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Shallow Geothermal Energy

Theory and Application

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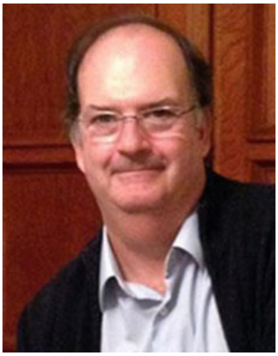

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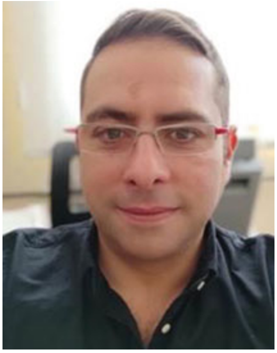

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Abbreviations

ACS	Agua Caliente Sanitaria
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CHE	Confederación Hidrográfica del Ebro
COP	Coefficient of performance
CTE	Código Técnico de Construcción
DHC	District Heating and Cooling Network
DMA	Directiva Marco del Agua
DX	Direct expansion
EAHP	Exhaust air heat pump
EGEC	European Geothermal Energy Council
EGRT	Enhanced geothermal response test
EPA	Environmental Protection Agency (USA)
ETIP	Plataformas Europeas de Tecnología e Innovación
ETT-NB	Energía Térmica Total no Balanceada
FLS	Finite line source
GEI	Gases de Efecto Invernadero
GEOTERZ	Modelo Geotérmico de la ciudad de Zaragoza
GHP	Guarded hot plate
GSHP	Ground source heat pump
GWHP	Groundwater heat pump
HAPs	Hidrocarburos Aromáticos Policíclicos
HDPE	High-density polyethylene
HFCs	Hidrofluorocarburos
HVAC	Heating, ventilation and air conditioning
HWST	Hot water storage tank
ICS	Infinite cylindrical source
IGME	Instituto Geológico y Minero de España

IGSHPA	International Ground Source Heat Pump Association
ILS	Infinite line source
IPCC	Intergovernmental Panel on Climate Change
IRENA	Agencia Internacional de Energías Renovables
IRF	Factor de Relajación Indirecto
LSI	Langelier saturation index
MILS	Moving infinite line source
MUSE	Managing urban shallow geothermal energy
NREAP	Planes de Acción Nacionales en Energía Renovable
PCTS	Perfil Característico de Temperaturas Subterráneas
PFCs	Perfluorocarbonos
RDPH	Reglamento del Dominio Público Hidráulico
RH&C	Renewable heating and cooling
RITE	Regulación para las Instalaciones Térmicas en Edificios
RSI	Ryznar stability index
SBM	Superposition borehole model
SCOP	Seasonal coefficient of performance
SEER	Seasonal energy efficiency ratio
STES	Seasonal thermal energy storage
SUHI	Subsurface urban heat island
TDS	Total dissolved solids
THM	Acoplamiento Termohidromecánico
TRT	Test de Respuesta Térmica
TTT	Test de Trazador Térmico
UHI	Urban heat island
UNFCCC	United Nations Framework Convention on Climate Change
UTA	Unidades Climatizadoras o de Tratamiento de Aire
UTES	Underground thermal energy storage
VER	Volume elemental representative
WGPS	Water-gravel pit storage

Symbols

Q	Heat (J)
m	Mass (kg)
C	Volumetric heat capacity (J m^{-3} K^{-1})
c	Specific heat capacity (J kg^{-1} K^{-1})
T	Absolute temperature (K)
J	Radiated heat flux (J s^{-1})
e	Emissivity (-)
σ	*Stefan–Boltzmann* constant (W m^{-2} K^{-4})
A	Surface area (m^{2})
t	Time (s)
E	Energy (J)
P	Power (W)
U	Internal energy (J)
W	Work (J)
p	Pressure (kg m^{-1} s^{-2})
H	Enthalpy (J)
ρ	Density (kg m^{-3})
F	Force (N)
V	Volume (m^{3})
η	Efficiency (-)
μ	Mass of a gas molecule (kg)
γ	Specific heat (-)
ϖ	*Boltzmann* constant (J K^{-1})
S	Entropy (J K^{-1})
r	Radius (m)
x	Position vector (m, m, m)
ϕ	Porosity (-)
l	Characteristic length (m)
q	Heat flow (W)
λ	Thermal conductivity (W K^{-1} m^{-1})
∇	Nabla operator (-)

$x,\ y,\ z$	Space coordinates (m)
g	Source/sink term (W m^{-3})
$\boldsymbol{g}$	Earth's acceleration constant (m s^{-2})
∇^2	Laplacian operator (-)
u	Internal energy per unit mass (J kg^{-1})
α	Thermal diffusivity (m^2 s^{-1})
v	Fluid velocity (m s^{-1})
D	Hydrodynamic thermal dispersion (m)
R	Thermal resistivity (K W^{-1})
ϵ	Thermal expansion (K^{-1})
ε	Axial internal thermal expansion (-)
χ	Saturation (-)
τ	Shear stress (Pa)
μ	Dynamic viscosity (Pa s)
υ	Kinematic viscosity (m^2 s^{-1})
Re	Reynolds number (-)
k	Intrinsic permeability (m^2)
b	Heat transfer coefficient (W m^{-2} K^{-1})
Fo	Fourier number (-)
Pe	Peclet number (-)
K	Hydraulic permeability (m s^{-1})
h	Hydraulic head (m)
Q	Flow rate (m s^{-3})
ω	Medium compressibility (m kg^{-1} s^{-2})
S	Storage coefficient (m^{-1})
J	Radiation of heat (W m^{-2})
Υ	Long-wave radiation (W m^{-2})
G	CO$_2$ emissions (kg)
ξ	CO$_2$ emission factor (kg kWh^{-1})
D	Diameter (m)
a	Fit coefficient (-)
Θ	Dimensionless temperature (-)
Z	Depth dimensionless (-)
τ	Temperature change (K)
b	Aquifer (saturated) thickness (m)
φ	Velocity potential (s^{-1})
Ψ	Stream function (m^2 s^{-1})
R	Radius of influence (m)
a	Spacing distance (m)
κ	Heat recovery ratio (-)
ψ	Energy balance ratio (-)
Ex	Exergy (J)
Λ	Energy efficiency (-)
γ	*Euler-Mascheroni* constant (-)
δ	Extraction factor (-)

s	Dropdown (m)
T	Transmissivity (m^2 s^{-1})
M	Retardation factor (-)

Superscripts

X_{sys}	System
X_{ext}	Exterior
X_W	Work
X_Q	Heat
X_C	Convection
X_T	Total
X_K	Kinetics
X_V	Potential
X_{ent}	Environment
X_P	Constant pressure
X_0	Initial
X_F	Final
X_A	High
X_B	Low
X_{ref}	Reference
X_{abs}	Absolute
X_{rev}	Reversible
X_{irrev}	Irreversible
X_{Temp}	Constant temperature
$X_{x,y,z}$	Coordinates in space
X_f	Fluid
X_m	Solid mineral
X_w	Water
X_{fs}	Source-sink
X_V	Constant volume
X_e	Equivalent
X_D	Darcy
X_h	Hydrocarbons
X_{ga}	Gas
X_{tb}	Pipe
X_{con}	Heat conduction
X_{alm}	Storage
X_{po}	Pores
X_{co}	Pores interconnected
X_r	Real
X_{ef}	Effective
X_{int}	Internal

X_E	Latent
X_H	Sensible
X_a	Atmosphere
X_{ab}	Absorbed
X_t	Terrain
X_n	Clouds
X_G	Geothermal
X_{RF}	Refrigeration
X_{CF}	Heating
X_{cnd}	Condenser
X_{ev}	Evaporator
X_{ie}	Isentropic
X_{ad}	Adiabatic
X_{el}	Electric
X_{HP}	Heat pump
X_{sav}	Savings
X_{sps}	Substituted production system
X_i	In
X_o	Out
$X_{\boldsymbol{g}}$	Grout
X_{th}	Thermal
X_{s}	Borehole
X_{sup}	Superior
X_{ft}	Convective heat resistance
X_{ss}	Steady state
X_I	Exchanger
X_{2D}	Bidimensional
X_{ca}	Capture
X_{re}	Residence
X_{max}	Maximum
X_{cr}	Critical
X_{st}	Stagnation
X_b	Heat front
X_{rq}	Recovered
X_{B}	Background
X_d	Dissipated
X_{TC}	In place
X_R	Reservoir
X_{min}	Minimum
X_{adv}	Advection
X_{TEC}	Technical
X_{suf}	Ground surface

X_{geo}	Geological
X_s	Specific
X_{fm}	Mass flow

Superscripts

X^{adv}	Advection
X^{dis}	Hydrodynamic dispersion
X^r	Reflection
X^*	Absorption
X^{emi}	Emission
X^T	Total
X^{net}	Net
X''	Per unit of cross section
X^o	Per linear metre
$X^{\triangle}$	Triangular circuit
X^T	Tensor
X^{rq}	Recovered
X'	Per mass unit

Chapter 1
Introduction

1.1 Background

Planetary change in climate and ecological functioning associated with the phenomenon of global warming is attributed, with a high degree of acceptance in the scientific community (IPCC 2007, 2011, 2013), although not universally, to the massive emission of greenhouse gases (GHGs) (carbon dioxide, methane, nitrogen oxides, sulphur hexafluoride, HFCs and PFCs) derived from the production, distribution and consumption of energy. This energy is obtained through the use of fossil fuels as the main primary energy source in the production of electricity, heat or locomotion.

Since the Industrial Revolution, the world's population has grown exponentially as has per capita energy consumption (Glassley 2010). In the mid-twentieth century, after the Second World War, in order to meet the growing energy demand, there was a boom in the use of petroleum derivatives and fossil fuels in general, their use spreading across the planet. Since then, the combustion of carbon-rich fossil fuels has increased the concentration of CO_2 and other GHGs in the atmosphere to concentrations never before experienced on this planet. There is ample scientific evidence linking global warming to anthropogenic GHG emissions. Evidence includes instrumental, glacial and sedimentary records. Recent technological advances, especially in the field of satellite remote sensing, have made it possible to obtain ground-scale data on the decrease in infrared radiation over the last 40 years (Brindley and Bantges 2016). This is seen as unequivocal evidence of the anthropogenic origin of GHGs being responsible for the increase in global warming and, therefore, climate change.

Different possible strategies to reduce the concentration of GHGs in the upper atmosphere to sustainable levels include incorporating large amounts of low-carbon resources into the energy sector. The use of primary energy not based on fossil fuels, so-called *low-carbon energy*, has been promoted as a first energy policy for several years.

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The concerns of the scientific, technological and social community lie in understanding the relationship between climate and the chemical composition of the atmosphere and oceans, as well as predicting the impact on climate of different possible energy production scenarios. Global energy demand will double by 2050 due to global economic and population growth, with a large impact from the emerging market economy (Whitesides and Crabtree 2007). In principle, this demand can be met by fossil fuel-based energy resources. However, even to maintain $_{CO2}$ levels in the atmosphere at twice pre-industrial levels by 2050 will require intervention in the energy production sector and decarbonisation at a magnitude equal to or greater than current global energy production.

The growing demand for energy can only be met in the future if supply is increased by using low-carbon technologies or through good management and deceleration of energy demand (Narsilio and Aye 2018).

The negotiation of protocols for action on climate change has been carried out at the international level through international conferences such as those held in Rio de Janeiro (Brazil) in 1992 and Kyoto (Japan) in 1997. These international conferences have sought to obtain commitments from participating nations to significantly reduce GHG emissions over the coming decades.

Everything seems to indicate the need to develop technologies capable of using primary energy sources that are not based on fossil fuels, that ideally do not run out and that are environmentally friendly, i.e. they must meet three conditions: (1) low-carbon energy (2) renewable energy and (3) clean energy. Energy sources and resources that meet these three premises are known as *renewable energy*.

The very concept of renewability depends on the rate of replenishment. If this replenishment occurs on the scale of a human lifetime, only then is it considered renewable. Oil and other hydrocarbons renew themselves but only after several hundred thousand years and are, therefore, not considered renewable. The most important renewable energy resources and sources are solar, hydro, wind, geothermal, solid biomass, biogas and biofuels. The contributions of these renewable energy sources and resources still play a minor role in global energy production. They have additional advantages, such as improving industrial profits and balance sheets, contributing to technological development and creating jobs.

There has been a succession of agreements within the framework of the *United Nations Framework Convention on Climate Change (UNFCCC)* to try to reduce carbon dioxide emissions into the atmosphere. At the 2015 convention (COP21), the 2015 *Paris Agreement* was signed, a binding climate agreement among 195 countries, with the aim of strengthening global response to the threat of climate change. A common goal was set to keep the average global temperature increase to less than 2 °C (preferably 1.5 °C) above pre-industrial levels, which entails keeping atmospheric CO_2 concentration below 450 ppm. A target was set to reduce GHG emissions by at least 40% below 1990 levels by 2030 (UNFCCC 2015).

The *Intergovernmental Panel on Climate Change* (IPCC) scientific consortium has identified the global need to phase out the use of fossil fuels in power generation by 20% by 2050 and to phase this use out completely by the end of the century.

We are searching for economically profitable energy generation technologies that meet society's energy demand and do not continue to damage the environment. However, there is also considerable scepticism that GHG emissions will be adequately reduced in time to significantly curb the effects of global warming. Strategies to be considered include reducing energy consumption, using energy sources that do not rely on carbon-intensive fossil fuels, and finding alternatives to atmospheric GHG emissions.

The use of shallow geothermal energy is one of the alternatives that contributes to achieving these goals. Geothermal heat pumps improve energy efficiency in air conditioning, compared to other conventional technologies that are based on the combustion of fossil fuels. They use renewable thermal energy and their GHG emissions are very low and even zero in some specific situations (EPA 1997; Saner et al. 2010). The Kyoto Protocol is being incorporated into European Community legislation and transposed into national legislation. In addition to requiring the energy efficiency of buildings, building regulations require the use of low-carbon technologies in thermal installations. In this context, the use of shallow geothermal heat production systems has important potential.

However, at the moment the whole world continues to consume energy based on fossil resources for social, economic and human development. Currently, 65% of the energy used for air conditioning in buildings comes from power plants based on fossil fuels such as hard coal and lignite, which are the source of the highest GHG emissions on the planet. Therefore, it is crucial to look for alternatives that require more efficient energy consumption for the air conditioning of these spaces.

Although the use of geothermal energy has clear advantages to be the technology with the most potential for decarbonisation of the global thermal sector, it is true that it does not necessarily lead to a drastic reduction of GHGs (Bayer et al. 2012; Blum et al. 2010; Saner et al. 2010). Shallow geothermal systems require a certain amount of electrical energy for operation of the integrated heat pump. If the fraction of electrical energy needed for the operation of a geothermal installation is based on fossil fuels, contribution to the reduction in greenhouse gas emissions is smaller. Disregarding the possible share of fossil fuel-derived electricity can lead to an overestimation of the technology's benefit, which has sometimes been counterproductive and has led to negative responses from the scientific community and industry. Overestimation of the technology's benefit has added to cases of bad practice due to poor design of shallow geothermal installations (Florea et al. 2017; Vienken et al. 2015). A responsible stance, adoption of good practices and efficient management of shallow geothermal resources are required.

In addition to the environmental cause, there are other compelling reasons to promote alternative primary energy sources over fossil fuels. From a geopolitical point of view, it is desirable to reduce dependence on fossil fuels, given the instability of the regions hosting the main hydrocarbon deposits and the obvious reasons for conflicts of interest between nations. From an economic and social point of view, shallow geothermal systems offer new services from borehole drilling companies, so that this activity is currently displacing the water borehole drilling market, especially in countries such as Norway and the UK (Banks 2011). Shallow geothermal activity has a positive impact on employment and the household economy, providing large savings to households in the medium term.

1.2 Shallow Geothermal Energy

1.2.1 Geothermal Energy

Geothermal energy, in the thermodynamic and general sense, refers to the internal energy of geological materials (rocks, groundwater, sediments, magma, etc.) contained between the earth's surface and down to the earth's core itself. Geothermal energy tends to transfer in a solidary way, from higher internal energy to lower internal energy. The process of transferring internal energy from one system to another, where internal energy is conserved, is known as heat. If, during the transfer of internal energy from one body to another, part of this energy is transformed into another type of energy, this transformation process is called work. Therefore, geothermal energy describes the potential ability of a geological system (rocks, groundwater, sediment, etc.) to transfer thermal energy in the form of heat or to perform work.

The study of how internal energy is transferred between systems is one of the fundamental objectives of thermodynamics. The geothermal energy discipline combines thermodynamic and geological knowledge to understand and quantify heat transfer in the subsurface and its possible exploitation as heat (direct use) or as work (electricity generation). Thermodynamics demonstrates how part of the heat flow from one body to another can be transformed into mechanical energy, through work on a steam turbine. It also establishes that the amount of work that can be done is a function of the difference in internal energy of the two systems.

1.2.2 Types and Classification of Geothermal Energy

In the absence of changes in the nature and internal structure of a geological thermodynamic system, the change in internal energy is accompanied by a more or less proportional increase in temperature. In the geological environment there is a great variety of systems at different temperatures. On a planetary scale, the highest internal energy of the planet is found in its core, with temperatures of about 6000 °C (Anzellini et al. 2013), more than a hundred times higher than earth's surface and atmosphere temperatures. The internal energy difference between these extremes induces an energy flow from the core to the earth's surface, known as terrestrial heat flow. The result of this continuous heat flow is an associated decreasing temperature gradient towards the surface. With this conceptual model, it can be roughly understood how geothermal energy is distributed on a planetary level.

In general, in regions where there is a normal geothermal gradient of approximately 25–32 °C km^{-1} (Limberger et al. 2018), boreholes of several kilometers deep are required to reach geological materials presenting temperatures exceeding 175 °C, which are needed for electrical power generation. Therefore, geological materials at a depth of several kilometers could be of economic interest for geothermal energy transformation into electricity through mechanical work. In volcanic areas, where the geothermal gradient can be much higher (up to 200 °C km^{-1}), electrical power can be generated by very shallow boreholes. This primary energy source has enormous potential, and its development has resulted in the production of electricity from geothermal energy on a commercial scale (Narsilio and Aye 2018). Once access to geological materials with sufficient internal energy is gained using deep piped boreholes, steam is recirculated and heated by *hot* rock at a high temperature. It is then conducted to steam turbines to generate work capable of producing economically exploitable electricity (Toth and Bobok, 2017). This type of geothermal exploitation and its study is known as *deep geothermal energy* or *high-temperature* (*enthalpy*) *geothermal* energy (Fig. 1.1).

Lower temperature geological materials with lower geothermal energy are closer to the surface and are therefore more technically and economically accessible. However, their internal energy transferred to another system in the surface would not be able to generate economically exploitable work. They do, however, constitute a thermal reservoir of great interest for internal energy transfer as heat. It should not be forgotten that Western society consumes approximately 50% of the total energy produced for heating and cooling (Sanner et al. 2013). The internal energy exchange of geological materials with surface thermodynamic systems to satisfy a heat demand without its transformation into work is called *direct geothermal use.* The term *direct* refers to the absence of transformation of internal energy into work; a direct use of geothermal energy is realised through the transfer of internal energy, i.e. heat.

Since prehistoric times, direct use of geothermal energy has been carried out in several ways such as in caves, avoiding environmental extreme temperatures, or in the use of natural hot springs. Throughout the history of mankind, attempts have been made to maximise productivity of thermal water reservoirs with existing drilling technology. With the advent of mechanical drilling machines in the nineteenth century until the present day, it has been possible to reach geothermal reservoirs of varying depths. This has made it possible to utilise geothermal energy for direct use in buildings and district heating networks. As drilling and heat pump technologies have been developed, the great potential for transferring thermal energy with the more accessible subsoil (first 400 m of depth) has become increasingly apparent, to a point where it has become economically viable, and even viewed as the most economical option in the long term. Two types of geothermal energy use can be distinguished according to the drilling technology considered which, in turn, is a function of the maximum drilling depth expected. These are deep well drilling technology (technology similar to oil drilling) and shallow well drilling technology (technology similar to groundwater drilling). The drilling cost per linear meter is radically different. In fact, deep drilling is usually only costeffective for oil wells. This is evidenced by the conversion of abandoned oil wells into geothermal wells (Templeton et al. 2014). This type

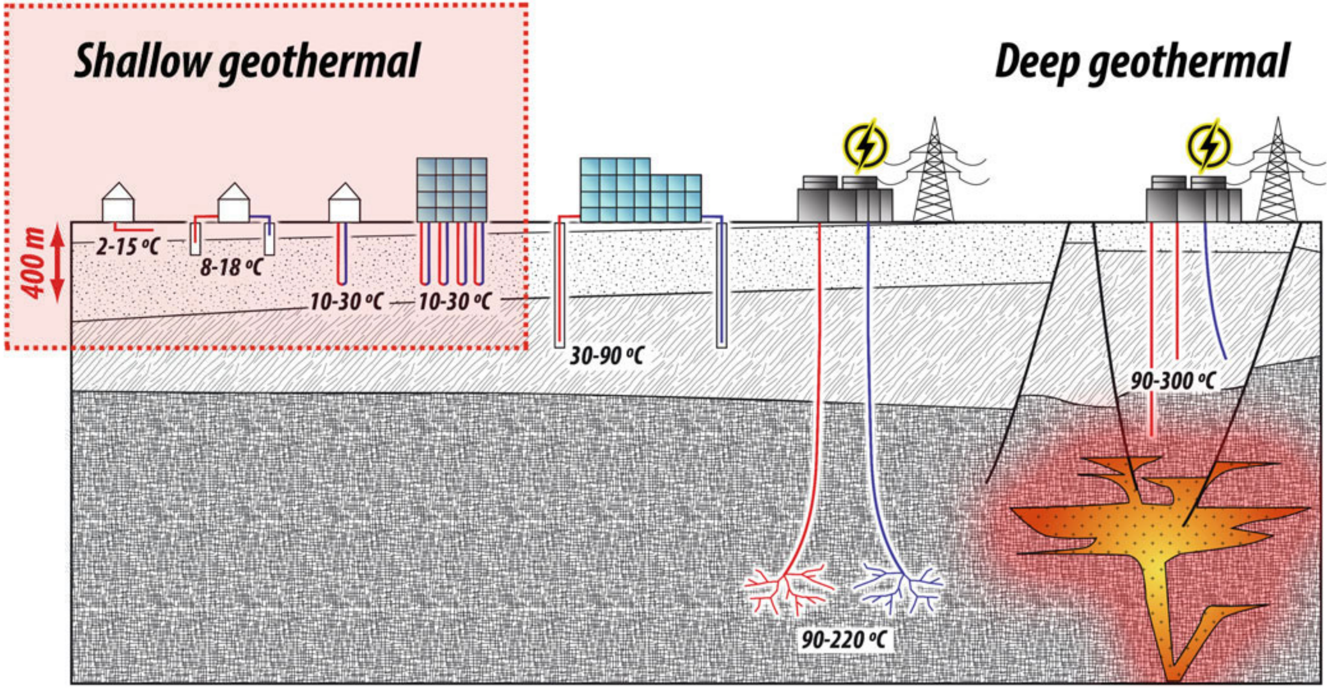

Fig. 1.1 Conceptual diagram of shallow geothermal energy versus medium and deep geothermal energy. Modified from www.alpine-space.eu/projects/greta

of geothermal exploitation and its study is known as *medium geothermal energy* or *medium or low temperature (enthalpy) geothermal energy* (Fig. 1.1). Shallow (arguably conventional) drilling technology, although cheaper, requires considerable initial investment. However, the low primary energy consumption in heat production enhances offsets of the initial investment, resulting in a quick payback. This type of geothermal exploitation and its study is known as *shallow geothermal energy* or *very low temperature (enthalpy) geothermal energy* (Fig. 1.1). Furthermore, it should be noted that while medium and deep geothermal energy (cogeneration) are capable of providing heat for heating, only shallow geothermal energy has potential for cooling, since the subsurface temperature in the shallow domain roughly coincides with the annual average atmospheric temperature of the region. Therefore, the shallower ground (<400 m) can provide heating and cooling, including domestic hot water (DHW), all year round (Banks 2012). Another very significant difference between shallow and deep geothermal energy, apart from its economic efficiency and its use as a heat sink, is its ubiquity. While deep and medium geothermal energy (to some extent) depend on thermal anomalies in the ground, shallow geothermal energy is available everywhere, independent of the geology found. Geology and hydrogeology will condition the design to maximise the efficiency of exploitation but do not question its economic viability. Figure 1.2 represents a summary of the classification of geothermal energy according to depth and type of end use.

Geothermal energy, in general, is a huge and versatile resource capable of helping to meet the world's energy demand and reduce the use of fossil fuels as primary

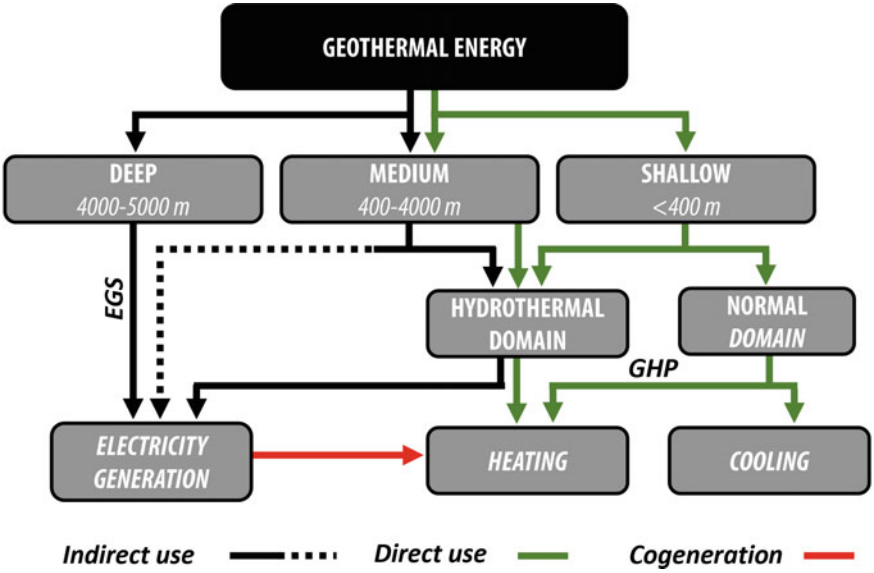

Fig. 1.2 Classification of geothermal energy according to depth and type of end use. EGS: Enhanced geothermal systems. GHP: Geothermal heat pump

energy. Geothermal energy can produce electricity and efficiently meet the needs for air conditioning and DHW generation in residential, commercial and industrial buildings (Glassley 2010; Narsilio and Aye 2018).

1.2.3 Shallow Geothermal Energy

The first 400 m below the ground surface is a unique thermal reservoir for the transfer and storage of thermal energy. All the thermal energy that can be transferred as heat to this thermal reservoir, either by heat dissipation or heat absorption, is called shallow geothermal energy. The shallowest subsurface, together with bodies of surface water and the atmosphere, form the main thermal reservoirs of ambient thermal energy (Fig. 1.3). The set of industrial processes aimed at optimising heat transfer with these environmental reservoirs are called *geothermal* (shallow), *hydrothermal* and *aerothermal*.

Among the ambient thermal reservoirs, the shallow geothermal reservoir is the most efficient in the long term. Nevertheless, this technology requires a significant initial investment in the drilling of the necessary geothermal heat exchangers (Fig. 1.3). The shallow geothermal reservoir is characterised by a constant stable temperature throughout the year and is renewable, thus offering immense potential, not only for heating, ventilation and air conditioning (HVAC) of domestic and commercial buildings, but also for heat production in industrial and other infrastructures.

The threshold value of 400 m depth is conditional on the depth limits of conventional drilling technologies needed to construct geothermal heat exchangers. As drilling technology advances, this threshold value could increase. Shallow geothermal energy is also known as very low temperature (or enthalpy) geothermal energy, since the vast majority of the shallow subsurface of the continental domain is in thermal equilibrium with atmospheric conditions and solar radiation (Oke 1987). Under these conditions, shallow geothermal reservoirs present stable temperatures throughout the year of about two degrees Celsius above the annual mean atmospheric temperature. The shallow geothermal reservoirs are constituted by rocks, unconsolidated sediment and groundwater with relatively similar thermal properties. These properties, which do not vary in large amounts, ensure the cost-effective use of shallow geothermal energy in any part of the territory considered.

The continuous development of heat pump technology, based on the vapour compression cycle, has made its heat transfer efficiency even higher and more competitive. When highly efficient heat pumps are combined with shallow geothermal reservoirs, the resulting technology, known as geothermal heat pumps, becomes the most efficient technology for heating and cooling buildings (EPA 1993). The energy efficiency of ground source heat pumps is 50–70% higher than that of conventional heating systems, and 20–40% better than air-to-air heat pumps used in aerothermal systems (Letcher 2013). The use and promotion of ground source heat pumps is also justified by the decarbonisation of the heating sector as a measure of

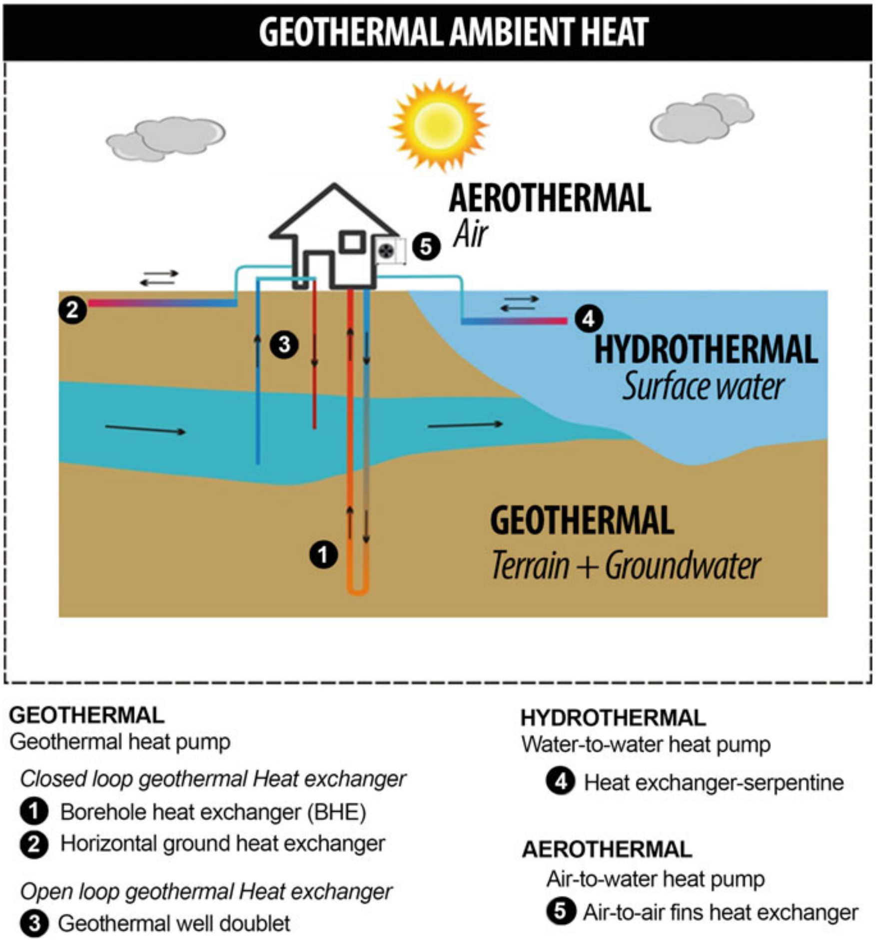

Fig. 1.3 Environmental thermal energy concept. Figure courtesy of Gregor Göetzl (*Geologische Bundesanstalt für Österreich*)

mitigating climate change. In 2008, the use of around 879,000 thermal installations with ground source heat pumps in 19 European countries saved 3.7×10^6 tCO_2eq compared to thermal installations making use of conventional production systems based on the combustion of fossil fuels (Bayer et al. 2012).

GHG emissions and particulate air pollution only occur indirectly and far from urban areas where most of the electrical energy is consumed. Its high efficiency consumes approximately 1 kWh electrical for every 4–8 kWh of thermal heat transfered (Self et al. 2013). Therefore, GHG emissions will depend on the emissions caused during the production of electrical energy (electricity mix), with zero emissions when the electrical energy consumed by the heat pump is produced entirely from renewable energy. Minimal electricity consumption and low GHG emissions