Methodology for Geothermal Ressource Assessment

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CONTENT

- What is resource assessment

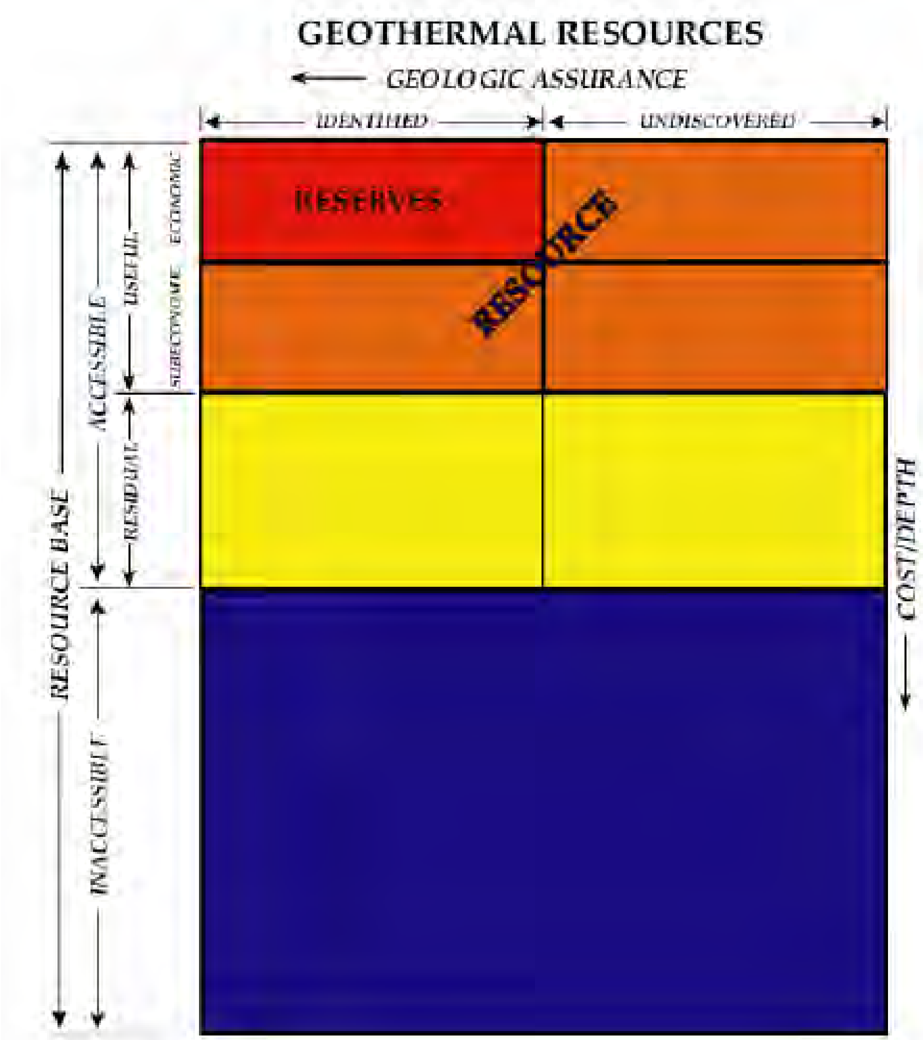
Fitting to the aim of Geo-ELEC

- Build resource assessment of Europe for geothermal power
- Time horizons of 2020 and beyond

- Build on extisting methodologies
- Proposed assessment methodology
- Presentation on pan-european scale

What is natural resource assessment

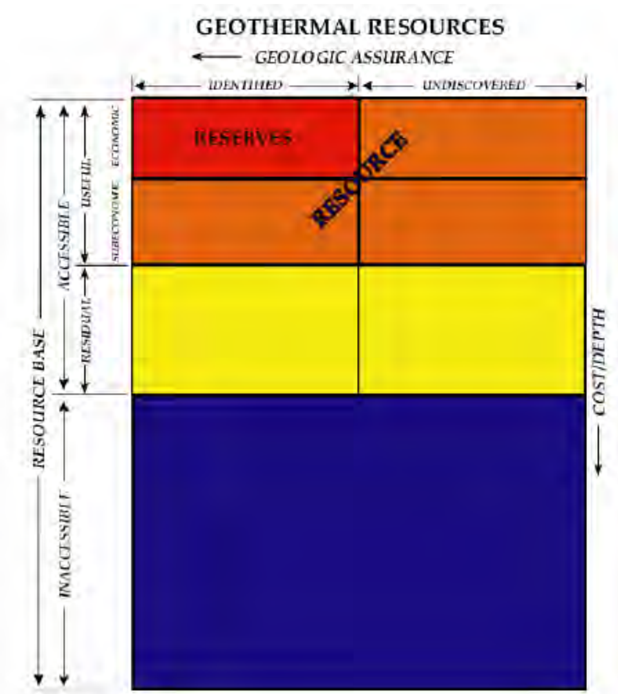
- **Quantitative assessment of accessible and useful earth system resources, subdivided in:**
  - **Reserves** which are demonstrated economically recoverable
  - **Resources** are possible future reserves, subdivided in
    - *Identified* or contigent
    - *Undiscovered* or prospective



McKelvey diagram (Williams et al., 2008)

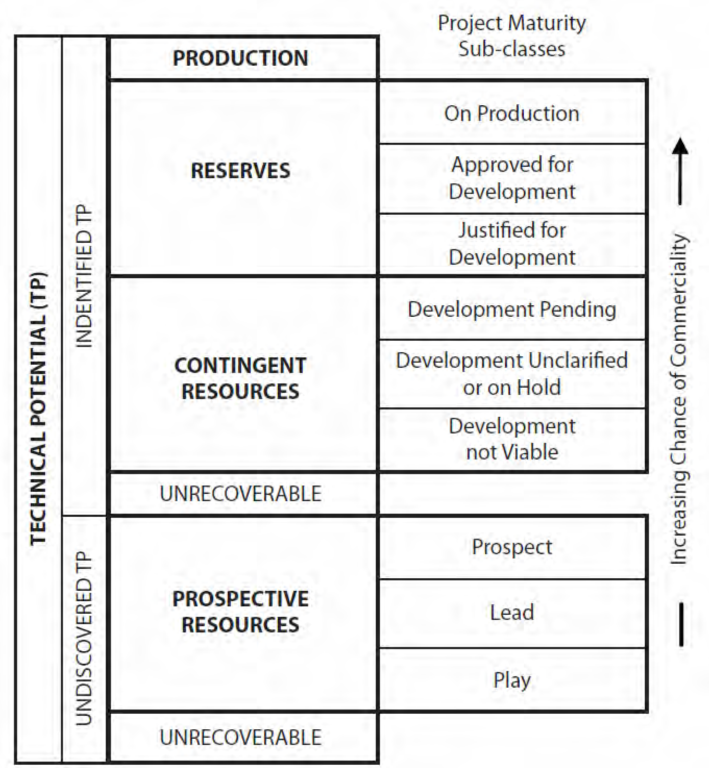
Resources are developed in Exploration workflow: prospective resources → Contigent resources → Reserves

Situational scheme



McKelvey diagram (Williams et al., 2008)

Project oriented scheme



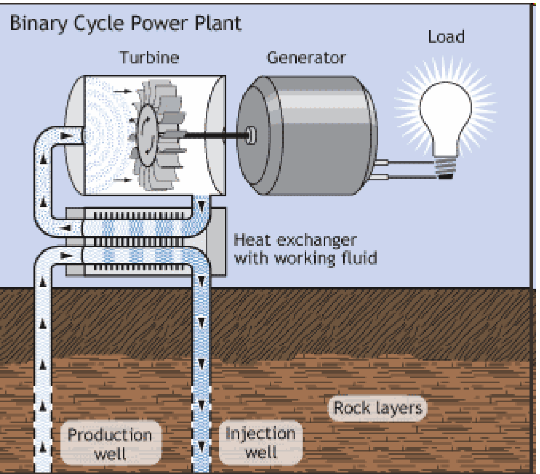
Project workflow (modified from Etherington & Ritter, 2007)

A bit more definition: Play, Leads and Prospects

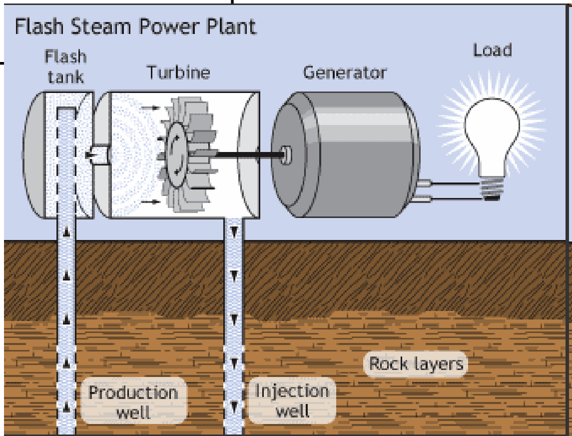
- **Project phases**
  - Play ➔ Lead ➔ Prospect ➔ Drilling ➔ Production
- **Play**
  - Spatial (geographically / in depth) delimited area
  - Specific subsurface conditions which allow
    - Sufficient flow rate
    - Sufficient T
    - Suitable P and chemical conditions
- **Lead**
    - Discrete subsurface reservoir
    - Identified by surface exploration
- **Prospect**
  - Reservoir being studied thoroughly by surface exploration
  - Earmarked to be drilled

Suitable subsurface conditions for power production

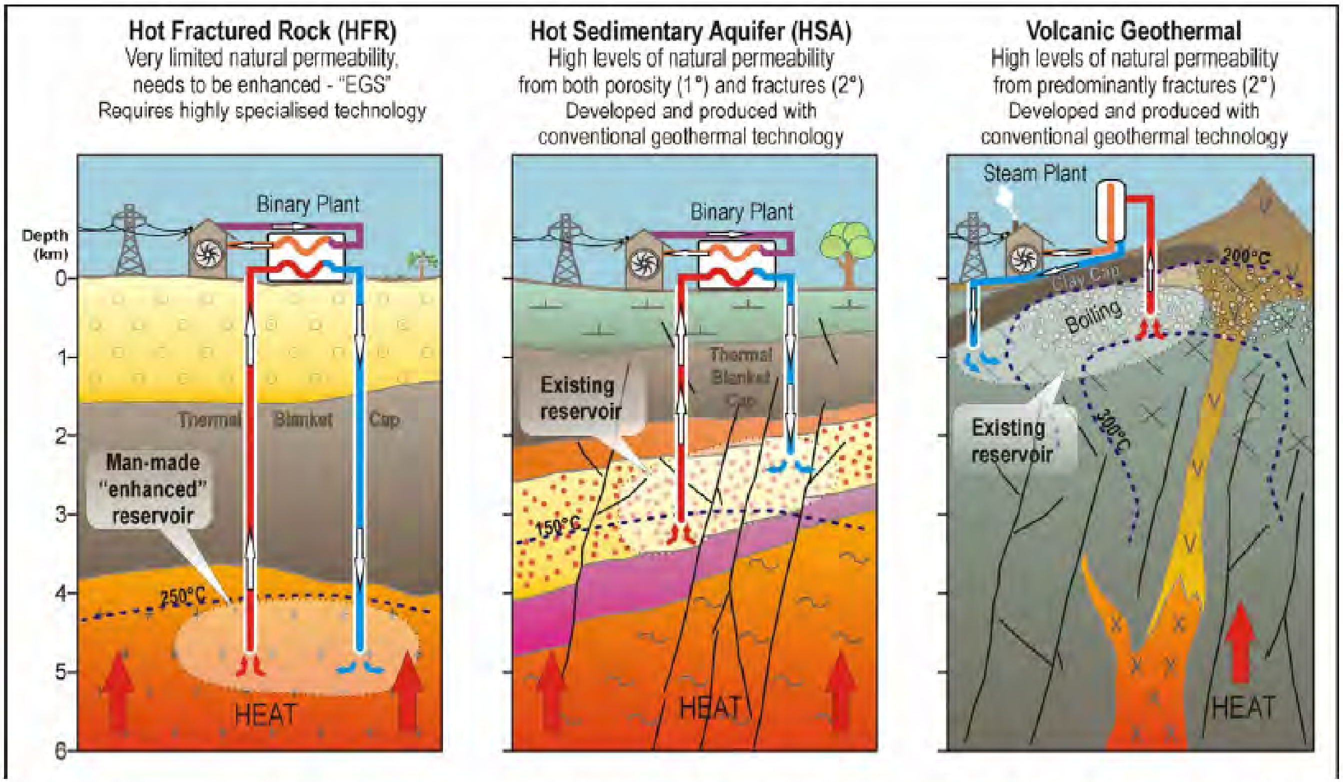
Parameter \ application	Binary	Conventional (steam/flash)
Minimum production temperature [°C]	100	175
Return temperature [°C]	80	90
Maximum production depth [km]	3-10	3-10
Energy conversion efficiency	MIT(2006)	MIT(2006)



Figures: US DOE



Looking at the subsurface resources: Play Types for power production



No commercial operations

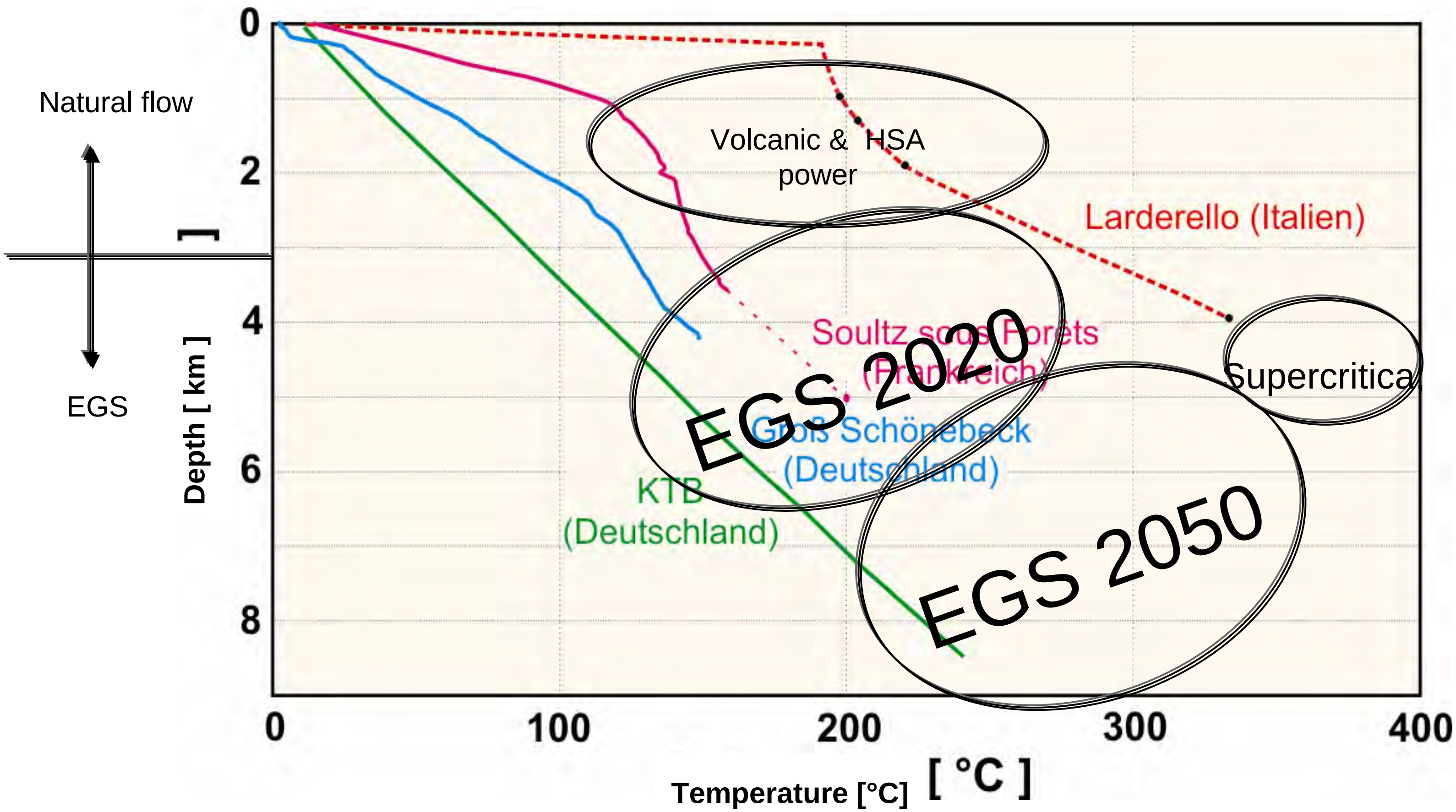
Operating for over 25 years

Operating for nearly 100yrs
96% of installed generation capacity

EGS

Source:Hot Dry Rock Ltd.

How do we get the power in different time-lines in different play types



How critical are subsurface conditons

- ***temperature is critical*** → drilling cost is major investement and increases exponentionally with deph → **target high temperature gradient areas**
- **HSA** , **volcanic** (and supercritical) and **active faulting** rely on occurance of specific geological conditions for **natural fluid pathways** for production (porosity-overpressure, fractures, karst and faults) and chemistry. Probability of natural fluid path ways generally decreases rapidly with depth → **maximum depth is limited**
- **EGS/HDR** : fluid path way is enhanced through stimulation → drilling deeper is possible but requires novel drilling and stimulation techniques to increase performance and public acceptability → **maximum depth is not limited**

Different protocols on resource assessment and relevance to geoELEC (summary)

- **Regional potential (prospective resources only)**
  - **Level 1** regional assement for (EGS) assesment (IPCC, 2011, Beardsmore et al., 2010, Williams et al., 2008,) Temperature only used as input → theoretical → technical potential
  - **Level 2** Modification of Level 1 based on specific play information
- **Level 2 +3: Ongoing exploration and production for specific leads and prospects and producing fields**
  - Reporting on exploration and production activities
  - Reporting codes well defined for geothermal in Canadian and Australia geothermal reporting coces CanGEA and AGEA

- Uncertainty → State of the art of oil and gas industry on best practices in reporting and assessment of

LEVEL 1- **Theoretical and Technical Potential (1)**

- Expressed as recoverable geothermal energy [MW_e]
  - ➔ „technical potential“
- Assumption: Resource development within 30 years
- Calculation according to Beardsmore et al. (2010) or Willams et al., (2008),concept used in IPCC (2011) and thermoGIS worldedition (2011)
  - Considers heat in place of sediments and crust
    - Beyond threshold depth
    - Cutoff T according to electricity production schemes and
    - Theoretical capacity: $E_{heat\_in\_place} * c_e$
  - Theoretical ➔ technical potential: ultimate recovery factor (UR)
    - <u>Global assessment:</u>
      - Globally: UR ~ 1% of $E_{heat\_in\_place} * c_e$ (IPCC, 2011)
      - Plays, prospects: locally much more than 1% UR → 10-50%,

LEVEL 1 :Theoretical and Technical Potential (2)

Heat Energy in place ➔ Resource Asssessment (Technical Recoverable Potential)

1. Grid geographic region in 5’ x 5´ cells	**Each cell becomes a node in the regional resource estimate. A temperature vs depth profile to 10 km depth will be derived for each cell.**
2. Determine temperature field	**Determine temperature field from surface heat flow, surface temperature, thermal properties, borehole temperatures and tectonic setting**
3. Determine theoretical potential for depth intervals with temperature exceeding 100°C and 175°C respectively	**From temperature model derive amount of theoretical power in node [Mwe] for a number of depth intervals for binary (>100°C) and conventional power systems (>175°C?).Use best practice on energy conversion following Beardsmore et al., 2010.**
4. Determine technical potential for depth intervals with temperature exceeding 100°C and 175°C respectively	**Convert theoretical power to technical power adopting a reasonable recovery factor, reflecting the probability of achieving high enough productivity (flow rate). The recovery for global assessment is in the order of 1%. For specific prospects, leads or plays the recovery factor typically varies from 10-50%.** **An estimate of recovery factor for undiscovered resources should include the probability that the resource maybe unrecoverable.**

after Beardsmore et al. (2010)

LEVEL 1: Example of US assessment of undiscovered resources (1)

		Identified Resources (MWe)				Undiscovered Resources (MWe)				Enhanced Geothermal Systems (MWe)			
State	N	F95	F50	Mean	F5	F95	F50	Mean	F5	F95	F50	Mean	F5
Alaska	53	236	606	677	1,359	537	1,428	1,788	4,256	NA	NA	NA	NA
Arizona	2	4	20	26	70	238	775	1,043	2,751	33,000	52,900	54,700	82,200
California	45	2,422	5,140	5,404	9,282	3,256	9,532	11,340	25,439	32,300	47,100	48,100	67,600
Colorado	4	8	11	30	67	252	821	1,105	2,913	34,100	51,300	52,600	75,300
Hawaii	1	84	169	181	320	822	2,027	2,435	5,438	NA	NA	NA	NA
Idaho	36	81	283	333	760	427	1,391	1,872	4,937	47,500	66,700	67,900	92,300
Montana	7	15	51	59	130	176	573	771	2,033	9,000	16,100	16,900	27,500
Nevada	56	515	1,216	1,391	2,551	996	3,243	4,364	11,507	71,800	101,300	102,800	139,500
New Mexico	7	53	153	170	343	339	1,103	1,484	3,913	35,600	54,400	55,700	80,100
Oregon	29	163	485	540	1107	432	1,406	1,893	4,991	43,600	61,500	62,400	84,500
Utah	6	82	171	184	321	334	1,088	1,464	3,860	32,600	46,500	47,200	64,300
Washington	1	7	20	23	47	68	223	300	790	3,900	6,300	6,500	9,800
Wyoming	1	5	31	39	100	40	129	174	458	1,700	2,900	3,000	4,800
Total	248	3,675	8,356	9,057	16,457	7,917	23,739	30,033	73,286	345,100	507,000	517,800	727,900

LEVEL 3

LEVEL 2
Play factors based
Natural flow

LEVEL 1
Temperature based

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Play based assessment (1 – LEVEL 2

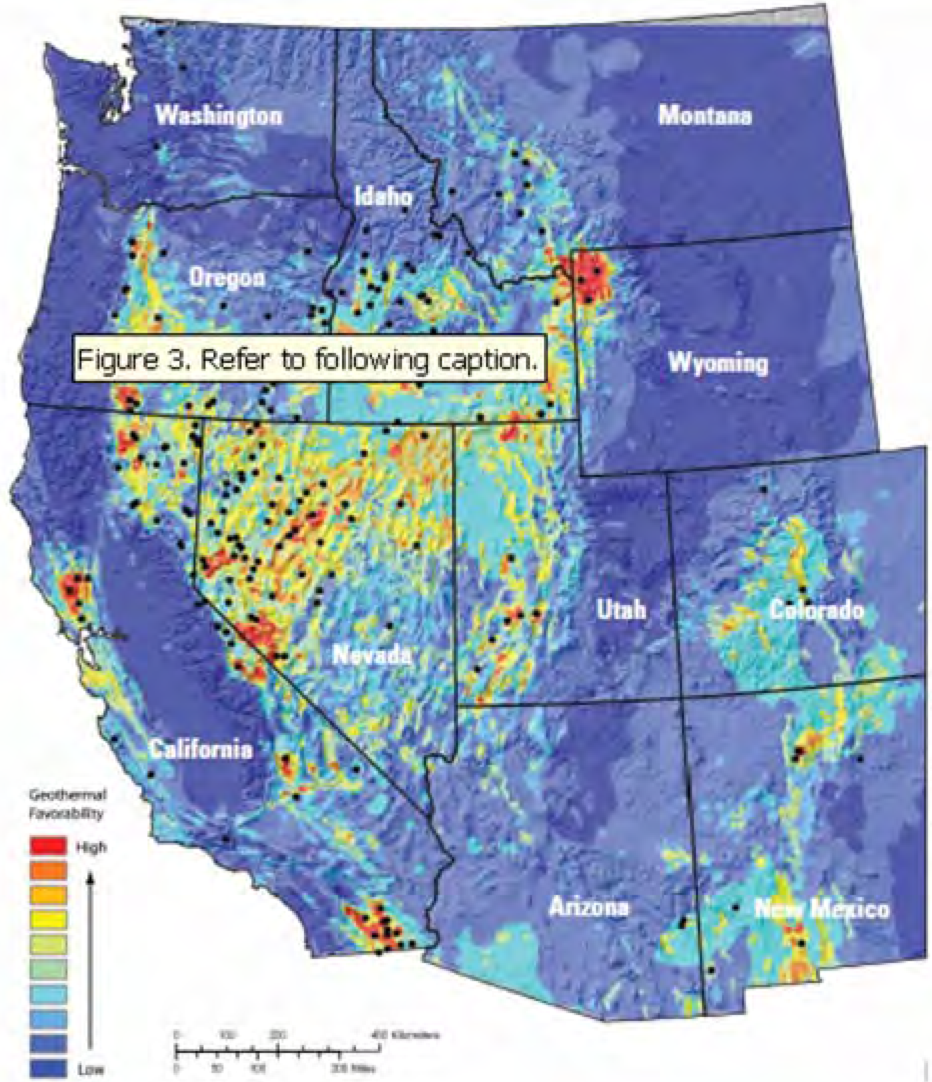


Figure 3. *Example map from one of a series of 28 spatial models showing the relative favorability of occurrence for geothermal resources in the western contiguous United States. The other models differ in details but show generally similar favorability patterns. Warmer colors equate with higher favorability. Identified geothermal systems are represented by black dots.*

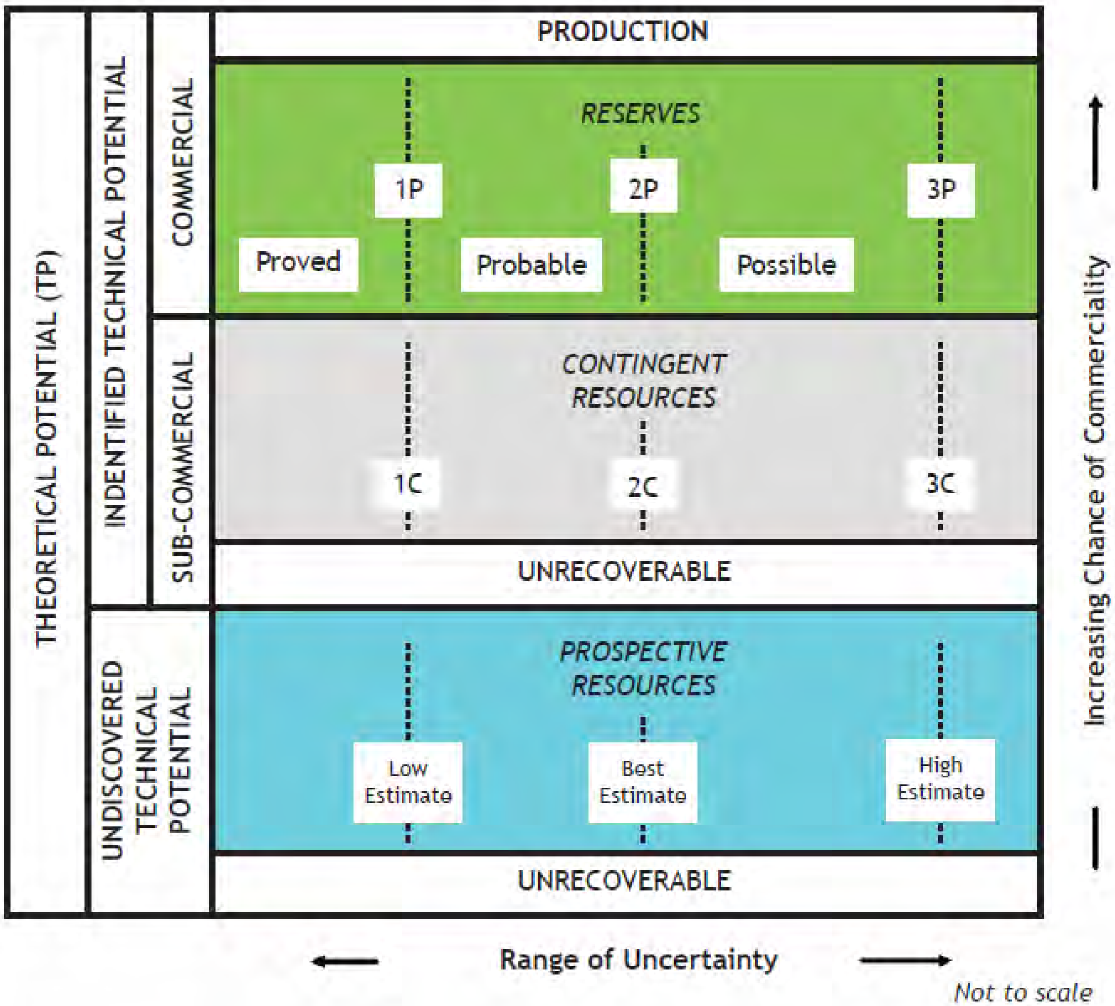
UNCERTAINTY: Resource Categorisation / Certainty of Recovery

- Resource estimates at any sub-class level may be associated with / categorized by the certainty of their recovery
- Major Sources of uncertainty:
  - The temperature and size in the reservoir
  - The ultimate recovery
  - Uncertainty in the commercial conditions that impact the quantities recovered and sold
- Ranges of uncertainty:
  - There should be at least a 90% probability (P90) that the quantities actually recovered will equal or exceed the low estimate.
  - There should be at least a 50% probability (P50) that the quantities actually recovered will equal or exceed the best estimate.
  - There should be at least a 10% probability (P10) that the quantities actually recovered will equal or exceed the high estimate.

Uncertainty in Reserve/Resource Categorisation Terminology (1)

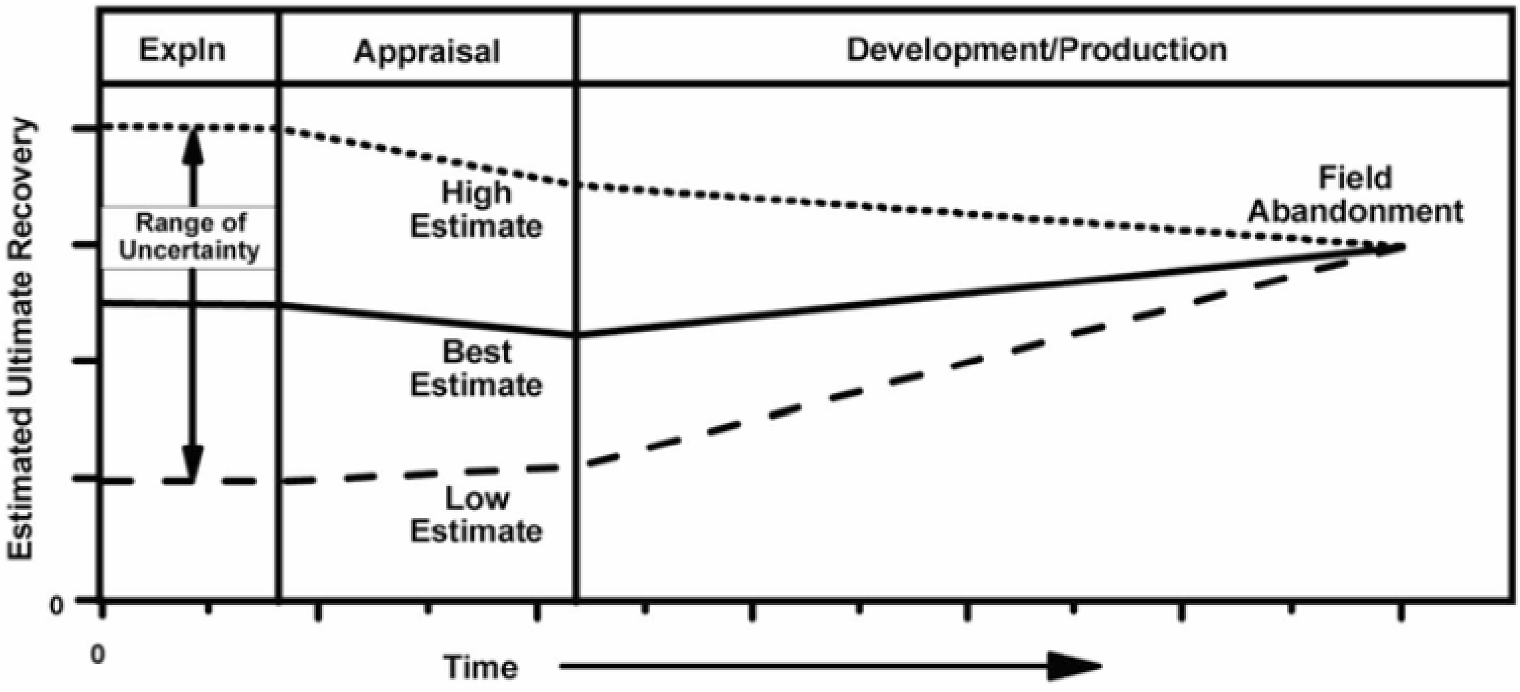
- Incremental terminology for *reserves*:
  - Proved, Probable, Possible
  - PRMS guidance:
    - 1P: proved
    - 2P: proved + probable
    - 3P: proved + probable + possibl
  - Contingent resources:
    - 1C/2C/3C
    - Same criteria as for reserves
    - Commercial specifications are not me
  - Prospective resources:
    - No incremental categories defined
    - Cumulative scenarios: low, best, high

Reserve/Resource Categorisation Terminology (2)

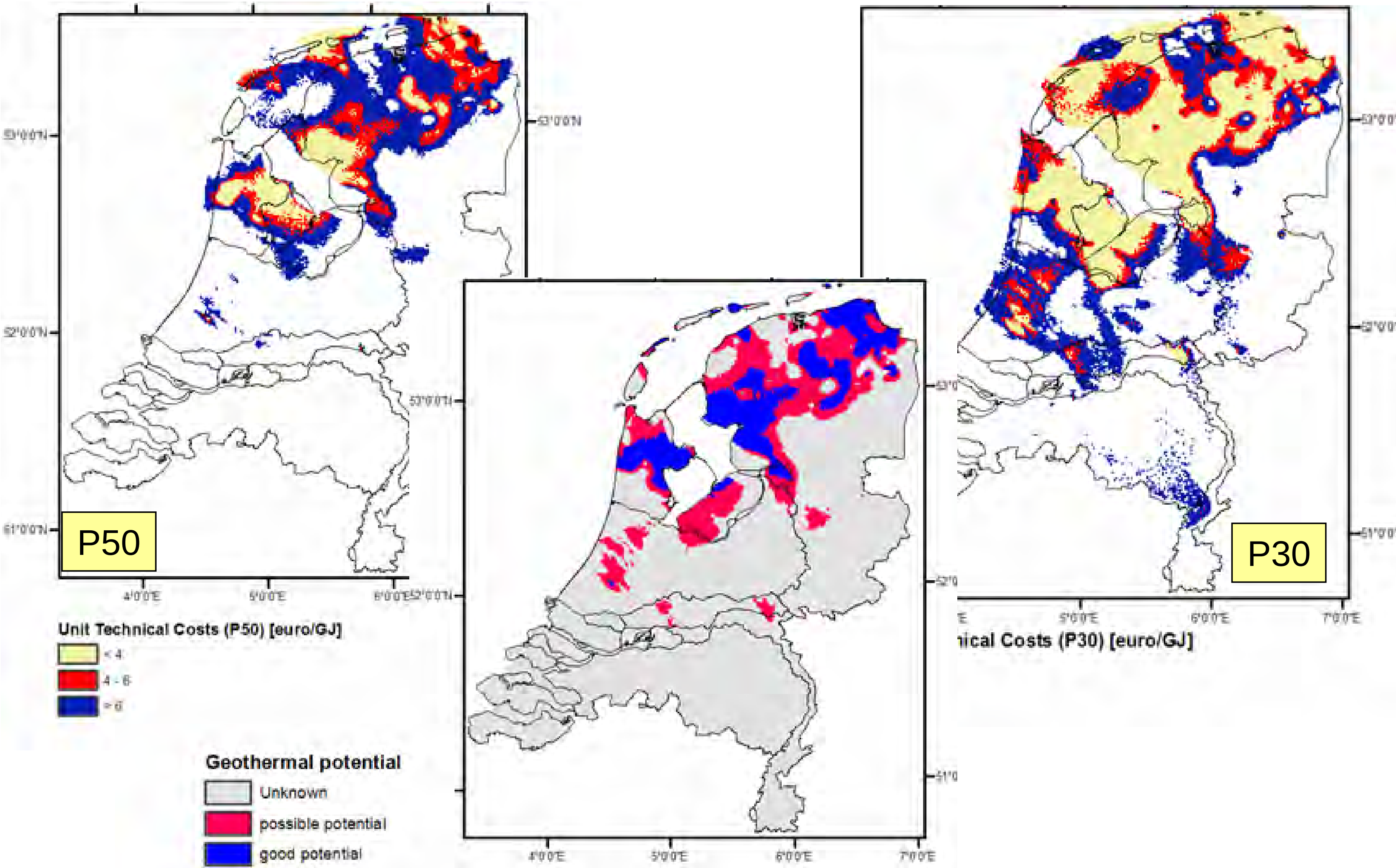


Funneling Uncertainty During Project Lifetime

- Cumulative scenarios
- Declining uncertainties with increasing lifetime



Potential Map for an aquifer in Netherlands



Existing Reporting Code for Geothermal Projects

- **Australian Geothermal Reporting Code (AGEA-AGEC, 2010)**
- **Canadian Geothermal Reporting Code (CANGEA, 2010)**
- Applicable for particular locations
- Not suitable for global assessments
- Aimed at transparency for investors
- Generic worldwide for two geothermal plays:
  - D1: naturally convective systems and hot sedimentary aquifers
  - D2: hot rock, suitable for stimulation
- Reporting is subdivided in stages along the workflow process, being:
  - A: pre drilling exploration technical data
  - B: tenement, environmental and infrastructural data
  - C : subsurface and well discharge data (exploration and production)

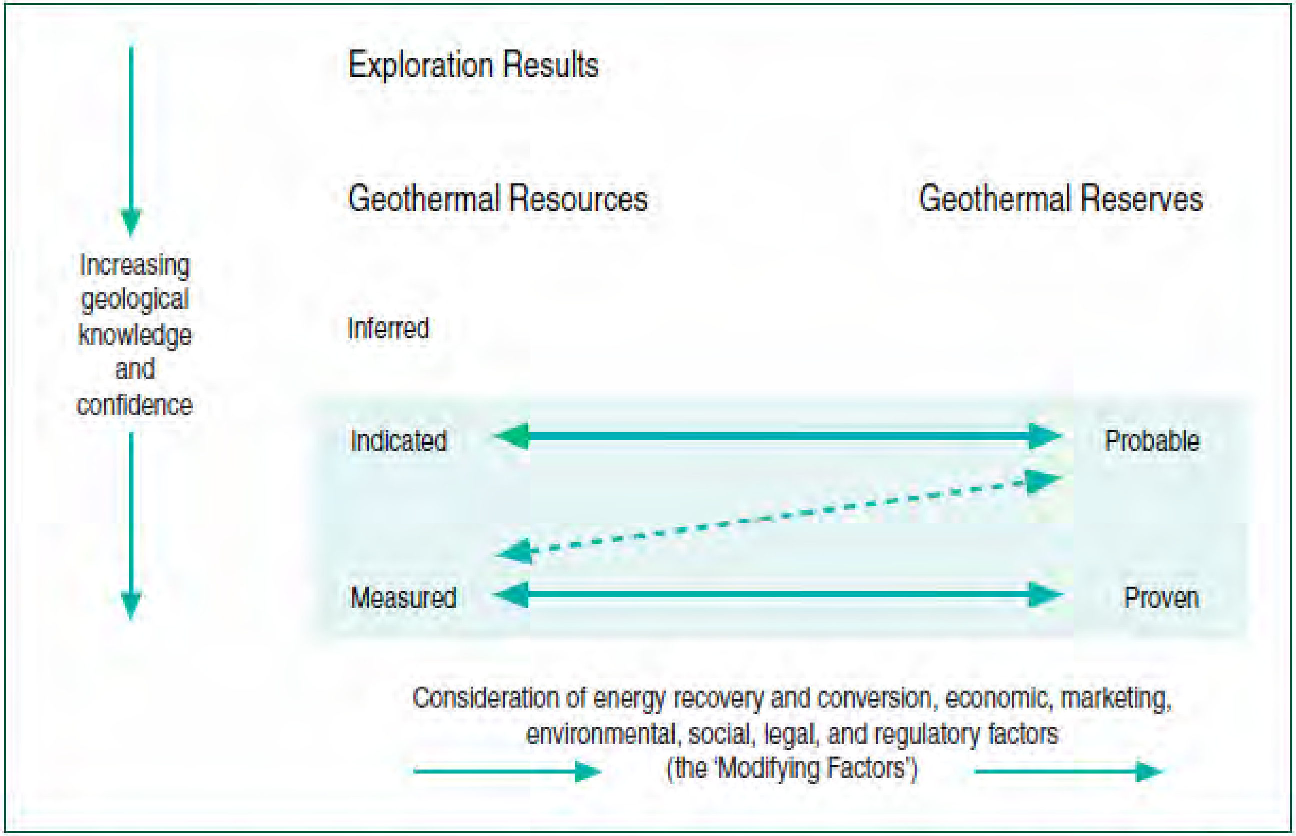


Figure 1. Relationship between Exploration Results, Geothermal Resources and Geothermal Reserves. The Geothermal Code recognises three levels of Geothermal Resource (Inferred, Indicated and Measured) based upon increasing levels of geological knowledge and confidence which directly affect the assessment of the probability of occurrence. Geothermal Reserves are further estimated from Geothermal Resources by consideration and application of "Modifying Factors" which directly affect the likelihood of commercial delivery (e.g. production, economic, marketing, legal, environmental, land access, social and governmental factors). Two categories of Geothermal Reserve are recognised (Probable and Proven) based upon confidence in both the underlying Geothermal Resource estimate and the Modifying Factors. General relationships and pathways between the various Geothermal Resource and Reserve categories that are permitted under the Geothermal Code are as shown.

AGEA-AGEC (2010)

Applicability of the AGEA/CanGEA Codes in GEO-ELEC

- Appropriate for any country in Europe
  - For reporting specific exploration outcomes
  - Results on resources and reserves, if available

- Applicable for the purposes of GEO-ELEC
  - GEO-ELEC targets resources prior to selecting specific project locations

Australian Code: Format Definition

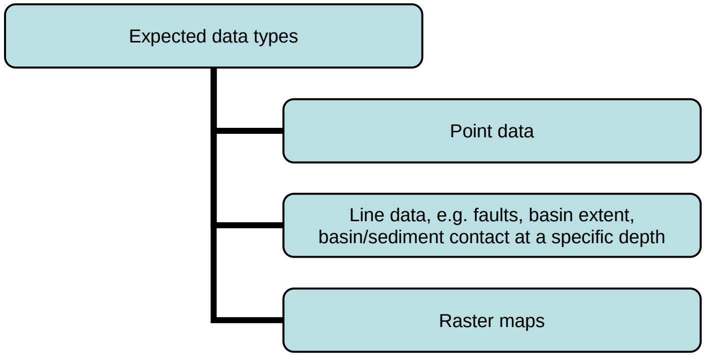
	Exploration Results	Resource			Reserve	
		Inferred	Indicated	Measured	Probable	Proven
Commerciality	No implications regarding commerciality.	Commerciality not yet established. Possibly feasible with current or future technology, prevailing and/or more favourable market conditions.			Commercial. Feasible with existing technology and prevailing market conditions.	
Definition	Data from exploration that is of material value to Geothermal Resource estimation, but which in itself is insufficient to define a Geothermal Resource category.	An area/volume that has enough direct indicators of Geothermal Resource character or dimensions to provide a sound basis for assuming that a body of thermal energy exists, estimating temperature and having some indication of extent.	A more reliably characterised volume of rock than the Inferred Geothermal Resource. Sufficient indicators to characterise temperature and chemistry, although with few direct measures indicating extent.	A drilled and tested volume of rock within which well deliverability has been demonstrated, with sufficient indicators to characterise temperature and chemistry and with sufficient direct measurements to confirm the continuity of the reservoir.	Equivalent to an Indicated Resource for which commercial production for the assumed lifetime of the project can be forecast; or Equivalent to a Measured Resource for which commercial production for the assumed lifetime of the project cannot be forecast with sufficient confidence to be considered a Proven Reserve. The chance of occurrence is 'more likely than not'.	Applies directly to production satisfying all Modifying Factors. Directly related to a Measured Resource for which commercial production for the stated lifetime of the project can be forecast with a high degree of confidence.
Correlation With Probabilistic Estimates					~P50	~P90
Units	As appropriate.	Thermal Energy in Place (PJ) with assumptions stated.	Thermal Energy in Place (PJ) and optionally Recoverable Thermal Energy (PJ), with assumptions stated. May also be reported as assumed electricity generation with assumptions and rate stated (MWe) or GWh in total.	Thermal Energy in Place (PJ) and optionally Recoverable Thermal Energy (PJ), with assumptions stated. May also be reported as assumed electricity generation with assumptions and rate stated (MWe) or GWh in total.	Thermal Energy in Place (PJ) and Recoverable Thermal Energy (PJ), defined in relation to a stated technology and recovery rate. Electricity generation should be presented as net electrical output (MWe) for a defined period or GWh in total.	Thermal Energy in Place (PJ) and Recoverable Thermal Energy (PJ) defined in relation to a stated technology and recovery rate. Electricity generation should be presented as net electrical output (MWe) for a defined period or GWh in total.

AGEA-AGEC (2010)

Proposed Resource Assessment in GEO-ELEC

1. Global European prospective resource assessment for EGS	European wide assessment (cf. Beardsmore et al., 2010). Determine technical potential for different depth ranges for EGS, key input are base maps of temperature, and rock type to identify theoretical potential. Filter maps with information on natural reserve areas etc. Assume relatively low ultimate recovery in agreement with whole depth column (cf. IPCC, 2011). distinguish relative attractiveness, low, mid, high estimates according to drilling depth required to reach temperature
2. Prospective undiscovered resource assessment for differentplay types	Identify delimited areas with a particular play type (e.g. Hot Sedimentary Aquifer (HSA), EGS (previous), magmatic convective). Include data relevant to exploration of particular play types and exploration outcomes (cf. AGEA-AGEC, 2010) for exploration data relevant to resources assessment
3. Contingent (discovered) resources and reserves	From industry and government reporting obtain information on drilled prospects and producing reserves

Regional Workshops



- Goals:
  - Increase the detail of resource assessment of different geothermal plays by the input of the individual parties
  - Building public database systems containing key parameters, such as spatially resolved temperatures, permeabilities, mainly as raster map data
  - Partners: provide supporting knowledge, supporting data, and, if available, models.
    - Supporting knowledge: conceptional geologic knowledge, static geologic models, and other relevant models.
  - TNO: Individual evaluation how models can be build/extended/improved for the purpose of geothermal resource assessment.

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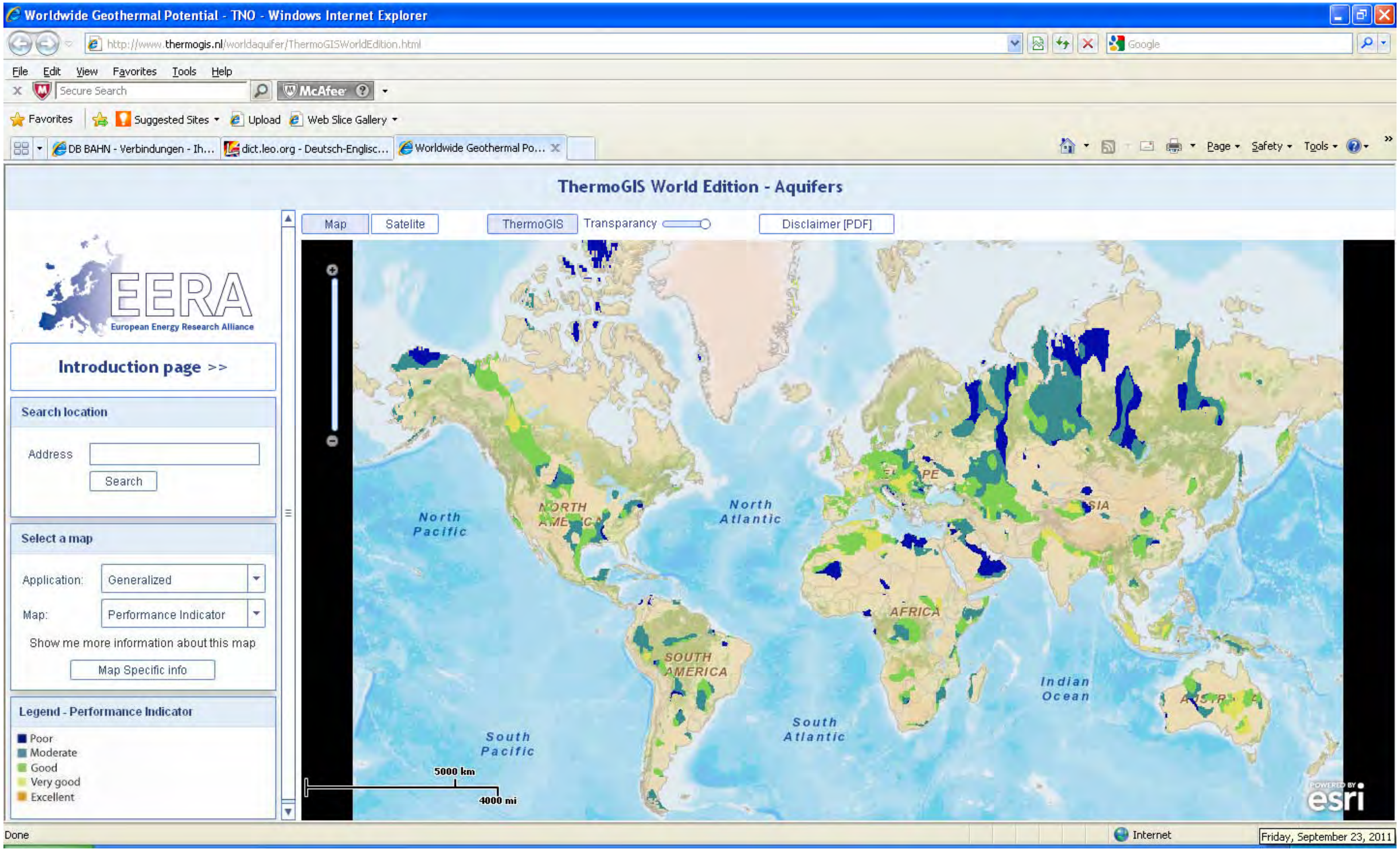
WEB-GIS Application: EERA Thermogis World Edition



Global European Prospective Resource Assessment for Geothermal Power including EGS

- **Level 1** is a **global European assessment** of geothermal electricity potential in Europe at time horizons of 2020 and beyond
- Follows a global assessment strategy at 5‘ x 5‘ nodes
- Does not consider particular play systems
- 1% recovery through conventional power and EGS
- Further assessments (play-oriented):
  - Hot sedimentary aquifers (HSA)
  - EGS partially enhancing natural permeability
  - Volcanic naturally convective
  - Supercritical

Global European Assessment

The calculation routine involves determination of:

- Temperature field, based on:
  - Geothermal atlas (Hurtig et al., 1992) and European heat flow (Cloetingh et al., 2010), International HF commission, extrapolation to greater depth
  - **Country improvements through bore hole temperatures, surface heat flow measurements and thermal properties and country temperature models**
- Geographical recovery
  - **Fixed number, but can be adjusted to Restricted areas for geothermal (high population density, natural reserves, subsurface use for other purposes – oil/gas)**
- Recovery factor
  - **Adjustment of technical recovery for particular depth levels based on level 2 specific play information.**
- Average surface temperature
  - from NASA or more detailed from country information
- **More?**

Hot sedimentary aquifers

This implies: karstified, undeep, and over pressurized aquifer rocks

Criteria:

- Not too deep (< 4 km) ➔ required: depth maps of the basin
- Lithology ➔ sedimentary, permeability through pores and natural fractures (karsts) → permeability data
- Permeability is reduced through mechanical compaction but can be retained through overpressure and natural fractures → pressure info
- Karst Is dependent on geological history

Supply data from partners:

- Raster maps on depth, porosity, permeability, lateral extend of lithologic units which are potentially suitable
- Porosity-_Permeability measurements or concepts for poro-perm relationships_and Porosity/depth relationship
- Overpressure data
- Indication Seismic control and well data density for maps?
- Exploration data on prospective resources

TNO:

- Assistance in evaluation of the natural permeability of aquifers
- Evaluation of the potential suitability of lithologic units

EGS partially enhancing natural permeability -Criteria

Criteria for active faults:

- Faults in questions have been active during since the Tertiary
- Differentiation of tectonic activity in the Tertiary and Quaternary
- Indications for vertical flow conduits, e. g. thermal springs, thermal anomalies

Criteria for low permeability aquifers

- Permeability sufficiently high to enhance with fracturing

General

- Fraccability of rocks

EGS partially enhancing natural permeability - Tasks

Supply data from partners:

- Active faulting regions
- Natural seismicity
- Rock data
- Stress data
- Exploration data on prospective resources

TNO:

- Feasibility evaluation concerning the faults' suitability for EGS operations
- Estimations regarding expectable flow rates
- Evaluation of rock fraccability
- Estimation of EGS potential

Volcanic naturally convective

<u>criteria</u>

- high temperature
- fluid flow convection possible

<u>Supply data from partners:</u>

- volcanic regions
- surface temperature measurements
- thermal springs - geothermometers
- tomography
- base natural seismicity
- zones of active faults relays and vertical fluid flow conduits
- rock types (fractures, extent porous rocks e.g. tuffs)
- geochemistry (not to aggressive, CO2 content etc)

Supercritical

- Example: IDDP, Iceland Deep Drilling project
  - 400 – 600 °C
- General: Derived from magma body proximities at some depth
- criteria and suply data to be expected from partners will be similar to those obtained for „volcanic naturally convective“ system but with a strong emphasize on
  - precisely locating/assessing volumes of partially molten rocks (mush) at depth
  - the physics and thermodynamics associated with magma-water interaction

Contingent (discovered) resources and reserves

- Obtain information on drilled prospects and producing reserves from industry and government reporting

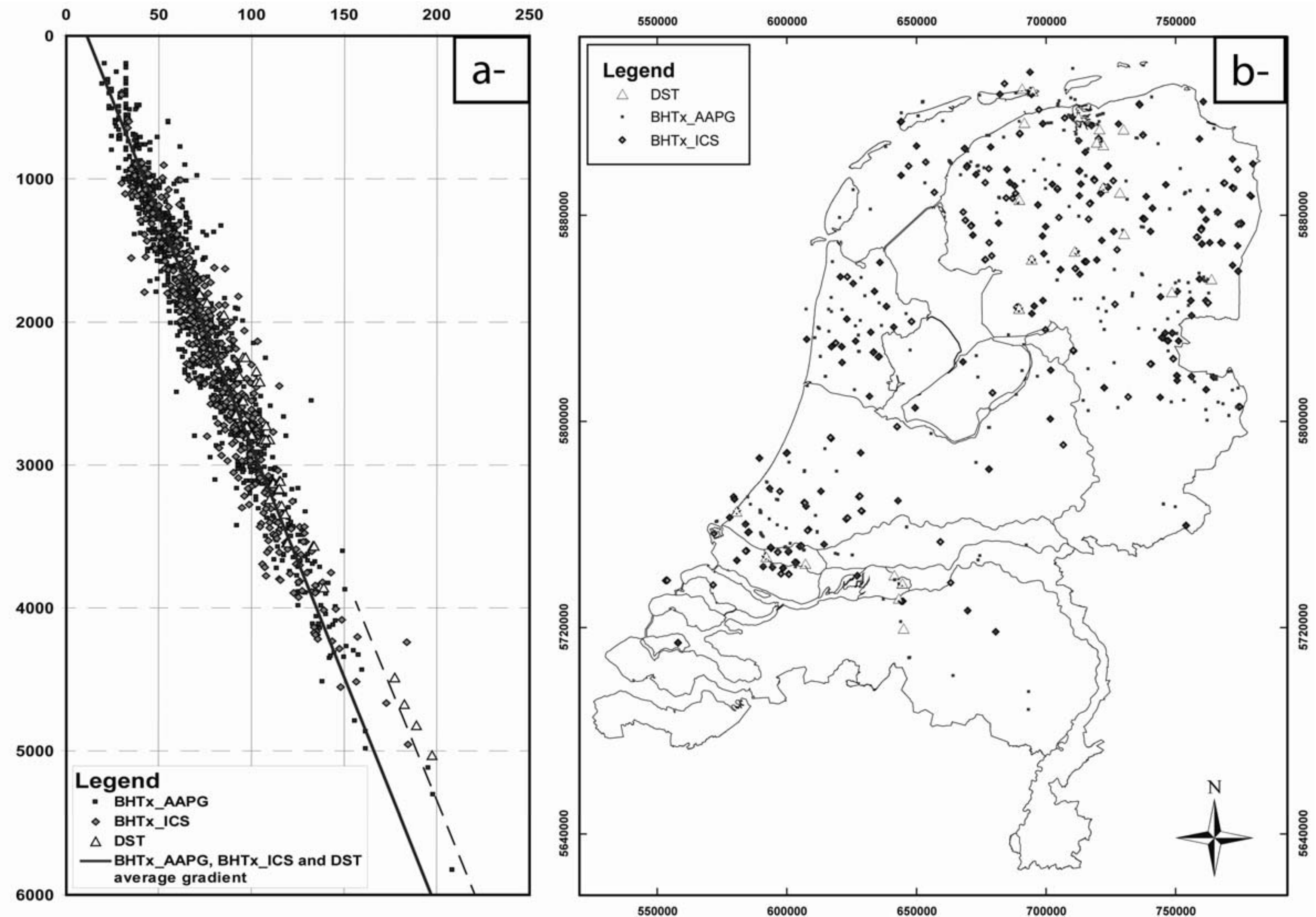
What do we want to deliver in GEOELEC

- WebGIS with resource potential in map view
  - Theoretical and Technical potential per km2, fr different depth intervals or anticipated time window (e.g. 2020, 2050)
  - Underlying reference data (as maps)
    - Temperature
    - UR map based on spatial variability in Play quality(if feasible) → based on maps of active faults, natural seismicity, volcanoes, thermal springs, HSA, sediment-basement interface, reserved areas etc. I
    - Stress regime
- Data tables to be linked possibly through IGA
  - Ongoing exploration and production activuities. Specific Areas, sites, production and reserves statistics

What do we expect from you in this workshop

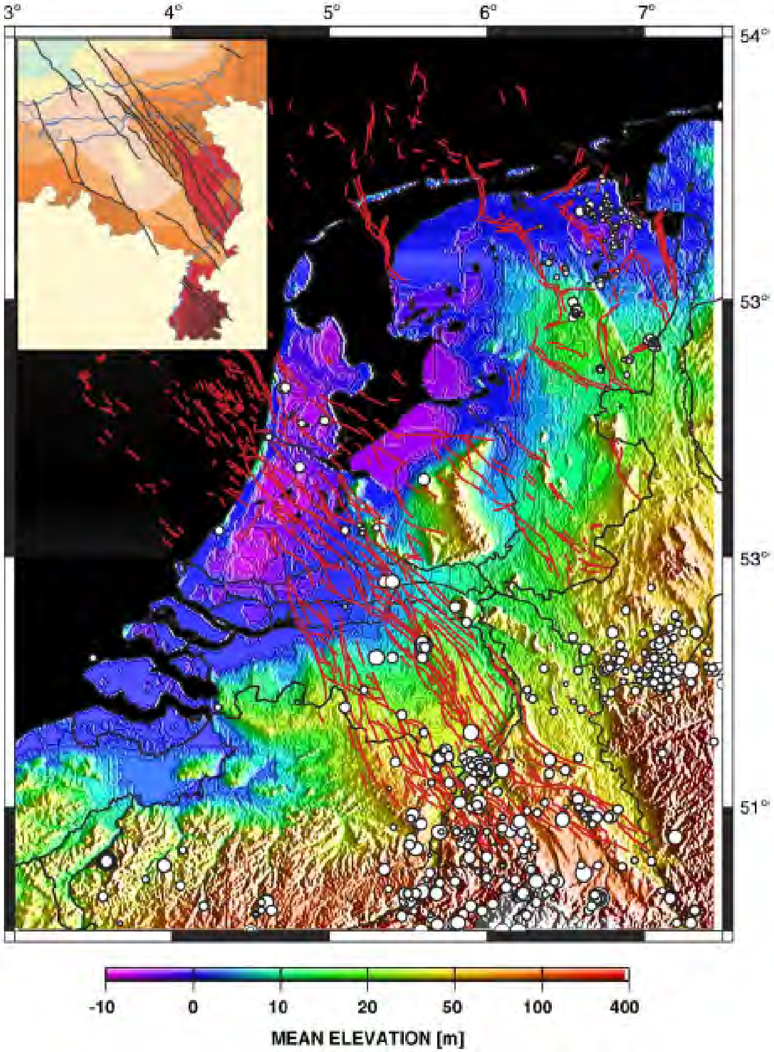
- Access to relevant data global assessment
  - LEVEL 1 EGS → information on **temperature** data. What is publicallt available to compile in terms of heat flow, BHT data. Do you have models of deep sediment and upper crustal temperature. If not can you provide relevant sediment (e.g. thickness) and basement data which can be used to derive a model.
  - LEVEL 2 → different plays: do you have supporting data and models relevant to assessment of specific plays (e.g. HSA, volcanic), increasing local recoverablity of theoretical potential or locally modifing conditions not captured in regionalised models. DO YOU AGREE WITH DISPLAY OF GEOLOGICAL INFORMATION IN ONEGEOLOGY, can you provide us with access to data in right projecten for GEOELEC
- information on Specific plays, prospects, leads to be colleced in a database (what is your country reporting procedure)

Example from the Netherlands: temperature data



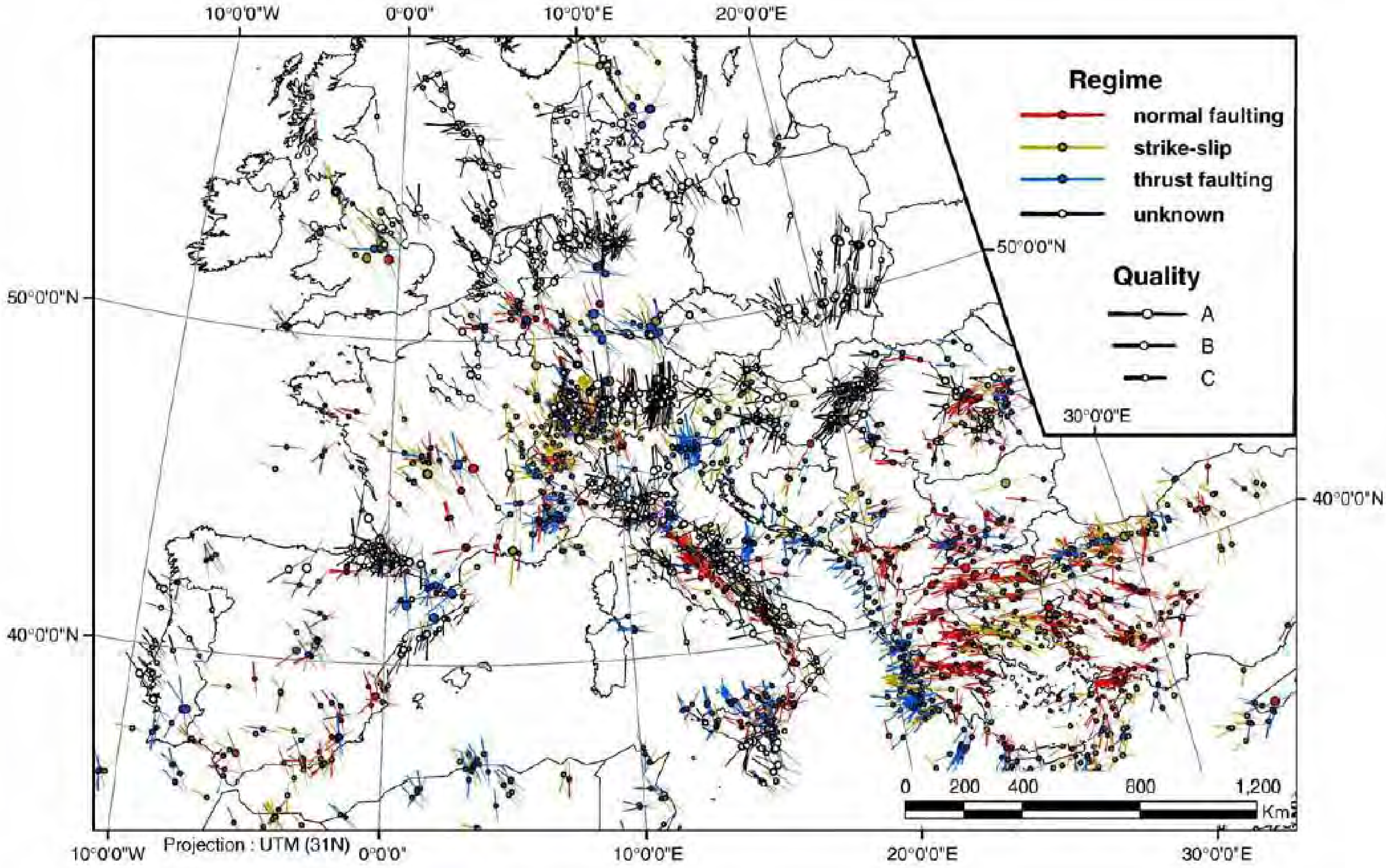
Bonte et al., submitted

Example from the Netherlands: active faults and seismicity



Cloetingh et al., 2010

Reference data on European scale: stress regime



(source Cloetingh et al., 2010)

Reference data to use/include:

- Updated heat flow map
- Geothermal atlas
- Volcanoes
- Sediment-basement map of europe (which is best, can you contribute?)
- Primary probability trends with depth
- Probability for secondary permeability (e.g. Bavaria)
- Active faults overview
- Natural seismicity
- 3D strength/ temperature (through VU Amsterdam)

Thank you for your attention!

Back-up definitions and discussion

Discussion points

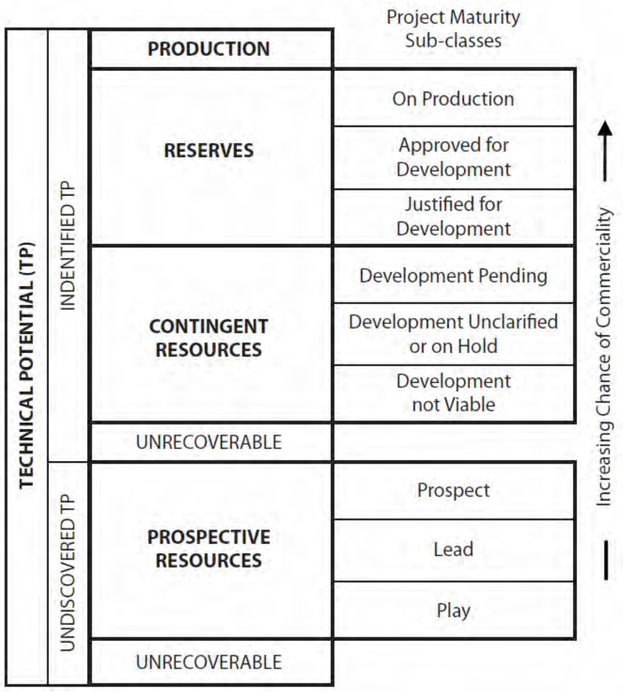
- What is the applicability of the methodology originally defined for petroleum reserves/resources?
- What are the play related temperature delimitations?
- How to go from grid cell to temperature field?
- What is the current state of the temperature database?
- What can be considered as excluded areas
- What which formations/rocktypes do we consider as being suitable for geothermal power generation?
- How can/do we make a distinction between crystalline and sedimentary aquifers

Existing Reporting Code: Hydrocarbon Industry

- HC industry:well matured system
- Etherington & Ritter (2007):
  - Recent and accepted resource management system for O&G
  - Prospective resources:
    - Estimated to be commercially recoverable
    - Yet undiscovered
    - Assuming confirmed discovery
    - Discovery confirmed by one or more exploratory wells
    - Geothermal: confirming a resource by drilling
    - Discovered resources: „Contingent Resources“
      - Fraction may be reserves
    - Commerciality implies high confidentiality, intention for D&P
    - Timeframe for development: individual, benchmark : 5 years

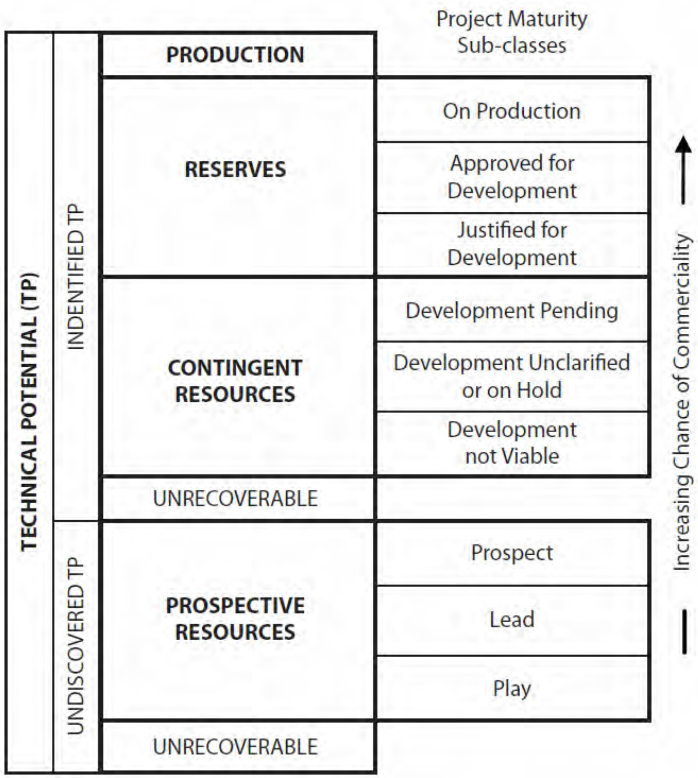
Differences to Geothermal Systems

- Convective hydrothermal systems differ from HC systems:
  - Renewable through recharge
  - recharge slower than extraction
  - Recharge rate dependent on the system
  - Influenced/stimulated by production
- Different resource classification workflow:
  - Target utilization: Minimum T
  - Stimulated, "man made" reservoirs:
    - External, non-natural factors



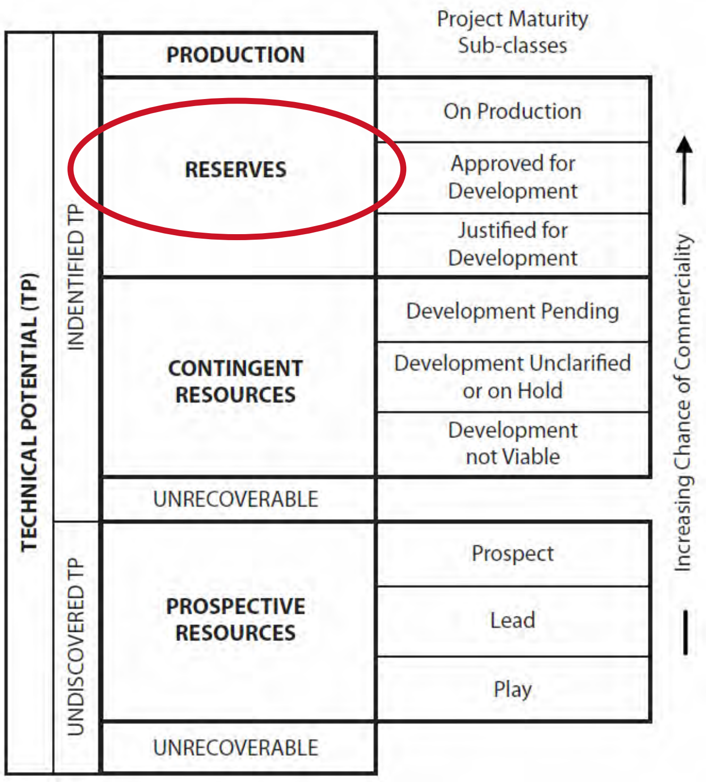
Project Status

- More detailed resource reporting: subdivide according to project maturity
- Characterization by
  - standardized sub-classes
  - Chance of reaching production status
- Project maturity reflects business decisions required to move toward production status



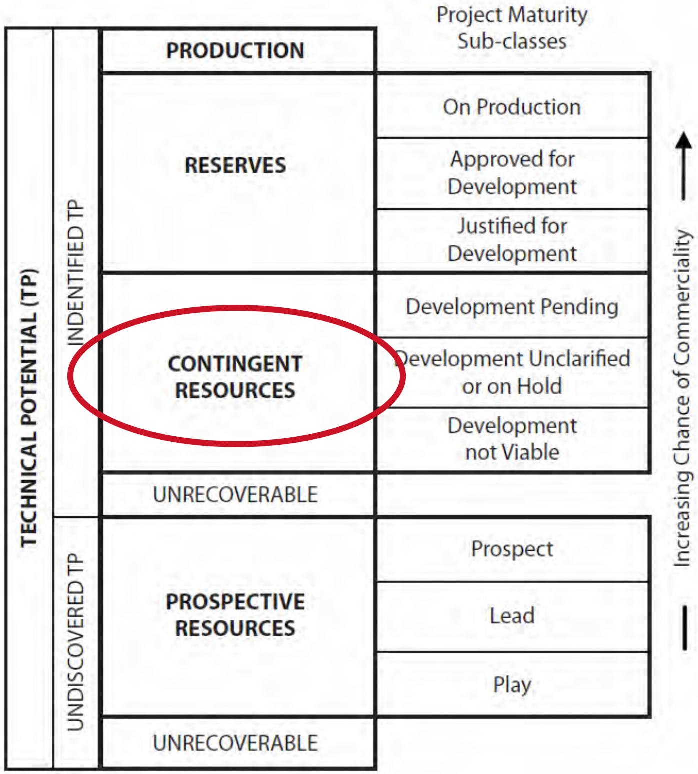
Reserve status

- Reserve status: once projects satisfy commercial risk criteria
  - Modifiers defined by SPE:
    - Developed producing, developed non-producing, undeveloped
- Reserve quantities may be subdivided into several reserve categories allocated to specific confidentialities, *independent of project maturity*
- Economic status
  - All projects classified as reserves must be economic under defined conditions



Contingent Resources Status

- Marginal Contingent Resources are associated with *technically feasible* projects that are *currently economic, or projected to be economic* with reasonably forecast improvements in conditions, but are currently not committed for development
- Sub-Marginal Contingent Resources are those discoveries for which there is *insufficient information* to clearly *define a recovery plan*, or analysis indicates that portions of the discovery, although technically feasible to recover, could *not be economically developed* under reasonably forecast improvements in conditions



Undetermined/Unrecoverable Project Status

- “Undetermined”
  - Incomplete resource evaluations
  - Premature for defining chance of commerciality

- “Unrecoverable”
  - In-place-volumes for which no feasible development projects are defined