

#### **Geothermal Energy**

Jordens varme

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# GEOTHERMAL ENERGY JORDENS VARME

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### **Plan of the presentation**

Theoretical overview

- Planet Earth
- The origin of geothermal energy
- How hot is the Earth

Brief History of the use of geothermal energy

The basic principles behind the geothermal utilization

- Direct and indirect use
- Geothermal energy systems:
  - Heat storage systems
  - Producing electricity systems

Geothermal usage in the world, Europe, Iceland, Denmark

## **The Planet Earth**

The 3<sup>rd</sup> rock from the Sun -<sup>(2)</sup> Created appr. 4.5 milliard years ago

https://pixfeeds.com/images/astronomy/solar-system/1280-1200-520442503solar-system-planets.jpg

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### Layered structure Core: mostly iron (with a bit of nickel) Neptune https://phys.org/news/2016-09-temperature-earth-crust.html Mantle - plastic : Uranus **Crust** -solid: 100-2900 km Saturr 0-100 km Outer core - liquid iron: 2900-5100 km Jupiter Inner core - solid iron: /enus 5100-6380 km, Earth Inge Lehmann Mercuri

Crust and mantle: silicates

### The Planet Earth: layered structure



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### Ever changing and evolving

All the parts are in constant motion:

- Rotation around the Sun
- Convection (Mantle, Core)
- Tidal waves
- Plate tectonics (Crust, Mantle)



### Sources / Origin of Geothermal Energy Internal: Physical and Chemical Processes



Formation of the planet

Gravitation and Rotation  $\rightarrow$  friction

Radioactive - decay of isotopes

Chemical& physical reactions due to high pressure and high temperature: mineral transitions  $\rightarrow$  release heat

Latent crystallization: outer/inner core -> transition liquid to solid – releases heat

### **External: the Sun**









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DTU GEOTER	MI = JORDENS VARME	Celsius	Kelvin		
<b>BASIC TERMS - BEGREB</b>	ER	° C	к		
Temperature:		100	373.15		
Daily life: Celsius (SI): 0 °C – freezing	water, 100 °C – boiling water				
Fahrenheit: 0 °F (original) – 1	freezing of brine (equal parts water, salt, ice)				
• Science (Physics, Chemistry, Engineering, etc.): Kelvin – the absolute temperature (absolute 0) 0.01					
0 ºK = -273.15 ºC =- 459.67 ºF − t	he lowest possible temperature in our universe	0.00	273.15		
Outer space/ interplanetary tempera	ture – appr. 2.7 °K				
Enthalpy, Entropy: refer to the energy contained/stored in a system					
The absolute zero (0 °K) – temperature at whi	ch the enthalpy / entropy of an ideal gas are at mini	<b>mum</b> -273.15	0		
Geothermal potential – the possible energy (in Watt or Joule) that can be extracted from geothermal sources					
Sometimes, geothermal	potential is expressed in <u>enthalpy</u>				
Thermal conductivity – the ability to conduct heat (similar to electrical conductivity)					
Geothermal gradient – change of temperature in depth					



### How hot is the Earth?

Temperatures in the Earth's interior are not measured directly

 Lab experiments on melting of basalt, iron under extreme pressures (100-200 GPa), 1 Gpa =10000 atm.

Temperature in the mantle – more or less "fixed" ~2-400 °C to ~4000 °C

The temperature in, especially the inner core – still debated

Large uncertainty in the experimental set ups to detect material conditions at the centre of the Earth

Experiments in early 1990's (1993, Nature)

1993: ~ 5000 °C @ Pressure ~ 200 GPa

Experiments at the European Synchrotron (ESRF), published in Science:

- 2013: > 6000 °C @ Pressure ~ 200 GPa
- 2015: ~ 3090 °K @ Pressure = 103 GPa

#### **Temperature scala:**

- Celsius (°C), Fahrenheit (°F) daily life
- Kelvin (°K) planetary sciences
- 0 °C = + 273.15 °K; 0 °K = 273.15 °C





### How hot is the Earth?

Average surface ground temperature (global): ~ 15 °C (2017 data, <u>www.space.com</u>)

### **Direct Temperature measurements in the crust**

- North Sea (wells): ~ 150-160 °C at 5 km
- Amager (wells): ~ 73 °C at 2.5 km
- S. Africa (gold mine): ~ 55 °C at 3.9 km
- Volcanos (lava): ~ 700-1200 °C

Temperature at the Crust/Mantle boundary: From 2-400 to ~8-900 °C



planet outwards →"Thermal conductivity"

### **GEOTHERMAL ENERGY USAGE: 2 basic parametrs**

Thermal conductivity: The ability to conduct/transfer heat (e.g. from the Earth's core to surface)

Geothermal gradient: By how much the temperature changes per unit of depth, fx 1 m , or 1 km



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### **GEOTHERMAL ENERGY USAGE: 2 basic parametrs**

The geothermal gradient is different in the different parts of the planet:

• largest in the crust (the part we use)





In the crust, the geothermal gradient (°C/km) depends by how far way is the heat source and by the thermal conductivity of the rocks/soils

	Region	Geothermal Gradient (°C/km)
"Normal"	North Europe / DK	25.0-30.0
Hot Spot, Volcano	Iceland, Hawaii	≥ 100.0
Active tectonics	California	> 50.0
Old crust	Fennoscandia	≤ 20.0
Young crust	Mediterranean	≥ 40.0
Average	World	33.0
-		

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### **HOW TO USE GEOTHERMAL ENERGY**

### **DIRECT USE: HEATING**



https://www.energy.gov/eere/articles/heat-beneathground-working-advance-deep-direct-use-geothermal

### **INDIRECT: TURN IT INTO POWER**

Very simple principle: heat is used to turn a turbine of a generator



to produce electricity or movement or other kinds of mechanical energy

Even offshore oil fields can be transformed to geothermal: DUNQUIN (Offshore Ireland)



https://www.independent.ie/business/irish/oil-explorer-couldstrike-it-rich-after-finding-hot-water-in-sea-37628149.html



### **DIRECT USE OF GEOTHERMAL ENERGY**

### **DIRECT USE: HEATING/COOLING – ATES (Aquifer Thermal Energy System)**

In addition to the "classic" hot water/steam usage:

#### ATES: Aquifer Thermal Energy Storage

- uses the low thermal conductivity of the rocks to store heat
- uses temperature differences
- works with low temperatures (20-50 °C)

During summer – excess of heat/warm water (solar, wind, but also IT datacentres, servers etc.) → pump it and store it underground

During winter – need for heat/warm water → pump the water from the underground

**Needs a reservoir** – porous rock (aquifer) where to put the water with low thermal conductivity to keep the warmth

**Example - Stenlille** 



#### NB. Similar mechanism can be used for underground CO<sub>2</sub> storage

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#### **GEOTHERMAL HEATING POTENTIAL IN EUROPE**

 This maps shows where in Europe the geological conditions (aquifer / porous rocks with suitable thickness and thermal conductivity) are favourable for producing geothermal heat.

Stratego

### NB. The map does not show the temperature of the rocks or the geothermal gradient.



Pan-European Thermal Atlas/ Heat Roadmap Europe 20150 (source: heatroadmap.eu)

### HEAT FLOW IN THE WORLD

The hottest areas are the plate boundary regions





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### **GEOTHERMAL ENERGY SOURCES**

- Underground steam (temperature ≥ 100 °C) → the first industrial usage (Italy)
   Where: Italy, Japan, USA, Iceland, S. Europe, etc.
- High-temperature (≥ 60 °C) hydrothermal shallow sources (≤ 1 km depth)
   Where: volcanic regions: Iceland, Italy, USA, Turkey, Japan, etc.
- Low-temperature (20 60 °C) aquifer (porous rock layers)–,
- Where: Many places, Denmark, Germany, Poland, S. Europe, etc.
- Hot rocks layers everywhere in the world
  - ≥ 100 °C at appr. 3 km depth (deep) North Sea (150°C at 5 km)
    ≥ 200 °C at appr. 5-6 km depth (ultra deep) Finland (6km well, 2018)
- Magma volcano and/or hot spot regions, plate boundaries Where: Iceland, Italy, Hawaii, Japan, USA, etc.





## GEOTHERMAL ENERGY/ GEOTERMI = JORDENS VARME

#### **USAGE / HVORDAN MAN BRUGE GEOTERMISK ENEGRI**

- Well being: Thermal baths & spa ("Salute Per Acqua" "Helbred fra Vand") : used since the Paleolithic, oldest China, 3<sup>rd</sup> century B.C.
- Heating –public buildings (antiquity), district heating / fjernvarme
- Pavement /Road de-icing (Iceland);
- Agriculture greenhouses;
- Chemical (boric acid, Italy); aluminium (Iceland) or other substances production;
- Electricity/power production Italy , Iceland, USA, Turkey, etc.;
- Cooling, etc.

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### **INDUSTRIAL USAGE OF GEOTHERMAL ENERGY**

#### TOSCANA, ITALY – First in the world and the only one until 1958

- 1827 Francesco de Larderel (France, Italy): invented the "Lagone coperto" capturing the geothermal vapour from natural vents.
  - First Geothermal plant at Larderello (close to Pisa) to produce boric acid



https://it.wikipedia.org/wiki/Soffione\_boracifero#/media/File:Lagoni\_1868.jpg Capture of the vapour Pipeline Pipeline Evaporation tanks Final product (boric acid)

- Steam temperature: 202 °C NB. Not a volcano!
  - 1904 Electricity production (5 light bulbs), Prince Piero Ginori Conti (Firenze, Italy; married to the granddaughter of de Larderel): building upon the invention of de Lardarel
  - **1911** First geothermal power plant
  - 1916 produced 2750 kW
  - Today: Italy is still among the top 10 producers of geothermal electricity in the world



### **GEOTHERMAL ELECTRICITY PRODUCTION**

- 1911 First geothermal power plant uses steam to rotate a turbine  $\rightarrow$  generates electricity
- 1958 New Zealand the Waikarei station → the first flash steam technology (details follow). Problems with subsidence
- 1960 USA The Geysers in California
- 1967 USSR: developed the binary cycle power plant more details later
- 1970's (Oil crisis) geothermal power production accelerates
- 1977 USA R&D 1st demo project on Deep Geothermal Systems (details later)
- 1981 USA introduces the binary cycle power technology
- 2006 Alaska producing electricity form only 56 °C hot water
- 2007 Australia a large research funding to Enhanced/Engineered Geothermal Systems EGS a game changer

#### EGS projects worldwide

- Landau-Pfalz (Germany)
- Soultz-sous-Forets (France) produces 1.5MW
- Basel, Switzerland terminated (suspected possible induced earthquake)
- Australia, USA, UK, Finland, Sweden, etc.

**Still to improve:** Efficiency - low 10-13% (compare to wind, solar)  $\rightarrow$  constantly improving

Best in class: Capacity factor (For a given time period: Produced electricity/Maximum possible electricity production) very large 74.5% (2008), demonstrated that can be up to 96%

### 

### **GLOBAL GEOTHERMAL ELECTRICITY PRODUCTION**

International Energy Agency (IEA) https://www.iea.org/topics/renewables/geothermal/



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### **INSTALLED GEOTHERMAL ELECTRICAL CAPACITY**

### TOP 10 GEOTERMAL COUNTRIES IN THE WORLD - 2018, Global Capacity (2018): 14,369 MW

#### http://www.thinkgeoenergy.com/global-geothermal-capacity-reaches-14369-mw-top-10-geothermal-countries-oct-2018/



Source: TGE Research (2018), GEA (2016), IGA (2015), JESDER (2018)



### **GEOTHERMAL POWER STATIONS FOR ELECTRICITY**

### Dry steam power station

#### Dry steam power stations:

- The oldest (Italy), simplest and most efficient
- Uses directly geothermal energy

### **Produces only steam**

#### Needed:

 Steam ≥ 150 °C, which requires a source of very hot water underground (> 200 °C)

### Used in very limited places:

Italy, Iceland, Japan, USA

Reservoir depletion (The Geysers, CA) Not suitable for the most of the world



### How it works:

- Well or pipes bring the steam to the turbine
- The steam turns the turbine and generates electricity
- The steam is conducted to the condenser where it cools and go back to water
- From the condenser the water can be released into a water stream/lake/pool (the Blue Laguna in lceland) or re-injected into the subsurface by another well



### **GEOTHERMAL POWER STATIONS FOR ELECTRICITY**

#### Flash steam power stations:

The most common today ٠

#### Produces hot water and turns it to steam

### Needed:

Deep hot water reservoirs • with  $\geq$  180 °C, high pressures

**Difference with the dry** steam station Most used today

Sustainable: re-charge the reservoir

### Flash steam power station



### How it works:

- Well accessing the hot water ٠ reservoir and brings the hot water at surface
- The pressure decreases and part of the water is turned into steam
- The steam is separated by the water
- The steam turns the turbine and generates electricity
- The steam is conducted to the condenser where it cools and go back to water
- Sustainability: The leftover water and condensed steam may be injected back into reservoir

### **GEOTHERMAL POWER STATIONS FOR ELECTRICITY**

#### **Binary cycle power stations:**

- The most recent development
- Power cycle combination of high and low temperatures

#### Produces hot water and transfer the heat to a secondary fluid with much lower boiling point

#### Needed:

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• Moderately hot water with  $\geq$  55 °C



Most common station to **build** today, Can be used many places

### Low efficiency: 10-13%

### How it works:

- Moderately hot water is pumped to surface
- In the heat exchanger the water is in contact with a fluid with low boiling point
- The fluid vaporize and turns the turbine and generates electricity
- The vapour is conducted to the condenser where it cools and goes back to the exchanger
- The water may be injected back into reservoir or led to streams/lakes/pools

### **ENHANCED (or ENGINEERED) GEOTHERMAL SYSTEM (EGS)**

R&D funding 2007, Australia

- Cold water reservoir
- Pumps 2.

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- 3. Heat Exchanger
- Turbine 4
- Production well (producer) 5.
- Injecting well (injector) 6.
- Hot water to district heating

### Where/ When it is useful:

- No shallow source of high ٠ temperature water or steam
- Low water pressure ٠
- Dry, impermeable rocks



#### Advantages:

- Can be used everywhere in the world
- Does not need hydrothermal or steam resoures
- Provides inexhaustible source of hot water
- Very low CO<sub>2</sub> emissions

### **Disadvantages**

- Cost of drilling
- Cost of maintenance pumps, tubing
- Water chemistry corrosion, scaling, erosion
- Induced seismicity

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### **ELECTRICITY PRODUCTION BY DEEP GEOTHERMAL**

Further technology development:

#### **MOVING HEAT INSTEAD OF WATER**

A nest of horizontal wells underground

The heat exchanger is underground

Combing EGS with Binary cycle (Duratherm fluid) – no fracking



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### **POTENTIAL FOR GEOTHERMAL USE IN EUROPE**

Modified, (Grosse, Christopher, Stefan, Geyer & Robbi, 2017)



HT-ATES = High Temperature Aquifer Thermal Energy Storage EGS = Enhanced or Engineered Geothermal Systems



### **ECONOMICS AND ENVIRONMENTAL IMPACT**

**Major economics issue** – the need to drill wells (dublets, triplets)

Depending on how deep the well is – the cost can be up to 10 Million USD

• District heating in Bavaria: estimated drilling cost 1 Million Euro per MW

Always risks – do not find a suitable reservoir

The cost of pumps, pipes, maintenance

Depending on water chemistry – erosion, scaling, corrosion

When all these costs are paid – the cheapest heating (Thisted)

#### **Geothermal power plants**

- Use much less energy and fresh water than coal, oil & gas, nuclear
- Emit MUCH less CO<sub>2</sub>
- Do not need batteries to store excessive energy

### Some environmental issues

- Drilling
- Underground gasses and fluids at surface
  - $\blacktriangleright$  H<sub>2</sub>S, sulphur, methane, ammonia, CO<sub>2</sub>
  - traces of mercury, arsenic, boron, antimony
- When pumps are used need for energy from polluting sources
- Reservoir depletion alternation of natural resources
- Subsidence New Zealand etc.
- In case of EGS possible induced seismicity (Basel, Switzerland)

### When we know the risks – solutions/alternatives are (or can be) found:

- Better/cheaper drilling methods;
- Filters/utilization of the underground gasses and fluids > The Italians are dealing with this since 1830
- More efficient pumps
- Re-injection
- Etc., etc., etc.

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200 volcanos.

### **EXAMPLE: GEOTHERMAL IN ICELAND**



- Started to use geothermal in 1907,
- Very intensively since the 1970's (the oil crisis)
- Combined potential ~ 10-13 TWh/y (2003)

### In total (incl. hydropower) 99.96% renewable energy supply

### 7 major geothermal plants

- Total production 5245 GWh (2013)
- 25-29% of the electricity supply
- 66% of the housing heating



#### Utilisation of geothermal energy 2013 https://nea.is/geothermal/electricity-generation/



### Generation of electricity – geothermal energy



## The Iceland Deep Drilling Project (IDDP)

https://nea.is/geothermal/the-iceland-deep-drilling-project



Long-term study of high-temperature hydrothermal systems (HTHS) to test if deep geothermal fluids can improve economics of geothermal power production

Temperatures ~450-600 °C at 5 km depth

Geothermal well at 2.5 km ~ 5MWe (2003)

Why it is needed:

- Energy demand is increasing
- Cost efficiency
- Environmental impact of present day utilization of hydropower & geothermal fields

## GLOBAL ENERGY DEMAND AND SUPPLY



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### World's Total Primary Energy Supply (TPES) by source of energy in 2017



### 2017: TPES = 13 972 Mtoe (Mega Ton Oil Equivalent)

Renewables (hydro, biofuels & waste, solar, wind, geothermal and tidal) in total: 13.5%

#### Huge potential



### **RENEWABLE ENERGY**

International Energy Agency (IEA) https://www.iea.org/staistics/renewables





40.1%

### **GLOBAL RENEWABLE ENERGY**

### Use of geothermal energy, 2016

https://www.iea.org/topics/renewables/geothermal/





https://www.iea.org/statistics/renewables/

energy supply, 2000-2018

### Why so little geothermal?

G	eology/Technical	Economics/Cost	Ο	rganizational/Legislation		
•	Availability Geothermal	<ul> <li>Drilling &amp; related risks</li> </ul>	•	Who is doing what?		
•	Risk	<ul> <li>Maintenance</li> </ul>	•	Responsibility		
•	Depth	Consumer	•	Legislation	FUI: in 2017 9 new geoth	ρ
•	Energy efficiency	willingness/possibility to pay	•	State support (taxes, incentives)	nut in operation	5
•	Equipment	<ul> <li>Competing technologies</li> </ul>	•	Public opinion: NIMBY – Not In	France Italy and the Neth	e
•	Etc.	• Etc.		My Back Yard)	Mainly – district heating (	fi

Example: Turkey – the state is covering the drilling cost and risk – huge increase in geothermal projects (more than 5 times in 5 years)

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## DTU GEOTHERMAL ENERGY IN DENMARK – District heating/fjernvarme

64% of all households in Denmark use district heating (fjernvarme) –huge potential for geothermal energy usage

### **GEUS**

Geothemisk window: 800 – 3000 m Geologiske "krav":

- Sandstone permeable (Gassum)
- Thickness > 25 m
- Good lateral permeability and conductivity

### **Barrierer:**

- Geologiske/tekniske
- Økonomiske
- Organizatoriske/lovgivning



ATES jordvarme (ikke geotermi)

Hot geothermal water can be transported at approximately max 2 km from the facility – too much heat losses on the way

Deep geothermal wells Only hot water No electricity production

### **GEOTHERMAL ENERGY IN DENMARK**

64% of all households in Denmark use district heating (fjernvarme) –huge potential for geothermal energy usage

#### http://data.geus.dk/geoterm/

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#### Ca. 1000 ATES Anlæg I Danmark

- Størrest Bispebejrg Hospital, Mart 2019
- Tre fjernvarme anlæg med geotermi
  - Thisted 1984, 45 °C, 1200 m: 2000 husstandes årlig varmeforburg
  - Margretheholm (Amager) 2005 (pt lukket), 73 °C, 2600 m, ca. 4600 husstandes årlig varmeforburg
  - Søndeborg 2013, 48 °C, 1200 m, 2400 husstandes årlig varmeforburg

#### https://www.geus.dk/energi/geotermi-og-jordvarme/



### **GEOTHERMAL ENERGY IN DENMARK**

#### Goals:

- Reduce CO<sub>2</sub> by 70%,
- Reduce fossil fuels,
- Fossil free by 2050,
- etc. etc. etc.

The energy systems of the future: a mix of various types of energy: solar, wind, geothermal etc.



### **NEED FOR MORE RESEARCH!**

- Improve energy efficiency
- Risk Mitigation,
- New and/or cheaper drilling methods,
- New geological mapping (existing- aimed at the O&G industry),
- New emerging technologies to address corrosion, erosion, scaling
- etc.

### **GEOTHERMAL ENERGY SUMMARY**

THERE IS HUGE POTENTIAL IN THE USE OF GEOTHERMAL ENERGY IT MUST BE PART OF THE ENERGY MIX OF THE FUTURE

It is most suitable for:

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- Heating/cooling of buildings and other infrastructure DENMARK
- Agriculture green houses
- Recreation/well being
- Electricity production
- Industry chemicals/aluminium etc. production

#### **ADVANTAGES** (among many):

- Stable and reliable 24/7
- In principle inexhaustible
- Small/discrete installations
- No storage need
- Low CO<sub>2</sub> emissions
- Relatively cheap (main cost drilling)
- Sustainable
- No use of fuels

DISADVANTAGES	POSSIBLE SOLUTIONS		
Not everywhere is easy to access it – North Europe / Denmark	ATES/EGS, new developments		
Drilling – cost, risk, pollution	State Investment (examples: wind energy, Turkey,) Improving technology		
Cannot be transported at long distance – district heating – max 1.5 km	Improving technology, new insulating materials		
Deep underground chemicals and gasses at surface Corrosion, scaling, water chemistry	Already in place: Filters, capture and utilization (Italy) New materials		
Reservoir depletion → Subsidence	Improved reservoir management – lessons from the O&G sector		
Low efficiency	New research and technology solutions		