ICTP

IGA
International Geothermal Association

Consiglio
Nazionale delle
Ricerche

International Union of Geodesy and Geophysics
IUGG
UGGI
Union Géodésique et Géophysique Internationale

International School on

'Geothermal Development'

December 7 - 12, 2015
(Miramare, Trieste, Italy)

GROUND RESPONSE TEST (GRT) AND HEAT PUMP DESIGN

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Università di Pisa

Unione
Geotermica
Italiana

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SUMMARY

1. Heat pumps: basic concepts and fundamentals
2. Thermal sources: types, pros & cons
3. GSHP – Ground Source Heat Pump systems
4. Ground source modeling
5. Ground source characterization: site-investigation methods
   a) Thermal response test / Ground response test
   b) Pumping test

MAIN TOPICS

Influence of thermal sources characteristics on HP performances

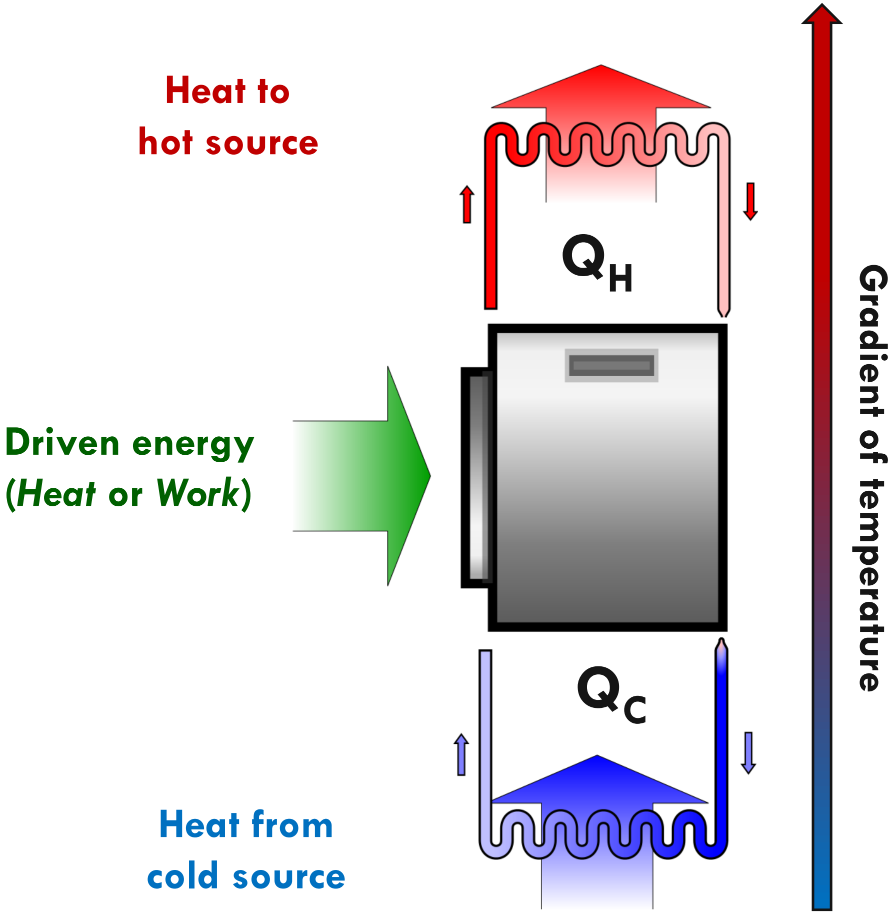
Ground source modelling and main parameters

Ground source characterization: *in-situ* test methods

Standard/handbook design procedures for:

- Vertical boreholes
- Horizontal ground heat exchangers
- Water wells for open-loop systems

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS



Heat to hot source

Q_H

Driven energy (*Heat or Work*)

Q_C

Heat from cold source

Gradient of temperature

✓What is an heat pump?

Heat pumps is a device able to transfer heat from a cold source to an hot source, against the natural direction of flow. To do that, driven energy is required (heat or work)

✓ Coefficient of performance

- Heating mode

$$COP = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$$

- Cooling mode

$$EER = \frac{Q_C}{W} = \frac{Q_H}{Q_H - Q_C}$$

P. Conti: Ground response test (GRT) and heat pump design . *International school on geothermal development. Miramare (TR), Italy, 7 – 12 Dec 2015.*

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Why heat pumps?

Traditional Boiler

Q_{in}

Primary Energy

(fossil fuels)

90 ÷ 115

Q_{out}

Useful energy

100

$$\eta_{gen} = \frac{Q_{out}}{Q_{in}} \approx 1$$

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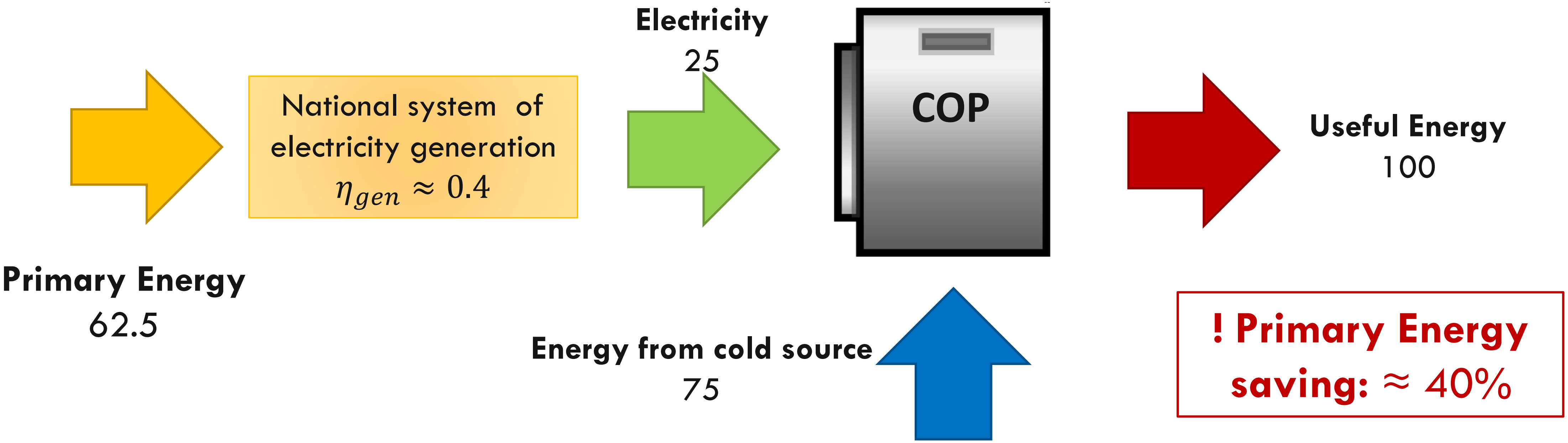
1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Why heat pumps?

Electrically-driven HPs – Heating & DHW mode



Primary Energy
62.5

National system of electricity generation
$\eta_{gen} \approx 0.4$

Electricity
25

COP

Useful Energy
100

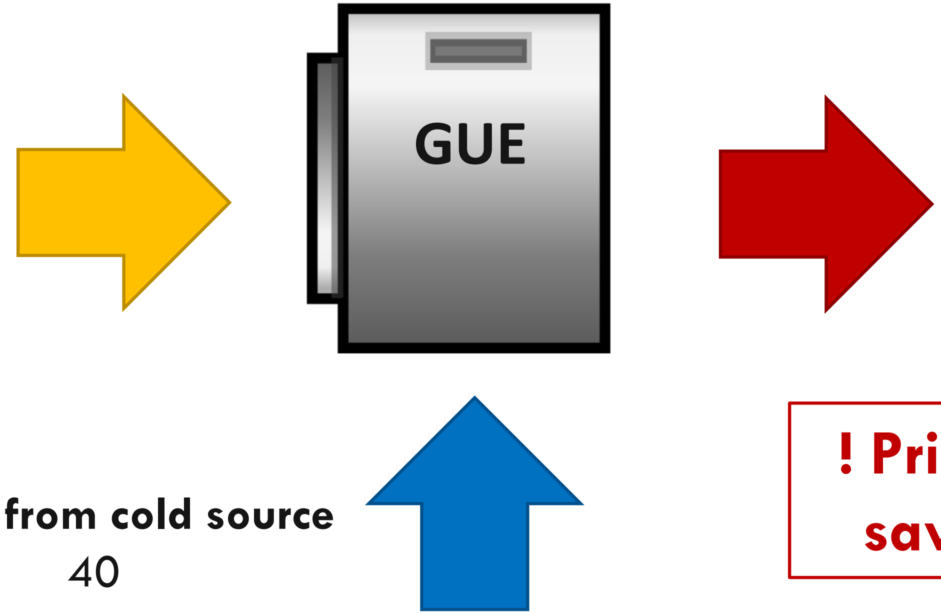
Energy from cold source
75

! Primary Energy saving: ≈ 40%

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Why heat pumps?

Adsorption HPs – Heating & DHW mode



Primary Energy
(fossil fuels)
60

Useful Energy
100

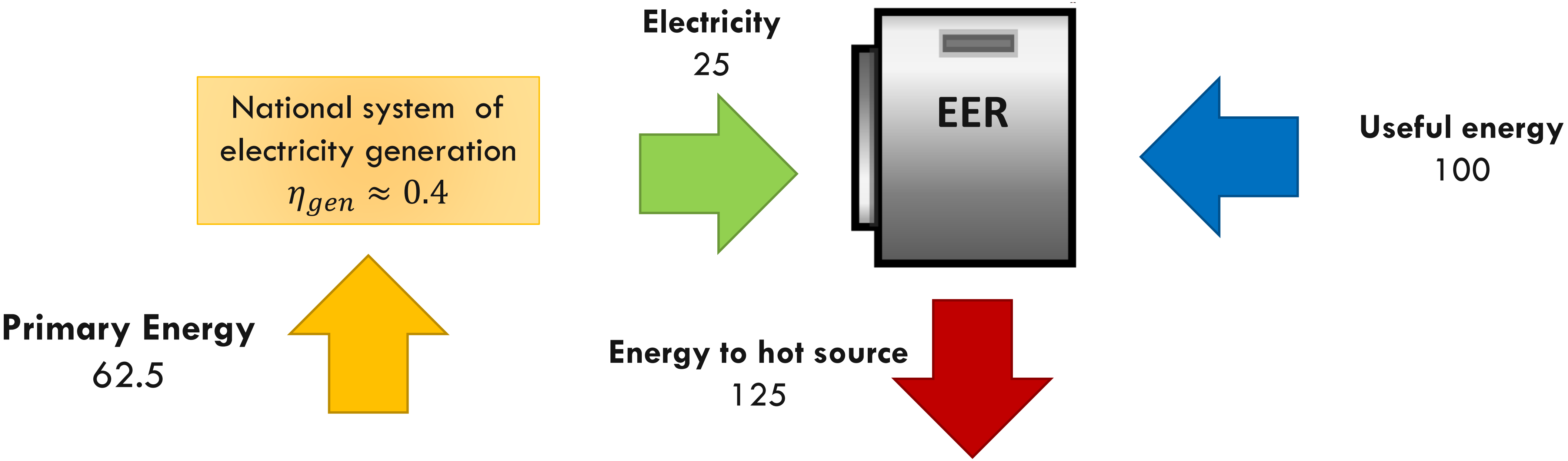
Energy from cold source
40

! Primary Energy saving: ≈ 40%

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Why heat pumps?

Electrically-driven HPs – Cooling mode



National system of electricity generation

$\eta_{gen} \approx 0.4$

Electricity

25

Useful energy

100

Primary Energy

62.5

Energy to hot source

125

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1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Why heat pumps? *(if properly sized and managed)*

Energy

HPs are remarkable energy-saving devices for both heating and cooling, resulting in notable primary energy savings

Environment

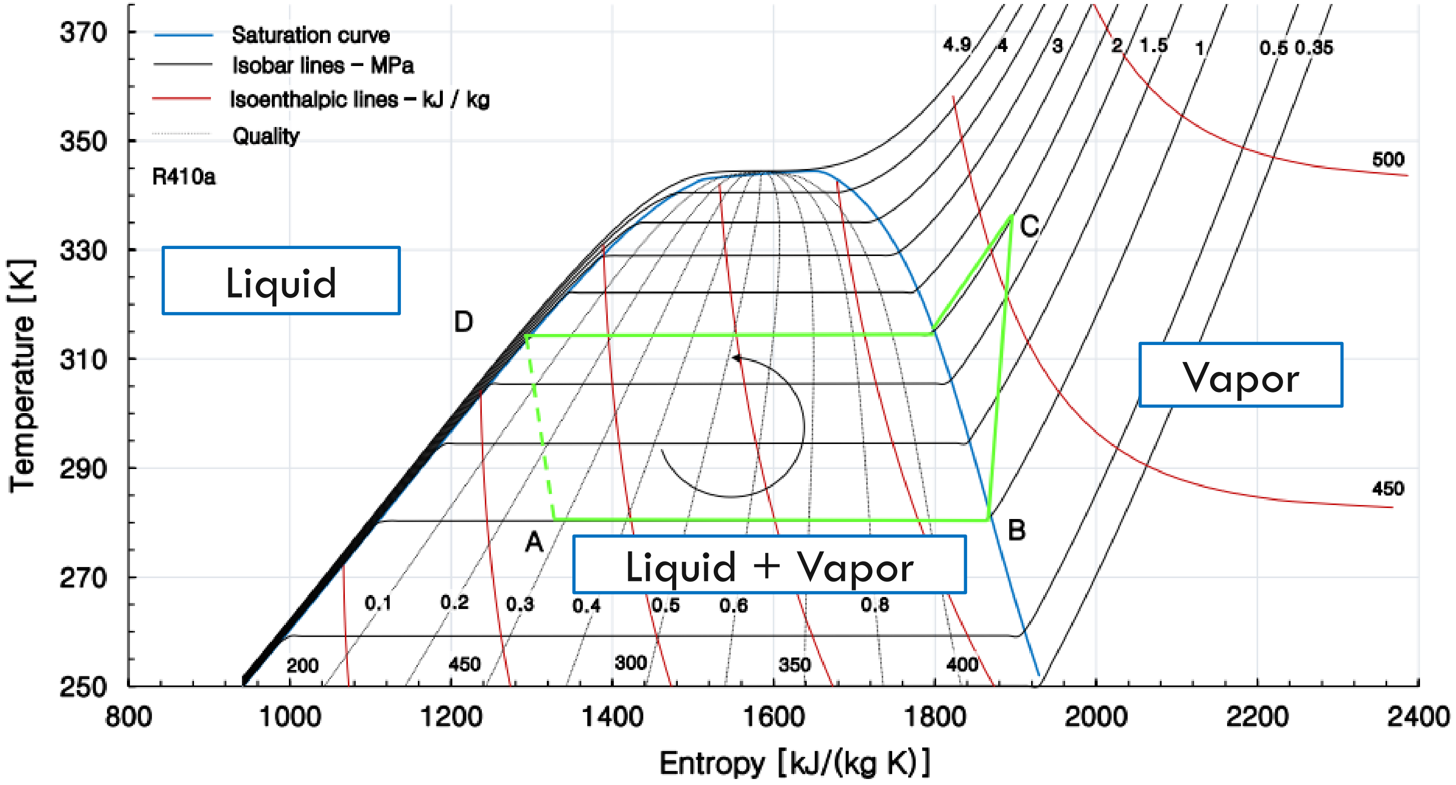
HPs reduce fossil fuels consumption in favor of RES utilization

Economy

According to local economy context (energy and equipment prices), HPs result in a profitable investment

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

How does it works? *Reference thermodynamic cycle*



Four main processes:

A – B Evaporation

B – C Compression

C – D Condensation

D – A Lamination

Suitable working fluids

Vapor-compression cylce

R134a, R410a, !R22

R-744 (C02),

Adsorption

NH3-H20; LiBr-H20

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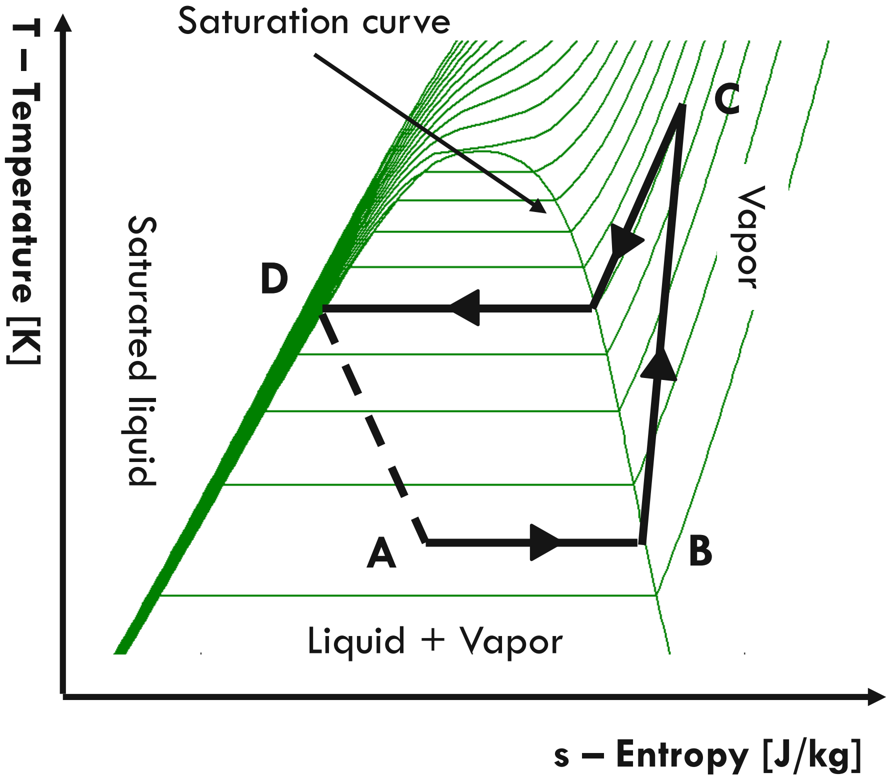
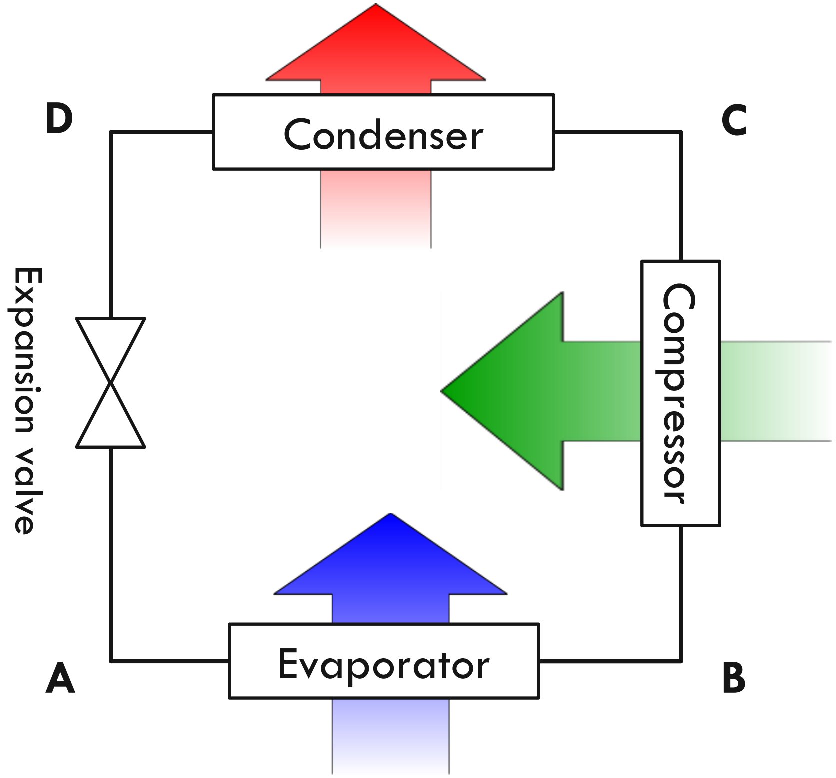
1. HEAT PUMPS: BASIC CONCEPTS AND PRINCIPLES OF WORK

Thermodynamic reference cycle



Components diagram



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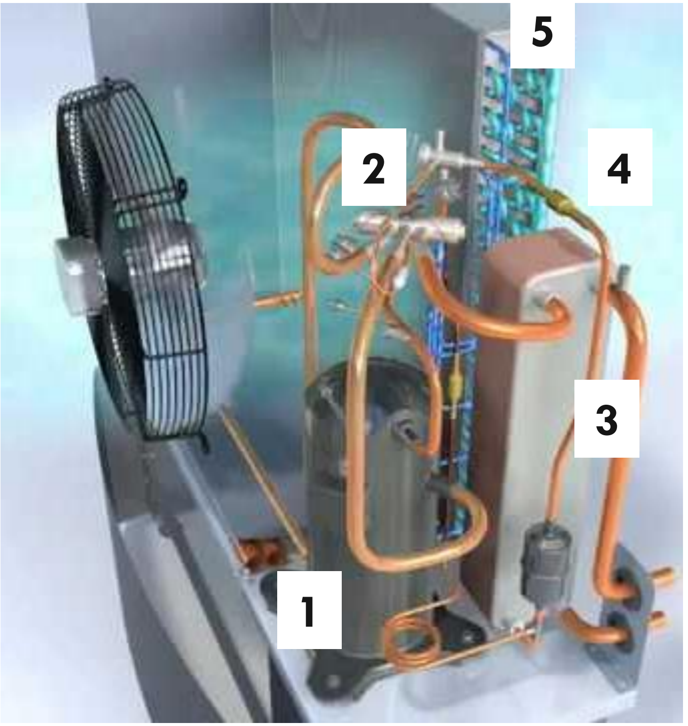

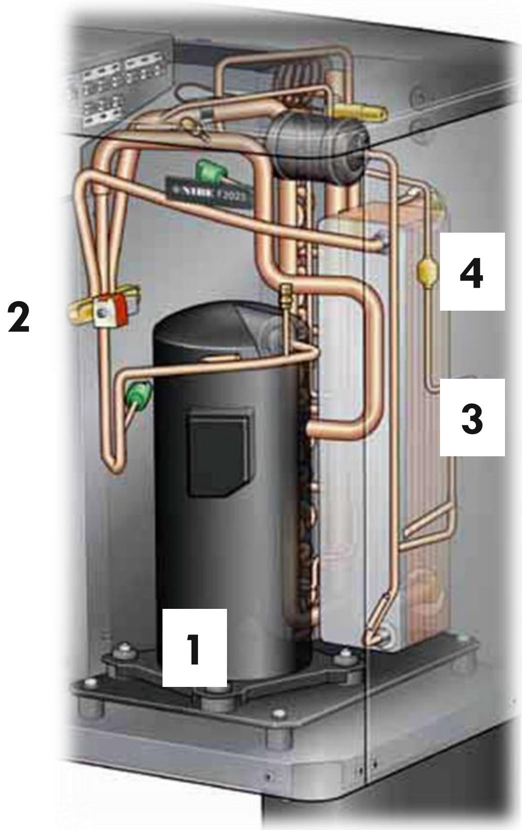

Components

1. Compressor
2. 4-way valve
3. Condenser
4. Lamination valve
5. Evaporator

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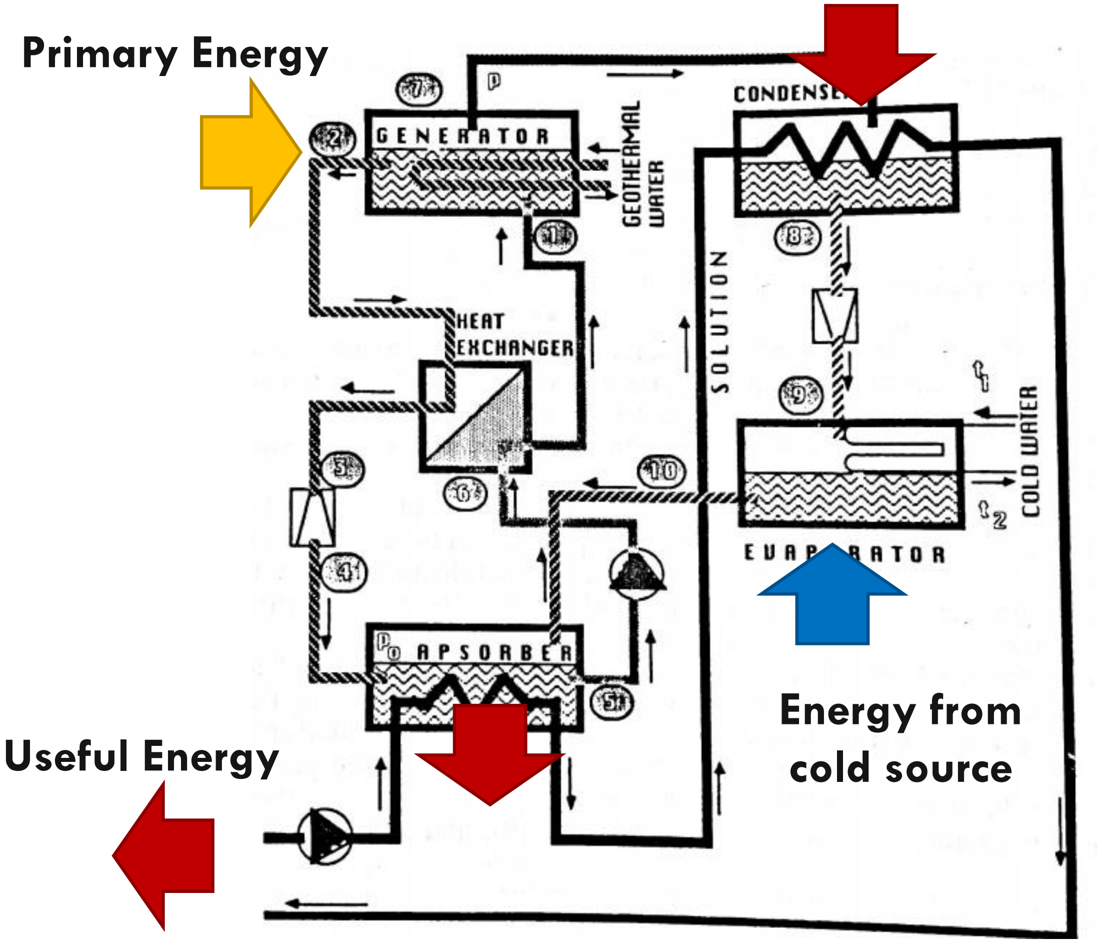

Primary Energy

Useful Energy

Energy from cold source

Compressor is replaced by a generator/absorber system containing a refrigerant/absorbant mixture

Heat (primary energy) is used to “generate” refrigerant from mixture

Refrigerant follows the typical thermodynamic processes of inverse cycles (i.e. evaporation, condensation, lamination)

Useful heat is removed from absorber and condenser

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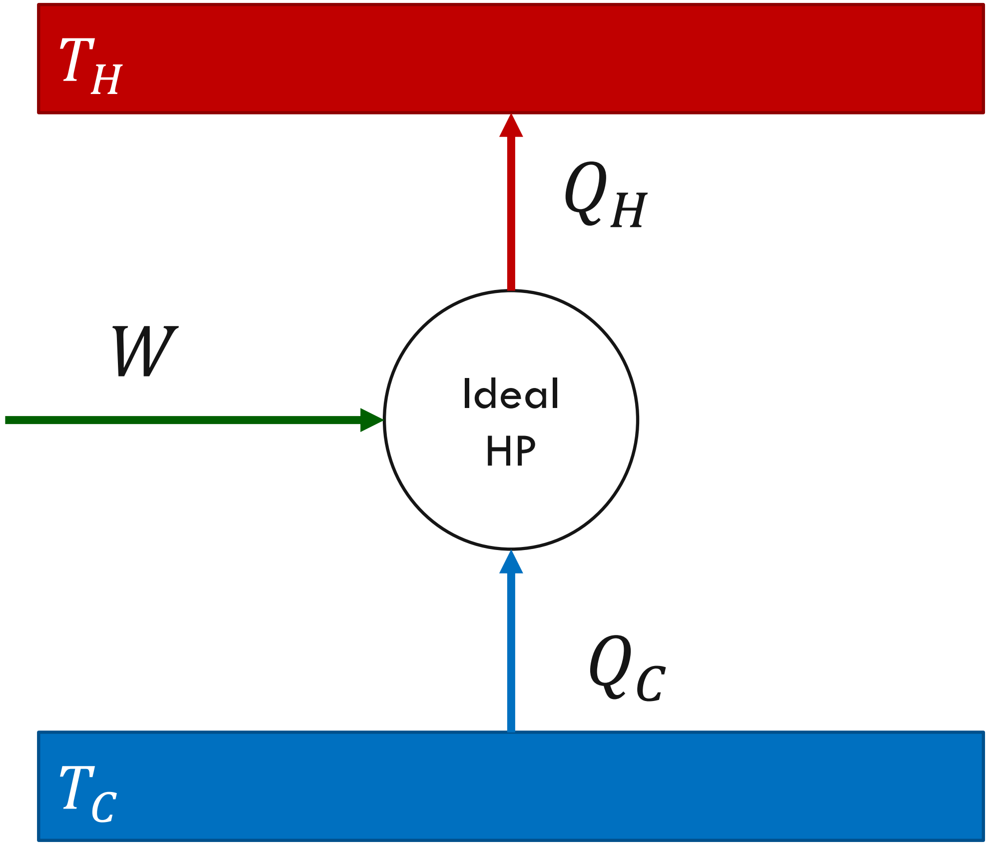


Maximum theoretical performances

Carnot cycle

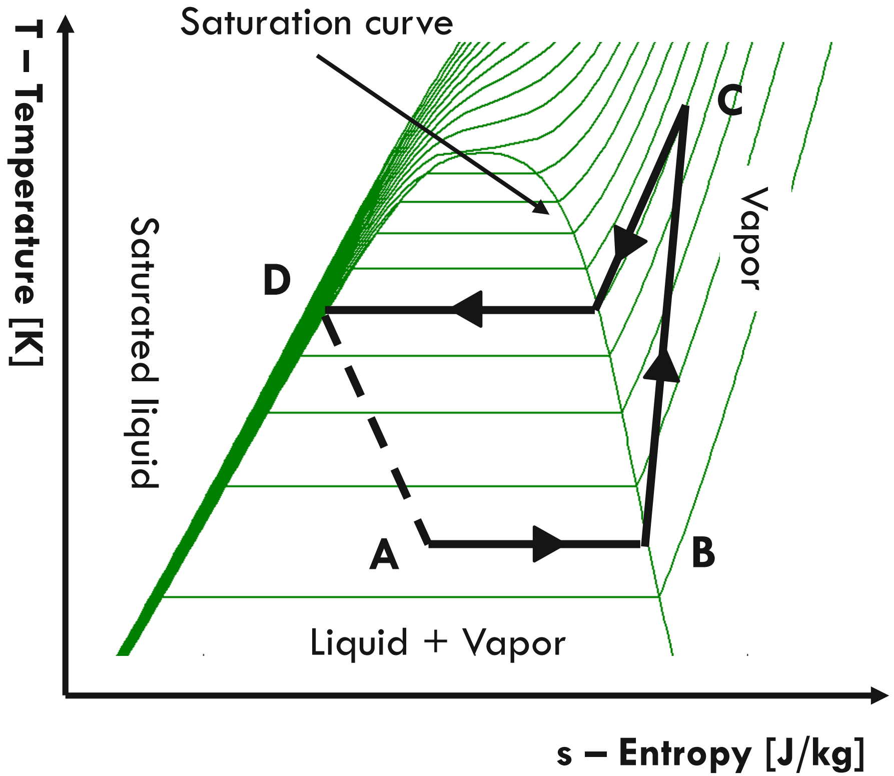
$$COP_{id} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C}$$

$$EER_{id} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_C}{T_H - T_C}$$

! Energy conversion efficiency depends on temperature lift between thermal sources

1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Performances of real units



$$COP = \frac{\dot{Q}_{cond}}{\dot{W}} = \frac{\dot{Q}_{cond}}{\dot{Q}_{cond} - \dot{Q}_{eva}}$$

$$EER = \frac{\dot{Q}_{eva}}{\dot{W}} = \frac{\dot{Q}_{eva}}{\dot{Q}_{cond} - \dot{Q}_{eva}}$$

Equivalent Carnot Temperature

$$\bar{T}_{cond} = \frac{\dot{Q}_{cond}}{s_C - s_D} \qquad \bar{T}_{eva} = \frac{\dot{Q}_{eva}}{s_C - s_D}$$

$$COP = \frac{\bar{T}_{cond}}{\bar{T}_{cond} - \bar{T}_{eva}} \quad \mathrm{EER} = \frac{\bar{T}_{eva}}{\bar{T}_{cond} - \bar{T}_{eva}}$$

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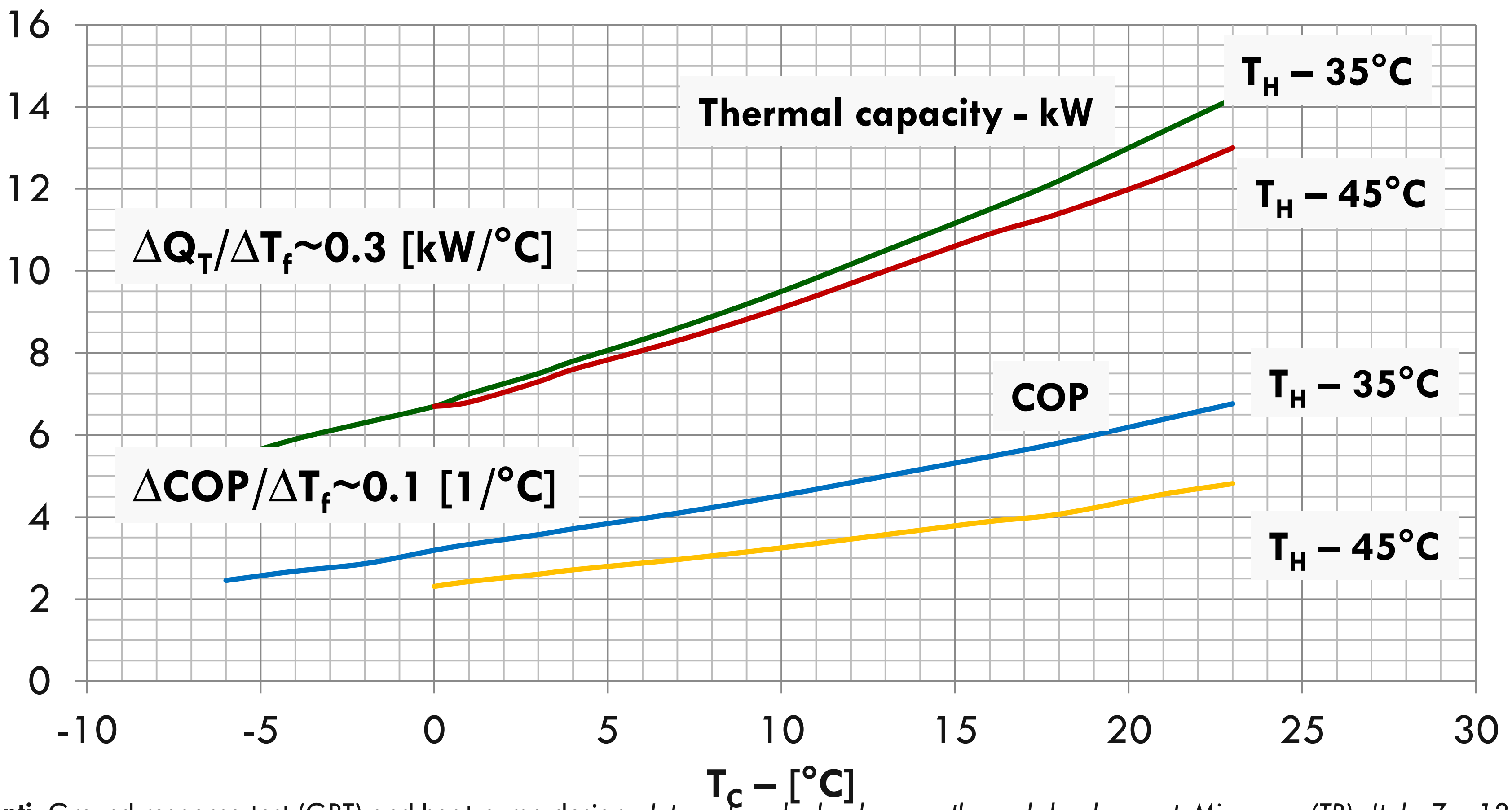
1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Performances of real units



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1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Performance evaluation: Reference temperatures for real units

Nominal data refer to standard rating condition of thermal sources (e.g. UNI EN 14511-2:2013)

Nominal performances	
Heating capacity – kW	15.1
Total power input – kW	3.6
COP	4.2

Secondary fluid (Evaporator): Inlet 10°C / Outlet 7°C
Secondary fluid (Condenser): Inlet 30°C / Outlet 35°C

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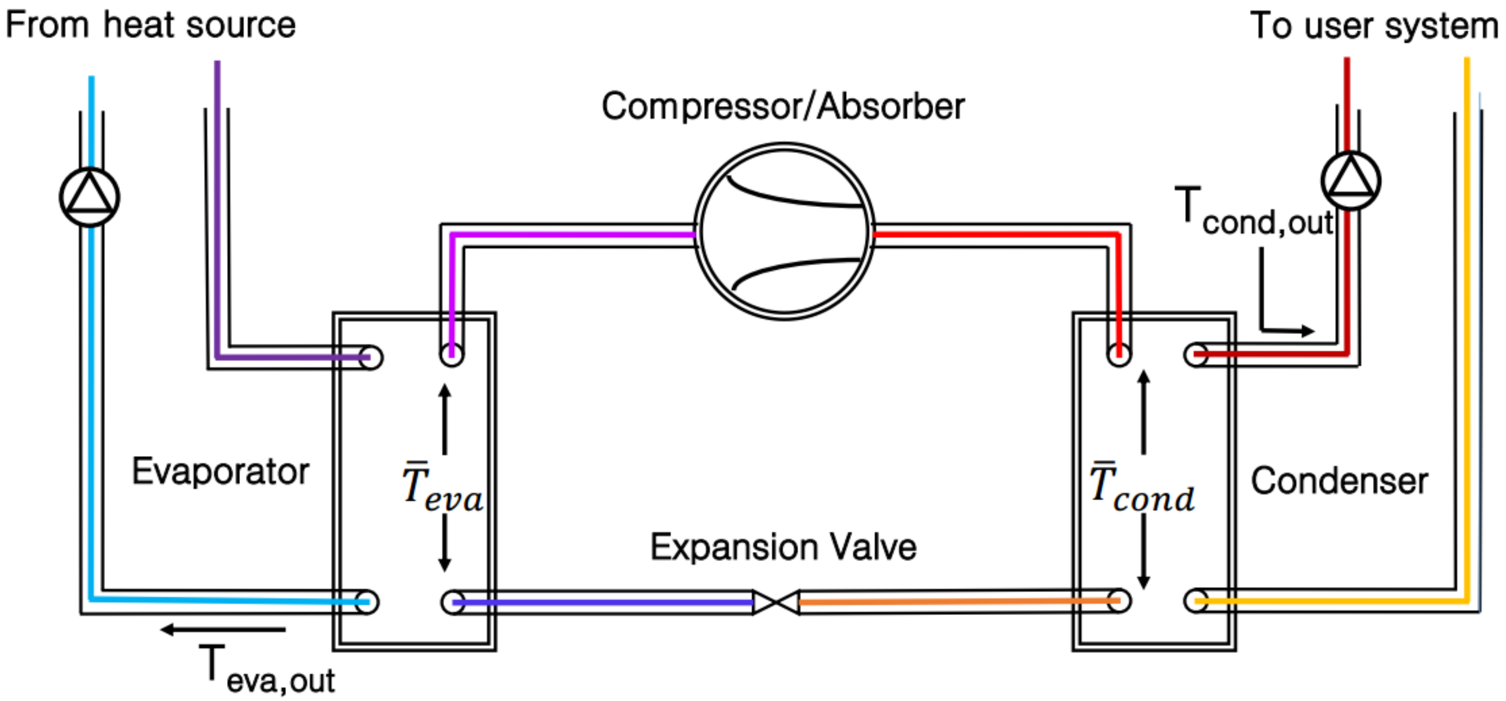
1. HEAT PUMPS: BASIC CONCEPTS AND FUNDAMENTALS

Performance evaluation: Reference temperatures for real units



$$COP_{id} = \frac{T_{cond,out}}{T_{cond,out} - T_{eva,out}}$$

$$EER_{id} = \frac{T_{eva,out}}{T_{cond,out} - T_{eva,out}}$$

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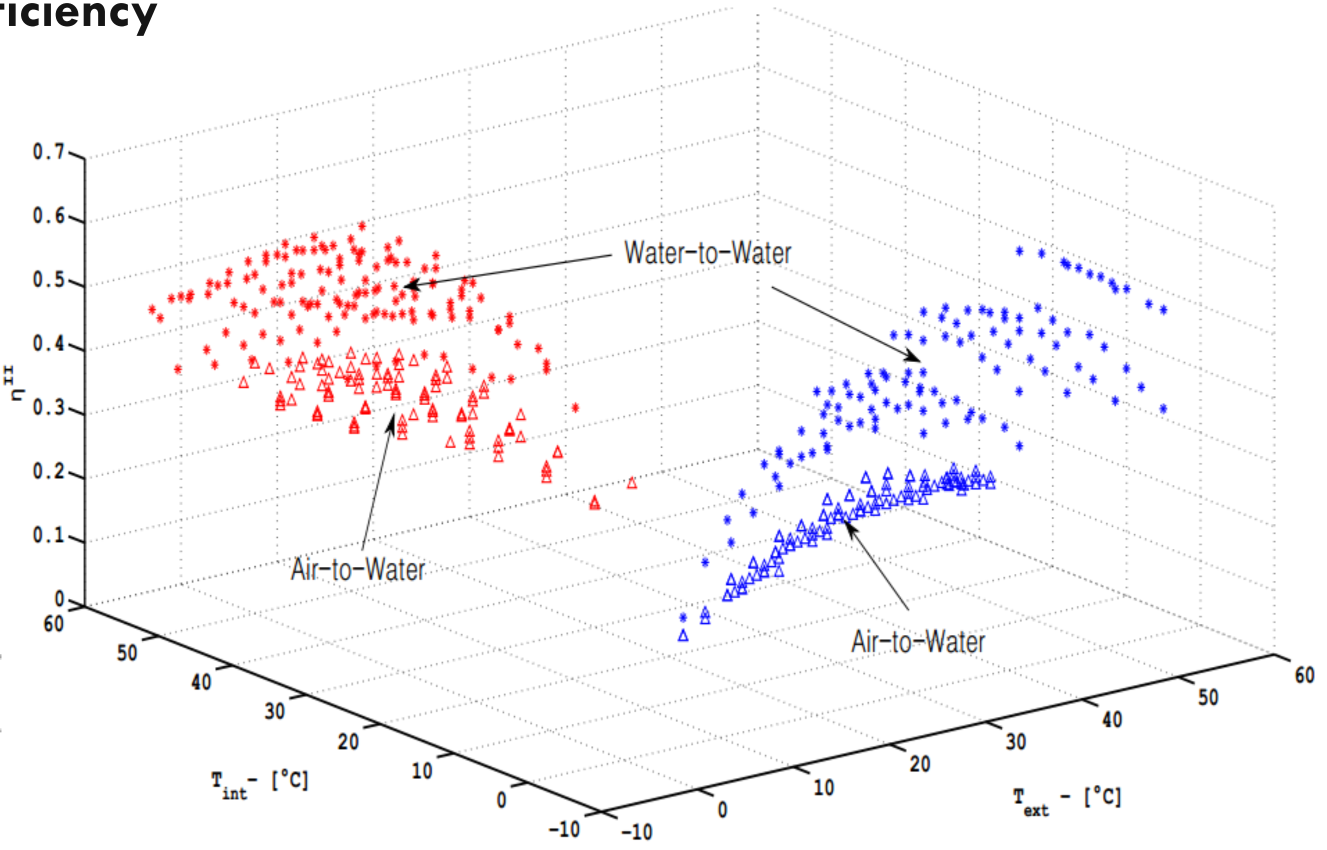
1. HEAT PUMPS: BASIC CONCEPTS AND PRINCIPLES OF WORK

Performances of real units: second-law efficiency

$$\eta_H^{II} = \frac{COP}{COP_{id}}$$

$$\eta_C^{II} = \frac{EER}{EER_{id}}$$

	Heating mode	Cooling mode
Water-to-water units	0.48 – 0.55	0.37 – 0.47
Air-to-water units	0.30 – 0.38	0.15 – 0.25



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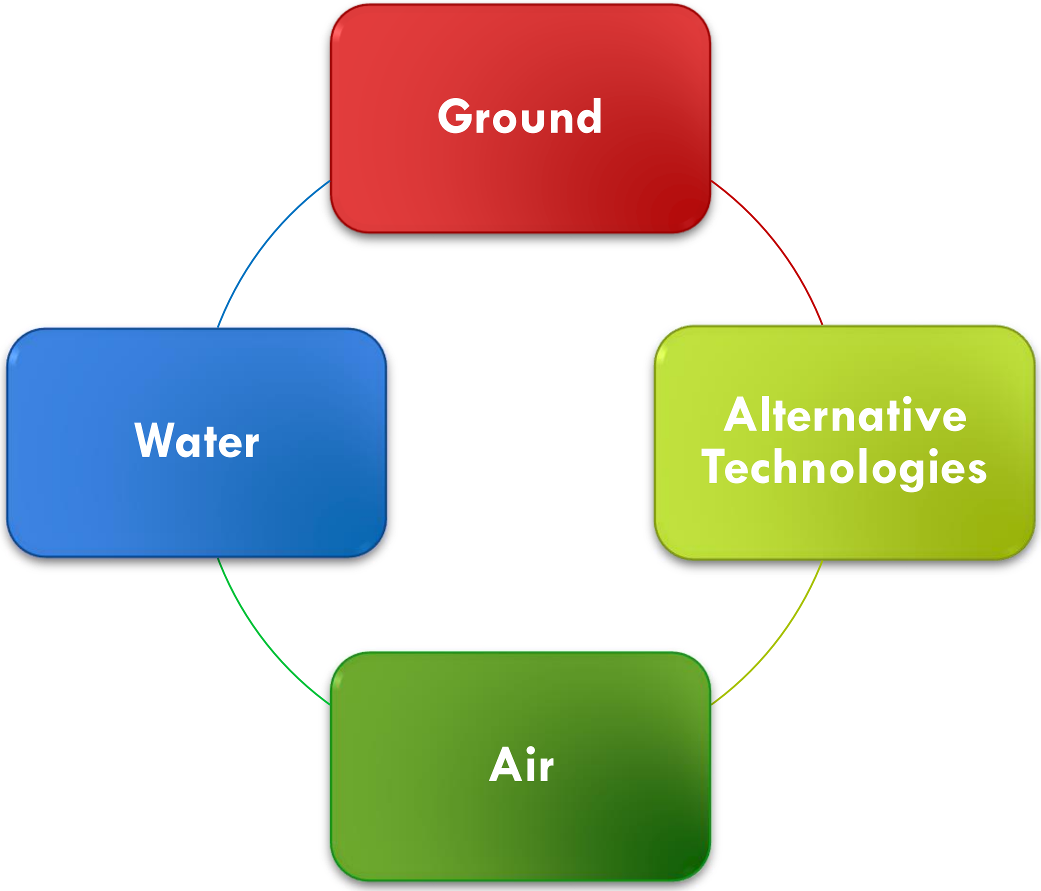
2. THERMAL SOURCES: TYPES, PROS & CONS



Ground

Water

Alternative Technologies

Air

✓Which source should I use?

✓Can I use more than one source?

✓Which are selection and design criteria?

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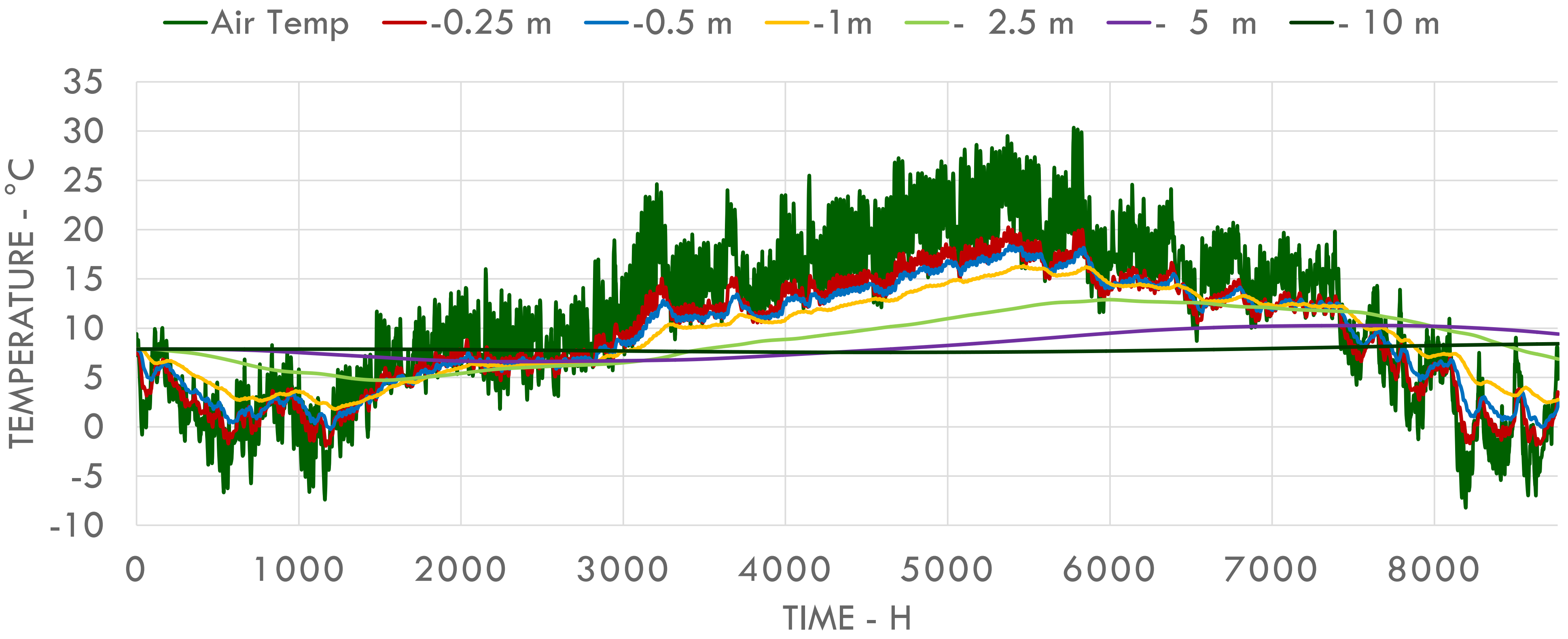

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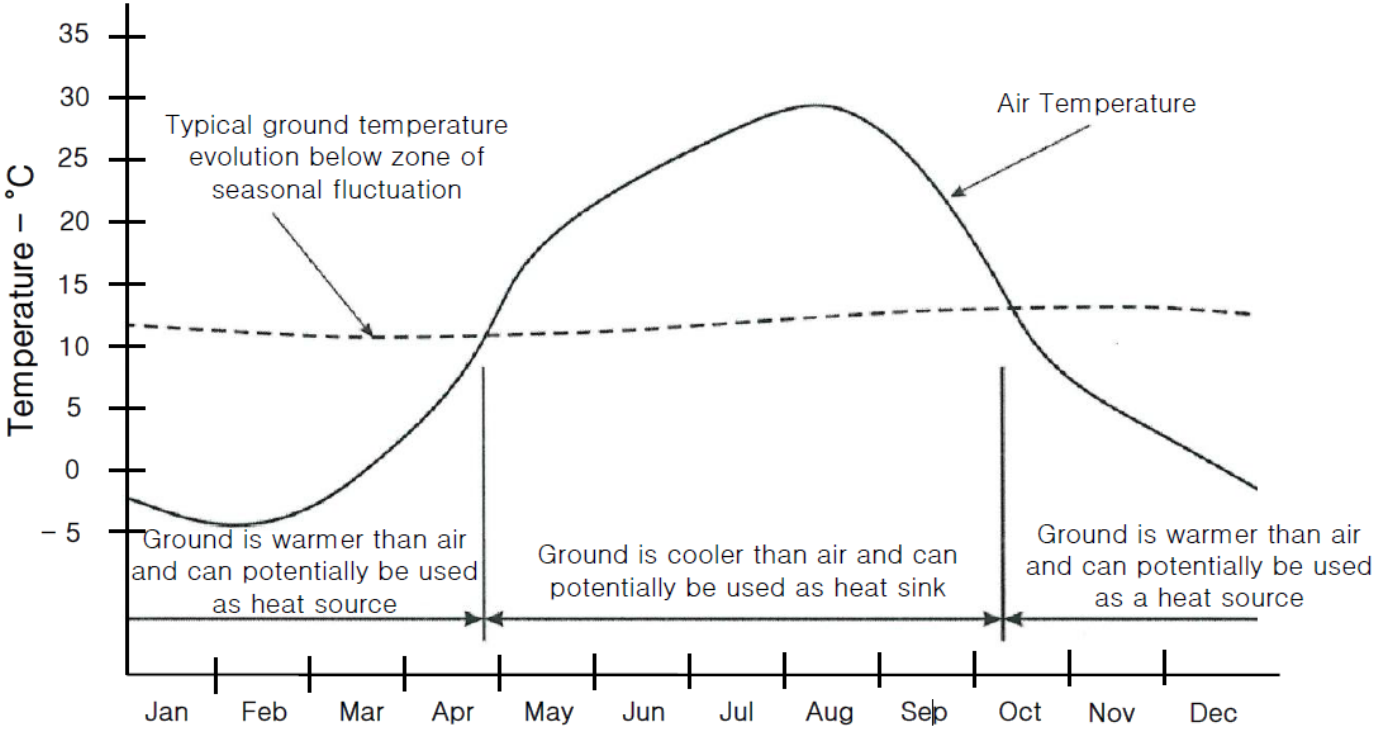
2. THERMAL SOURCES: TYPES, PROS & CONS

The annual air temperature fluctuation is higher than ground one

Theoretically, this results in very advantageous heat source

! NOTE: this is the undisturbed condition (no GSHP operation)



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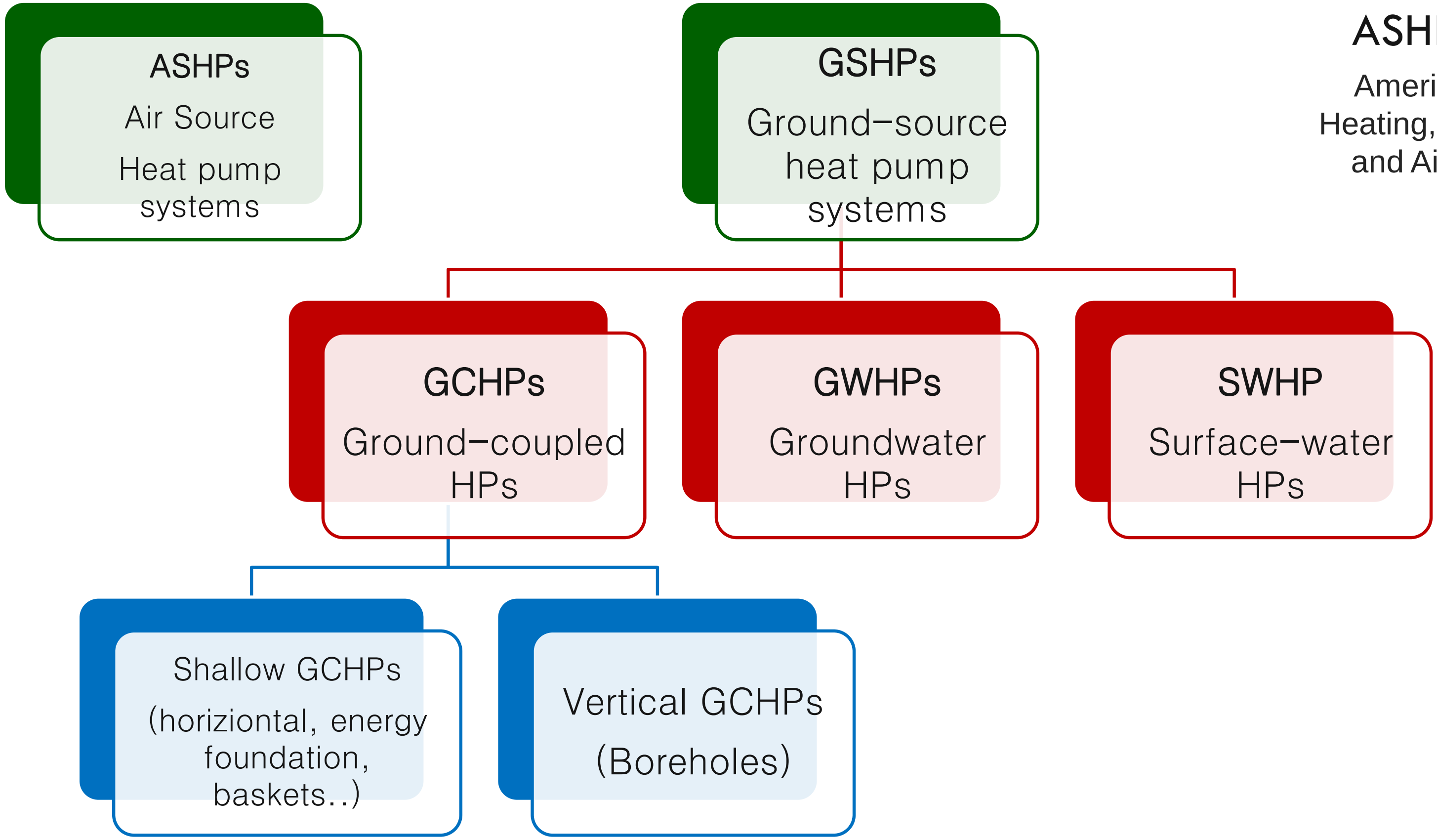
2. THERMAL SOURCES: TYPES, PROS & CONS

Reference:

ASHRAE, 2011

American Society of Heating, Refrigerating, and Air-Conditioning Engineers



ASHPs
Air Source
Heat pump systems

GSHPs
Ground–source heat pump systems

GCHPs
Ground–coupled HPs

GWHPs
Groundwater HPs

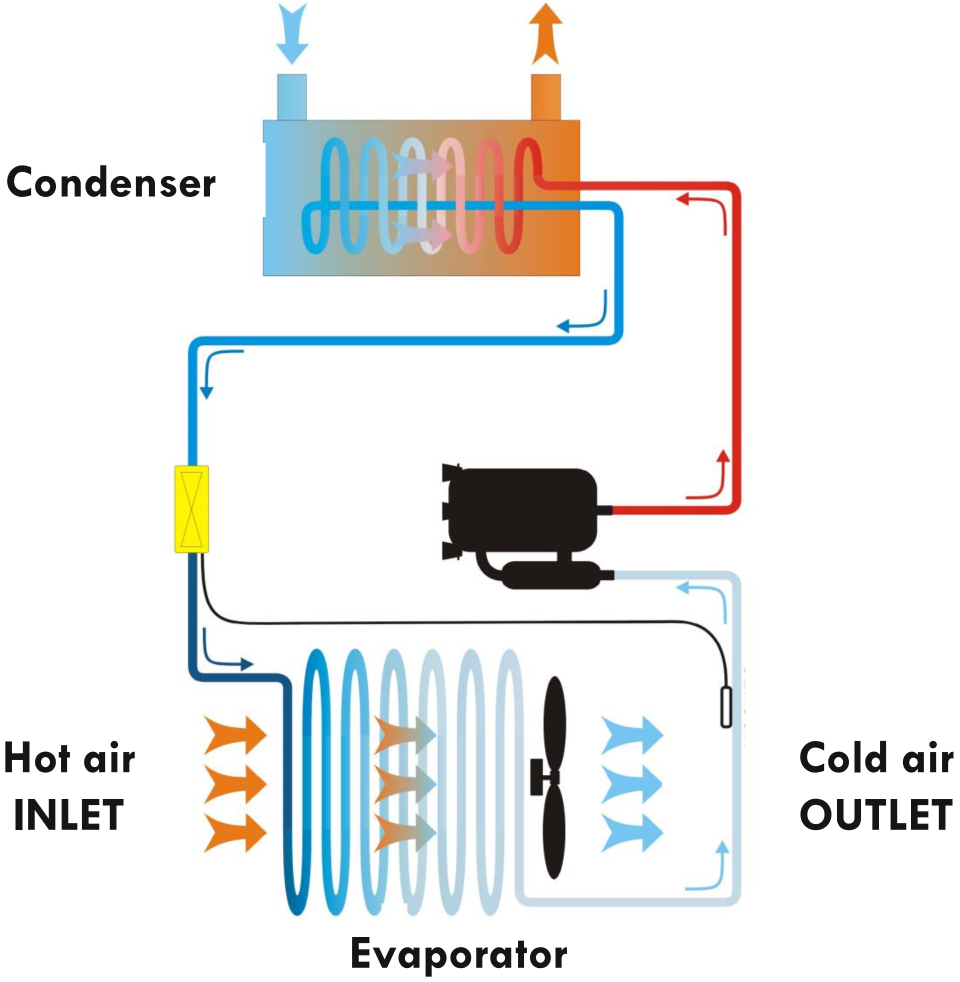
SWHP
Surface–water HPs

Shallow GCHPs
(horiziontal, energy foundation, baskets..)

Vertical GCHPs
(Boreholes)

2. THERMAL SOURCES: TYPES, PROS & CONS

ASHPs – Air Source Heat pumps



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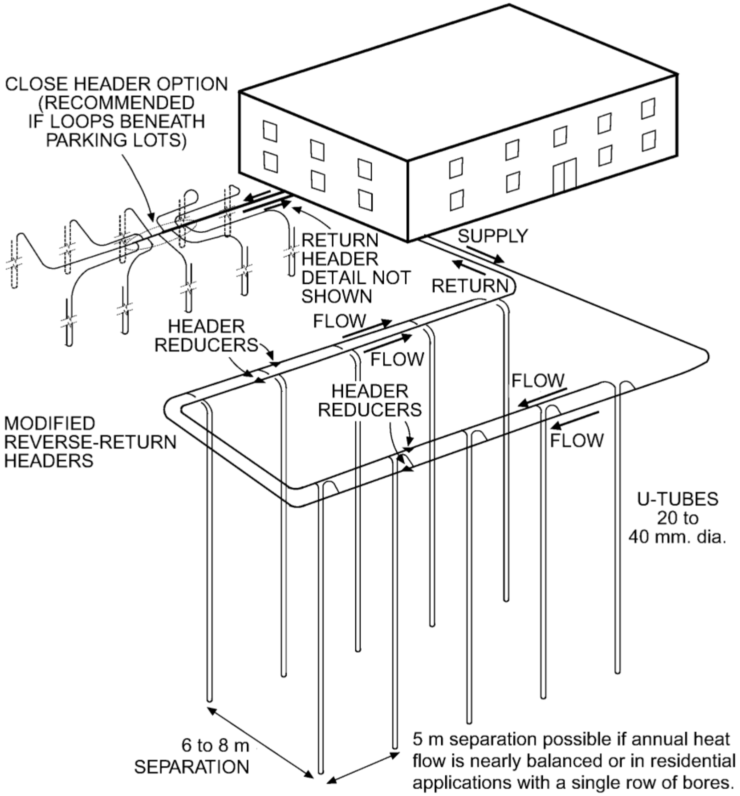
2. THERMAL SOURCES: TYPES, PROS & CONS

Vertical GCHPs



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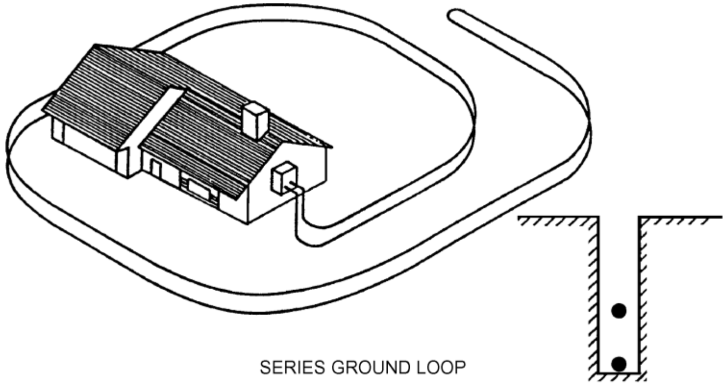
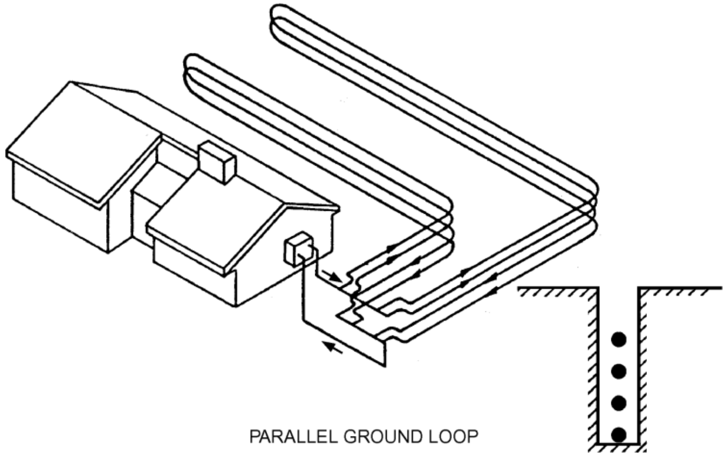
2. THERMAL SOURCES: TYPES, PROS & CONS

Horizontal GCHPs



SERIES GROUND LOOP



PARALLEL GROUND LOOP

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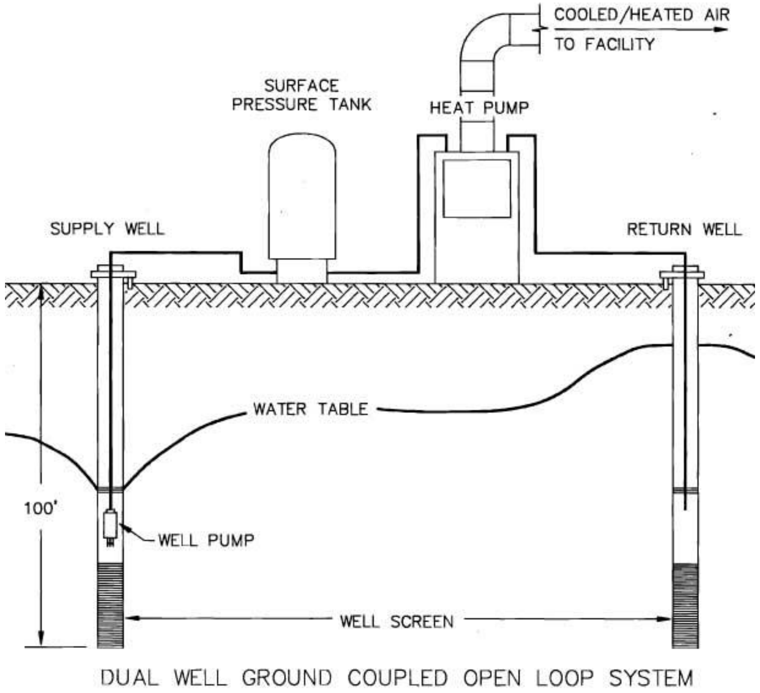
2. THERMAL SOURCES: TYPES, PROS & CONS

GWHPs – Groundwater heat pumps



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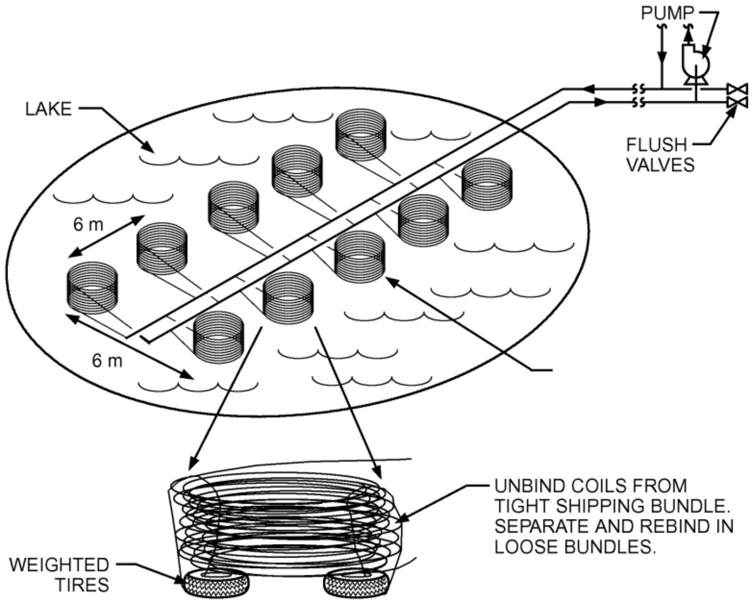
2. THERMAL SOURCES: TYPES, PROS & CONS

SWHPs – Surface-water heat pumps



2. THERMAL SOURCES: TYPES, PROS & CONS

Evaluation criteria

Suitability, seen as the potentiality of the medium to be used as a thermal source

Sustainability, seen as the aptitude of the medium to maintain advantageous conditions for exploitation during all the operational life of the coupled HP system

Availability, seen as the level of accessibility and technical feasibility with current technologies

Installation costs, seen as the total expenditure to purchase equipment and installation works

O&M, seen as the estimation of operative performance and maintenance required

Thermo-physical properties, seen as the temperature at its undisturbed/initial state and heat transfer aptitude

2. THERMAL SOURCES: TYPES, PROS & CONS

Qualitative evaluation

	Suitability	Availability	Installation Cost	O&M Cost	Temperature
ASHPs	GOOD	EXCELLENT	LOW	MODERATE	VARIABLE
Vertical GCHPs	MODERATE	GOOD / EXCELLENT	HIGH	MODERATE	GOOD
Horizontal GCHPs	MODERATE	MODERATE/GOOD	MODERATE	MODERATE	GOOD / EXCELLENT
GWHPs	GOOD	GOOD	MODERATE	MODERATE/HIGH	GOOD / EXCELLENT
SWHPs	GOOD	MODERATE	MODERATE	MODERATE/HIGH	GOOD

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3. GROUND SOURCE HEAT PUMP SYSTEMS

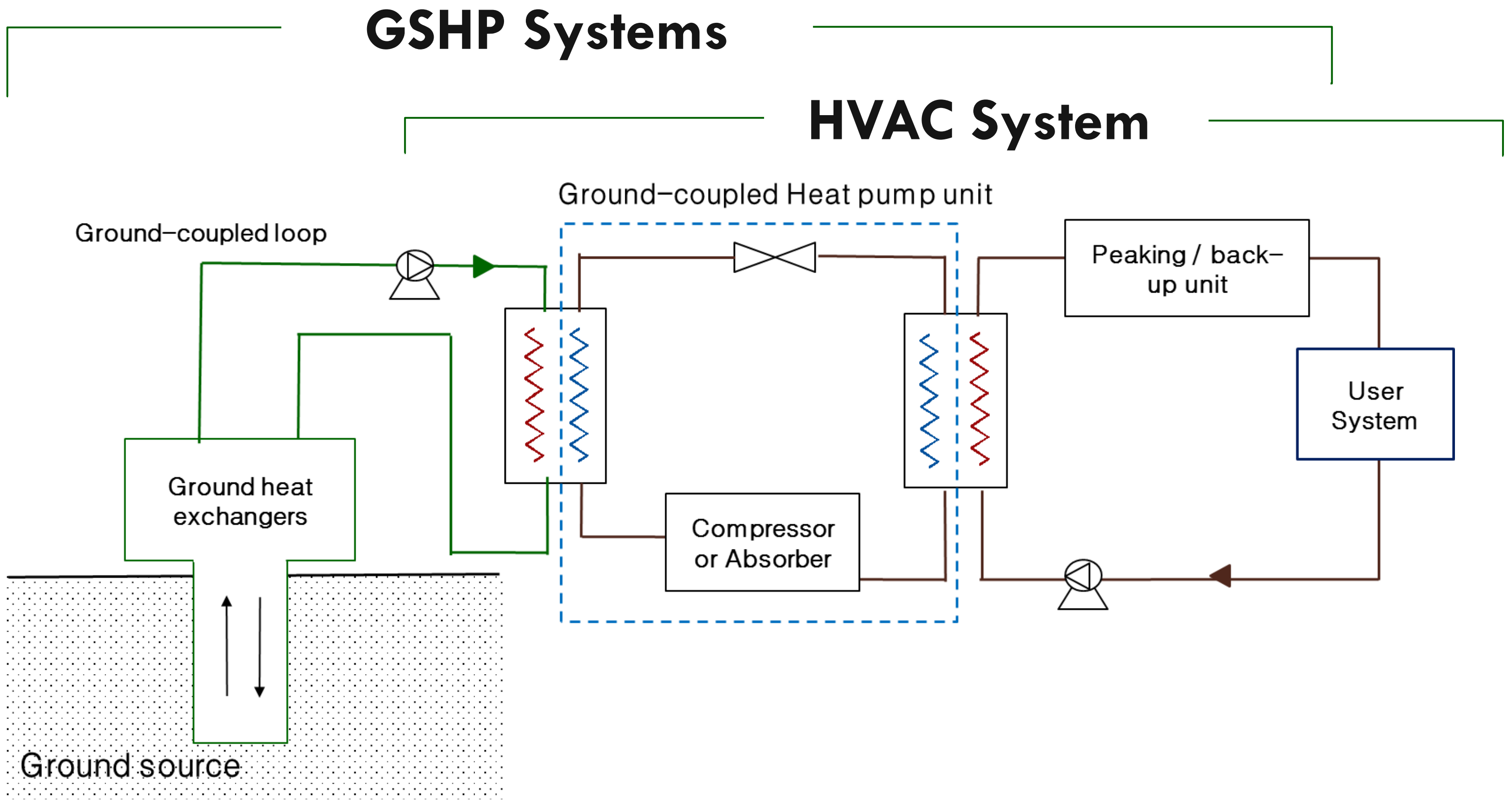
Main GSHP design issues:

1. Real systems are neither thermodynamic cycles nor HP unit
   - GSHPs are complex system made of different technologies, with several physical mechanisms involved (multidisciplinary competences are required)
   - Technological characteristics and inefficiencies of real devices (head losses, joule losses, heat losses, thermodynamic losses…)
   - Difference among evaporation/condensation temperatures (i.e. the thermodynamic unit) and thermal source ones
   - Back-up/peaking unit (multi-source system): control strategy is required.
   - Ancillary systems (i.e. HP COP is different from overall COP)

2. Thermal load profile evolves with hourly, daily, and monthly time scale.
3. Heat exchanges due to GSHP operation modify the undisturbed ground temperature evolution (i.e. sustainability)

3. GROUND SOURCE HEAT PUMP SYSTEMS

GSHPs: equipment layout



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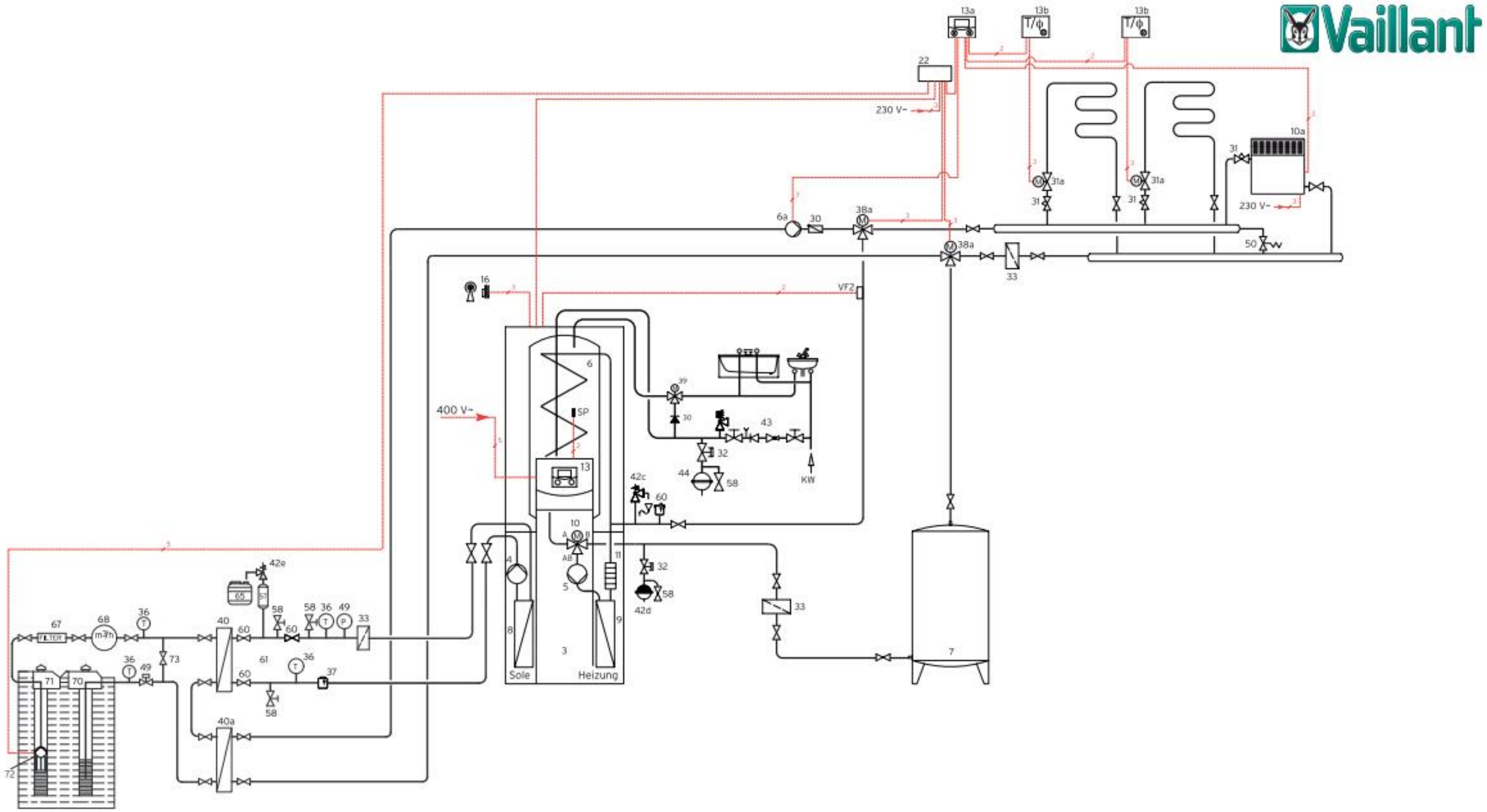
3. GROUND SOURCE HEAT PUMP SYSTEMS



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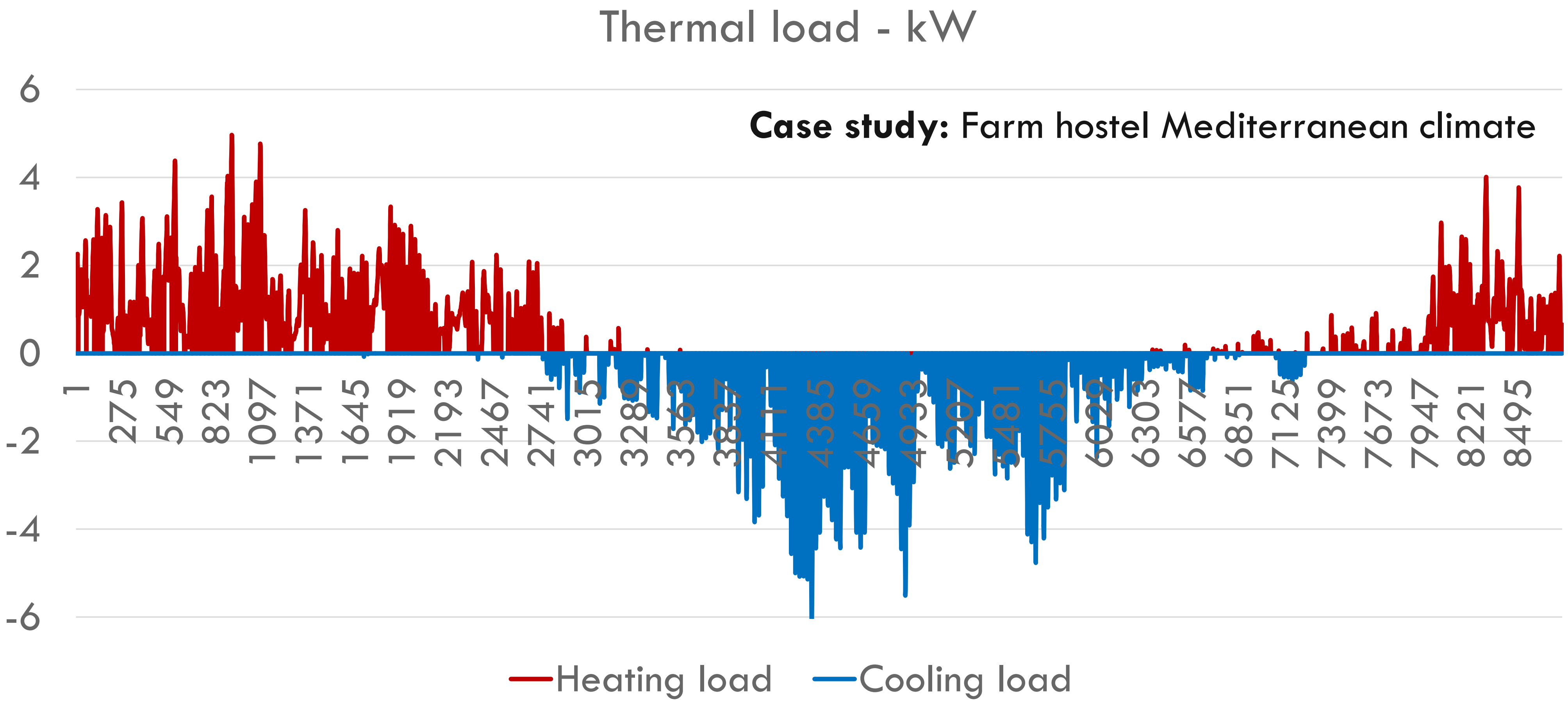
3. GROUND SOURCE HEAT PUMP SYSTEMS



Case study: Farm hostel Mediterranean climate

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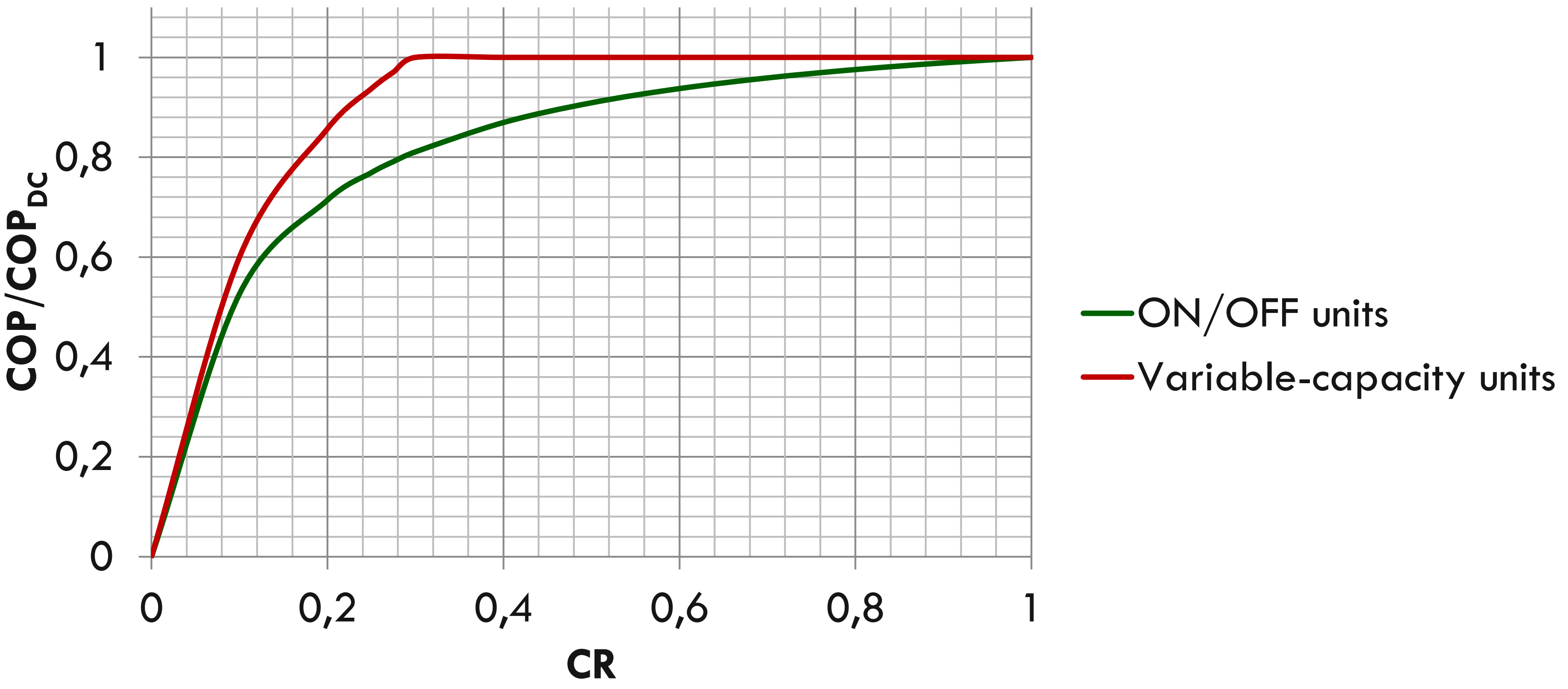
3. GROUND SOURCE HEAT PUMP SYSTEMS

COP penalization factor (UNI EN 14825:2012)



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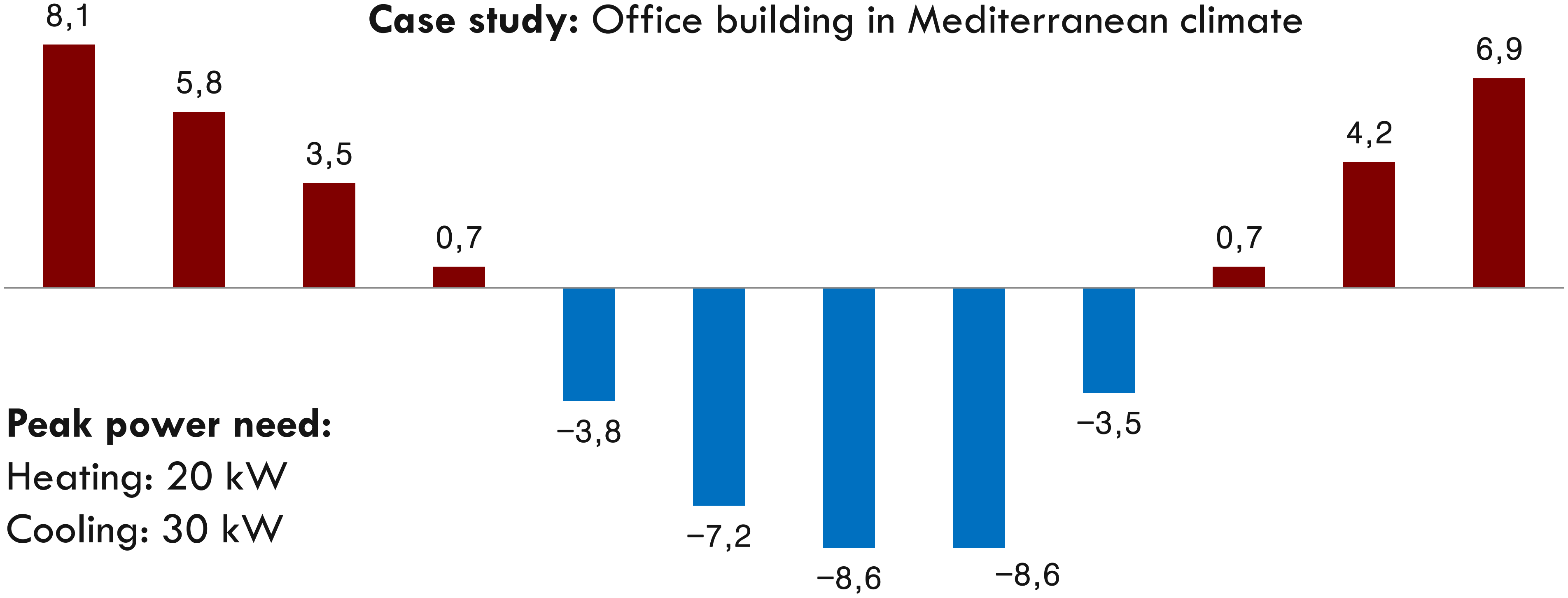
3. GROUND SOURCE HEAT PUMP SYSTEMS

Monthly heating and cooling loads [MWh]

Case study: Office building in Mediterranean climate



Peak power need:
Heating: 20 kW
Cooling: 30 kW

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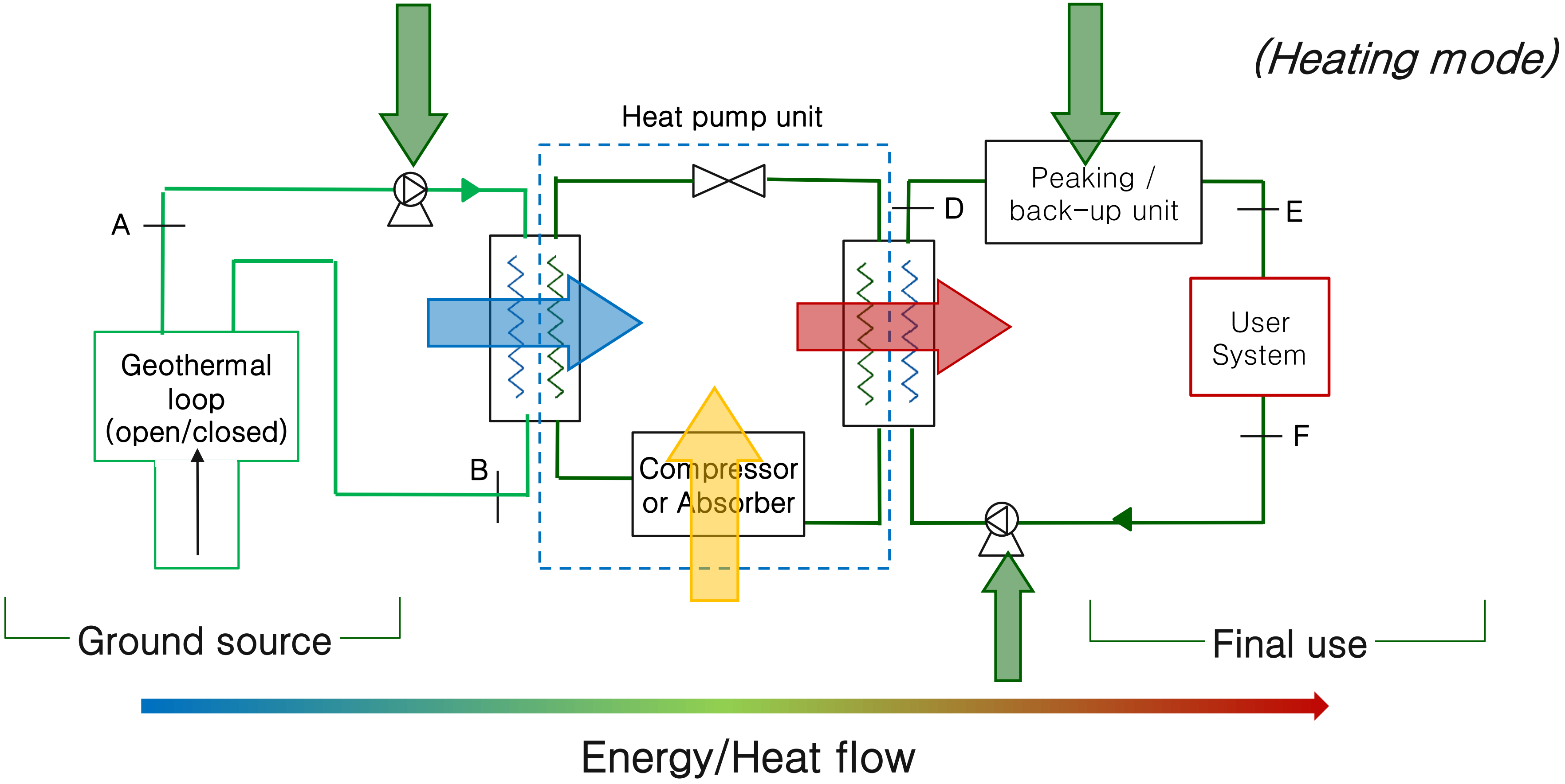
3. GROUND SOURCE HEAT PUMP SYSTEMS



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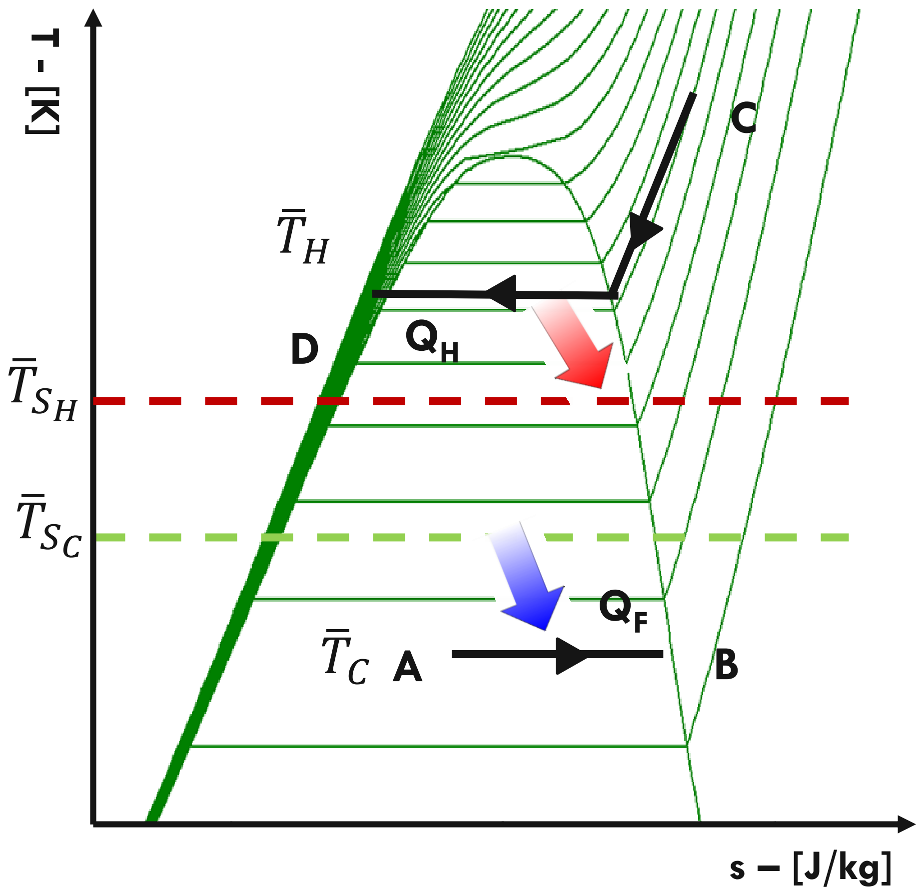
3. GROUND SOURCE HEAT PUMP SYSTEMS

Thermal sources VS. operating fluid



HP efficiency depends on condensing/evaporation temperatures (not sources)

$$T_H < \bar{T}_{cond}$$
$$T_C < \bar{T}_{eva}$$

$\bar{T}_{H,C}$ -> thermal sources

$\bar{T}_{cond,eva}$ -> working fluid

$$COP(T_H; T_C) > COP(\bar{T}_{cond}, \bar{T}_{eva})$$

✓GSHP efficiency is strongly affected by heat transfer apparatus

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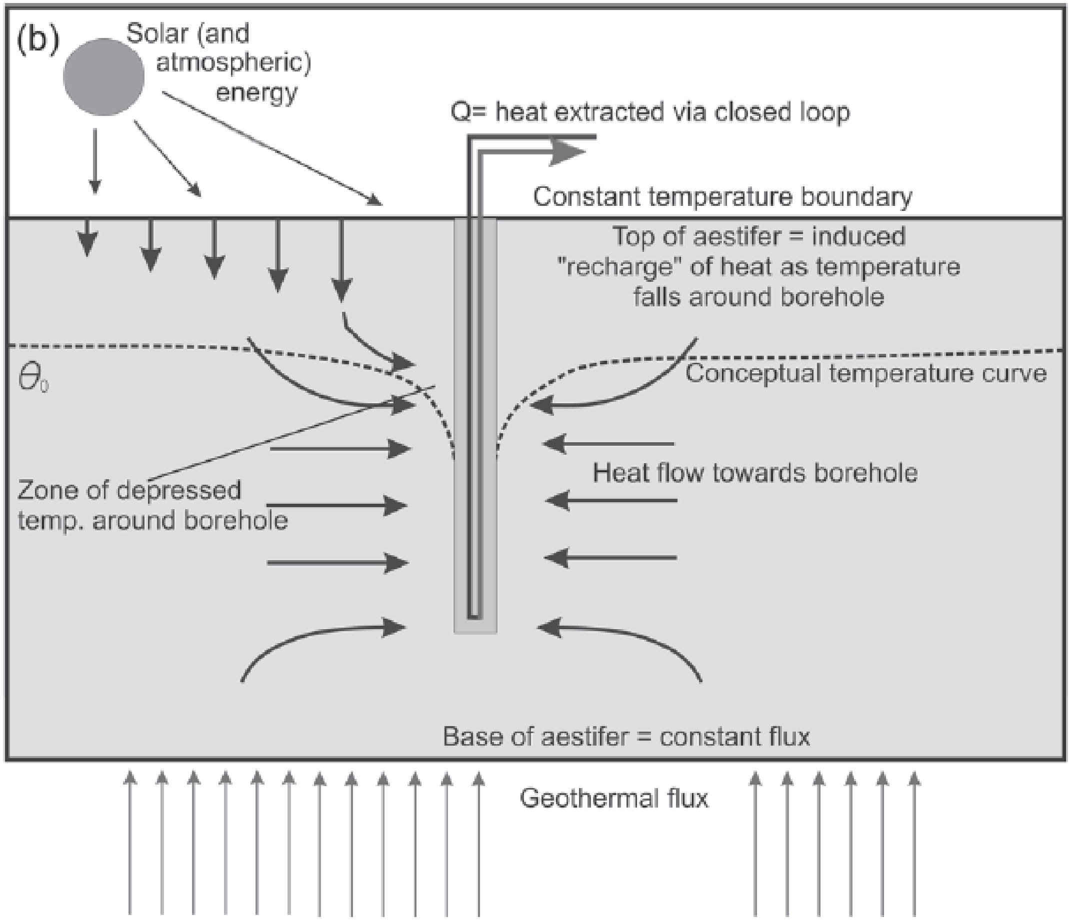
3. GROUND SOURCE HEAT PUMP SYSTEMS

Energy balance of the ground source: closed-loop systems



Parameters influencing system performances:

- Depth of installation (vertical /horizontal)
- Thermal conductivity, W/(mK)
- Thermal diffusivity, m2/s
- Groundwater movment
- Operational temperature/flow rate of the ground-coupled loop

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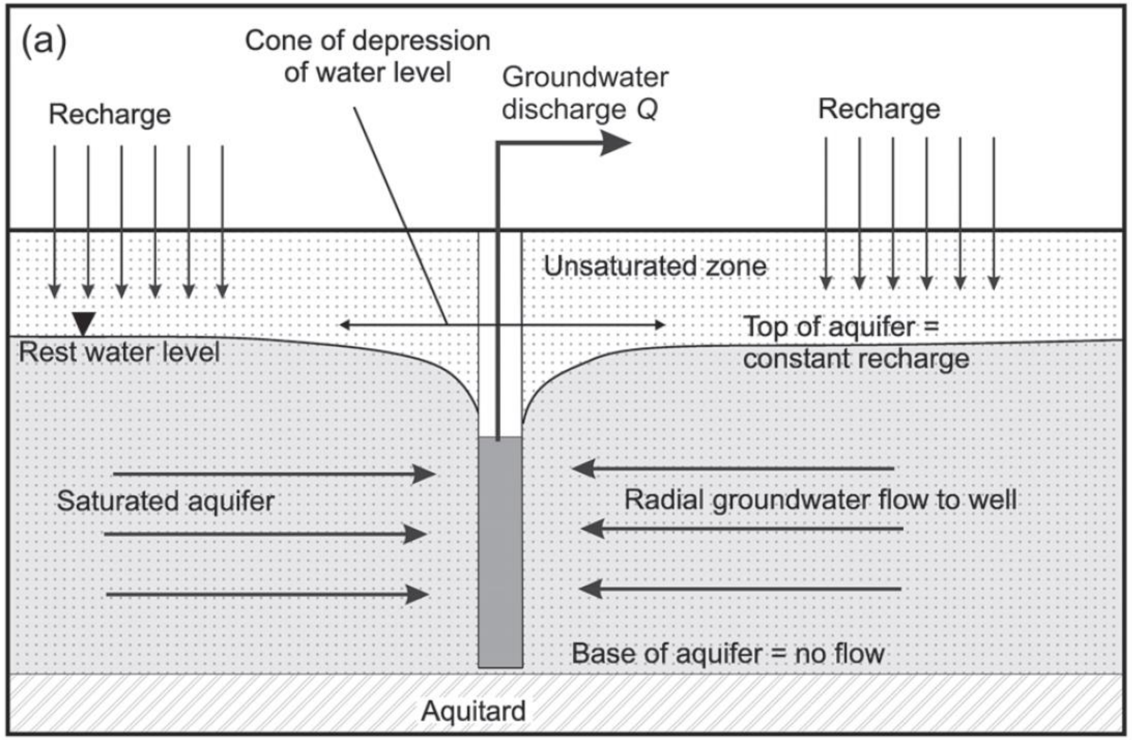
3. GROUND SOURCE HEAT PUMP SYSTEMS

Energy balance of the ground source: open-loop systems



Parameters influencing system performances:

- Hydraulic conductivity, m/s;
- Porosity;
- Static water level, m;
- Drawdown, m;
- Specific capacity, l/(s m) ;
- Well hydraulic resistance, m/(kg/s)

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4. GROUND SOURCE MODELING

Physical models of ground source in GSHP applications

Purely conductive media

(no significant groundwater movemnt)

Temperature field - Fourier Law

$$\dot{q} = -\lambda \nabla T$$

$$\rho c \frac{\partial T}{\partial t} = k \, \nabla T + \dot{q}_{gen}$$

Porous media

Velocity field - Darcy law

$$\boldsymbol{v} = \frac{K}{\mu} \nabla p \quad \text{(Darcy Law)}$$

Temperature field - Darcy law + Fourier law

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c)_f \, \mathbf{v} \cdot \nabla T = \nabla \cdot (k_m \, \nabla T) + q_m'''$$

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4. GROUND SOURCE MODELING

Analytical models

Pros
- Low computational effort
- General indications on involved physical mechanisms
- General indications not related to a single case
- Recommended for feasibility studies

Cons
- Accuracy
- Simplified boundary conditions and geometries

Numerical models (i.e. software)

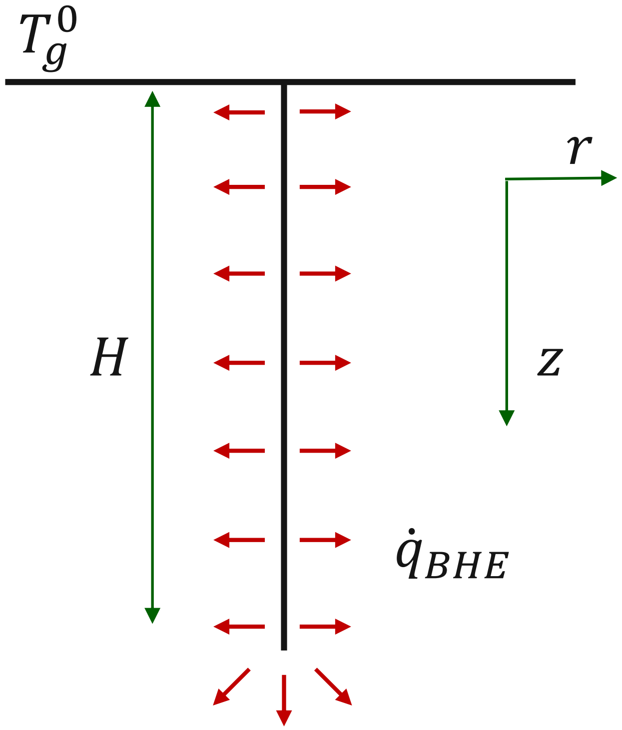
Pro
- High accuracy for the specific project
- Unlimited possibility of geometries and boundary conditions

Cons
- Results are strictly related to the specific case
- Results do not provide general indications
- Physical phenomena are practically the same of analytical models
- Results soundless depends on the accuracy parameters and boundary conditions

4. GROUND SOURCE MODELING

Pure conductive medium: Finite line source – FLS

Reference:
Carslaw & Jeager, 1959



$$\Theta_g = \frac{1}{4\pi}\int_0^1 \left[\frac{1}{d/L}\, erfc\left(\frac{d/L}{2\sqrt{Fo}}\right) - \frac{1}{d'/L}\, erfc\left(\frac{d'/L}{2\sqrt{Fo}}\right)\right] dH'$$

$$Fo = \frac{\alpha t}{H^2} \qquad R = \frac{r}{H} \qquad Z = \frac{z}{H}$$

$$\Theta_g = \frac{\left(T_g - T_g^0\right)\lambda_g}{\dot{q}_{BHE}}$$

$$d/L = \sqrt{R^2 + (Z - H')^2}$$

$$d'/L = \sqrt{R^2 + (Z + H')^2}$$

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4. GROUND SOURCE MODELING

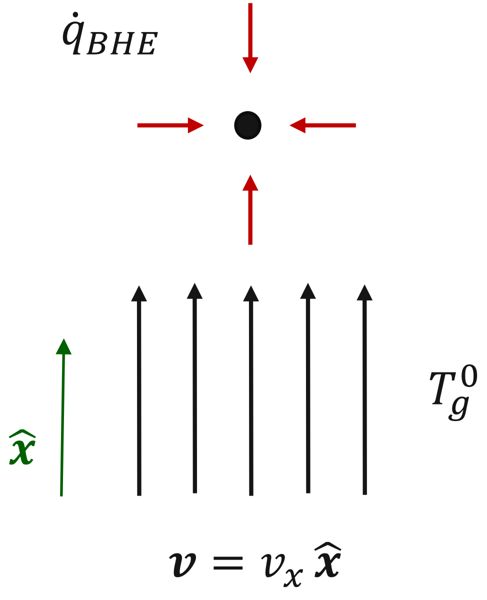
Reference:
Sutton et al., 2003

Saturated Porous media: Moving infinite line source - MILS

$$
\begin{cases}
\alpha_{eff}\left(\dfrac{\partial T_g}{\partial x^2}+\dfrac{\partial T_g}{\partial y^2}\right)=\dfrac{\partial T_g}{\partial t}+U_{eff}\dfrac{\partial T_g}{\partial x} \\
T_g(r\to\infty,t)=T_g^0 \\
T_g(r,t=0)=T_g^0 \\
\dot{q}(r\to 0,t)=-(2\pi r)\lambda_g \left.\dfrac{\partial T_g}{\partial r}\right|_{r\to 0}=\dot{q}
\end{cases}
$$

$$v=\frac{K}{\mu}\nabla p \quad \text{(Darcy Law)}$$

$$U_{eff}=\phi\frac{\rho_f c_f}{[\phi\rho_f c_f+(1-\phi)\rho_s c_s]}v \qquad \alpha_{eff}=\frac{\phi\lambda_f+(1-\phi)\lambda_s}{[\phi\rho_f c_f+(1-\phi)\rho_s c_s]}$$



3. GROUND SOURCE HEAT PUMP SYSTEMS

GHEx field: Space and time superposition

Linearity of the equations

(Duhamel's principle)

$$\overline{T}_g(t) = \frac{1}{\lambda}\int_0^t \overline{\Theta}_g(t-\beta)\frac{d\dot{q}}{dx}(t)d\beta$$

Generic formulation to evaluate the temperature field evolution within a BHEs field

$$T_g(\mathbf{x}, t = n\Delta t) = T_g^0 - \sum_{b=1}^{N_{BHE}} \sum_{i=1}^{n} \frac{\Theta_g\left(\left|\mathbf{x} - \mathbf{x}_b\right|, t = i\Delta t\right)}{\lambda_g} \left[\dot{q}_{BHE}^{n-i+1} - \dot{q}_{BHE}^{n-i}\right]$$

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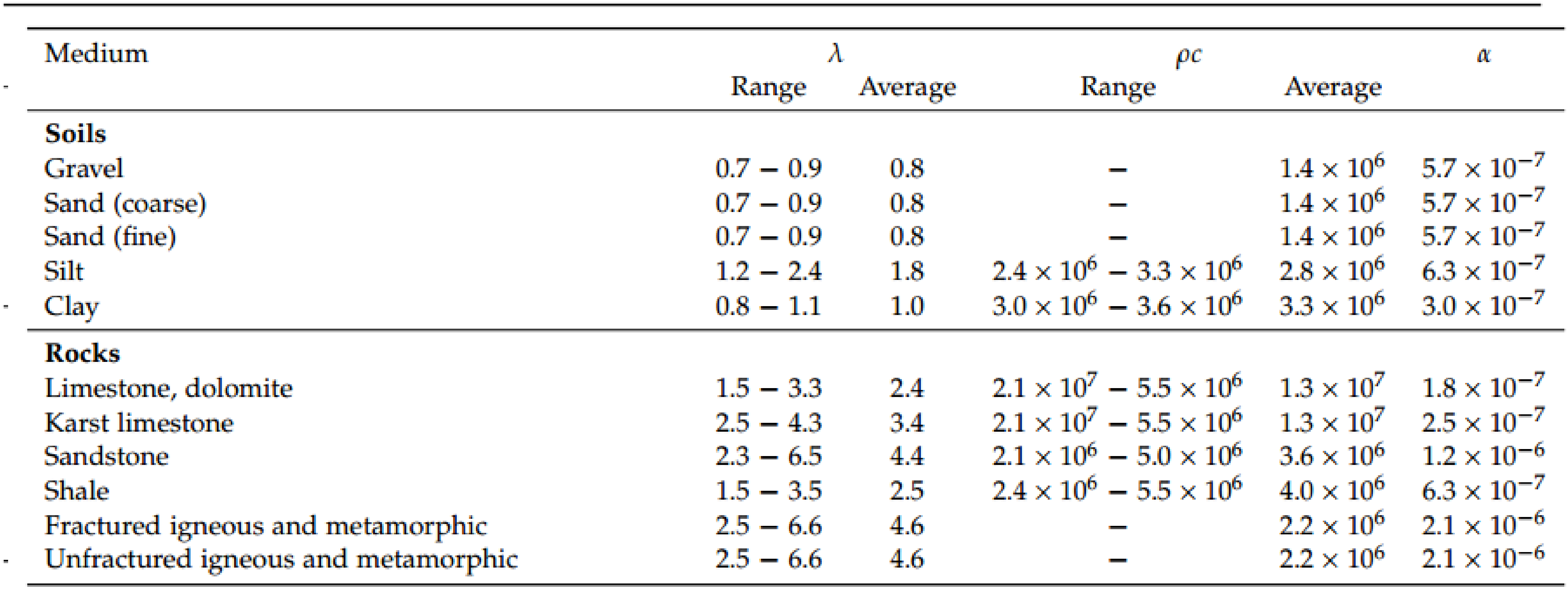
7. SITE-INVESTIGATION METHODS

Ground thermo-physical properties affect both thermal performance and sustainability of source exploitation (i.e. thermal field, water table)

Reference values (from literature or previous nearby projects) can be used for preliminary feasibility studies. However, in-situ test procedures should always be performed for actual projects

Thermal/Ground response test (TRT/GRT) and pumping test are the two most widespread methods for ground source characterization.

7. SITE-INVESTIGATION METHODS



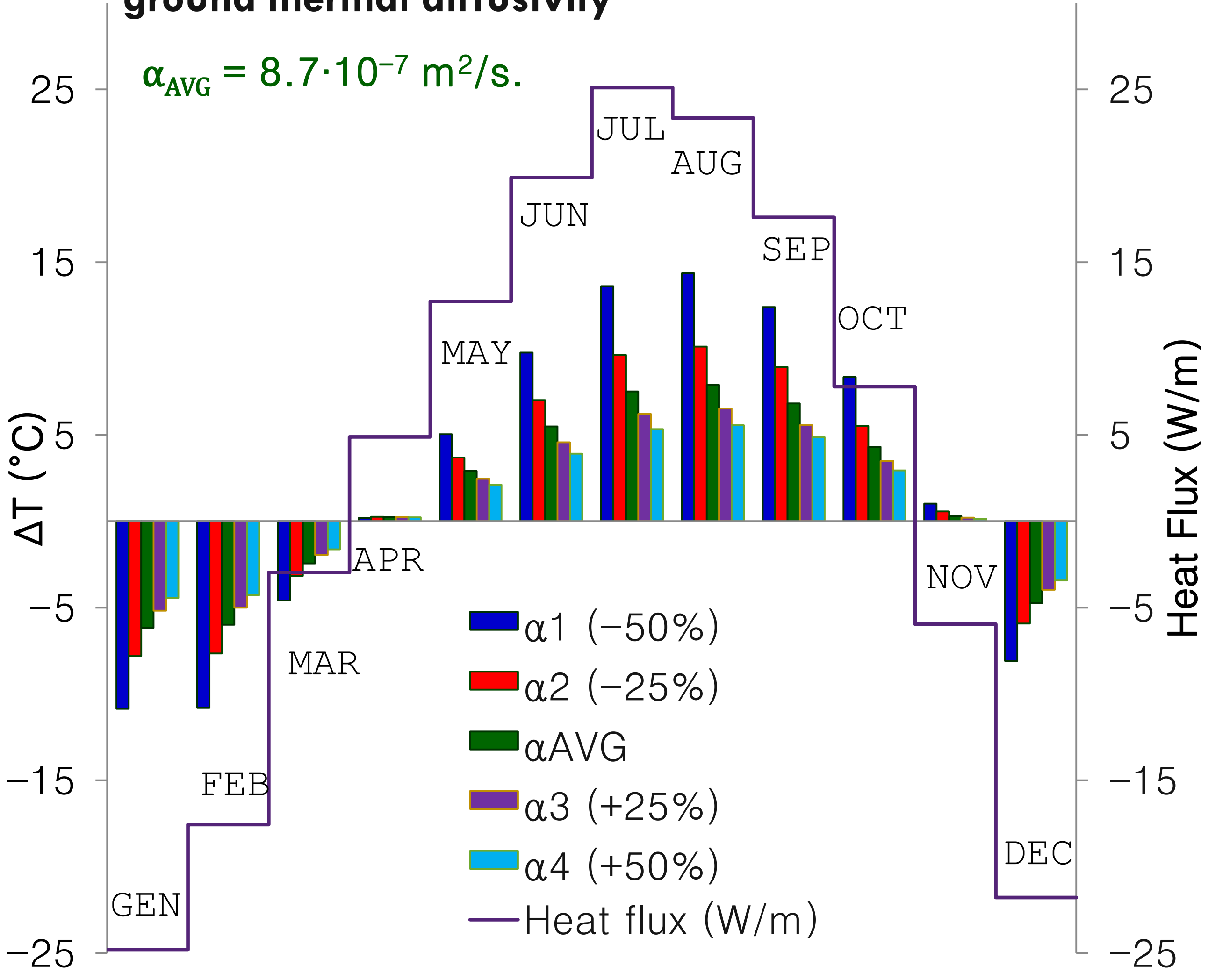
Medium	λ		ρc		α
	Range	Average	Range	Average	
Soils					
Gravel	0.7 – 0.9	0.8	–	1.4×10^6	5.7×10^{-7}
Sand (coarse)	0.7 – 0.9	0.8	–	1.4×10^6	5.7×10^{-7}
Sand (fine)	0.7 – 0.9	0.8	–	1.4×10^6	5.7×10^{-7}
Silt	1.2 – 2.4	1.8	$2.4 \times 10^6 - 3.3 \times 10^6$	2.8×10^6	6.3×10^{-7}
Clay	0.8 – 1.1	1.0	$3.0 \times 10^6 - 3.6 \times 10^6$	3.3×10^6	3.0×10^{-7}
Rocks					
Limestone, dolomite	1.5 – 3.3	2.4	$2.1 \times 10^7 - 5.5 \times 10^6$	1.3×10^7	1.8×10^{-7}
Karst limestone	2.5 – 4.3	3.4	$2.1 \times 10^7 - 5.5 \times 10^6$	1.3×10^7	2.5×10^{-7}
Sandstone	2.3 – 6.5	4.4	$2.1 \times 10^6 - 5.0 \times 10^6$	3.6×10^6	1.2×10^{-6}
Shale	1.5 – 3.5	2.5	$2.4 \times 10^6 - 5.5 \times 10^6$	4.0×10^6	6.3×10^{-7}
Fractured igneous and metamorphic	2.5 – 6.6	4.6	–	2.2×10^6	2.1×10^{-6}
Unfractured igneous and metamorphic	2.5 – 6.6	4.6	–	2.2×10^6	2.1×10^{-6}

7. SITE-INVESTIGATION METHODS

Relative ΔT deviation as a function of the error in α estimation

Δα (%)	January	August
	ΔT (%)	ΔT (%)
-50 %	75.88%	81.84%
-25 %	26.57%	28.00%
–	–	–
+25 %	-16.24%	-17.41%
+ 50%	-27.88%	-29.53%

Borehole surface temperature as a function of ground thermal diffusivity



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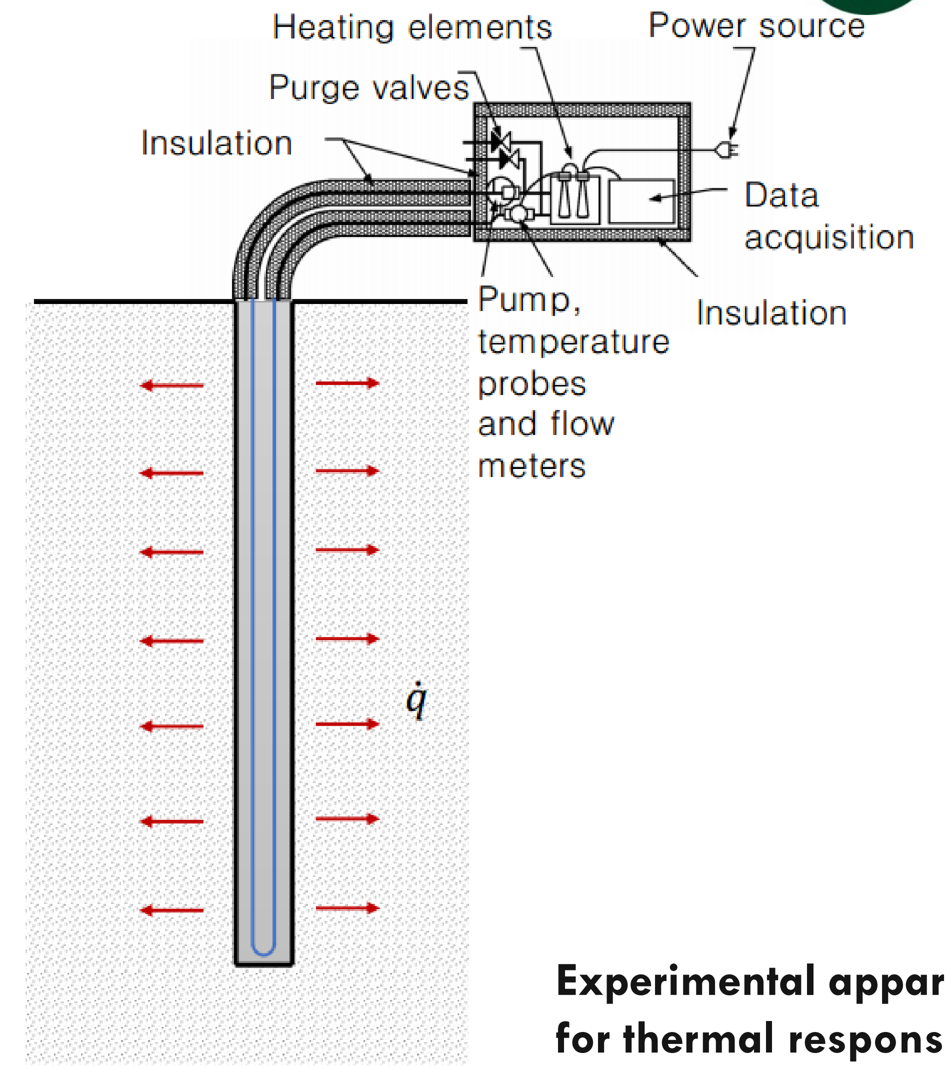
7. SITE-INVESTIGATION METHODS

1. A pilot borehole is installed in the construction site. Dimensions should approximate the size and depth of the actual heat exchangers planned for the project
2. The initial/undisturbed temperature of the ground along BHE depth is measured.
    a. By dipping the borehole with a temperature probe and taking readings at every, say, 2 m.
    b. By circulating a carrier fluid (without any heat input/output) and reading stationary outlet temperature.
3. Heat is added in a water loop at a constant rate (by means of an electrical resistance)
4. Data collection and analysis



Experimental apparatus for thermal response test

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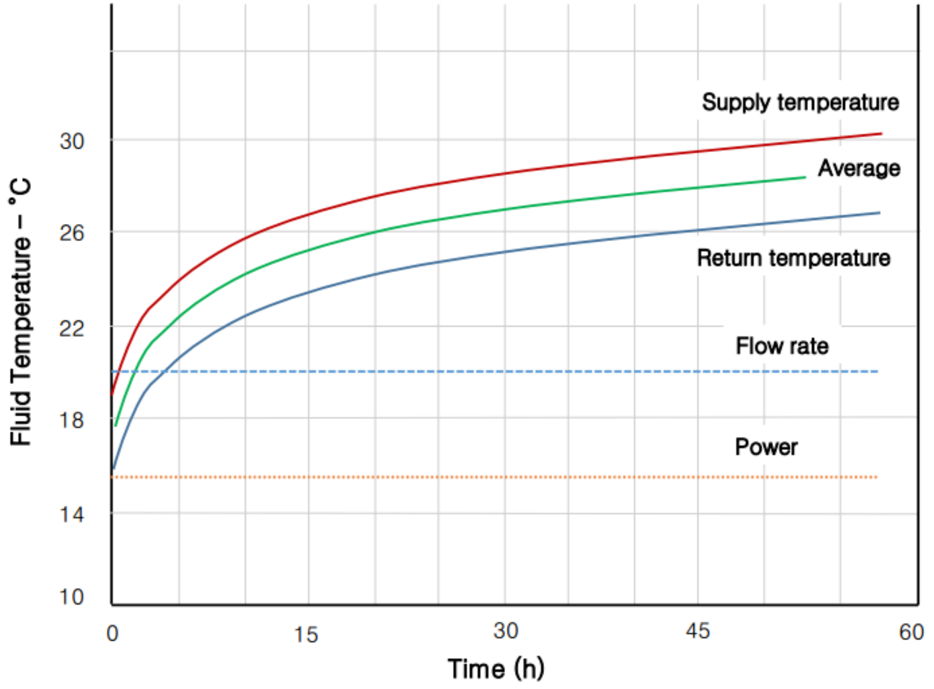
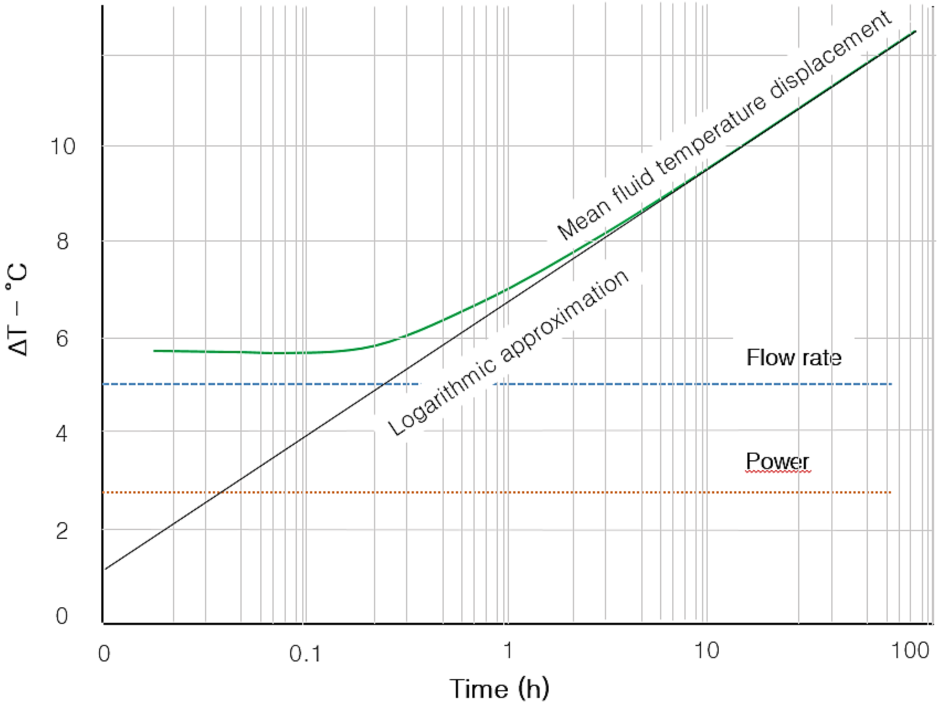
7. SITE-INVESTIGATION METHODS

Typical evolution of fluid temperatures in a TRT





(semi-log graph)

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7. SITE-INVESTIGATION METHODS

Inverse methods are applied to find ground thermo-physical properties (i.e. λ_g and α_g) or borehole heat transfer resistance

Infinite line source model (ILS) is the most simple and common model to process data from a thermal response test. At sufficient long time, the temperature displacement of circulating fluid reads:

$$\bar{T}_w - T_g^0 = \frac{\dot{q}_{BHE}}{4\,\pi\,\lambda_g}\left[\ln\left(\frac{4\alpha_g t}{r_{BHE}^2}\right) - 0.5772\right] + \dot{q}_{BHE} R_b$$

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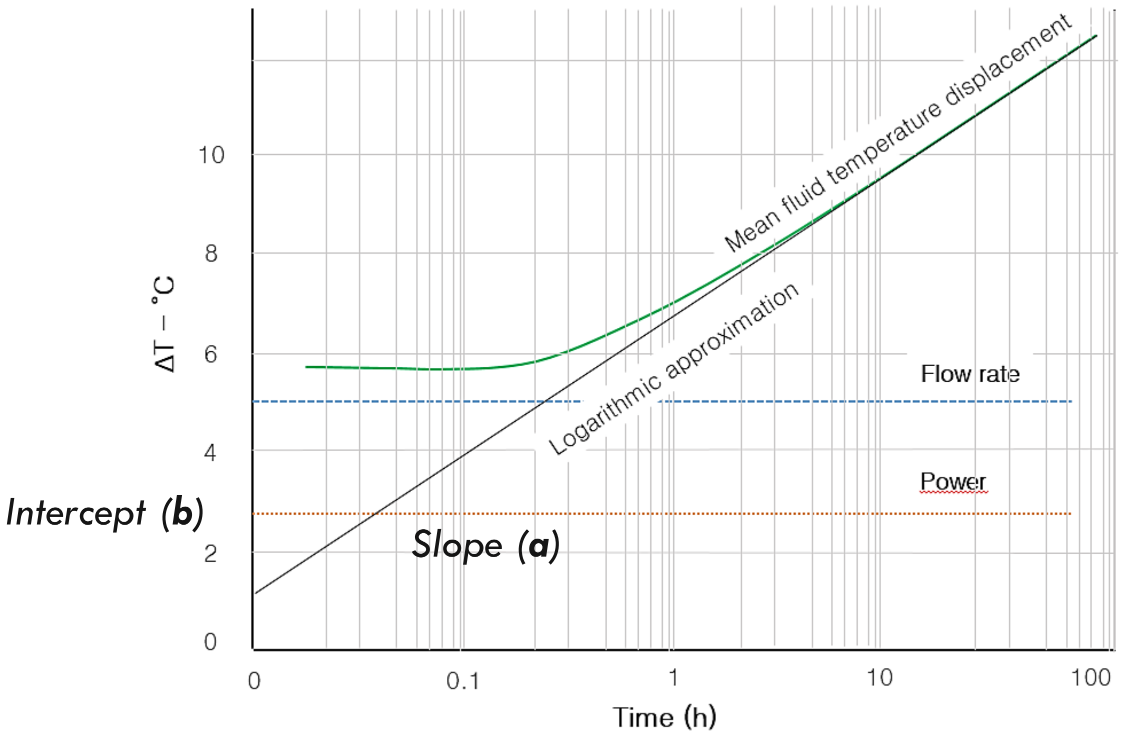
7. SITE-INVESTIGATION METHODS



$$a = \frac{\dot{q}_{BHE}}{4\,\pi\,\lambda_g}$$

$$b = T_g^0 + \frac{R_b + \left[\frac{1}{4\pi\lambda_g}\left(\ln\frac{4\,\lambda_g/(\rho c)_g}{r_{BHE}^2} - 0.5772\right)\right]}{\dot{q}_{BHE}}$$

The plot of temperature displacement in a semi-log chart has a slope proportional to λ_g

The intercept can be used to evaluate borehole thermal resistance, R_b, and ground volumetric heat capacity, $(\rho c)_g$, alternatively.

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7. SITE-INVESTIGATION METHODS

Recommended test specifications by ASHRAE (2011)

1. TRT should be performed for 36 to 48 h
2. TRT $\dot{q}_{BHE}$ should be 50 to 80 W/m, which are the expected peak loads on the U-tubes for an actual heat pump system
3. Resulting temperature variation should be less than ± 0.3 K from a straight trend line of a log (time) versus average loop temperature
4. Accuracy of temperature measurement and recording devices should be ± 0.3 K
5. A waiting period of five days is suggested for low-conductivity soils (i.e. $\lambda g = 1.7$ W/m/K)) after the ground loop has been installed and grouted (or filled) before the TRT is initiated. A delay of three days is recommended for higher conductivity formations (i.e. $\lambda\ g \geq 1.7$ W/m/K). This period of time is needed to dissipate the heat released during the installation phase (i.e. drilling friction and grouting consolidation)
6. Data collection should be at least once every 10 min;

7. SITE-INVESTIGATION METHODS

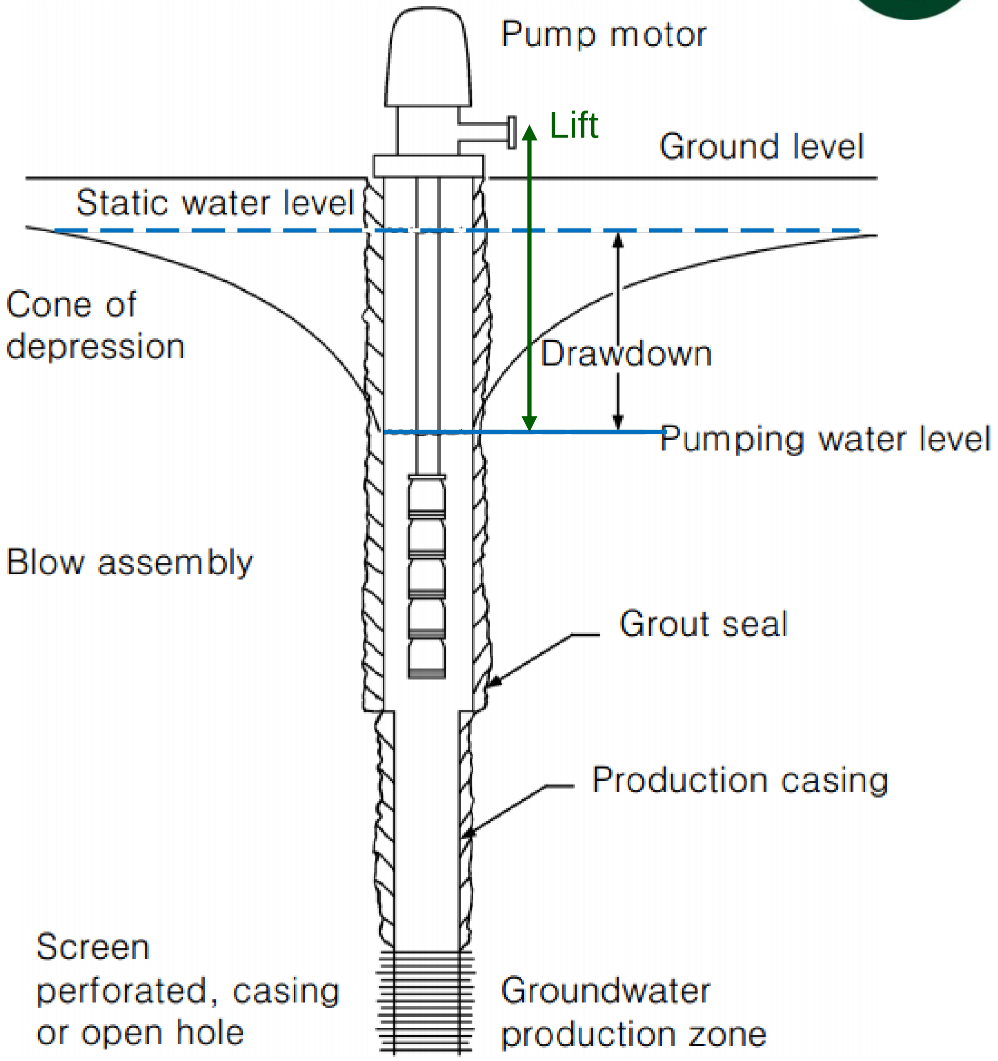
Static water level (SWL) is the level that exists under static (non-pumping) conditions

Pumping water level (PWL) is the level that exists under specific pumping conditions. It depends on pumping flow rates, well, and aquifer characteristics.

Drawdown (s_w) is the difference between the SWL and the PWL.

The *specific capacity* of a well is given by the pumping rate per meter of drawdown, l s^{-1} m−1

Total pump head is composed of four primary components: lift, column friction, surface requirements, and injection head due to aquifer conditions and water quality.



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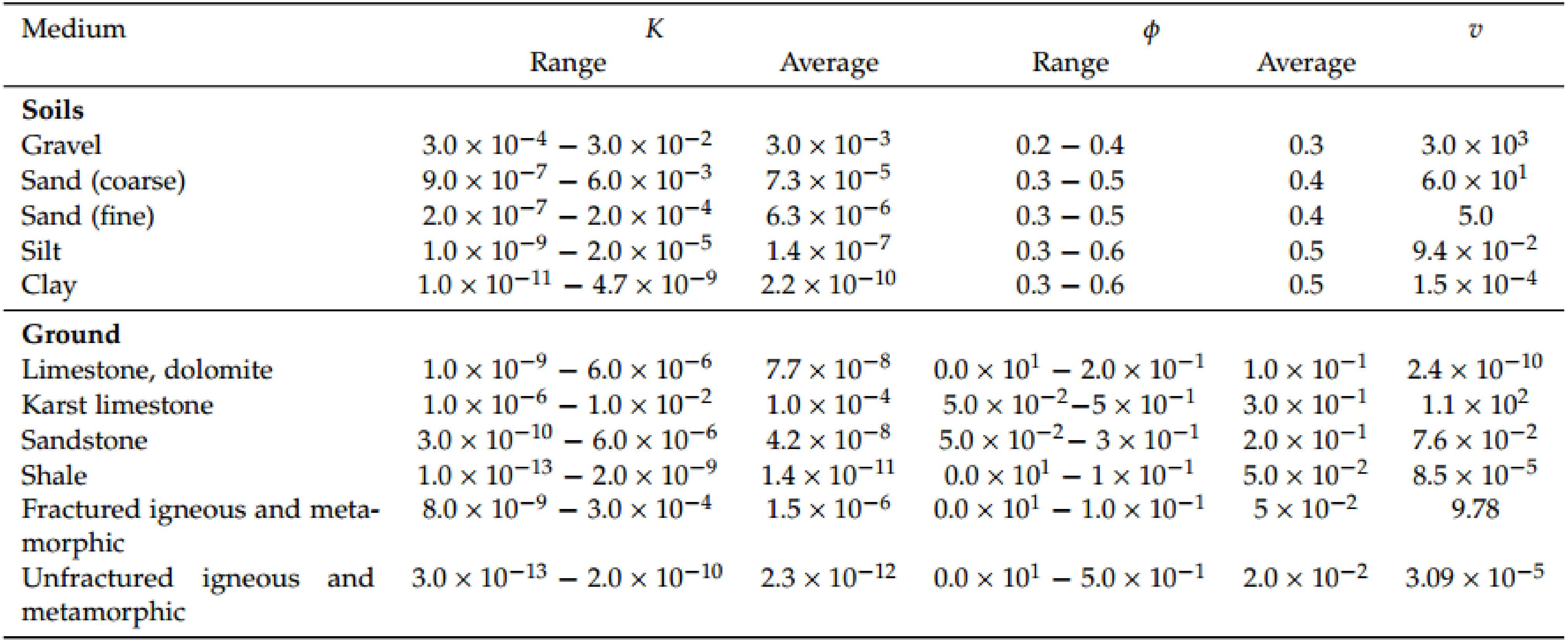
7. SITE-INVESTIGATION METHODS



Medium	K Range	K Average	ϕ Range	ϕ Average	v
Soils					
Gravel	$3.0 \times 10^{-4} - 3.0 \times 10^{-2}$	3.0×10^{-3}	$0.2 - 0.4$	0.3	3.0×10^{3}
Sand (coarse)	$9.0 \times 10^{-7} - 6.0 \times 10^{-3}$	7.3×10^{-5}	$0.3 - 0.5$	0.4	6.0×10^{1}
Sand (fine)	$2.0 \times 10^{-7} - 2.0 \times 10^{-4}$	6.3×10^{-6}	$0.3 - 0.5$	0.4	5.0
Silt	$1.0 \times 10^{-9} - 2.0 \times 10^{-5}$	1.4×10^{-7}	$0.3 - 0.6$	0.5	9.4×10^{-2}
Clay	$1.0 \times 10^{-11} - 4.7 \times 10^{-9}$	2.2×10^{-10}	$0.3 - 0.6$	0.5	1.5×10^{-4}
Ground					
Limestone, dolomite	$1.0 \times 10^{-9} - 6.0 \times 10^{-6}$	7.7×10^{-8}	$0.0 \times 10^{1} - 2.0 \times 10^{-1}$	1.0×10^{-1}	2.4×10^{-10}
Karst limestone	$1.0 \times 10^{-6} - 1.0 \times 10^{-2}$	1.0×10^{-4}	$5.0 \times 10^{-2} - 5 \times 10^{-1}$	3.0×10^{-1}	1.1×10^{2}
Sandstone	$3.0 \times 10^{-10} - 6.0 \times 10^{-6}$	4.2×10^{-8}	$5.0 \times 10^{-2} - 3 \times 10^{-1}$	2.0×10^{-1}	7.6×10^{-2}
Shale	$1.0 \times 10^{-13} - 2.0 \times 10^{-9}$	1.4×10^{-11}	$0.0 \times 10^{1} - 1 \times 10^{-1}$	5.0×10^{-2}	8.5×10^{-5}
Fractured igneous and metamorphic	$8.0 \times 10^{-9} - 3.0 \times 10^{-4}$	1.5×10^{-6}	$0.0 \times 10^{1} - 1.0 \times 10^{-1}$	5×10^{-2}	9.78
Unfractured igneous and metamorphic	$3.0 \times 10^{-13} - 2.0 \times 10^{-10}$	2.3×10^{-12}	$0.0 \times 10^{1} - 5.0 \times 10^{-1}$	2.0×10^{-2}	3.09×10^{-5}

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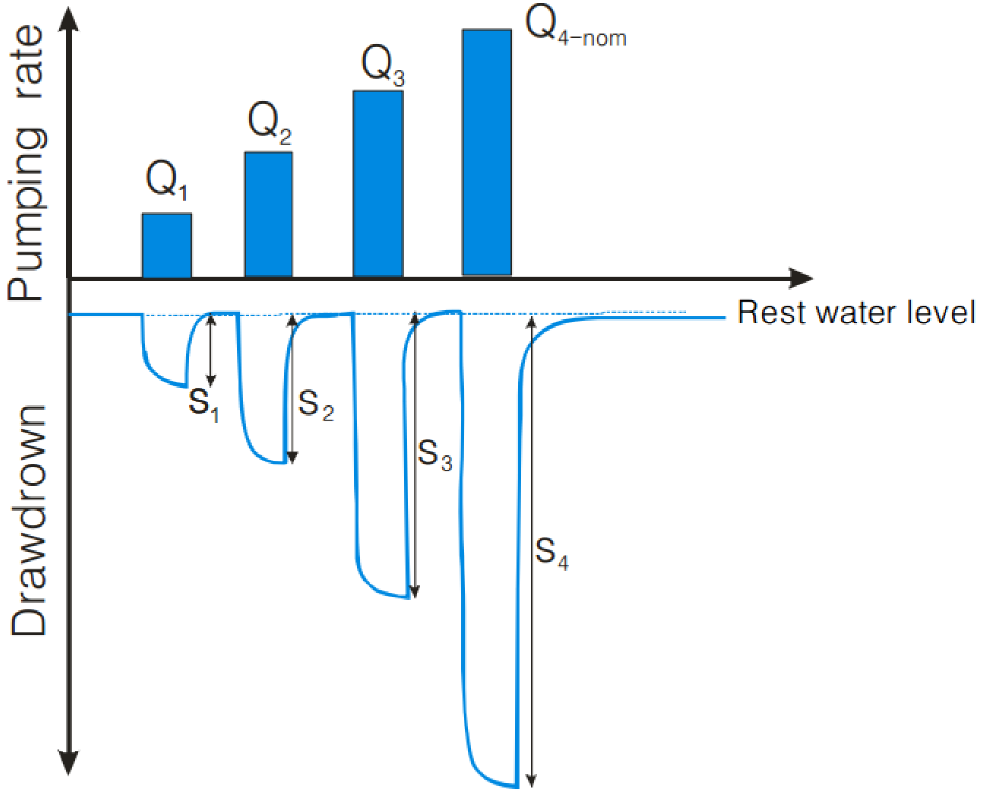
7. SITE-INVESTIGATION METHODS



Short-term test

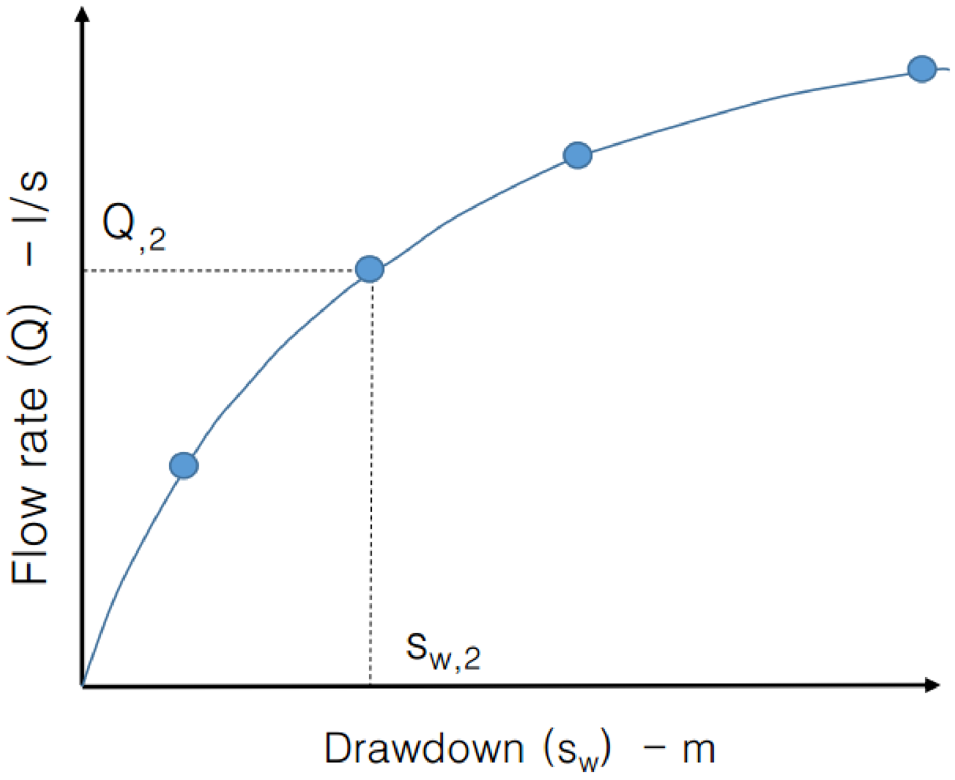
It is used to evaluate head losses due to the well characteristics, that are predominant for short time scale.

It takes from 4 to 24 h

It normally comprises a sequence of four or five short 100 – 120 minute tests at increasing pumping rates Q1 . . . Q5. Generally, the large flow rate coincides with the nominal capacity of the well.

Water level and pumping rate should be stabilized at each point before flow is increased.

7. SITE-INVESTIGATION METHODS



The simplest model for well behavior reads:

$$s_w = B\dot{Q} + C\dot{Q}^2$$

where *B* and C can be considered constant for short time-scales

B depends on the aquifer characteristics

C is related to the hydraulic resistance of the well structure and several fluid dynamics mechanisms

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7. SITE-INVESTIGATION METHODS

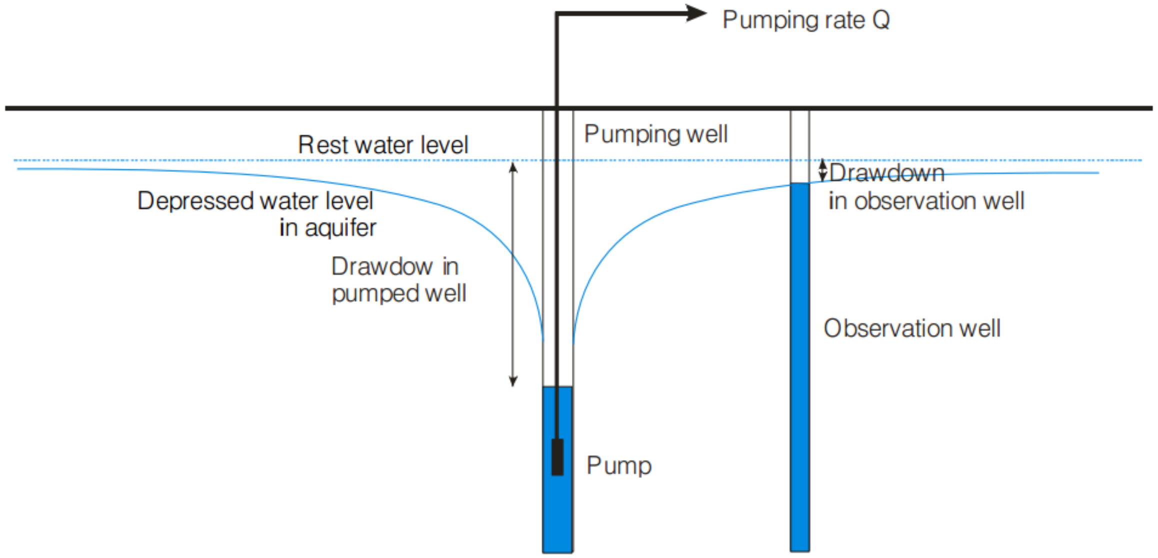
B coefficient is not constant at long time

For continuous long time operations, aquifer characteristics becomes predominant on well productivity.

Aquifer carachteristics can be evaluated by means of the *Theis's equation* and *constant rate test.*

Long-term tests of up to 30 days providing information on the **hydraulic transmissivity,**
storage coefficient, **reservoir boundaries**, and **recharge areas of the aquifer.**

Normally these tests involve monitoring nearby wells to evaluate interference effects



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7. SITE-INVESTIGATION METHODS

Inverse methods are applied to find aquifer thermo-physical properties (i.e. trasmittivity, T, and storativity, S)

The mathematical model describing the drawdown evolution is the *Theis's equation*. At large time, it can be approximate by the so-called *Cooper-Jacob equation*:

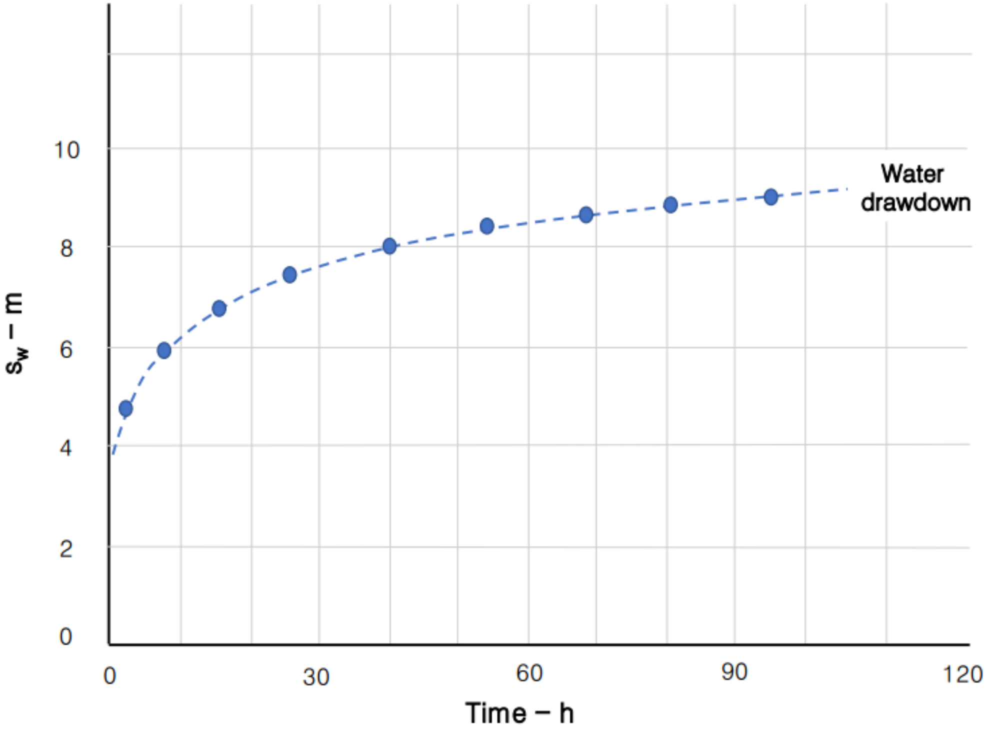
$$s_w \approx \frac{\dot{Q}}{4\,\pi\,T}\left[\ln\left(\frac{4Tt}{r_{well}^2 S}\right) - 0.5772\right] + C\dot{Q}^2$$

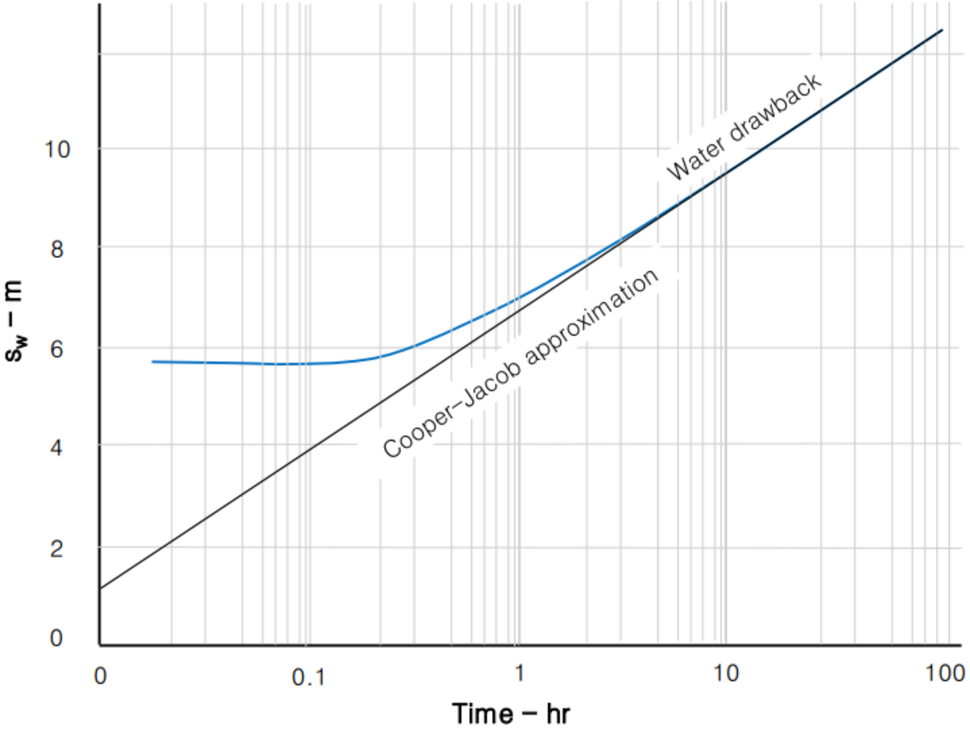
!Note the analogies with ILS

As for TRT, the trasmittivity (*T*) can be calculated evaluating the slope of the black line. Storativity value, *S*, can be derived from the intercept.

7. SITE-INVESTIGATION METHODS

Typical water level in a long-term pumping test





(semi-log graph)

GROUND RESPONSE TEST (GRT) AND HEAT PUMP DESIGN

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ICTP

IGA
International Geothermal Association

Consiglio
Nazionale delle
Ricerche

International Union of Geodesy and Geophysics
IUGG
UGGI
Union Géodésique et Géophysique Internationale

International School on

'Geothermal Development'

December 7 - 12, 2015
(Miramare, Trieste, Italy)

THANKS FOR YOUR KIND ATTENTION!

Paolo CONTI, Ph.D
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Italian Geothermal Union

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