International Finance Corporation
World Bank Group

Success of Geothermal Wells: A Global Study

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IFC is a Leading Investor in Emerging Markets Power offering a comprehensive suite of solutions

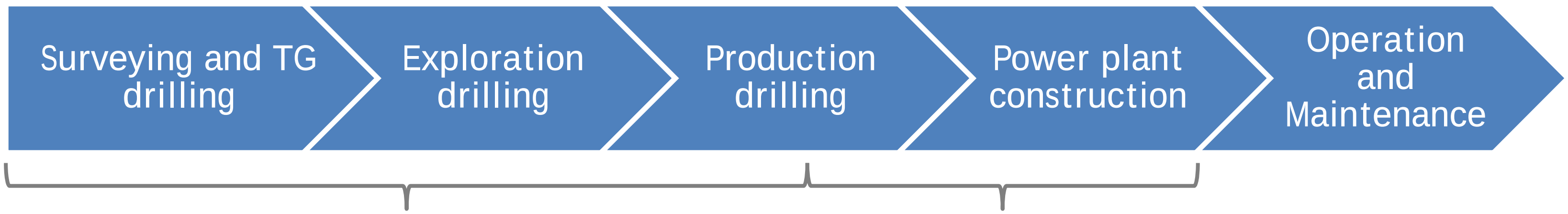
Investment

- 300 power investments in 65 countries since 1967
- We invest in:
  - **Generation** – 30,000+ MWs to date
  - **Transmission** – on a select basis
  - **Distribution** – reaching ~160 million customers
  - **Early stage start ups** in the renewable energy space
  - **Financial intermediaries** (banks, PE funds) who reach smaller assets/companies
- 2/3 of our business is climate-friendly, mainly through renewables

Advisory Solutions

- **Policy advice**: e.g. feed-in tariffs, permits, PPAs, housing efficiency regulations
- **Awareness and skills for firms:** e.g. cleaner production audits, capacity building for project developers & banks
- **Transaction support to demonstrate new business models,** e.g. technical assistance to banks, PPPs for concessions in renewable energy generation/access
- **Best practices, industry benchmarks and lessons learned**

IFC works across the geothermal project cycle



Advisory Services

- Exploration best practices
- Exploration risk insurance

Investment Services

- Direct investment through equity, mezzanine, and debt finance

- Advisory Services provides technical assistance to geothermal companies to reduce project risks
- Investment Services provides financing to geothermal projects and companies

Well Success: Background

- Key questions for Geothermal developers, investors insurers:
  - How big are drilling risk?
  - What factors affect the risk and by how much?
- The ability to accurately estimate drilling success rates increases confidence in a geothermal project
  - Helps to quantify the expected risk
  - Supports resource modeling assumptions
  - Improves access to financial support
- Previously, there has been little historical record that can be used to justify forecasted success rates
  - Well data is often confidential, proprietary information
  - No central database
  - Local databases may be incomplete, giving an inaccurate picture

→ **IFC conducted the first comprehensive analysis of geothermal wells**

A summary of available data

- The database covers:
  - 14 countries
  - 57 fields
  - 2,613 wells, thought to represent ~70% of all commercial wells drilled around the world
    - 7,700MW installed in the fields in the database, compared with 10,700MW installed worldwide

- Categories of data include
  - Completion date
  - Well status
  - MW capacity of wells
  - Depth
  - Resource type
  - Geology type
  - Production casing size
  - Pumped and re-drilled status

•Data compiled by GeothermEx

How to define success?

- There is no recognized basis for defining drilling success
- Any well that is drilled but isn't used is unsuccessful, but what about partial success?
  - Completely dry holes are rare
  - Wells with low productivity may be pumped, re-drilled, or used for injection or observation
  - Wells' output may deteriorate over time, in which case, was it initially successful?
- Ultimately, success depends on the ROI of each well
  - Factors in cost of well and economics of power plant
  - Hard to calculate on a well-by-well basis
  - Availability of data
  - MW output per $ of drilling cost may be simpler
- A simple MW threshold has been used in this analysis, where other data isn't available
  - Statuses of 12% of wells in database are unknown

Phases of a project

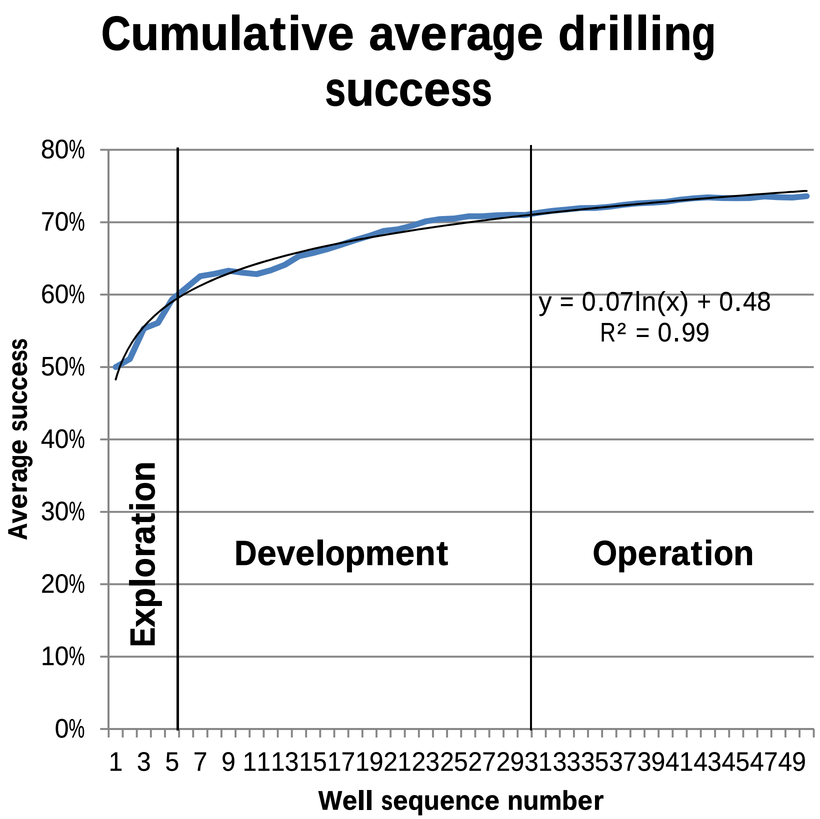
- As a project develops, understanding of the reservoir improves
- This aids in targeting of wells and should improve the success rate
- A project can be split in to different stages:
  - Exploration
    - Early stage drilling to establish reservoir characteristics
  - Development
    - Drilling to reach planned capacity output
  - Operation
    - Drilling to replace lost capacity
- Length of each stage will vary between projects

Highlights

Stage	Well numbers	Success rate	MW Capacity		% re-drilled
			Mode	Average	
Exploration	<=5	59%	4	6.0	15%
Development	>5,<=30	74%	2-5	7.3	14%
Operation	>30	83%	3	7.5	18%
OVERALL	**All**	**78%**	**3**	**7.3**	**16%**

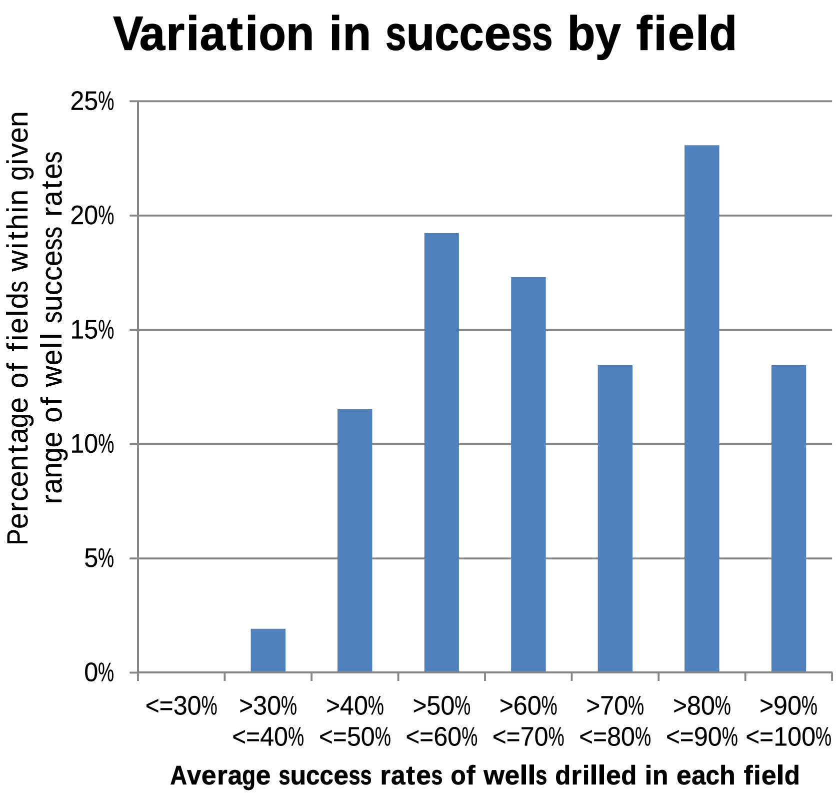
- Success rate improves as the project progresses (learning curve)
- Capacity of wells does not significantly improve beyond the exploration phase
- Re-drilling is equally common in each phase

Evidence for the “learning curve” effect



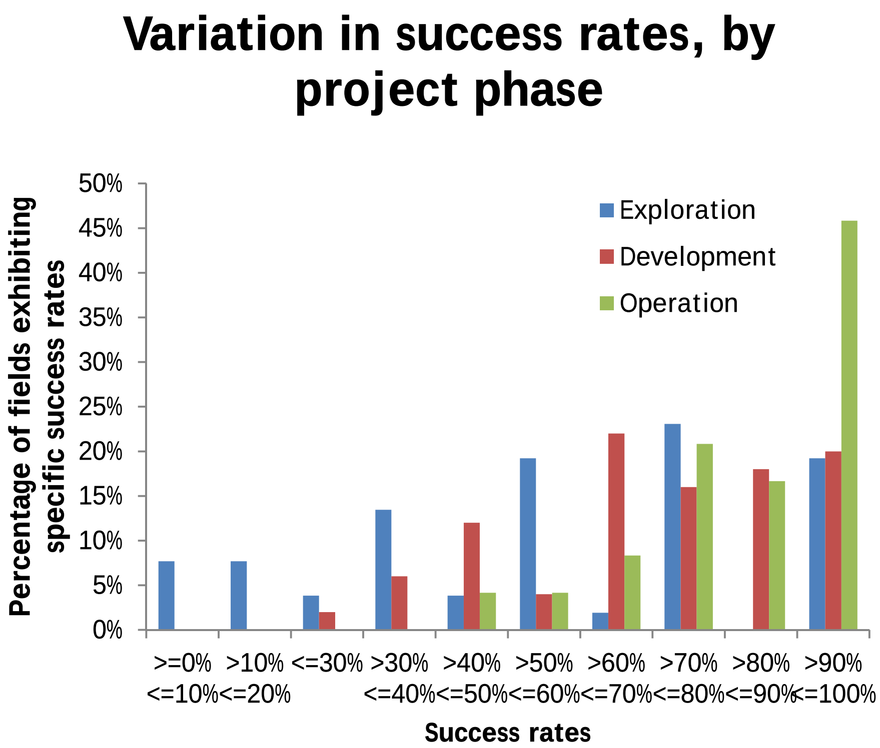
- It is expected that well drilling becomes more successful with more wells drilled in a field
  - Each well drilled helps to refine knowledge of the size and location of the resource
- The available data supports this theory
  - Success on the first well appears to be about 50:50, on average
  - Cumulative success rate rises rapidly in the first few wells
  - The cumulative success rate continues to rise as later wells are consistently more successful

Variations in success



- Developers and financers are not just interested in absolute risk, but also the risk variability
- The database suggests that most fields have an overall success rate of over 50%, and 80-90% is the most common
  - Implies new projects should expect success rates above 50% but could be significantly higher

Variations in success by phase



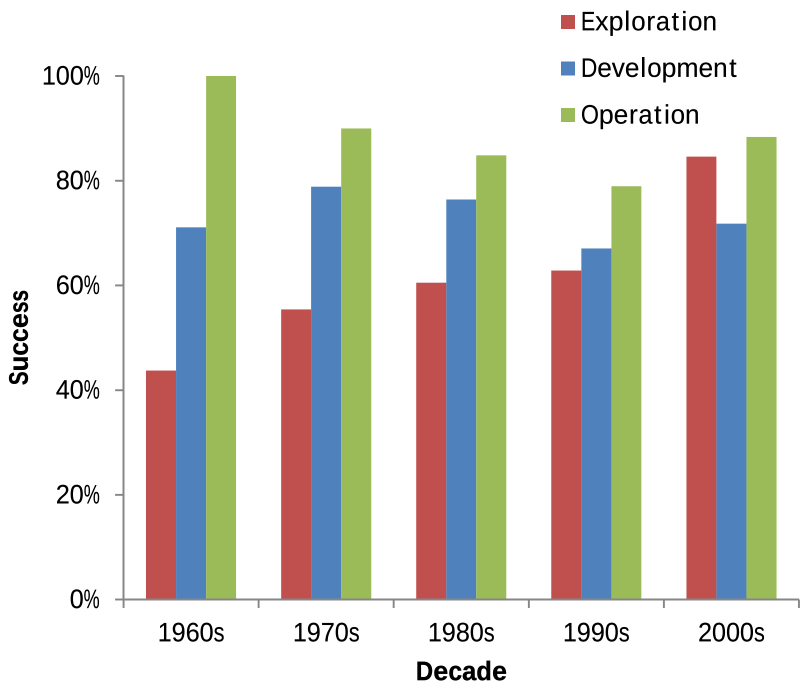
- There is a wide range of success rates seen in the Exploration phase => no real way of assessing likely success rate

- Success in the Development phase is most frequently around 60-70%, though also commonly above this

- Success in the Operations phase is higher, normally 90-100%

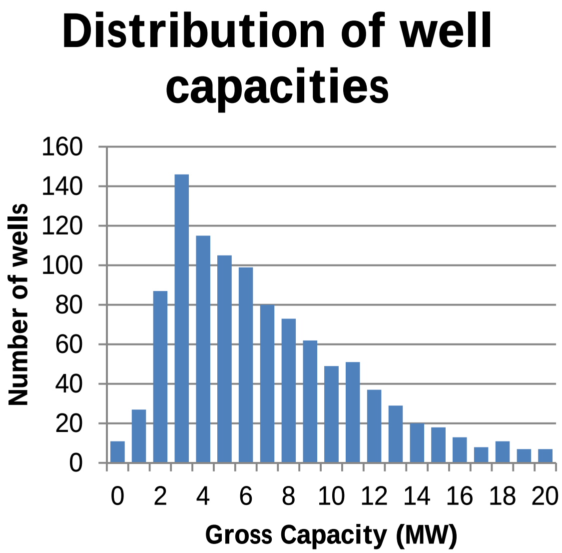
Improvements over time

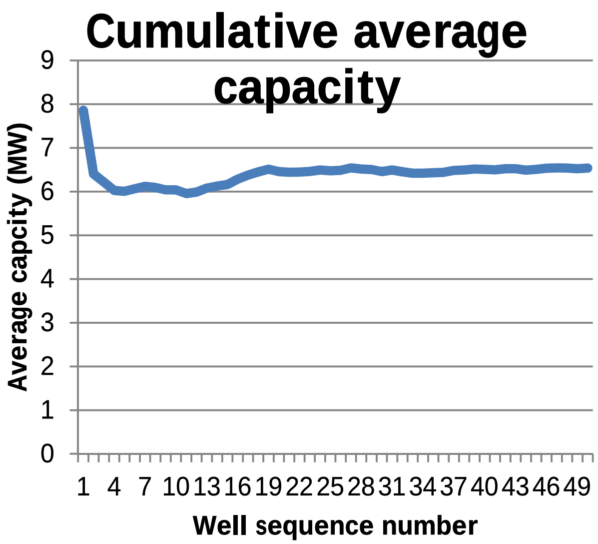
Drilling success rates over time, by project phase



- Exploration appears to have become more successful over the last 50 years
  - Possibly caused by better exploration techniques
  - NB. Wide variation in success rates in this stage makes averages potentially mis-leading
- No significant changes in success rates of development wells over time
- Operation wells appear to have become less successful
  - Possibly caused by older fields being fully exploited

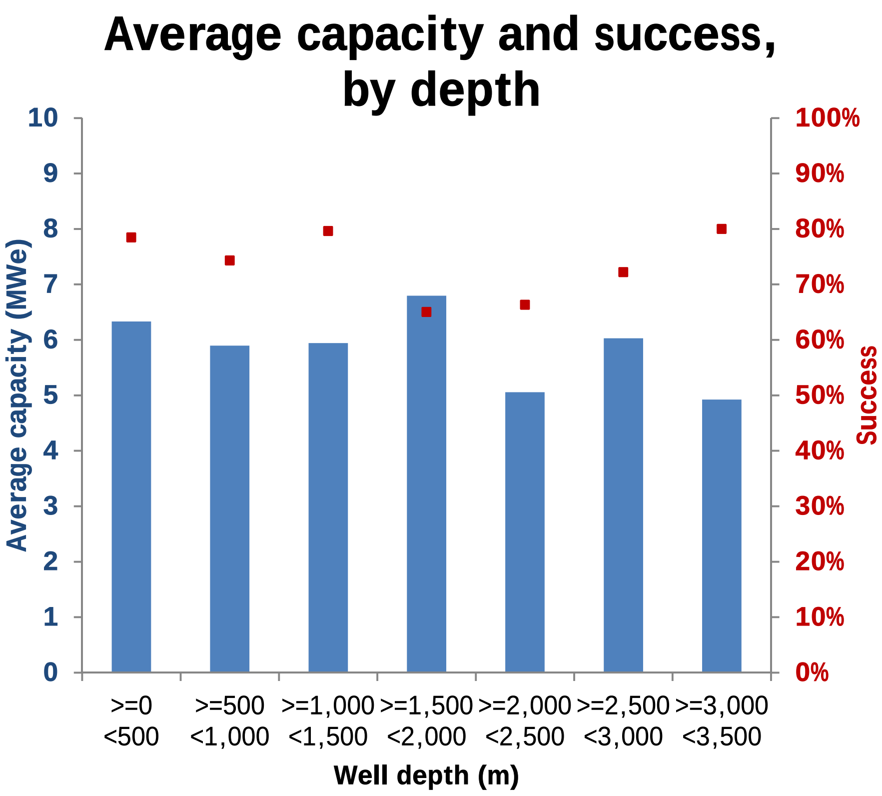
Distribution of well capacity





- Well capacity follows a positively skewed distribution
  - Mode is 3MW
  - Average is 7.3MW
  - Skew is 1.64
- A wide range of capacities are possible
  - Maximum capacity of a single well in the database is 54MW
- There is very little improvement in the capacities of wells as drilling progresses

Impact of depth on capacity and success



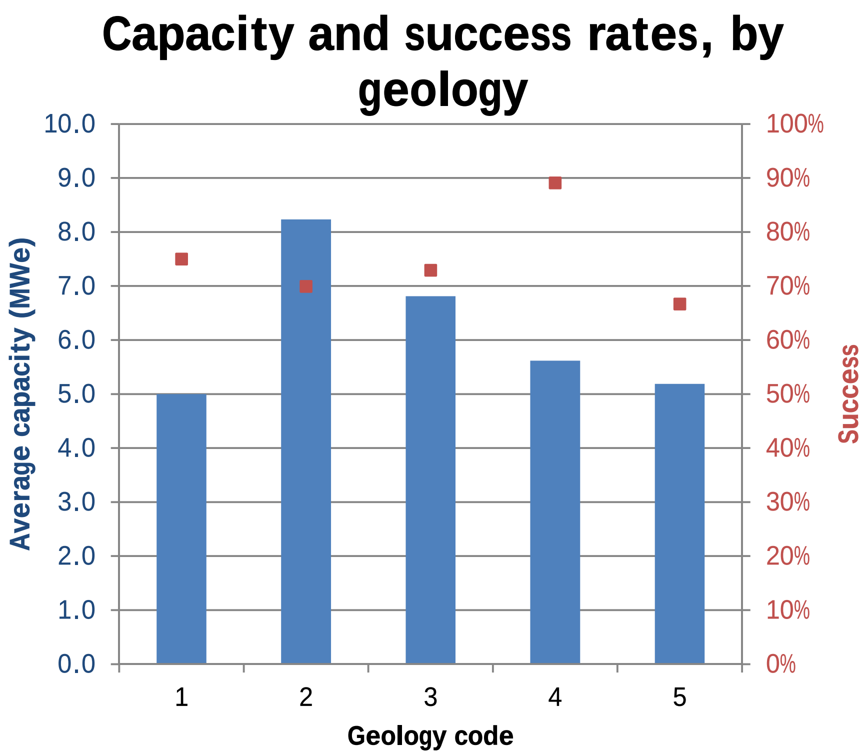
- Might expect it to be easier to drill shallow wells => higher success
- There does not appear to be any correlation between well depth and success or capacity
  - Shallow wells not necessarily more successful or more productive
- However, it is cheaper to drill shallower wells, so a low productivity well may be considered successful if it is shallow/cheap
  - Cost factor is not picked up in our definition of success here

Geology and enthalpy

Average capacity (MW)		Geology code				
		1	2	3	4	5
Resource code	1					
	2					3.6
	3		3.4		3.0	
	4	4.8	6.4	6.7		6.1
	5	5.0	5.9	5.4		
	6			7.6	8.2	
	7		8.4	6.9		

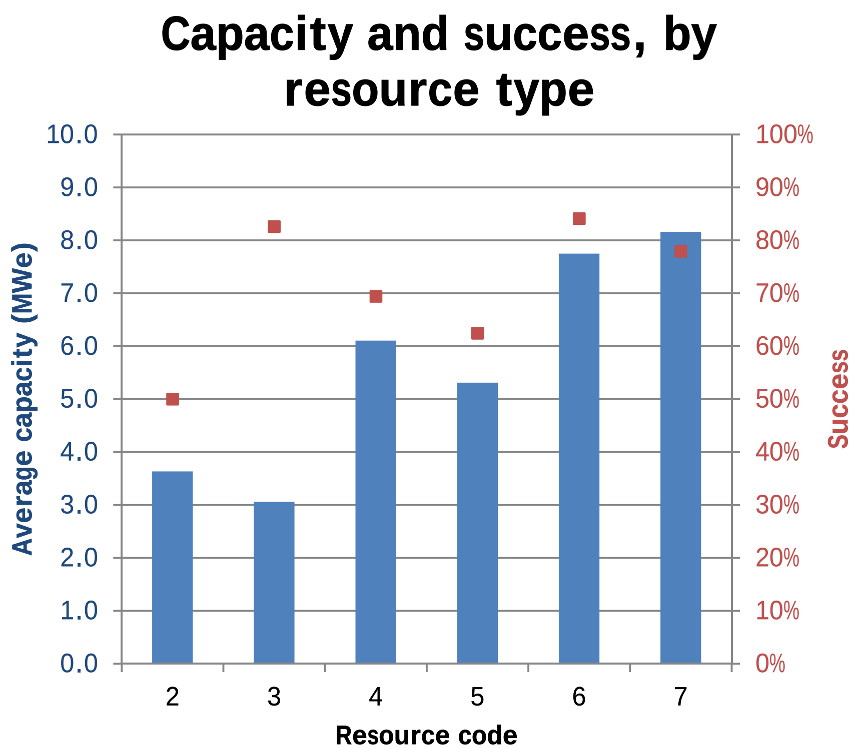
- Rock formation and enthalpy of the resource should significantly affect the productivity
- Expect capacity to increase with enthalpy
  - Enthalpy increases with resource code
- Expect rock formations with high permeability to boost capacity
  - Especially old volcanic
- Capacity roughly follows expectations

Impact of geology on capacity and success



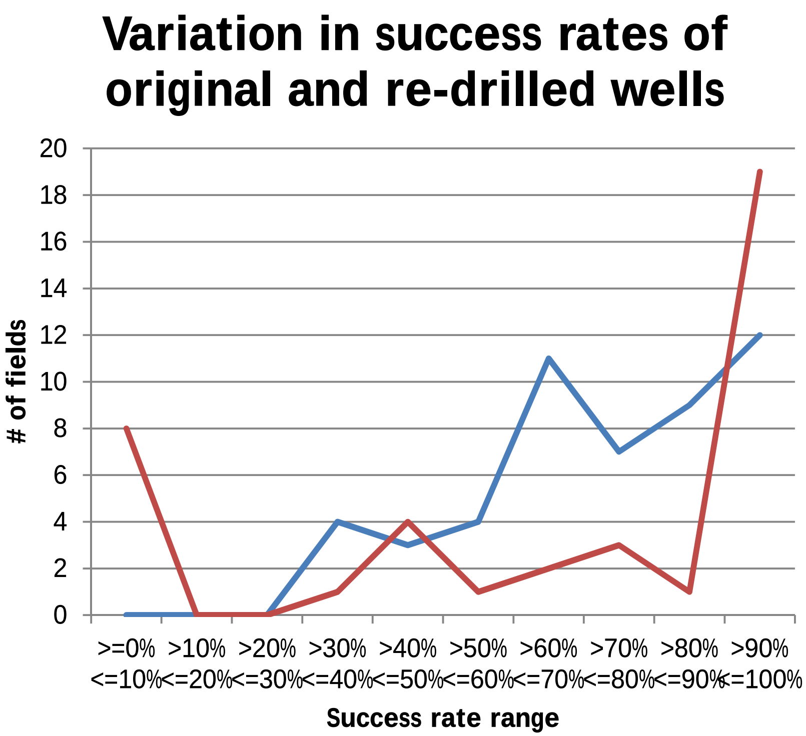
- Granitic rocks tend to have low porosity/unpredictable permeability (depending on fractures) and hence capacity is low
- The cracks present in old rock formations boost productivity
  - Volcanic rock may be alternate layers of ash and lava – permeability changes significantly between layers
- Basement rocks have similar permeability to granitic, if cracks are lacking
- Geology does not appear to affect success rates
  - Higher rate for Code 4 due to lower MW threshold of success for some fields

Impact of enthalpy on capacity and success



- Resource code is closely related to enthalpy
  - Capacity should increase with enthalpy
- Capacity does generally increase with resource code, but not strictly
  - Estimations of resource temperature in the exploration phase will be key in estimating future well capacities
- **Maximum** capacity of a well does increase with resource code
- Success appears independent of resource code

Impact of re-drilling on capacity and success



- 16% of wells have been re-drilled
- Re-drilling does improve success
  - 77% of original wells are successful
  - 87% of re-drilled wells are successful
- Re-drilling tends to have almost 100% success, or 0% success, depending on the field
- Re-drilled wells also tend to have a higher capacity
  - 7.2MW for original wells
  - 8.1MW for re-drilled wells

Conclusions

- ROI is the best measure of drilling success, but is often not practical
  - Drilling cost per MW is easier, but just the MW output is normally used, irrespective of cost
  - Assigning low productivity wells as injectors or observation wells complicates things further
- Overall, 78% of wells drilled were successful and the most common capacity is 3MW, though average capacity is 7.3MW
  - A strong learning curve is seen in success, but not in capacity, as a project progresses
  - Success is very unpredictable in the Exploration phase
- Wells can be drilled to almost any depth (<5km is normal), though 2.2km is the most frequent depth
  - Most fields have wells drilled to a wide range of depths
  - Depth does not impact likely success or capacity
- Enthalpy and geology affect well capacity, but not success
- Re-drilling improves success and capacity

ANNEX

Quantifying geology and resource types

We have attempted to categorize the geology and resource characteristics of the geothermal fields so that we may assess the impact on success rates

Geology type

Code	Description
1	Granitic / higher-grade metamorphic
2	Tertiary and older volcanic/volcaniclastic - large-scale volcanic structures absent
3	Younger volcanic/volcaniclastic - large-scale volcanic structures (volcanoes, calderas) preserved
4	Sedimentary Basin - clastic, drilled above basement
5	Sedimentary Basin - clastic, wells drilled into basement

Resource type - enthalpy

Code	Description	Temperature
1	Non-electric	<100ºC
2	Very low temp.	100ºC to 150ºC
3	Low temp.	150ºC to 190ºC
4	Moderate temp.	190ºC to 230ºC
5	High temp.	230ºC to 300ºC
6	Ultra high temp.	300ºC +
7	Steam field	230ºC to 240ºC