Energy geostructures: general context

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Outline

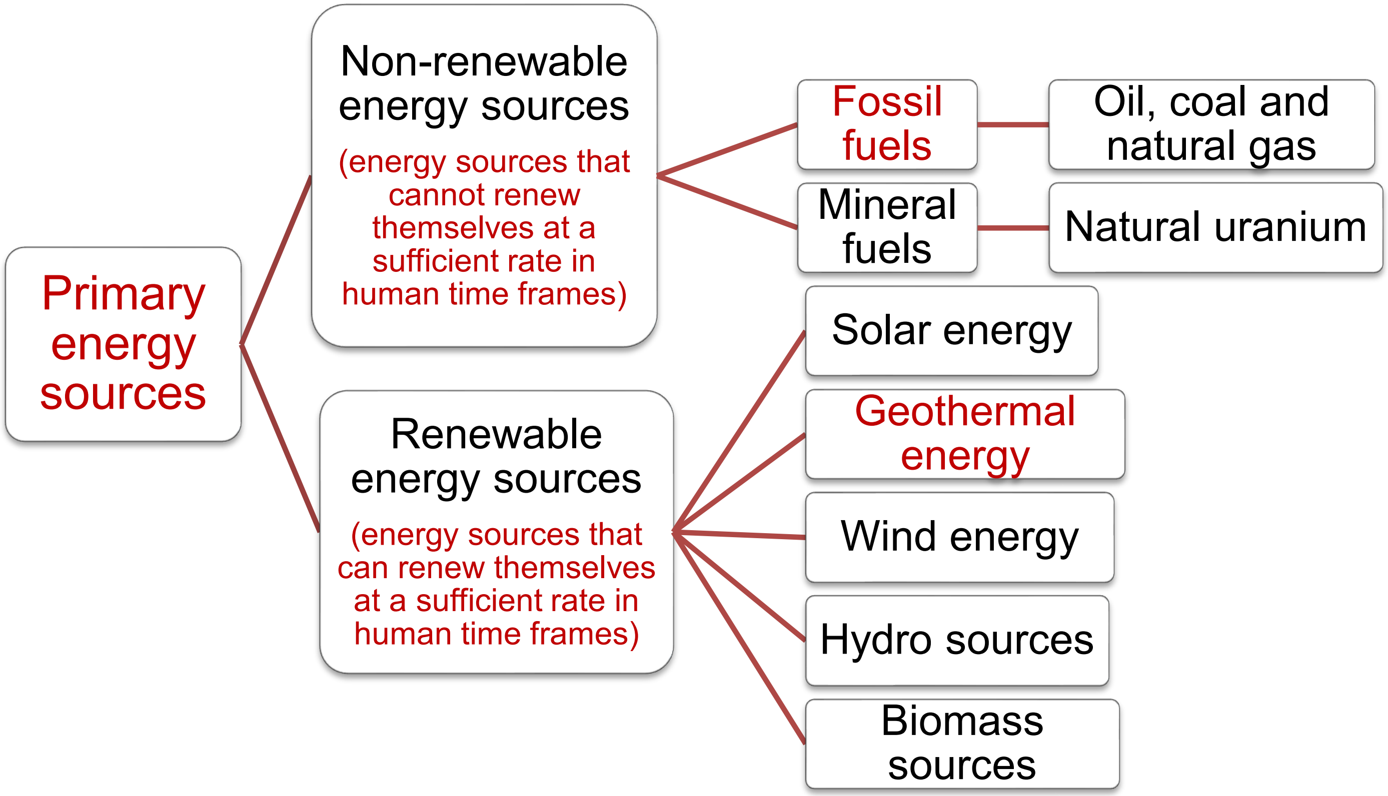
- Context and motivation
- Geothermal energy
- Energy geostructures
- Challenges and design considerations

Context and motivation

Energy sources

Primary energy sources: an energy form that has not been subjected to any conversion and is available in nature

Secondary energy sources: an energy form that has been transformed from primary energy sources and is not available in nature

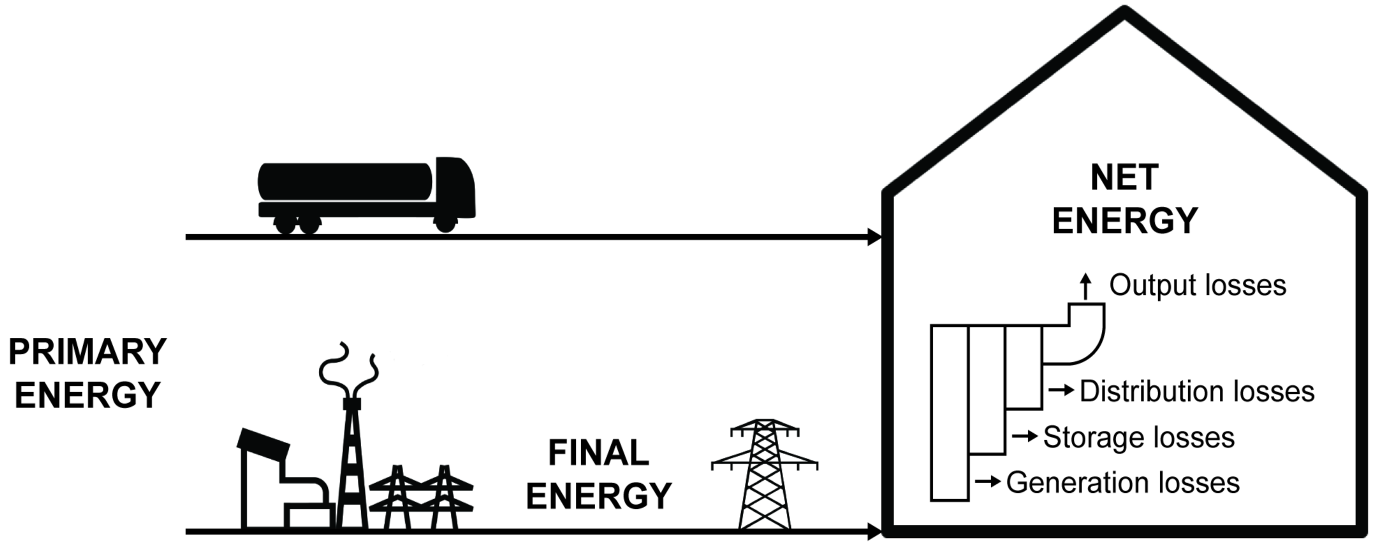


Some energy units

Name	Symbol	Description
Joule	[J]	1 Joule is equal to energy transferred to an object when a force of 1 Newton acts on that object in the direction of its motion through a distance of 1 metre (1 J = 1 Nm) Basic energy unit of the metric system (SI)
Calorie	[cal]	1 calorie is the amount of heat required to raise the temperature of 1 gram of water by 1 °C, from 14.5 °C to 15.5 °C. The calorie can be defined in terms of the Joule (thermo-chemical calorie: 1 cal = 4.184 J)
Watt-hour	[Wh]	The standard unit of electricity production and consumption (1 Wh = $3.6 \cdot 10^3$ J)
Gigatonne of oil equivalent	[toe]	1 toe is the amount of energy released by burning one tonne of crude oil (1 toe = 41.868 GJ), i.e., an energy equivalence for oil
Watt	[W] or [J/s]	A derived unit of power that expresses 1 Joule per second and can be used to quantify the rate of energy transfer

Energy classification

- Primary energy consumption: Primary energy consumption refers to the direct use or supply at the source of energy that has not been subjected to any conversion or transformation process (often termed primary energy or crude energy as well)
- Final energy consumption: the total energy consumed by end users, excluding the energy that is used by the energy sector itself
- Net energy consumption: the amount of energy supplied that is necessary to run the generator of cold and heat



(Laloui and Rotta Loria, 2019)

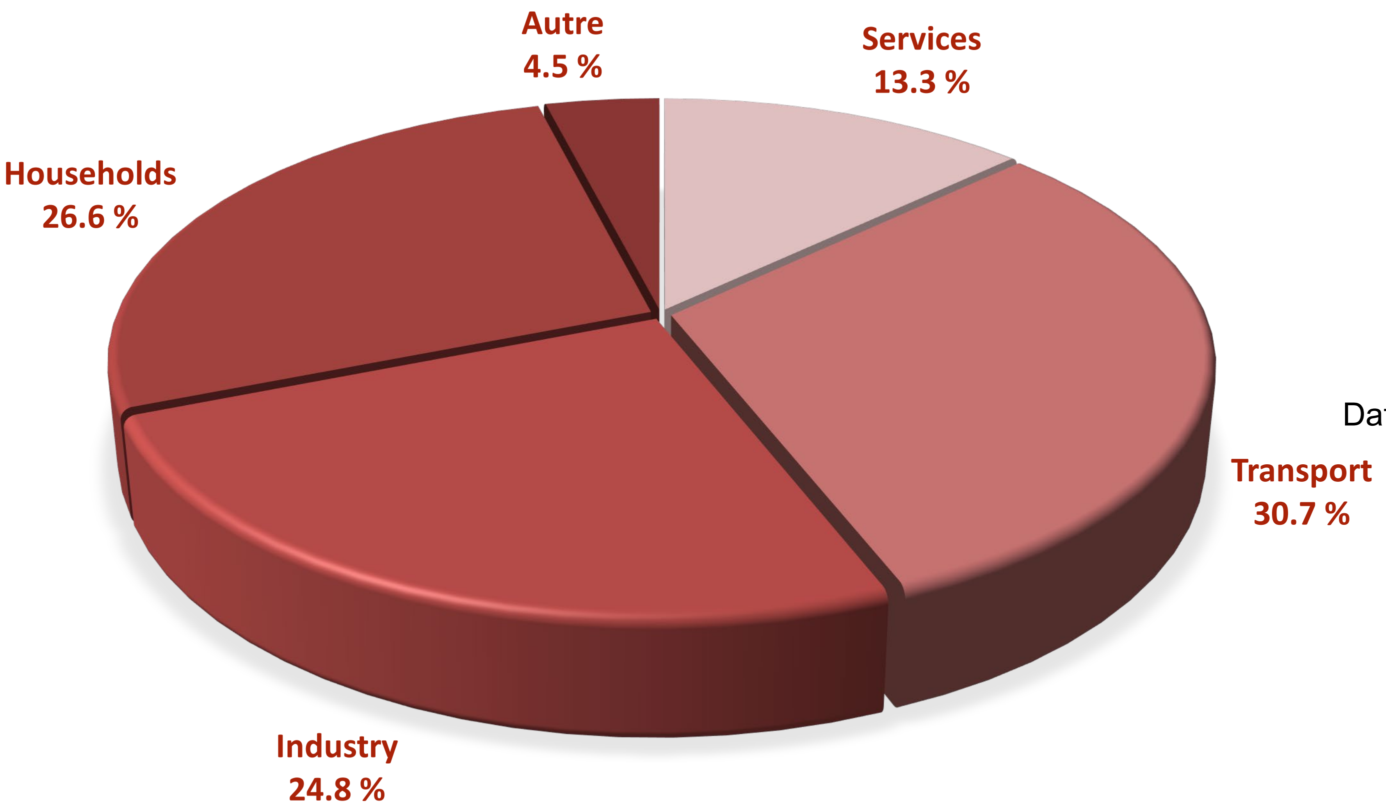
Framework: 2-50-75-80

Cities occupy 2% of the world’s surface, but they are host up to 56% of the world’s population, are responsible for 75% of global energy consumption and 70% of greenhouse gas emissions

(IEA, 2024)

Final energy consumption by different end users

- In the EU and typical OECD countries, 3 end users dominate the final energy consumption: the building, industry and transportation sectors

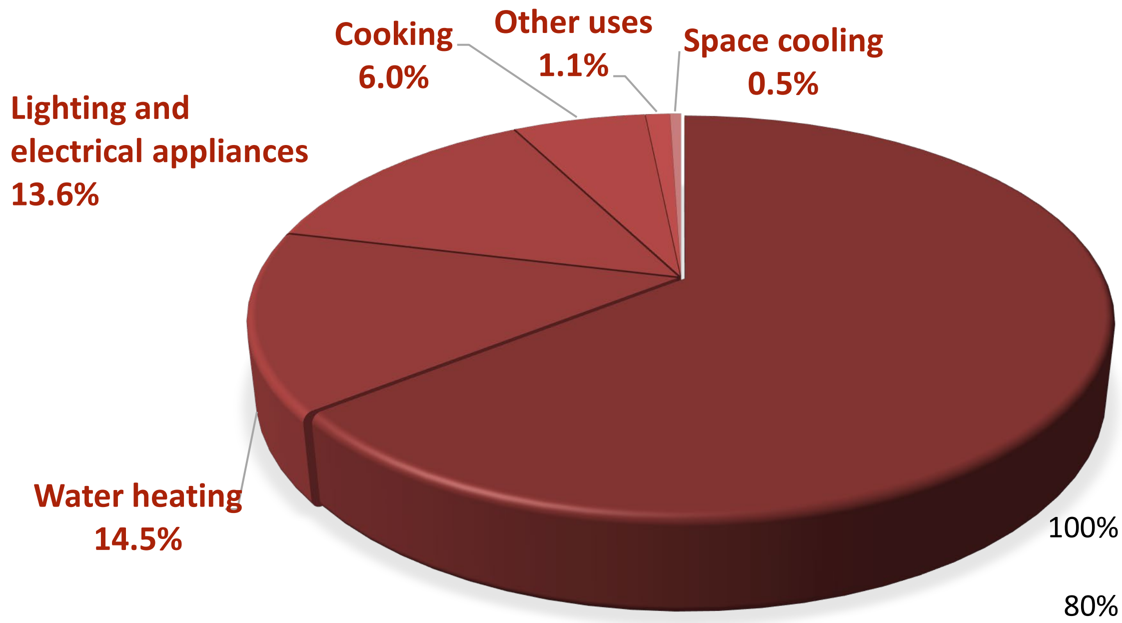


Data from Eurostat (2022)

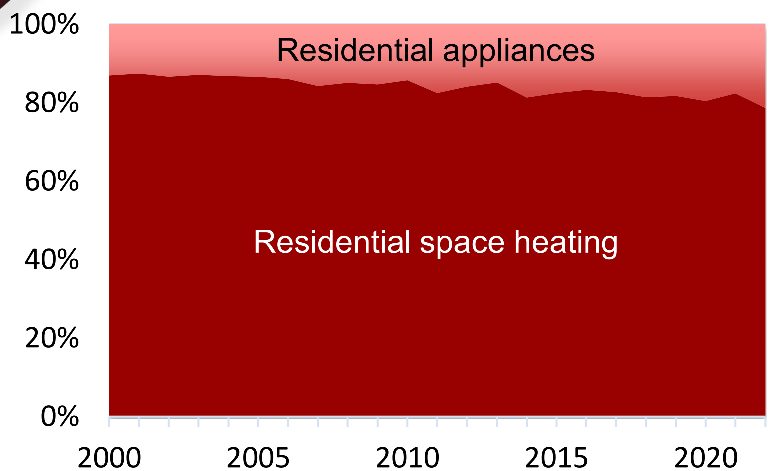
Final energy consumption: total energy consumed by end users, excluding the energy that is used by the energy sector itself

Final energy consumption in EU households

- In Switzerland, as in typical OECD countries, 60 to 85% of the final energy consumption is used for space conditioning and hot water production



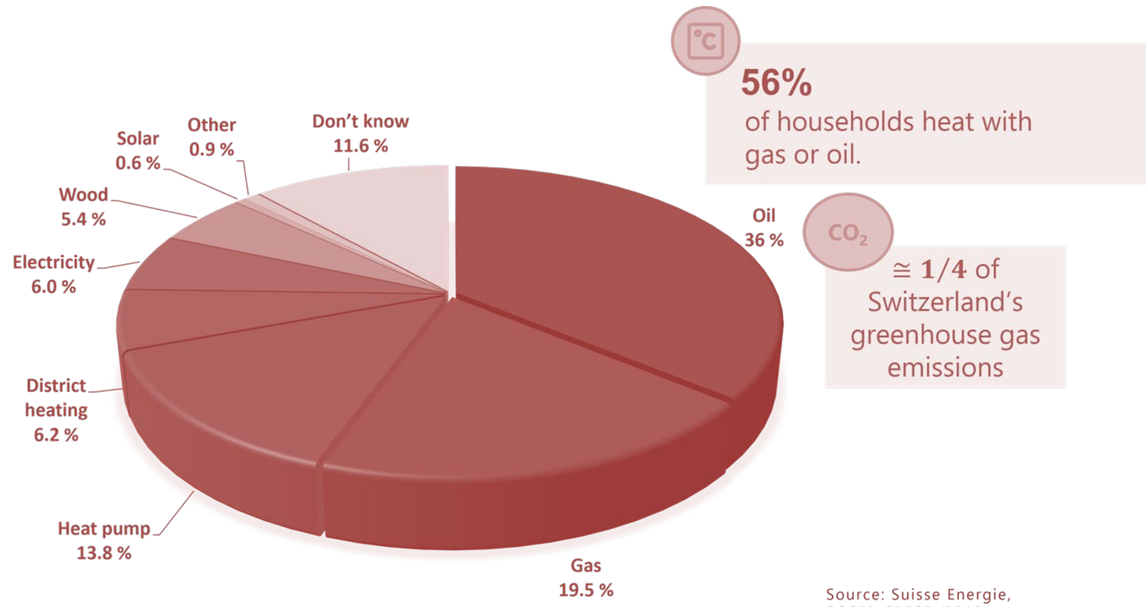
Data from Eurostat (2021)



Consumption by end use – residential – Switzerland IEA (2024)

Energy use in buildings

In Switzerland, the main energy sources are still based on fossil fuels



Source: Suisse Energie, SCCER CREST (2018)
FOEN (2021)

WHERE DOES THE MONEY GO?

LIGHTING — **2%** on average, of your enery bill is spent lighting your home

DEVICES — **8%** on average, of your enery bill is spent for household appliances

HEATING — **40%**, of your enery bill is spent heating your home

New directives in the construction sector

From 2020, new buildings and infrastructures will need to harvest renewable energy sources available on site

EU - NZEB:

France - BEPOS:

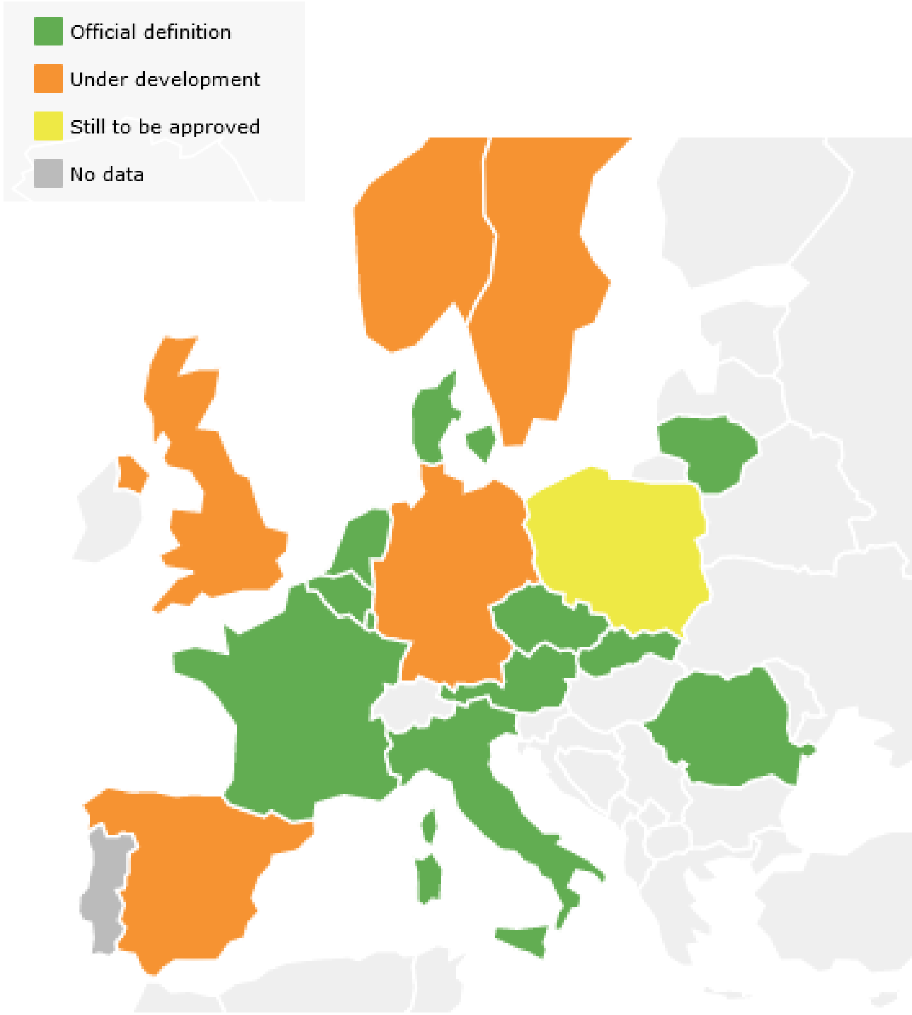
USA – ZNEB:

New directives in the construction sector

EU - NZEB concept : « A building with **very high performance**, where the **amount of energy** required **is almost null** because it is **largely covered by renewable energy sources produced locally or nearby. »**

France - BEPOS concept : « A building **producing more energy than it consumes** for its operation»

USA – ZNEB concept : «a building with zero net energy consumption»



Last update May 2016, Zebra Data Tool, BPIE

Governmental incentives and goals

- Energy Performance of Buildings Directive, 2002
- Energy Performance of Buildings Directive, 2010
- The Carbon Neutral Design Project

- The ASHRAE Vision 2030

To develop a low-carbon built environment i.e., buildings and infrastructures using:

- Integrated passive design strategies

- High performance building envelopes and energy efficient HVAC systems, lighting and appliances

- Technologies harvesting on-site renewable energy sources

Switzerland Governmental activities

- Switzerland aims for net zero greenhouse gas emissions by 2050 under the Paris Agreement.
- The Federal Council's strategy targets halving emissions by 2030 compared to 1990.
- The proposed KIG law seeks to establish net zero targets by 2050 with a 75% reduction by 2040.
- EP2050+ outlines reduction paths for building sector emissions.
- Organizations work on SIA 390 standard, studies on negative emissions, and harmonization of building labels.
- Eastern Switzerland's energy agencies propose definitions focusing on significant building operation emissions reductions by 2040 and 2050.

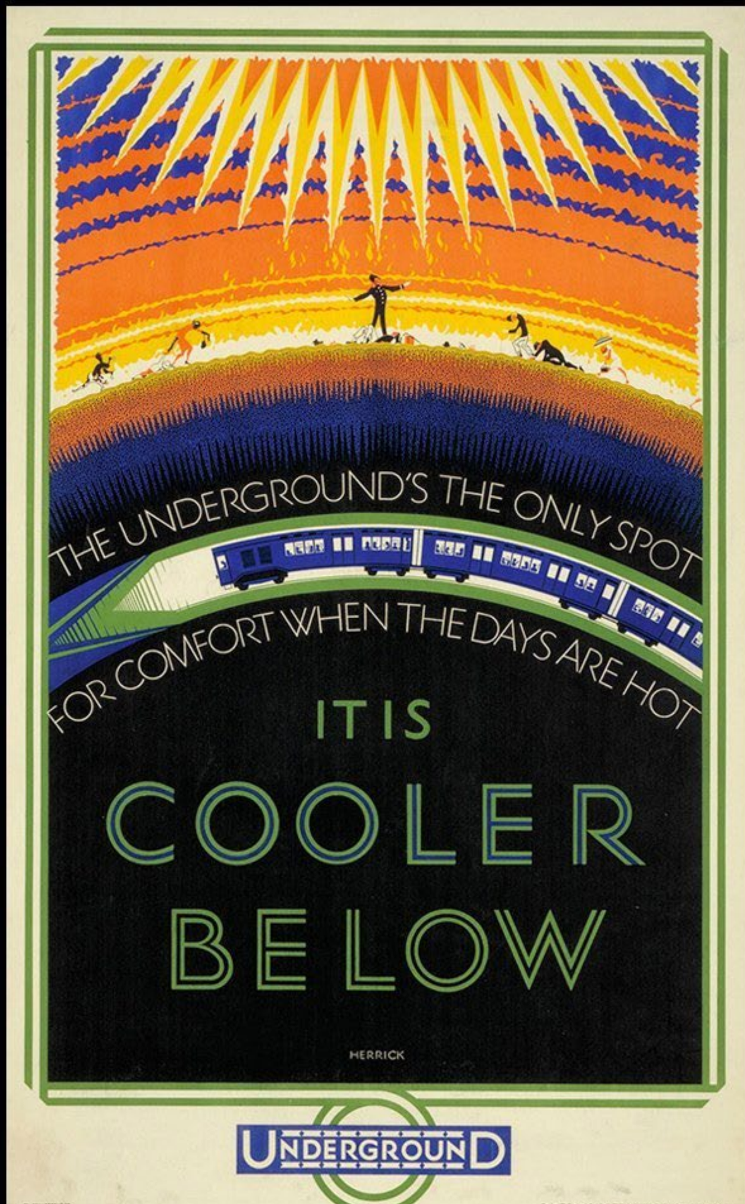
One of the possible solutions

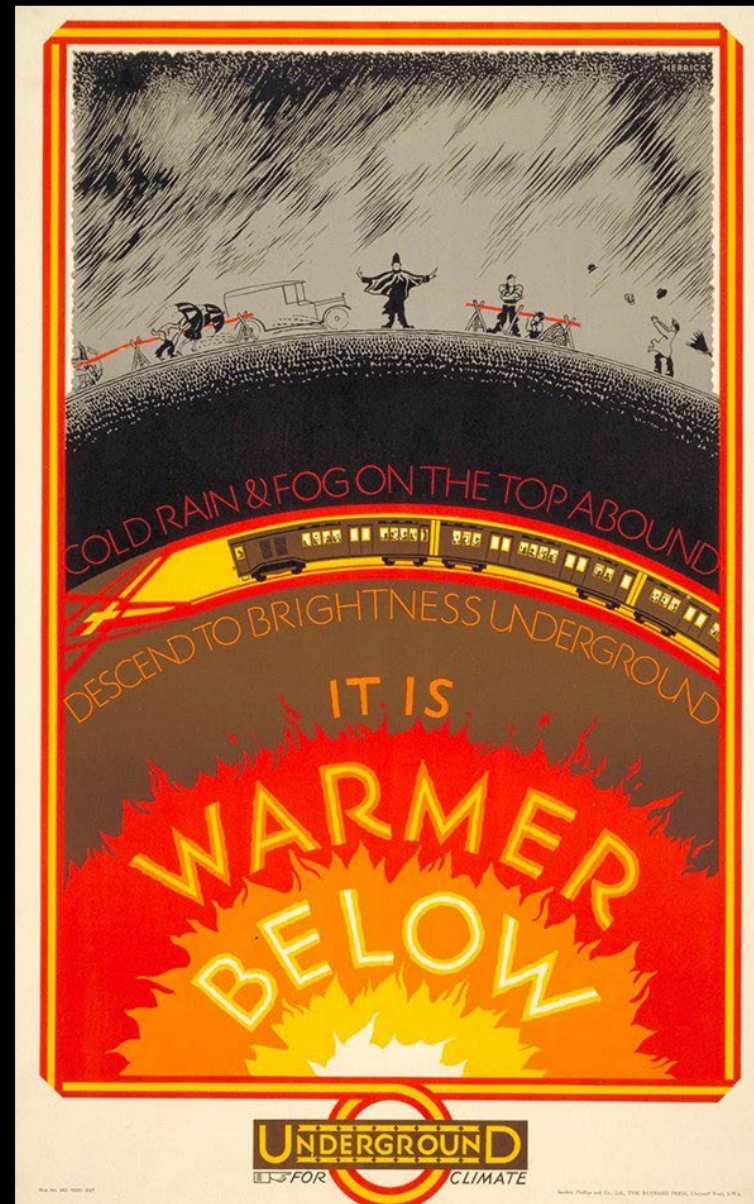
This course covers the fundamentals of the **analysis** and **integrated design** for the successive application of one of such environmental friendly technologies, i.e.,

ENERGY GEOSTRUCTURES

an innovative multifunctional technology that couples the structural support role of conventional geostructures with the heating-cooling role of conventional geothermal heat exchangers

Soils: the oldest mean for storing/capturing heat





Posters (1926-1927) of Frederick Charles Herrick for London Underground

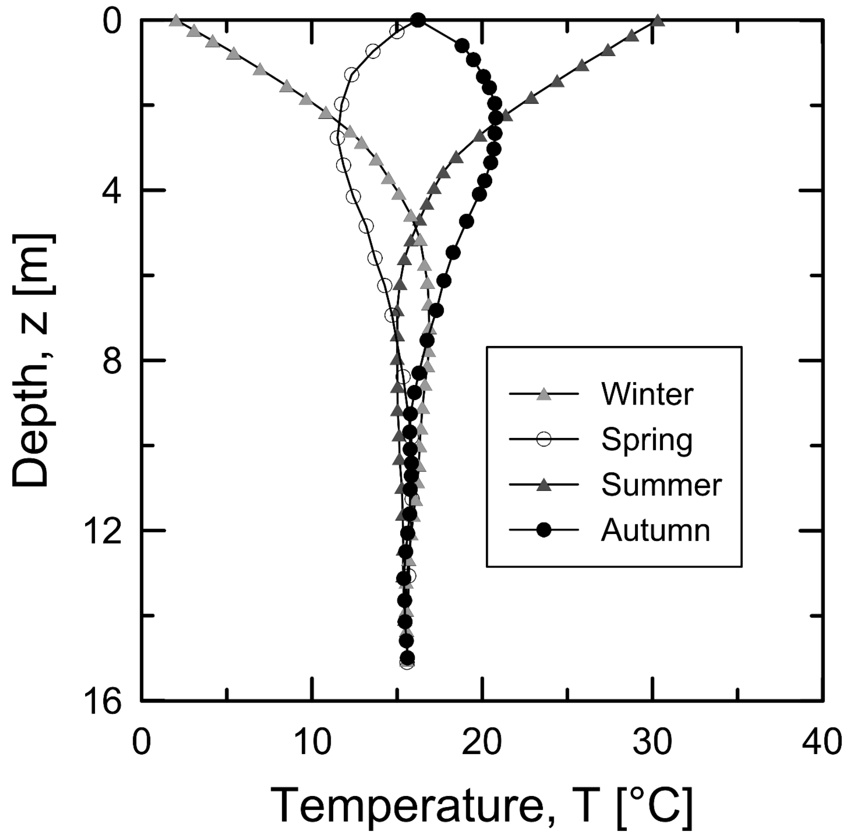
Geothermal energy

Geothermal energy

- Renewable and sustainable energy (Lund, 2009)
- The second most abundant source of primary energy on Earth, after solar energy (Lee et al., 2007)
- Available continuously, regardless of the weather, in contrast to other renewable energy sources:
  - Solar energy is not available at night or during cloudy days
  - Wind energy is not available without wind and wind turbines are not constructed close to cities
- It generates no (or minimal) greenhouse gas emissions (no chemical reactions are involved) (Lee et al., 2007)
- It involves a reduction of energy imports (Brandl, 2006)

Temperature field in the subsurface

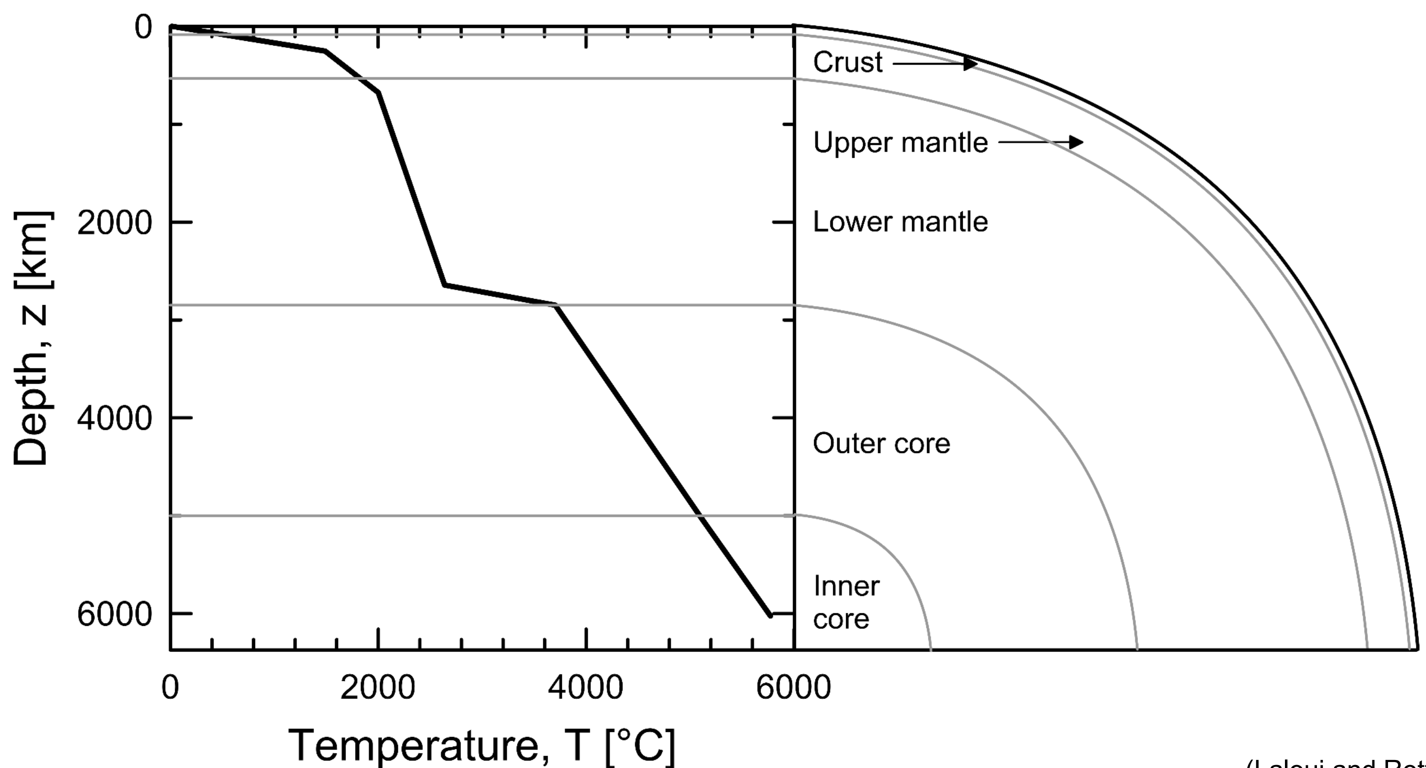
- The temperature field in the subsurface is typically sensitive to atmospheric conditions within the first 4-6 m



(Laloui and Rotta Loria, 2019)

Temperature field in the subsurface

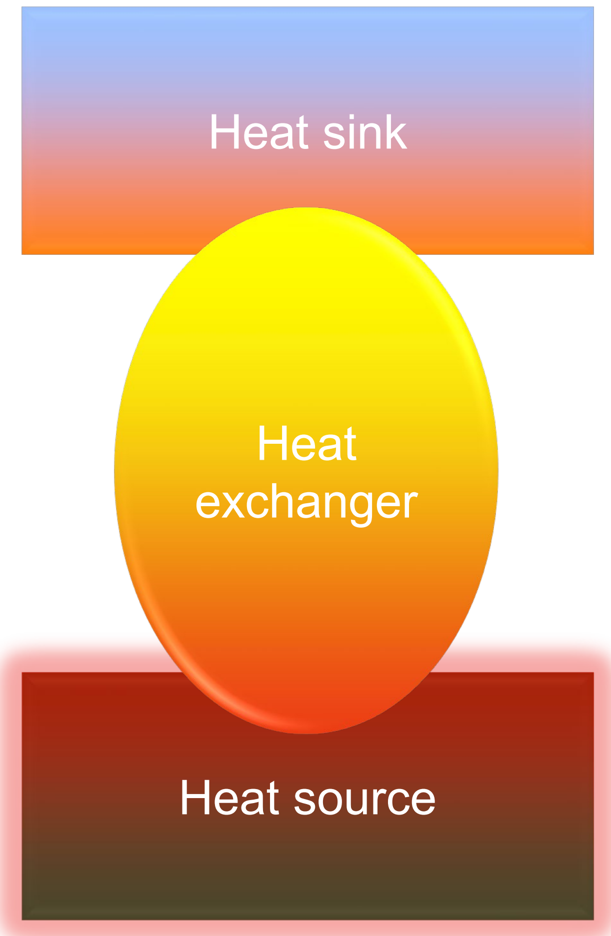
- From the aforementioned values, the temperature increases with depth in the Earth crust (Barbier, 2002)
- Average geothermal gradient = 3 °C per 100 m of depth



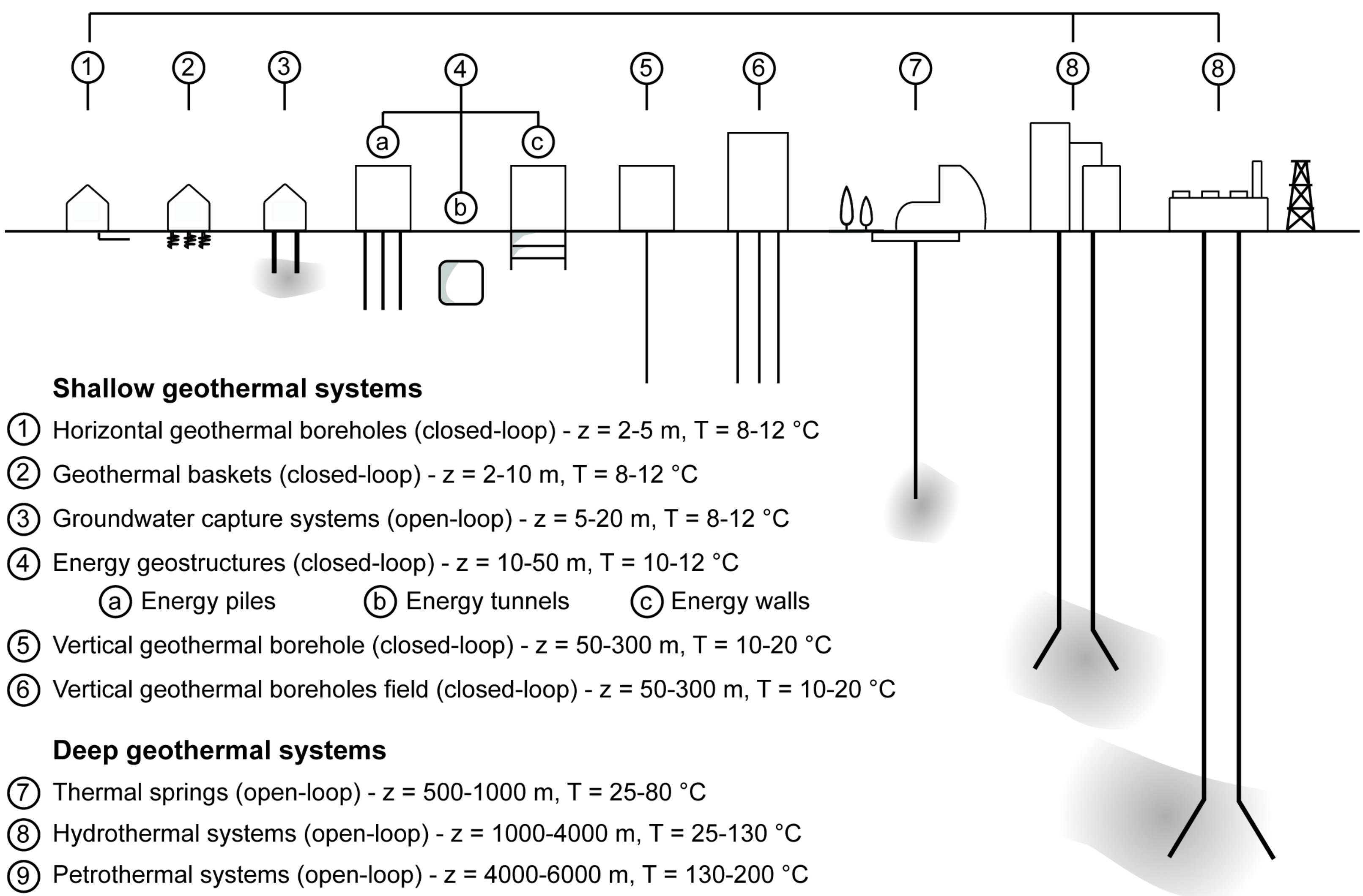
(Laloui and Rotta Loria, 2019)

Geothermal systems

- *Three key components*:
  - A heat sink (e.g., building)
  - A heat exchanger (e.g., one or more elements containing a fluid that transfers the heat between the heat source and sink)
  - A heat source (e.g., ground)



Classification of geothermal systems



Shallow geothermal systems

① Horizontal geothermal boreholes (closed-loop) - z = 2-5 m, T = 8-12 °C

② Geothermal baskets (closed-loop) - z = 2-10 m, T = 8-12 °C

③ Groundwater capture systems (open-loop) - z = 5-20 m, T = 8-12 °C

④ Energy geostructures (closed-loop) - z = 10-50 m, T = 10-12 °C

ⓐ Energy piles ⓑ Energy tunnels ⓒ Energy walls

⑤ Vertical geothermal borehole (closed-loop) - z = 50-300 m, T = 10-20 °C

⑥ Vertical geothermal boreholes field (closed-loop) - z = 50-300 m, T = 10-20 °C

Deep geothermal systems

⑦ Thermal springs (open-loop) - z = 500-1000 m, T = 25-80 °C

⑧ Hydrothermal systems (open-loop) - z = 1000-4000 m, T = 25-130 °C

⑨ Petrothermal systems (open-loop) - z = 4000-6000 m, T = 130-200 °C

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

Uses of geothermal systems

- Shallow geothermal systems: typically serve indirect heat uses
  - Use of machines or devices that modify the energy input transferred between the ground and the target environment
- Deep geothermal systems: typically serve direct heat uses
  - Do not use of machines or devices that modify the energy input transferred between the ground and the target environment

Shallow geothermal systems

(1) Horizontal geothermal boreholes (closed-loop) - z = 2-5 m, T = 8-12 °C

(2) Geothermal baskets (closed-loop) - z = 2-10 m, T = 8-12 °C

(3) Groundwater capture systems (open-loop) - z = 5-20 m, T = 8-12 °C

(4) Energy geostructures (closed-loop) - z = 10-50 m, T = 10-12 °C

(a) Energy piles (b) Energy tunnels (c) Energy walls

(5) Vertical geothermal borehole (closed-loop) - z = 50-300 m, T = 10-20 °C

(6) Vertical geothermal boreholes field (closed-loop) - z = 50-300 m, T = 10-20 °C

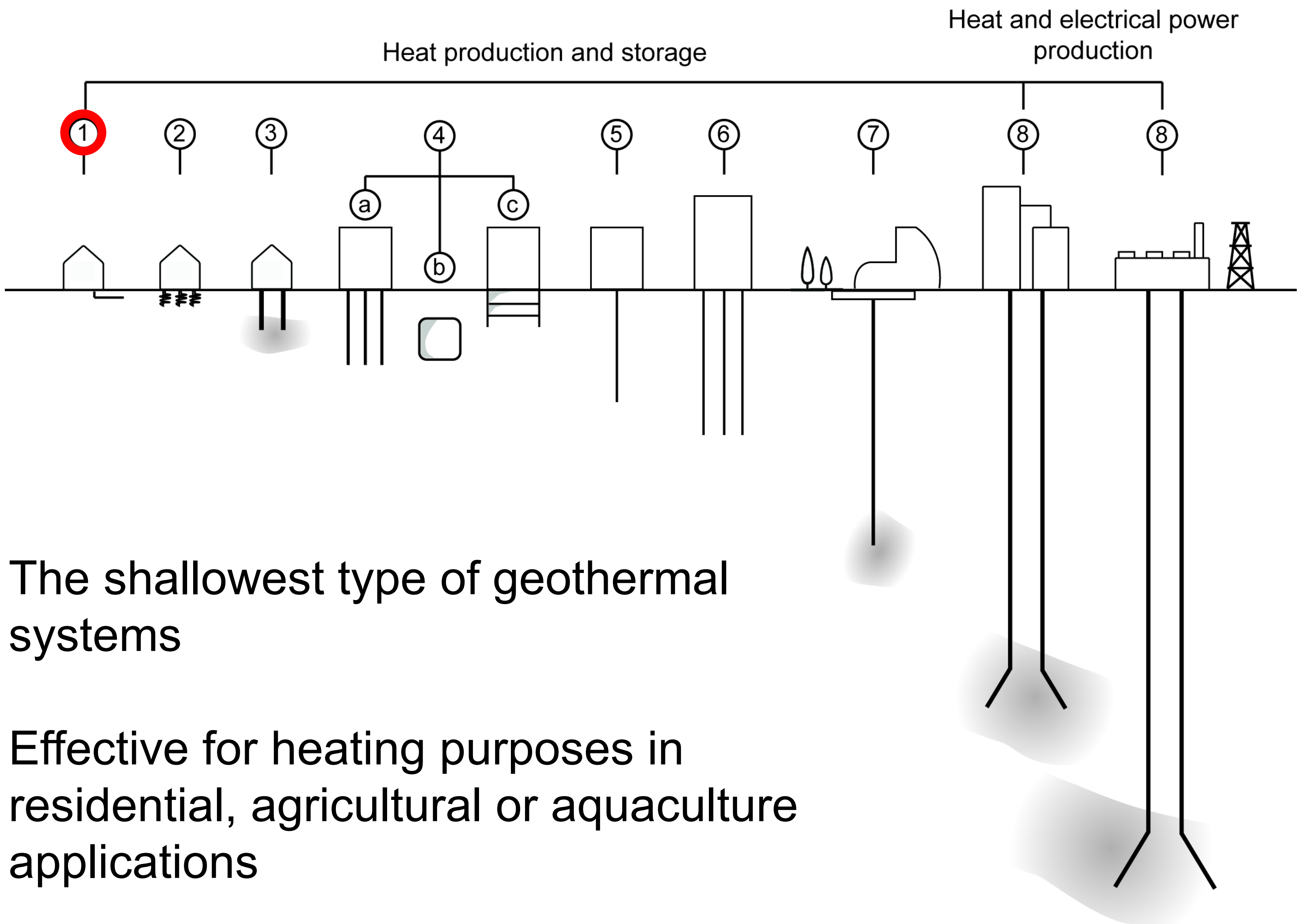
Deep geothermal systems

(7) Thermal springs (open-loop) - z = 500-1000 m, T = 25-80 °C

(8) Hydrothermal systems (open-loop) - z = 1000-4000 m, T = 25-130 °C

(9) Petrothermal systems (open-loop) - z = 4000-6000 m, T = 130-200 °C

Horizontal geothermal boreholes

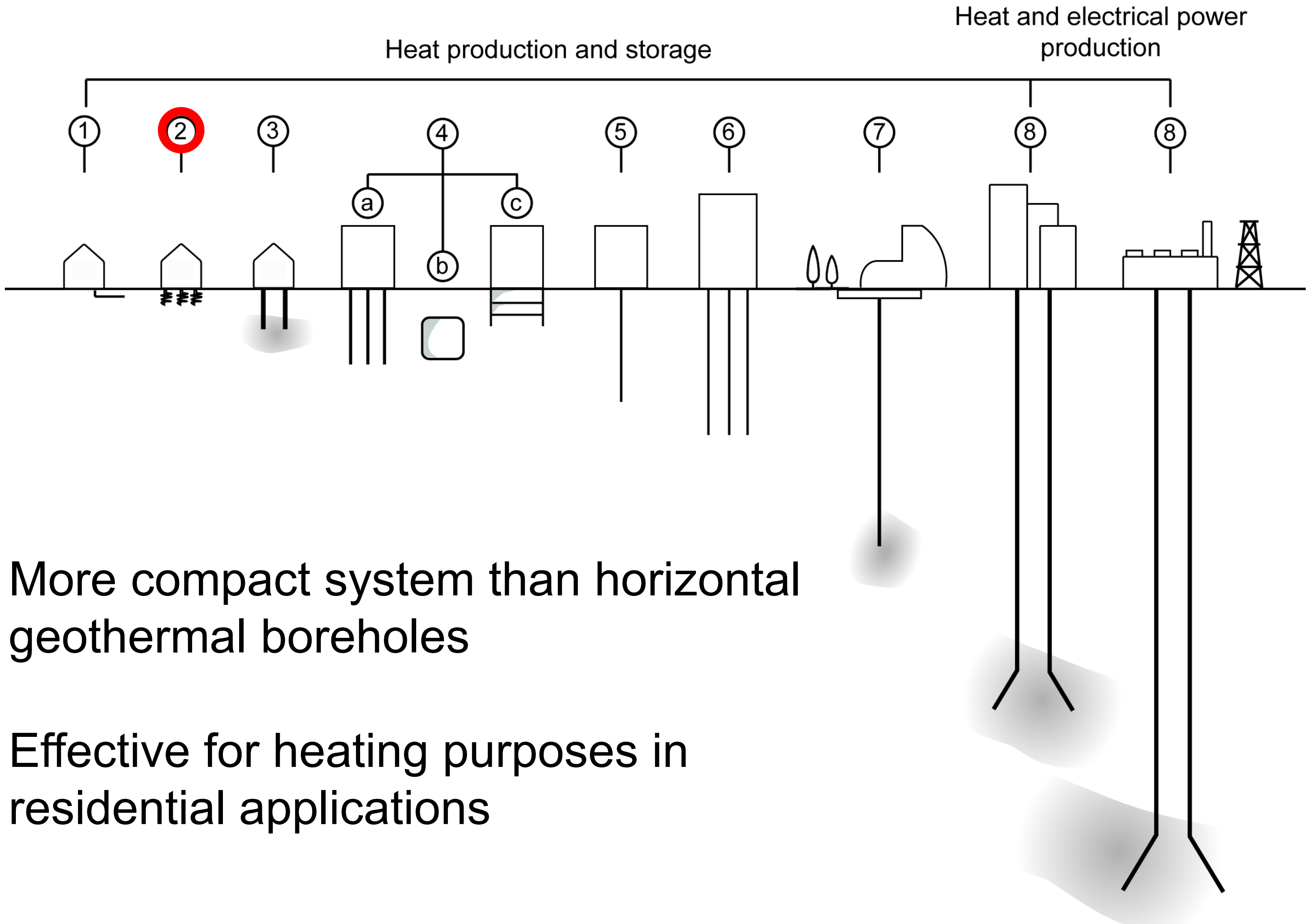


- The shallowest type of geothermal systems

- Effective for heating purposes in residential, agricultural or aquaculture applications

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

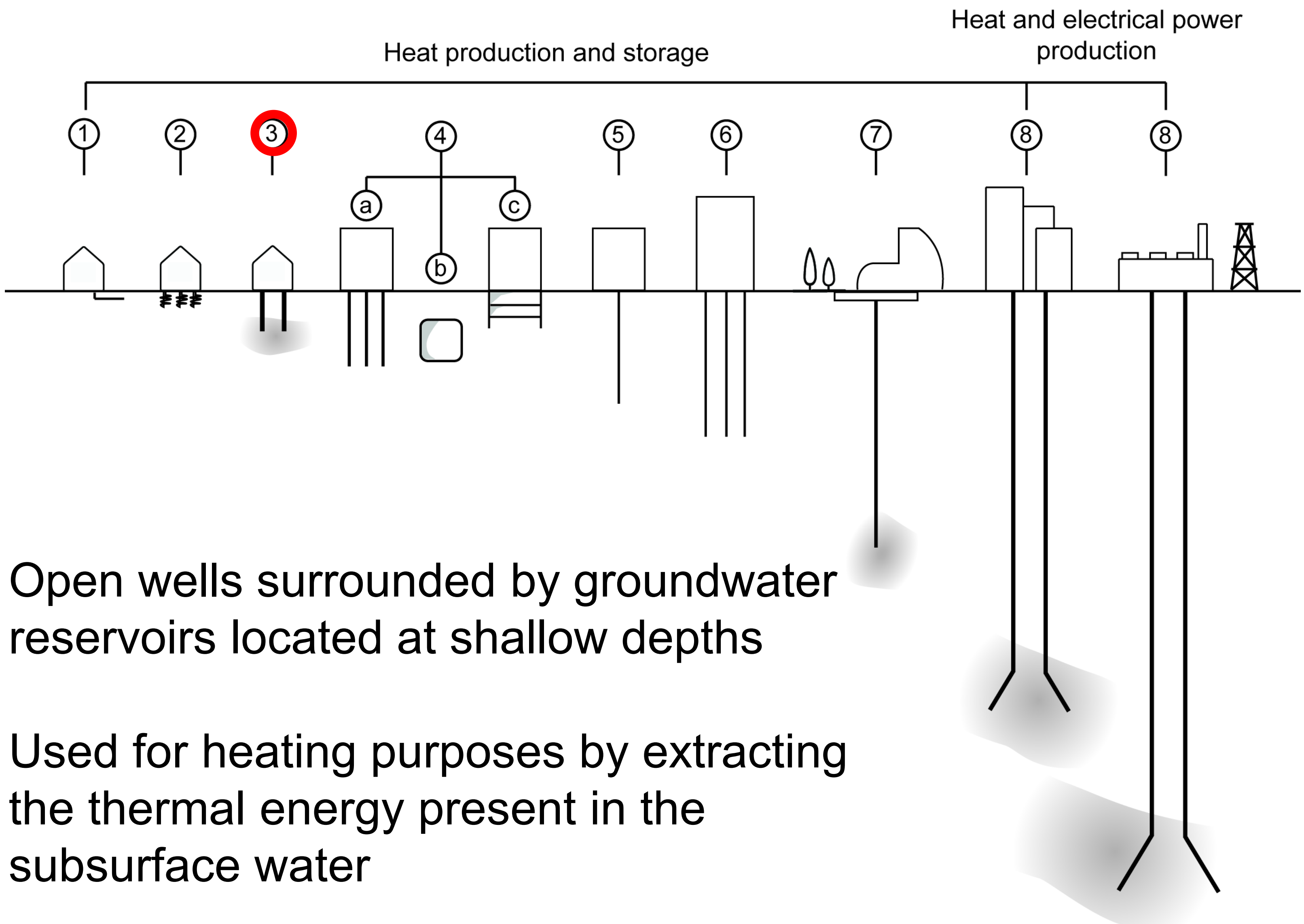
Horizontal baskets



- More compact system than horizontal geothermal boreholes
- Effective for heating purposes in residential applications

(Laloui and Rotta Loria, 2019;
redrawn after Geothermie Schweiz)

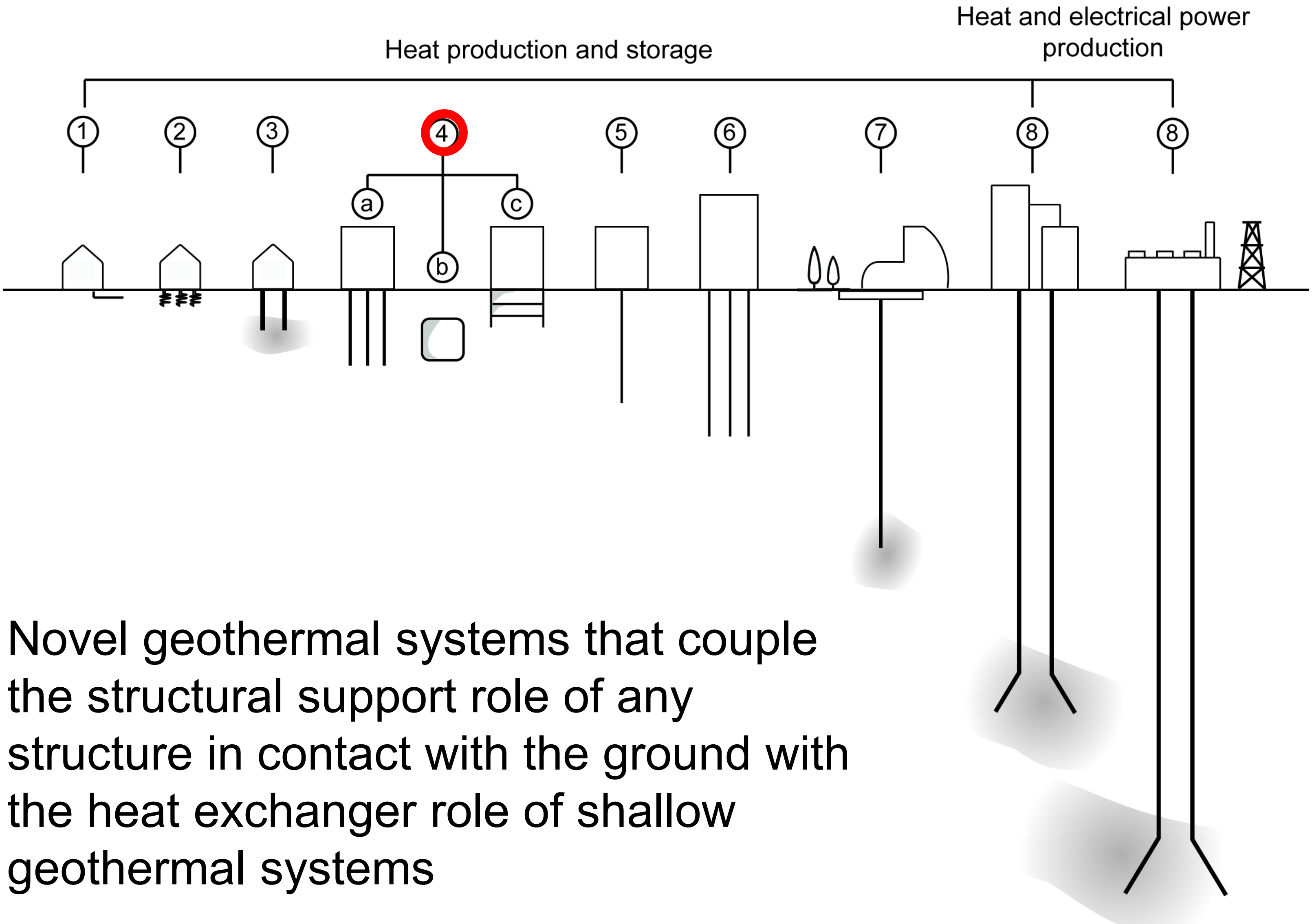
Groundwater capture systems



- Open wells surrounded by groundwater reservoirs located at shallow depths
- Used for heating purposes by extracting the thermal energy present in the subsurface water

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

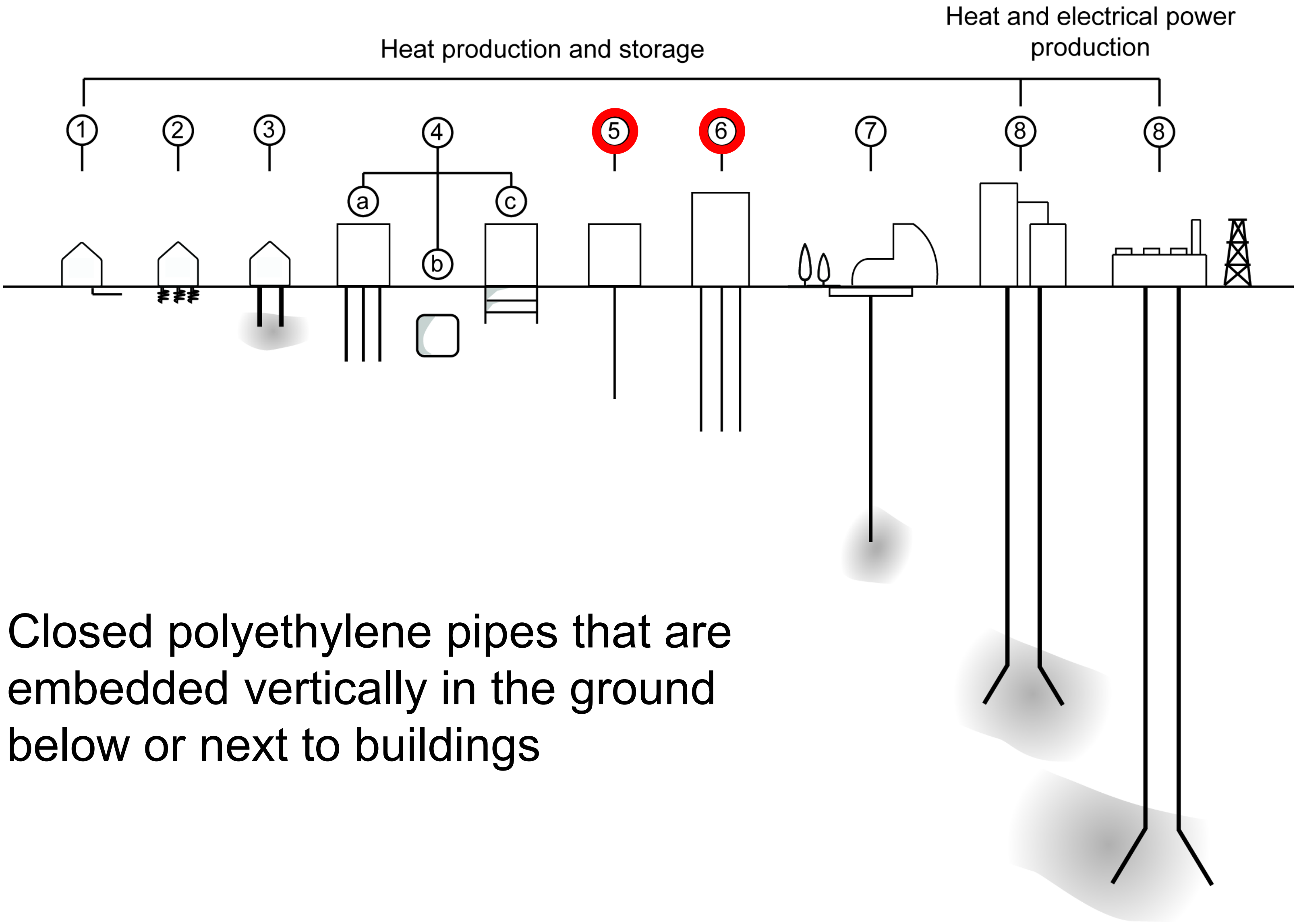
Energy geostructures



- Novel geothermal systems that couple the structural support role of any structure in contact with the ground with the heat exchanger role of shallow geothermal systems

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

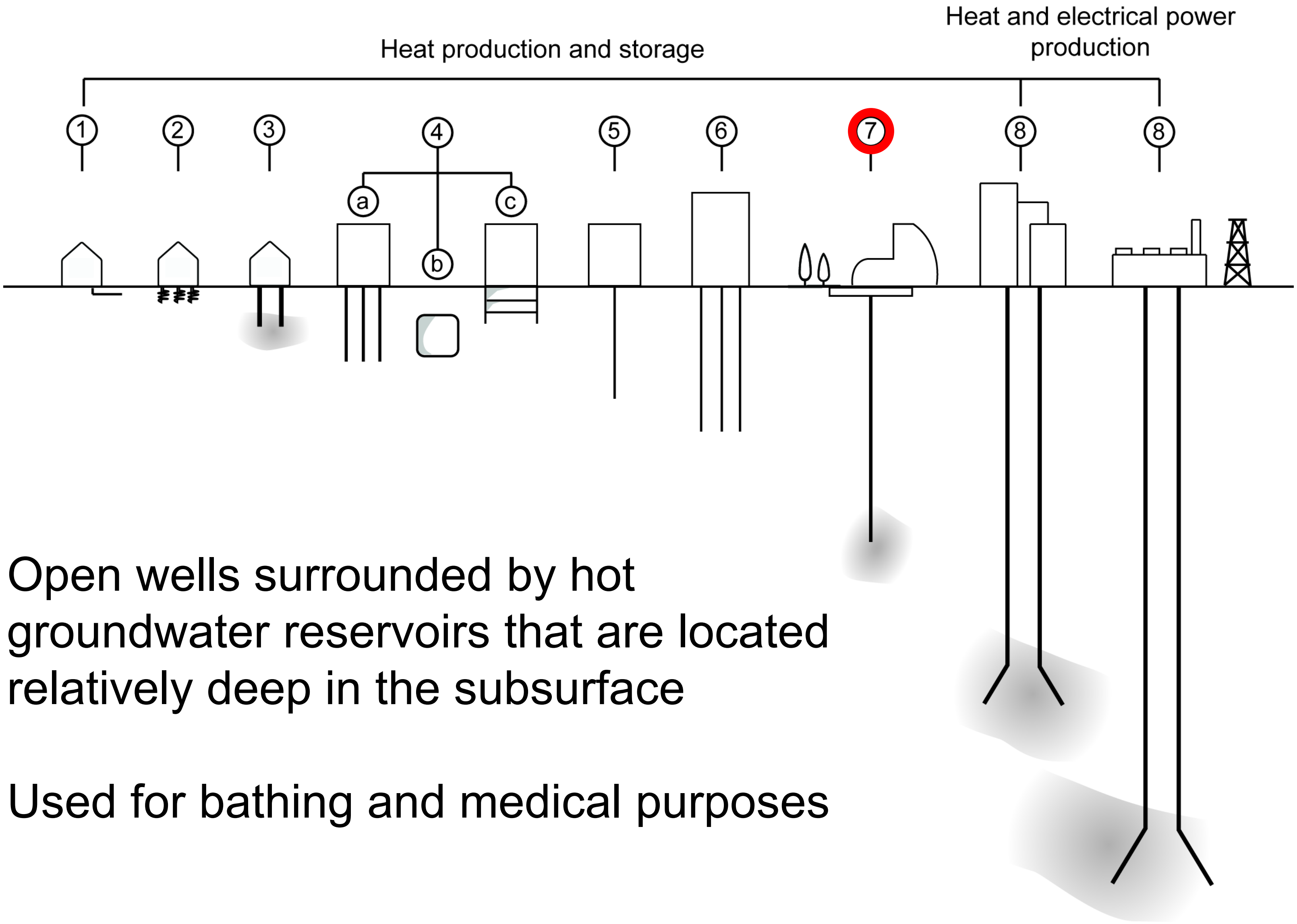
Geothermal boreholes (and fields)



- Closed polyethylene pipes that are embedded vertically in the ground below or next to buildings

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

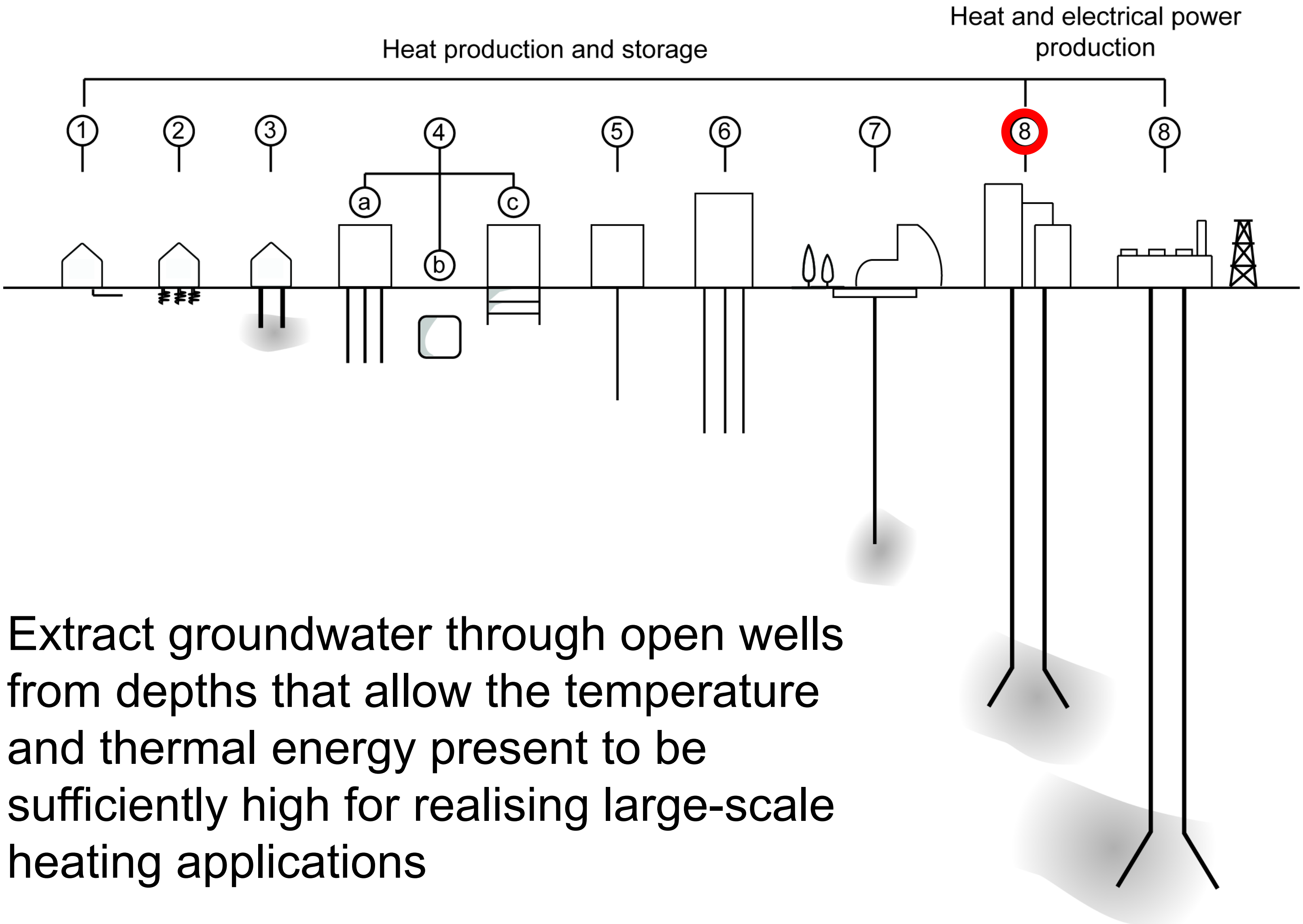
Thermal springs



- Open wells surrounded by hot groundwater reservoirs that are located relatively deep in the subsurface
- Used for bathing and medical purposes

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

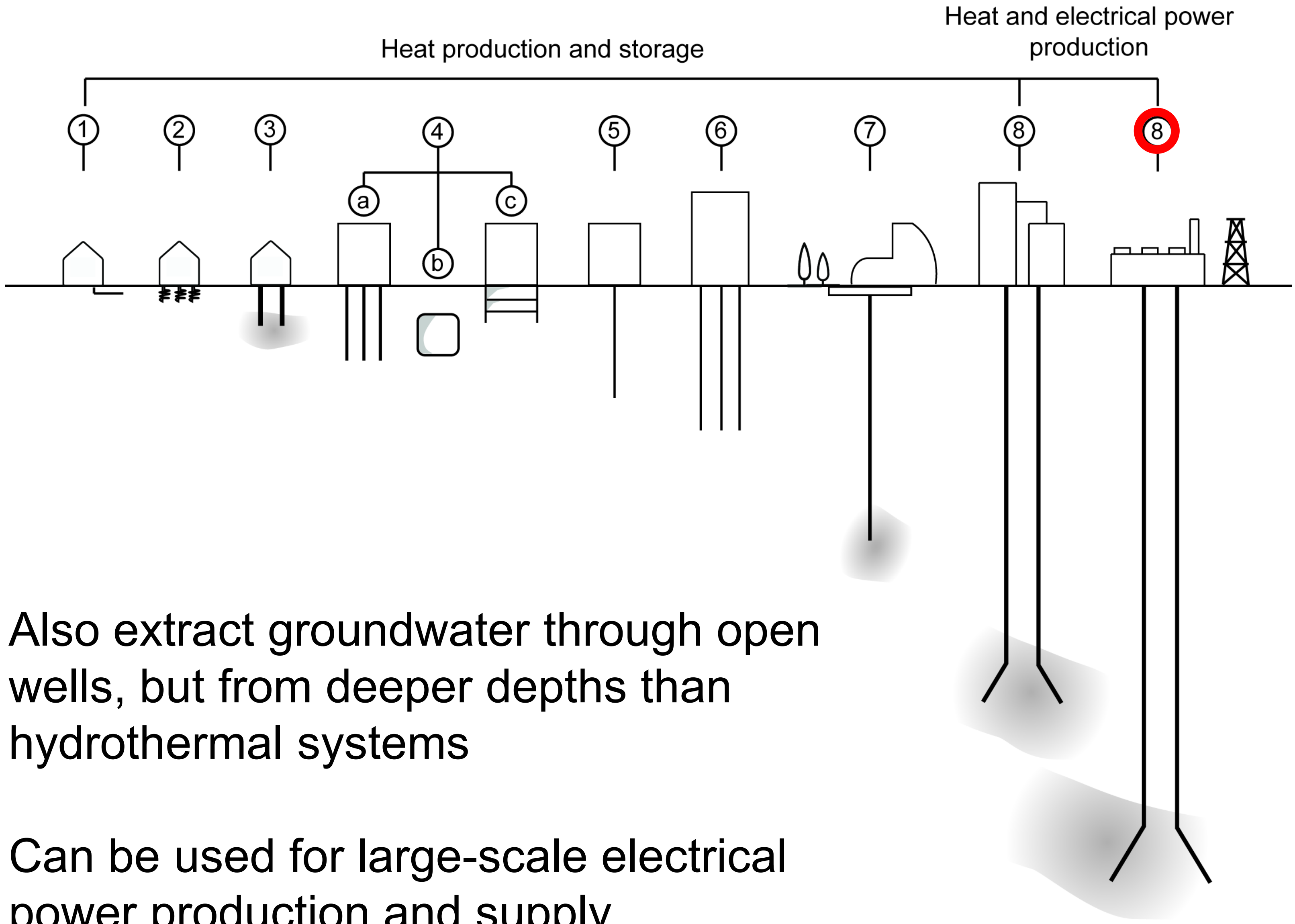
Hydrothermal systems



- Extract groundwater through open wells from depths that allow the temperature and thermal energy present to be sufficiently high for realising large-scale heating applications

(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

Petrothermal systems



- Also extract groundwater through open wells, but from deeper depths than hydrothermal systems
- Can be used for large-scale electrical power production and supply

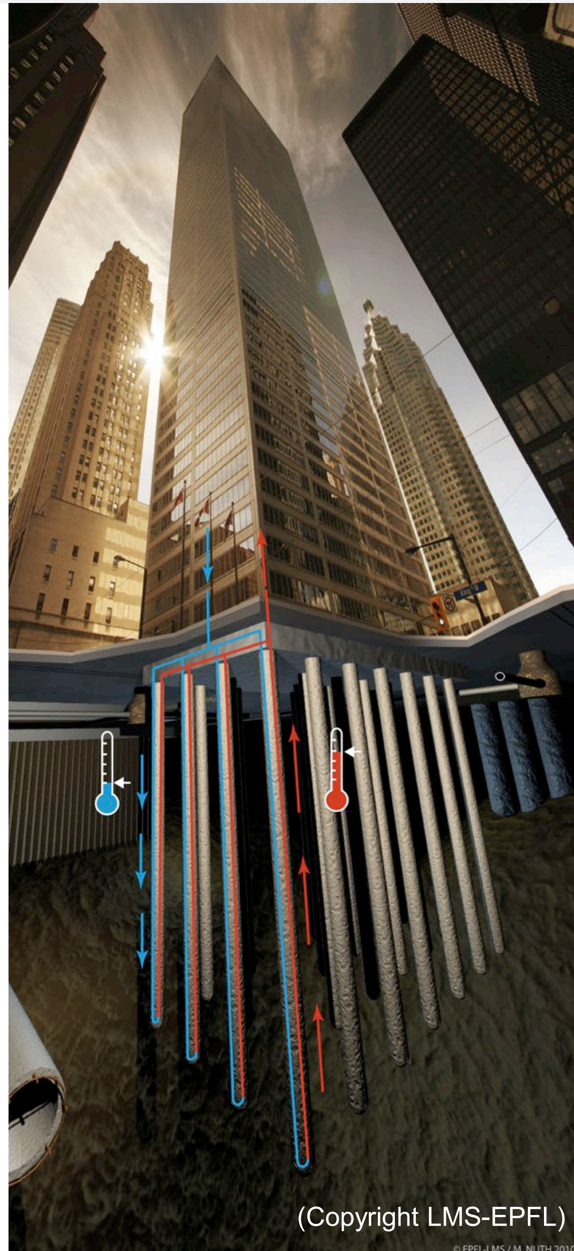
(Laloui and Rotta Loria, 2019; redrawn after Geothermie Schweiz)

Energy geostructures

Energy geostructures

All ground-embedded structures that can be used to exchange heat with the ground, e.g.,

- Energy piles
- Energy sheet pile walls
- Energy diaphragm walls
- Energy tunnels
- Energy anchors
- Energy pavements



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Energy piles and other energy geostructures

Concept

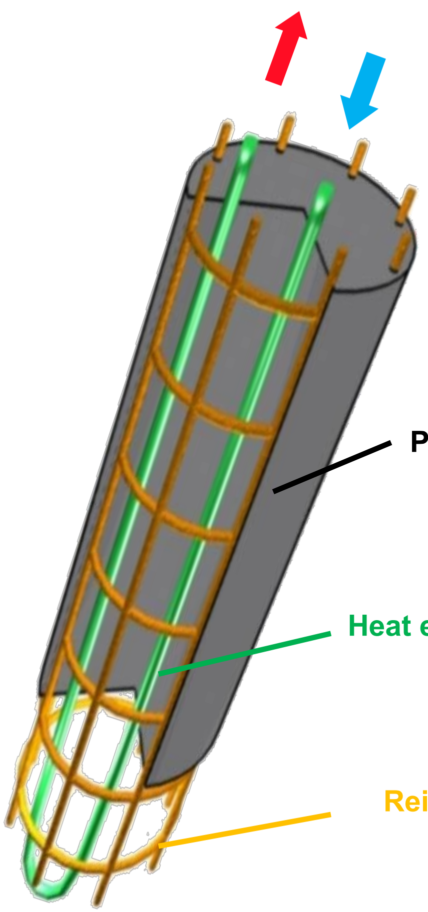
- Couple the structural support role of geostructures with the heating/cooling role of geothermal heat exchangers

Technology

- Pipes fixed along the reinforcing cage
- Heat carrier fluid flowing in the pipes

Purpose

- Provide superstructures with structural support and *renewable energy* supply:



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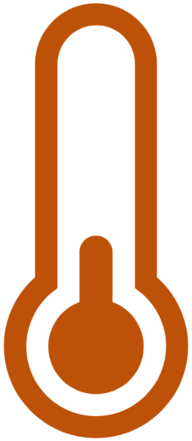
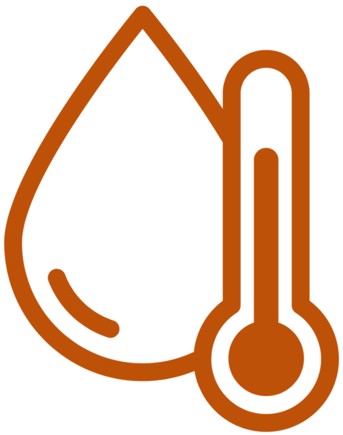
Uses of energy geostructures

Heating & cooling



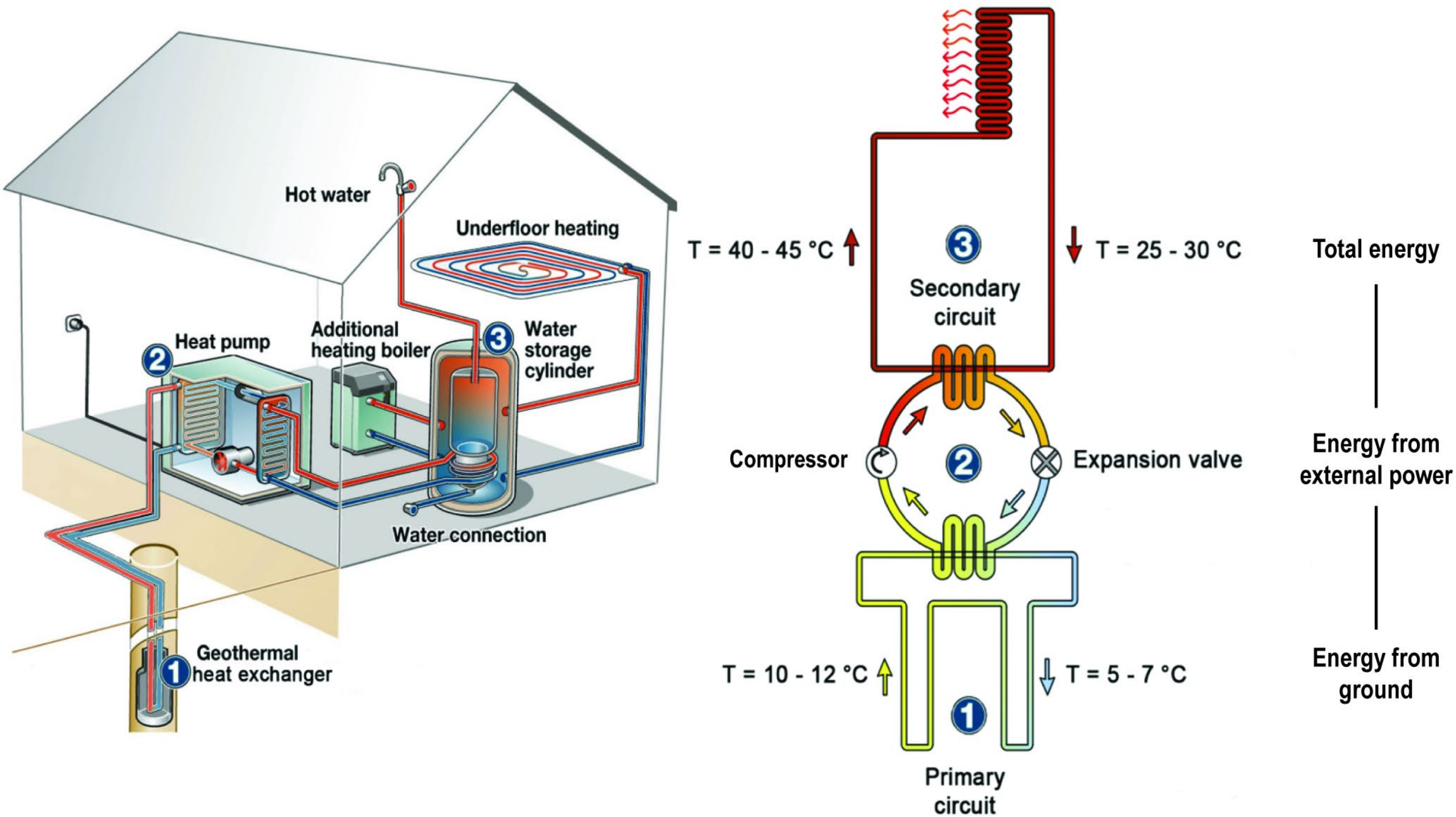
Hot water production



De-icing

Underground thermal energy storage

The Ground Source Heat Pump System



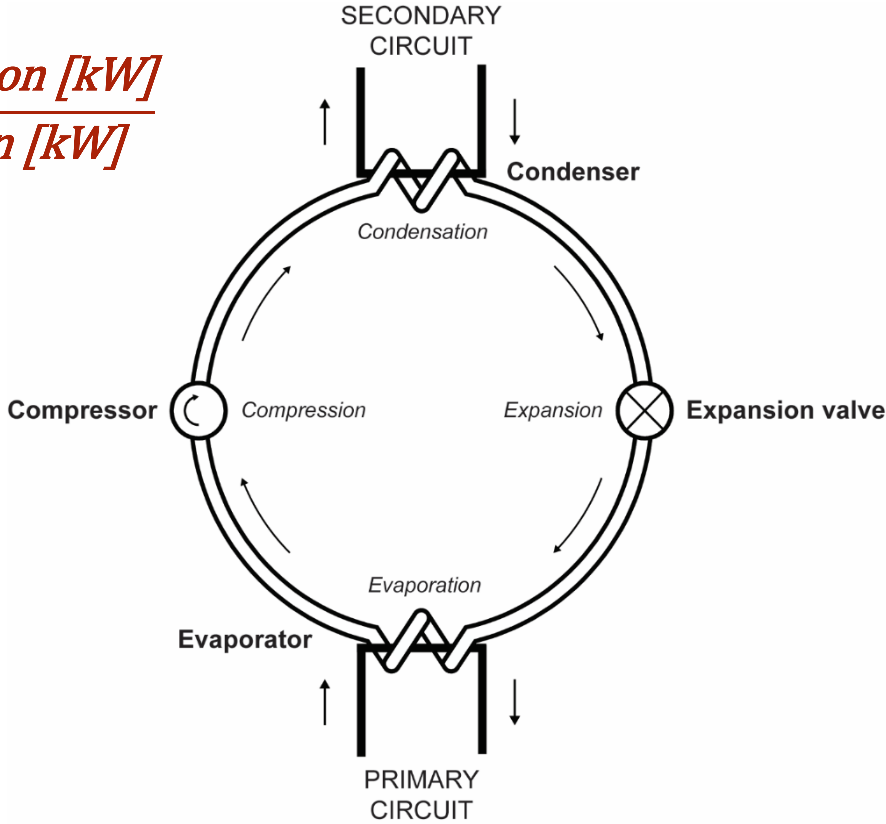
(Laloui and Rotta Loria, 2019;
modified after Agentur für Erneuerbare Energien)

The heat pump

$$COP = \frac{Energy\ output\ after\ heat\ pump\ operation\ [kW]}{Energy\ input\ for\ heat\ pump\ operation\ [kW]}$$

- The higher the COP, the lower the external energy input compared to the energy output (e.g., useful heat)

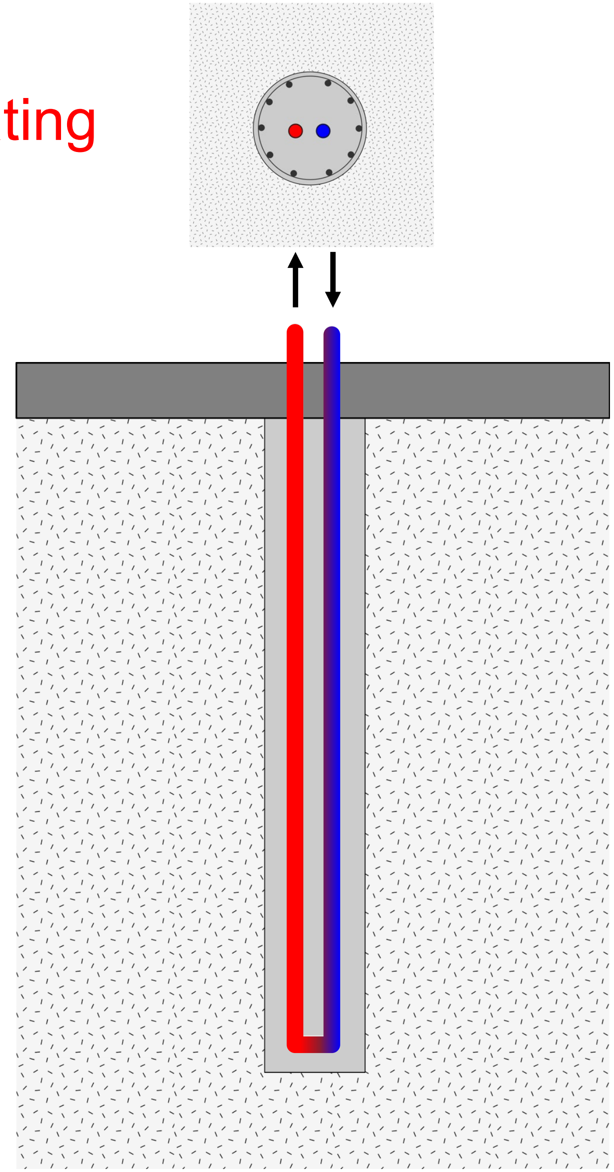
- A COP of 4 means that from one unit of electrical energy and three units of thermal energy, four units of usable energy are derived.



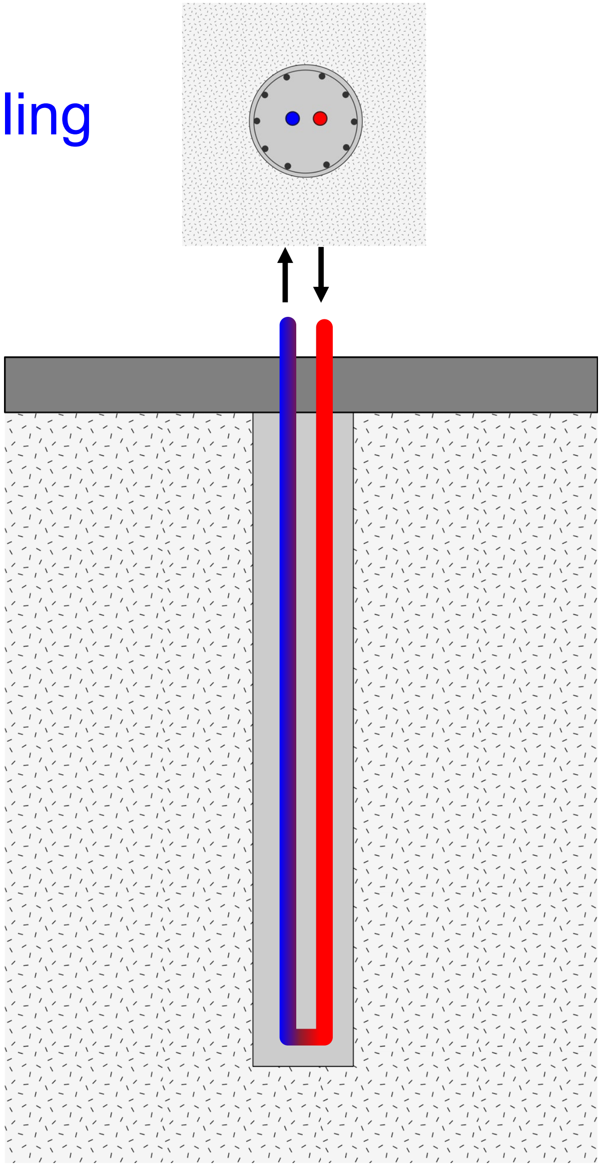
(Laloui and Rotta Loria, 2019)

Technological aspects: energy piles

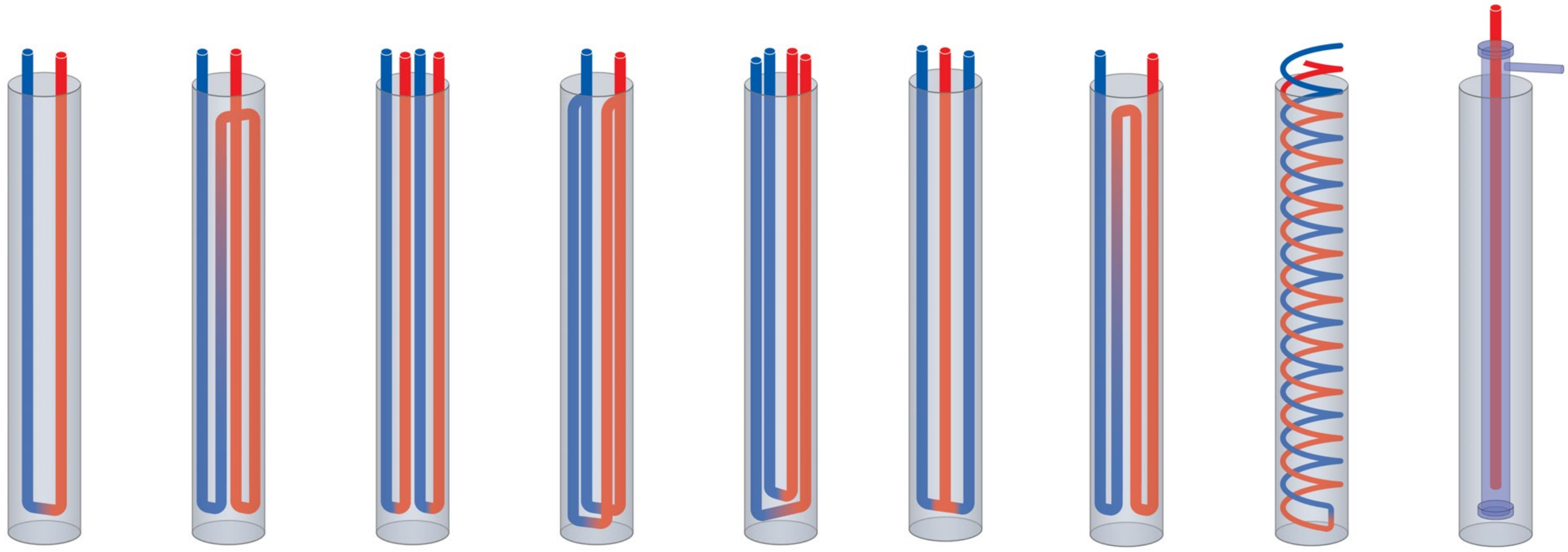
Heating



Cooling



Technological aspects: energy piles



Different pipe configurations can be employed and yield to a remarkable variation in the energy performance of such systems

(Laloui and Rotta Loria, 2019)

Technological aspects: energy piles

Materials

- Typically made of reinforced concrete
- Plastic pipes made of high-density polyethylene (d_p of 17-40 mm)
- Heat carrier fluid made of water with antifreeze

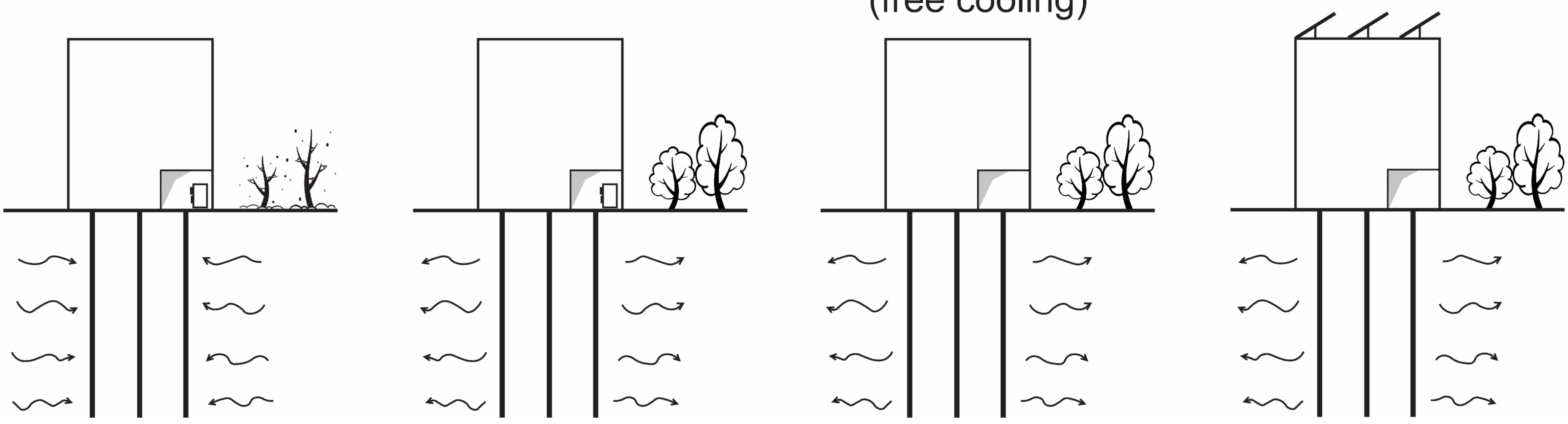
Dimensions (e.g., energy piles)

- Lengths of up to L = 50 m
- Diameters from D = 0.3 to 1.5 m
- Slenderness ratios of L/D = 20-150

Dimensions (e.g., borehole heat exchangers)

- Lengths of up to L = 200 m
- Diameters from D = 0.2 to 0.4 m
- Slenderness ratios of L/D = 200-1000

Typical applications: energy piles

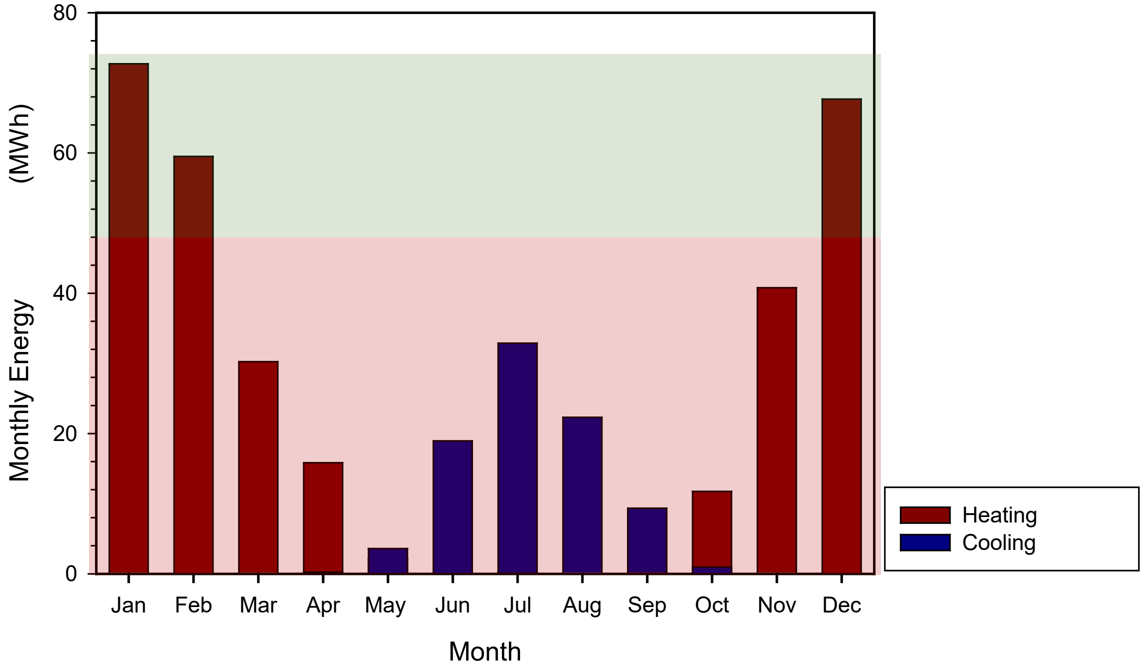


Heat extraction with heat pump	Heat injection with reversed heat pump	Heat injection without heat pump (free cooling)	Heat injection (storage)
40-60 W/m	50-100 W/m	20-40 W/m	100-150 W/m
T_{EP} = 2-15 °C	T_{EP} = 25-35 °C	T_{EP} = 10-16 °C	T_{EP} = 35-50 °C

Energy geostructures can be effectively coupled with other technologies harvesting renewable energy (e.g., thermal solar panels)

(Laloui and Rotta Loria, 2019)

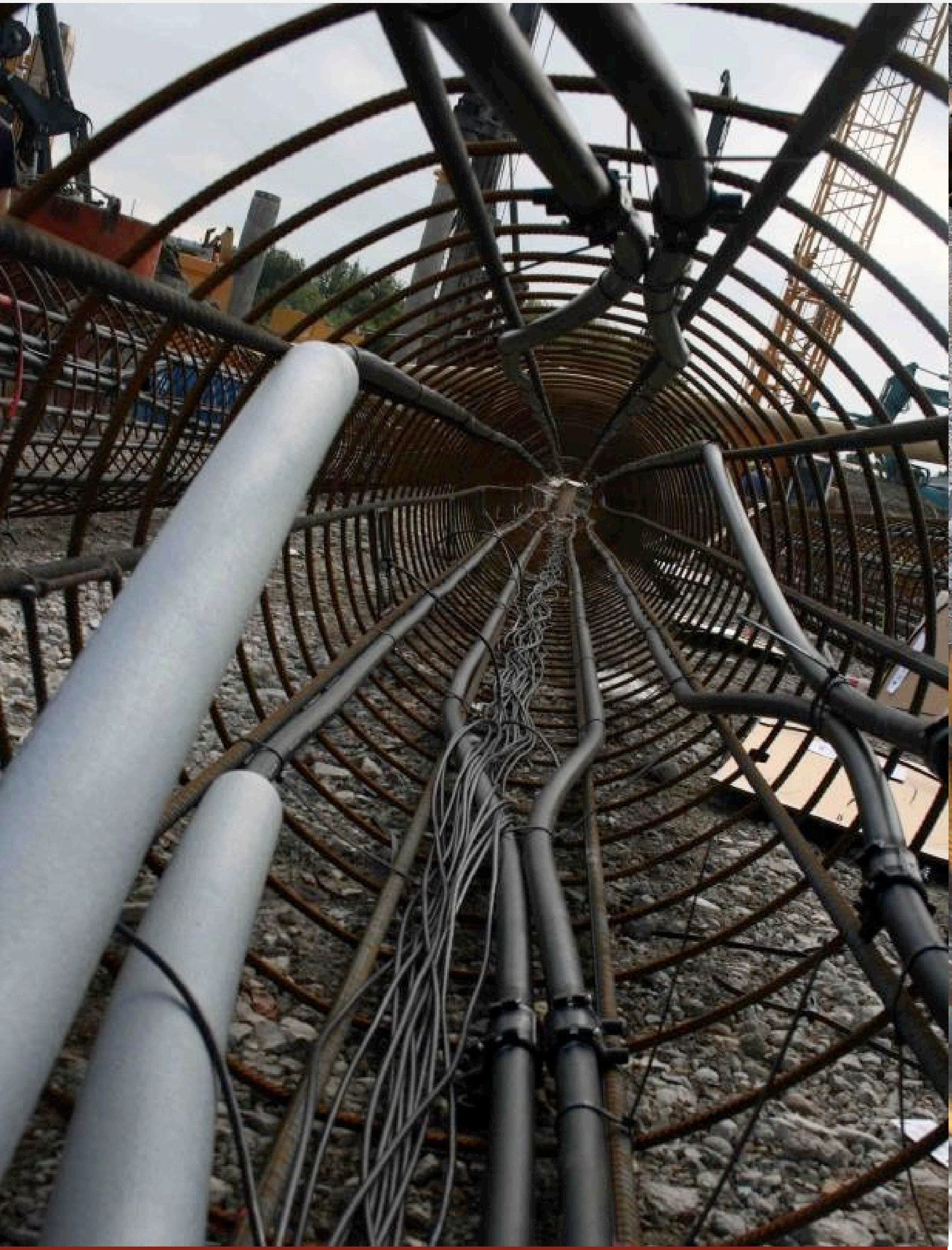
Typical applications: energy piles

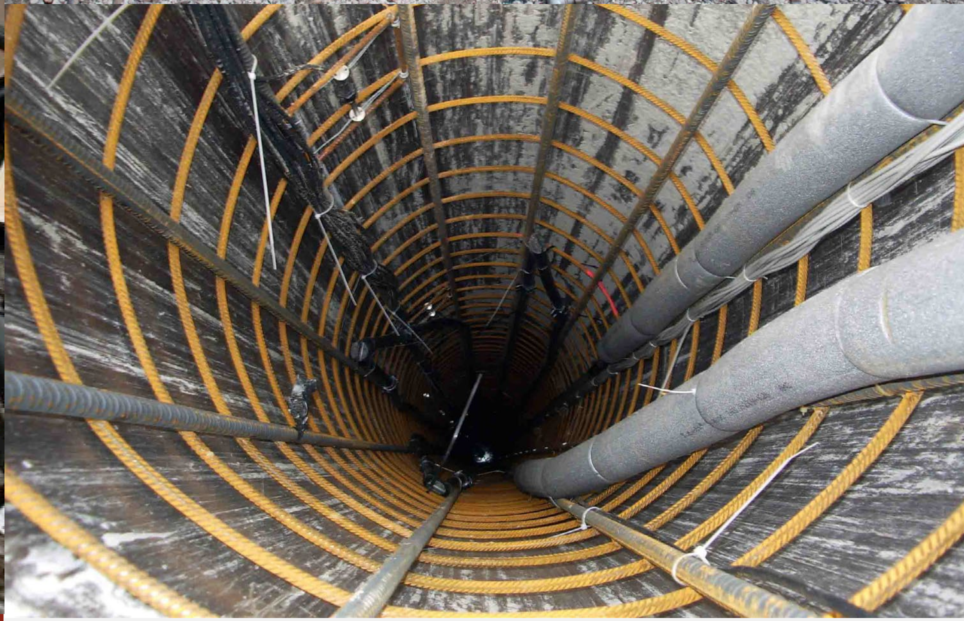


Geothermal energy supply for a typical office building in Europe

As a conservative example (30 W/m), energy piles can supply 60% of heating and 100% of cooling needs of a five-storey office building in Europe by coupling energy geostructures with a GSHP system

The technology: energy piles





The technology: energy piles

The Swiss Tech Convention Center energy piles

The technology: energy piles

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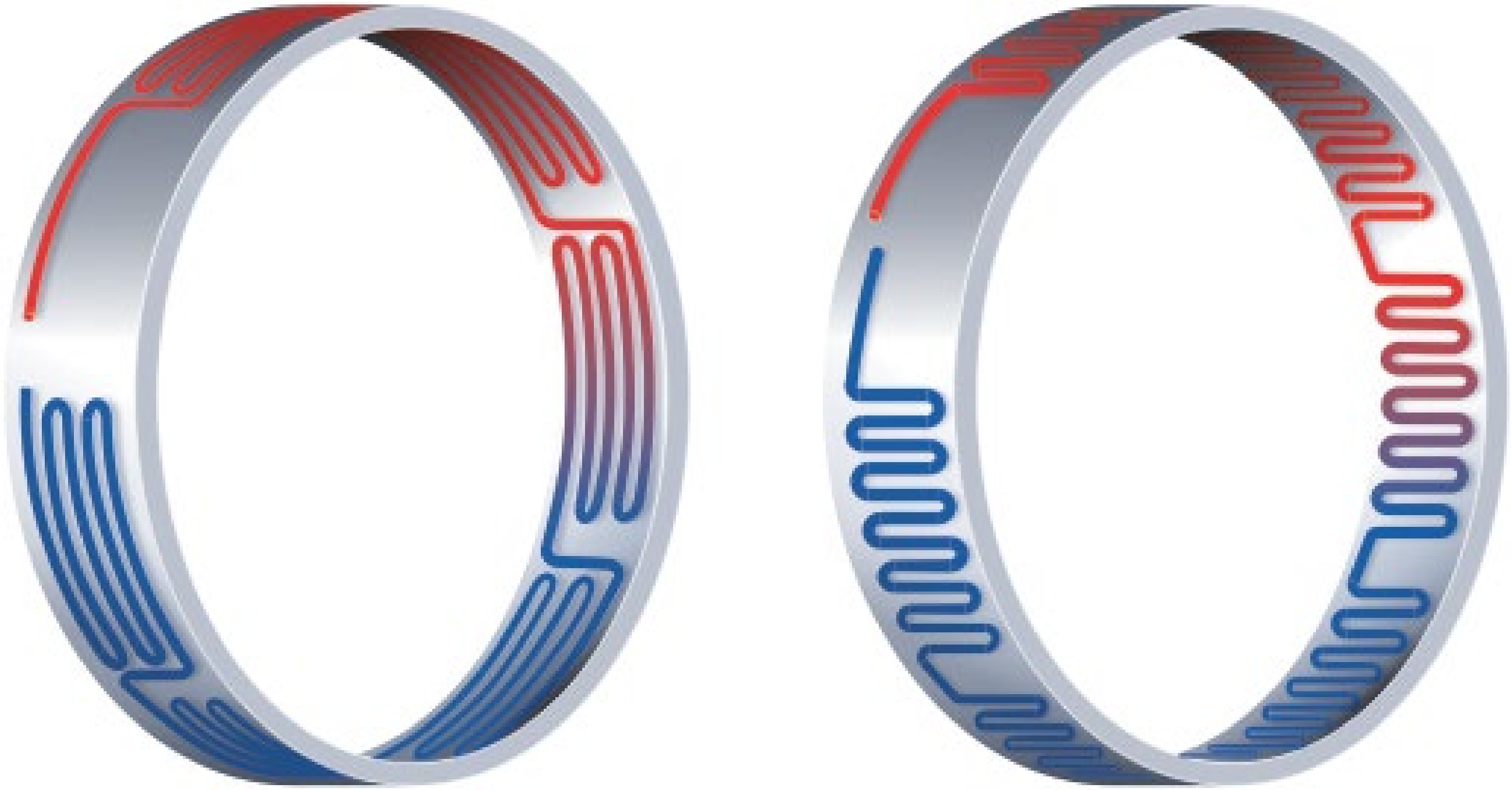
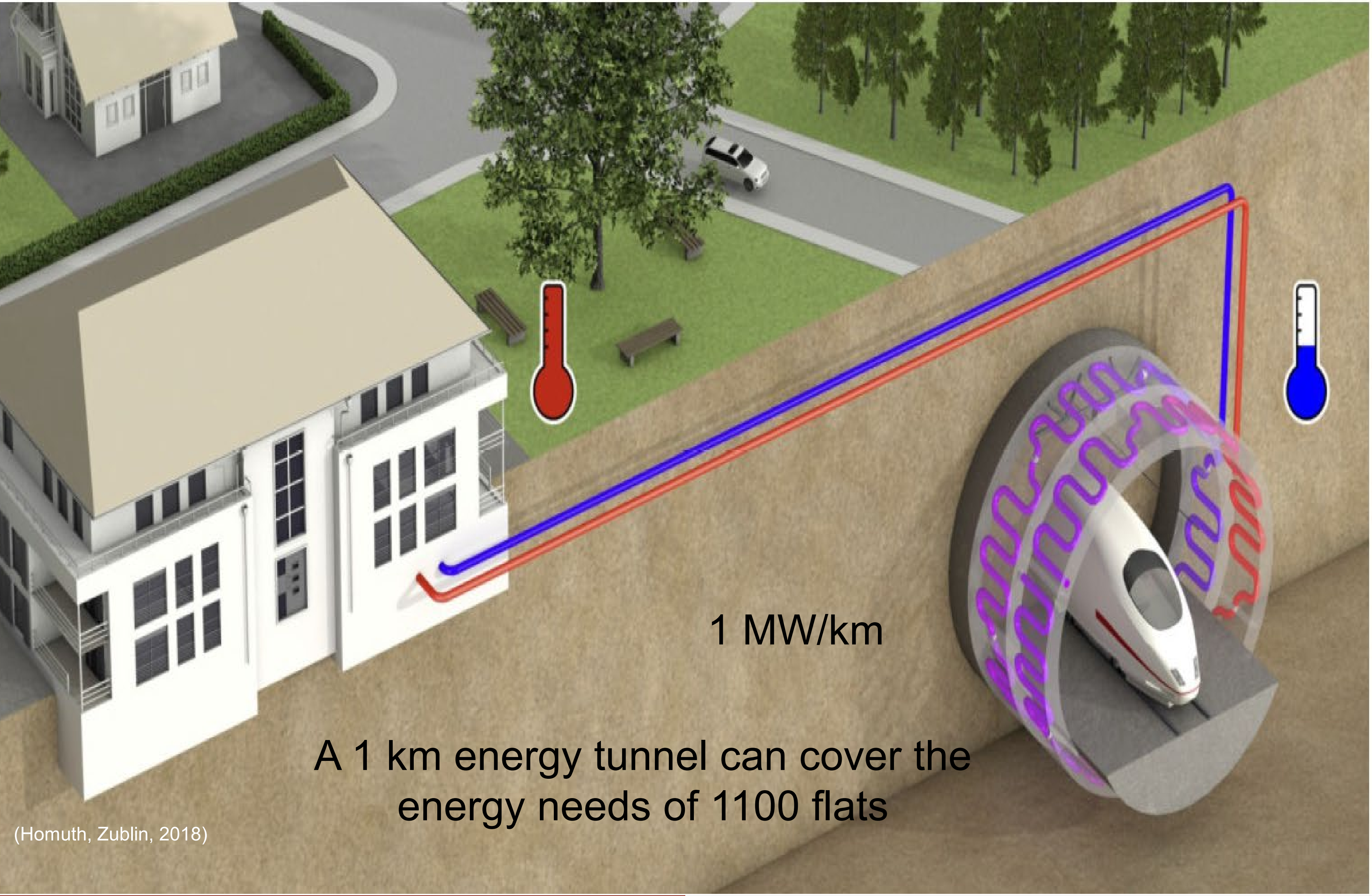
Technological aspects: energy tunnels



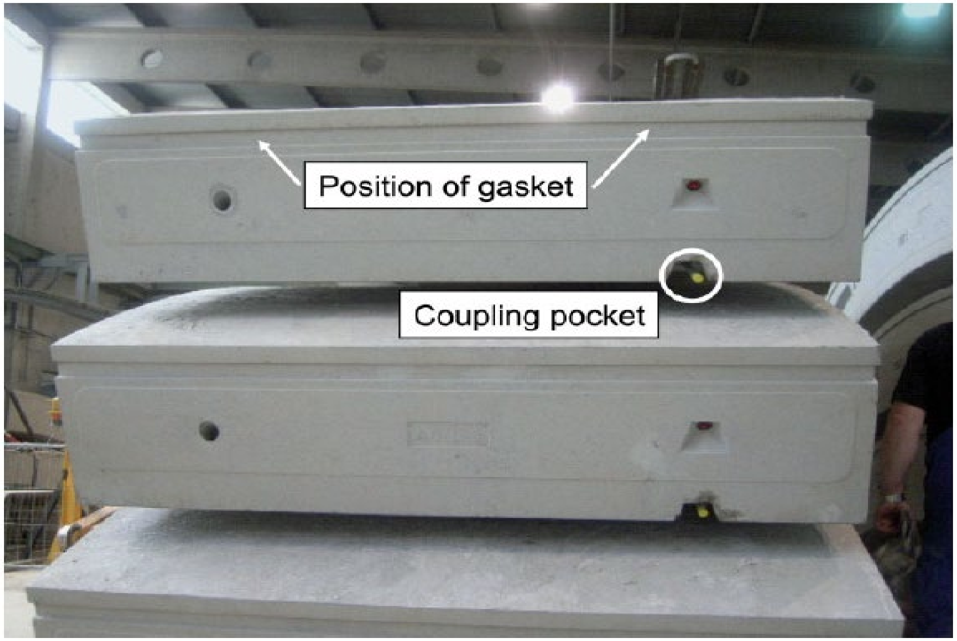
(Laloui and Rotta Loria, 2019)

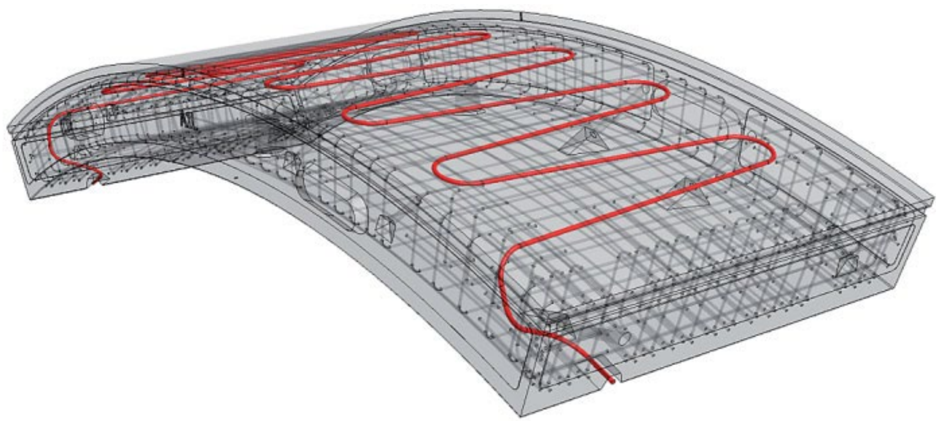
Typical applications: energy tunnels



The technology – energy tunnels

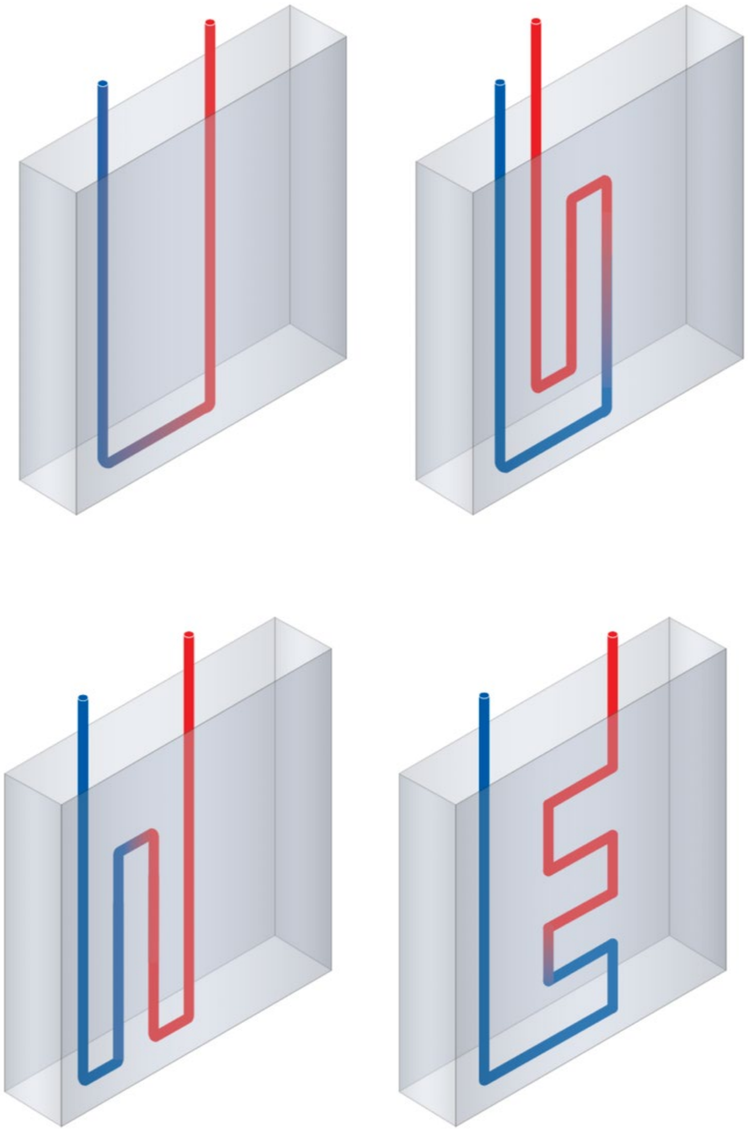
(Frodl et al., 2010)

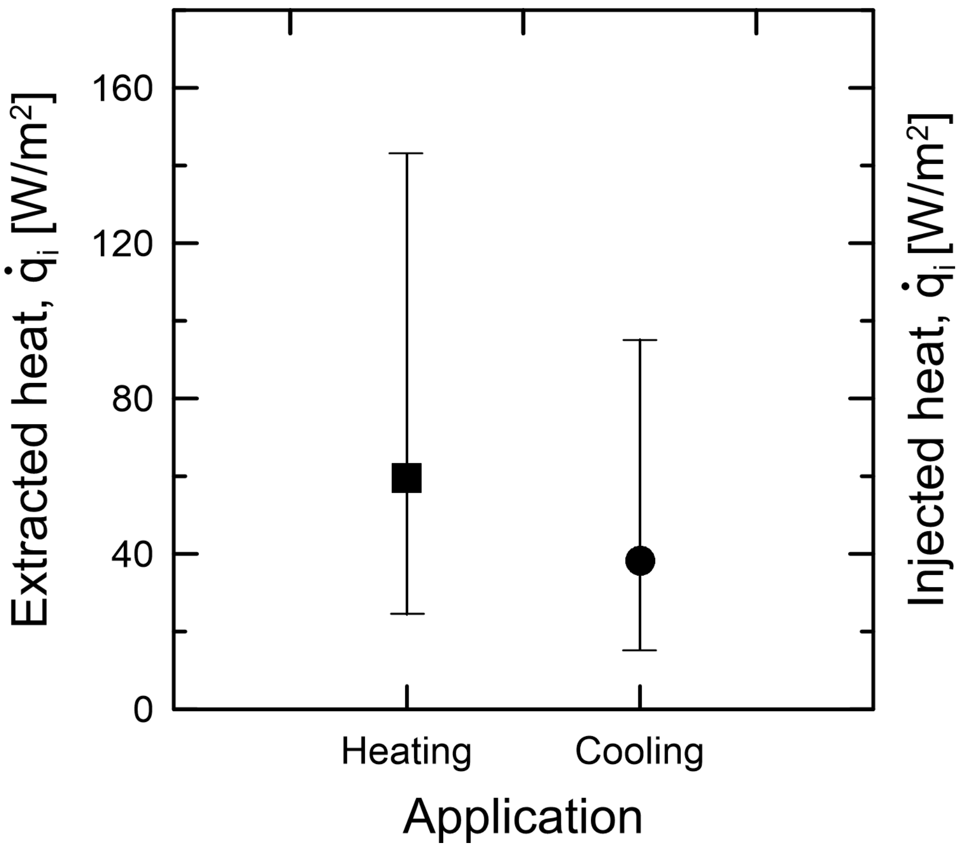




Technological aspects: energy slabs and walls

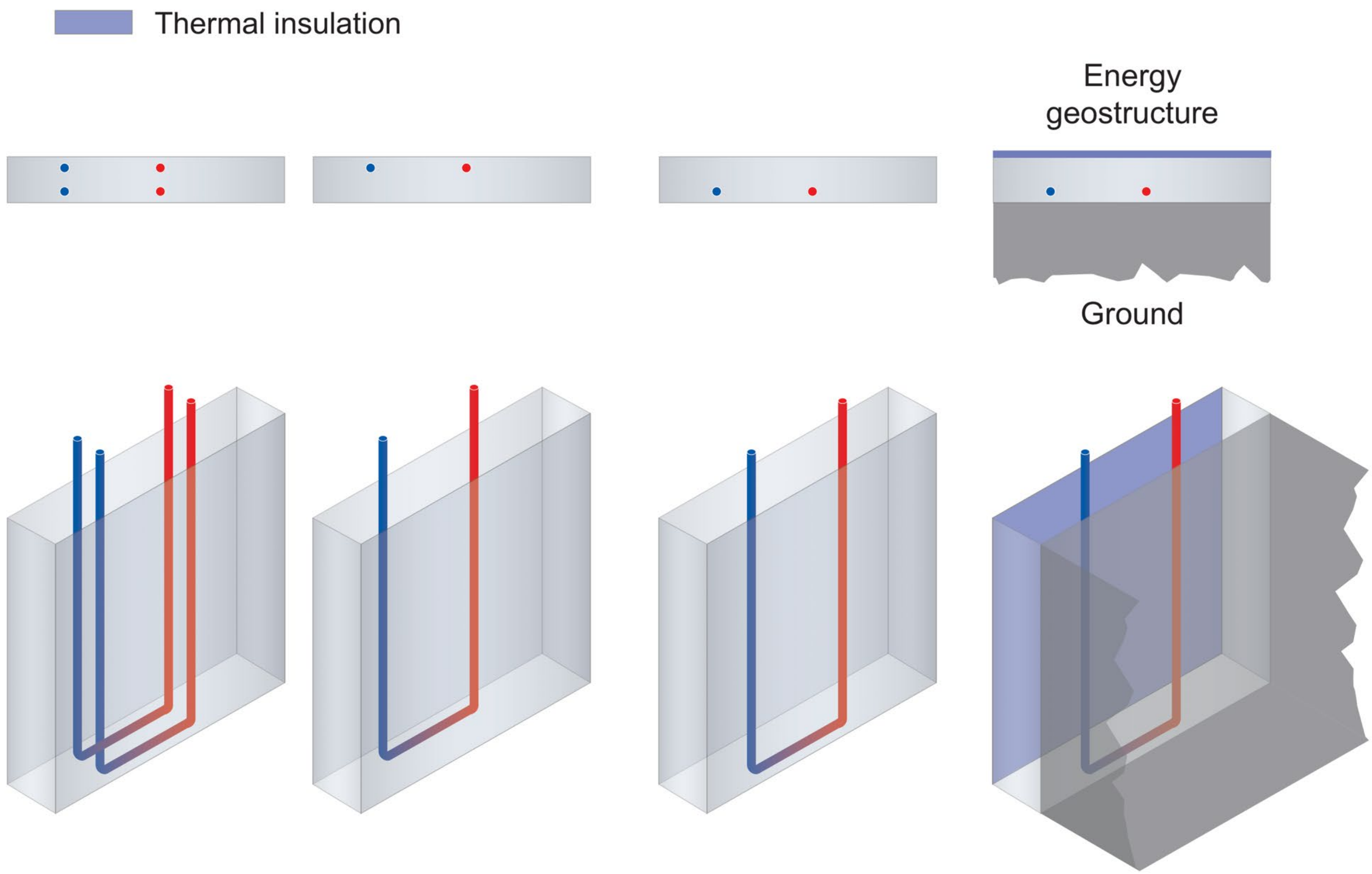
(Laloui and Rotta Loria, 2019)





Technological aspects: energy slabs and walls

(Laloui and Rotta Loria, 2019)



Heat can be exchanger from both sides of the geostructures or just from one side depending on the environmental conditions

The technology: energy slabs and walls

The technology – energy pavements

- Aimed to guarantee the same road surface conditions along the year
- Supply temperature of heat transfer fluid lies generally below 10°C
- The typical average heat output of the system is around 100 W/m^2

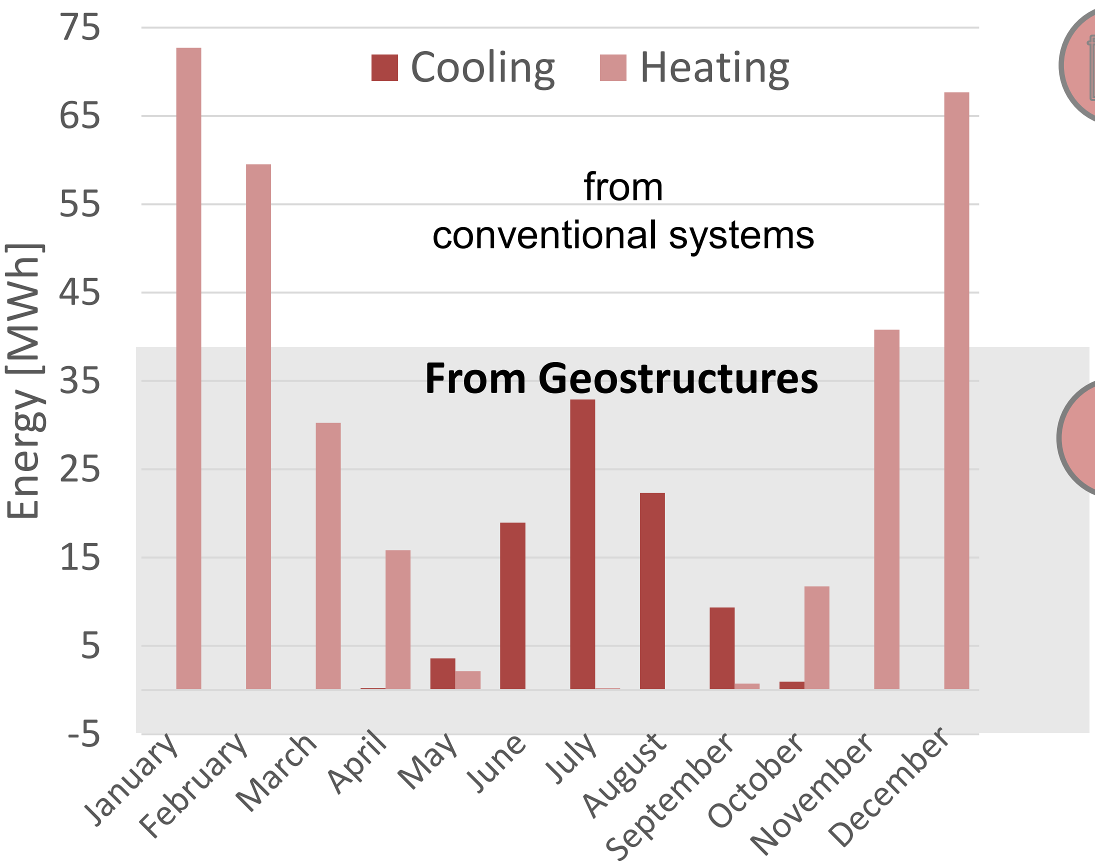
The technology – energy pavements and slabs

The technology – energy pavements and slabs

Comparison with conventional geothermal technologies

- In contrast to conventional geothermal systems, energy geostructures are already required for structural reasons
- They allow achieving savings with respect to separate applications of structures and geothermal technologies
- Heat exchange is more favourable in energy geostructures: concrete has more favourable thermal properties than the grout of conventional heat exchangers, e.g., bentonite
- Energy geostructures do not rely on the geothermal heat flux but only on the constant temperature in the ground
- Energy geostructures provide heating and cooling and can employ the ground as a heat source/sink

Example



5 floors Building

Administrative

2400 m^2 of heated area

Energy supply

60% of heating needs

100% of the cooling requirements

Development – energy piles

UK – London – The One New Change

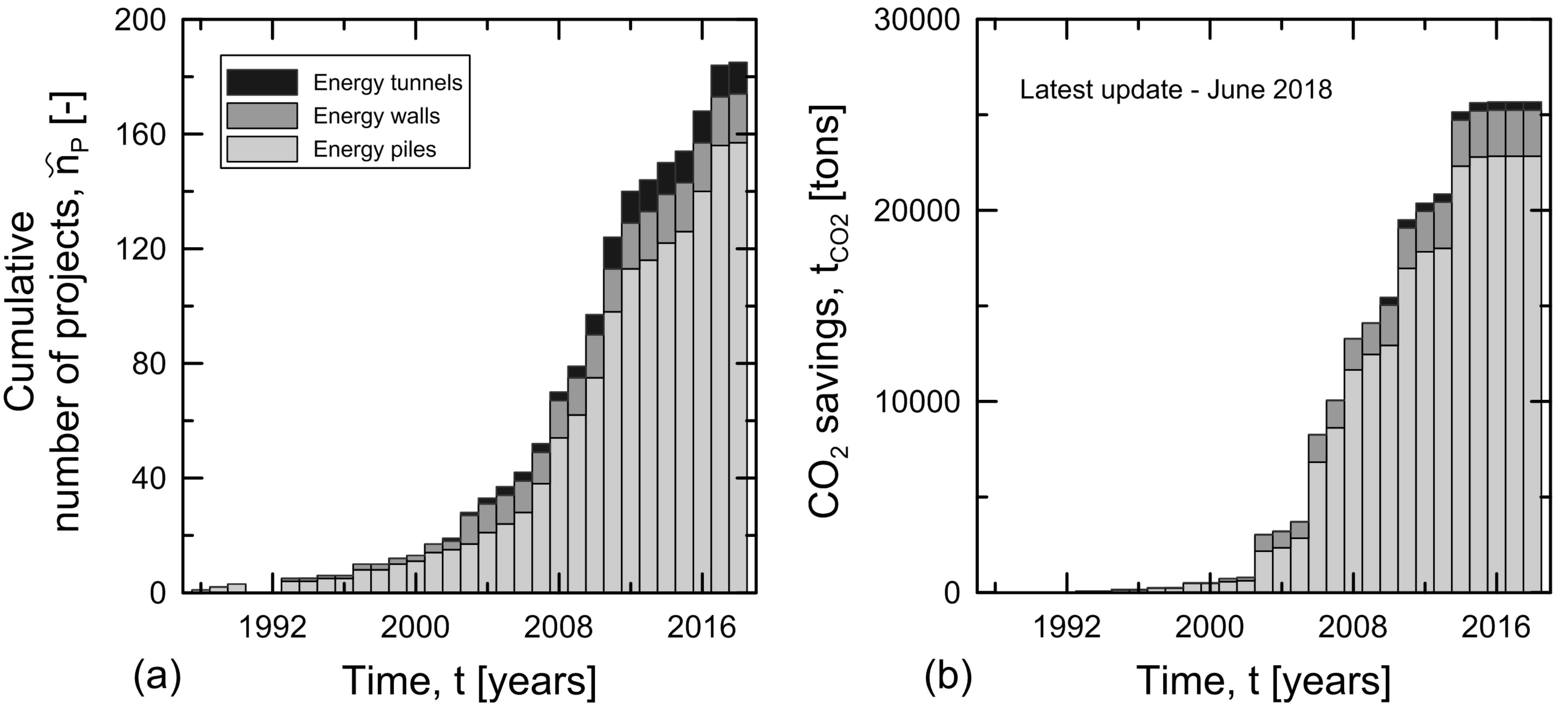
Switzerland – Zürich
The Dock Mielfield Zürich Airport

Austria - Vienna – The UNIQUA Tower

China – Shanghai – The Shanghai Tower

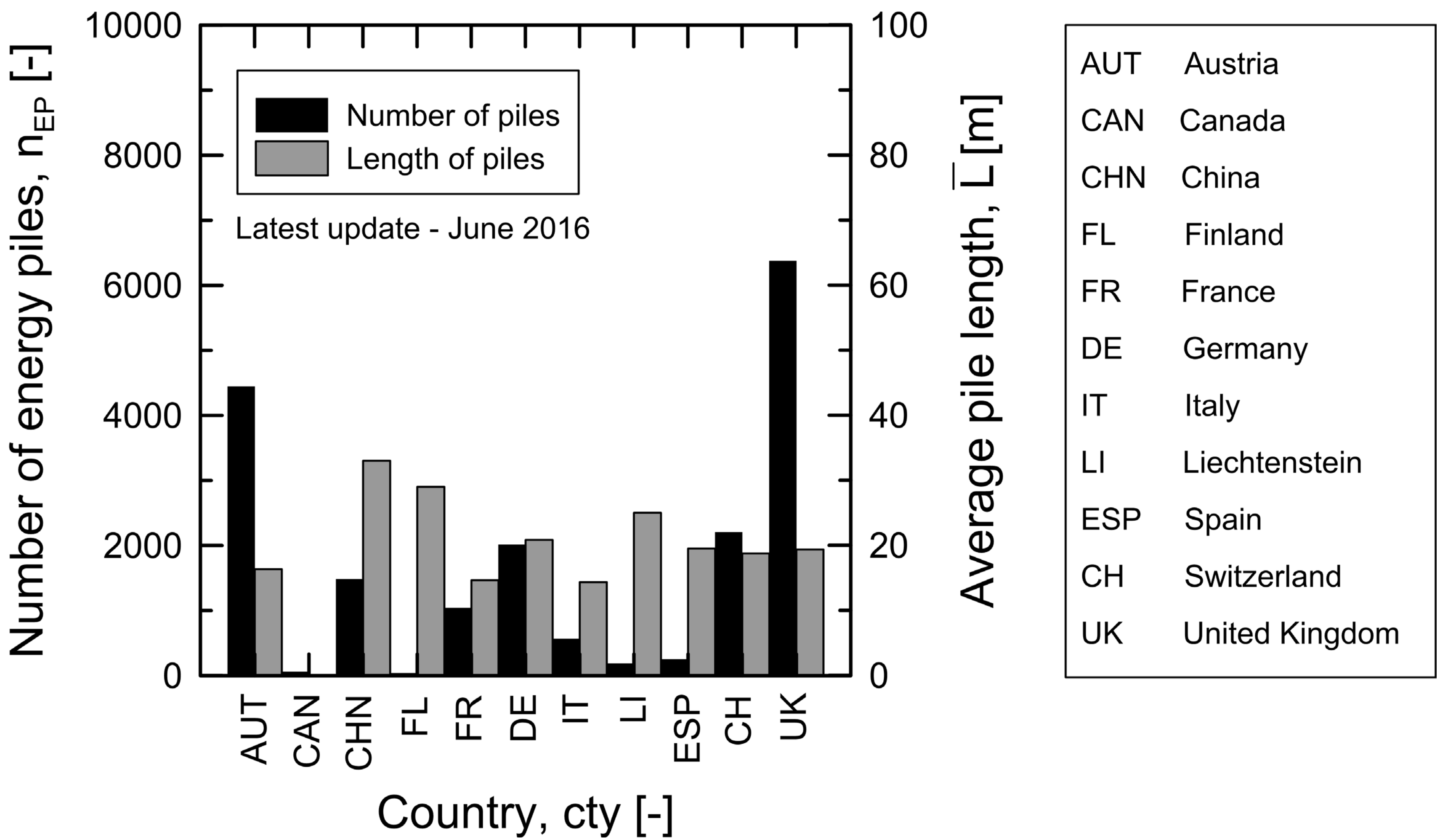
Germany – Frankfurt - The Main Tower

Development – energy piles



(Laloui and Rotta Loria, 2019)

Development – energy piles

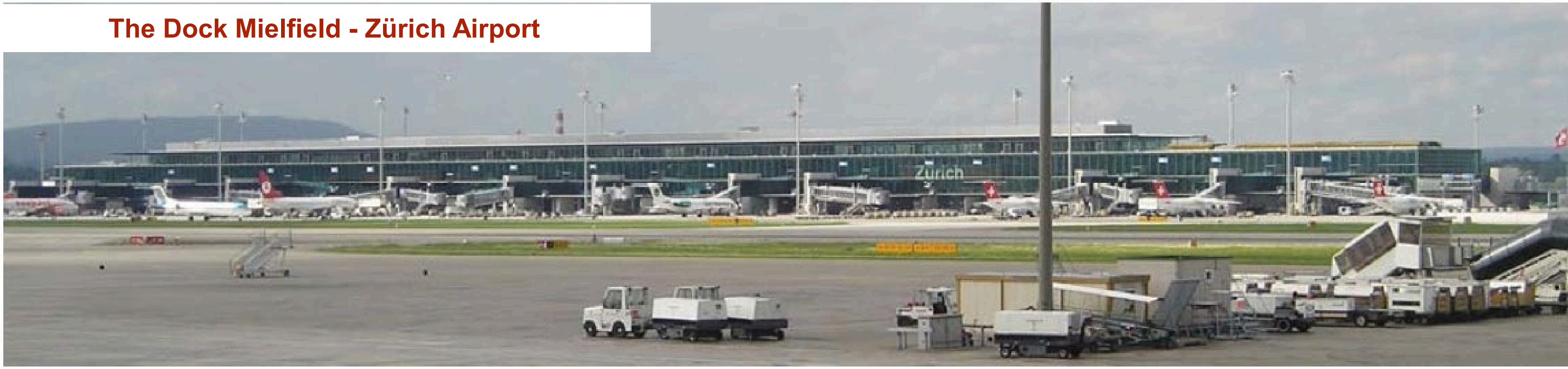


(Laloui and Rotta Loria, 2019)

Development – energy piles

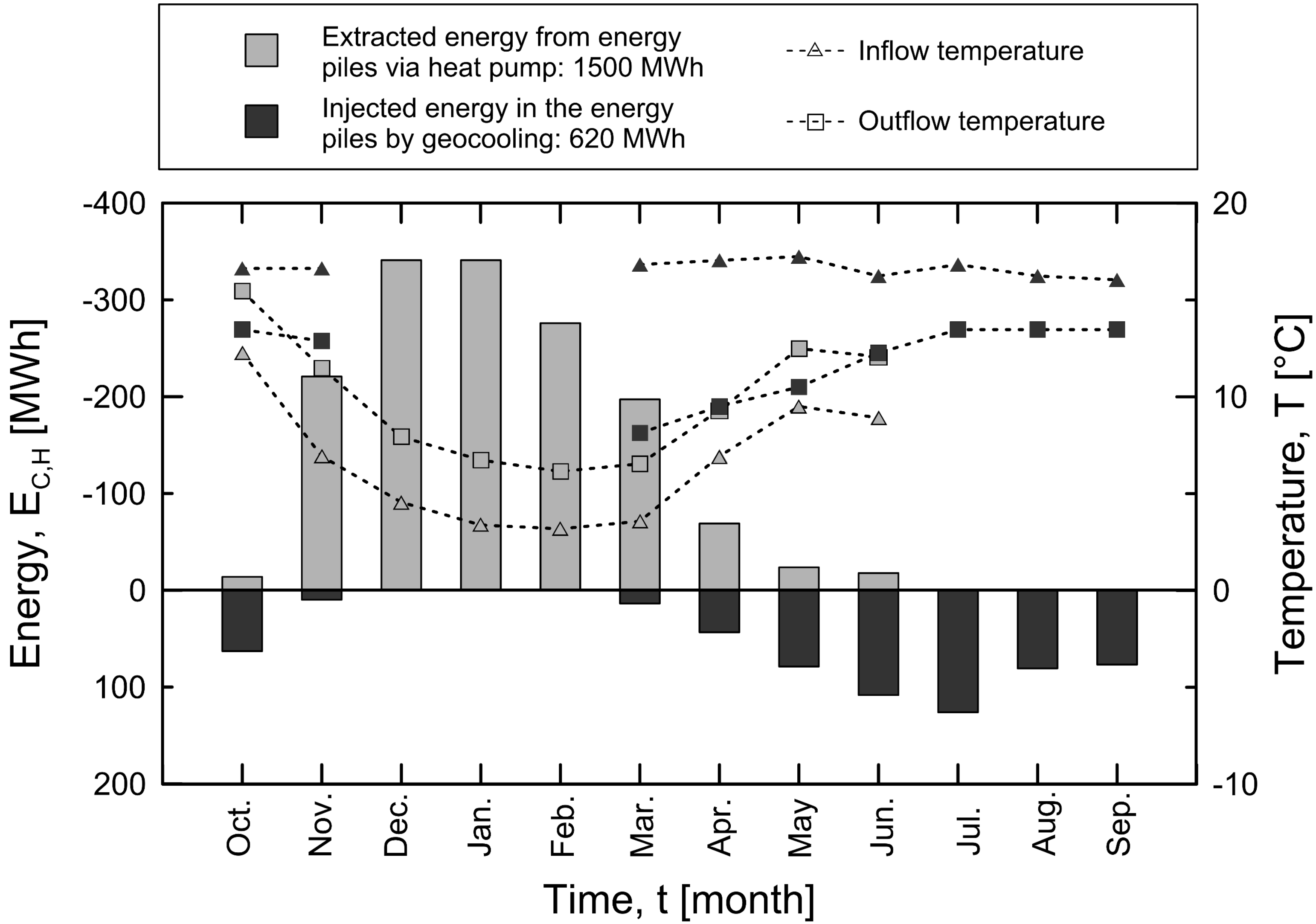
(Pahud and Hubbuch, 2007)

The Dock Mielfield - Zürich Airport



- Building 500 m long and 30 m wide
- 440 foundation piles, comprising more than 300 energy piles
- Piles of 0.9-1.5 m in diameter and 30 m length
- Renewable energy expected to meet:
  - 65% of the heating needs
  - 70% of the cooling needs

Development – energy piles



(Laloui and Rotta Loria, 2019;
redrawn after Pahud and Hubbuch, 2007)

Development – energy piles

(Pahud and Hubbuch, 2007)

The values are referred to the active pile length	Design	Measurement
Pile heat extraction rate		
maximum (W/m)	49	72 (+47%)
average (W/m)		45
Pile annual heat extraction		
(kWh/(m y))	135	183 (+36%)
Pile heat injection rate		
maximum (W/m)	49	33 (-33%)
average (W/m)		16
Pile annual heat injection		
(kWh/(m y))	48	74 (+54%)
Ratio injected over extracted	36%	41% (+14%)

Measures for 2005-2006

$$\eta = \frac{E_{prov}}{E_{req}} > 5$$

E_{prov} = Thermal energy delivered (heating and cooling)

E_{req} = Total electrical energy required to run it
(all the circulation pumps and the heat pump / cooling machine)

Development – energy piles

(Pahud and Hubbuch, 2007)

System	energy piles	conventional	difference
Investment	670’000 €	80’000 €	590’000 €
Annual cost			
capital	46’170 €	5’450 €	+40’720 €
maintenance	10’070 €	3’170 €	+6’900 €
energy	71’660 €	156’180 €	- 84’520 €
Total annual cost	127’900 €	164’800 €	- 36’900 €
Thermal energy cost	0.04 €/kWh	0.05 €/kWh	

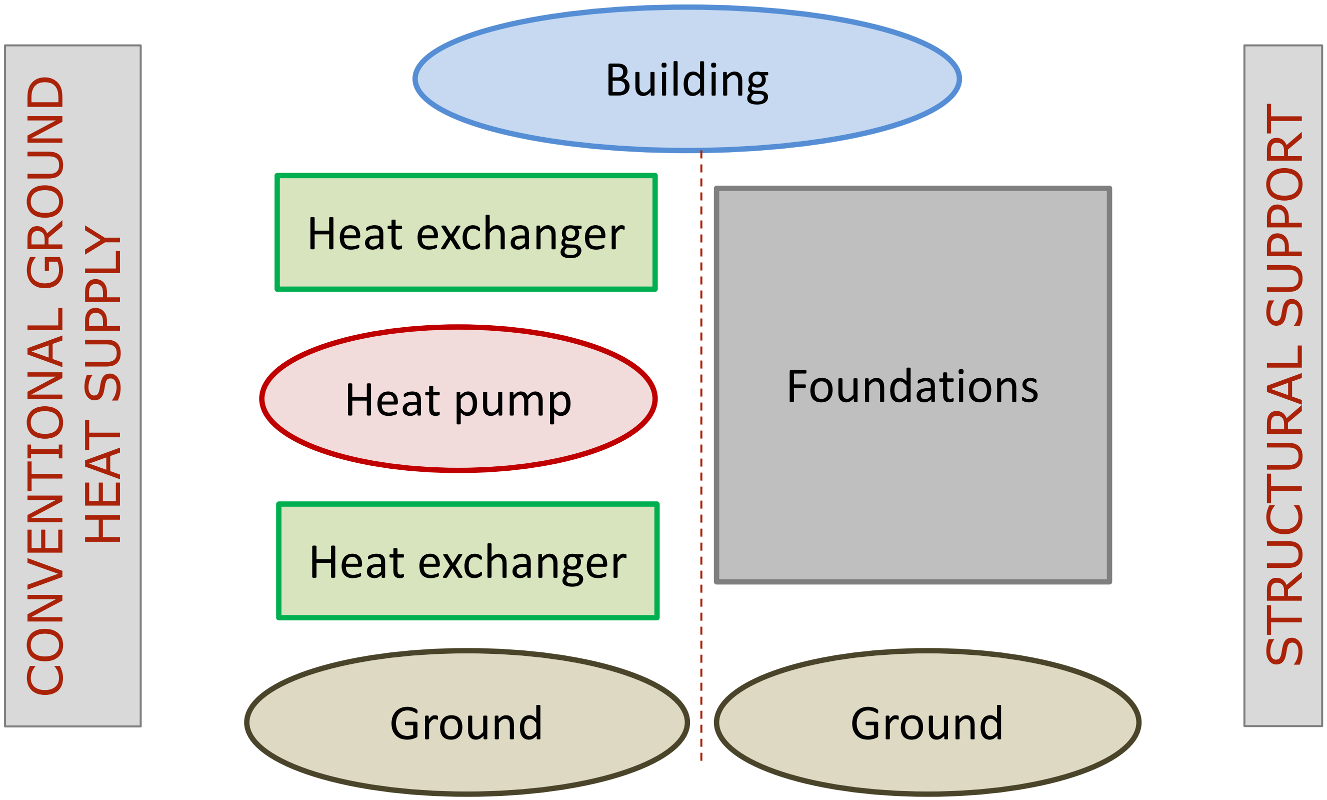
Economical aspects of the pile system
and comparison with a conventional system

- Additional installation costs recovered after 8 yrs relative to a conventional system (interests of the invested capital is not taken into account)

Challenges and design considerations

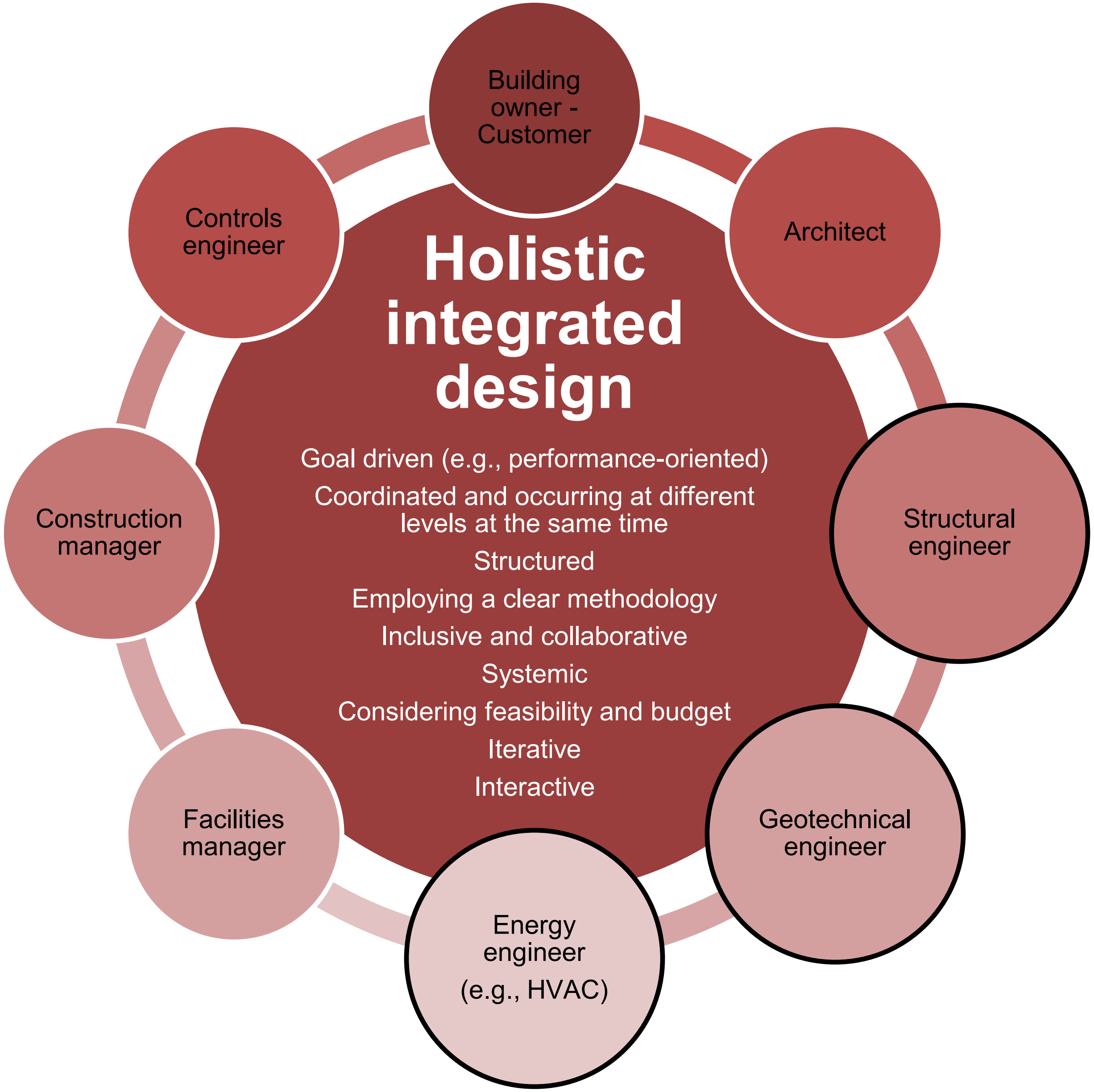
Integrated design framework

Challenges



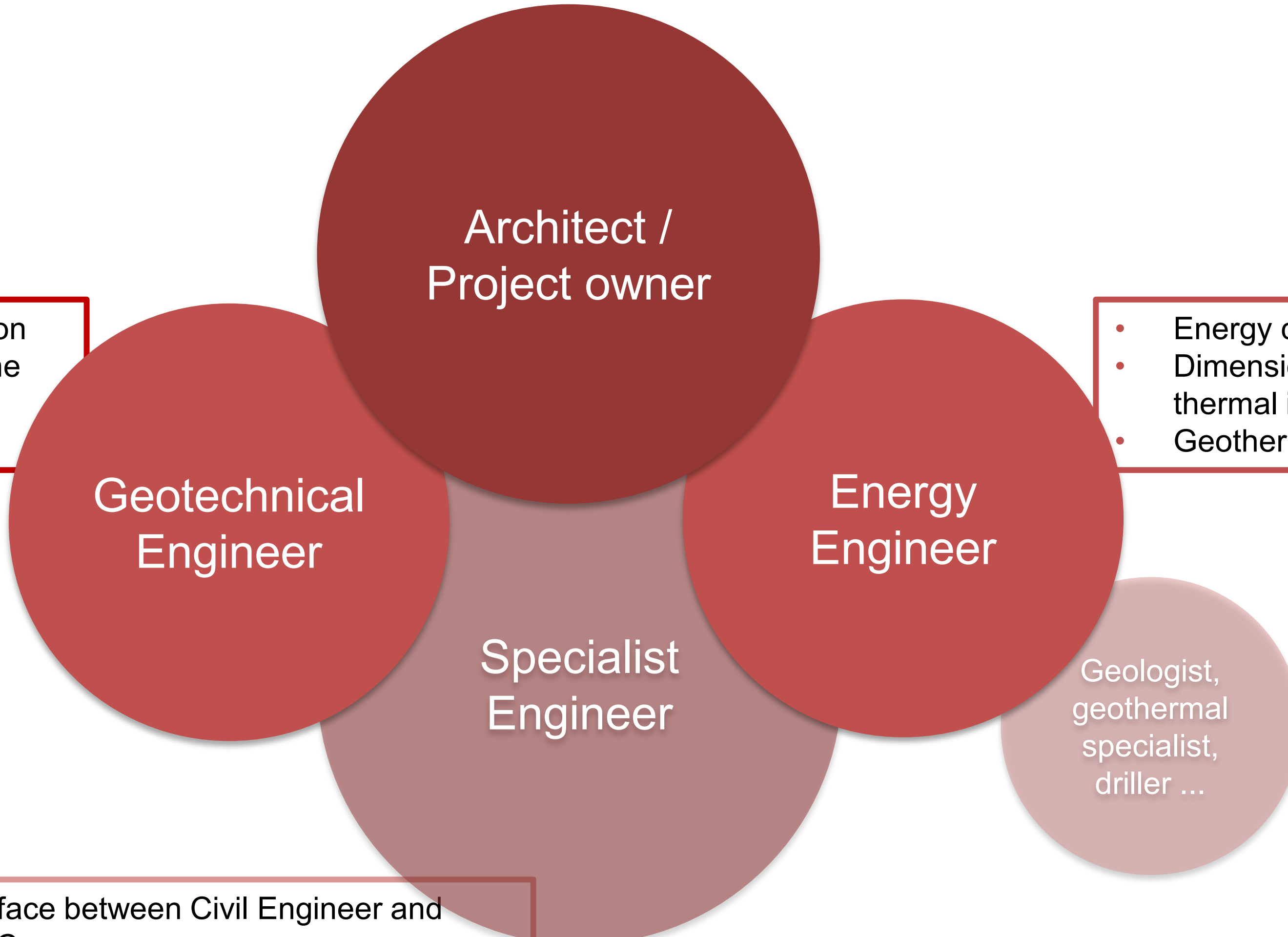
CONVENTIONAL GROUND HEAT SUPPLY
Building
Heat exchanger
Heat pump
Heat exchanger
Ground
Foundations
Ground
STRUCTURAL SUPPORT

Integrated design framework



Challenges

- Soil characterization
- Dimensioning of the foundations
- etc.



- Energy concept
- Dimensioning of thermal installations
- Geothermal sizing

- Interface between Civil Engineer and HVAC
- **Multidisciplinary skills**
- **Energy** dimensioning at the geostructure level
- **Structural** verifications

Typical aspects to consider

Short-term

Mechanical performance

Geotechnical and structural behaviour:

- **Stress in the ground structure**
- **Displacement of the ground structure**

Thermally and mechanically induced effects on soil behaviour

Thermally and mechanically induced effects on soil-structure interaction

Thermal performance

Energy behaviour:

- **Thermal power extracted and/or injected from and into the ground**

Time constants

Thermal recharging of ground

Storage potential of ground

Long-term