CHECKLIST FOR HEAT PUMP APPLICATIONS IN BUILDINGS

Deliverable 8 Ground-Reach

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"Reaching the Kyoto targets by means of a wide introduction of ground coupled heat pumps (GCHP) in the built environment"

Project supported by

Checklist for heat pump applications in buildings

About this Technical Report

This report provides a study on the influence of various site specific parameters on the performance of ground coupled heat pump systems and guidelines for space conditioning systems designers regarding the conditions under which heat pumps are more advantageous compared to classical space conditioning systems in order to encourage selection of heat pump systems in situations where they provide the most benefits.

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Contents

1 Introduction

It is the objective of the Buildings Performance Directive1 to promote the improvement of the energy performance of buildings within the Community, taking into account outdoor climatic and local conditions as well as indoor climate requirements and cost-effectiveness. This objective is based on the fact that buildings will have an impact on long-term energy consumption and buildings should therefore meet minimum energy performance requirements tailored to the local climate.

This work, part of Work Package 4 of the Ground-Reach project, refers to the following paragraphs of the Buildings Performance Directive:

- "As the application of alternative energy supply systems is generally not explored to its full potential, the technical, environmental and economic feasibility of alternative energy supply systems should be considered; this can be carried out once, by the Member State, through a study which produces a list of energy conservation measures, for average local market conditions, meeting cost-effectiveness criteria. Before construction starts, specific studies may be requested if the measure, or measures, is deemed feasible." (L 1/64 (12))
- "New buildings. Member States shall take the necessary measures to ensure that new buildings meet the minimum energy performance requirements set by the Member States. For new buildings with a total useful floor area over 1 000 m^2, Member States shall ensure that the technical, environmental and economic feasibility of alternative systems such as:
  - decentralised energy supply systems based on renewable energy,
  - CHP,
  - district or block heating or cooling, if available,
  - heat pumps, under certain conditions,

  is considered and is taken into account before construction starts." (Article 5, L 1/68)

This Directive defines "heat pump" as follows: "a device or installation that extracts heat at low temperature from air, water or earth and supplies the heat to the building." (Article 2, L 1/67)

[1] DIRECTIVE 2002/91/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2002 on the energy performance of buildings (4.1.2003 L 1/66 Official Journal of the European Communities)

The present report explores the influence of site specific parameters on ground coupled heat pump (GCHP) performances. Specifically, the following parameters are explored:

- Soil type/properties;
- Aquifer;
- Available space for the ground heat exchanger;
- Presence of other ground heat exchangers in the neighbourhood;
- Space conditioning distribution system.

Building type, size and climates were already studied in the course of deliverable 7 (Pinel & Brychta, 2008). The influences of these parameters are evaluated using a combination of theory, existing literature and computer simulations.

Finally, guidelines are provided to allow designers to determine when projects are particularly suited for heat pump applications in order to encourage selection of heat pump systems in situations where they make the most sense.

2 Methodology

Deliverable 8 is not meant to explore every detail of system design, a task which would certainly require major resources and time, but to explore the conditions already in place at the time of system selection which would influence the future performance of the system. Design details are better left to be explored at the design stage of a specific system.

Besides the building type/size and climatic conditions, which are already explored in the frame of Ground-Reach Deliverable 7 (Pinel & Brychta, 2008), the main parameters influencing the performance of a future heat pump system would be concerned with:

- The type of soil present in the region where the ground loop is planned
- The characteristics of the aquifer
- The space available to install the ground loop
- The presence of other geothermal heat pump system(s) in the surroundings
- The space conditioning distribution system already installed in the case of a retrofit

Exploring in detail the influence of each of these parameters would be a large research undertaking. Therefore, parameters are varied to view tendencies but not all possible variations are explored. Tendencies observed during simulations are supported by scientific studies from a literature review if those are available and found. For cases where no study can be found, tendencies are simply expressed and the need for further exploration is highlighted.

2.1 Building cases studied

Since it is neither possible nor pertinent to vary all these parameters for each of the building loads used in the course of Deliverable 7, a limited number of load profiles are used. The emphasis of the package being on the residential sector, the loads obtained for residential buildings are used. It would be interesting to explore higher and lower load intensities as well as balanced and unbalanced (heating or cooling dominated) loads. Calculated space conditioning loads, presented in section 3.1 of Deliverable 7, show the most unbalanced loads to occur in cold climate for lower energy efficiency buildings while the most balanced loads occur in warm climate for higher insulation cases. Therefore, the four following cases from Deliverable 7 are used for most parameter variations.

- Low efficiency single family house in cold climate
- Low efficiency multi family building in cold climate
- High efficiency single family house in warm climate
- High efficiency multi family building in warm climate

2.2 Parameter variations

The following chapters explain how each of the selected parameters influence heat pump performances and how they were varied. For cases where different building scenarios need to be explored, the specific scenario is mentioned in the text. Table 2.1 summarizes these scenarios.

Table 2.1 Studied scenarios in the course of Deliverable 8

Parameter	Climate	Loads	Variations/Task
Soil	- Cold - Warm	- Single family house - Multi family building	- Unfavourable soil - Medium soil - Favourable soil
Water table	- Cold	Single family houses	- Horizontal exchangers - Many variations of aquifer depth
		Multi family building	- Boreholes - Aquifer close to boreholes bottom
Space available	- Cold - Warm	- Single family house - Multi family building	- Borehole systems - Separations: 6m, 8m, 10m
		- Single family house	- Horizontal exchangers - Separations: 30cm, 50cm, 80cm
Other systems (neighbours)	- Cold	- Single family house	- 1,2 and 3 neighbours - Yard lengths: 15m, 20m, 25m
Distribution system	- Cold - Warm	- Single family house - Multi family building	- High temperature distribution - DHW production: Heat Pump, tankless gas or electric

2.3 Comparisons

Comparisons are made with the heat pump (identified in this report as base cases) and conventional space conditioning systems simulated in the course of deliverable 7 to evaluate the effect of each varied conditions (parameters) on the effectiveness of the heat pump system to help achieve the goal of the Buildings Performance Directive1. The performances of GCHP systems evolve over time according to the thermal reaction of the surrounding soil. Therefore, the energy consumption on the last year of the simulation was assumed as the performance value of interest over the life cycle of the system. The last year was the 10th year for borehole systems and the 5th year for horizontal ground heat exchangers.

The variation of each parameter requires re-designing the ground loop of the heat pump systems to be able to accomplish the space conditioning task while respecting the design temperature limits of the system. Since the space conditioning efficiency of these re-designed systems in their new environment (parameters) does not vary extensively from the performance of the base systems for most parameter variations, the main comparison criteria is life cycle cost, namely the effect of re-design on this cost.

The data used to evaluate life cycle costs (LCCs) of heat pump and alternative systems are described in section 4.4 of Deliverable 7. LCCs presented in this report (Deliverable 8) are based on the following assumptions:

- 30 years system life;
- 3% annual increase in the cost of energy;
- Costs investment for conditioning systems reimbursed in a period of 5 years;
- 5 % annual interest rate on the systems costs investment.

Similarly, data for the CO_2 emissions and primary energy consumption analysis of section 7 can be found in sections 4.1 and 4.2 of Deliverable 7.

2.4 Models

The procedure and models to evaluate building loads, conditioning systems performances and borehole ground exchangers' temperatures are described in Deliverable 7. Deliverable 8 introduces simulation of horizontal ground exchangers. These are simulated using a model similar to the borehole model: resolution of the cylindrical heat source equation (see section 3.1) around one tube to obtain the short-term thermal response to heat impulsions and use of a finite volume model to obtain the medium/long-term interactions among tubes and with the environment. The performance of horizontal exchangers is simulated for a shorter period (5 years) compared to borehole systems (10 years) since their temperature fields tend to stabilize faster. Table 2.2 describes the different assumptions (parameter fixing) used for simulation of these exchangers.

Table 2.2 Assumptions for horizontal ground exchangers

Parameter	Assumption
Number of tubes	12
Length of tubes	Varied to respect the design EWT (heat pump Entering Water Temperature)
Distance between tubes	50 cm (default), Varied in section 4
Depth at which the tubes are buried	0.8 m in warm climate 2 m in cold climate
Distance between the tubes and the water table	200 m (default), Varied in section 5
Thickness of the sand layer around tubes (protect and insure good contact with ground)	5 cm
Distance from the last tube to the adiabatic far field in each direction (East, West, North, South)	50 m
Number of tubes connected in series in each parallel branch	1
Tubes dimensions	25 mm SDR-11
Far field temperature	Average ambient temperature

	Cold: 5.31°C Warm: 17.61°C
Thermal conductivity of the tubes	HDPE (k = 0.4 W/m°C)
Ground around the exchanger and in the far field	Limestone (default) Varied in section 3
Ground in the region located on top of the GHX	Same as for the far field
Heat transport fluid	Water/Glycol (30%)

3 Influence of the soil properties

Ground coupled heat pump applications require ground heat exchangers capable of injecting or extracting a certain amount of heat while respecting the temperature limits under which the heat pump operates efficiently. Typically, ground exchangers are designed so their return fluid temperature, also called the EWT (heat pump Entering Water Temperature), are not lower than -5°C in heating mode or higher than 35°C in cooling mode. In the course of Ground-Reach Work Package 4, the EWT limits have been fixed as:

- Cold climate: -5°C in heating, 30°C in cooling;
- Temperate climate: -5°C in heating, 30°C in cooling;
- Warm climate: 0°C in heating, 35°C in cooling;

In these conditions, good sol properties for GCHP applications would be one that results in smaller temperature difference between the fluid in a given heat exchanger and the undisturbed ground when this exchanger injects/extracts heat to/from the ground. Such a ground would result in a smaller, and therefore cheaper, heat exchanger being required to inject/extract the required heat from the building space conditioning system while respecting the EWT limits. Since the ground exchanger is often the costliest component of a GCHP system, the ground properties have a major impact on the economics of the system.

A higher ground thermal conductivity (*k*) results in a lower temperature difference between boreholes and the undisturbed ground for a defined thermal impulsion. Similarly, a higher thermal inertia (*ρCp*) should also result in a lower temperature variation. The following sections attempt to determine the influence of these parameters.

3.1 Theory

A typical equation used to evaluate the temperature distribution around a single borehole is the cylindrical heat source solution. The cylindrical heat source method was developed by Carlslaw & Jaeger (1947) and introduced to GCHP applications by Ingersol & al. (1954).

$$T - T_g = \frac{-q}{k_s} G\left(F_0(t), p\right) \qquad (3.1)$$

Where:

- T is the temperature at the location of interest, the borehole interface with the ground in that case (°C);
- T_g is the undisturbed ground temperature (°C)
- q is the heat impulsion at the borehole/ground interface per length of borehole (W/m);

- $p = \dfrac{r}{r_0}$ (3.2)

  is the ratio of the radius at the location of interest to the borehole radius, so *p=1* at the borehole/ground interface;

- $G(F_0, p) = \dfrac{1}{\pi^2}\int_0^\infty \dfrac{e^{-\beta^2 F_0} - 1}{J_1^2(\beta) + Y_1^2(\beta)}\left[J_o(p\beta)Y_1(\beta) - J_1(\beta)Y_0(p\beta)\right]\dfrac{1}{\beta^2}d\beta$ (3.3)

- J_0, J_1, Y_0 et Y_1 are Bessel functions of order 0 and 1;

- β is an integration variable;
- $F_0 = \dfrac{\alpha t}{r_0^2}$ is the Fourrier number; (3.4)
- $\alpha = \dfrac{k_s}{\rho Cp}$ is the soil's thermal diffusivity (m²/s); (3.5)
- k_s is the ground's thermal conductivity (W/m°C);
- ρ is the density of the ground (kg/m³);
- Cp is the specific heat of the ground (J/kg°C);
- t is the duration of the impulsion (s).

Figure 3.1 illustrates the solution of equation 3.1 for a 15 cm diameter borehole, submitted to a 1 W/m impulsion for a period of 1 hour, as a function of ground thermal conductivity (k in W/m°C) and inertia (rhoCp in kJ/m³°C). As can be seen, higher thermal conductivity and inertia both effectively lead to lower temperature differences.

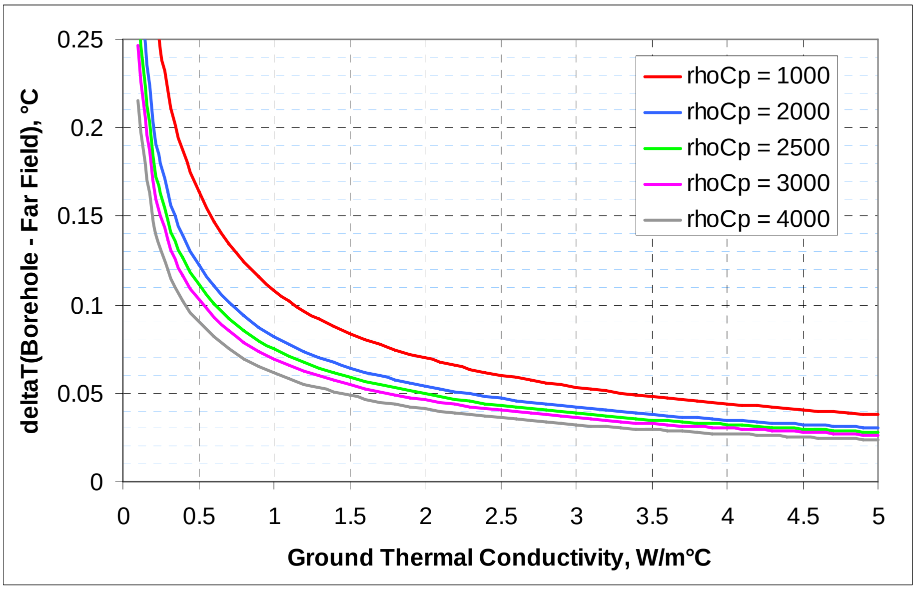


Figure 3.1 Temperature reaction of a borehole

Figure 3.1 can be used directly to assess the influence of ground properties on design requirements for one borehole. For example, in the case of a ground with a thermal inertia of 2000 kJ/m^3°C, a 1 hour impulsion of a 1 W/m heat impulsion would result in temperature increases of:

- 0.054 °C for a ground conductivity of 2 W/m°C,
- 0.035 °C for a ground conductivity of 4 W/m°C.

Therefore, the borehole in the ground with a conductivity of 4 W/m°C could reject 54% more energy to the ground for the same temperature increase. Its size would need to be 65% of the size of the borehole in the ground with a 2 W/m°C conductivity, substantially reducing the initial investment.

3.2 Influence on heat pump performance

For multiple boreholes, the analysis is relatively more complex as boreholes interact thermally with each other in the long term. In order to evaluate the effect of ground properties, 4 building and climate cases from Deliverable 7 (Pinel & Brychta, 2008) are examined with 3 typical but different grounds. The selected ground and their thermal properties from VDI 4640 (2008) are:

- Unfavourable: Dry sand
    - o k = 0.4 W/m°C
    - o ρ = 2000 kg/m^3
    - o Cp = 725 J/kg°C
- Medium: limestone
    - o k = 2.7 W/m°C
    - o ρ = 2550 kg/m^3
    - o Cp = 882 J/kg°C
- Favourable: Granite
    - o k = 3.2 W/m°C
    - o ρ = 2700 kg/m^3
    - o Cp = 944 J/kg°C

Table 3.1 resumes the cases studied. Cases for medium (limestone) ground were already simulated in deliverable 7, so 8 new ground exchangers must be designed and simulated. These exchangers are presented in table 3.2

Table 3.1 Building, climate, efficiency and ground cases studied

Building	Climate	Energy Efficiency	Ground	Ground exchanger Boreholes: nX x nY x Length
Single Family House	Cold	Low	Unfavourable	3 x 2 x 97
			Medium	2 x 1 x 81
			Favourable	2 x 1 x 73
	Warm	High	Unfavourable	2 x 2 x 74
			Medium	2 x 1 x 74
			Favourable	1 x 1 x 108
Multi Family House	Cold	Low	Unfavourable	7 x 7 x 97
			Medium	4 x 3 x 113
			Favourable	4 x 3 x 106
	Warm	High	Unfavourable	5 x 5 x 79
			Medium	3 x 3 x 78
			Favourable	3 x 3 x 70

* N.B. Greyed out exchangers were designed/simulated in the course of Deliverable 7.

Figure 3.2 shows the electricity consumption from these heat pump systems on the 10th year of operation per area of building conditioned floor space. The expressions SFH and MFH stand for Single Family House and Multi Family House respectively.

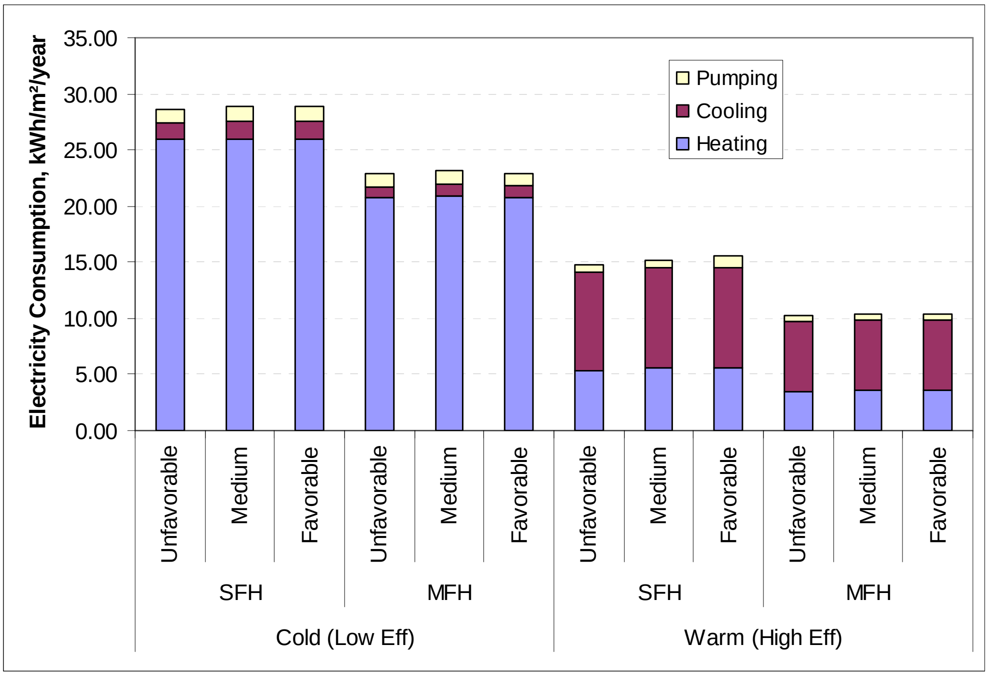


Figure 3.2 Heat pump systems electricity consumption for different grounds.

As can be seen on the figure, the energy consumption values of the systems are almost identical regardless of the ground properties. This trend is expected since the systems and loads are the same while the ground exchangers are designed to perform similarly in the different soils. As a result, the ground properties don't have a considerable effect on the CO_2 emissions, primary energy consumption and operating costs of the heat pump systems. Designing different ground exchangers depending on the ground properties mostly affects the initial cost for the exchanger and therefore the life cycle costs of the systems. Consequently, the comparison concentrates on life cycle cost (LCC).

The life cycle cost analysis is performed using the procedure described in section 4.4 of Ground-Reach Deliverable 7 (Pinel & al. 2008). In the Deliverable in question, price of borehole exchangers are evaluated using the relationship:

$$Price_{Bore}\ (€) = 550 + 45 * Length_{drilling}(m)$$

This yields the following costs per area of conditioned building space for the exchangers presented in Table 3.1. As can be seen, there are substantial differences, especially for exchangers in unfavourable ground conditions which tend to cost significantly more.

Table 3.2 Costs of ground exchangers

Building	Climate	Energy Efficiency	Ground	Ground exchanger Cost €/m²
Single Family House	Cold	Low	Unfavourable	191.7
			Medium	55.7
			Favourable	51.1
	Warm	High	Unfavourable	104.4
			Medium	51.4
			Favourable	38.6
Multi Family House	Cold	Low	Unfavourable	166.1
			Medium	47.8
			Favourable	44.8
	Warm	High	Unfavourable	69.3
			Medium	24.9
			Favourable	22.2

Figure 3.3 presents annual life cycle costs for heat pumps and alternative conditioning systems.

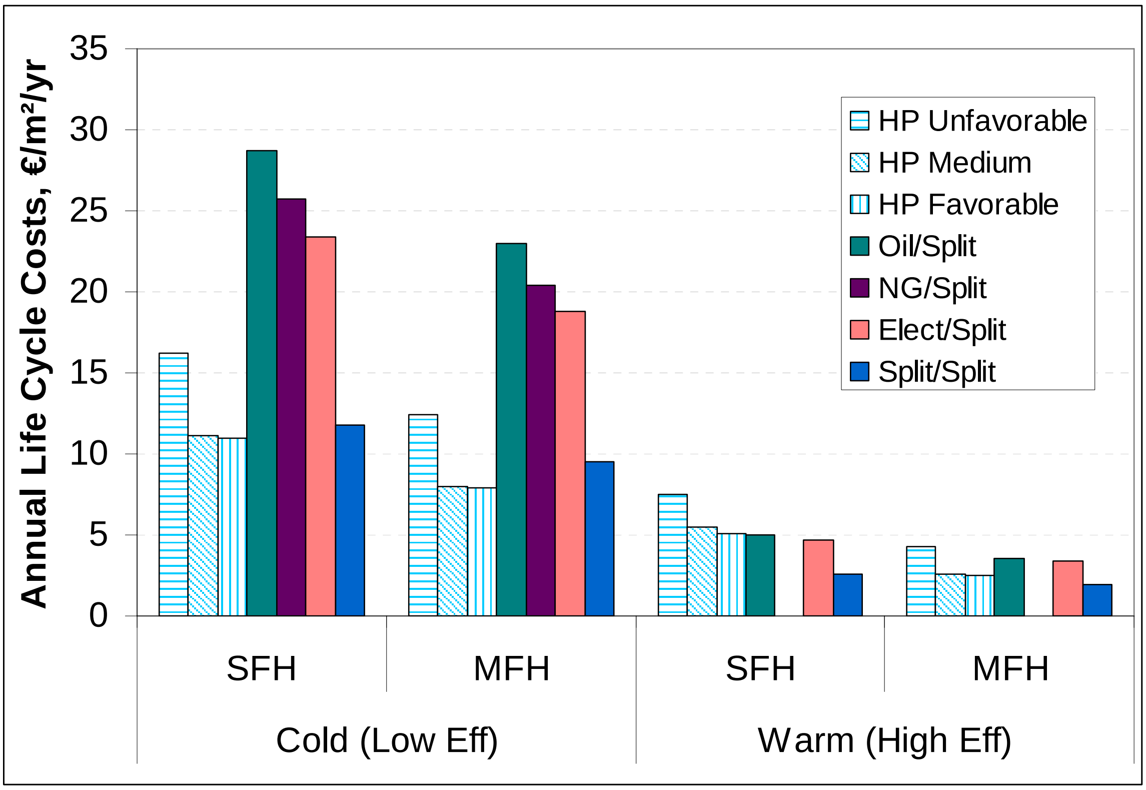


Figure 3.3 Life cycle costs of heat pump and alternative systems for different ground properties

*Legend
- Cold (Low Eff): Low energy efficiency building case in a cold climate
- Warm (High Eff): High energy efficiency building case in a warm climate
- SFH: Single Family House
- MFH: Multi Family House
- HP Unfavourable: Heat pump for heating and cooling with boreholes in unfavourable ground
- HP Medium: Heat pump for heating and cooling with boreholes in medium ground
- HP Favourable: Heat pump for heating and cooling with boreholes in favourable ground
- Oil/Split: Oil boiler for heating, split system for cooling
- NG/Split: Natural gas boiler for heating, split system for cooling
- Elec/Split: Electric resistance for heating, split system for cooling
- Split/Split: Split system for heating and cooling

Please note that, as mentioned in Deliverable 7, no comparisons are performed with natural gas systems in warm climates since there is no considerable market and data for this fuel in Greece.

As can be seen from Figure 3.3, there is no substantial difference between medium and favourable ground LCCs. Only unfavourable ground properties result in a substantially higher LCC. This result agrees with Figure 3.1 which shows there is no major performance difference between grounds with thermal conductivities above 2 W/m°C but considerable degradation below that conductivity.

From the life cycle cost perspective, heat pump systems are always superior in Sweden to fossil based or electric resistance systems. If the ground conditions are unfavourable, it may be preferable to select split systems even in this climate: the other advantages of heat pump systems regarding CO_2 emissions and primary energy savings demonstrated in sections 4.1 and 4.2 of deliverable 7 should also be considered though.

In Greece, the results demonstrate again that split systems have lower life cycle costs than heat pumps. Fossil and electric based systems also have lower LCCs than heat pumps when the ground properties are unfavourable.

4 Influence of available space

Not all projects utilize the same yard space to install ground heat exchangers. For projects where the system is large or the space limited, borehole heat exchangers are usually preferred since they exchange heat with the deep ground and therefore do not occupy as much space at the ground surface. For some projects, the available space is so limited that the distance between boreholes must also be reduced. This also has an impact on long term performances of the exchanger as closer boreholes interact thermally to a greater extent, i.e. the presence of nearby boreholes result in a lower (heating) or higher (cooling) fluid temperature at the outlet of a borehole. Decreasing distance between boreholes therefore requires increasing their length in order to respect the limit EWTs of the heat pump, resulting in corresponding supplementary costs for the GHX construction.

Similarly, large available yard space could result in horizontal exchangers being advantageous. Such exchangers circulate the fluid in horizontal tubes buried near the surface. The fact that the exchanger is buried closer to the surface results in lower installation costs. As with boreholes, performances are dependant on distance between tubes meaning that such an exchanger installed in a larger space (larger tube separation) would require less tubes and therefore be less expensive.

4.1 Cases explored

This section explores the influence of borehole or tube separation on LCCs. Borehole separation is varied from 5 to 10 meters for the buildings/climates explored in section 3. Horizontal exchangers are also simulated for single family houses since small buildings are usually their main area of application. For these horizontal exchangers, tube distances of 30, 50 and 80 cm are explored. Table 4.1 summarizes the cases explored and describes the required ground exchangers and their cost per area of building conditioned space.

Table 4.1 Cases explored for influence of space availability

Borehole heat exchangers					
Building	Climate	Energy Efficiency	Separation m	Ground exchanger	
				Boreholes: nX nY x Length	Cost €/m²
Single Family House	Cold	Low	5	2 x 1 x 80.4	55.62
			8	2 x 1 x 79.9	55.29
			10	2 x 1 x 79.3	54.91
	Warm	High	5	2 x 1 x 74	51.51
			8	2 x 1 x 73.8	51.37
			10	2 x 1 x 73.6	51.25
Multi Family House	Cold	Low	5	4 x 3 x 121.8	51.40
			8	4 x 3 x 114.4	48.31
			10	4 x 3 x 109.2	46.12
	Warm	High	5	3 x 3 x 79.4	25.34
			8	3 x 3 x 78.1	24.95
			10	3 x 3 x 77.5	24.74
Horizontal heat exchangers					
Building	Climate	Energy Efficiency	Separation cm	Ground exchanger	
				nTubes x length	Cost €/m²
Single Family House	Cold	Low	30	12 x 138	28.39
			50	12 x 119	24.42
			80	12 x 104	21.45
	Warm	High	30	12 x 103	21.15
			50	12x 90	18.48
			80	12 x 84	17.19

* greyed out cases are base cases from Deliverable 7

Costs of borehole exchangers are evaluated using the relationship presented in section 3.2 while horizontal exchangers are assumed to cost € 2.4 per meter of tube. It should be noted that this cost structure constitutes somewhat of an oversimplification as horizontal exchangers are considered to be located at a depth of 2 m in Sweden and 0.8 m in Greece, making digging considerably more difficult in Sweden. Since obtaining precise digging cost data is not straightforward and depends on many parameters like terrain (rocks, etc…), an average cost for Austria (2.4 €/m), where horizontal exchangers are buried 1.2 m, is used.

Intuitively, the impact of borehole separation is more important for larger fields. This can be explained by these fields having a lower ratio of their boreholes located on the periphery where they can exchange heat directly with the far field. These "trapped" boreholes are highly dependant on the space between them and their neighbours to exchange heat and therefore more affected when that space is reduced.

4.2 Simulations results

Energy consumptions evaluated for the last (10th for boreholes, 5th for horizontal) year of operation simulated are presented in Figure 4.1. As can be seen, the electricity required for space conditioning is slightly lower with horizontal exchangers than with boreholes. The separation does not have any effect on energy consumption since the exchanger has been redesigned for the different separations.

Figure 4.1 Electricity consumption from heat pumps for space conditioning

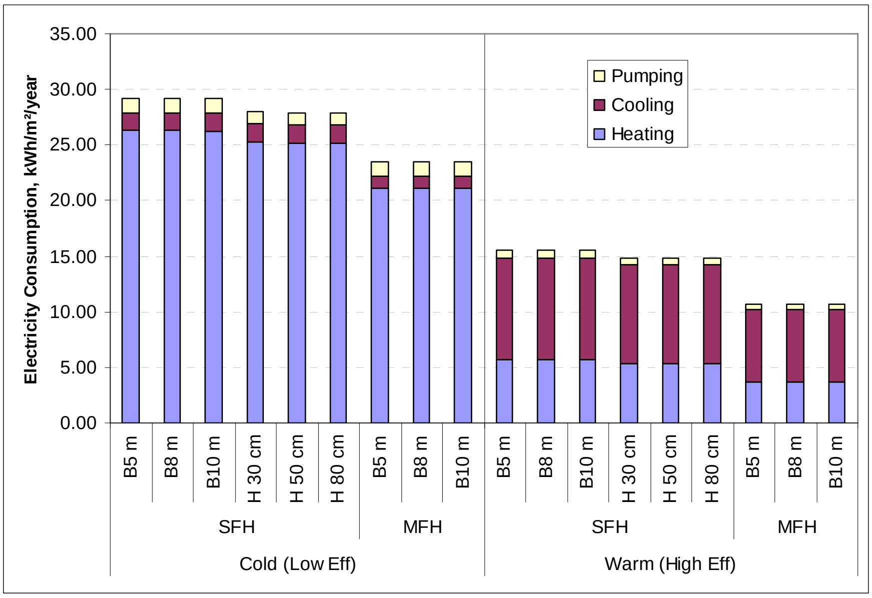
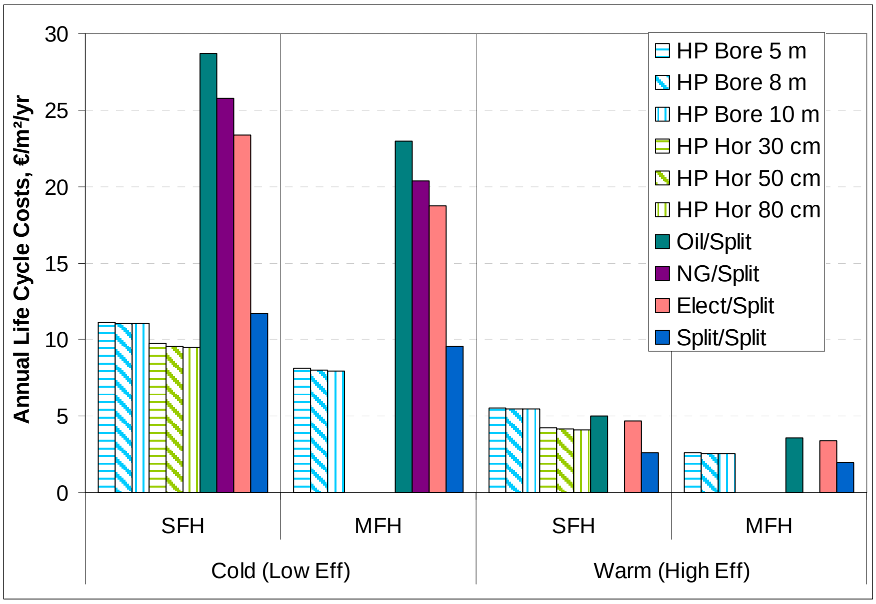


Figure 4.2 presents the corresponding life cycle costs. Horizontal heat exchangers usually display lower LCC since both their initial cost and the resulting heat pump electricity consumption are lower. Changing the separation between tubes or boreholes, while changing the initial cost of the exchanger by as much as 20% (Table 4.1) does not have a significant impact on LCC.

Figure 4.2 Life Cycle Cost as a function of separation



*Legend
- Cold (Low Eff): Low energy efficiency building case in a cold climate
- Warm (High Eff): High energy efficiency building case in a warm climate
- SFH: Single Family House
- MFH: Multi Family House
- HP Bore 5m: Heat pump for heating and cooling, boreholes with a 5 m separation
- HP Bore 8m: Heat pump for heating and cooling, boreholes with a 8 m separation
- HP Bore 10m: Heat pump for heating and cooling, boreholes with a 10 m separation
- HP Hor 30 cm: Heat pump for heating and cooling, horizontal exchanger with a 30 cm separation between consecutive tubes
- HP Hor 50 cm: Heat pump for heating and cooling, horizontal exchanger with a 50 cm separation between consecutive tubes
- HP Hor 80 cm: Heat pump for heating and cooling, horizontal exchanger with a 80 cm separation between consecutive tubes
- Oil/Split: Oil boiler for heating, split system for cooling
- NG/Split: Natural gas boiler for heating, split system for cooling
- Elec/Split: Electric resistance for heating, split system for cooling
- Split/Split: Split system for heating and cooling

5 Influence of the aquifer

Ground water temperatures are usually relatively stable throughout the year. So nearby aquifers tend to stabilise temperatures around ground exchangers and therefore improve their performance.

Generally quantifying the effect of aquifers on ground coupled heat pumps would be a major task as there are many variables that could have an impact on that influence. Some of these variables include:

- The size of the aquifer;
- The flow of water in the aquifer which would have an effect on its heat transfer characteristics (convection, capacity);
- The location of the aquifer.

So the following analysis is relatively simplified and should be regarded as purely qualitative; quantitative analysis would be best suited to specific system designs. It supposes a large aquifer located below the heat exchanger. This aquifer is assumed to be at a constant and uniform temperature equal to the far field temperature. It is assumed to exchange heat with the ground with a convection coefficient of 20 $W/m^2°C$.

5.1 Cases explored

The few cases studied are described in table 5.1. Prices of ground loops are presented per area of conditioned building space.

Table 5.1 Cases explored for influence of water table

Borehole heat exchangers					
Building	Climate	Energy Efficiency	Distance between bottom of boreholes and water table (m)	Ground exchanger	
				Boreholes: nX nY x Length	Cost €/m^2
Multi Family House	Cold	Low	1	4 x 3 x 113	47.71
			200	4 x 3 x 114.4	48.31
Horizontal heat exchangers					
Building	Climate	Energy Efficiency	Distance between tubes and water table (m)	Ground exchanger	
				nTubes x length	Cost €/m^2
Single Family House	Cold	Low	1	12 x 88	18.2
			2	12 x 111	22.8
			5	12 x 124	25.4
			10	12 x 118	24.3
			200	12 x 119	24.4

The computed maximum required ground exchanger size being for a water table location 5 meters below the exchanger is counter-intuitive. It can be explained by the fact that, from that distance, the water table is too far to stabilise the temperatures around the heat exchanger quick enough to influence its shorter-term performance when faced with the seasonal loads. It is close enough to remove some of the longer-term seasonal storage effect though. If an exchanger injects heat in the ground during cooling season, that heat will help it perform better during heating season. Inversely, heat extracted during the heating season helps the exchanger perform better during cooling season. The water table reducing this storage effect results in a larger exchanger being required to handle the same loads while keeping the EWT above the design temperature (-5° C in that case).

Therefore, there is a range of locations at which the presence of a water table is detrimental to the performance of a ground exchanger. Figure 5.1 presents the minimum EWT (heat pump Entering Water Temperature) encountered for 12 x 118.5 exchangers as a function of water table distance. As can be seen, for the conditions (ground, water table temperature and heat transfer characteristics, loads, etc…) simulated, that range is from 2.8 to 8 meters. Generalising where that range is located for all conditions would be a major study that would exceed the scope of this study.

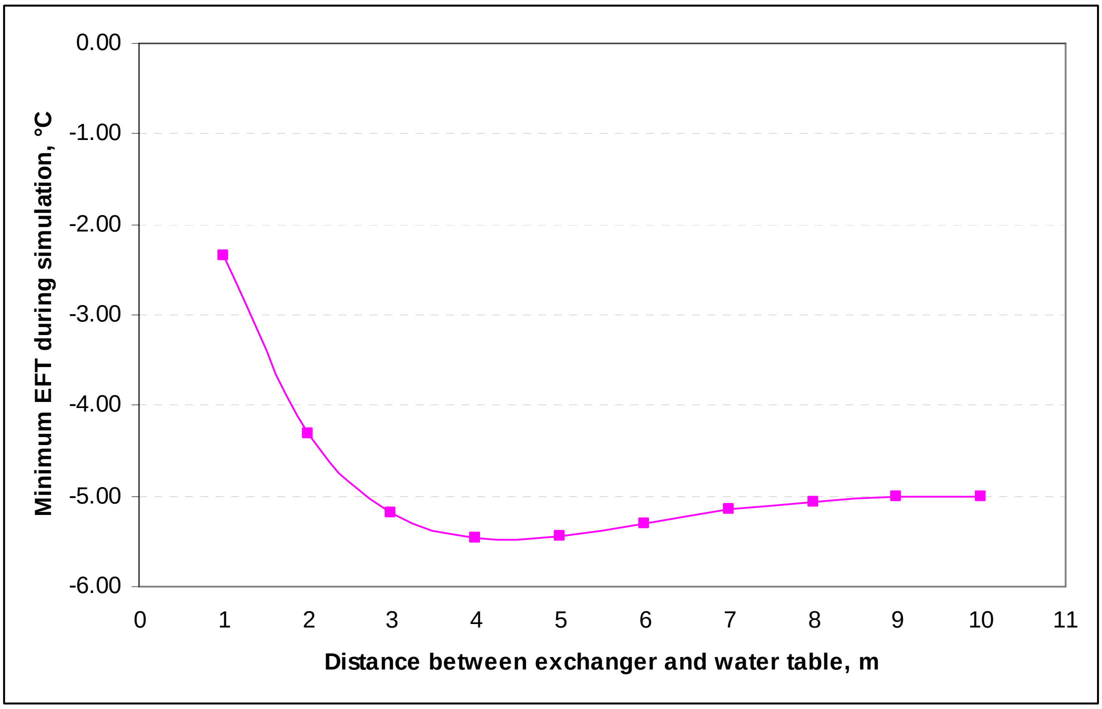


Figure 5.1 Minimum EWT as a function of water table location

5.2 Simulation Results

Figure 5.2 and 5.3 present the energy consumption and life cycled cost of the systems presented in Table 5.1. The water table location does not have much influence on the energy consumption of the systems since the systems are designed to perform according to specifications in their respective conditions.

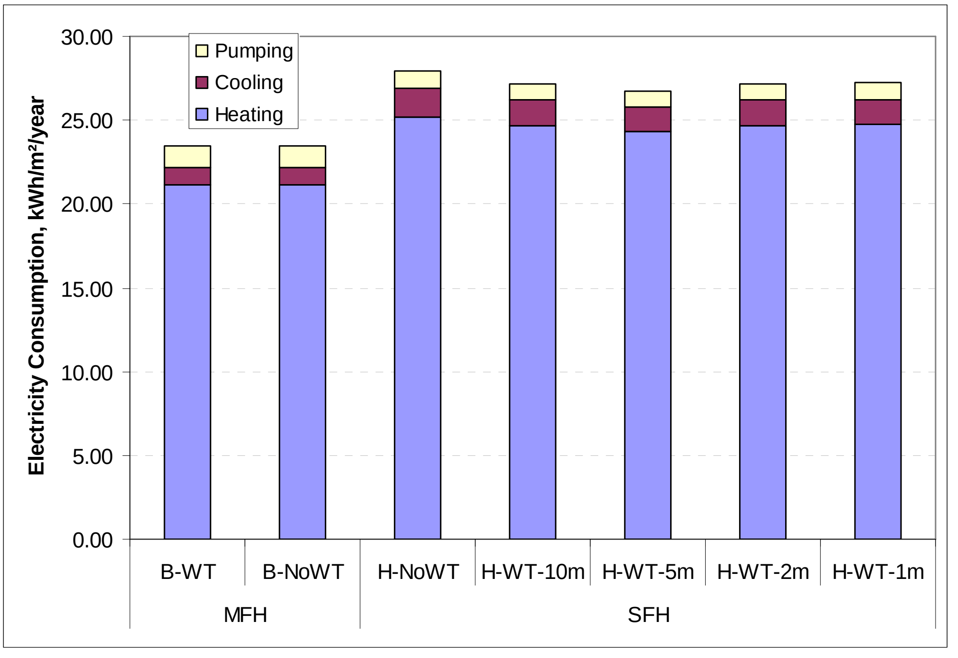


Figure 5.2 Energy consumption of GCHP systems with aquifers

Similarly, the considerable differences in ground loop costs from Table 5.1 do not have a large impact on the life cycle costs of the considered heat pump systems. These systems can be assumed to have the same performance when compared with fossil or electricity based conventional systems.

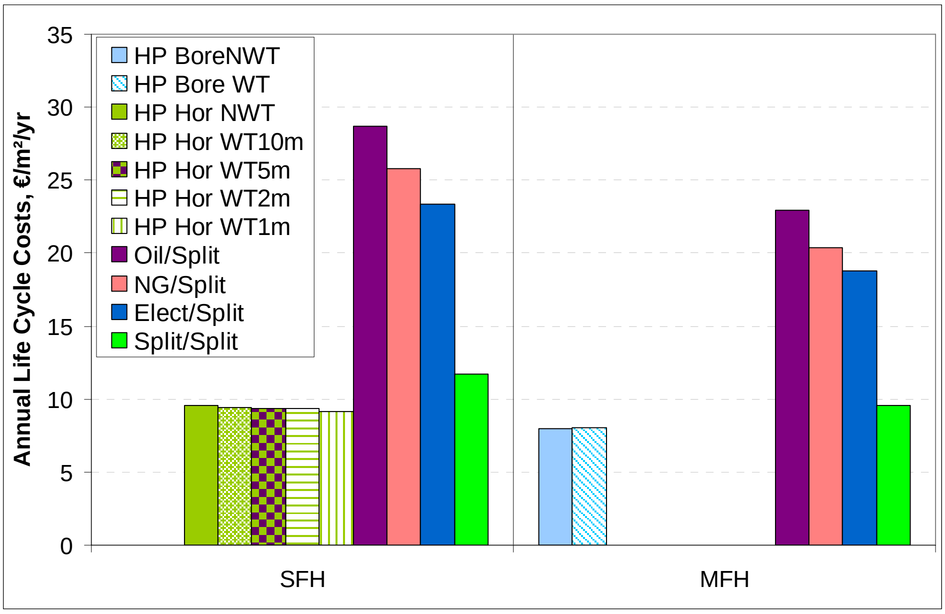


Figure 5.3 Life cycle costs of systems with aquifers

*Legend
- SFH: Single Family House
- MFH: Multi Family House
- HP Bore NWT: Heat pump for heating and cooling, boreholes with no water table
- HP Bore WT: Heat pump for heating and cooling, boreholes with water table close to bottom
- HP Hor NWT: Heat pump for heating and cooling, horizontal exchanger with no water table
- HP Hor WT 10m: Heat pump for heating and cooling, horizontal exchanger with water table located 10 m below the exchanger
- HP Hor WT 5m: Heat pump for heating and cooling, horizontal exchanger with water table located 5 m below the exchanger
- HP Hor WT 2m: Heat pump for heating and cooling, horizontal exchanger with water table located 2 m below the exchanger
- HP Hor WT 1m: Heat pump for heating and cooling, horizontal exchanger with water table located 1 m below the exchanger
- Oil/Split: Oil boiler for heating, split system for cooling
- NG/Split: Natural gas boiler for heating, split system for cooling
- Elec/Split: Electric resistance for heating, split system for cooling
- Split/Split: Split system for heating and cooling

6 Influence of neighboring geothermal exchangers

There are certain discussions at the moment, in regions like Sweden where ground coupled heat pumps are widely used, about the impact of the density of systems on heat accumulation/depletion of the ground. If many neighbors install geothermal exchangers, these exchangers may eventually interact thermally affecting their long term performance, especially if the loads are unbalanced.

6.1 Cases explored

The present analysis concentrates on single family houses in Sweden. One, two (1 on each side), and three (1 on each side and one in the back) neighboring systems are considered. These neighboring systems and their loads are assumed to be identical to the one explored so the boundaries located midway between the studied system and its neighbor(s) are considered adiabatic. The dimensions of each system/house yard, which has an effect on the distance between systems, is also considered. All exchangers are boreholes. Table 6.1 summarizes the case simulated.

Table 6.1 Cases explored for influence of system density

Borehole heat exchangers					
Building	Climate	Neighbours	Yard Length m	Ground exchanger	
				Boreholes: nX nY x Length	Cost €
Single Family House Low energy efficiency	Cold	0	NA	2 x 1 x 79.9	55.29
		1	15	2 x 1 x80.6	55.74
			20	2 x 1 x 80	55.36
			25	2 x 1 x 79.9	55.29
		2	15	2 x 1 x 82.5	56.96
			20	2 x 1 x 81.1	56.06
			25	2 x 1 x 80.3	55.55
		3	15	2 x 1 x 83.9	57.86
			20	2 x 1 x 81.8	56.51
			25	2 x 1 x 80.3	55.55

Since there are two boreholes assumed to be distant from 8 meters in that system, the separation is subtracted from the yard dimension to evaluate the location of the adiabatic boundary. For example, for a 15 m yard, the boundary is located at a distance (15 – 8)/2 = 3.5 m from the last borehole. For neighbor systems in the back (3rd neighbor), the boreholes are assumed to be located in the center of the yard and the distance to the boundary is 15/2 = 7.5 m.

6.2 Simulations results

Figure 6.1 shows the calculated heat pump system electricity consumption values. As for the previous cases studied, the redesigned systems energy consumption values are very similar to the those of the original heat pump system.

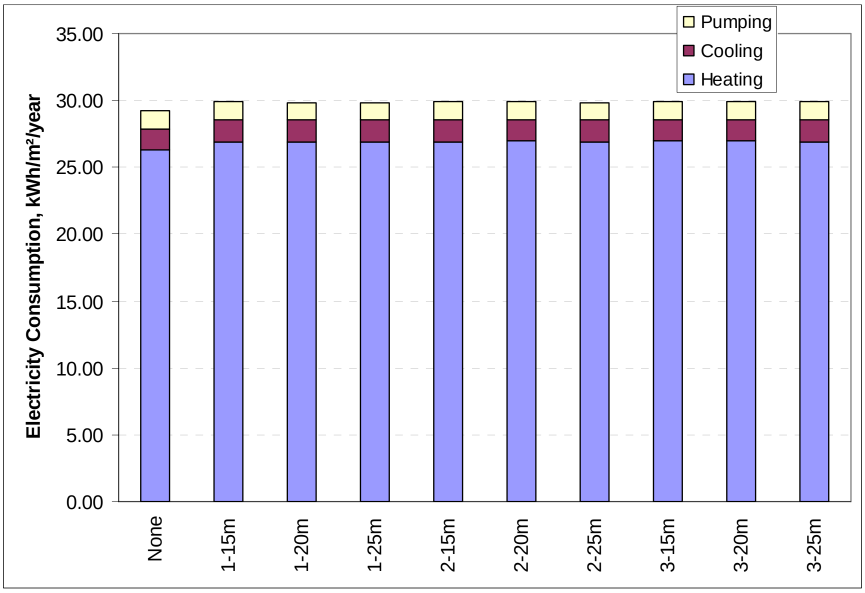


Figure 6.1 Electricity consumption of heat pump systems with neighbors

Computed annual life cycle costs are presented in Figure 6.2. As can be seen, the redesign of the systems has very little impact on LCC even if it has a certain impact on the initial system cost.

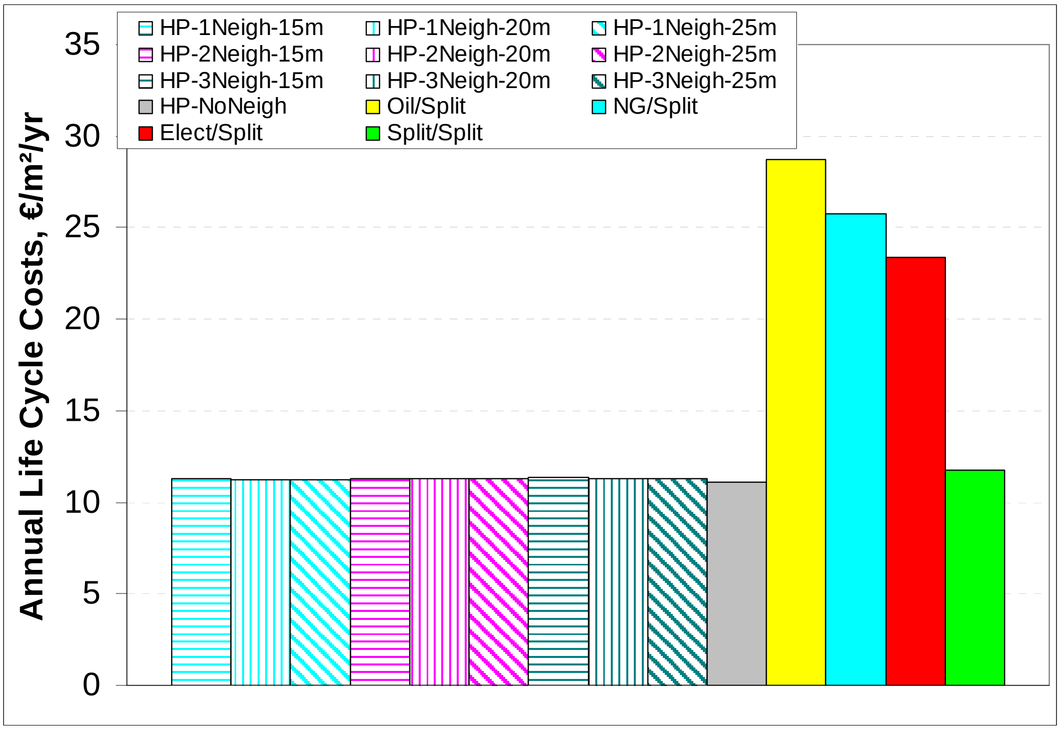


Figure 6.2 Impact of neighbor systems on life cycle cost

*Legend
- HP-1Neigh-15m: Heat pump for heating and cooling, 1 neighbour system, 15 m backyard
- HP-1Neigh-20m: Heat pump for heating and cooling, 1 neighbour system, 20 m backyard
- HP-1Neigh-25m: Heat pump for heating and cooling, 1 neighbour system, 25 m backyard
- HP-2Neigh-15m: Heat pump for heating and cooling, 2 neighbour systems, 15 m backyard
- HP-2Neigh-20m: Heat pump for heating and cooling, 2 neighbour systems, 20 m backyard
- HP-2Neigh-25m: Heat pump for heating and cooling, 2 neighbour systems, 25 m backyard
- HP-3Neigh-15m: Heat pump for heating and cooling, 3 neighbour systems, 15 m backyard
- HP-3Neigh-20m: Heat pump for heating and cooling, 3 neighbour systems, 20 m backyard
- HP-3Neigh-25m: Heat pump for heating and cooling, 3 neighbour systems, 25 m backyard
- Oil/Split: Oil boiler for heating, split system for cooling
- NG/Split: Natural gas boiler for heating, split system for cooling
- Elec/Split: Electric resistance for heating, split system for cooling
- Split/Split: Split system for heating and cooling

7 Influence of space conditioning distribution system

The nature of the heat/cold distribution system also has an impact on the performances of the space conditioning systems. For example, heat pumps tend to demonstrate lower performance factors when producing heat at higher temperatures. This is particularly important for retrofitting of systems as the designer often does not have a choice but to work with the distribution system already in place.

7.1 Cases explored and assumptions

The following analysis is concerned with the effect of producing heat at a higher temperature. This higher temperature heat is also used to produce domestic hot water in some cases. Only cases of low efficiency residential (single and multi family) buildings in a cold climate and high efficiency buildings in a warm climate are studied. Table 7.1 describes the cases compared.

Table 7.1 Cases studied for high temperature distribution

Heating System	DHW System
HP ($T_{Heat} \approx 30°C$)	Electric tank
	Tankless NG
HP ($T_{Heat} \approx 60°C$)	Heat Pump
	Electric tank
	Tankless NG
NG Boiler	Boiler
	Electric tank
	Tankless NG
Oil Boiler	Boiler
	Electric tank
	Tankless NG
Electricity	Electric tank
	Tankless NG
Split System	Electric tank
	Tankless NG

All heat pump systems are assumed to use borehole heat exchangers as a heat source. Tankless (on demand) hot water systems are assumed to have an efficiency factor of 0.8 while systems with tanks are assumed to have an energy factor of 0.9.

According to Figure 19 of Ground-Reach Deliverable 1 (Lindner & Bhar, 2007), the mean hot water consumptions per capita is 102 l/day/person in Sweden and 7 l/day/person in Greece. This yields 853 l/year in Sweden and 87 l/year in Greece of hot water consumption per square meter of conditioned space since the occupancies in the residential sector for these countries are respectively 0.0229 and 0.0339 occ/m² according to section A.I.1.3 of Deliverable 7.

Energy consumption of conventional hot water systems is evaluated using the relationship:

$$Q_{DHW} = \frac{\dot{q}_w \rho_w Cp_w \left(T_{setpoint} - T_{tap}\right)}{1000 \times EF}$$

Where: $\dot{q}_w$ is the hot water consumption (l/year), EF is the energy factor of the system, ρ_w is the density (1000 kg/m^3) of the water and Cp_w is its specific heat (4.186 kJ/kg°C). The setpoint temperature is assumed to be 60°C while the incoming tap water temperature is assumed to be the average ambient temperature (5.31°C in Sweden and 17.61°C in Greece). This results in the following energy consumption for the conventional systems studied:

- 67.8 kWh/m²/year of natural gas for tankless heaters in Sweden
- 5.32 kWh/m²/year of natural gas for tankless heaters in Greece
- 60.2 kWh/ m²/year of electricity consumption for heaters with tanks in Sweden
- 4.73 kWh/ m²/year of electricity consumption for heaters with tanks in Greece

For dynamic simulations of high temperature heat pumps producing domestic hot water, the following consumption schedules from VDI 6002 (2007) are used. Note that the 100% value on these charts corresponds to 0.2405 l/hr/m^2 for Sweden 0.0244 l/hr/m^2 for Greece.

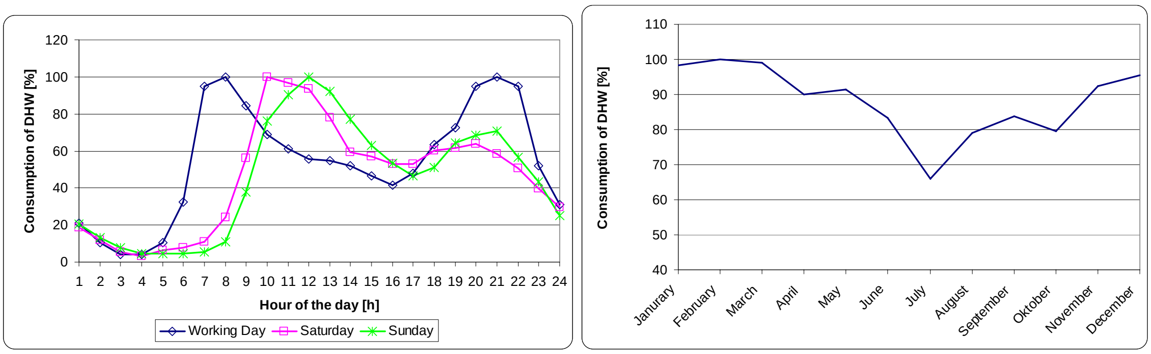


Figure 7.1 Domestic hot water consumption schedule: daily (left) and annual (right)

Table 7.2 presents the borehole systems designed for each heat pump system simulated. It is interesting to note that, for the same heating loads, the high temperature systems require shorter boreholes for space heating. This can be explained by the fact that the high temperature systems being less efficient, they transform more electricity in heat and therefore require less heat from the ground.

Table 7.1 Designed borehole heat exchangers

Building	Climate	Energy Efficiency	Distribution System	Ground exchanger	
				Boreholes: nX nY x Length	Cost €/m²
Single Family House	Cold	Low	Low Temperature	2 x 1 x 79.9	55.3
			High Temperature	2 x 1 x 70.4	49.2
			High Temperature + DHW	2 x 1 x 95.7	65.4
	Warm	High	Low Temperature	2 x 1 x 73.8	51.4
			High Temperature	2 x 2 x 68.9	48.2
			High Temperature + DHW	2 x 1 x 73.8	51.4
Multi Family House	Cold	Low	Low Temperature	4 x 3 x 114.4	48.3
			High Temperature	4 x 3 x 92.9	39.3
			High Temperature + DHW	4 x 3 x 132.9	56.0
	Warm	High	Low Temperature	3 x 3 x 78.1	25.0
			High Temperature	3 x 3 x 72.3	23.1
			High Temperature + DHW	3 x 3 x 76.6	24.5

7.2 Simulations Results

Figure 7.2 presents the energy consumptions per area of conditioned space for the different systems studied. As can be seen by comparing the HPL-NG and HPH-NG bars in the cold climate, more electricity is required from the heat pump for the higher distribution temperature.

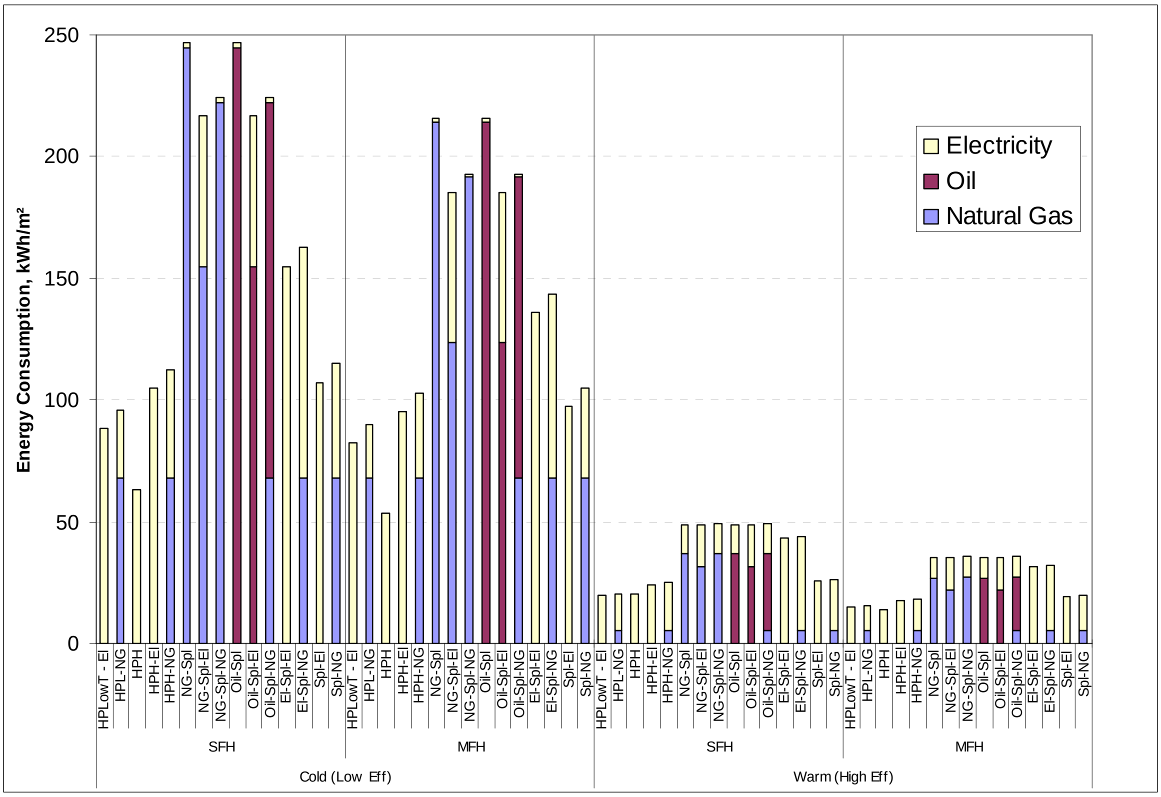


Figure 7.2 Energy consumption by source for production of space heating and DHW

*Legend

Code	Heating	Distribution Temperature	Cooling	DHW
HPL-EL	Heat Pump	Low	Heat Pump	Electric tank
HPL-NG	Heat Pump	Low	Heat Pump	Natural Gas tankless
HPH	Heat Pump	High	Heat Pump	Heat Pump
HPH-El	Heat Pump	High	Heat Pump	Electric tank
HPH-NG	Heat Pump	High	Heat Pump	Natural Gas tankless
NG-Split	Natural gas boiler		Split	Boiler
NG-Split-El	Natural gas boiler		Split	Electric tank
NG-Split-NG	Natural gas boiler		Split	Natural Gas tankless
Oil-Split	Oil boiler		Split	Boiler
Oil-Split-El	Oil boiler		Split	Electric tank
Oil-Split-NG	Oil boiler		Split	Natural Gas tankless
El-Split-El	Electric resistance		Split	Electric tank
El-Split-NG	Electric resistance		Split	Natural Gas tankless
Split-El	Split		Split	Electric tank
Split-NG	Split		Split	Natural Gas tankless

Figures 7.3 and 7.4 present the CO_2 emissions and primary energy consumption. As can be seen, producing higher temperature heating water as well as DHW with the heat pump is beneficial from an environment standpoint in Sweden where hot water consumption is high and electricity is relatively clean. In Greece, where electricity is not as clean, it could be preferable to produce lower temperature heating water and complement with an individual DHW unit. In every cases, heat pump systems outperform compared systems from the environmental perspective.

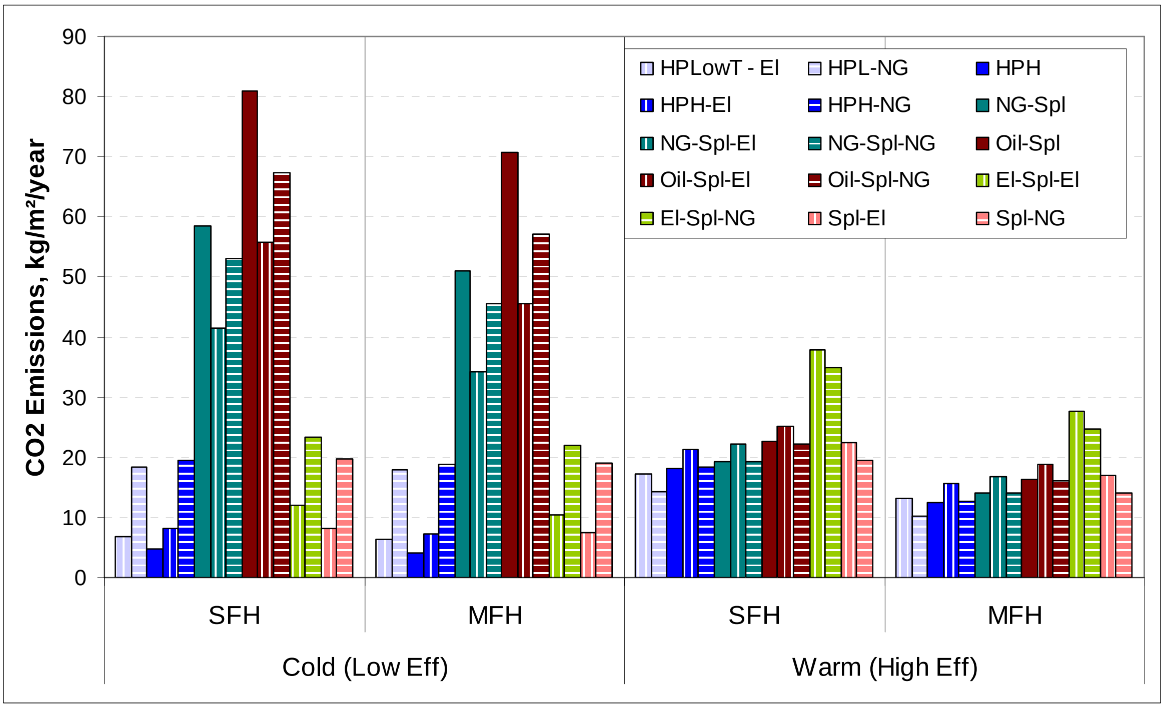


Figure 7.3 CO_2 emissions for space conditioning and DHW production

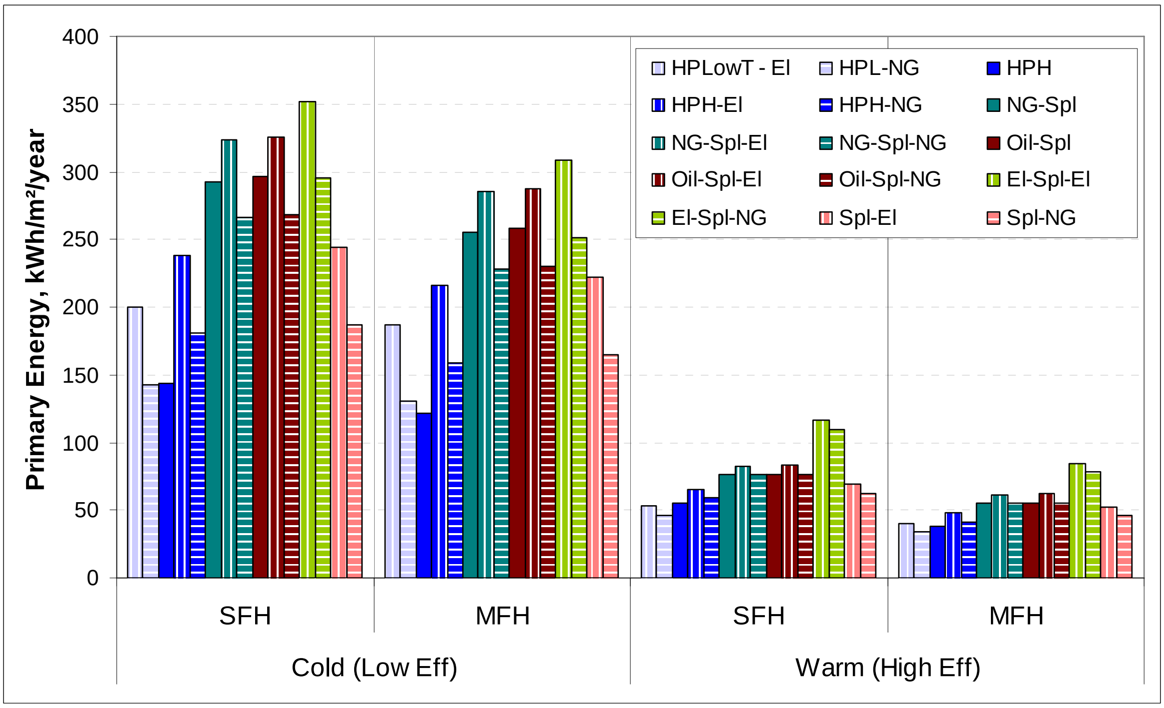
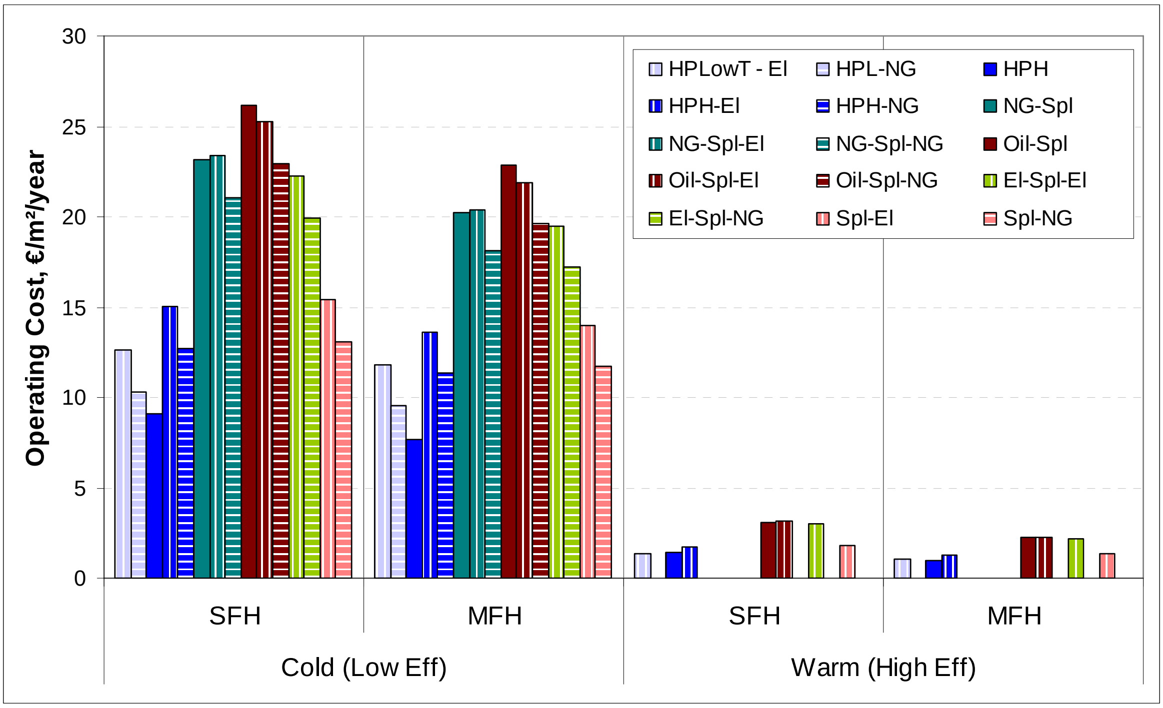
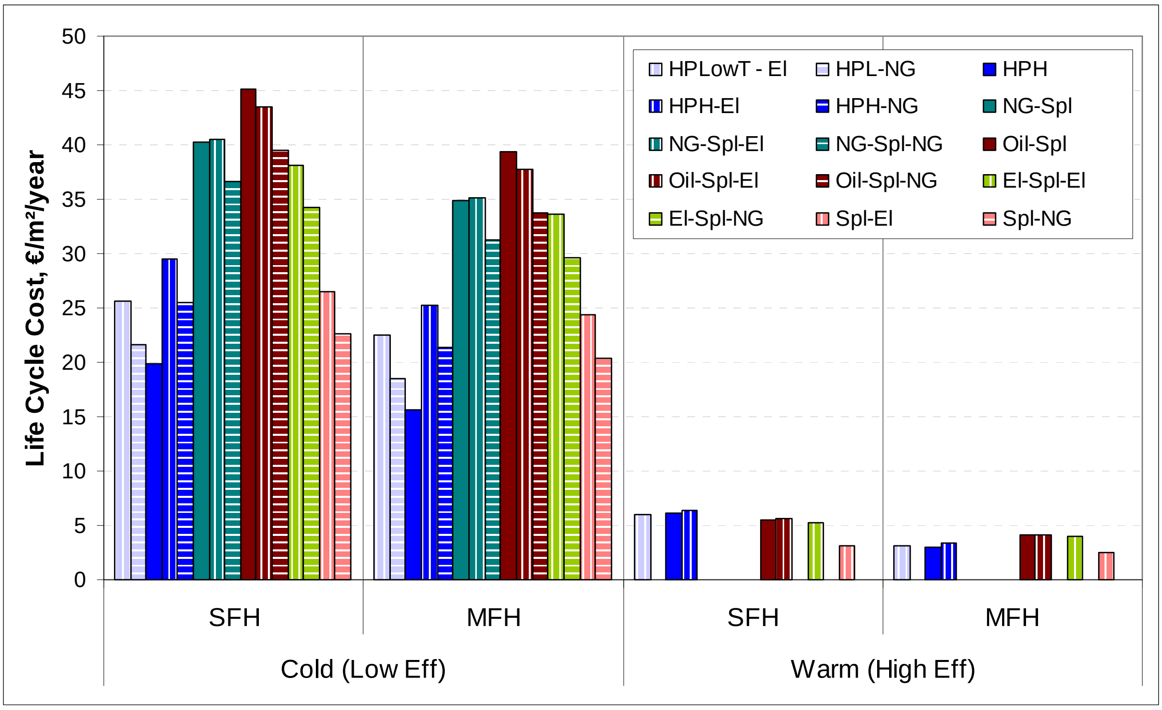


Figure 7.4 Primary energy consumption for space conditioning and DHW production

Figures 7.5 and 7.6 present the operating and life cycle costs for operating these systems per area of conditioned space. Note that no costs for systems using natural gas are presented since there is no significant market in Greece.



7.5 Operating cost for space conditioning and DHW production



7.6 Life cycle cost for space conditioning and DHW production

In Sweden, producing domestic hot water from the heat pump would present advantages from the economic perspective. Producing heating at a higher temperature without also producing DHW from the heat pump would be disadvantageous when compared to a heat pump with lower distribution temperature though.

In Greece, it would seem that the most advantageous systems would be heat pumps from an operating cost perspective and split systems complemented with an individual DHW system from the LCC perspective. This can be explained by the low initial cost of split systems, the low consumption of DHW and the low cost of energy in Greece.

8 Design guidelines

The present work explored the influence of project site specific parameters which can affect the performances of ground coupled heat pump systems. The goal of this work was to identify situations where heat pumps systems are most efficient in order to promote their use where they make the most sense.

Ground properties:

If the system is well designed for the ground at the site where it is installed, thermal properties of the ground will not influence its performances, only its initial cost. Higher thermal conductivity or thermal inertia of the ground were shown to reduce required geothermal exchanger size and cost. Results indicate that there is no significant variation of life cycle cost for ground thermal conductivities above 2 W/mºC; for thermal conductivities below that value, the life cycle cost increases as conductivity decreases.

Space available for the ground exchanger:

Simulations were performed for borehole systems and horizontal exchangers by varying the distance between tubes/boreholes. Systems coupled to horizontal ground exchangers exhibited lower life cycle costs and lower energy consumption (better environmental performance) than those coupled to boreholes for the cases studied. Reducing the distance between boreholes/tubes in order to reduce occupied space results in higher required initial system costs but not sufficiently to have a considerable impact on the LCC.

Water table:

Simulations demonstrated that the presence of a water table nearby has an influence on the performance of the ground exchanger and therefore the entire system. That influence showed beneficial for water tables very close to the exchanger and detrimental for water tables at a certain distance. Evaluating all exact situations where water tables have positive or negative impacts would be a major work exceeding the scope of the current report. Suffice to say that this influence was shown to have little effect on life cycle cost and performance of the system if this system is well designed.

Neighboring ground exchanger:

The presence of another ground coupled system nearby was shown to result in a slightly larger exchanger being required to perform the space conditioning task; and therefore in higher investment cost. This higher initial cost was shown to be insufficient to result in a considerable impact on the life cycle cost.

Nature of the distribution system:

The production of higher temperature heat to supply a higher temperature distribution system was shown to reduce heat pump efficiency, resulting in higher CO_2 emissions, primary energy consumption and operating costs. Nevertheless, the production of such high temperature heat for the dual heating/DHW purpose was shown to be the most environmentally friendly and cheapest solutions explored for Sweden. For Greece, this solution was almost on par with lower temperature heat pumps for CO_2 emissions, primary energy consumption and operating costs while split systems with individual DHW systems displayed lower life cycle costs.

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Project Description

The GROUND-REACH project is expected to effectively assist EU policy towards both short and long term market penetration of ground coupled heat pumps, through analysing the market for ground coupled heat pumps and providing best practices, guidelines for local/regional authorities and key professional groups, conferences, meetings, website, brochure and other promotional tools. It will facilitate: A better understanding of ground coupled heat pumps merits and benefits and their importance towards Community policy objectives in relation to Kyoto targets and the buildings performance directive. An increased awareness and improved knowledge and perception of the ground coupled heat pumps technology among key European professional groups for short term market penetration.

The work is grouped in the following work packages:

WP#1 – Project management

WP#2 - Estimating the potential of ground coupled heat pumps for reducing CO_2 emissions and primary energy demand for heating and cooling purposes in the built environment: evaluation of available statistical information, definition of competing heating/cooling technologies, analysis of existing calculation tools, CO_2 emissions calculation.

WP#3 - Compiling and evaluating existing ground coupled heat pumps best practice information in Europe: identifying and updating information from all European member states, including case studies, and technical guidelines.

WP#4 - Analysing the contribution of ground coupled heat pump technologies to reach the objectives of the Buildings Performance Directive: Analysis of the technical, environmental and economic feasibility of ground coupled heat pump technologies; Guideline for supporting planners and architects in detailed technical aspects and in general questions; Standards review, evaluation and proposals.

WP#5 - Defining measures to overcome barriers for broader market penetration and setting up a long term dissemination plan: identification of market barriers including legal/ regulatory, economical and technical, proposals for long term EU level interventions to overcome them, including a new directive on RES-Heat.

WP#6 - Launching a large scale promotional campaign at European level: brochure, poster, promotional text, presentations, interactive Internet site, setting-up the European Geothermal Heat Pump Committee, publications, international conference and exhibition, a series of regional meetings targeting key professional groups.

WP#7 - Common dissemination activities

Project partners

Project Coordinator: Centre for Renewable Energy Sources (CRES)

SVEP Information & Service AB (SVEP)

Ecofys Netherlands b.v. (ECOFYS)

Cestec SpA

European Geothermal Energy Council (EGEC)

University of Oradea (UOR)

The Energy Efficiency Agency (EEA)

Agence de l'environnement et de la Maîtrise de l'energie (ADEME)

European Heat Pump Association (EHPA)

BESEL S.A. (BESEL)

Escola Superior De Tecnologia De Setubal (ESTSetubal)

Narodowa Agencja Poszanowania Energii S.A. (NAPE)

Österreichisches Forschungs- und Prüfzentrum Arsenal Ges.m.b.H (ARSENAL)

COWI A/S (COWI)

Ellehauge & Kildemoes (E & K)

Fachinformationszentrum Karlsruhe G mbH

EnPro Engineers Bureau Ltd (ENPRO)

Bureau de Recherches Géologiques et Minières (BRGM)

Flemish Institute for Technological Research (VITO)

Geoteam Technisches Büro für Hydrogeologie, Geothermie und Umwelt Ges.m.b.H (GEOTEAM)

TERA Energy S.r.l. (TERA)