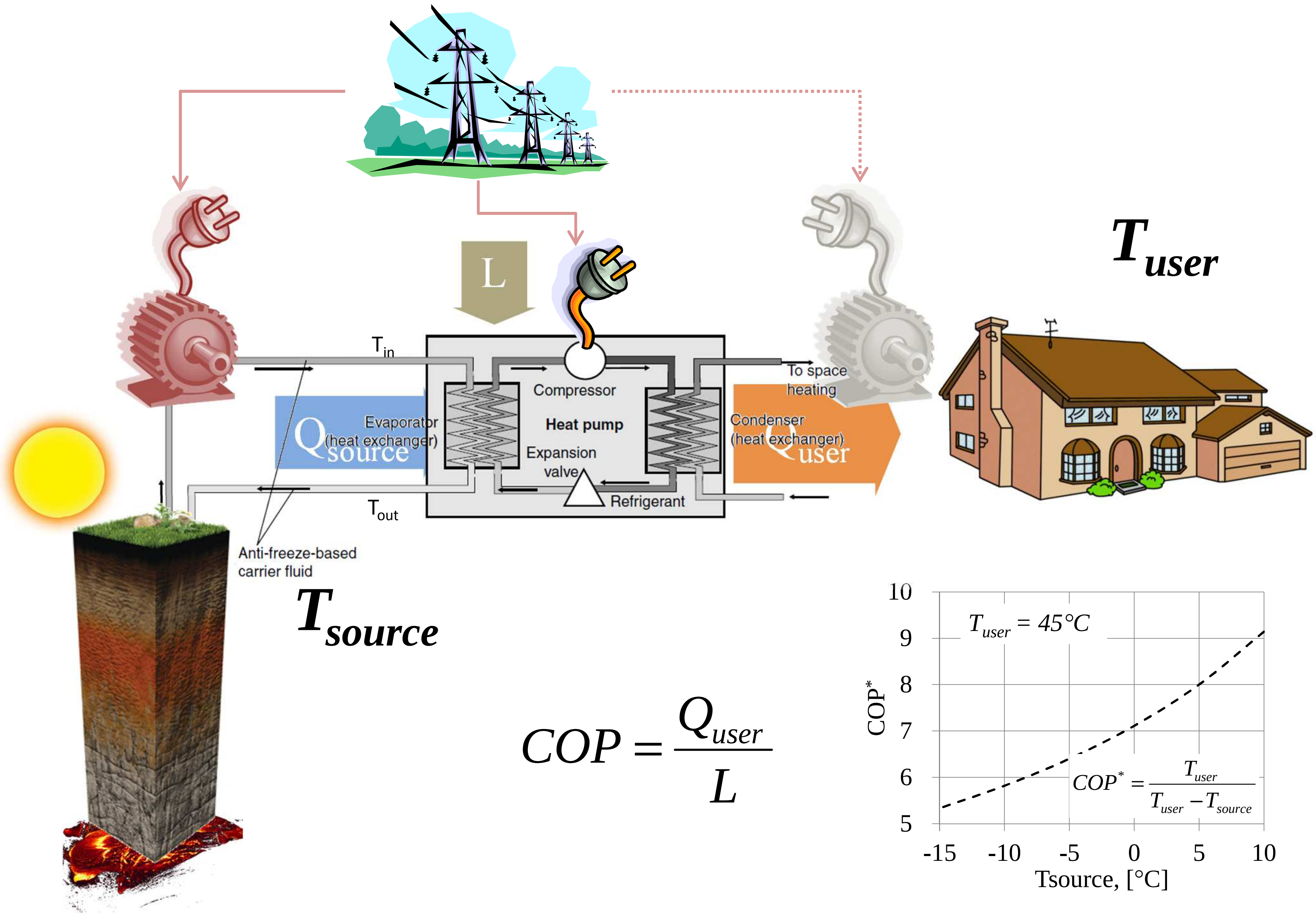
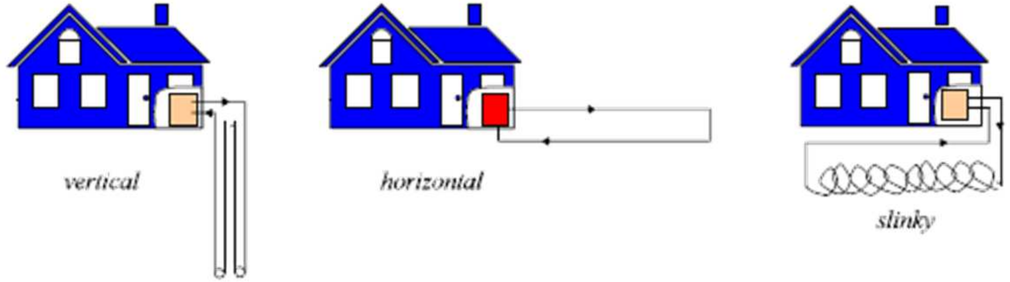
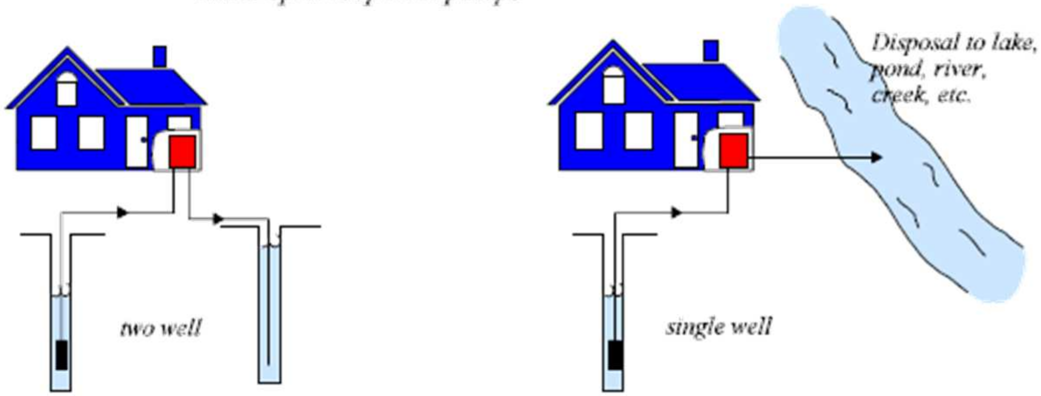


L
T_in
T_out
Compressor
Heat pump
Expansion valve
Refrigerant
Evaporator (heat exchanger)
Q_source
Condenser (heat exchanger)
Q_user
To space heating
Anti-freeze-based carrier fluid
T_source
T_user
COP = Q_user / L
T_user = 45°C
COP* = T_user / (T_user − T_source)
COP*
Tsource, [°C]
10
9
8
7
6
5
-15
-10
-5
0
5
10

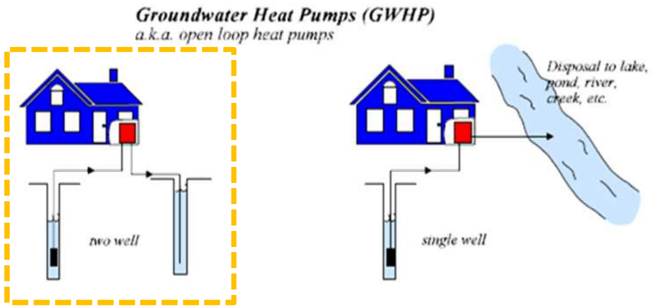
Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps

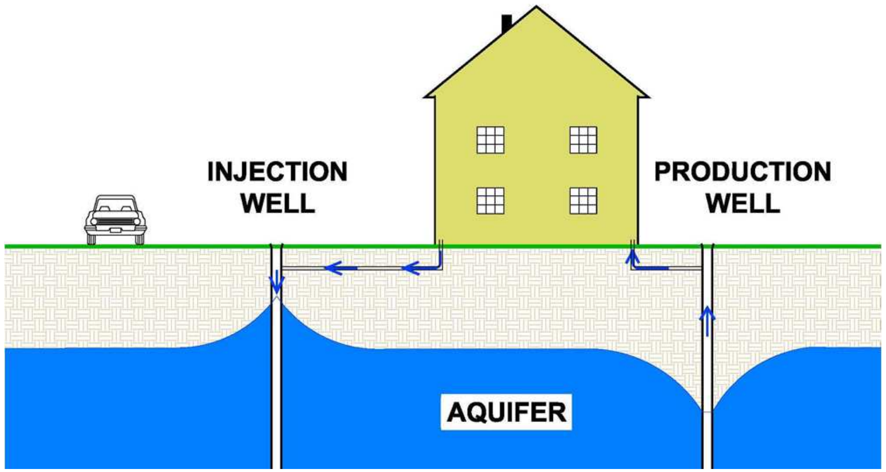


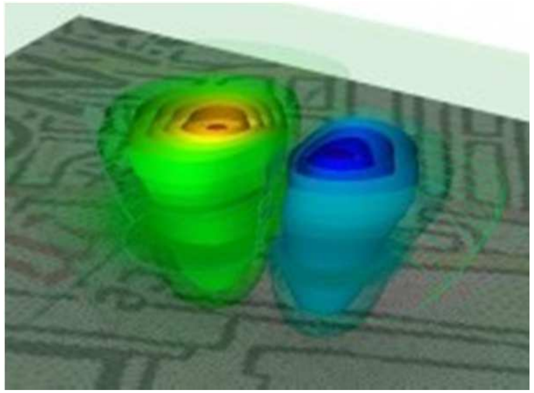
Groundwater Heat Pumps (GWHP)
a.k.a. open loop heat pumps



Surface Water Heat Pumps (SWHP)
a.k.a. lake or pond loop heat pumps



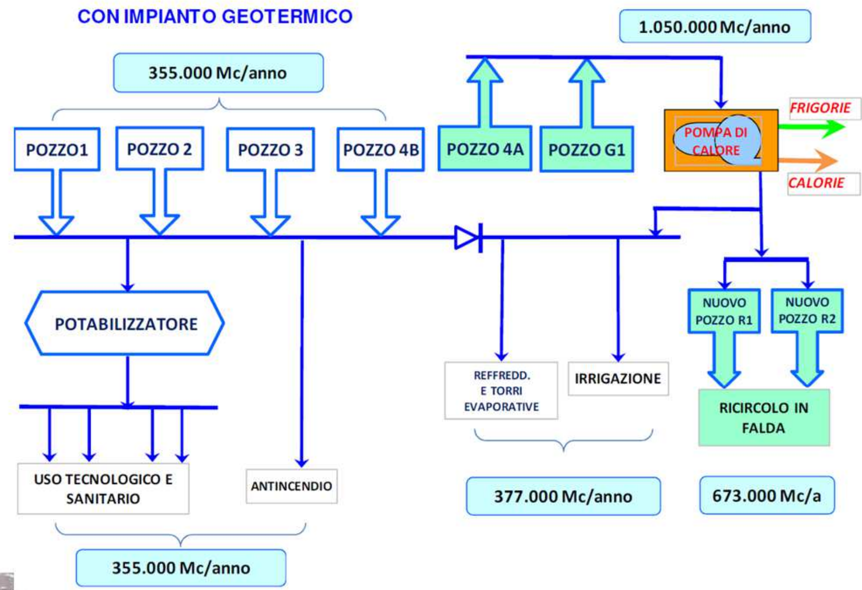


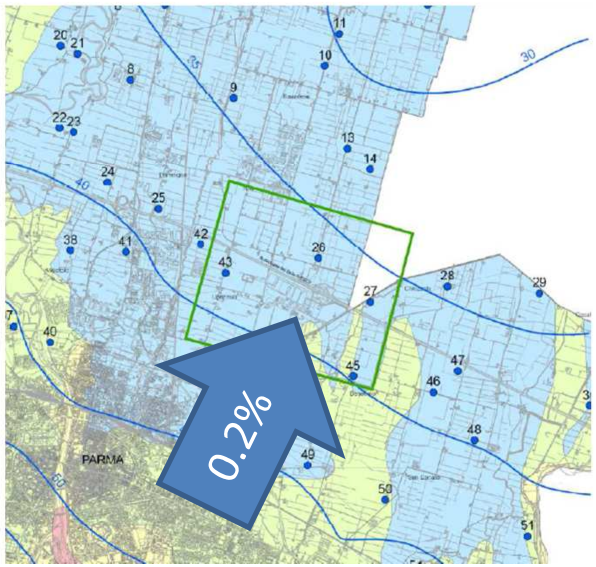


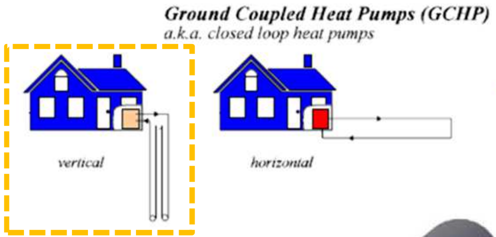
Subsidence
Thermal short-circuit
GW regulation

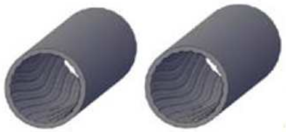
(200 l/h;5 K) $\rightarrow$ ***1 kW*** $_t$

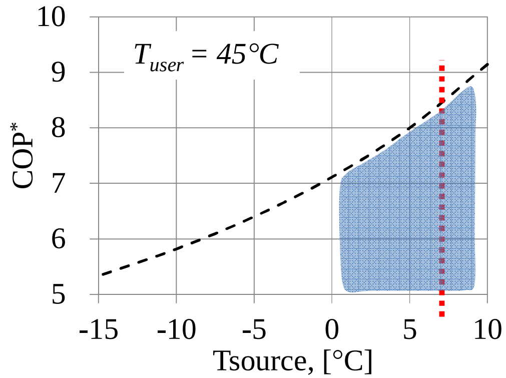
- 0.9 MW (H/C)
- 1.0^6 m^3/y
- $\Delta T = 5°C$
- 48 l/s
- 2+2 wells (80m)

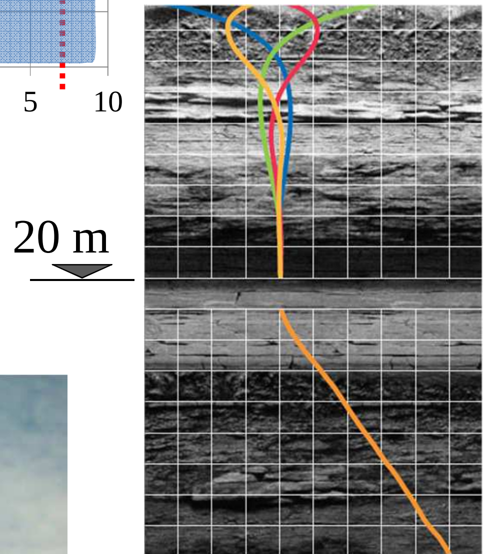


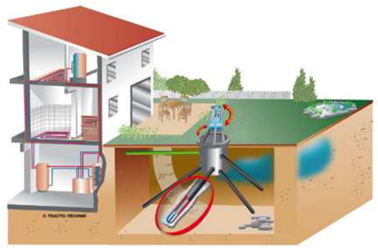



Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps
vertical
horizontal
slinky




T_{user} = 45°C
COP*
Tsource, [°C]
10
9
8
7
6
5
-15
-10
-5
0
5
10

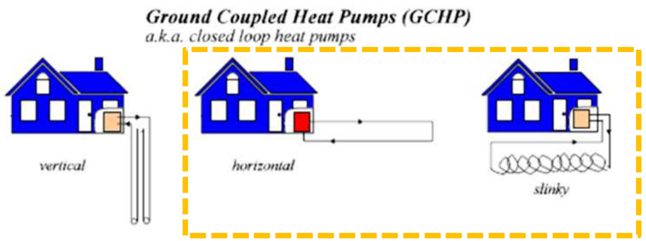

20 m

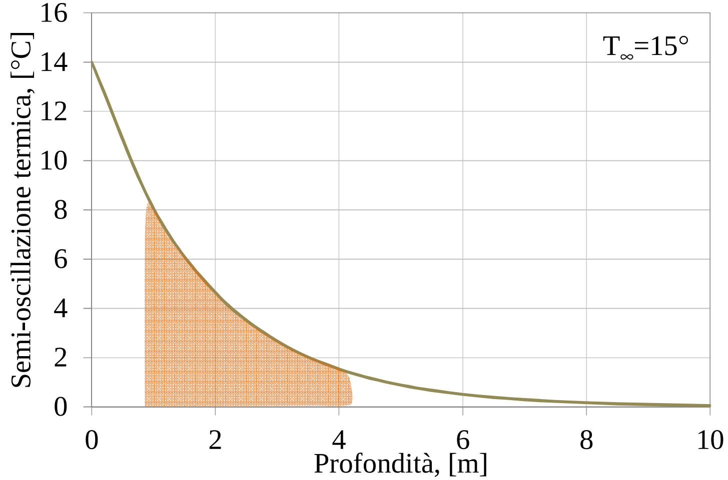


- 1.2 MW (H/C)
- 212 BHEs x 146 m/BHE (31 km)
- 2.2 M€

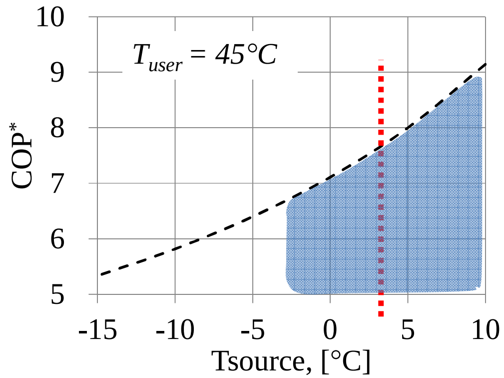
70 €/m
38 W/m

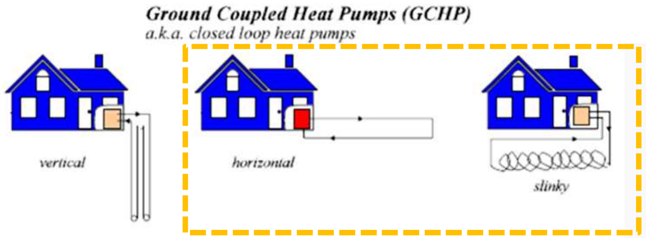
1.85 €/W


Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps
vertical
horizontal
slinky

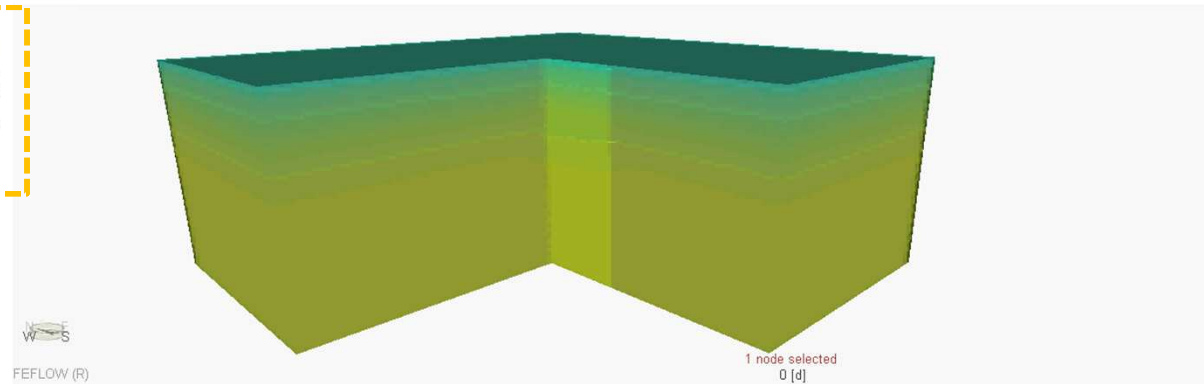

16
14
12
10
8
6
4
2
0
Semi-oscillazione termica, [°C]
0
2
4
6
8
10
Profondità, [m]
T∞=15°


UNIFE

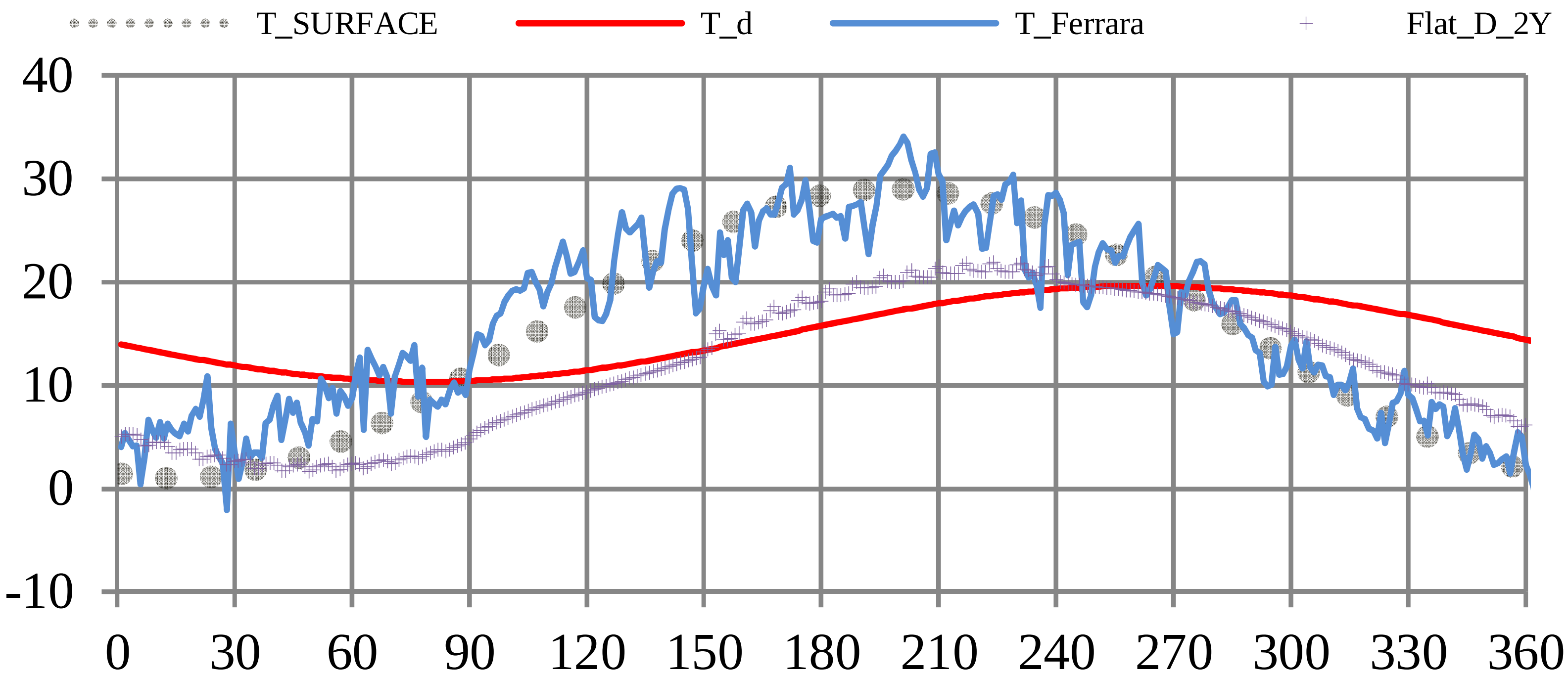

10
9
8
7
6
5
COP*
-15
-10
-5
0
5
10
Tsource, [°C]
Tuser = 45°C



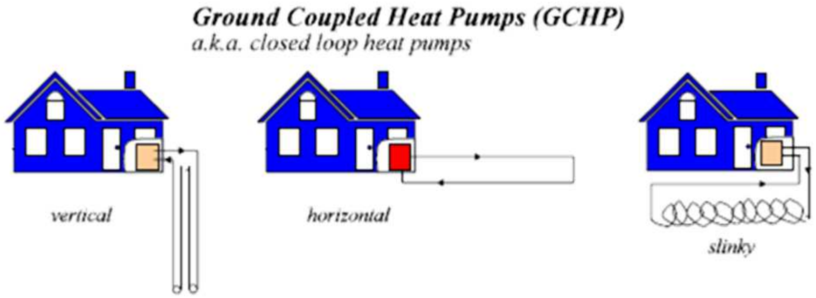
Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps
vertical
horizontal
slinky



FEFLOW (R)
1 node selected
0 [d]



T_SURFACE
T_d
T_Ferrara
Flat_D_2Y
40
30
20
10
0
-10
0
30
60
90
120
150
180
210
240
270
300
330
360



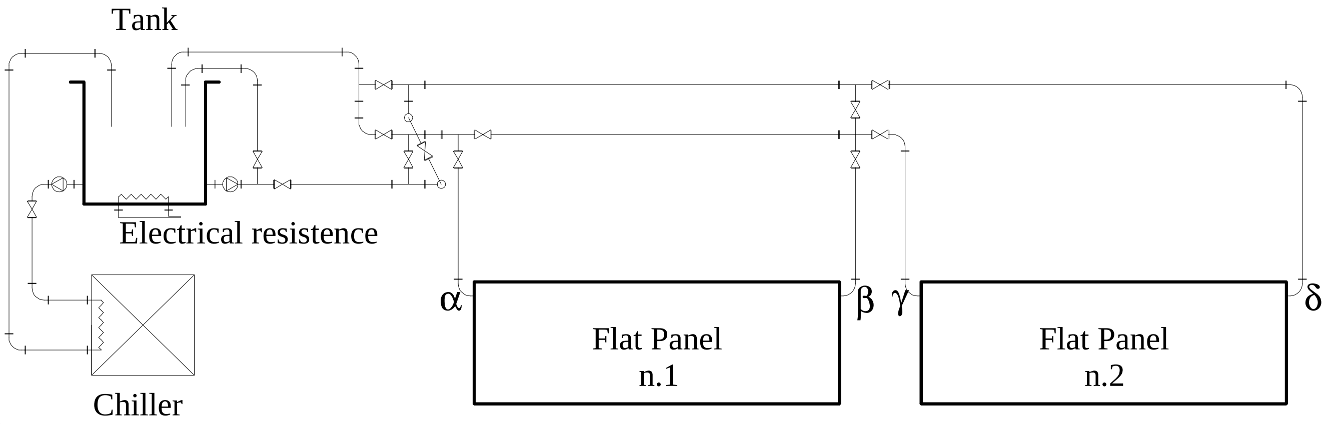
	HGHE	BHE
Energy performance	☹	☺
Soil use restriction	😐	☺
Maintenance	☺	☹
GW contaminant risk	☺	😐
Building cost	☺	😐
Building equipment	☺	😐
Building permission	☺	😐
Design	😐	☺
Thermal drift	☺	☹

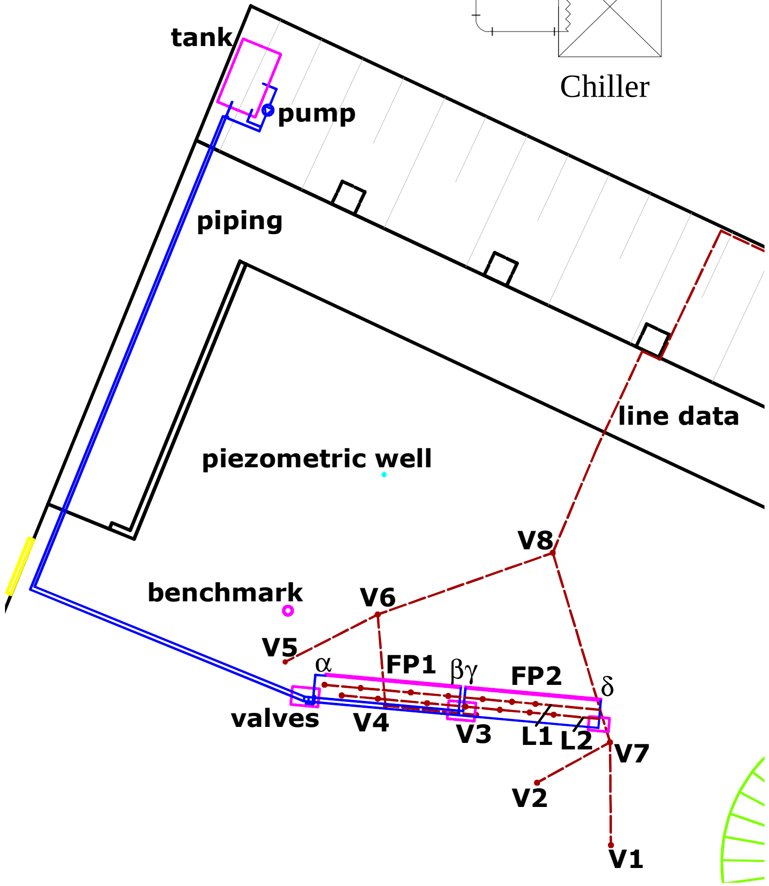
	H	C
dT	10	15
T_{max}	-	35
T_{min}	≅0	-

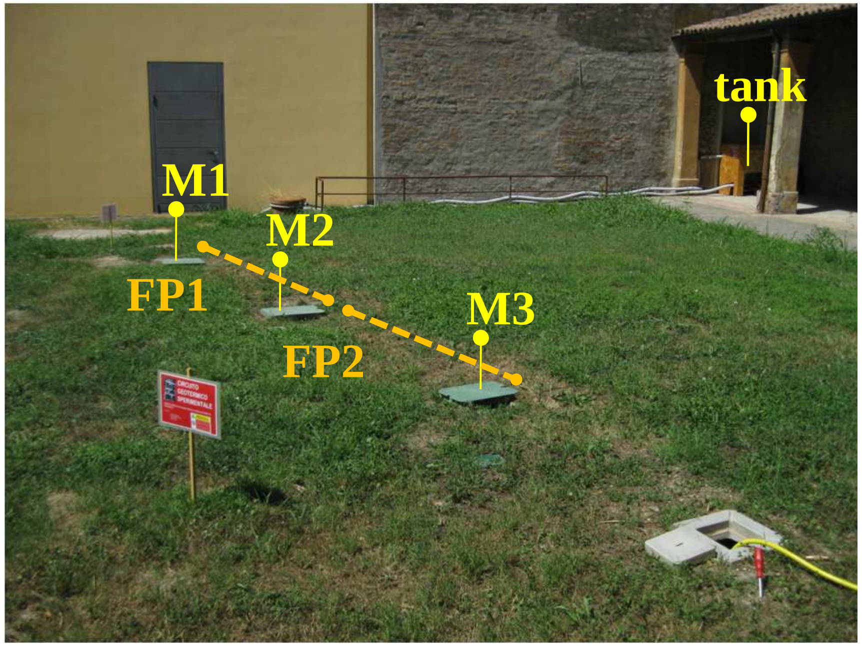
20-25 m/kW_t

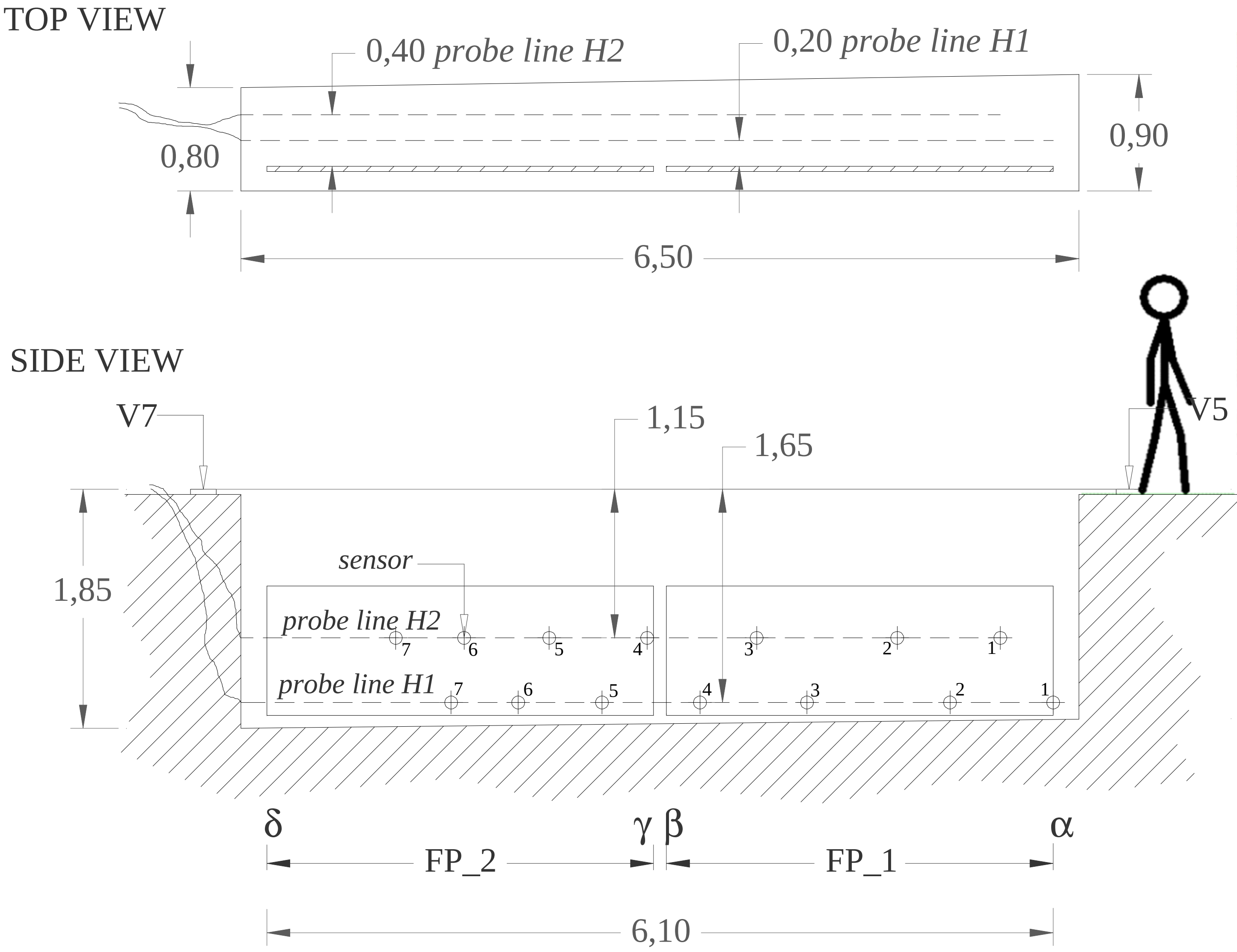
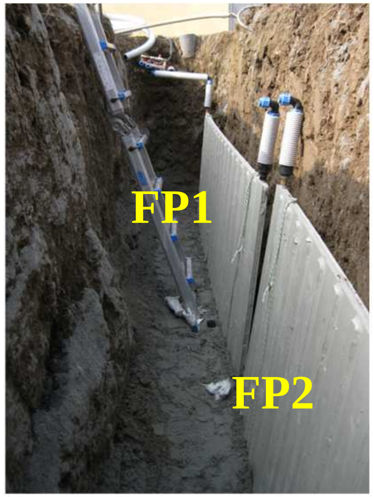

tank
pump
piping
piezometric well
benchmark
exchangers
valves
V4
V3
L1
L2
V7
V2
V1

23 x 14 m^2 of grassland
hydraulic closed loop
two flat-panels
monitoring system

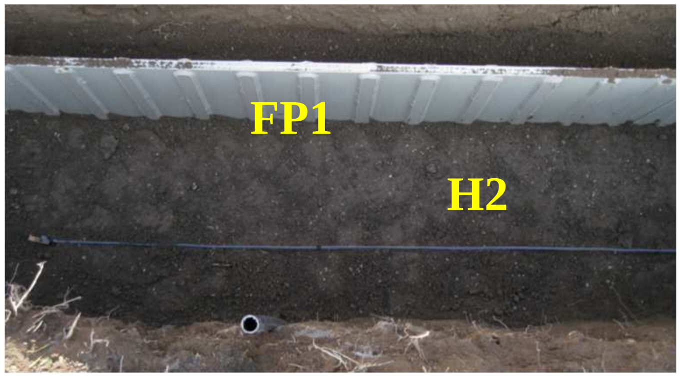


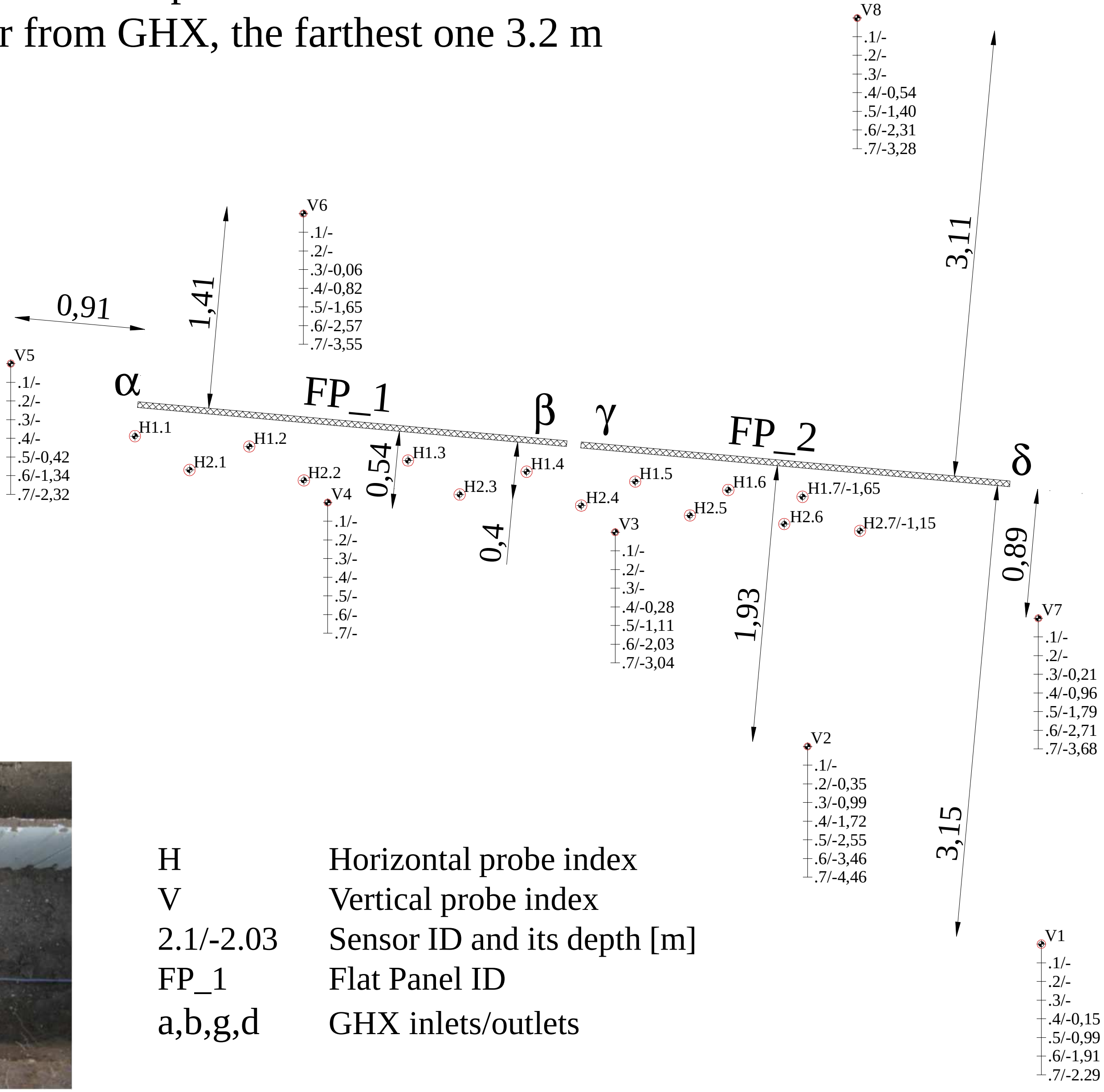





TOP VIEW
0,40 probe line H2
0,20 probe line H1
0,80
0,90
6,50
SIDE VIEW
V7
1,15
1,65
V5
1,85
sensor
probe line H2
probe line H1
7
6
5
4
3
2
1
δ
γ β
α
FP_2
FP_1
6,10

FP1
FP2


The monitoring system reaches 5 m deep in soil.
The nearest sensor is 0.2 m far from GHX, the farthest one 3.2 m





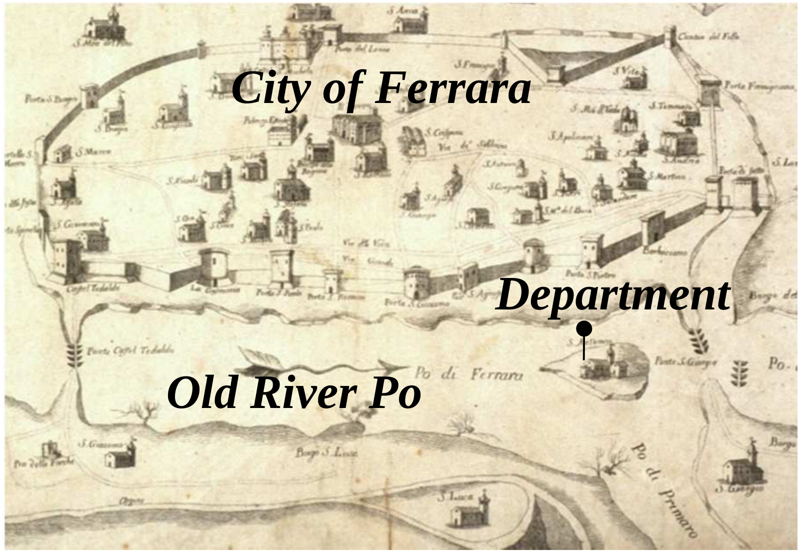
H	Horizontal probe index
V	Vertical probe index
2.1/-2.03	Sensor ID and its depth [m]
FP_1	Flat Panel ID
a,b,g,d	GHX inlets/outlets

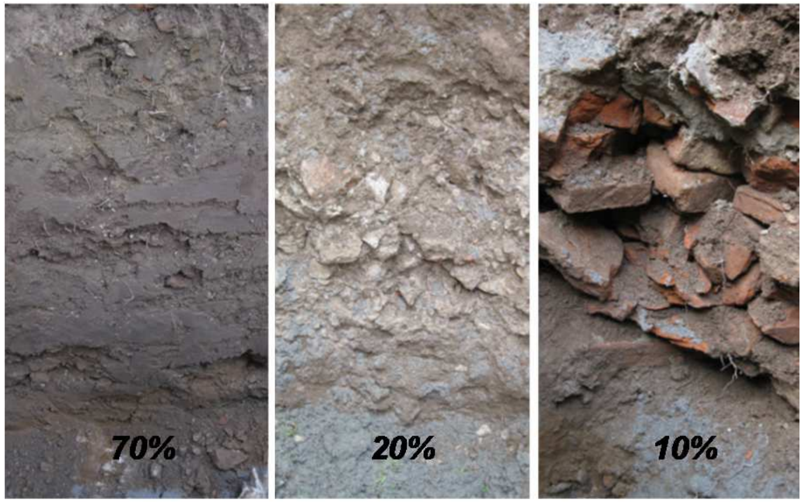
This area was an island of the old river Po.
The groundwater is 5 meters deep (*dry conditions*).

The soil is sandy silt /sandy clay, and its properties are following:

Density	1,720 kg/m^3
Porosity	0.36
Specific heat	1.35 kJ/kgK
Thermal conductivity	1.4 W/mK

But, the ground is very non homogeneous.
In the first 2 meters, we found rubble, pottery and … bones.

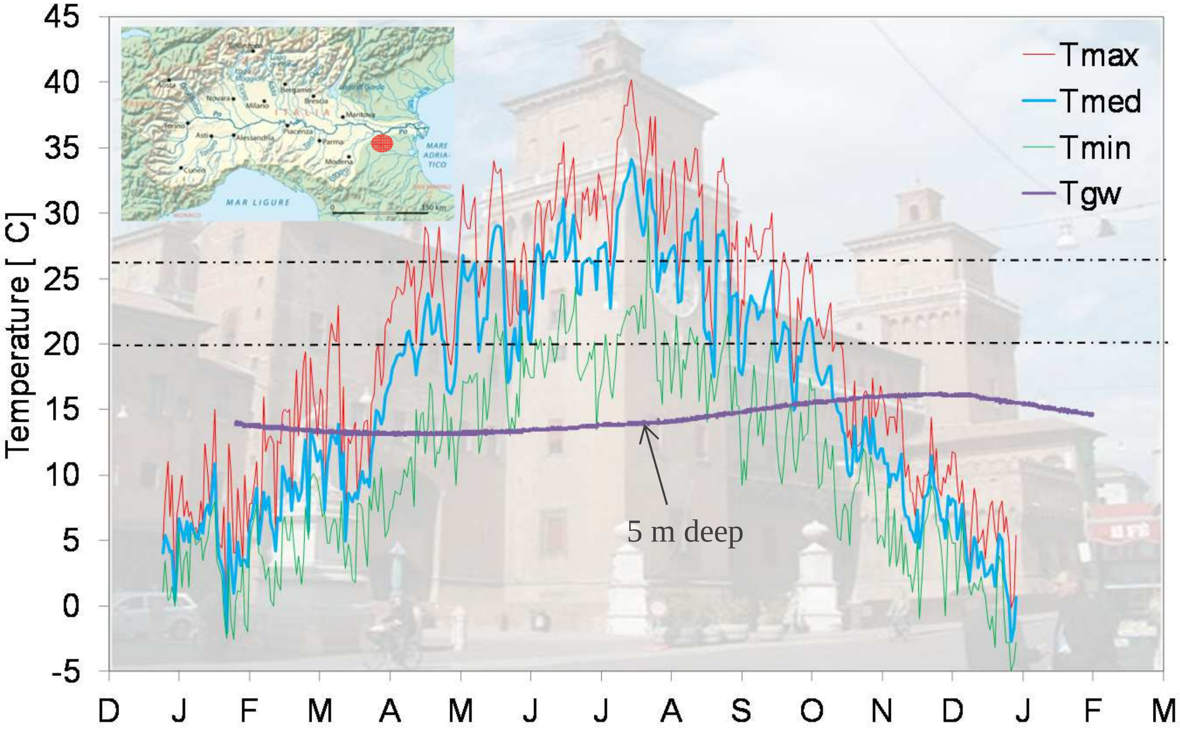




Ferrara is characterized by a continental climate.
Hot summer (38°C) and cold winter (0°C) .

Relative humidity is frequently close to the saturation.

The shallow groundwater temperature is 15°C.



The heat transfer mode was carried out with different temperatures of the working fluid and several operations.

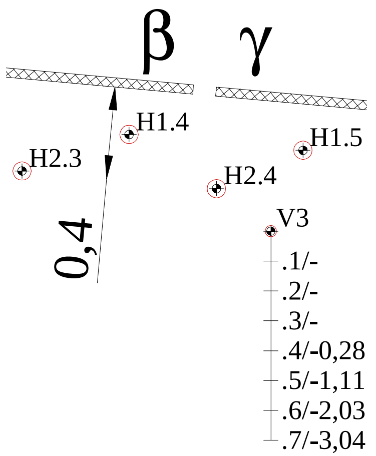
Mode	Unaltered soil temperature (1.4 m deep)	Working fluid temperature	ΔT
Heating	12÷22	35÷38	16÷23
Cooling	10÷19	2÷8	8÷11
Free	12÷19	6÷12	6÷7

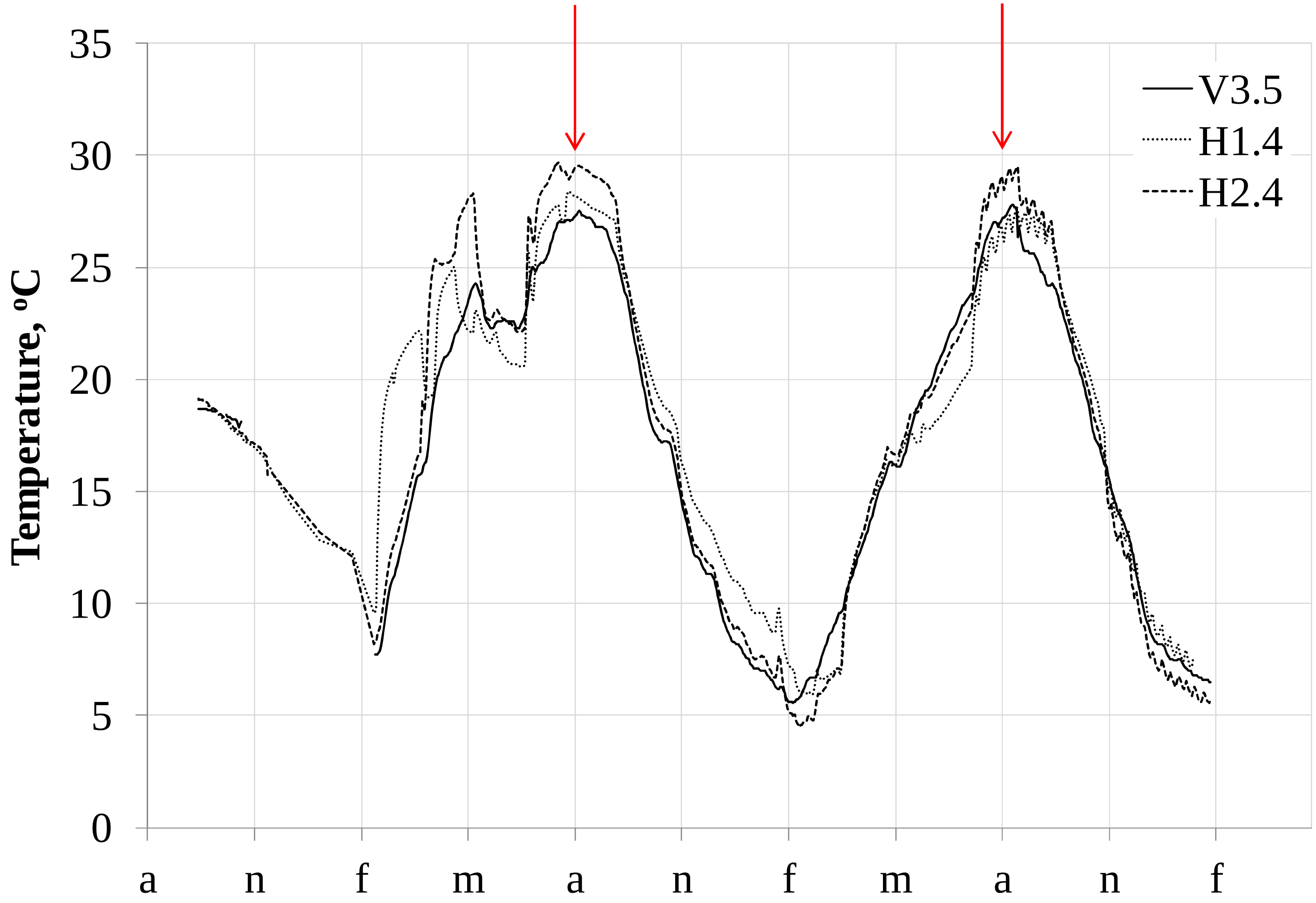
Unlike with the vertical systems, long-term subsurface thermal energy build-up or depletion wouldn't be expecting by shallow GHE.

Period	Mode	Day *[d]*	Energy *[kWh]*	Time on *[h]*	Length *[m]*	Power [*W/m*]
2011, March → Sept.	Heating	161	990	2907	4.2	61 / 81
2011, Nov.→ Dec.	Free	42	28	351	6.0	5 / 13
2012, January	Free	31	13	225	6.0	4 / 10
2012, Feb. → April	Cooling	56	225	843	6.0	28 / 44
2012, July → Sept.	Heating^{P}	68	264	585	6.0	27 / 75
2012, Nov. → Dec.	Cooling^{P}	48	117	364	6.0	17 / 54
2013, Jan. → Feb.	Cooling^{P}	41	101	352	6.0	17 / 48

The maximum temperatures did not change in August 2011 and 2012, even if the heat transfer was different.

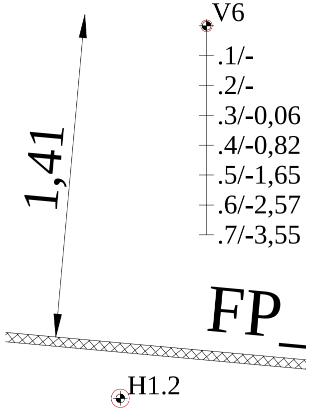
Still up to 40 cm far from the GHX, the pulsed operation mode is clear.

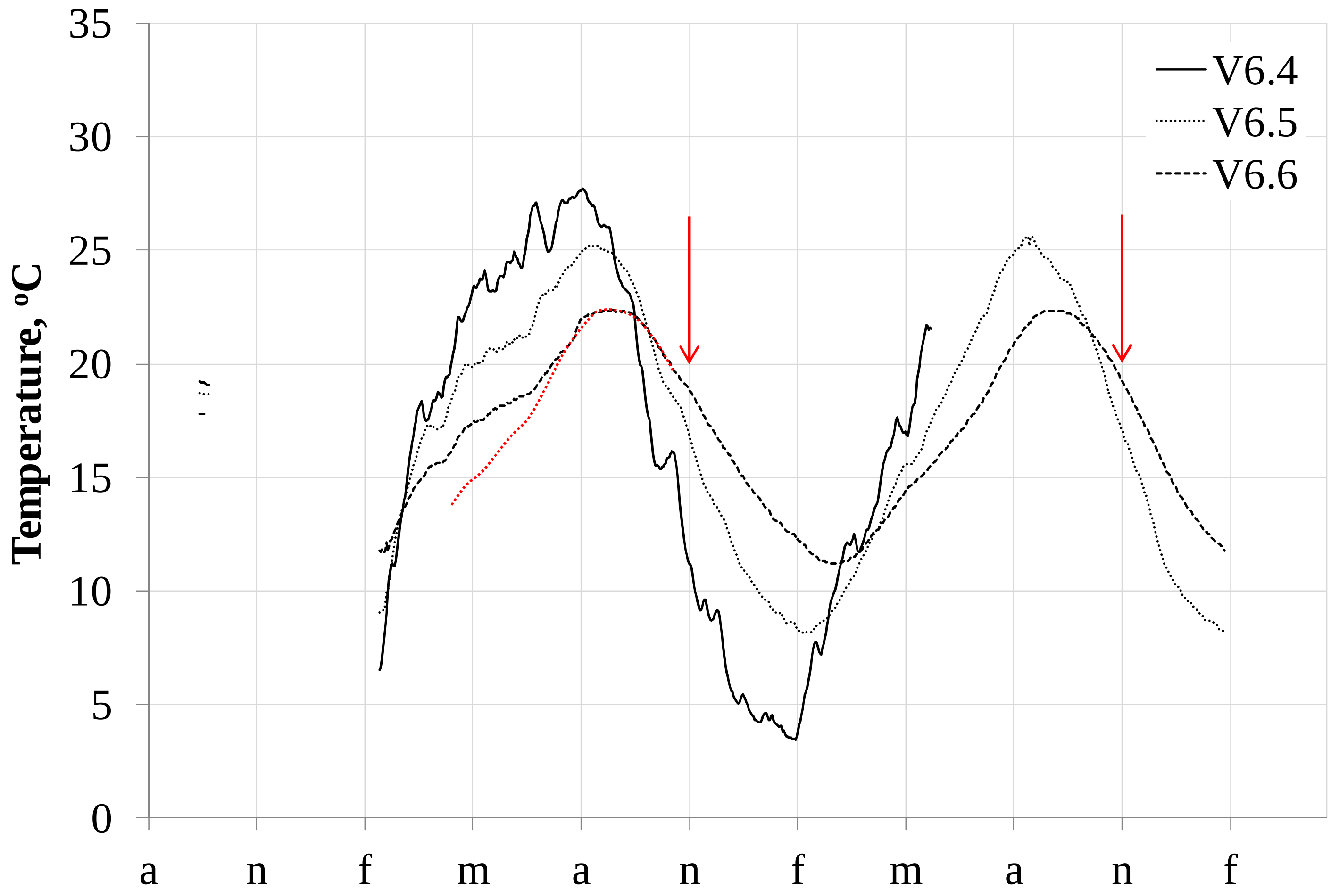




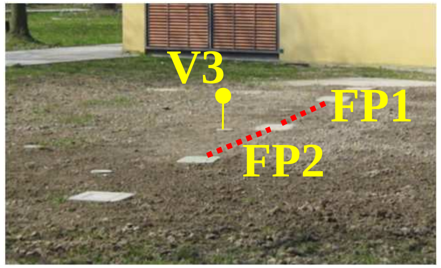
The temperatures did not change in November 2011 and 2012, even if a considerable heat transfer was carried out during the summer 2011.

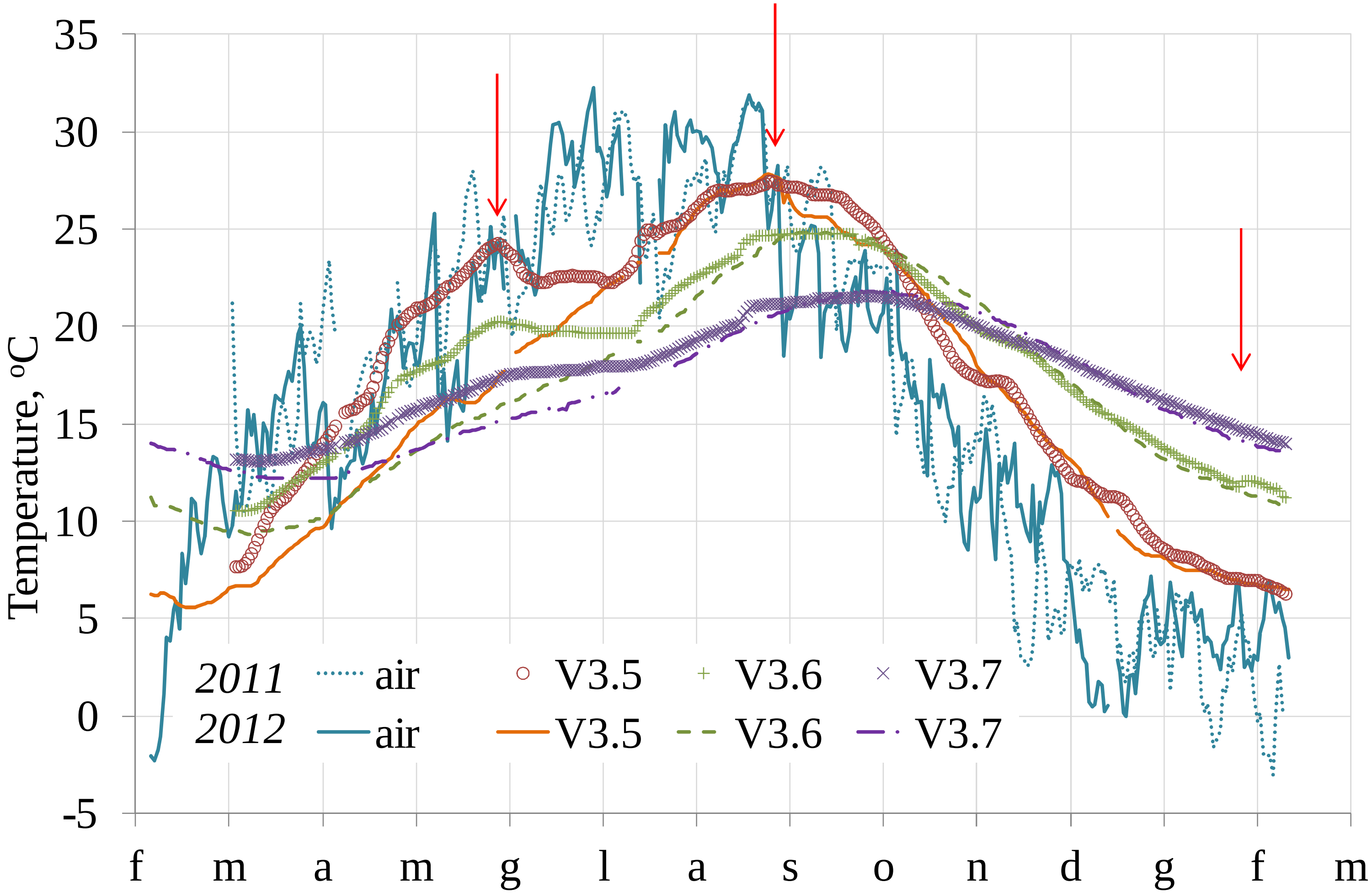
The heat transfer achieved clearly 1.4 m far from the GHX.



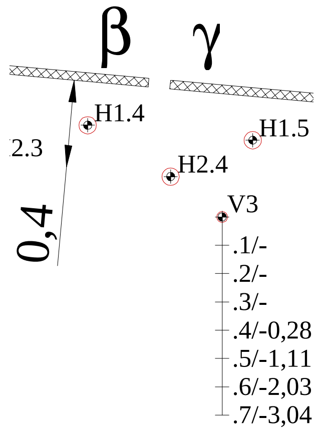


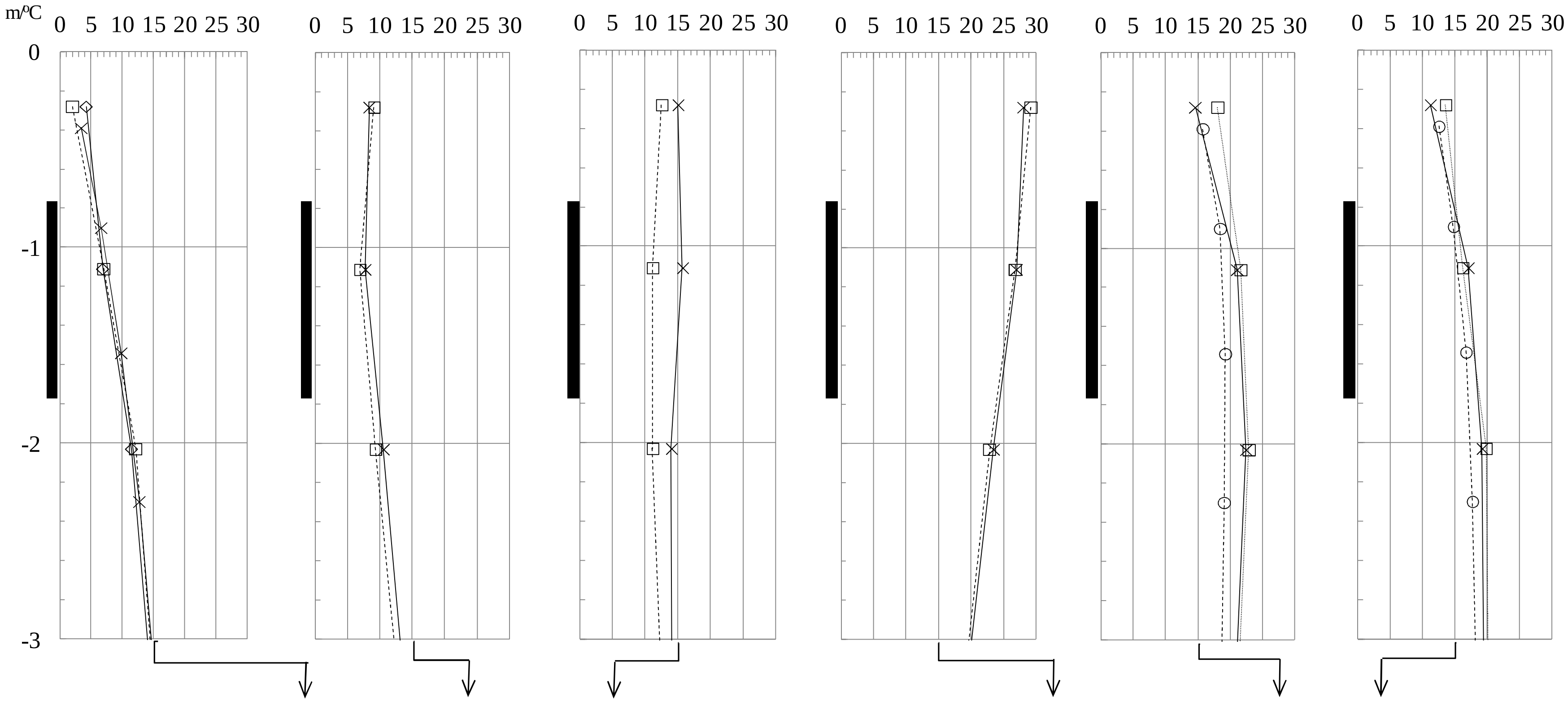
Even if the system transferred a lot of heat in spring 2011, the maximum temperature were the same in both summers 2011 and 2012.





The temperatures in February were comparable, even if a cooling mode was operating in winter 2012.





Heating / *Cooling* / *Free*	Jan.	Feb.	Mar.	Apr.	May	Jun	July	Aug.	Sept.	Oct.	Nov.	Dec.
2010										O	O	O
2011	X	X	X	X	X	X	X	X	X	X	X	X
2012	□	□	□	□	□	□	□	□	□	□	□	□
2013	◇	◇										

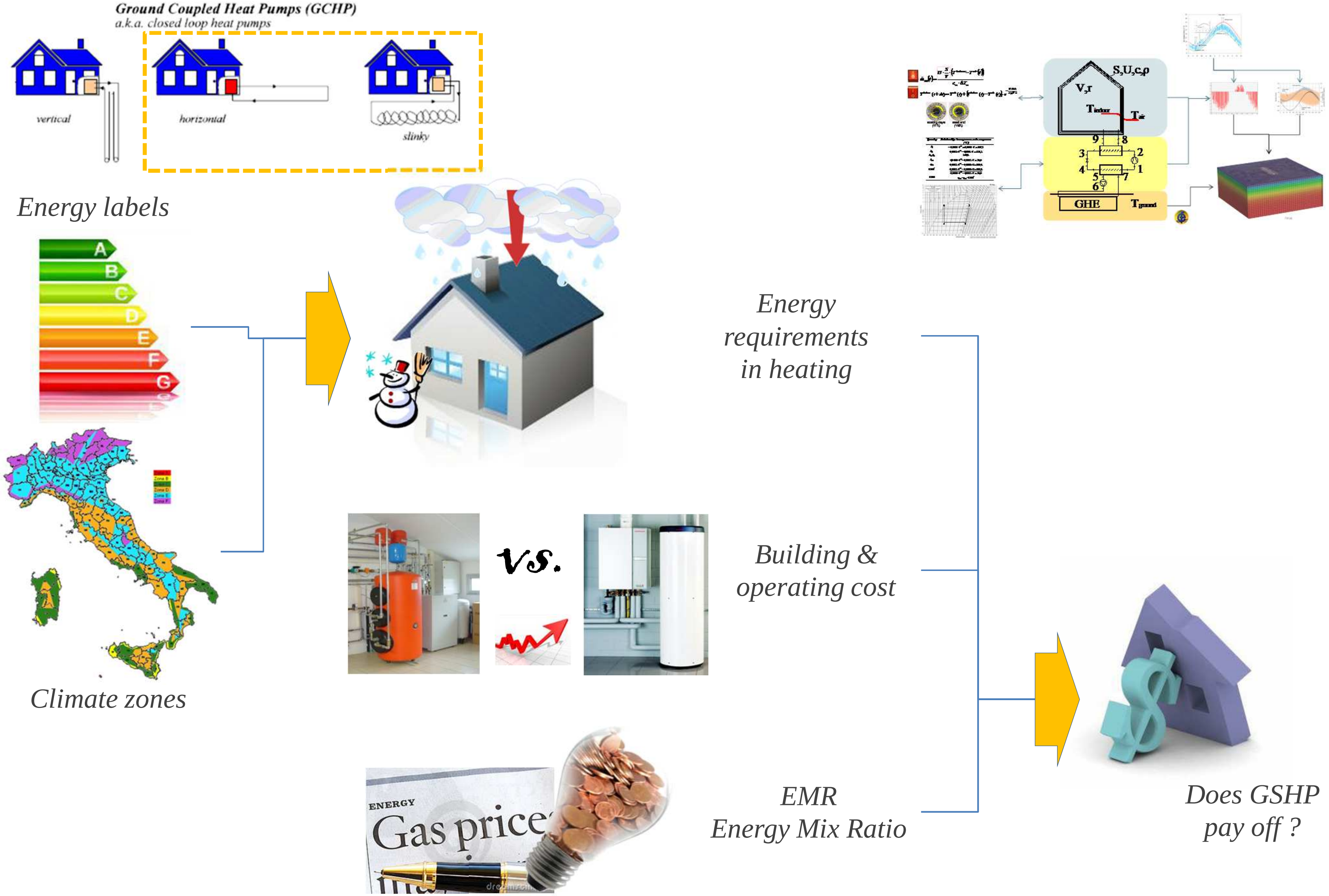
The flat-panel shows high energy performance:

- 45 W/m in cooling mode, with a thermal average working difference of 10 K
- 80 W/m in heating mode, with a thermal average working difference of 15 K

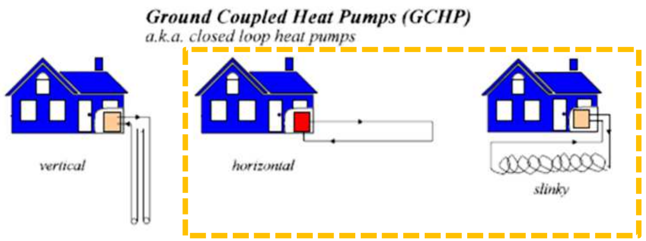
Similar temperatures were naturally achieved after few time of inactivity.

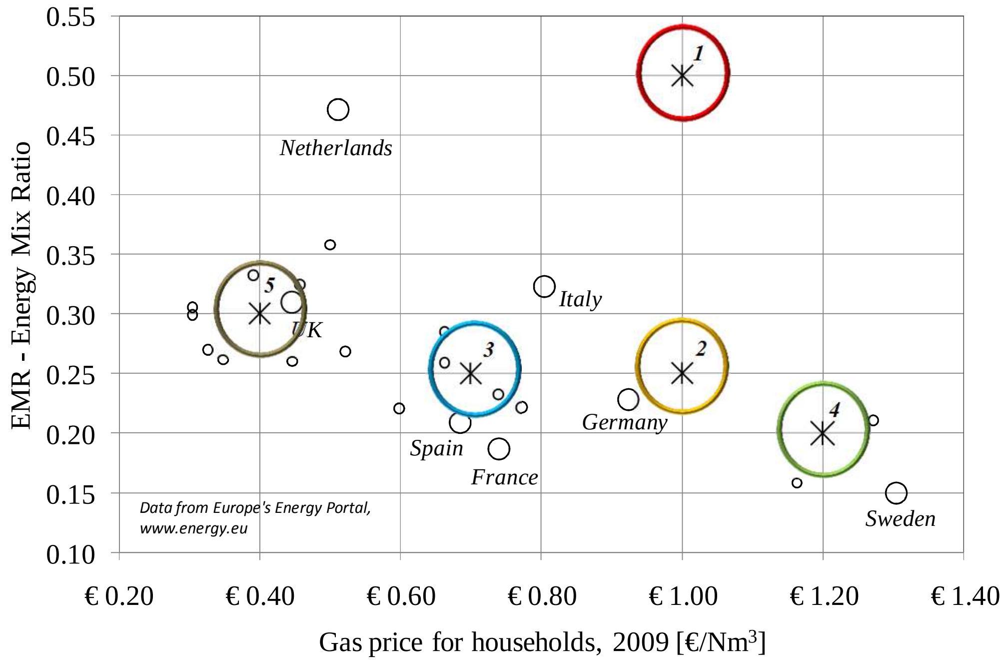
So, the heat transfer over the soil surface deletes the thermal memory of the energy exploitation carried out by shallow GHXs.

Unlike with the vertical exchangers, its behaviour highlights that long-term subsurface thermal energy build-up or depletion wouldn't be expecting by shallow GHXs.

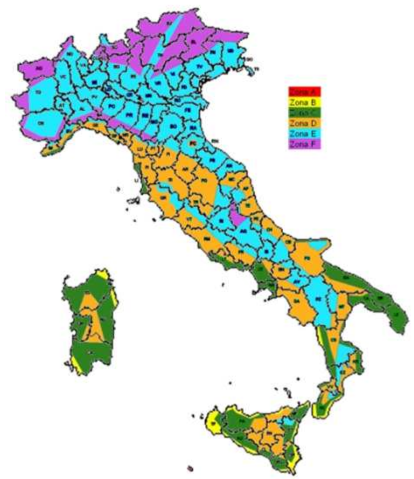


Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps
vertical
horizontal
slinky
Energy labels
A
B
C
D
E
F
G
Climate zones
vs.
ENERGY
Gas price
GHE
Energy requirements in heating
Building & operating cost
EMR
Energy Mix Ratio
Does GSHP pay off ?

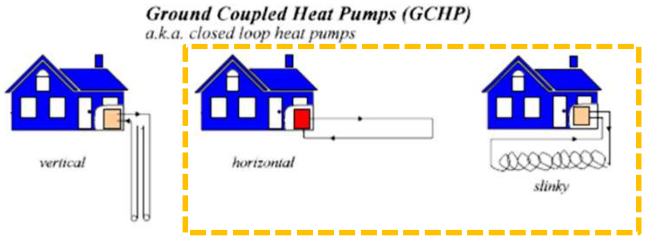




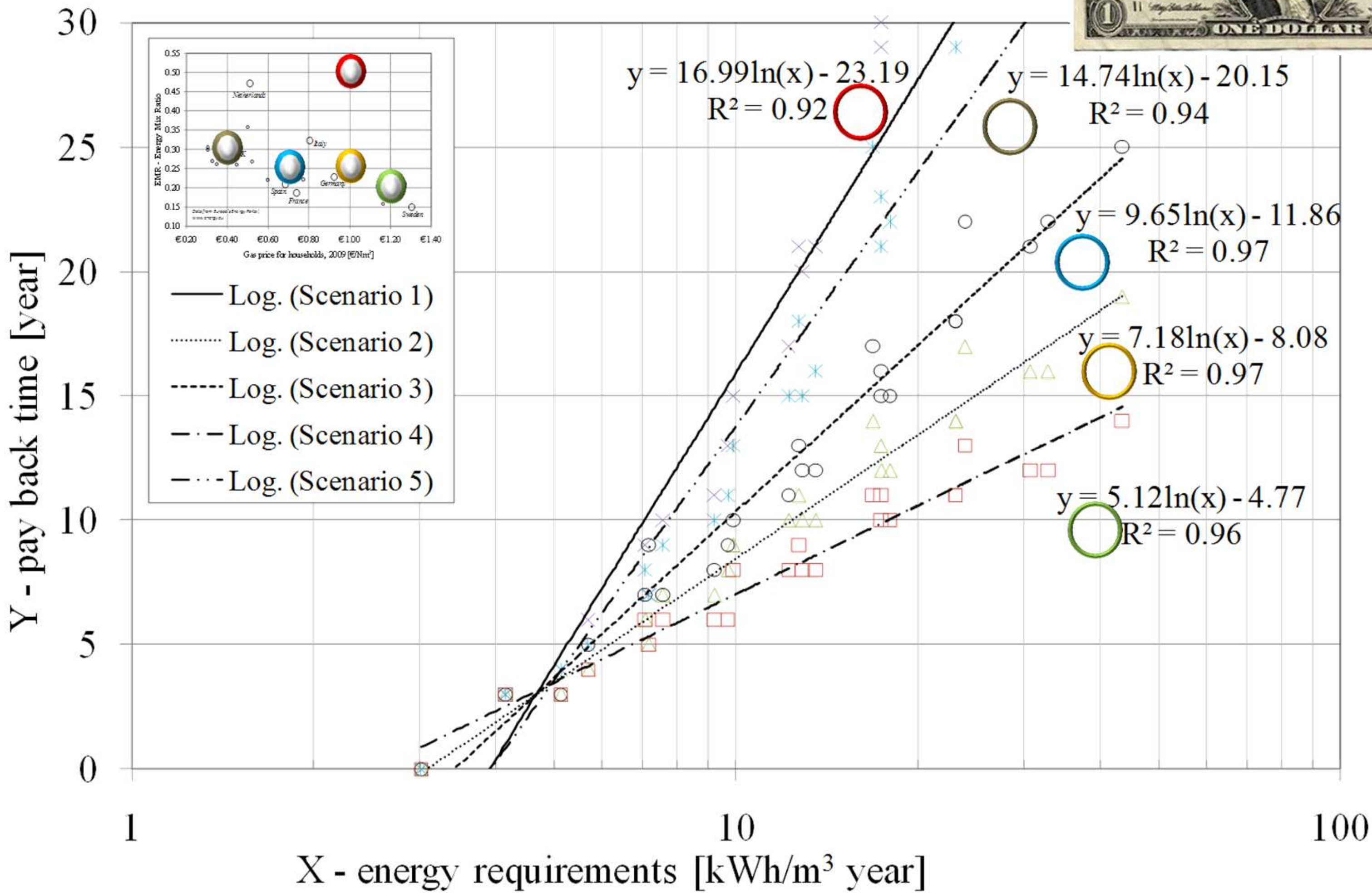
- Only heating mode
- No reduction
- GHE cost : 1 €/W
- Cut-off: 30 y



$E_L^{\$}$	1	2	3	4	5
a	10	7	7	6	9
b		10	12	8	15
c		12	15	10	
d		14		11	
e				12	
f				14	



Ground Coupled Heat Pumps (GCHP)
a.k.a. closed loop heat pumps
vertical
horizontal
slinky



y = 16.99ln(x) - 23.19
R² = 0.92
y = 14.74ln(x) - 20.15
R² = 0.94
y = 9.65ln(x) - 11.86
R² = 0.97
y = 7.18ln(x) - 8.08
R² = 0.97
y = 5.12ln(x) - 4.77
R² = 0.96
Log. (Scenario 1)
Log. (Scenario 2)
Log. (Scenario 3)
Log. (Scenario 4)
Log. (Scenario 5)
EMR - Energy Mix Ratio
Gas price for households, 2009 [€/Nm³]
Netherlands
Italy
Spain
France
Germany
Sweden
Y - pay back time [year]
X - energy requirements [kWh/m³ year]

For shallow GHEs, PCMs could represent a method:

1. to restore the UTES benefit, according to the seasonally regeneration
2. to smooth the thermal wave produced by the HP

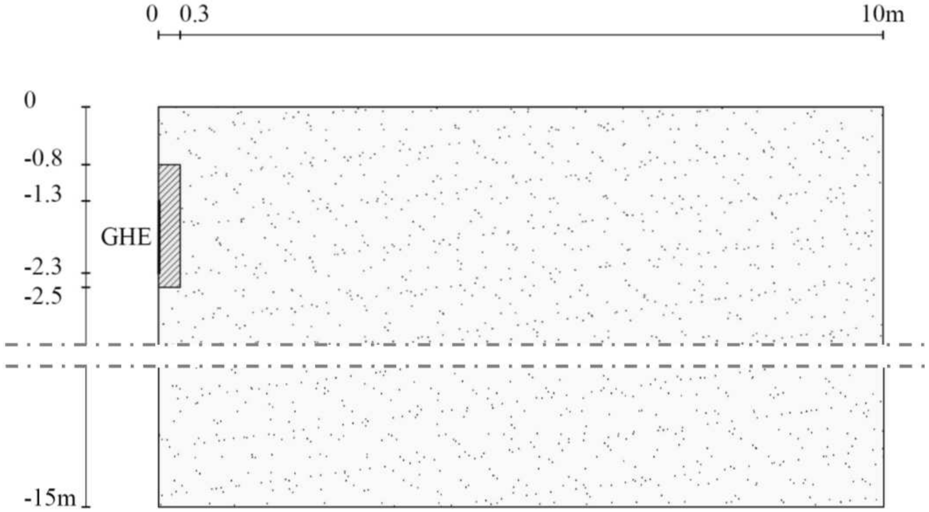
Two kinds of energy requirement: heating & cooling
Then, two melting points.

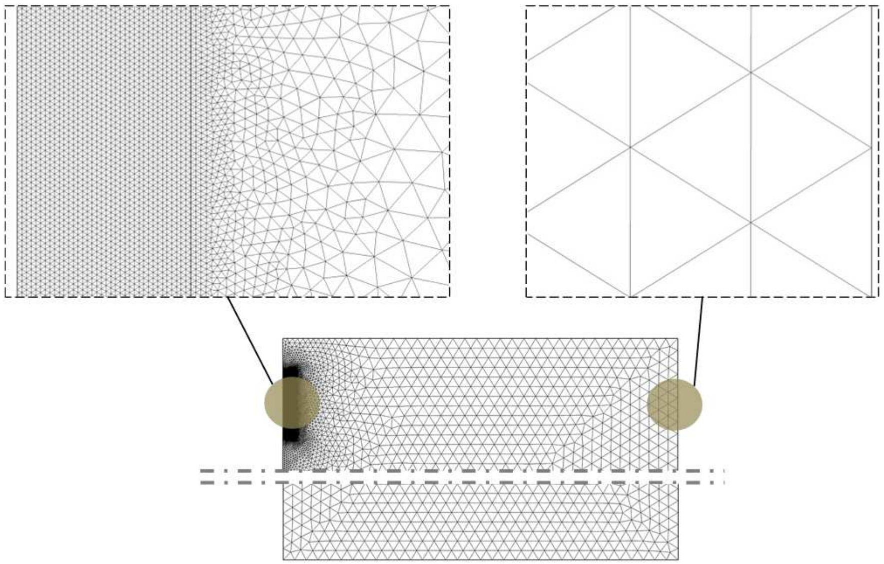
Thus, two PCMs are needed.

A numerical model has been implemented to analyze the benefit occurring by their application

Model domain

A 2D numerical approach was carried out to assess the behaviour of a flat-panel with/without PCMs





2D transversal section	10x15 m
PCM layer	30x170 cm
N° elements	23.000
Min element size	0.16 cm^2
Max element size	1600 cm^2

COMSOL's module:
Heat Transfer in Solids, advanced

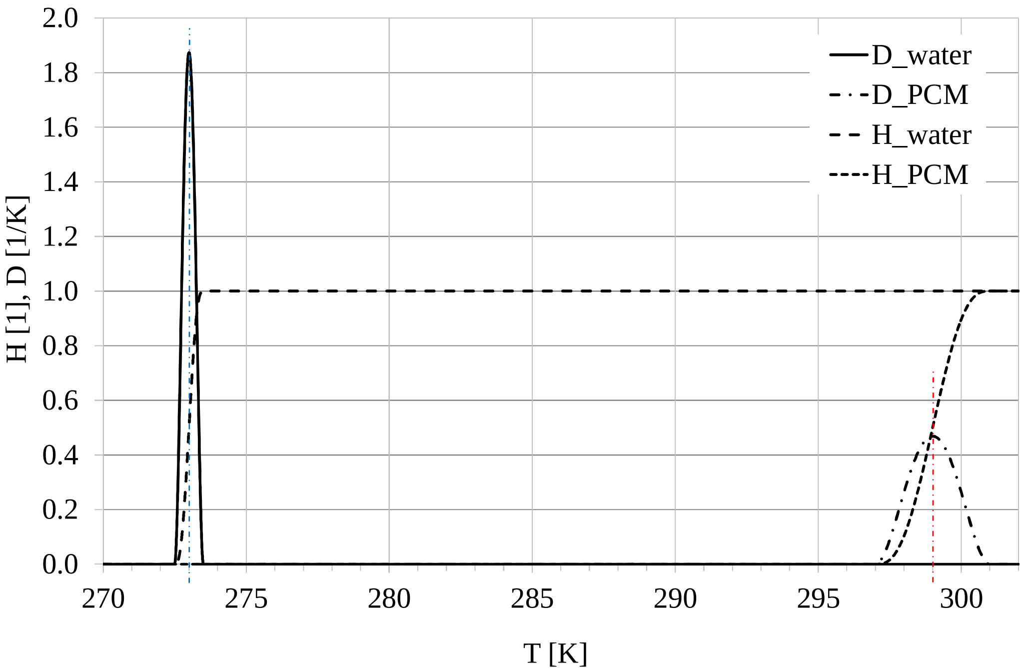
$$\rho_{eq} c_{eq} \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda_{eq} \nabla T \right)$$

H&D functions

Two functions (*H&D*) control the phase change in the model

H(T) controls the phase change
D(T) modulates the latent heat

The latent heat was introduced as *Equivalent Specific Heat*



SOLID

$$\left(1-\sum_{i=1}^{n} r_i\right)\cdot c_G + \sum_{i=1}^{n} r_i \cdot \left(1-H_i(T)\right)\cdot\left(c_i^S + h_i^{SL}\cdot D_i(T)\right)$$

$$\left(1-\sum_{i=1}^{n} r_i\right)\cdot \rho_G + \sum_{i=1}^{n} r_i \cdot \left(1-H_i(T)\right)\cdot \rho_i^S$$

$$\left(1-\sum_{i=1}^{n} r_i\right)\cdot \lambda_G + \sum_{i=1}^{n} r_i \cdot \left(1-H_i\right)\cdot \lambda_i^S$$

LIQUID

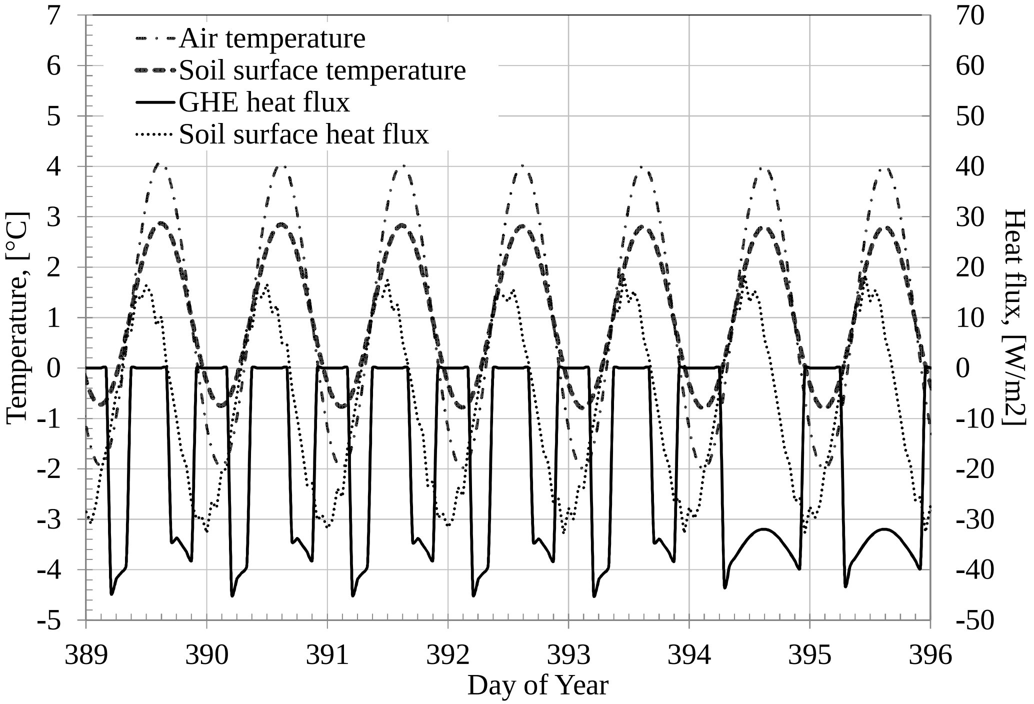
$$\sum_{i=1}^{n} r_i \cdot H_i(T)\cdot\left(c_1^L + h_i^{SL}\cdot D_i(T)\right)$$

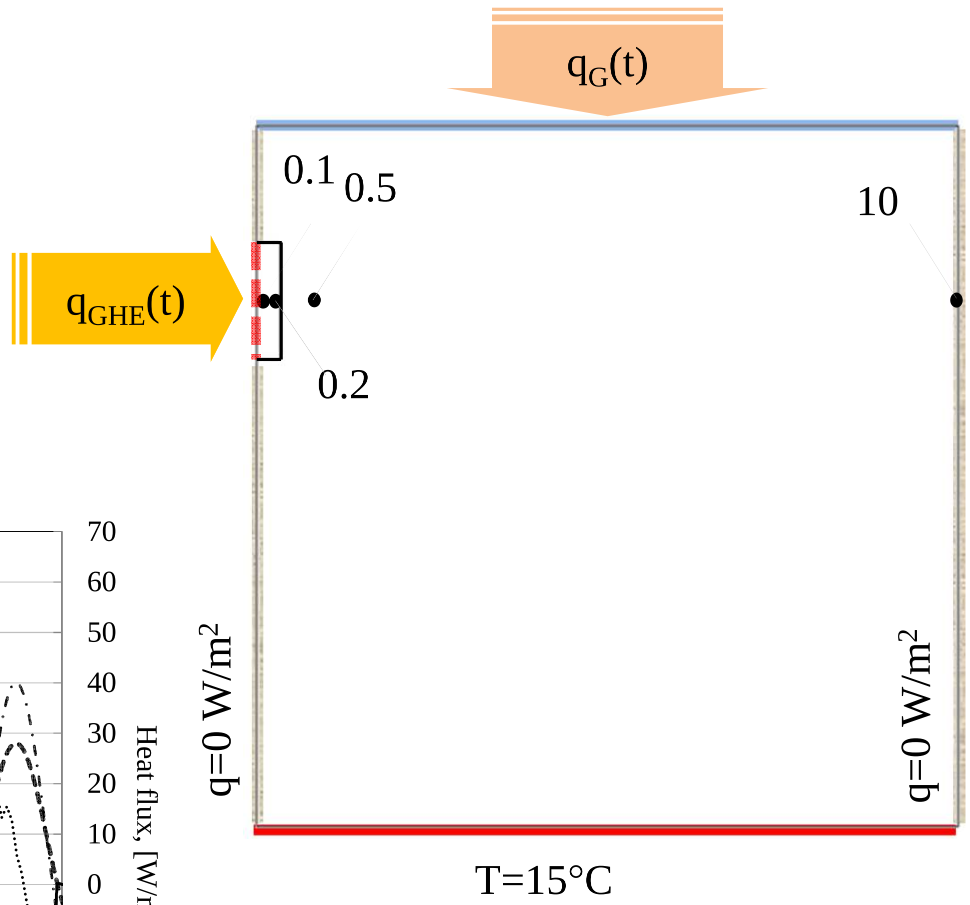
$$\sum_{i=1}^{n} r_i \cdot \rho_i^L \cdot H_i(T)$$

$$\sum_{i=1}^{n} r_i \cdot H_i(T)\cdot \lambda_i^L$$

Boundary conditions

- Time varying heat flux at the GHE wall
- Time varying heat flux at the soil surface
- Constant temperature at the bottom
- All other boundaries as adiabatic

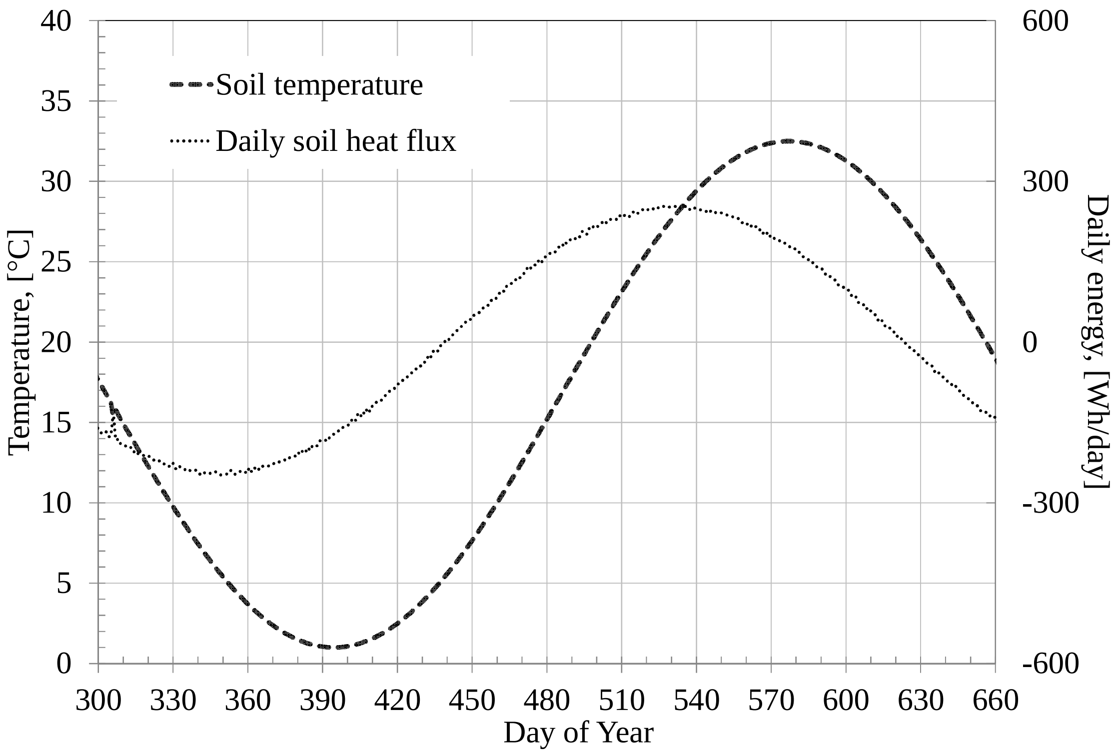


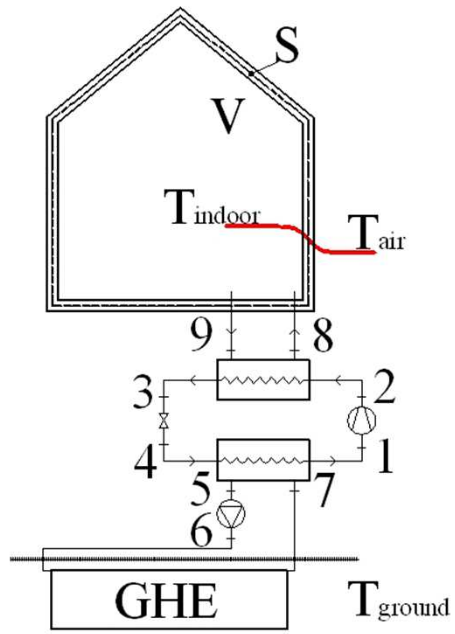


Heat fluxes

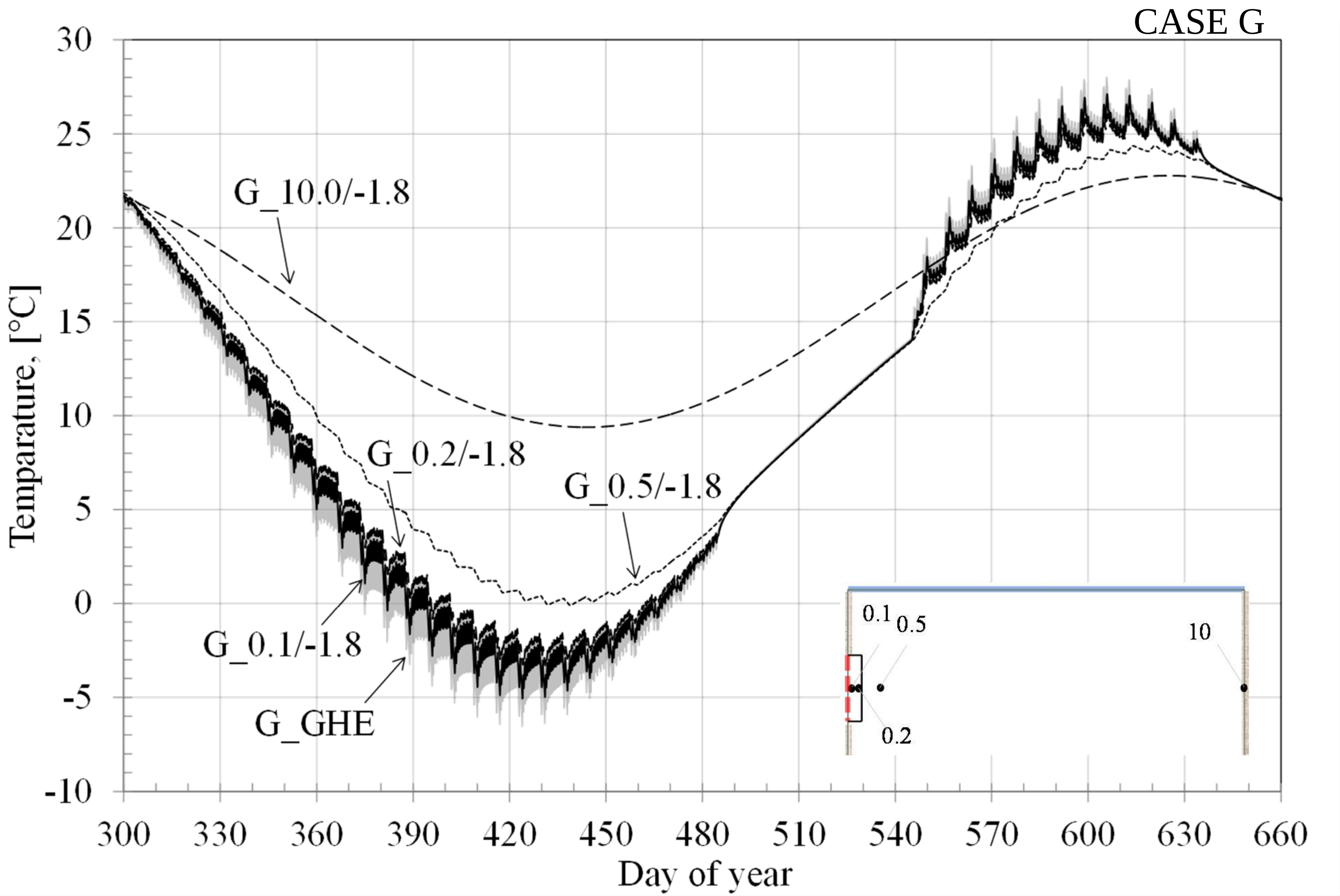
$$T(t) = T^{air}(t) + \left(T_{off} - T^{air}(t)\right) \cdot e^{-\frac{US \cdot (t - t_{off})}{r_b V \cdot \rho_b c_b}}$$

$$\dot{q}(t_{on}) = U \cdot \frac{S}{V} \cdot \left(T^{h/c} - T^{air}(t_{on})\right) + r_b \cdot \rho_b c_b \cdot \left(T^{h/c} - T(t_{on})\right)$$

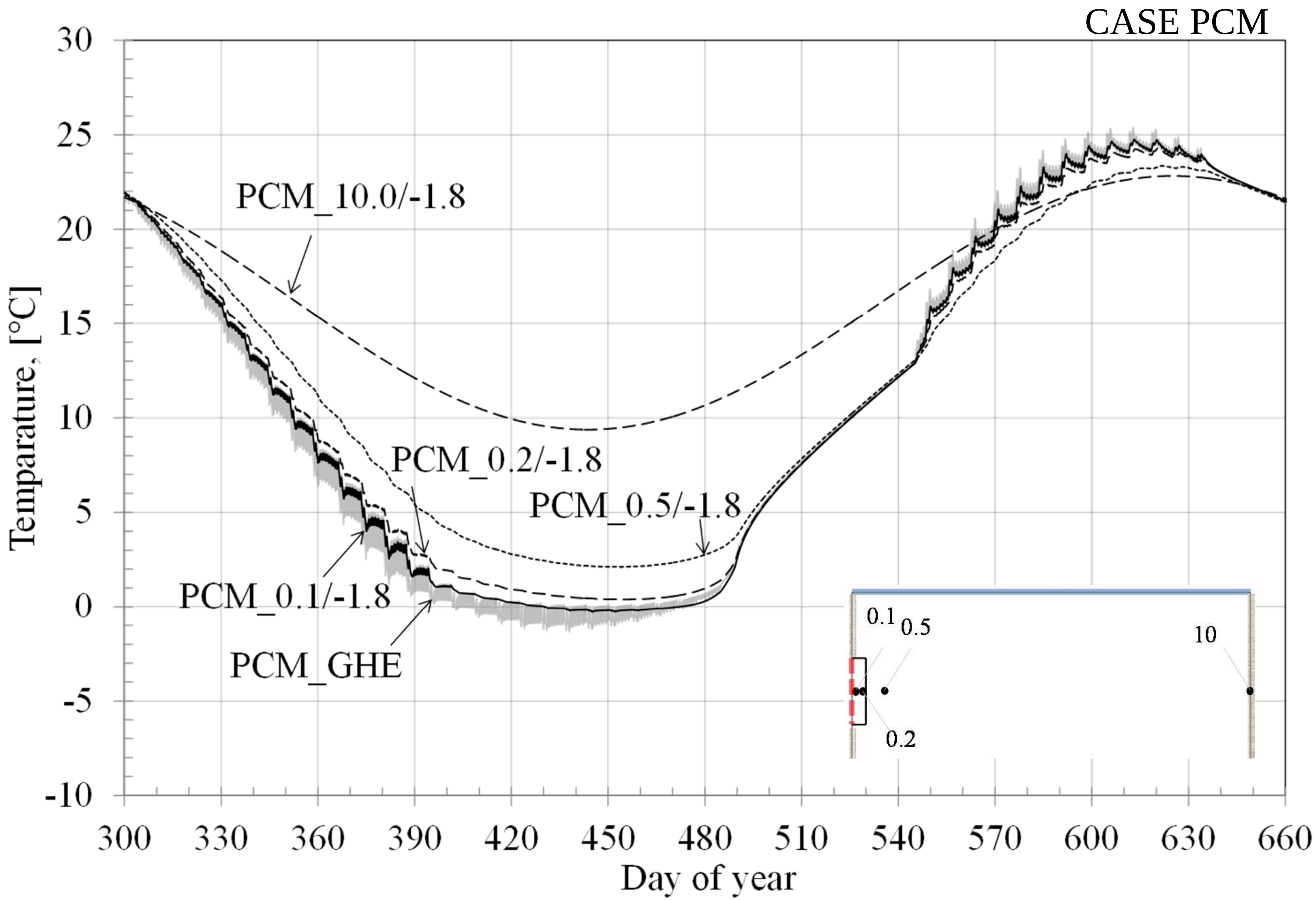




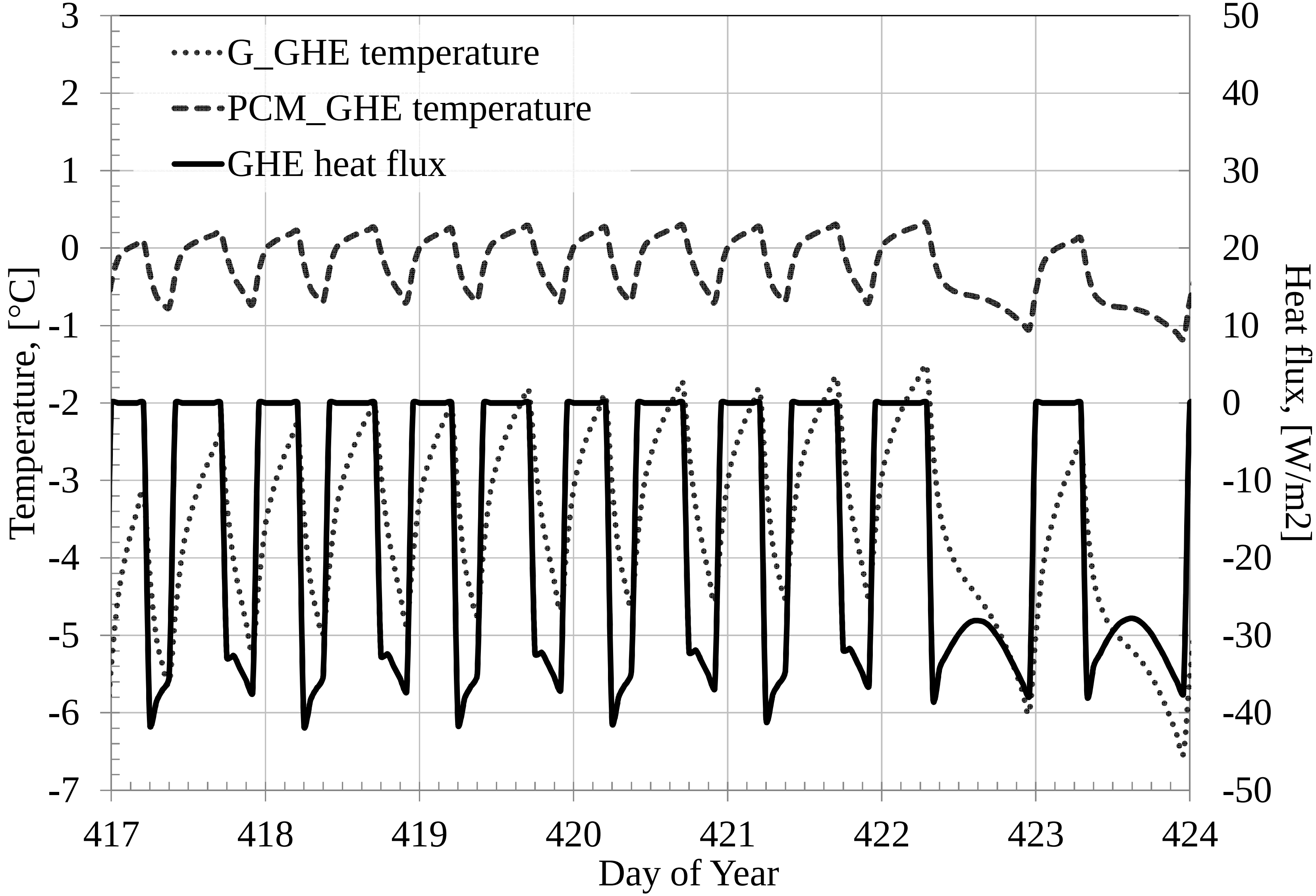
<u>*Temperatures without PCMs*</u>



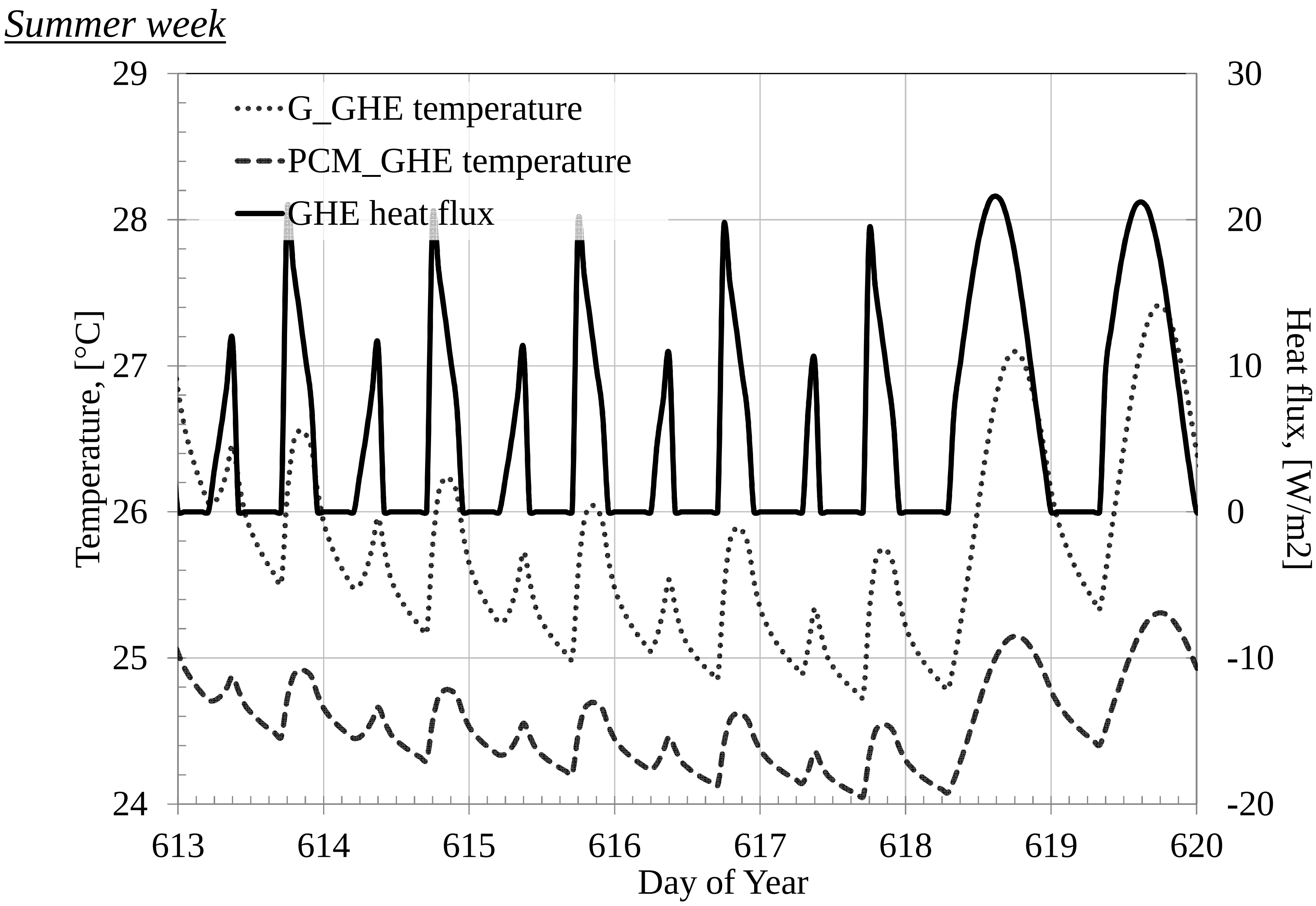
Temperatures with PCMs, case PCM



Winter week

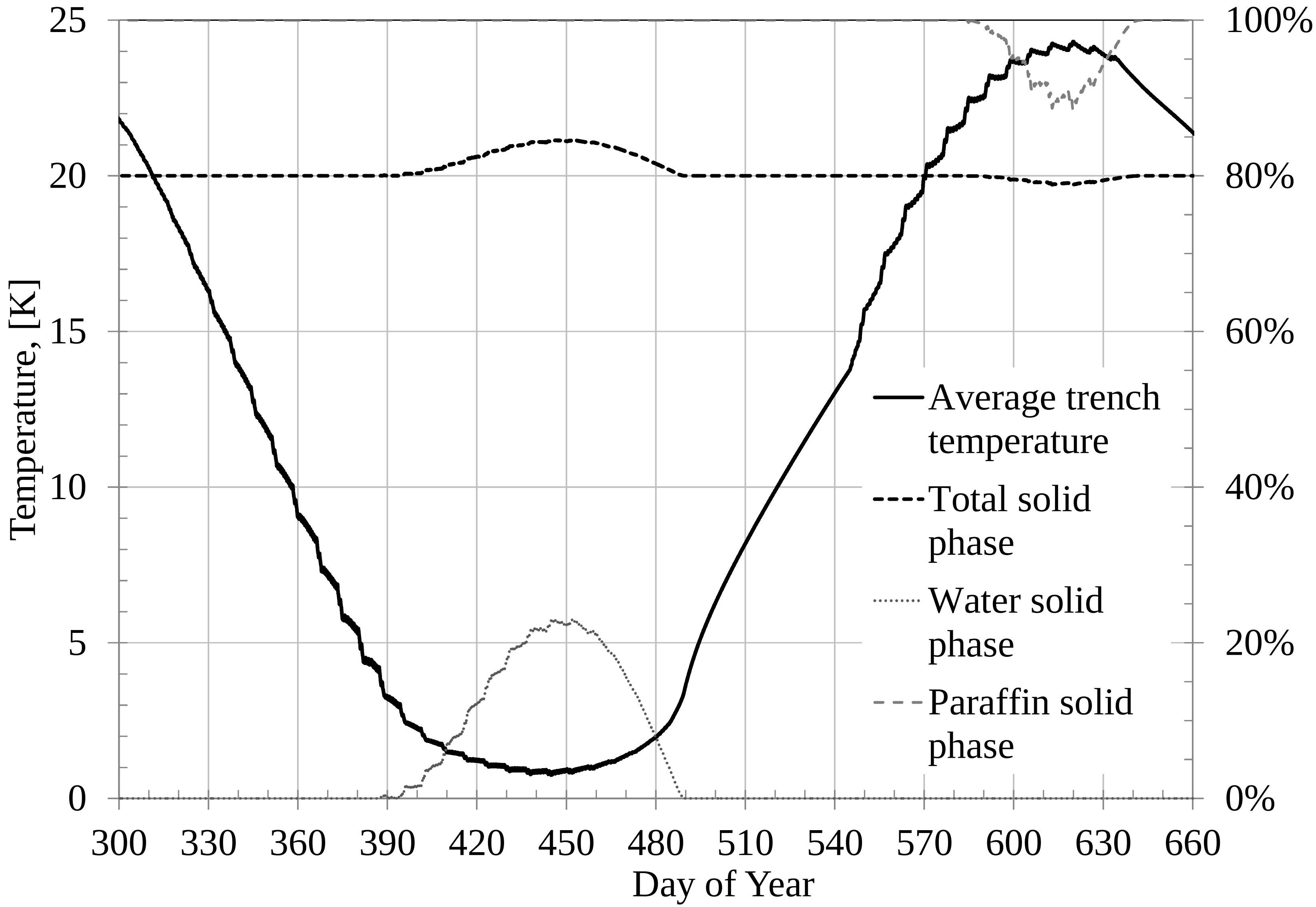


G_GHE temperature
PCM_GHE temperature
GHE heat flux
Temperature, [°C]
Heat flux, [W/m2]
Day of Year
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
50
40
30
20
10
0
-10
-20
-30
-40
-50
417
418
419
420
421
422
423
424



Summer week
G_GHE temperature
PCM_GHE temperature
GHE heat flux
Temperature, [°C]
Heat flux, [W/m2]
Day of Year
29
28
27
26
25
24
30
20
10
0
-10
-20
613
614
615
616
617
618
619
620

Solid phase



25
20
15
10
5
0
100%
80%
60%
40%
20%
0%
300
330
360
390
420
450
480
510
540
570
600
630
660
Day of Year
Temperature, [K]
Solid phase in trench
Average trench temperature
Total solid phase
Water solid phase
Paraffin solid phase

Equivalent specific heat