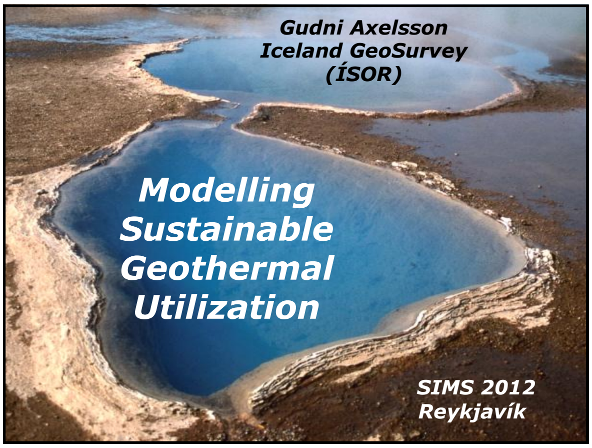


Contents

- Sustainable development
- Can geothermal contribute to sustainable development?
- The time scale
- Long case histories
- **Sustainability modelling**
- Modelling issues

Sustainable Development

Brundtland report (1987):

Development that meets the needs of the present without compromising the ability of future generations to meet their needs

- Very general definition which has been applied to all aspects of human existence and development
- Has become quite fashionable and is sometimes abused
- Twofold definition:
  (1) Utilization of the Earth's resources must be restrained
  (2) The Earth's environment needs to be protected

Sustainable Development

- Energy needs and development at the core of the issue
- ***Geothermal energy*** can play a role
- Increasing attention the last decade
- Definitions + policies missing
- Term also misused by geothermal industry
- Work ongoing in geothermal sector last 10–15 years (see references in paper)

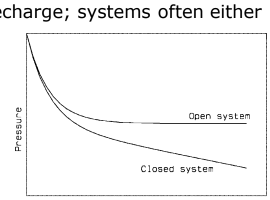
Renewability vs. Sustainability

- A clear distinction necessary, some confusion in literature/discussions
- The term **renewable** refers to the nature of a resource
- The term **sustainable** refers to how a resource is utilized

Resource Capacity

Long-term response and hence production capacity mainly controlled by:

- Size and energy content of system
- Permeability structure
- Boundary conditions (BC), i.e. significance of natural and production induced recharge; systems often either **open or closed**
- Reinjection management



Geothermal Sustainability

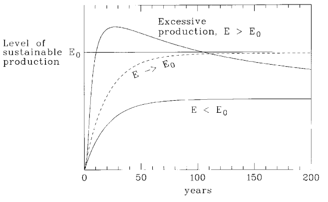
Two main issues:

- Can geothermal resources be utilized in a sustain-able manner? Confirmed by long utilization histories and modelling studies (see later)
- What timescale should be used when assessing sustainability? Geological time-scale much too long compared with time-scale of human endeavors

Sustainable Geothermal Production

Definition by Icelandic expert-group (2001):

*For each geothermal system, and for each mode of production, there exists a certain level of maximum energy production, **E_0**, below which it will be possible to maintain constant energy production from the system for a very long time (100-300 years). If the production rate is greater than **E_0** it can not be maintained for this length of time. Geothermal energy production below, or equal to **E_0**, is termed **sustainable production** while production greater than **E_0** is termed **excessive production.***



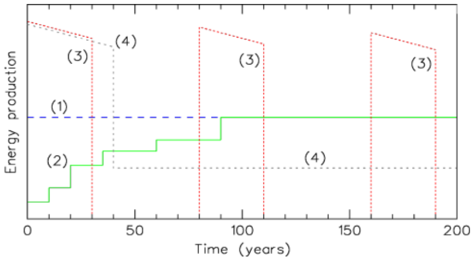
The Timescale

- The timescale of the definition (100-300 years) is much longer than conventional pay-back periods for power plants (30-50 years)
- Shorter than historical timescales (a few thousand years) or a geologically relevant timescale, i.e. the time since the end last ice-age (10.000 years)
- **Therefore, the sustainable potential is greater than the natural recharge of a system**

Sustainable Geothermal Production

Difficult to establish sustainable production level E_0

- Poorly known during initial step of utilization
- Can be expected to increase with increased knowledge, i.e. through exploration, drilling and monitoring
- Also through technological advances, e.g. in exploration methods, drilling technology (deeper drilling) and utilization efficiency (reinjection, generation methods, etc.)



A schematic diagram showing how geothermal resources can be utilized in a sustainable manner through different modes: (1) production at sustainable limit, (2) step-wise increase, (3) cyclic production and (4) reduced production following excessive period

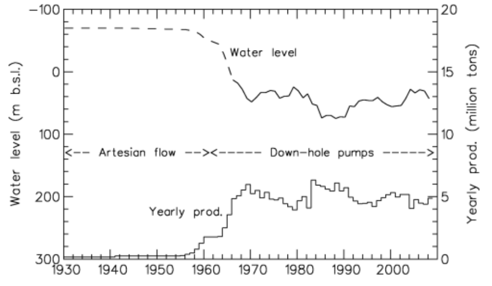
Long Case Histories

- E_0 controlled by energy content and pressure decline (if recharge is limited)
- Long (>30 years) utilization histories show that many geothermal systems can be utilized for several decades at semi-equilibrium because pressure decline causes fluid/energy recharge equilibrating with mass extraction
- In other cases reservoir changes are very slow
- When reinjection is applied thermal decline can be managed for decades
- Modelling studies have “extended” periods to 1 or 2 centuries

Long Case History Examples

1) Ahuachapan, El Salvador, since 1976
2) Cerro Prieto, Mexico, since 1973
3) Geysers, California, USA, since the 1960's
4) Larderello, Italy, since the 1950's
5) Paris Basin, France, since 1969
6) Hungarian Basin, Hungary, since the 1930's
7) Laugarnes, Iceland, since 1930
8) Hamar, Iceland, since 1969
9) Krafla, Iceland, since 1976
10) Svartsengi, Iceland, since 1976
11) Olkaria, Kenya, since 1981
12) Beijing Urban Area, China, since the late 1970's
13) Matsukawa, Japan, since 1966
14) Palinpinion, Philippines, since 1983
15) Tiwi, Philippines, since 1979
16) Wairakei, New Zealand, since 1958

Laugarnes, Iceland
Example of Semi-equilibrium

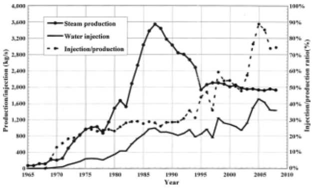


Paris Basin

- Hosts a vast limestone geothermal resource
- Mainly used for space heating through production/ reinjection doublets with 100% reinjection
- Utilisation started in 1969, later more than 50 plants constructed. Today doublets are being revitalized and new ones drilled
- Production and reinjection wells separated by 1000 m to minimize cooling danger
- No significant cooling yet (after 3-4 decades)
- The extensive experience gained provides an invaluable basis for sustainable management of sedimentary resources (**see presentation by Simon Lopez**)

Long Case History Examples

- Note that **not all** the examples are examples of sustainable production
- Yet all provide invaluable information for understanding sustainable geothermal resource management
- Geysers example of excessive (non-sustainable) production



How to estimate E_0?

- For "known systems": Based on predictions of pressure- and energy changes calculated by dynamic models. Changes must be within acceptable limits
- For "new systems": Based on results of volumetric assessments [based on geology, geophysics, geochemistry, etc.]
- Estimate should be updated every few years

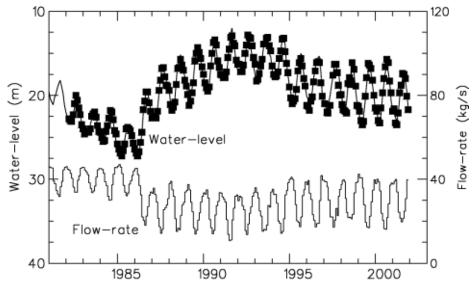
Dynamic Sustainability Modelling

- Modelling is the most powerful tool for assessing the sustainable potential
- Possible to use detailed numerical models (TOUGH2), which can be quite accurate
- Simple models, such as lumped parameter models, can also be quite powerful
- The basis of all reliable modelling studies are comprehensive and accurate data on geological structure, physical state and last but not least production response [monitoring data]
- Response data most important, must last ~decade or more if assessment is to be reliable

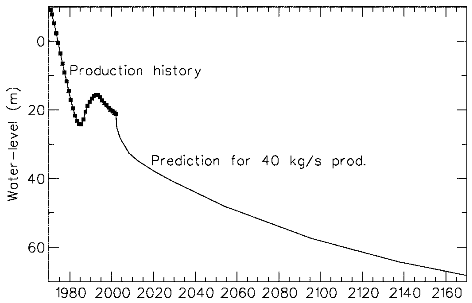
Modelling Examples

1) Dalvík, N-Iceland, low-temperature
2) Beijing Urban Area, China, low-temperature
3) Ahuachapan, El Salvador, high-temperature
4) Hengill, SW-Iceland, high-temperature
5) Wairakei, New Zealand, high-temperature
6) Olkaria, Kenya, high-temperature

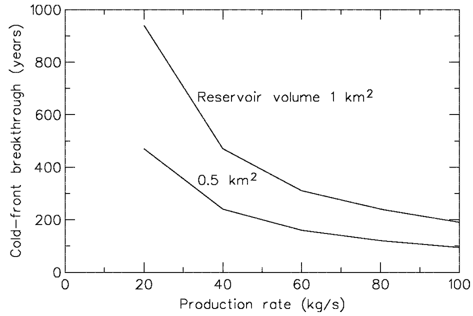
Dalvík – reservoir pressure history simulated by a lumped parameter model



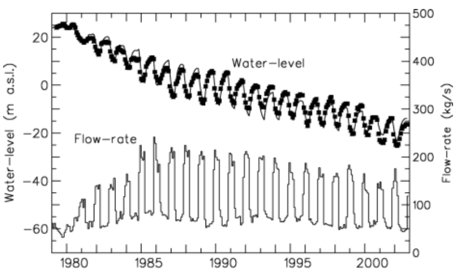
Dalvík – reservoir pressure evolution predicted by a lumped parameter model



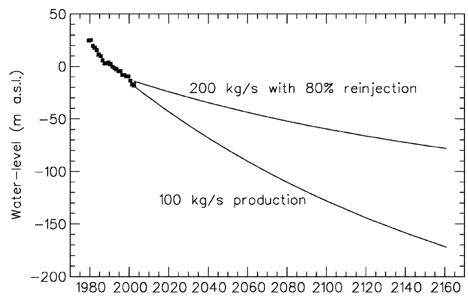
Dalvík – reservoir cooling predicted by a simple model of a hot cylindrical reservoir



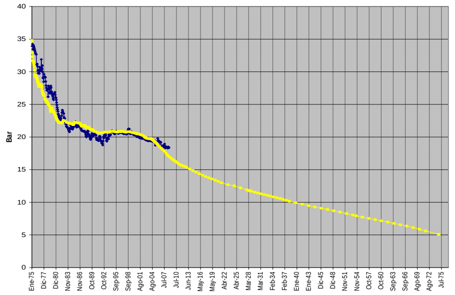
Beijing Urban – reservoir pressure history simulated by a lumped parameter model



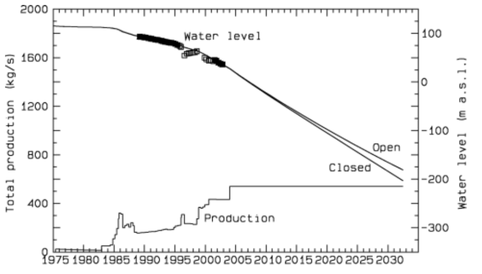
Beijing Urban – reservoir pressure evolution predicted by a lumped parameter model



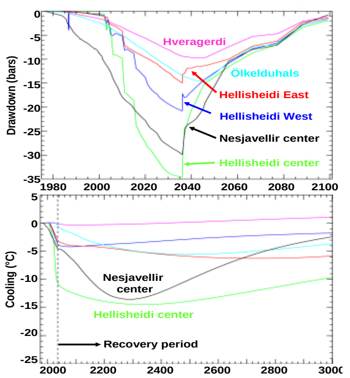
Ahuachapan – reservoir pressure evolution predicted by a detailed numerical model



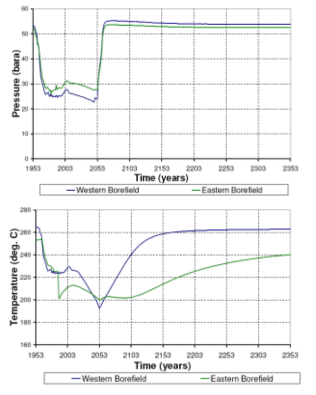
Nesjavellir – reservoir pressure evolution predicted by a lumped parameter model



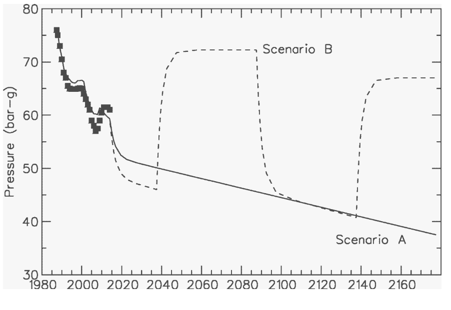
Hengill: long-term reservoir pressure and temperature evolution predicted by a detailed numerical model (production stopped after ~40 yrs.)



Wairakei: long-term reservoir pressure and temperature evolution predicted by a detailed numerical model (production stopped after 100 yrs.)



Olkaria – reservoir pressure evolution predicted by a lumped parameter model



Sustainability Modelling Issues

- Boundary conditions not well known
- Nature of bottom boundary, does hot natural recharge e.g. increase during production?
- Significance of production induced cold recharge
- Long-term (~100 yrs) effect of reinjection, difficult to model in detail with full-scale models
- Coupling reservoir and well-bore models
- More data needed to calibrate models in addition to reservoir data, e.g. geophysical data (resistivity, seismicity, gravity changes, etc.)
- Estimating uncertainty in predictions


Thank you!