Geothermal energy is a form of renewable energy that is available around the clock, irrespective of weather, climate, and daylight. It comprises useable heat from the Earth’s interior, and it has long been associated with hot springs, steam vents and hydrothermal activity. Consequently, geothermal energy in the form of hot water from natural springs has been used for a very long time for bathing and cooking, and heating. In the last 100 years, it has also been used for electricity generation. Geology plays a critical role in dictating the location and the grade of a resource. However, unlike other geoenergy resources such as hydrocarbons, it cannot be stored and transported.

My name is Stuart Simmons, and I am one of the geoscientists on the Utah FORGE project based at EGI, University of Utah. This presentation is an introduction to geothermal resources. It is directed at an audience that has interest in energy resources, geoscience and/or engineering disciplines. One goal is to describe where and how geothermal energy is utilized. Another goal is to introduce basic concepts of heat transfer, enthalpy, and power.

In this title slide, you can see the Blundell power plant at Roosevelt Hot Springs in southwestern Utah. This power station was commissioned in 1984 after roughly a decade of concerted exploration. It is the largest producing field in Utah.
Key Points

- The Earth is a huge thermal battery with vast geothermal resource; heat is generated continuously by radioactive decay of U, Th, and K.
- Heat transfer occurs by conduction & convection; geology dictates how & where geothermal energy can be utilized.
- The hottest resources (120-330°C) are used to generate electricity, based on production of dry steam, two-phase steam+water, or hot water, only.
- Cooler resources (<150°C) have a wide range of direct use applications, including heating/cooling of buildings.
- New technologies are required to unlock the geothermal resource potential.

Here are the key points. The Earth is a huge thermal battery with vast energy resources, and heat is being continuously generated by radioactive decay of elements like uranium, thorium and potassium in the Earth’s interior. Heat transfer occurs by conduction & convection; geology dictates how & where geothermal energy can be utilized. The hottest geothermal resources (120-330°C) are used to generate electricity, based on production of dry steam, two-phase mixtures of steam+water, or hot water, only from deep production wells. Cooler geothermal resources (<150°C) are used for a wide range of direct use applications. New technologies are required to unlock Earth’s geothermal resource potential.
So, let’s start with Earth’s heat. The cross-sectional view shows that Earth’s internal structure is made of concentric layers comprising the core, mantle and crust, and each has a distinct thermal regime. The hottest temperature in the core exceeds 5500 degrees kelvin. At the base of the crust, the temperature is just below 2000 degrees kelvin. Between this level and the surface, the thermal gradient is very sharp. This is because the rocks making up the outer skin of the Earth have excellent thermal insulating characteristics.
Locally, high heat flows develop where molten rock in the form of lava erupts, and these occur at mid ocean ridges, volcanic arcs associated with subduction zones, and mantle plumes. Not surprisingly, these are where the hydrothermal systems that host the best geothermal resources occur. The total heat flow to the surface is about 47 TW, which is enormous and which is why geothermal energy is important.
The distribution of geothermal resources is shown in this map of the world. The legend shows that they are divided into various types. The highest grade resources are shown as the red-filled circles and they are associated with volcanoes or magmatic intrusions.
Lower grade resources associated with extensional fault systems are shown as grey-filled circles and they are found in the western USA and western Turkey.
Other geothermal resources in sedimentary basins are represented by diagonal lines and these occur in China and Europe.
In summary, geothermal resources are widespread. They also tend to be concentrated in belts associated with zones of active volcanism, including the rim of fire that encircles the Pacific ocean basin as well as certain islands that are volcanically active like Iceland and Hawaii.

The oldest producing field is located in northern Italy at Larderello where electricity generation commenced just over 100 years ago. It has been in continuous production ever since, which is an important feature of geothermal resources; that is they produce energy for very long periods of time. Larderello currently generates almost 600 MWe from production of dry steam from deep wells.

The largest geothermal field is located in northern California, called the Geysers, where it generates 850 MWe, again from dry steam produced from deep wells. We will look at this map again to consider some other examples in just a few slides, but first I need to define some terms.
A geothermal system is the set of processes that transfers heat to the surface. The mechanisms of heat transfer involve conduction and convection.

Geothermal energy is the useable heat that can be extracted and produced for electricity generation or direct use applications.

A geothermal reservoir is the volume of rock from which thermal energy is extracted. It contains fluid(s) in fractures & pores made of hot water & sometimes steam. Note, the thermal energy stored in rock is huge (>10^{17} J/km^3).
The geothermal gradient represents the change in temperature with depth. Most areas in the upper continental crust have a conductive thermal gradient of between 10 and 40 degrees C/km. Only in a few anomalous places do thermal gradients exceed 100 deg C/km.

The straight line represents the average gradient of 25 deg C/km. That the gradient is uniform, increasing steadily with increasing depth and having a constant slope, is characteristic of conductive heat transfer.

The maximum thermal gradient is represented by the red curved line designated boiling point curve. Everywhere along this line, hot water is just at boiling condition. Such gradients are achieved in tectonically and volcanically active regions and these are usually related to deep heat transfer by the movement of hot fluids called convection.
Strictly, a convective thermal gradient is perfectly vertical because rising fluid (typically water) transfers all the heat, assuming no heat has been lost to surrounding rock. Hot water rises naturally due to buoyancy and lower density compared to cold water in the rock that surrounds the geothermal system. Once the convective upflow intersects the bpd condition, the temperature of the rising fluid decreases, as steam is produced from the depressurizing water. As I said, this is the maximum temperature as a function of depth in the upper crust.
Definitions: Geothermal Gradient

The yellow-brown area is marked out to show the temperature-depth regime from which thermal energy can be extracted economically; in other words, this is where producing reservoirs are located.
The last set of definitions relates to energy and power. The Joule is a unit of energy in the international system and the watt is the unit of power, wherein $1\text{W} = 1 \text{J/second}$. A megawatt is $1,000,000$ watts. Geothermal systems produce thermal power and this is converted to electrical power by various means discussed later on. Such power conversion has 10-15% efficiency. Thermal power is reported as such generally in respect to direct use. In the United States, $1\text{ MW electrical}$ can provide for between 500 and 1500 houses depending on climate and the use of electricity within the household.
Returning to the global distribution of geothermal power production, I want to point out two things: 1) The installed capacity for electricity generation is about 13 GW total (i.e., 13,000 MW), which is small compared to wind at 500 GW and solar at 400 GW.
The second point I want to make deals with a scale comparison between two premier thermal provinces in contrasting tectonic regimes but with comparable electricity generation, the Taupo Volcanic Zone (TVZ) in the North Island, New Zealand and the Basin and Range province in the western USA.
Let’s start with the Basin and Range, which covers most of the state of Nevada but also incorporates the western part of Utah and the eastern edge of California. These three states are the top producers, with California ranked first, Nevada second, and Utah third. Within the Basin and Range, there is a total of about 1000 MW of generating capacity across 20 producing fields. Coso in California is the hottest and largest resource, producing about 300 MW. Roosevelt Hot Springs, from the title slide, is located here in southwestern Utah. Most of the geothermal fields produce between 10 and 100 MWe. Geologically, the Basin and Range province represents a very large region with elevated heat flow due to tectonic extension, crustal thinning, and localized intrusion and eruption of magma.
Turning to New Zealand, and the Taupo Volcanic Zone, the total electricity production is about 1000 MWe, just like the Basin and Range, but there are only 7 fields that produce electricity, and they range from 40 to 380 MW. You can see clearly that the area represented in the map of the Taupo Volcanic Zone is considerably smaller so geothermal power production is concentrated here compared to the Basin and Range.

Geologically, the Taupo Volcanic Zone is an intensely active thermal belt and similar to Yellowstone National Park in northwest Wyoming, having very high natural heat flow. Rather than being related to a mantle plume, the TVZ is southwestward extension of the Tonga Kermadec volcanic arc-subduction zone complex.

The region is dotted with towns and cities, and much of the surrounding land is used for a range of agricultural activities, plus geothermal energy utilization. Let’s look at some examples, starting with Rotorua, where thermal energy is used for district heating. Then we will look at Mokai, Wairakei, and Ohaaki, where geothermal electricity is generated.
Rotorua is a major urban center and it has a population over 50,000 people. The city is built on top of a high-temperature geothermal system and in the foreground, you can see Pohutu geyser erupting. For Rotorua, natural thermal activity is a major tourist attraction and an important source of revenue. Geothermal energy is also used to heat the hospital and a number of buildings near the city center.
Mokai is located in rural setting and the farms here are used for dairy production. The power plant, which was commissioned in 1999, produces 111 MWe. Over here is a very large greenhouse complex that uses heat for growing vegetables, representing an example of direct use. Another example of direct use is the Miraka dairy factory, which uses heat to make powdered milk and other products for export. Mokai nicely demonstrates how geothermal energy can be used in multiple ways.
The Wairakei geothermal field was the first hot water or liquid-dominated reservoir to be developed for electricity generation anywhere in the world. The 145 MW power station was commissioned in 1958 and it has been running continuously ever since. It is located by the Waikato River for cold water supply used in the condensing turbines. There are now 380 MWe of installed capacity, including the 15 MW binary plant which extracts additional heat and energy out of flashed and separated water. The prawn farm like the green house at Mokai is yet another example of direct use, in this case for aqua culture.
Turning to field development, let’s just look briefly at what it takes to bring a geothermal resource on line to produce power. This involves exploration surveys, drilling and well testing. Exploration involves field surveys, usually in small teams, to acquire information on geology, heat flow, hot spring compositions, and other geoscientific data. From these data, drill targets are selected and wells are drilled and surveyed, particularly in respect to temperature gradient. The last phase of testing involves discharge and flow to determine productivity.
All of these data are put into a geospatial context, as shown here for Ohaaki, in terms of a map of surface thermal activity and zones of hot ground, a map showing the distribution of wells, including an outline of the reservoir at a specified depth, and a cross section showing the distribution of rock types, temperature, and fluid flow.
This is the aerial view of the Ohaaki field, noting that north is pointed to the right. The white colored squares and rectangles represent drill pads which host well heads. The production zone is outlined by the black dashed line.

Pipes connecting the well heads to a centralized separator take geothermal steam (red dashed line) to the station where power is generated, whereas waste separated water (blue dashed line) is injected on the margin of the production field.
Having provided a sense of how geothermal resources are developed, we can now pay a bit more attention to thermodynamic properties of water and vapor.

Most of you are probably familiar with the basic pressure-temperature relationships which are shown on the far left. The vertical or y-axis represents pressure and the x-axis represents temperature. The vapor-saturated curve separates the liquid field above from the vapor field below.

This graph is expanded to the right to show enthalpy, and this is done with another horizontal axis that is at a right angle or 90 deg to the temperature axis. Remember enthalpy represents energy per unit mass, which in this case is kilojoules per kilogram.

The critical point at 374 deg C is represented at the top of the solvus by the black filled circle. At 250 deg C, where water and vapor coexist, the enthalpy of hot water is 1086 kJ/kg and the enthalpy of vapor is 2800 kJ/kg.

This is the main point that I wanted to show you, which is that vapor or steam has much higher energy and enthalpy than coexisting water at the same temperature and pressure.
The two dimensional version of the same relationship is shown in this graph. And this lets me show you as well that vapor-dominated reservoirs have higher energy/mass compared to liquid-dominated reservoirs. This becomes important in the next slide in which different modes of fluid production are shown.
There are three basic modes of fluid production used in electricity generation based on the temperature and the energy grade of the fluid in the reservoir. I want to spend a bit of time to explain these features, and to follow you will want to look at the legend on the far right, which identifies the different fluids that will be discussed, including hot water, steam, isopentane, and cooled water.

We will start on the left side with a vapor-dominated reservoir, which for reasons just explained is the highest-grade energy resource. You see two wells one producer marked in red with rising steam and one injector marked in blue with descending cooled water. Although the reservoir is made up of coexisting hot water and steam (i.e., it is two-phase), only steam enters the well due to hydrodynamic effects. So dry steam is produced at the well head, and this can be piped directly to a turbine to generate electricity. The condensate from the back side of the turbine is cold and is returned to the subsurface via an injection well.

In the middle, production and generation relates to a liquid-dominated reservoir. At the fluid entry point, hot liquid water enters the well. As it rises, steam forms due to depressurization and this process is called flashing. Flashing resembles boiling. In flashing, however, two-phase conditions are attained by depressurization, whereas in boiling, two-phase conditions are attained by heating (like when you boil water on the stove). The produced fluid is a mixture of steam and water and the two phases have to be separated from one another in a cylindrical vessel called a cyclone separator. The separation of hot water and steam are critical because the steam turbine cannot accept any water, not even droplets of water. So, while steam is piped to the turbine, separated water is reinjected in the subsurface. I’ll show you the separator in the
next slides, but I need to show you the last mode of production and generation first. Before that, note in both the first and second modes, the wells are self flowing.

On the far right, the reservoir is again liquid-dominated and hot water under pressure is produced at the well head, noting the production well is pumped; this fluid then passes through a heat exchanger. The energy from the heat exchanger is used to heat and vaporize a second fluid, usually an organic compound like isopentane, which has a boiling point that is lower than water. This second working fluid is run through a power cycle in a closed loop. After being vaporized at the heat exchanger, isopentane gas is run through a turbine to generate electricity, condensing back to a liquid and then recirculated for reheating and revaporization. The hot water that was produced cools after it runs through the heat exchanger, and it is injected back into the subsurface.

Just to summarize, the three modes reflect the different ways of generating electricity as a function of temperature and grade of resource. The highest-grade resources have vapor-dominated reservoirs in which dry steam is produced at the well-head. I’ve already mentioned Larderello and The Geysers production fields, the first being the oldest producing geothermal field and the second being the largest producing geothermal field. In both cases, the resources are both large and high-grade, but there are few other examples in the world and so they are rare.

Liquid-dominated reservoirs that produce two-phase water+steam at the well head are the next highest-grade resource and these dominate global production. This type of resource was first developed at Wairakei. It required the deployment of cyclone separators, and this breakthrough made it possible to develop similar such resources elsewhere in the world. The lowest grade resource, with coolest reservoir temperatures (<200 deg C), produce hot water from pumped wells in which electricity is generated with a binary plant.

Binary plants were invented in the Soviet Union in the 1960s, representing another milestone achievement. Although they are not as efficient in terms of power conversion, binary plants are profitable and they have greatly extended power production in high temperature fields, such as Wairakei, and also Roosevelt Hot Springs, and they have extended the lower temperature range of geothermal resources that can be developed globally.

So the three modes, from left to right reflect the order and history of technological advance that have increased the uptake and utilization of geothermal energy worldwide.
Wells produce two-phase fluid: 25% steam & 75% water

Let’s look more closely at the cyclone separator which made it possible to develop liquid dominated reservoirs. In the schematic (left), you can see the well head and the rising red arrow indicates production of two-phase fluid made of steam and hot water. The flow is high velocity at roughly 100 kg/s. The pipe work redirects the flow to a horizontal direction where it enters the separator on a tangent, causing the hot water and steam to spin around inside. Centrifugal forces separate liquid from vapor, while gravity pulls the dense water downward to drain out via the blue colored pipeline, whereas dry steam is concentrated at the top of the vessel and it is drawn out via the red pipe, which transmits it to the power station.

The photo on the right shows a well head, separator and connecting pipe work with arrows showing the direction of fluid flow.
This view of the western borefield at Wairakei shows that each well head has a dedicated cyclone separator. Steam is collected into a manifold pipeline and transmitted to the power station. Such steam field design is dated and in modern production fields, a cluster of wells serves a single separation plant like at Ohaaki. The main thing is to emphasize the impact of engineering and the design of fluid collection systems in making geothermal energy work.
Earlier, I mentioned that geothermal resources are found in three main types of settings and here they are compared side by side to get a sense of geometry and scale. Note that in all cases, the outlined reservoirs occupy limited volumes within the geothermal system. Furthermore, they are located at a depth that is accessible by the drilling of wells, generally <3 km.

In sedimentary basins, reservoirs can be laterally extensive and confined to horizontally bedded strata represented by particularly porous and permeable horizons. In extensional fault settings, hydrothermal fluid flow is confined to a narrow buoyant plume that is restricted to sub-vertical planar structures that have elevated permeability. In volcano-intrusion settings, magmatic heat drives convective circulation, producing hydrothermal plumes that host reservoirs within the upflow zone and sometimes in shallow outflow zones, noting that this setting hosts both vapor-dominated and liquid-dominated resources.
Now let’s summarize the temperature depth range of geothermal resources. Ground sourced heat pumps are deployed at the shallowest and coolest range of conditions. We have not discussed this type of application, but they are widely used for heating and cooling buildings and homes. Next, direct use applications tap reservoirs having temperatures ranging up to about 120 deg C. Binary plants have reservoirs that range from 120 to 200 deg C. Lastly flash plants and steam turbines are based on reservoirs that range from 200 to >300 deg C.

The future of geothermal development lies at deeper levels where elevated temperatures are widespread. Porosity and permeability however are greatly reduced so while the rock is hot, there is little natural hydrothermal circulation. New technologies need to be developed to produce this energy, hence they are called enhanced geothermal systems or EGS and this is the focus of research and the Utah FORGE project.
Summary

- Geothermal energy is a renewable resource.
- It is used for electricity generation & direct use.
- It is clean, always available; it complements wind, solar, and hydro generation.
- The best resources are localized by favorable geological conditions.
- New EGS technologies are required to unlock the large resource potential.

In summary, geothermal is a renewable energy source that has a wide range of applications, including electricity generation and direct use. It is clean, always available, and it complements other renewable energy resources such as wind, solar and hydro. Although they are widespread, the best conventional geothermal resources are localized by favorable geological conditions. The future of geothermal energy is tied to unlocking the vast resource potential lying at deeper levels and across much larger regions using EGS technologies.
This presentation is sponsored by US Department of Energy. For more information about geothermal technologies and Utah FORGE, please visit our website.
References


In 2014 DOE initiated the FORGE program. The project was divided into three phases: Phase 1 was a desktop study of 5 sites in the US. In Phase 2, deep drill holes were drilled at two sites to confirm characteristics. We are completing analyses of stimulation activities and numerical simulations performed at the end of Phase 2 now. In Phase 3, we will build the FORGE laboratory.