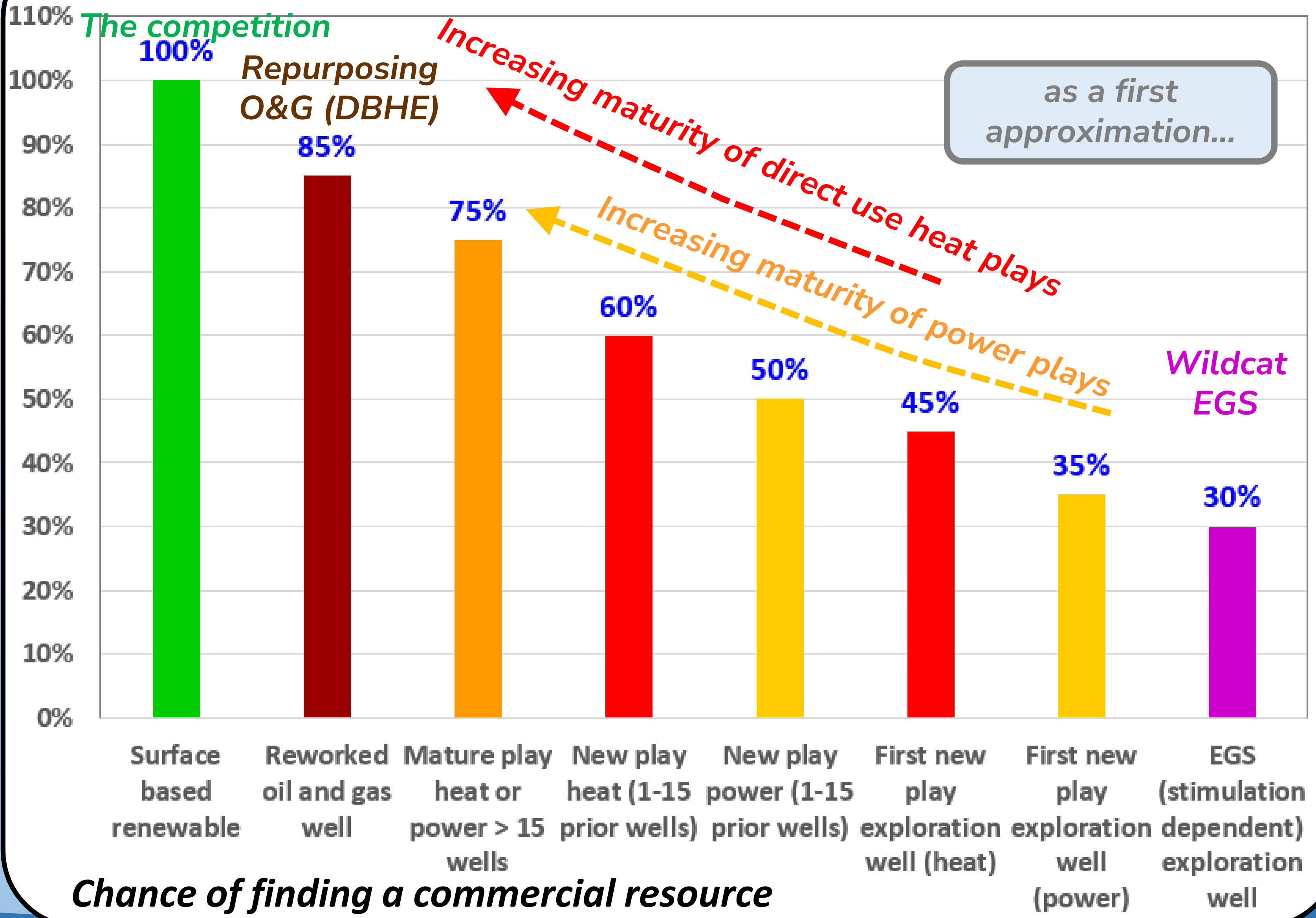
- Customers have to be happy with some risk, BUT…
- Success rates of accessing a useable resource NOT THAT BAD
- Customers happy with 60-85% success rates have a lot to gain IF:
  - Decarbonisation is a big priority
  - Budgets big enough for drilling CAPEX
  - In it for the long haul
  - Can see scalability of a multiple project portfolio
- => Various types of INDUSTRIAL HEAT and/or power are a low-hanging-fruit

The risk is often not so bad

Two antidotes to risk:

1) Improving success rates – usually with tech and/or local area learning curves
2) Multiple project portfolios to spread risk

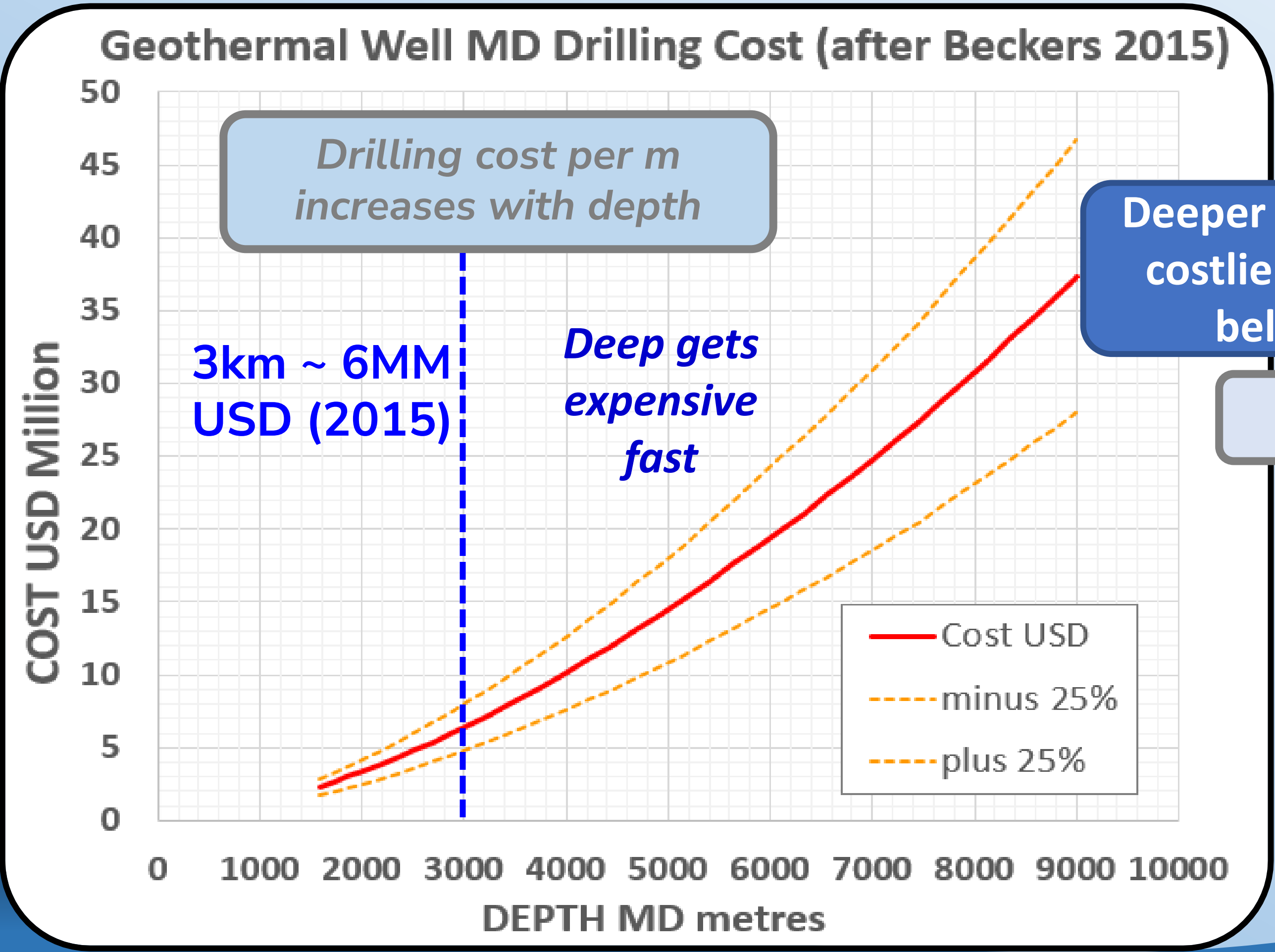
Generalised geothermal success rate observations



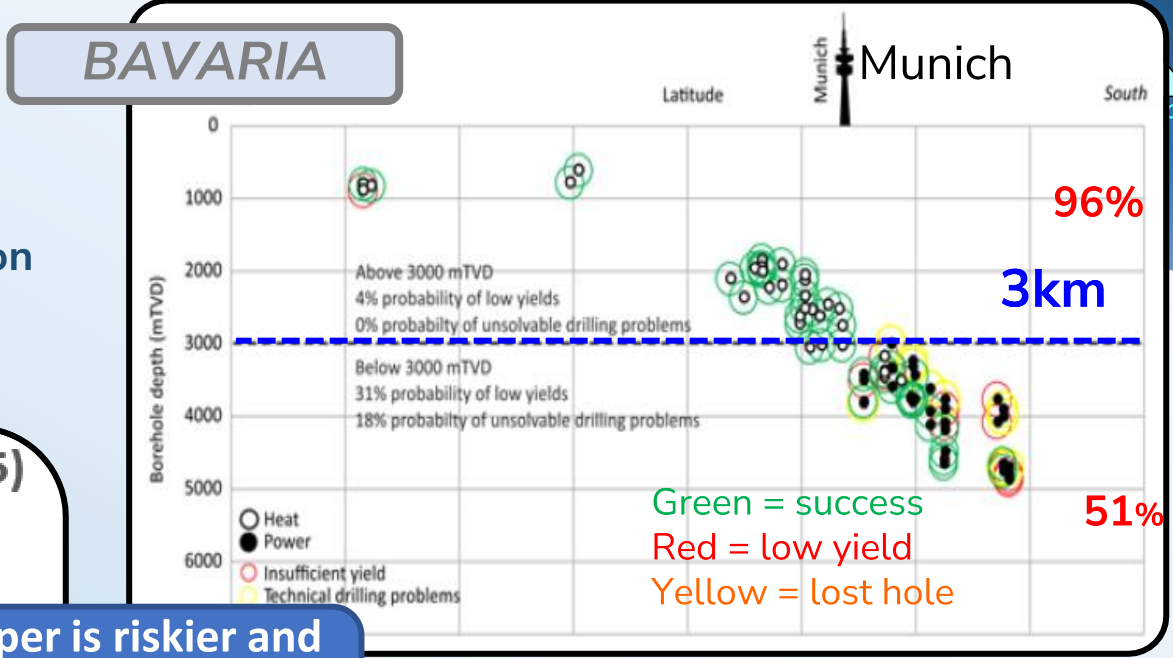
Chance of finding a commercial resource

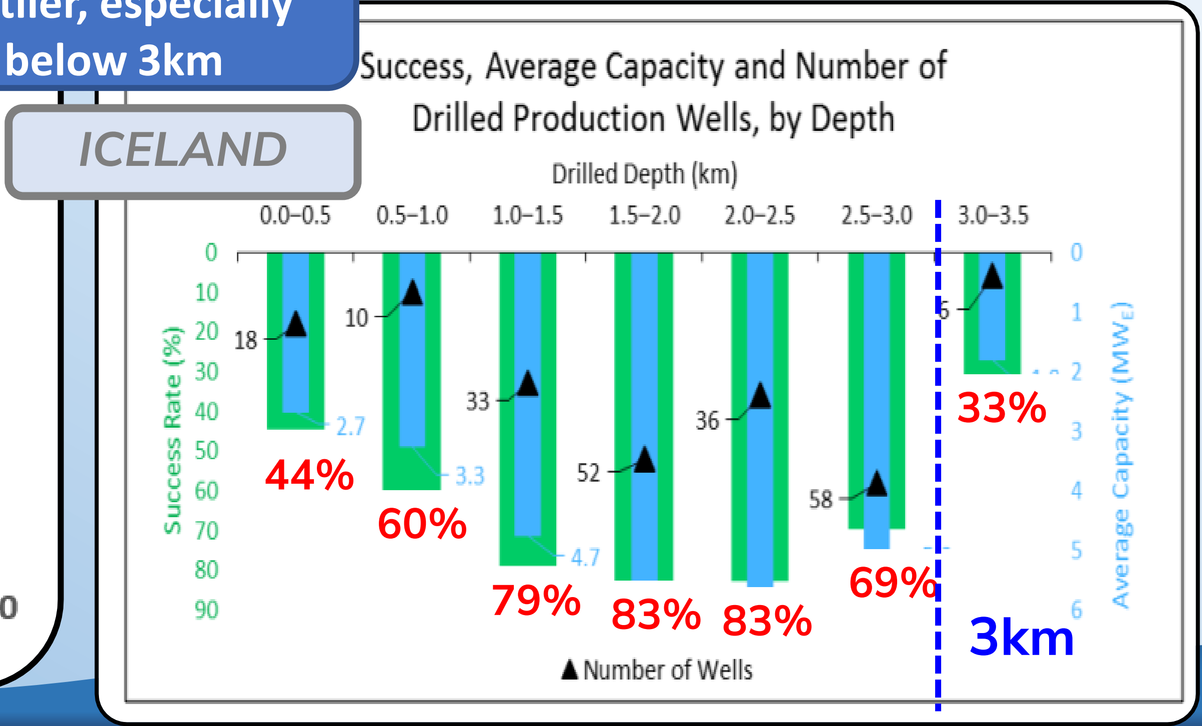
DEPTH & Success rate, cost

- In Bavaria, from 96% to 51% below 3km TVD
- In Iceland, from 79% to 33% below 3km TVD
- Drilling cost per metre increases non linearly as a function of depth
- Drilling improvements and planning at scale help



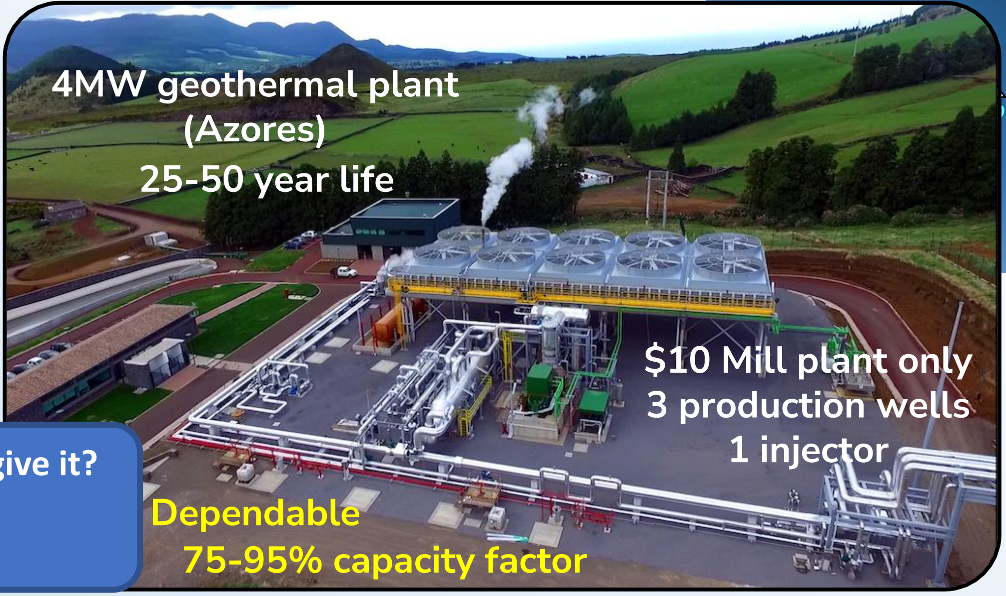
Deeper is riskier and costlier, especially below 3km



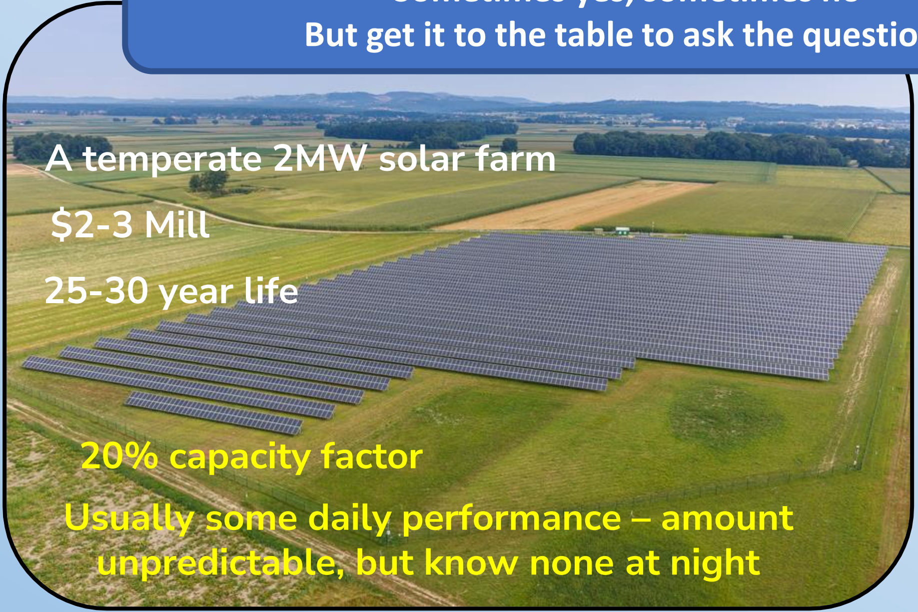


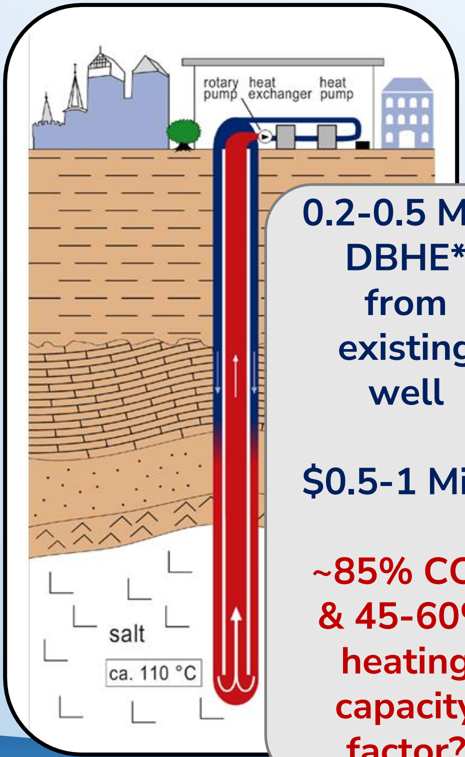
The customer CAPEX-COS crunch

- Emissions, capacity factor, dependability, longevity, works for sure, for geothermal
- But it is in tension with up front cost and risk – COS (chance of success)
- Also longer payback time and time to deployment from project kick-off
- Different customers have different tolerances
- Opting for an intermittent wind or solar supply, might also require costs of energy storage as well to truly compare



What does the customer want and does geothermal give it?
Sometimes yes, sometimes no
But get it to the table to ask the question!





0.2-0.5 MW DBHE* from existing well

$0.5-1 Mill?

~85% COS & 45-60% heating capacity factor?

Customer trade offs – risk, energy delivery, dependability, planning effort, speed

*DBHE = deep borehole heat exchanger

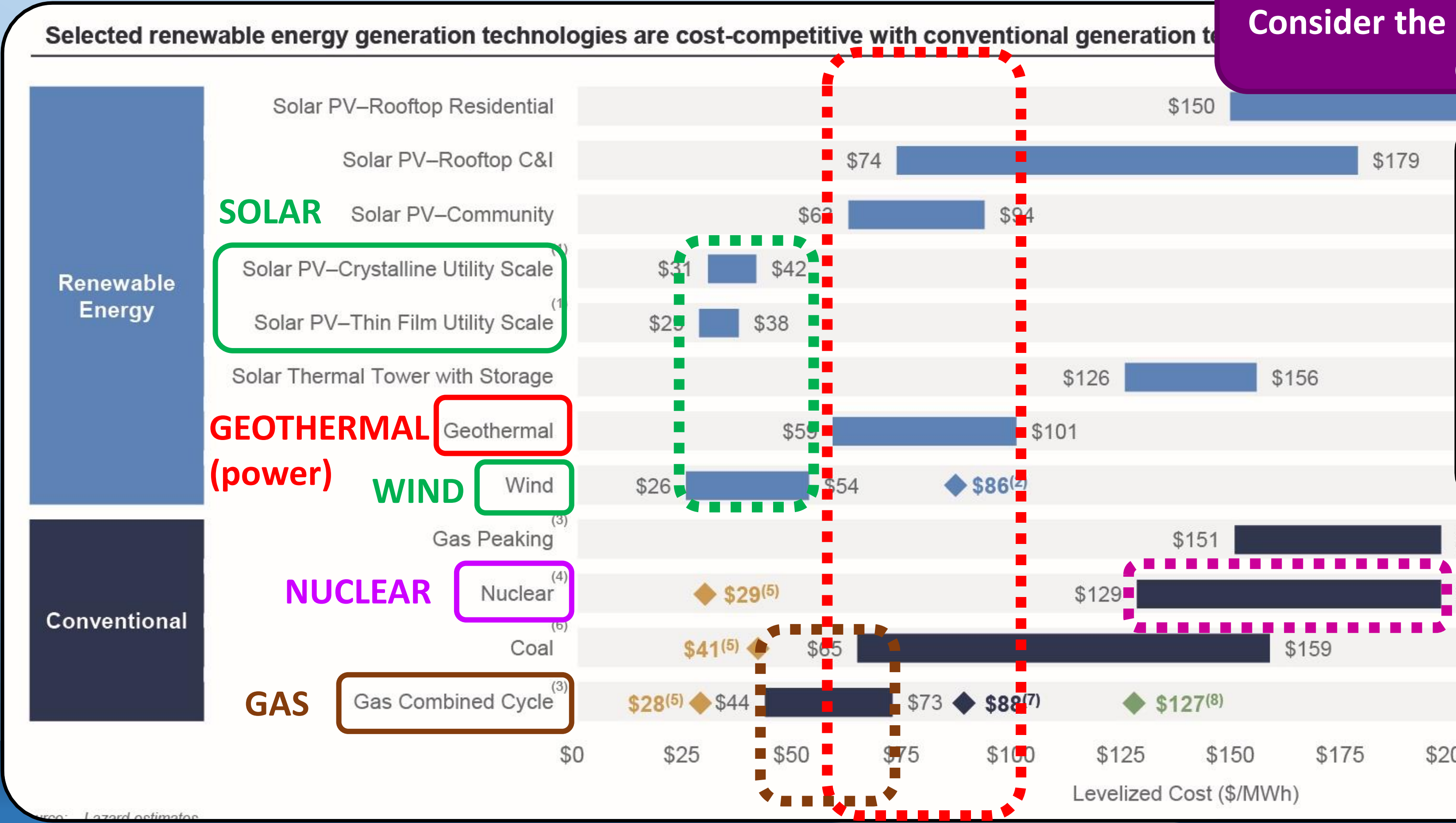
COST Efficiency - how much does Levelised Cost Of Energy (LCOE) matter?

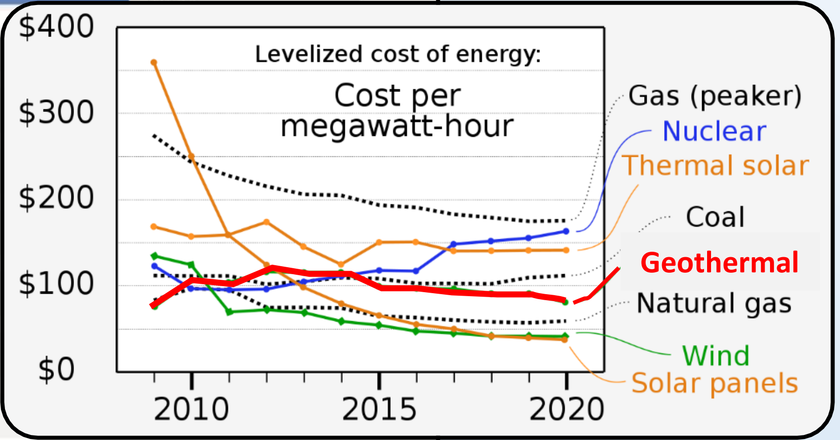
- Solar and wind has a lower LCOE than geothermal & trends say will stay that way
- How much does this matter for geothermal?
- Why not do it all with solar?
- **Geothermal = Baseload** versus **solar & wind = intermittent** – SO key question – how much do **energy storage costs** reduce any solar & wind advantage?

LCOE is not everything
But it matters & wind, solar, gas, compete on it
But low carbon baseload "flavour" *without energy storage costs* is a geothermal win c.f. wind & solar

THE LCOE of something doesn't matter if it can't on its own deliver enough – WHAT IS THE COST OF ENERGY SHORTFALL? Consider the averaged LCOE of the whole system sufficient to deliver enough, not just one sector

https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-a





https://commons.wikimedia.org/wiki/File:20201019_Levelized_Cost_of_Energy_%28LCOE,_Lazard%29_-_renewable_energy.svg

Energy Storage & Transmission

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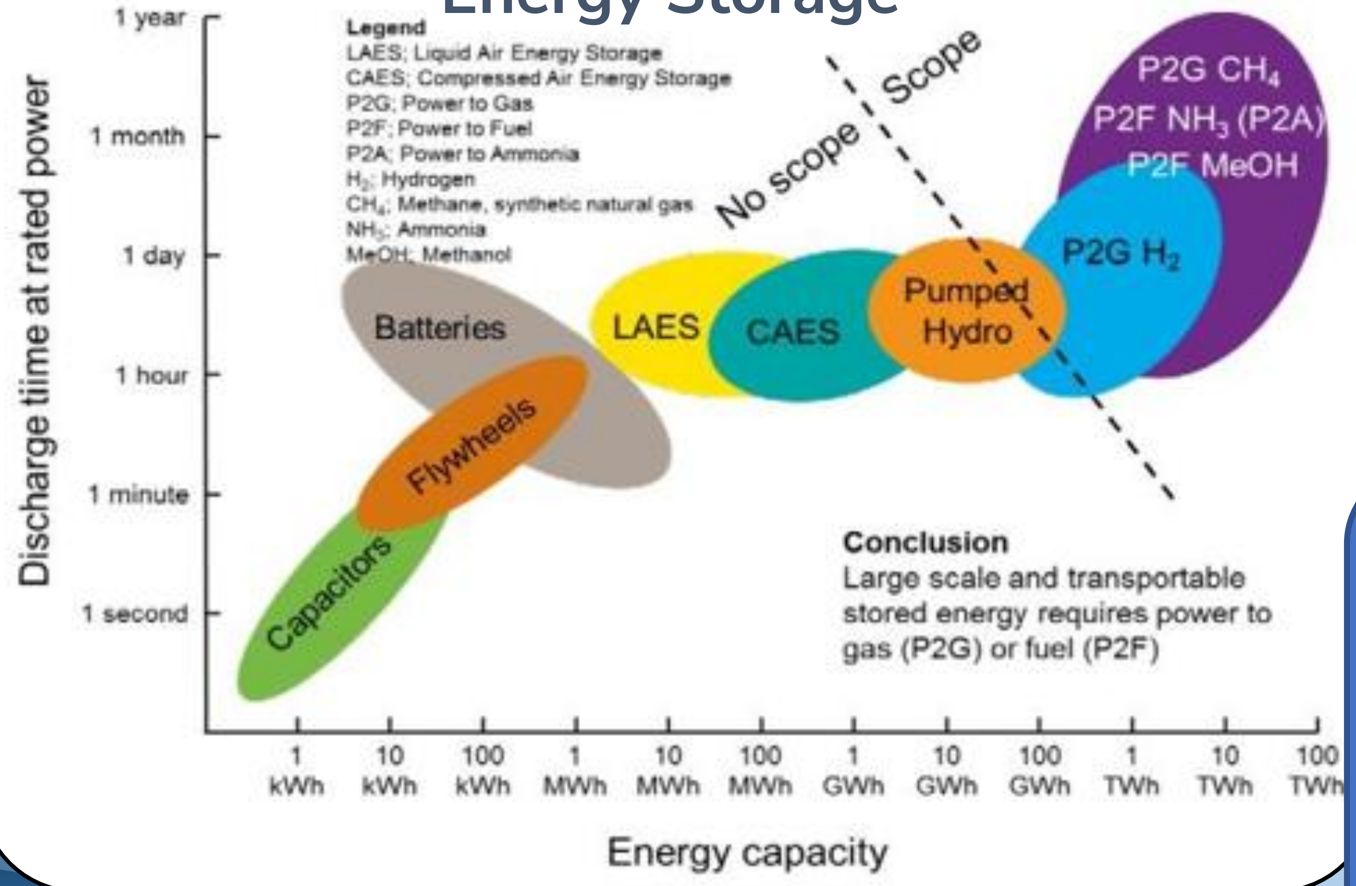
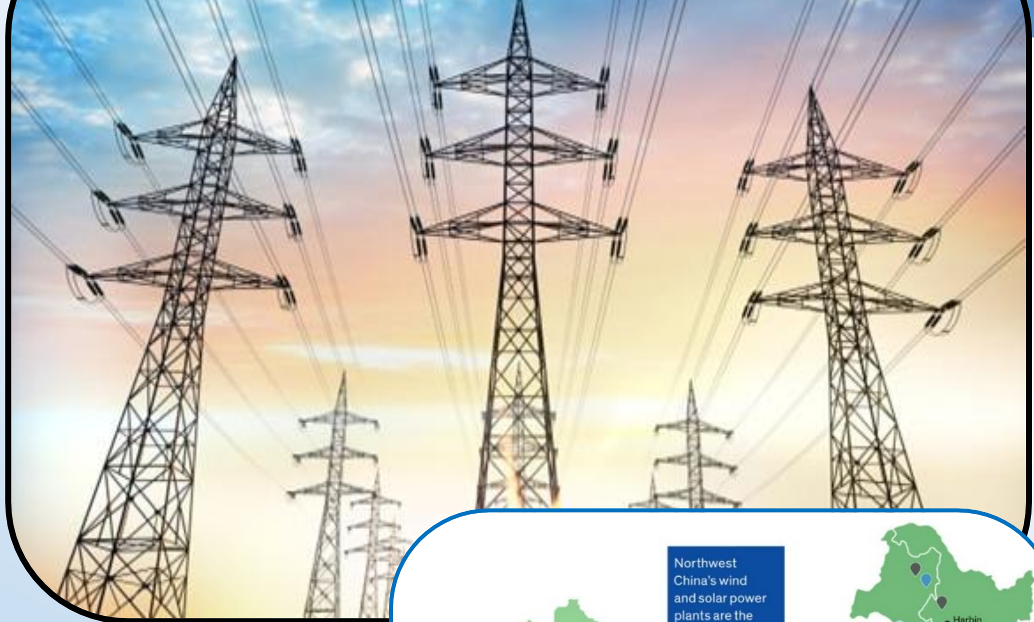
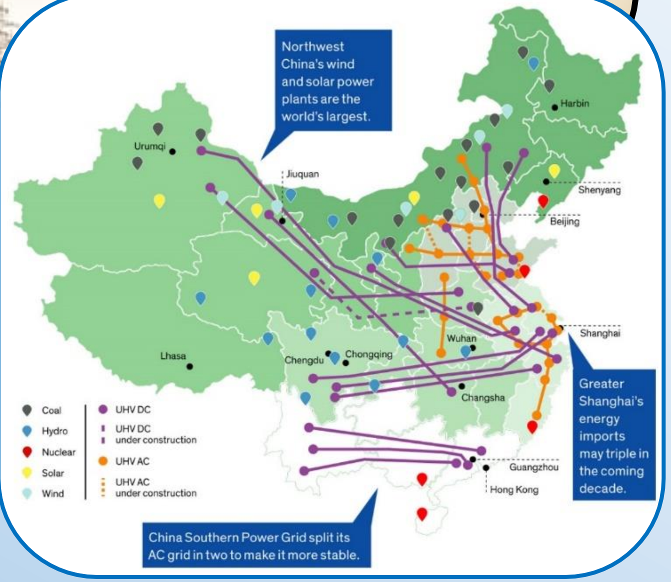
- New storage and distal transmission options will help address intermittency issues
- Baseload differentiation with geothermal will decrease with time & tech
- But it is an added cost for intermittent renewables, that geothermal doesn't have

Energy Storage



Distal Transmission

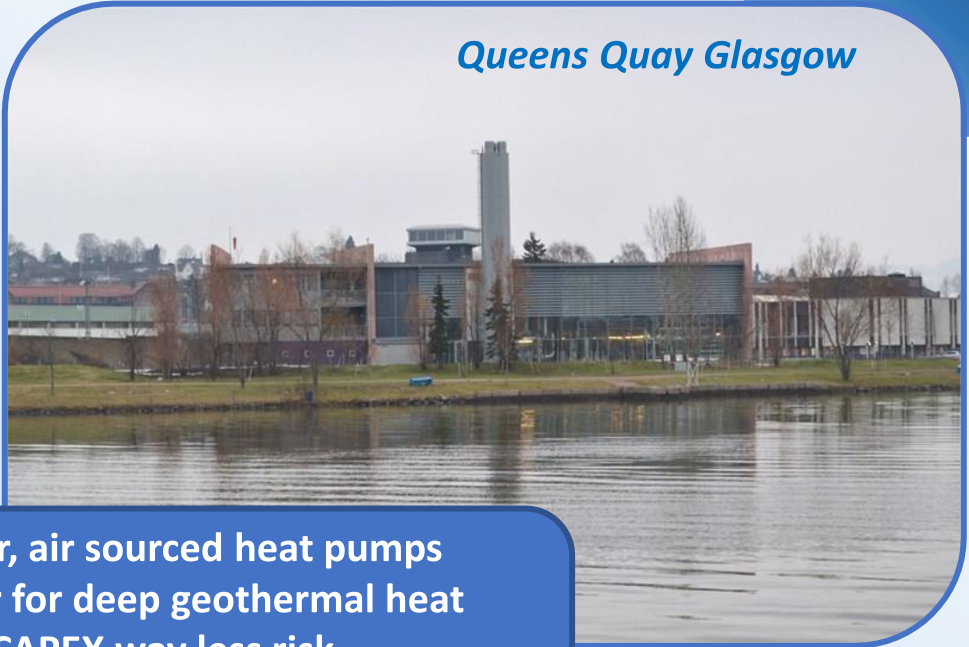




Comparative renewables intermittency & storage or distal transmission costs is going to be a big part of any geothermal upscale
ing economics

Ground/water/air sourced vs geothermal

- **Near surface ground/water/air sourced heat pumps**
  - Important competitor
  - Cheaper – lesser or no deep drilling cost
  - Little risk involved
  - Applicable fairly ubiquitously - **but smaller scale applications**
    - GSHP needs sufficient land (or depth) for building size
    - WSHP needs a water body to access – but there are quite a few of those, and one very big one
  - 24/7 potential but requires some power input to harvest
  - Deep geothermal can deliver a bigger energy punch
  - Only heat not power
  - Only enters truly "geothermal realm" if > 20 m deep



Queens Quay Glasgow

Ground, water, air sourced heat pumps
Key competitor for deep geothermal heat
Way less CAPEX way less risk...
...But addresses the smaller customers
For big customer & big energy punch - go deep...

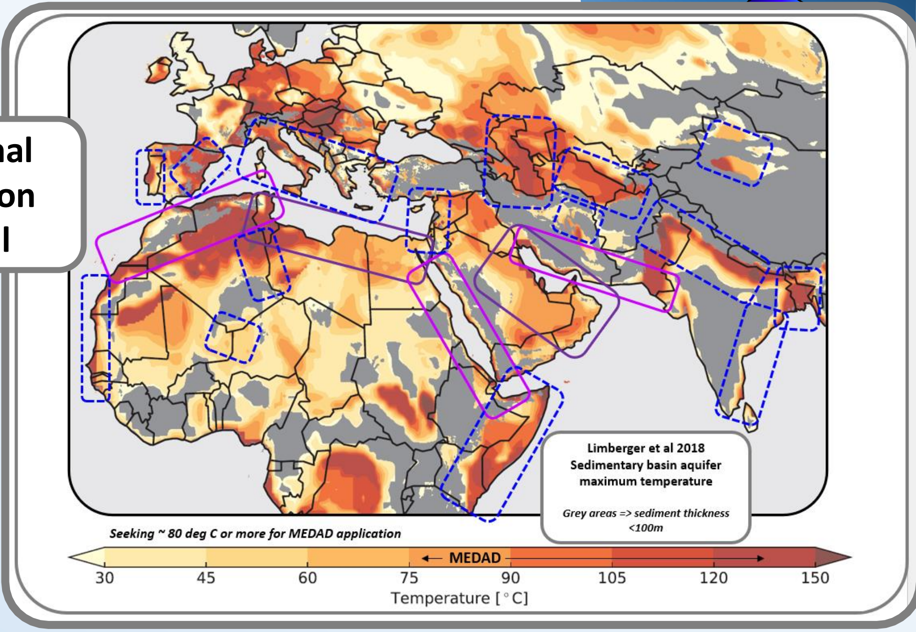
- **Geothermal**
  - Carries more technical risk, but can potentially deliver a way bigger punch in the success case
  - But longer payback times for the drilling CAPEX
  - Worth it if you need scale of resource for a long time
  - Big customer, big wallet, long haul project – works well

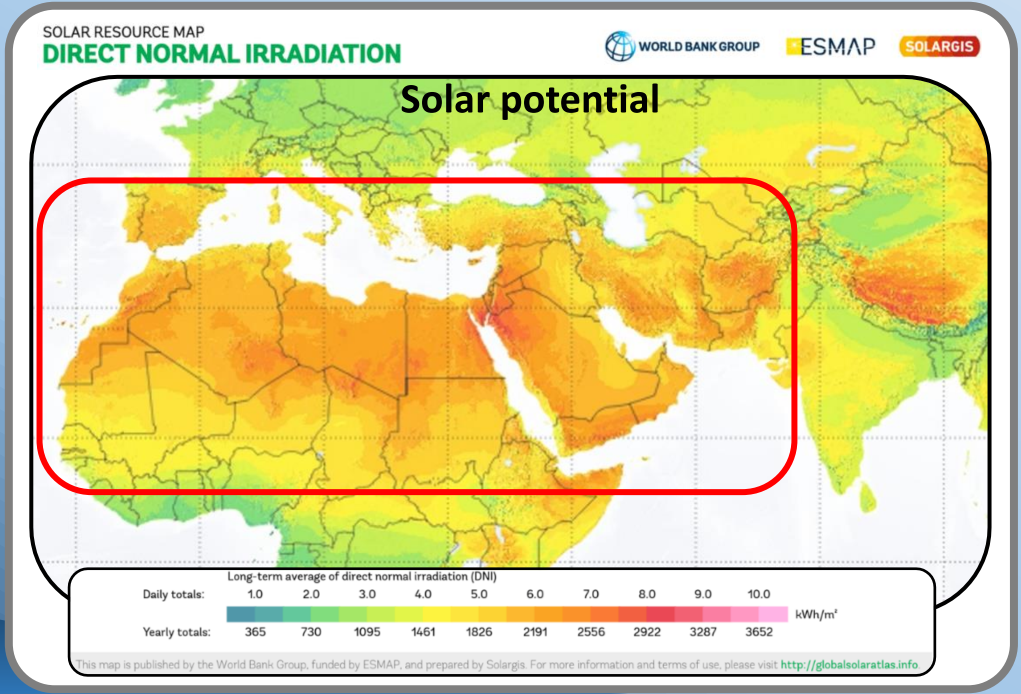
El Ejido Spain

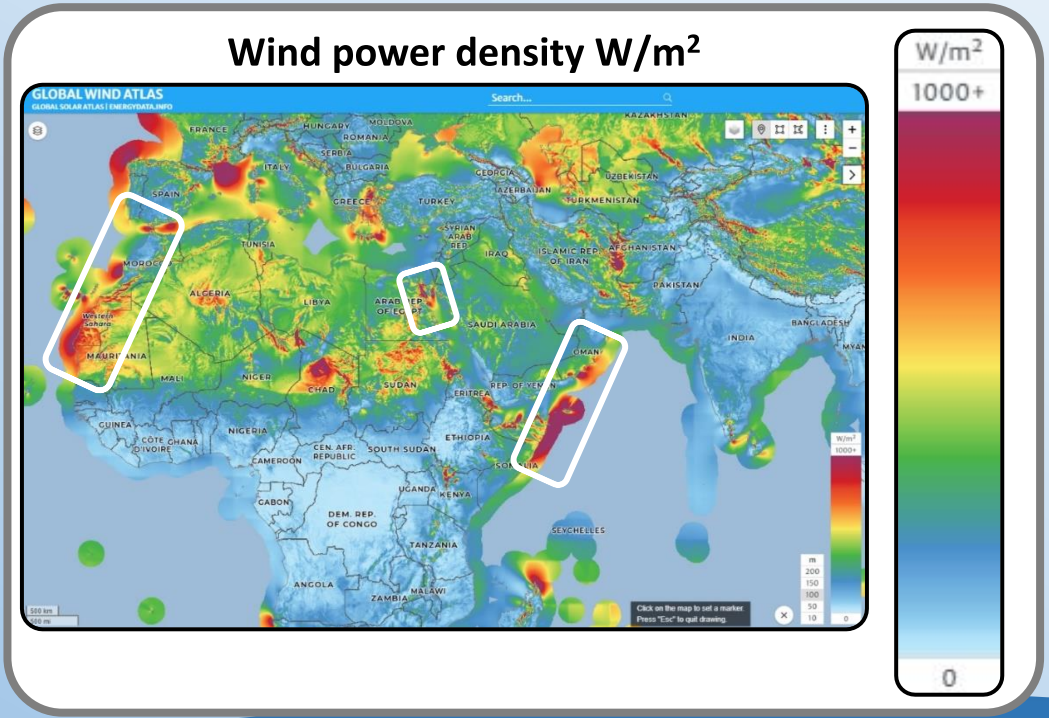
The renewable competition – MENA desalination case study

- The main competitor to geothermal in most regions is now solar.
- Wind sometimes makes a show too, especially offshore
- It used to be cheap gas, but maybe those days are over
- But new MED thermal desalination techniques have competitive efficiencies and need 65 deg C input – very achievable geothermally in much of the area
- Solar is ubiquitous and plentiful
  - But it takes up land and it's not 24/7 without lots of costly storage – and that's no small issue
  - Lots of international interconnection helps but it's no magic solution
  - Maybe if geothermal can do desalination, solar is better used in other ways to optimise overall cost efficiencies & profits...

Geothermal desalination potential







Geothermal might not always be the cheapest local option in isolation

But if we use it for heat where we can...

..it may enable greater profits from wind, solar & hydro power export elsewhere Providing net gain

Conclusions

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Conclusions

The geothermal game plan

Big Picture Review	Zoom in the sweet-spots	Assemble the jig-saw pieces	Tell the story	Establish	Build-out
Internal review	Get the data	Analyse	Investors	Start with the best	Learn & repeat

- **The drive to decarbonise is activating new investment**
- **True geothermal has large underexploited potential - but that said, is unlikely to ever replicate the scale of oil and gas**
- **The size of resource is less important than the recovery factor possible and cost of accessing it compared to the competition**
- **Geothermal is especially good for large heat & power customers with big long lived projects looking for baseload energy & energy cost stability**
- **Technical & commercial risk, large upfront CAPEX, times to deployment and agility of competing renewables constrain the likely expansion**

Popocatepetl, Mexico

Conclusions

Reverse engineer the problem – Customer & facilities driven exploration

Primary Customer & Competition	Secondary revenue streams	Facilities and wells required	Hubs and modules	Where's the resource to support	How many can it support
Market	Bonus market	Kit constraints	Geo-Lego	Siting	Bespoke scaling

- Knowing the market, knowing the customer, is a key to scaling up – the geoscience is important but often not the project critical thing
- Planning and operational optimisations are key – getting down the hole is just the start – keeping it going for the life of the facility- critical
- Clever well and facilities engineering is often the activator – the more modular the better
- New technologies are interesting but take time, have risk, and meanwhile there is huge running room with existing technologies
- One great strategic application is to apply geothermal heat where we reasonably can, freeing up power sources to seize other profitable opportunities and address other needs
- Thinking holistically about whole system levelised cost of energy LCOE, not just the individual sectors – geothermal is one of many but it has a role to play
- Lots of reasons to be cheerful, good reason to anticipate expansion, but good also to be measured in expectations – competition is fierce

Beppu, Japan


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