INTERNATIONAL HELLENIC UNIVERSITY

Modeling a hybrid GSHP – PV system for a house

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

November 2013

THESSALONIKI – GREECE

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Abbreviations

AC	Alternating Current
A/C	Air Condition
BHE	Borehole Heat Exchanger
COP	Coefficient of Performance
DC	Direct Current
DHW	Domestic Hot Water
DST	Duct Storage
EER	Energy Efficiency Ratio
FDM	Finite Difference Method
GCHP	Ground Coupled Heat Pump
GHE	Ground Heat Exchanger
GHP	Geothermal Heat Pump
GHX	Ground Heat Exchanger
GSHP	Ground Source Heat Pump
GWHP	Groundwater Heat Pump
HGSHP	Hybrid Ground Source Heat Pump
HP	Heat Pump
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilation and Air Conditioning
MPP	Maximum Power Point
NOCT	Nominal Operating Cell Temperature
NZEB	Net Zero Energy Building
NZEH	Net Zero Energy Home
NPV	Net Present Value
PPC	Public Power Corporation

PV	Photovoltaic
PVT	Photovoltaic Thermal
SRC	Standard Rating Conditions
ST	Solar Thermal
SWHP	Surface Water Heat Pump
TESS	Thermal Energy Systems Specialists
TMY	Typical Meteorological Year
VC	Vapour Compression
ZNEH	Zero Net Energy Home
ZERB	Zero Energy Residential Building

Nomenclature

Financial analysis

A	total external surface area of the building
A_j	surface area of the construction element j
AS_{it}	alternative heating/cooling source cost not paid in year t
CF_t	cash flow in year t
C_{OMt}	annual cost for operation and maintenance of the system
E_{oil}	heating energy needed from the oil to heat the house
E_c	annual cooling energy needed from the A/C
$E_{el,c}$	annual electric energy needed to operate the A/C in cooling mode
$E_{el,h}$	annual electric energy needed to operate the HP in heating mode
E_h	annual heating energy needed from the HP
N	life of the system
n	Total number of construction elemetns
n_b	efficiency of the boiler
P_{gen}	maximum heating power needed form the boiler to heat the house
P_{oil}	maximum heating power needed from the oil to heat the house
PV_{it}	income from the excess energy produced from the PV array in year t
r	discount rate
U_j	thermal transmittance of the construction element j

U_m	average thermal transmittance of the whole building surface
ΔT	temperature difference for the dimensioning of the boiler system

Type 504b: Water Source Heat Pump

$C_{p,a}$	specific heat of air
$C_{P,fl}$	specific heat of the heat transfer fluid
$F_{a,fr}$	fraction of fresh air entering the heat pump
Fl_a	air flow rate
Fl_{fl}	flow rate of the heat transfer fluid
$h_{a,fr}$	fresh air enthalpy
$h_{a,in}$	entering air enthalpy
$h_{a,out}$	outlet air enthalpy
$h_{a,re}$	return air enthalpy
$P_{a,in}$	inlet air pressure
$P_{a,out}$	outlet air pressure
ΔP_{HP}	pressure rise through the heat pump
Po_{bl}	power of the blower of the heat pump
Po_{comp}	power of the compressor of the heat pump
Po_{cont}	power of the controller of the heat pump
Po_{HP}	power of the heat pump from the data files
$Q_{fl,abs}$	heat absorbed from the heat transfer fluid
$Q_{fl,rej}$	heat rejected in the heat transfer fluid
$Q_{Lat,C}$	latent heat of the air, in cooling mode
$Q_{Sens,C}$	sensible heat transfer from air, in cooling mode
$Q_{Tot,C}$	total heat transfer from air, in cooling mode
$Q_{Tot,H}$	total heat transfer to air, in heating mode
$T_{fl,in}$	heat transfer fluid inlet temperature

$T_{fl,out}$	heat transfer fluid outlet temperature
$w_{a,fr}$	fresh air humidity ratio
$w_{a,in}$	entering air humidity ratio
$w_{a,out}$	outlet air humidity ratio
$w_{a,re}$	return air humidity ratio

Type 557a: Vertical Ground Heat Exchanger

A_p	cross sectional area of the ground region of a ground heat exchanger
B	duct spacing
C	volumetric heat capacity
C_f	volumetric heat capacity of the fluid
$C(i,j)$	heat capacity of cell (i,j)
E_k	amount of injected to a subregion k in the local problem
$F_r(i,j)$	radial heat flow between cell $(i-1,j)$ and (i,j)
$F_z(i,j)$	vertical heat flow between cell $(i-1,j)$ and (i,j)
$K_r(i,j)$	radial heat conductance between cell $(i-1,j)$ and (i,j)
$K_z(i,j)$	vertical heat conductance between cell $(i-1,j)$ and (i,j)
l	a characteristic heat transfer length between the fluid in the pipe and the surrounding ground
L_p	total pipe length in the storage volume
q	constant heat injection rate
q_{fp}	fluid flow rate, in respect to a heat balance per unit length of pipe
q_{fv}	fluid flow rate, in respect to a heat balance of a unit volume in the storage
q_l	heat source term used to transfer heat from the local to the global problem

q_{sf}	heat source term used to transfer heat from the steady-flux problem to the global problem
Q	total heat injection
Q_f	total fluid flow rate
$Q_l(i,j)$	net contribution from the local heat source to cell (i,j)
$Q_{sf}(i,j)$	net contribution from the steady flux heat source to cell (i,j)
r	radial distance from the center of a pipe
r_1	radial distance from the center of a pipe to the boundary of the ground region
r_b	the pipe outer radius
R_b	total thermal resistance, per unit length of the pipe, between the fluid and the ground at r_b
s	length coordinate along the flow path
t	time
t_g	global time-step
Δt	time step
$T(i,j)$	Temperature in cell (i,j)
T_α	the surrounding ground temperature
T_c	constant initial temperature in the cylindrical region around the pipe
$T_f(t)$	fluid temperature
T_{fin}	fluid inlet temperature
T_{fout}	fluid outlet temperature
T_g^k	mean global temperature in subregion k
T^k	average temperature of a local cell, immediately outside subregion k
T_l	local temperature
$T_m(t)$	mean temperature
T_{sf}	fluid temperature used in the steady-flux part

ΔT_g	temperature increase in subregion k of the global solution
V	storage volume
V_k	volume of subregion k
$V_{k,j}$	volume of the gobal cell j in subregion k
α	thermal diffusivity
α_p	the heat transfer coefficient between the fluid and a point in the surrounding ground, in respect to a heat balance per unit length of pipe
α_v	the heat transfer coefficient between the fluid and a point in the surrounding ground, in respect to a heat balance of a unit volume in the storage
β	damping factor
λ	thermal conductivity

Type 3b: Variable Speed Pump

C_p	is the specific heat of the fluid
F_{par}	is the fraction of the pump power converted to fluid thermal energy
$\dot{m}$	is the pump mass flow rate
$\dot{m}_{\max}$	is the maximum flow rate (when $\gamma = 1$)
P	is the power consumption of the pump
P_{max}	is the maximum power consumption (when $\gamma = 1$)
T_i	is the inlet fluid temperature
T_o	is the outlet fluid temperature
γ	is the control function ($0 \le \gamma \le 1$)

Type 696b: Air Stream Conditioning Device

h_{in}	enthalpy of air entering the conditioning device
h_{out}	enthalpy of air exiting the conditioning device, before any possible reheating
h_{reheat}	enthalpy of air exiting the conditioning device, after possible reheating
HFG	latent heat of vaporization for water
$\dot{m}_{air}$	mass flow rate of air entering the conditioning device
P_{in}	pressure of air entering the conditioning device
P_{out}	pressure of air exiting the conditioning device
ΔP	pressure drop of air as it passes through the conditioning device
$\dot{Q}_{lat,cool}$	latent cooling energy transferred from the air stream
$\dot{Q}_{reheat}$	energy used to reheat the air stream after dehumidification
$\dot{Q}_{tot,cool}$	total cooling energy transferred from the air stream
$\dot{Q}_{tot,heat}$	total heating energy transferred to the air stream
ω_{in}	humidity ratio of air entering the conditioning device
ω_{out}	humidity ratio of air exiting the conditioning device

Type 194: Photovoltaic Array

a	modified ideality factor
a_{ref}	modified ideality factor at reference conditions
E_g	material band gap
G_T	insolation on module
I	current
I_L	light current
$I_{L,ref}$	light current at reference conditions

I_{mp}	current at the maximum power point along the I-V curve
$I_{mp,ref}$	current at the maximum power point along the I-V curve, reference conditions
I_o	diode reverse saturation current
$I_{o,ref}$	diode reverse saturation current at reference conditions
I_{sc}	short circuit current
$I_{sc,ref}$	short circuit current at reference conditions
k	Boltzmann constant
K	glazing extinction coefficient
$K_{\tau\alpha}$	incidence angle modifier
L	glazing thickness
M	air mass modifier
M_{ref}	air mass modifier at reference conditions
n	effective index of refraction of the cell cover
N_s	number of cells in series within a module
n_i	diode ideality factor
q	electron charge constant
R_s	module series resistance
$R_{s,ref}$	module series resistance at reference conditions
R_{sh}	module shunt resistance
$R_{sh,ref}$	module shunt resistance at reference conditions
S	absorbed solar irradiance
S_{ref}	absorbed solar irradiance at reference conditions
T_a	ambient temperature
T_c	module temperature
$T_{c,ref}$	module temperature at reference conditions
T_{ref}	the reference temperature

U_L	module loss coefficient
V	voltage
V_{mp}	voltage at maximum power point along the I-V curve
$V_{mp,ref}$	voltage at maximum power point along the I-V curve, reference conditions
V_{oc}	open circuit voltage
$V_{oc,ref}$	open circuit voltage at reference conditions
$V_{oc,Tc}$	open circuit voltage at some cell temperature
α	module absorptance
α_{Isc}	temperature coefficient of the short circuit current
β_{Voc}	temperature coefficient of the open circuit voltage
η	module electrical efficiency
θ	angle of incidence for solar radiation
θ_r	angle of refraction
θ_z	local zenith angle
τ	module transmittance

Type 48a: Inverter

eff_i	efficiency of the inverter
P_A	power from solar cell array
P_D	power demanded by load
P_L	power sent to load from PV through the inverter
P_U	power supplied by, or fed back to the utility

1 Introduction

The aim of this project is to perform a parametric study of a ground source heat pump (GSHP), covering the heating/cooling demand of a single-family residential building in the four climatic zones of Greece, and of a photovoltaic (PV) system, covering the electricity load of the GSHP. The software used for this study is the simulation program TRNSYS 16.

The house is connected to the grid and is able to sell any excess energy produced by the PV array. In case the PV array does not produce enough energy to cover the GSHP needs, the utility can supplement the energy needed. The main goal is to achieve a nearly zero energy building (NZEB) in each climatic zone, in respect to the energy needed for heating/cooling.

In that perspective, the thermal transmittance (U-Value) of the building elements is selected to be 50 [%] less than the U-Value of a B category building, according to the Greek legislation. The U-Values of the openings are determined according to existing technical capabilities. The U-Values of the building elements are different for each climatic zone.

The modeling of the building loads, the GSHP and the PV is on an hourly basis. The weather data is taken from TRNSYS data libraries, for the four climatic zones of Greece. The U-values of the building elements are considered constant for each climatic zone, while the PV and GSHP parameters are variables.

Chapter 2 contains a review of related work, regarding the operation of GSHP, it's simulation with software tools, the simulation of NZEB and several software tools used for simulation purposes.

In chapter 3 the methodology for the simulation is discussed. The tools used in the simulation are analyzed. The residential building's characteristics are reported for each climatic zone. Each model used in the simulation of the PV and the GSHP is explained and it's parameters and inputs reported.

In chapter 4 the results of the simulation for each climatic zone, are reported. These include the sensible heating and cooling capacity of the GSHP, the temperature inside the house, the COP of the GSHP and the electric power it needs to operate, also the energy the PV array produces and the energy traded with the grid are reviewed.

In chapter 5 a sensitivity analysis of the PV array power is discussed. In this analysis the PV array energy produced and the energy traded with the grid are reported.

In chapter 6 a pre-feasibility study of the GSHP-PV system is discussed. The initial costs for the installation of the system and the annual operation and maintenance costs are reported. A, NPV rule, financial study is performed, comparing the system with an oil boiler-A/C system and an air-HP system for heating and cooling.

Finally in chapter 7 the four climatic zones systems are discussed in comparison with each other, in respect of the simulation results, the sensitivity analysis and the financial study of each system.

2 Literature Review

Geothermal Heat Pumps (GHP) exploit the low temperature geothermal resources, which are abundant and can be utilized in most locations around the world. Low temperature resources are near ambient temperature and are mostly attributable to the solar energy incident on the ground and ambient air. GHPs can provide an environmentally and economically advantageous option for space heating and cooling. Stuart J. Self et al [11] explain the operation of ground source heat pumps and compare it with other heating options.

Ground Source Heat Pumps (GSHP) are comprised of three main systems:

The Geothermal Heat Pump, which moves heat between building and ground and modifies its temperature.

The earth connection that facilitates heat extraction from the ground, via a heat exchanger loop, for use in the heat pump unit.

The interior heat distribution system, which conditions and distributes heat throughout the space.

A GHP moves thermal energy between the earth and the heated space by controlling pressure and temperature by means of compression and expansion. Five major components are incorporated in a heat pump: a compressor, an expansion valve, a reversing valve and two heat exchangers.

The heat distribution system of a GHP system moves heat supplied by the heat pump throughout the space. Two main types of distribution systems exist: water to air and water to water. Water to air systems transfer thermal energy from the ground to air, which is used as the transport medium within the space, while water to water systems use water or another fluid as the heat transfer medium.

GHPs use the surrounding ground as a heat source for heating or a heat sink for cooling. The ground has a relatively constant temperature, depending on the depth, which is warmer than the ambient air during winter and cooler in summer. Earth connection or ground loop heat exchangers are comprised of a collection of pipes that transfer fluid between the heat pump unit and the ground. There are several ground loop configurations, the main categorization is:

- Double loop
    - Closed loop
        - Vertical loop
        - Horizontal loop
        - Spiral loop
        - Pond loop
    - Open loop
        - Extraction wells
        - Extraction and reinjection wells
        - Surface water systems
- Single loop

According to Stuart J. Self et al [11] the growth of GHP technology has been slower than for some other renewable and conventional energy technologies. Limited growth can be attributed to many factors including non-standardized system designs, significant capital cost compared to other systems, limited individuals knowledgeable in the installation of GHPs, limitations placed on use through government policies, and economies of scale and scope are rarely exploited.

Developments in GHP system technology are reported in the article, which are:

- Auxiliary component cooling, in which compressor and pump waste heat can be used to preheat the refrigerant within the heat pump cycle.
- Ground frost loop. In this case heat is extracted from the area around the foundation ensuring that the building does not affect the ground temperature drastically, in areas of permafrost.
- Standing column well heat exchange systems, which combine aspects of open and closed water heat exchange systems.

Geothermal heat pumps have high efficiencies, as reflected in their COPs. Typical equivalent COPs for various heating systems are the following:

- Ground source heat pumps: 3–5
- Air source heat pumps: 2.3–3.5
- Electric baseboard heaters: 1
- Mid-efficiency natural gas furnaces: 0.78–0.82
- High-efficiency natural gas furnaces: 0.88–0.97

Geothermal heat pumps have substantially higher initial costs than conventional heating systems, mainly because of the capital costs of the heat pump unit and the ground connection (including drilling or trenching). But GHPs can have low operating costs due to their high efficiencies.

GHPs do not directly emit CO_2, the emissions originate in the power plants that produce the electricity. When electricity is produced in high-emission power plants, the CO_2 emissions of GHP systems are correspondingly high. The threshold at which GHP systems become environmentally advantageous is related to the CO_2 associated with producing the electricity used by the heat pump, its COP, and the efficiency of conventional heating systems.

Stuart J. Self et al [11] conclude that Geothermal Heat Pumps are highly efficient heating technologies that allow for reductions in CO_2 emissions, the potential avoidance of fossil fuel usage and economic advantages. Heat pumps utilize significantly less energy to heat a building than alternative heating systems.

Olympia Zogou et al [9] used TRNSYS 16 simulation software in order to compare two systems. System “A” using a boiler for heating purposes and a chiller for cooling, and system “B” using a ground source heat pump (GSHP) with a horizontal ground coil.

A detailed transient simulation of the building envelope and the heating, ventilation and air conditioning (HVAC) equipment and its control is made. The building is a two store residential building with a basement. The location of the building was chosen to be in Volos, Greece. The maximum heating power for both systems was set to 11 [kW].

The TRNSYS component models used in the simulation are the following:

- Type 56, Multi-zone building.
- Type 2, ON/OFF differential controller.
- Type 3, Pump.
- Type 6, Auxiliary heater (modified).
- Type 108, Five-stage room thermostat.
- Type 54, Weather generator.
- Type 16, Solar radiation processor: total horizontal only known.
- Type 33, Psychrometrics: dry bulb and relative humidity known.
- Type 69, Effective sky temperature for long-wave radiation exchange.
- Type 68, Shading mask.

Also the following TRNSYS types belonging to the TESS library were employed:

- Type 753a, Heating coil using bypass fraction approach– free floating coil (modified).
- Type 655, Air-cooled chiller (modified).
- Type 654, Single speed pump.
- Type 556, Horizontal ground-coupled heat exchanger.
- Type 668 Water to water heat pump (modified).
- Type 501, Soil temperature profile.

The building was separated into three thermal zones. As regards the building envelope characteristics used in the building model, insulation values according to the Greek standards were inserted. Ventilation is assumed to have 0.5 air changes per hour. Internal heat gains are taken according to ASHRAE. For the sake of comparison, the building operation schedule is simplified to provide heating and cooling day and night. Both systems use fan-coils to distribute heating and cooling to the zones. For heating the room thermostat control temperature was set to 20 [^{o}C], with a tolerance of +/- 1 [^{o}C]. For cooling the room thermostat control temperature was set to 24 [^{o}C], with a tolerance of +/- 1 [^{o}C].

Climatic data in the form of a typical meteorological year (TMY) for the city of Volos are employed. Hourly values of the following data for the full TMY are employed in the simulation: Dry Bulb temperature, Relative Humidity, wind direction and speed, total and direct solar horizontal radiation.

According to the simulation results it is noted that in system “A”, during the higher temperature days, when the thermostat cycles quickly between on and off, the boiler is not allowed to stay on for enough time to reach an aqua-stat setting. As for system “B” a lot less on/off cycling is revealed during the heating period. In both systems the heating device is continuously on during the first hours, then goes in an on/off mode, unless there is a very cold day. During the cooling period the chiller has a time lag of several hours but otherwise they both have a few on/off cycles.

Also a sensitivity analysis is made in regards to boiler sizing, COP of chiller and heat pump and control setting. It is concluded that setting the thermostat in 22 [^{o}C] in system “A” increases the energy demand substantially, while the simulation does not give realistic results for the boiler oversizing. As for the chiller the thermostat setting to 26 [^{o}C] leads to the non-operation of the device. So the need for a better COP chiller in the Volos climate is questioned. As for the GSHP, better efficiency equipment is recommended in regards to the heating mode.

The article concludes that there is a need for system optimization through simulation tools and that GSHPs are preferable.

Jeff S. Haberl et al [6] explain the operation of Ground Source Heat Pumps (GSHP) and the analytical and numerical models used to calculate the Ground Heat Exchanger (GHX) performance.

In the article a reference is made to the several GSHP systems, which include:

- Ground coupled heat pump (GCHP) system, which has closed loop GHXs that circulate fluid through tubes in contact with the ground.
- Groundwater heat pump (GWHP) system, which has opened loop GHXs that circulate fluid extracted from wells in the ground or from lakes or bodies of water.
- Surface water heat pump (SWHP) system that has closed loop or opened loop GHXs.

GCHP systems, which are often called closed-loop or earth-coupled heat pump systems, have the advantage that the entire system can be located inside a house with only two added pipes connecting the heat pump (HP) to the GHX.

The GCHP system is generally classified according to two types of GHX designs: vertical and horizontal. Vertical GHXs are normally more efficient than horizontal GHXs and require less piping since the ground temperature in a vertical well is steadier than in a horizontal trench for a year. However, closed loop GHXs with a vertical well are generally more expensive than closed loop GHXs with a horizontal trench.

To design a GCHP system, ground heat exchanger model is used to calculate the return water temperature from the GHX to the heat pump. A number of simulation models for the heat transfer outside the borehole have been developed, which were based on either an analytical or a numerical methodology. Analytical solutions lack in accuracy but are faster than numerical solutions. Numerical solutions offer a high degree of flexibility with acceptable accuracy, but can be computationally inefficient.

Two analytical models are generally used for the design of GHXs:

- Kelvin's Line Source Theory is a classic solution that calculates the temperature distribution around an imaginary line. The model assumes that the borehole is a line source. In this model the soil or ground is assumed as an infinite medium with a uniform and constant initial temperature.
- Cylinder Source Solution, which treats the two legs of the U-tube as a single pipe that is co-axial with the borehole.

Both the one-dimensional model using Kelvin's theory and the cylindrical source model developed by Kavanaugh (1985) neglect the axial heat flow along the borehole depth. Therefore they can be inadequate for analyzing the long-term operation of the GCHP systems.

A number of numerical models have been developed to calculate the temperature distribution around U-tube boreholes. These numerical models have been developed to examine the nature of heat transfer around borehole heat exchangers for research purposes. Two numerical approaches are the most common:

- The g-function model developed by Eskilson (1987), in which a two-dimensional numerical calculation is used for a single borehole in homogeneous ground with constant initial and boundary temperature.
- The duct storage (DST) model developed by Hellström (1989), in which heat is stored directly in the ground. A duct or channel system is used to exchange the heat between a heat carrier fluid, which is circulated through the duct, and the storage region.

Computer simulation programs for whole-building energy analysis with GCHP models are the following:

- eQUEST/DOE-2.2 program simulates the performance of a GCHP system at a particular hour using a modified water source heat pump system simulation module. The program uses an enhanced g-function algorithm, which uses the procedures developed by Yavuzturk & Spitler (1999), for fast calculation of the borehole wall temperature.
- EnergyPlus program uses the models for the water source heat pump with ground loop heat exchanger in the whole-building GCHP annual energy simulation. This program also uses the short time step g-function developed by Yavuzturk & Spitler (1999) as the GHX model.
- TRNSYS calculates water source heat pump performance with a ground heat exchanger for its GCHP system. This program uses the DST model developed by Hellström (1989) as the ground loop heat exchanger.
- EnergyGauge USA program evaluates the GCHP system performance for residential use only.

Jeff S. Haberl et al [6] conclude that none of the abovementioned programs had well documented models, which could easily model complex building shapes with acceptable run times. Hence there is a need to develop such a model.

Guilherme Carrilho da Graca et al [5] are investigating the feasibility of a solar powered Net Zero Energy Building (NZEB) in the mild Southern European climate zone, using the EnergyPlus software, for two different types of building.

- A Passive (P) house representing an optimal passive design, with low heating and cooling requirements.
- A Glazed (G) house representing a non-passive design, with large glazed areas and inadequate shading systems, resulting in poor summer performance.

According to the article a Net Zero Energy Home (NZEH) should have the following features.

- Present low building related energy needs (adequate use of natural light and ventilation, optimal passive heating and cooling).
- Have efficient building energy systems (including domestic appliances).
- Have adequately sized renewable energy systems.

Be connected to a flexible energy infrastructure – the electrical grid must be able to exchange energy with the building.

The building examined is a 110 [m^2] single story two-bedroom detached house of a single family (four occupants). The mild southern European climate is represented by Lisbon. The energy systems used in the house include.

- The interface with the electrical grid.
- The photovoltaic (PV) electrical system, which is sized to cover all the electrical needs of the house.
- The solar thermal (ST) hot water system.
- A heat pump (HP) that provides supplemental heating and space cooling in the summer.
- All the typical domestic appliances as well as highly efficient models, such as washing machines that can use preheated water.

The main heating and cooling source is an electrically powered heat pump. Internal heat exchange is done using a heated/cooled "radiant" floor. The entrance hall and restrooms are equipped with autonomous 100 [W] electrical heaters.

According to the article both houses have good solar passive performance in winter. In the case of the glazed house the passive heating capacity leads to excessive cooling load. The energy demand for heating is of the same order of magnitude in both cases, but cooling of the G house is one order of magnitude higher than heating for either house. Since the Domestic Hot Water (DHW) needs are determined by the level of occupancy, these are the same for both houses.

A simple evaluation of the trade off between PV and ST systems in terms of cost, in [€/Wp], reveals a large advantage for the solar thermal system: the process of converting solar radiation into heat stored in water has a higher efficiency than the more complex conversion into electricity that occurs in PV systems. If an overall efficiency of 50 [%] for the solar thermal system is considered an approximate cost of 1.4 [€/Wp] is obtained, one third of the representative value used for PV systems. However, since PV generated electricity, obtained from a system that costs 3.8 [€/ Wp], is used for producing thermal energy with a heat pump with COP 2.5, the final cost of this thermal energy is 3.8/2.5 = 1.52 [€/Wp], which is just 8.6 [%] above the solar thermal system cost. As the ST system increases further, the building no longer uses all the collected thermal energy, leading to wasted solar heat (in the summer time). The seasonal mismatch between solar energy availability and thermal demand, does not affect the PV system since the grid acts as an infinite storage.

According to Guilherme Carrilho da Graca et al [5], the simple payback time for NZEB systems is highly dependent on energy costs and access to micro-generation subsidy. An analysis using Portuguese energy costs of 2011 results in payback times of 13–18 years.

A more realistic, production related energy cost, leads to financially more feasible paybacks of 8–11 years. The micro-generation subsidized scenario leads to fast paybacks that are independent of system efficiency (8–10 years).

Affouda-Leon Biaou et al [1] discuss the simulation of a Zero Net Energy Home (ZNEH) using TRNSYS 15.3 software with the IISiBat 3 interface.

According to the paper ZNEHs are energy-efficient grid-connected buildings with on-site electrical production from renewable energy sources. ZNEH supply electrical energy to the utility when there is a surplus and draws from the same grid in the case of on-site energy production shortage. The goal of a ZNEH is to have a balance, on an annual basis, between the surpluses and the shortages.

The building simulated is a two-story 156 [m^2] residential house with an unheated basement. The level of insulation is similar to that encountered in a R-2000 house which typically uses at least 30 [%] less energy than a common house. The house is located in Montreal of Quebec in Canada. It is assumed that a family of four persons who perform light work occupies the house.

The main components of the ZNEH are:

- Photovoltaic (PV) arrays for electricity generation, located on the roof with a south orientation and 45^o inclination. The PV panels area is 85.4 [m^2]
- An inverter that transforms the direct current delivered by the PV array into alternative current required by the load.
- The local electric grid.
- A 2.5 tons ground source heat pump (GSHP) for space heating and cooling, with a closed-loop ground heat exchanger (GHE) inserted into a borehole.
- A desuperheater (included in the heat pump) for domestic water preheating.
- A regular 210 [liters] (1.5 [m] high) electrical hot water tank.
- The electric appliances of the house and the lights.

Component simulation models come from three sources, the TRNSYS standard models, models built in-house for this project and models from the TESS library. These models are:

- TRNSYS's Type 56 for the house. The house is separated in three thermal zones living quarters, attic and basement.
- TRNSYS's Type 9 in the WYEC2 format for the weather data.
- TESS's Type 127 for the GSHP. A thermostat TYPE, written by Lemire (1999) controls the operation of the heat pump. These set point temperatures are 20 [^oC] for heating and 25 [^oC] for cooling. The original model was modified to simulate the heat transfer from the desuperheater to the water.
- The ground heat exchanger (GHE) model used in this study is the one developed by the Department of Mathematical Physics from the University of Lund (Sweden), which has been implemented as a TRNSYS TYPE by Hellström et al. (1996).
- TRNSYS's Type 60 for the electrical hot water tank.

- TRNSYS's Type 94 for the PV array.
- TRNSYS's Type 48 for the inverter.

Affouda-Leon Biaou et al [1] conclude that on an annual basis, the grid supplies more electricity than it receives from the PV panels in the winter. However, the situation is reversed in the summer and overall, there is a near zero net energy balance at the end of the year.

Nikolaos G. Papatheodorou et al [8] discuss the simulation of the heating and cooling system of a University building in Athens, Greece with TRNSYS.

The hybrid ground source heat pump (HGSHP) installation under study has been designed to partially cover the heating and cooling demands of a School building at the National Technical University of Athens Campus in Greece. It combines a ground-source with a ground-coupled heat pump (GCHP) system, utilizing the thermal energy content of the groundwater and of the rocks present in the shallow earth adjacent to the building. Two ground source heat pumps (water-to-water) operate in bivalent heating and cooling mode, with electric energy. The heating/cooling distribution system into the building consists of dual-speed fan-coil units with maximum supply temperature of 47 [^{o}C], while a 5 [m^3] vertical cylindrical water tank separates the volume flows inside the heat pumps and the distribution circuit in order to promote the system's operating stability.

More precisely, the ground-source heat pump (GSHP) system utilizes the energy content of the aquifer confined within the Upper Marble formation of Mount Hymettus by means of a 280 [m] deep productive borehole yielding an optimum of 35 [m^3/h] of groundwater with an average temperature of about 22 [^{o}C]. The ground-coupled heat pump system utilizes both the energy content of the aquifer and of the rocks by means of a plate heat exchanger (PHE1), with a nominal capacity of 150 [kW], and 12 double U-tube borehole heat exchangers (BHEs).

The geology of the area where the field of the vertical borehole heat exchangers is established can be structured in three layers as follows:

- The first layer, which reaches a depth of 40 [m], is characterized by surface alluvial with loose marble conglomerates and clay matrix.
- The second layer is green schist, with thin marble intercalations, and has a 50 [m] thickness.
- The lowest layer starts at 90 [m] below grade and consists of fine-grained marble in tectonic contact to the green-schist and extends beyond the maximum well depth.

The building at National Technical University of Athens is a 3-storey one with maximum heating and cooling loads of about 1.9x106 [kJ/h] and 2.3x106 [kJ/h] respectively.

The ground source heat pumps operation in heating and cooling mode is thermostatically controlled in order to meet the desired fan-coils supply temperature. The first heat pump (HP1) is primarily responsible for the fan-coil units supply temperature to the desired set-point, while the second heat pump (HP2) operates supportively when needed. In heating mode an upper temperature set-point of 45 [^{o}C] at the central vertical node of the water storage tank is applied, with a lower dead band in the order of 2 [^{o}C] and 3 [^{o}C] for HP1 and HP2 respectively. In cooling mode a lower set-point temperature of 7

[^{o}C], with an upper dead band in the order of 2 [^{o}C] and 3 [^{o}C], controls the operation of HP1 and HP2 respectively. The operation of the system is characterized by a frequent on/off cycling of the heat pump units and the circulation pumps while the borehole heat exchangers operate either under full flow or no flow conditions.

Prior to the development of the simulation model, a 3D model of the building was implemented in Simcad v1.3 and was used as an input to TRNBuild where all thermal zones characteristics (construction materials, infiltration rates, occupancy etc) were defined. A building description file (.bui), was created to be used as an input to the TRNSYS simulation environment.

The models used in TRNSYS are the following:

- Type 109 for a weather data reader and radiation processor, using TMY2 weather data of Athens.
- Type 2 for standard differential on/off controller models.
- Type 668 for GSHP units.
- Type 10 for circulation pumps.
- Type 56 for multi-zone building model.
- Type 698 for five stage room thermostats.
- Type 644 for two-speed fan.
- Type 753 for heating coil-free floating.
- Type 508 for cooling coil-free floating.
- Type 11 for controlled flow mixers.
- Type 557 for the vertical borehole heat exchangers
- Type 5 for the plate heat exchangers
- Type 4a for a cylindrical storage tank.

It is observed that the lower the difference between inlet source and outlet temperatures, i.e. the energy that needs to be added through compression, the higher the coefficient of performance (COP) of the heat pumps.

Nikolaos G. Papatheodorou et al [8] conclude that the results obtained support the general consensus that transient simulation can prove to be a very reliable approach for the evaluation of the real-time operation and long-term energy performance of ground source heat pump systems.

S. Deng et al [10] discuss the simulation of two innovative energy supply systems based on the zero energy residential building (ZERB) design experience in Shanghai and Madrid.

Madrid and Shanghai have their own special weather condition, the annual humidity level of Shanghai is higher but in Madrid, dry weather dominates.

The first ZERB is an apartment, which will be built on the third floor of a green building in the campus of Shanghai Jiao Tong University. Its indoor function was designed according to China typical apartment for a family with one couple and one child. For the building an 8 kW air-cooled hybrid heat pump (HP), which uses solar thermal energy to assist electricity driven vapour compression (VC) air conditioning device is developed. The main parts of this device are a small solar assisted hybrid absorption chiller and a CO_2 heat pump. In summer, the solar thermal energy is collected, by heat pipe evacuated tube solar water collectors of 30 [m^2]. Then the hot water is transferred from the collect tank (500 [lt]) into the storage tank (300 [lt]) to promote the performance of HP and supply thermal energy to DHW. Hybrid heat pump supplies cooling energy to the fan-coil unit. In winter, the solar thermal energy can be directly supplied to the radiation floor (70 [m^2]). If water temperature of collector tank is not high enough, the heat pump is operated to provide heating to the storage tank. Then the thermal energy can be transferred to the indoor HVAC terminal units. In cloudy or rainy days, the hybrid heat pump works in independent operation mode. A heat recovery ventilator (HRV) of 127 [W] is used for recovering the latent and sensible heat from the exhaust air. A 64 [m^2] photovoltaic (PV) system was designed for this apartment and it is located on the slope surface of overhead holder above the roof.

The second ZERB case was planned and built by Stuttgart University of Applied Sciences for the 1st edition of the Solar Decathlon Europe (SDE) that took place in June 2010 in Madrid (Spain). The thermal and humidity gain profile of the building is based on the building occupancy (two people) and the electrical appliances of the house. The basic idea of the design is to use the traditional means for dealing with the hot and arid climate and to combine them with new technologies. Thermal mass (PCM), sun shadings and evaporative cooling help to achieve a comfortable indoor climate with passive means. The ventilation tower supplies passively part of the ventilation and cooling needs by evaporative cooling using the wind as driving force. Mechanical ventilation (AHU) with heat recovery and indirect evaporative cooling systems is used to reduce heat losses in winter and provide additional cooling in summer. Active cooling and heating is supplied through a radiant floor (30 [m^2]) by a reversible heat pump (2.4 [kW] cooling) powered by photovoltaic (12.5 [kWp]). In summer, a night radiant cooling system using hybrid photovoltaic thermal (PVT) collectors (38 [m^2]) regenerates the PCM ceiling (18 [m^2]) and takes up the heat rejected from the reversible heat pump by cooling down the ‘‘heat sink tank’’. If possible, ‘‘free cooling’’ is used, by pumping directly the cold water of the heat sink tank to the radiant floor. Dehumidification of the supply air can be done with the reversible heat pump through a fan-coil by cooling the air below the dew point. Domestic hot water (DHW) needs are covered by vacuum tube collectors (6.6 [m^2]), which feed a 300 [lt] solar tank with electrical heater back up. In winter, when necessary, the solar thermal system provides heat to the heat sink tank in order to increase the heat pump efficiency. The PV system consists of around 66 [m^2] of polycrystalline surface on both east/west facades and the roof and 33 [m^2] of monocrystalline cells for the PVT modules.

Both hot/dry and hot/humid climates from Madrid and Shanghai are considered in the simulation studies. The weather data used for the simulation are taken from Meteonorm.

Two detailed models about the houses and their equipments have been implemented in TRNSYS and the yearly simulations have been performed using a time step of six minutes. The simulation of the PV system for the 2nd building has been done separately with INSEL.

The temperatures and humidity for both climate conditions of the defined comfort zone are 20-26 [^oC] and 40-65 [%] relative humidity.

According to the results, compared to the first building, the second one has smaller energy consumption. The electricity balance is positive for both climates in both cases, although it is less favourable in Shanghai since the electricity consumption is higher and the PV generation is lower. Additional dehumidification devices would be necessary in building 2 for Shanghai climate. Some small-scale humidification devices for bedroom would be necessary in building 1 for Madrid.

A lifecycle analysis of the house has been done for the 2nd building in order to calculate the primary energy payback time (NPE) of the house for both climates. The conversion factors of GEMIS have been used to consider the electricity mix generation of Spain and China. GEMIS is a lifecycle analysis program and database for energy, material and transport systems. Also, the CO_2 equivalent emissions savings during the house lifetime have been estimated.

For the 2nd building in Madrid climate the NPE is equal to 10.1 years, which is acceptable. The CO_2 equivalent emissions savings, during 50 years building lifetime, are 74.4 [tons].

For the 2nd building in Shanghai climate the NPE is equal to 17.9 years, which is beyond the reasonable range. The CO_2 equivalent emissions savings, during 50 years building lifetime, are 109.8 [tons].

3 Methodology

Using the TRNSYS 16 software the simulation of a residential single-family house (Type 56b), in the four climatic zones of Greece, is performed in the current work. The house is connected with the weather data (Type 15-6), of each zone, in order to specify its heating/cooling needs. Those needs are met with the use of a GSHP (Type 504b), while the humidity demands are met with the use of a dehumidifier/humidifier (Type 696b). In order to operate, the GSHP is connected to a GHX (Type 557a), through a liquid pump (Type 3b), to ensure a steady fluid flow. The GSHP and the GHX are connected to the weather data, in order to simulate their operation. The heating/cooling operation of the GSHP is controlled through a thermostat controller (Type 8), which is connected to the temperature of the house. The electricity needed for the operation of the GSHP is supplied through a PV array (Type 194), which is connected with the GSHP through an inverter (Type 48a), for the conversion of direct current (DC) to alternating current (AC). The PV array is connected to the weather data for its operation. The connection of the components is shown in **Figure 3-1**.

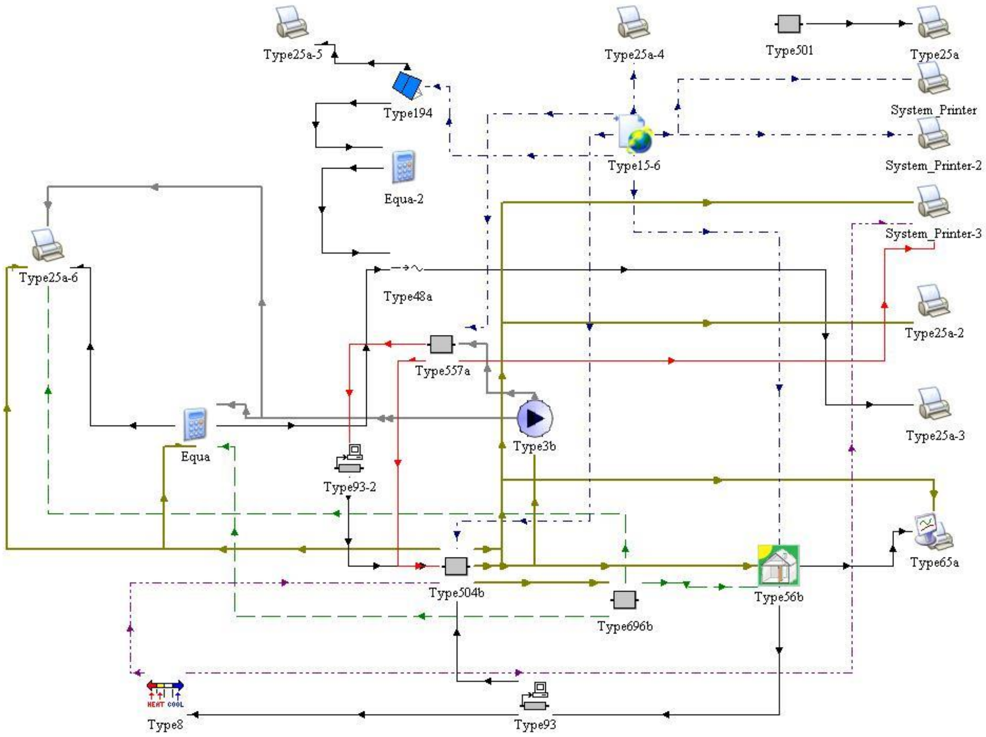

Figure 3-1: Single-family house with GSHP and PV array modeled in *TRNSYS 16*

Other models used in the simulation but not extensively analysed are the following:

- Type 93 used to access a value one time-step back. Necessary to operate the GSHP
- Type 501 used for the ground temperature profile.
- Type 25a, Type 65a and System Printer used for data recording and processing.

3.1 Simulation Tools

TRNSYS is a complete and extensible simulation environment for the transient simulation of systems. It is used to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behaviour, alternative energy systems (wind, solar, photovoltaic, hydrogen systems, etc). [18]

The main visual interface is the TRNSYS Simulation Studio. From there projects are created by drag-and-dropping components to the workspace, connecting them together and setting the global simulation parameters.

The tool used to enter input data for multizone buildings is TRNBuild. It allows the researcher to specify all the building structure details and everything that is needed to simulate the thermal behaviour of the building, such as windows optical properties, heating and cooling schedules, internal gains, ventilation operation, etc.

TRNSYS offers a broad variety of standard components, and many additional libraries are available to expand its capabilities:

- TRNLIB (free component library)
- TRANSSOLAR libraries
- TESS libraries

In order to operate the TRNSYS software and the several components used in the simulation the following manuals have been studied:

- TRNSYS “Getting Started” manual, which explains what TRNSYS is and what programs make the TRNSYS suite. It contains simple examples of the Simulation Studio and of TRNBuild (the Multizone Building interface). [18]
- TRNSYS “Using the Simulation Studio” manual, which describes the TRNSYS Simulation Studio in detail. [19]

- TRNSYS “Standard Component Library Overview” manual, which gives an overview of the available components in the standard TRNSYS library. [20]
- TRNSYS “Component Mathematical Reference” manual, which gives the mathematical description of all components available in the standard TRNSYS library. [21]
- TRNSYS “Multizone Building (Type56-TRNBuild)” manual, which describes in detail the TRNSYS multizone building (Type 56) and its visual interface (TRNBuild). [22]
- TRNSYS “Weather Data” manual, which describes the weather data distributed with TRNSYS 16. [23]
- TESS “Type504: Water Source Heat Pump” manual. [15]
- TESS “Type557: Vertical U-tube or Tube in Tube Ground Heat Exchanger” manual. [16]
- TESS “Type696: Air Stream Conditioning Device” manual. [17]

3.2 The Simulated House

The simulation of a single-family residential house, in the four climatic zones of Greece, has been made in TRNBuild interface. The values of the parameters and the coefficients were given or calculated according to Greek legislation. [12], [13]

The house is a detached four-sided, light-colored, ground floor building for a four-member family. The internal floor area of the house is 250 [m^2] while the internal height of the house is 2.7 [m] so the total air volume is 675 [m^3] and the air capacitance is approximately 810 [kJ/K]. The whole building is considered one thermal zone. A drawing of the house is shown in **Figure 3.2-1**

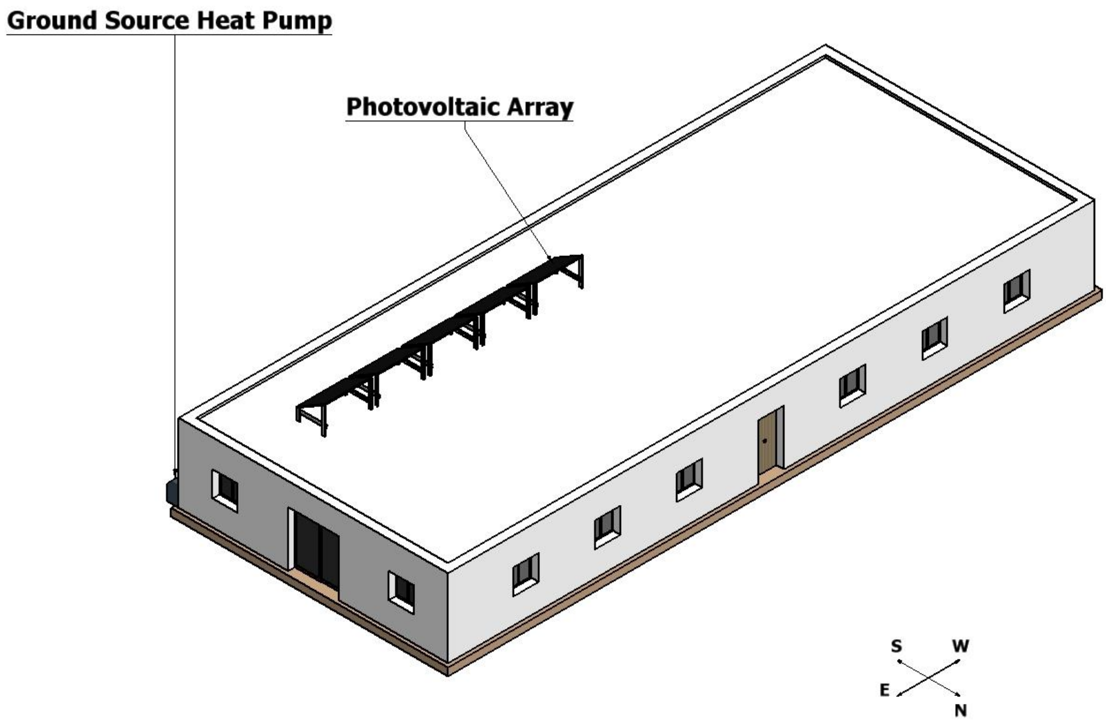

Figure 3.2-1: A single family house with GSHP and PV array

The U-value of the external walls of a B category building in each climatic zone of Greece, according to Greek legislation [12], is given in **table 3.2-1**. The house's external walls chosen U-value, total thickness and thickness of layers they consist of (from the inside to outside) [13] are given in **table 3.2-2.**

Table 3.2-1 U-value of external walls for a B category building in Greece

External Wall	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
U-Value [W/(m²*K)]	0.60	0.50	0.45	0.40

Table 3.2-2 Chosen values for external walls of the single-family residential house

External Wall	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
Chosen U-Value [W/(m²*K)]	0.282	0.247	0.22	0.198
Total thickness [m]	0.31	0.33	0.35	0.37

Layer of plaster [m]	0.02	0.02	0.02	0.02
Layer of hole brick [m]	0.09	0.09	0.09	0.09
Layer of extruded polystyrene [m]	0.12	0.14	0.16	0.18
Layer of holed brick [m]	0.06	0.06	0.06	0.06
Layer of plaster [m]	0.02	0.02	0.02	0.02

The absorptance of a light-colored vertical wall is equal to 0.4. The convective heat transfer coefficient of the air inside the wall is equal to 27.72 [kJ/(h∗m^2∗K)] and of the air outside the wall is equal to 90 [kJ/(h∗m^2∗K)].

The U-value of the roof of a B category building in each climatic zone of Greece, according to Greek legislation [12], is given in **table 3.2-3**. The house's roof is horizontal and its U-value, total thickness and thickness of the layers it consists of (from the inside to the outside) [13], for each climatic zone of Greece are given in **table 3.2-4**.

Table 3.2-3 U-value of roofs for a B category building in Greece

Horizontal Roof	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
U-Value [W/(m^2∗K)]	0.50	0.45	0.40	0.35

Table 3.2-4 Chosen values of the roof for the residential single-family house

Horizontal Roof	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
Chosen U-Value [W/(m^2∗K)]	0.237	0.224	0.192	0.175
Total thickness [m]	0.48	0.49	0.52	0.54
Layer of plaster [m]	0.02	0.02	0.02	0.02
Layer of reinforced concrete [m]	0.20	0.20	0.20	0.20
Layer of extruded polystyrene [m]	0.14	0.15	0.18	0.20
Layer of light concrete [m]	0.08	0.08	0.08	0.08
Layer of concrete tiles [m]	0.04	0.04	0.04	0.04

The absorptance of a light-colored roof is equal to 0.65. The convective heat transfer coefficient of the air inside the roof is equal to 36 [kJ/(h∗m^2∗K)] and of the air outside the roof is equal to 90 [kJ/(h∗m^2∗K)].

The U-value of the floor, adjacent to the ground, of a B category in each climatic zone of Greece, according to Greek legislation [12], is given in **table 3.2-5**. The house's ground floor U-value, total thickness and thickness of layers it consists of (from the inside to the outside) [13] are given in **table 3.2-6**.

Table 3.2-5 U-value of ground floors for a B category building in Greece

Ground Floor	Climatic Zone of Greece			
	A	B	C	D
U-Value [W/(m²*K)]	1.20	0.90	0.75	0.70

Table 3.2-6 Chosen values of the ground floor for the residential single-family house

Ground Floor	Climatic Zone of Greece			
	A	B	C	D
Chosen U-value [W/(m²*K)]	0.597	0.45	0.374	0.342
Total Thickness [m]	0.384	0.406	0.424	0.434
Layer of marble tiles [m]	0.02	0.02	0.02	0.02
Layer of gravel concrete [m]	0.06	0.06	0.06	0.06
Layer of waterproof bitumen [m]	0.004	0.004	0.004	0.004
Layer of reinforced concrete [m]	0.15	0.15	0.15	0.15
Layer of extruded polystyrene [m]	0.05	0.072	0.09	0.1
Layer of limestone [m]	0.1	0.1	0.1	0.1

The convective heat transfer coefficient of the air above the floor is 21.168 [kJ/(h*m^2*K)].

On the north wall there are a wooden door and six windows. The total external area of the wall, with the openings, is equal to 25.7 [m]*3 [m]=77.1 [m^2]. The wooden door covers an area of 2.2 [m^2], it has a thickness of 4 [cm] and a U-value of 2.194 [W/(m^2*K)]. The wooden door is medium colored, so its solar absorptance is equal to 0.6. The windows cover 1 [m^2] area each, they are insulated, double glazed with argon between the glasses. They have a U-value of 1.4 [W/(m^2*K)] and a g-value of 0.589, except for the house in the D climatic zone of Greece (D-House).The D-House has windows with U-value of 1.3 [W/(m^2*K)] and g-value of 0.298, because of a thicker inside glass. The frame percentage is 20 [%].

On the south wall there are three glass doors. The total external area of the wall, with the windows, is equal to 25.7 [m]∗3 [m]=77.1 [m^2]. The glass doors cover 4.4 [m^2] area each, they are insulated, double glazed with argon between the glasses. They have a U-value of 1.4 [W/(m^2∗K)] and a g-value of 0.589, except for the D-House. The D-House has windows with U-value of 1.3 [W/(m^2∗K)] and g-value of 0.298. The frame percentage is 20 [%]. The external shading factor has been set to 0.3.

On the east and west wall there is the same configuration of openings, two windows and one glass door. The total external area of each wall, including the windows, is equal to 10.7 [m]∗3 [m]=32.1 [m^2]. The glass door covers 4.4 [m^2] and the windows cover 1 [m^2] area each, they are insulated, double glazed with argon between the glasses. They have a U-value of 1.4 [W/(m^2∗K)] and a g-value of 0.589, except for the D-House. The D-House has windows with U-value of 1.3 [W/(m^2∗K)] and g-value of 0.298. The frame percentage is 20 [%]. The external shading factor has been set to 0.3.

Since the simulation is going to start in January the initial values of the zone temperature and relative humidity are taken, according to Greek legislation for winter period, equal to 20 [^oC] and 40 [%] respectively. [12]

The air infiltration through the openings is calculated, in [$m^3/h/m^2$], using tabulated prices, from the Greek legislation [12]. The total air infiltration in the house is equal to 184.98 [m^3/h] or 0.27 [1/h].

The heating/cooling of the house is achieved with the use of a GSHP connected with the ventilation system. The air, before entering the ventilation system, passes through a humidifier/dehumidifier. The heating/cooling energy transfered in the air depends on the entering air conditions and the liquid condition of the GHX.

The internal gains are taken into count, considering the persons living in the house, the artificial lighting and a personal computer of 230 [W] in the house. The heat gain from occupants is specified according to ISO 7730. The occupants are considered to do seated, light work (75 [W]). The number of persons inside the house is specified according to a schedule. The heat gain from artificial lighting is considered 5 [W/m^2] and the lamps are fluorescent tubes with 40 [%] convective part. The lights are turned on according to a schedule from 19:00 until 1:00.

For humidity the Simple Humidity Model (Capacitance Humidity Model) has been chosen.

3.3 Simulation Weather Data

In TRNSYS Simulation Studio the weather data of four different locations were connected to the aforementioned single-family residential house. The weather data reading and processing was done using TRNSYS Type 15-6 model, which is used for Meteonorm (TMY2 format) data.

The locations chosen from the Meteonorm library to represent the four differnt climatic zones of Greece are the following [23]:

1. For climatic zone A, the Larnaca airport of Cyprus was chosen. In the Meteonorm data base in TRNSYS 16 there was no Greek location coresponding to climatic zone A. So since Larnaca airport has a latitude of 34.88 [^{o}N] and several of the locations in climatic zone A have a latitude close to 35 [^{o}N] and are on islands [14], the aforemetnioned location was considered an aproppriate substitute.
2. For climatic zone B, the Athinai/Hellenkion of Greece was chosen, since it is near Athens, a city in climatic zone B. [14]
3. For climatic zone C, Thessaloniki of Greece was chosen, since the location is a city in climatic zone C. [14]
4. For climatic zone D, the Kastoria airport of Greece was chosen, since the location is near Kastoria, a city in climatic zone D. [14]

The weather data requested from the building, on an hourly basis, in order to run the simulation are the following:

- Ambient Temperature [^{o}C]
- Effective Sky Temperature [^{o}C]
- Relative Humidity [%]
- Total Horizontal Radiation [kJ/hr$*$m^2]
- Horizontal Beam Radiation [kJ/hr$*$m^2]
- Horizontal Incidence Angle [Degrees]
- North Total Radiation [kJ/hr$*$m^2]
- North Beam Radiation [kJ/hr$*$m^2]
- North Incidence Angle [Degrees]
- East Total Radiation [kJ/hr$*$m^2]

- East Beam Radiation [kJ/hr∗m^2]
- East Incidence Angle [Degrees]
- South Total Radiation [kJ/hr∗m^2]
- South Beam Radiation [kJ/hr∗m^2]
- South Incidence Angle [Degrees]
- West Total Radiation [kJ/hr∗m^2]
- West Beam Radiation [kJ/hr∗m^2]
- West Incidence Angle [Degrees]

The weather data requested from the rest of the models on an hourly basis, in order to run the simulation, are reported in each model inputs respectively.

3.4 Simulation of GSHP

The simulation of a Ground Source Heat Pump (GSHP) was made using the TESS models Type 504b (for water source Heat Pump), Type 557a (for a vertical u-tube ground Heat Exchanger) and TRNSYS Type3b model (for a single speed pump). Also for the control of the heating/cooling mode of the heat pump the thermostat model Type 8 is used.

3.4.1 Type 504b

This component, as referred in its manual [15], models a single stage liquid source heat pump. The heat pump conditions a moist air stream by either rejecting energy to a liquid stream (in cooling mode) or absorbing energy from a liquid stream (in heating mode).

This model is based on user-supplied data files containing catalog data for the capacity (both total and sensible in cooling mode) and power, based on the entering water temperature to the heat pump, the entering water flow rate and the air flow rate. Correction user-supplied data files are used for different air temperatures.

3.4.1.1 Mathematical Description

The air's (entering the heat pump) enthalpy and humidity ratio are calculated as

$h_{a,in} = h_{a,re}*(1-F_{a,fr})+h_{a,fr}*F_{a,fr}$ **Eq 3.4.1-1**

$w_{a,in} = w_{a,re}*(1-F_{a,fr})+w_{a,fr}*F_{a,fr}$ **Eq 3.4.1-2**

Where $h_{a,fr}$ and $h_{a,re}$ are established using a psychrometic table and the air temperature, pressure, relative humidity and humidity ratio.

The pressure of the entering air is considered the minimum between the fresh air pressure and the return air pressure.

Then from a psychrometric table, using the entering air enthalpy, humidity ratio and pressure, the rest of the air properties are established. These are the temperature, the wet bulb temperature, the relative humidity and the dry bulb air density. Also form the pressure and the temperature the air specific heat is established.

According to the mode of the heat pump three different procedures are followed.

<u>Cooling mode</u>

From the cooling performance data file, containing the total capacity, the sensible capacity and the power of the heat pump, (for different liquid temperatures, liquid flow rates and air flow rates) the appropriate capacities and power are established. Then according to the wet and dry bulb air temperature, those capacities and power are multiplied with the appropriate correction factor, taken from cooling correction data file.

The outlet air properties are calculated from the capacities

$$T_{a,out} = T_{a,in} - \frac{Q_{Sens,C}}{C_{p,a} * Fl_a}$$ **Eq 3.4.1-3**

$$h_{a,out} = h_{a,in} - \frac{Q_{Tot,C}}{Fl_a}$$ **Eq 3.4.1-4**

$$P_{a,out} = P_{a,in} + \Delta P_{HP}$$ **Eq 3.4.1-5**

The rest of the air properties are taken from the physchrometric tables. Those are the humidity ratio and the relative humidity.

"$Q_{Lat,C}$" is calculated from the following

$$Q_{Lat,C} = Q_{Tot,C} - Q_{Sens,C}$$ **Eq 3.4.1-6**

The equation for the power requirement of the compressor is

$$Po_{comp} = Po_{HP} – Po_{bl} - Po_{cont}$$ **Eq 3.4.1-7**

If "$Po_{,comp}$" is calculated negative, it is considered equal to zero (0)

The energy rejected in the fluid is calculated from this equation

$$Q_{fl,rej} = Q_{Tot,C} + Po_{comp} + Po_{bl} + Po_{cont}$$ **Eq 3.4.1-8**

The outlet fluid temperature is calculated as

$$T_{fl,out} = T_{fl,in} + \frac{Q_{fl,rej}}{C_{P,fl} * Fl_{fl}}$$ **Eq 3.4.1-9**

The COP is given from the following

$$COP = \frac{Q_{Tot,C}}{Po_{bl} + Po_{comp} + Po_{cont}}$$ **Eq 3.4.1-10**

While the EER is equal to

$EER = 3.414*COP$ **Eq 3.4.1-11**

Heating mode

From the heating performance data file, containing the total capacity and the power of the heat pump, (for different liquid temperatures, liquid flow rates and air flow rates) the appropriate capacity and power are established. Then according to the dry bulb air temperature, the capacity and power are multiplied with the appropriate correction factor, taken from heating correction data file.

The outlet air properties are calculated from the capacities

$w_{a,out}=w_{a,in}$ **Eq 3.4.1-12**

$$h_{a,out} = h_{a,in} + \frac{Q_{Tot,H}}{Fl_a}$$ **Eq 3.4.1-13**

$P_{a,out} = P_{a,in} + \Delta P_{HP}$ **Eq 3.4.1-14**

The temperature of the air and its relative humidity are established with the use of psychrometric tables. The power requirement of the compressor is calculated the same way as in the cooling mode.

The energy absorbed from the fluid is calculated as

$Q_{fl,abs} = Q_{Tot,H} - Po_{comp} - Po_{bl} - Po_{cont}$ **Eq 3.4.1-15**

The equation for the outlet fluid temperature is

$$T_{fl,out} = T_{fl,in} - \frac{Q_{fl,abs}}{C_{P,fl} * Fl_{fl}}$$ **Eq 3.4.1-16**

The COP. is calculated as

$$COP = \frac{Q_{Tot,H}}{Po_{bl} + Po_{comp} + Po_{cont}}$$ **Eq 3.4.1-17**

The EER is calculated the same way as in cooling mode

Only Fan open mode

When the fan is only open and the refrigerant cycle does not work, the properties of the outlet air are calculated from the following equations

$w_{a,out}=w_{a,in}$ **Eq 3.4.1-18**

$$h_{a,out} = h_{a,in} + \frac{Po_{bl} + Po_{cont}}{Fl_a}$$ **Eq 3.4.1-19**

$P_{a,out} = P_{a,in} + \Delta P_{HP}$ **Eq 3.4.1-20**

The rest of the outlet air properties (temperature and relative humidity) are established through the use of psychrometric tables.

The heat transfer to air is

$Q_{Tot,H} = Fl_{,a} * (h_{a,out} - h_{a,in})$ **Eq 3.4.1-21**

The COP and EER are calculated the same way as in the heating mode.

3.4.1.2 Parameters and inputs

The parameters used in this model are the following

1. Density of liquid stream: 1242 [kg/m^3]
2. Specific heat of liquid stream: 3.05 [kJ/kg*K]
3. Blower power: 100 [kJ/hr]
4. Controller power: 5 [kJ/hr]
5. Total air flow rate: 283.14 [l/s]

The density and the specific heat of the liquid stream are of a potassium carbonate (K_2CO_3) aqueous solution. [2]

The inputs used in this model are the following

1. Inlet liquid temperature: taken from GHX model, type 557a
2. Inlet liquid flow rate: taken from GHX model, type557a
3. Return air temperature: taken from the house model, type 56b
4. Return air relative humidity: taken from the house model, type 56b
5. Return air pressure: 1 [atm]
6. Fresh air temperature: taken from the weather model, type 15-6

7. Fresh air relative humidity: taken from the weather model, type 15-6
8. Fresh air pressure: taken from the weather model, type 15-6
9. Cooling control signal: taken from the thermostat model, type 8
10. Heating control signal: taken from the thermostat model, type 8
11. Fan control signal: 1 [-]
12. Fraction of outside air: 0.15 [-]
13. Pressure rise: 0 [atm]

The fan control signal is equal to one (1), because the fan needs to operate continuously, so that there is a continuous air flow-rate into the dehumidifier/humidifier model, type 696b.

3.4.2 Type 557a

This subroutine, as is explained in its manual [16], models a vertical U-tube heat exchanger that interacts thermally with the ground. A heat carrier fluid is circulated through the ground heat exchanger and either rejects heat to, or absorbs heat from the ground depending on the temperatures of the heat carrier fluid and the ground.

In typical U-tube ground heat exchanger applications, a vertical borehole is drilled into the ground. A U-tube heat exchanger is placed in the borehole and the borehole is filled with either virgin soil or some type of grout.

The program assumes that the boreholes are placed uniformly within a cylindrical storage volume of ground. There is convective heat transfer within the pipes, and conductive heat transfer to the storage volume. The temperature in the ground is calculated from three parts, a global temperature, a local solution and a steady flux solution. The global and local problems are solved with the use of an explicit finite difference method. The steady flux solution is obtained analytically. The temperature is then calculated using superposition methods.

3.4.2.1 Mathematical Description

The basic problem, as explained by Goran Hellstrom [4], in the analysis of the duct system for ground heat storage is the interaction between the local thermal process around the pipe and the global temperature process through the storage and the surrounding ground. The heat flow from the pipe to the ground is determined by the fluid temperature, the heat transfer properties and the temperature in the ground surrounding the pipe.

These temperatures, and thereby the heat flow, will vary along the pipes. The amounts of injected and extracted heat will govern the global process. The local values of the global temperature field are on the other hand necessary for the local problem.

The ground heat exchangers are assumed to be uniformly placed in the storage region. A certain region may be assigned to each heat exchanger due to symmetry. The cross sectional area of this region is calculated as

$A_p = \pi * r_1^2$ **Eq 3.4.2-1**

Where

$r_1 = 0.525 * B$ **Eq 3.4.2-2**

There is a local thermal process in the region between r_b and r_1. When the local process in considered the heat flux is zero at the outer boundary, r_1.

The thermal diffusivity is: $\alpha = \lambda / C$ **Eq 3.4.2-3**

The influence of the outer boundary is negligible during a certain initial period. The process is the same as that of a pipe in an infinite surrounding. The influence at the pipe of the outer boundary is felt after a time $\alpha t/r_1^2 = 0.2$, and thereafter the solution changes character. The temperature profile becomes constant. The mean temperature is:

$$T_m(t) = \frac{q}{\pi * C * r_1^2} * t$$ **Eq 3.4.2-4**

The heat flux is at each point constant in time. Between the fluid temperature and the mean temperature there is the following basic relation:

$$T_f(t) \cong T_m(t) + \frac{q}{2\pi\lambda}[2\pi\lambda R_b + \ln(\frac{r_1}{r_b}) - \frac{3}{4}] \qquad \frac{at}{r_1^2} > 0.2$$ **Eq 3.4.2-5**

The heat injection to the unit is proportional to the difference $T_f - T_m$:

$$\frac{q}{\pi r_1^2} = \frac{\lambda(T_f - T_m)}{l^2} \qquad \frac{at}{r_1^2} > 0.2$$ **Eq 3.4.2-6**

where

$$l = r_1\sqrt{\frac{1}{2}[\ln(\frac{r_1}{r_b}) - \frac{3}{4} + 2\pi\lambda R_b]}$$ **Eq 3.4.2-7**

The fundamental importance of the steady-flux regime and the heat transfer length is due to the fact that any time-varying injection/extraction *q(t)* may be considerer as a superposition of step-pulses of the considered type.

The ground in the storage volume is assumed to have homogeneous thermal properties. The heat flow process in the storage region and the surrounding ground is modeled using a rectangular two-dimensional mesh. The storage volume is divided into a number of subregions. There is one local solution for each subregion. They also define the flow path of the heat carrier fluid. The injection/extraction of heat gives a distribution of sources and sinks for the global solution, which satisfies

$$C\frac{\partial T}{\partial t} = \nabla * (\lambda \nabla T) + q_{sf} + q_l \qquad \textbf{Eq 3.4.2-8}$$

The short time variations are covered by the local problems. The slow redistribution of heat during extraction/injection and the interaction between the storage region and the surrounding ground are accounted for by the steady-flux and the global solution.

The global problem is essentially an ordinary heat conduction problem with two heat source terms in the storage region. One that transfers heat from the local problem and one that redistributes heat within the storage volume due to circulation of the heat carrier fluid.

The numerical model uses the explicit finite difference method (FDM). The simulated ground volume is divided into a two-dimensional mesh using a radial coordinate *r* and a vertical coordinate *z*.

The net heat flow to the cell changes the temperature so that energy is conserved. The heat flows are estimated by simple difference equations. The indices in the radial and vertical directions are denoted *i* and *j*. The radial heat flow between cell (*i – 1,j*) and (*i,j*) becomes:

$$F_r(i,j) = K_r(i,j) * [T(i-1,j) - T(i,j)] \qquad \textbf{Eq 3.4.2-9}$$

In the vertical direction the flow between cell (*i – 1,j*) and (*i,j*) is:

$$F_z(i,j) = K_z(i,j) * [T(i-1,j) - T(i,j)] \qquad \textbf{Eq 3.4.2-10}$$

When the values of the heat source terms, the temperatures of the nodal points and at the ground surface are known at a given time, the new temperature field is calculated. The new temperature for cell (*i, j*) becomes:

$$T(i,j)_{t+\Delta t} = T(i,j)_t + [F_r(i,j) - F_r(i+1,j) + F_z(i,j) - F_z(i,j+1) + Q_l(i,j) + Q_{sf}(i,j)]\frac{\Delta t}{C(i,j)}$$

Eq 3.4.2-11

When the temperature of the heat carrier fluid differs from the temperatures of the surrounding ground there will be a heat transfer between these two parts. So the fluids temperature will vary along its flow path through the storage volume. The amplitude of the temperature variations depends, among other things, on the fluid flow rate. If transient terms in the fluid are neglected, the heat balance equation for the heat carrier fluid may be written as:

$$C_f * q_{fp} \frac{\partial T}{\partial s} + \alpha_p (T_f - T_a) = 0 \qquad \textbf{Eq 3.4.2-12}$$

or

$$C_f * q_{fv} \frac{\partial T}{\partial s} + \alpha_v (T_f - T_a) = 0 \qquad \textbf{Eq 3.4.2-13}$$

A damping factor is defined as:

$$\beta = e^{-\frac{\alpha_v V}{C_f Q_f}} = e^{-\frac{\alpha_p L_p}{C_f Q_f}} \qquad \textbf{Eq 3.4.2-14}$$

The fluid temperature may now be expressed as:

$$T_{fout} = \beta * T_{fin} + (1 - \beta) * T_\alpha \qquad \textbf{Eq 3.4.2-15}$$

It is observed that when the fluid flow rate approaches zero the outlet temperature approaches the temperature T_α, while when the fluid flow rate goes to infinity $T_{fout} = T_{fin}$.

The total heat injected to the volume is:

$$Q = C_f Q_f * (T_{fin} - T_{fout}) \qquad \textbf{Eq 3.4.2-16}$$

Normalizing to unit volume it becomes:

$$q = \frac{C_f Q_f}{V} * (1 - \beta) * (T_{fin} - T_\alpha) \qquad \textbf{Eq 3.4.2-17}$$

These formulas are used to account for the effect of temperature variations along the fluid flow path. It is used both in the local and the steady-flux problem.

The thermal process around the individual ducts, due to short-time variations, is modeled using a one-dimensional radial mesh. The storage region V is divided into N subregions. The local problem is assumed to be the same around each pipe in a given subregion. The local temperature T_l satisfies the radial heat conductions equation with a sink:

$$C \frac{\partial T_l}{\partial t} = \lambda \left(\frac{\partial^2 T_l}{\partial r^2} + \frac{1}{r} \frac{\partial T_l}{\partial r} \right) - q_l \qquad r_b < r \le r_1 \qquad \textbf{Eq 3.4.2-18}$$

The outer boundary is totally insulated, i.e. there is no heat flow across this boundary.

The subregions are used to define the flow path through the storage volume. The fluid flows through V_1, V_2, $\ldots V_N$ when $Q_f > 0$ and the opposite direction when $Q_f < 0$. Each subregion normally contains several global cells. The average temperature of the local cell (j = 2) immediately outside the pipe for all cells in subregion k is:

$$T^k = T^k_{l,j=2} + T^k_g$$ **Eq 3.4.2-19**

The outlet temperature and the heat exchange of each subregion k is calculated with the equations for T_{fout} and Q, in respect to section k.

The heat source term q_l for subregion k is:

$$q_l = \frac{E_k}{t_g V_k}$$ **Eq 3.4.2-20**

Expressed as a temperature increase in subregion k of the global solution this is:

$$\Delta T_g = \frac{q_l t_g}{C} = \frac{E_k}{C V_k}$$ **Eq 3.4.2-21**

The heat transfer due to the source term q_l is effectuated as a mutual temperature change in the local and global temperature fields for each subregion.

The steady-flux solution gives the temperature field around a pipe for a constant heat exchange rate. It is used for the redistribution of heat within the storage due to the circulation of fluid.

The source term q_{sf} for a global cell j is proportional to the difference between the temperature of the cell $T^k_{g,j}$ and the mean temperature $T_g{}^k$ of the subregion k.

$$q_{sf} = \frac{C_f Q_f}{V_k}\left(1 - \beta^k_{sf}\right)\left(T^k_g - T^k_{g,j}\right)$$ **Eq 3.4.2-22**

The outlet temperature from subregion k is:

$$T^k_{sf,fout} = \sum_j \frac{V_{k,j}}{V_k}\left[\beta^k_{sf} T^k_{sf,fin} + \left(1 - \beta^k_{sf}\right)\left(T^k_{g,j} - T^k_g\right)\right] = \beta^k_{sf} T^k_{sf,fin}$$ **Eq 3.4.2-22**

The total fluid temperature is the sum of the fluid temperature used in the steady-flux part T_{sf} and that used in the local problem.

It should be noted that the steady-flux heat source term q_{sf} depends on the temperature of an individual cell whereas the local heat source term q_l is the same for each subregion.

The steady-flux temperature in the circular region around a pipe is:

$$T_{sf} = \left(T_g^k - T_{g,i,j}^k\right) * \frac{r_1^2}{2l^2} * h\left(\frac{r}{r_1}\right) \qquad \textbf{Eq 3.4.2-23}$$

Where

$$h\left(\frac{r}{r_1}\right) = \frac{1}{2}\left(\frac{r}{r_1}\right)^2 - \ln\left(\frac{r}{r_1}\right) - \frac{3}{4} \qquad \textbf{Eq 3.4.2-24}$$

The temperature in the ground is a superposition of three parts: local, global, and steady-flux temperature. In order to obtain the superposed temperature the radial distance to the nearest pipe has to be specified. First the global cell (*i*, *j*) is given. The appropriate subregion is then automatically calculated in the program. The radial distance from the pipe is obtained by specifying the coordinate *j'* for the appropriate nodal point in the local mesh. The superposed temperature now becomes:

$$T = T_{g,i,j}^k + T_{l,j'}^k + T_{sf,j'}^k \qquad \textbf{Eq 3.4.2-25}$$

3.4.2.2 Parameters and Inputs

The parameters used in this model, taken from the Geotrainet manual [7], are the following

1. Storage volume 3750 [m^3]
2. Borehole depth 60 [m]
3. Header depth 1 [m]
4. Number of boreholes 2 [-]
5. Borehole radius 50 [mm]
6. Number of boreholes in series 1 [-]
7. Number of radial regions 1 [-]
8. Number of vertical regions 10 [-]
9. Storage thermal conductivity 6.48 [kJ/(hr*m*K)]
10. Storage heat capacity 2400[kJ/(m^3*K)]
11. Outer radius of 20 [mm]
12. Inner radius of u-tube pipe 17.7 [mm]
13. Center-to-center half distance 23 [mm]

14. Fill thermal conductivity	5.4 [kJ/(hr∗m∗K)]
15. Pipe thermal conductivity	1.5122 [kJ/(hr∗m∗K)]
16. Gap thermal conductivity	5.040 [kJ/(hr∗m∗K)]
17. Gap thickness	0 [m]
18. Reference borehole flow rate	424.77 [kg/hr]
19. Reference temperature	30 [^oC]
20. Pipe to pipe heat transfer	-1 [-]
21. Fluid specific heat	3.05 [kJ/(kg∗K)]
22. Fluid density	1242 [kg/m^3]
23. Insulation indicator	0 [-]
24. Number of simulation years	1 [-]
25. Maximum storage temperature	100 [^oC]
26. Initial surface temperature	**table 3.4.2-1**
27. Initial thermal gradient	0 [$^oC/m$]
28. Number of preheating years	0 [-]
29. Average air temperature	**table 3.4.2-1**
30. Amplitude of air temperature	**table 3.4.2-1**
31. Number of ground layers	1 [-]
32. Thermal conductivity of layer	6.48 [kJ/(hr∗m∗K)]
33. Heat capacity of layer	2400 [kJ/(m^3∗K)]
34. Thickness of layer	1000 [m]

The density and the specific heat of the fluid are of a potassium carbonate (K_2CO_3) aqueous solution [2]. The storage-layer heat capacity and thermal conductivity values are for clay/silt, water saturated, type of rock. The fill thermal conductivity is for bentonite/quartzsand, 12/50 %, water, grout. The pipe thermal conductivity is for polyethylene PE DN40 PN8 pipe. The insulation indicator is zero (0), because there is no insulation.

The initial surface temperature, the average air temperature and the amplitude of air temperature are dependent on the weather, which changes for each climatic zone. These values are reported in **table 3.4.2-1**. The amplitude of air is the difference of the maximum air temperature and the mean air temperature

Table 3.4.2-1 GSHP temperatures dependent on the weather

	Climatic Zone of Greece			
	A	**B**	**C**	**D**
Initial surface temperature [°C]	18.98	18.38	15.54	11.62
Average air temperature [°C]	18.98	18.38	15.54	11.62
Amplitude of air temperature [Δ°C]	16.87	19.07	20.91	23.98

The inputs used in this model are the following:

1. Inlet fluid temperature — taken from the pump model, type 3b
2. Inlet flow rate (total) — taken from the pump model, type 3b
3. Temperature on top of storage — taken from the weather model, type 15-6
4. Air temperature — taken from the weather model, type 15-6
5. Circulation switch — 1 [-]

3.4.3 Type 3b

This pump model computes a mass flow rate using a variable control function, which must be between 0 and 1, and a fixed maximum flow capacity. Pump power consumption may be calculated as a linear function of mass flow rate. A user specified fraction of the pump is converted to fluid thermal energy. The inlet fluid flow rate input is used for convergence checking only.[20]

3.4.3.1 Mathematical Description

The outlet temperature is calculated, as explained in the models manual [21], by the following equation:

$$T_o = T_i + \frac{P * F_{par}}{\dot{m} C_p}$$ **Eq 3.4.3-1**

The outlet mass flow rate is simply

$$\dot{m}_o = \gamma * \dot{m}_{\max}$$ **Eq 3.4.3-2**

The power consumption of the pump is calculated as

$$P = \gamma * P_{max}$$ **Eq 3.4.3-3**

3.4.3.2 Parameters and Inputs

The parameters used in this model are the following

1. Maximum flow rate: 849.54 [kg/hr] (is the minimum allowable flow rate for the operation of the selected heat pump)
2. Fluid specific heat: 3.05 [kJ/kgK]
3. Maximum power: 100 [kJ/hr]
4. Conversion coefficient: 0.05 [-]

The inputs used in this model are the following

1. Inlet fluid temperature is taken from model 504b
2. Inlet mass flow rate is taken from model 504b
3. Control signal is set to 1

3.4.4 Type 8

A three-stage room thermostat is modeled to output three on/off control functions that can be used to control a system having a heat source, an auxiliary heater and a cooling system. The controller commands cooling at high room temperatures, first stage heating at lower room temperatures and second stage (auxiliary source) heating at even lower room temperatures.[21]

Parameters and inputs

The parameters used in this model are the following:

1. Nb. of oscillations permitted 5 [-]
2. 1^{st} stage heating in 2^{nd} stage? 1 [-]
3. Temperature for cooling 26 [^oC], 28 [^oC] for climatic zone D of Greece
4. 1^{st} stage heating temperature 20 [^oC]
5. 2^{nd} stage heating temperature -15 [^oC]

The input used in this model is the room temperature, which taken from the house model, type 56b.

3.5 Simulation of humidifier/dehumidifier

Because the GSHP model does not control the humidity conditions of the air stream, a humidifier/dehumidifier was needed. So an air stream conditioning device model, type 696, of TESS was used to simulate the humidifier/dehumidifier.

3.5.1 Type 696b

Type 696b, as is explained in its manual [17], models a simple air conditioning device that adds or removes sensible and latent energy from an air stream to meet a user-specified set point conditions of humidity. To use this component effectively as a de-humidifying coil, the humidity is set to a desired point, then the IREHEAT parameter is set to value 1 so that the air is returned (through reheat after dehumidification) to its in-let condition or set IREHEAT to 0 to allow for free-floating outlet temperature.

3.5.1.1 Mathematical Description

At each time step, type 696 performs a call to the TRNSYS Psychrometrics routine in order to obtain those air properties for the inlet air stream not specified by the user among the component's inputs. The user is required to specify the inlet air temperature, pressure and relative humidity. There are three states of operation for this component.

No flow condition

If air is not flowing through the device or if the humidity of the air stream is already within the user-specified set point ranges, type696 sets the outlet air temperature to the inlet temperature, sets the outlet air pressure to the inlet air pressure and sets the outlet air humidity ratio to the inlet air humidity ratio. The sensible, latent and total heating and cooling energies as well as the reheat energy are set to zero.

Humidification only

Type 696 operates in a humidification mode, where it checks whether the inlet air relative humidity is below the humidification set point. If the inlet air relative humidity is below the relative humidity set point, type 696 calls the psychrometrics routine with the inlet air temperature and set point air relative humidity. Psychrometrics returns the full air state, including the outlet air enthalpy h_{out}. The total energy transfer to the air stream is given by:

$$\dot{Q}_{tot,heat} = \dot{m}_{air}\left(h_{out} - h_{in}\right) \quad \textbf{Eq 3.5.1-1}$$

Dehumidification only

Type 696 operates in a dehumidification mode, where it checks whether the inlet air relative humidity is above the dehumidification set point. If the inlet air is above the set point, type 696 sets the air outlet pressure according to

$P_{out} = P_{in} - \Delta P$ **Eq 3.5.1-2**

Sets the outlet air temperature equal to the inlet air temperature and sets the outlet air relative humidity equal to the set point relative humidity and calls psychrometrics. Type 696 computes the total energy transfer from the air stream according to:

$\dot{Q}_{tot,cool} = \dot{m}_{air}(h_{in} - h_{out})$ **Eq 3.5.1-3**

The latent energy removed from the air stream is given by:

$\dot{Q}_{lat,cool} = \dot{m}_{air} * HFG * (\omega_{in} - \omega_{out})$ **Eq 3.5.1-4**

If reheating is allowed psychrometrics is called once again, this time with the outlet air pressure and both the dehumidification and temperature set points. The energy required to reheat the dehumidified air is given by:

$\dot{Q}_{reheat} = \dot{m}_{air}(h_{reheat} - h_{out})$ **Eq 3.5.1-5**

3.5.1.2 Parameters and inputs

The parameters used in this model are the following

1. Leaving cooling air relative humidity 90 [%]
2. Reheat mode 1 [-]
3. Dehumidification mode 0 [-]
4. Humidification mode 0 [-]

The inputs used in this model are the following

1. Inlet air temperature taken from the GSHP model, type504b
2. Inlet air relative humidity taken from the GSHP model, type504b
3. Inlet air flow rate taken from the GSHP model, type504b
4. Inlet air pressure taken from the GSHP model, type504b
5. Air side pressure drop 0 [atm]
6. Minimum outlet air relative humidity 40 [%]
7. Maximum outlet air relative humidity 45 [%]

3.6 Simulation of PV array

To operate the GSHP electricity is used from two alternative sources. One is the electricity grid and the other is a PV array. To simulate the PV electricity production and the electricity exchange with the grid two TRNSYS models were used. Type 194 to simulate the electricity production of the photovoltaic array and type 48a to simulate the inverter connected to the PV array, the GSHP, the liquid pump and the grid.

3.6.1 Type 194

This component, as referred in its manual [21], determines the electrical performance of a photovoltaic array. The model is based on the calculation method presented by DeSoto et al [3]. The model determines the current and power of the array at a specified voltage. Other outputs include current and voltage at the maximum power point.

3.6.1.1 Mathematical description

The model used in this component is based on the five-parameter equivalent circuit model. The main thrust of this model is to reliably extrapolate performance information provided by the manufacturer at standard rating conditions (SRC) (1000 [W/m^2], 25 [^{o}C]) to other operating conditions. The model is based on the equivalent circuit diagram show in **Figure 3.6.1-1**

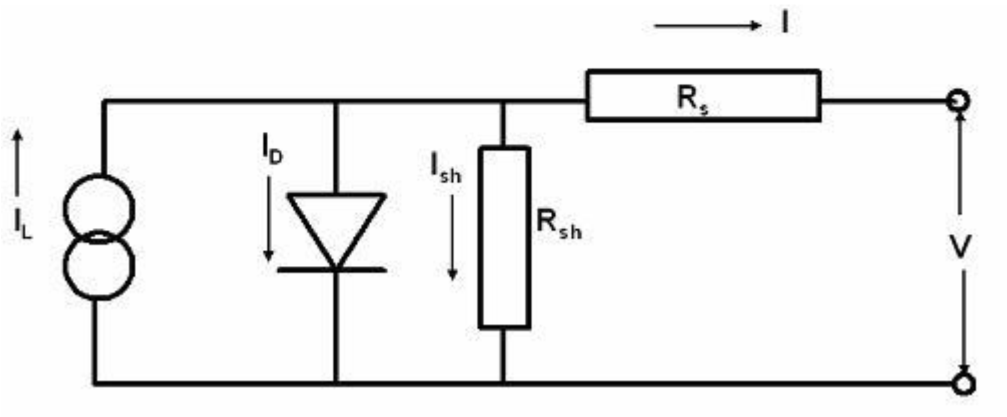

Figure 3.6.1-1: Equivalent electrical circuit

The current-voltage (I-V) characteristics of a PV array change with both insolation and array temperature. The model determines the I-V curve as a function of these environmental conditions using five array that are deduced from rating information provided by the manufacturer. The I-V equation for the circuit shown in **Figure 3.6.1-1** is as follows

$$I = I_L - I_o\left[e^{\frac{V+IR_s}{a}} - 1\right] - \frac{V+IR_s}{R_{sh}}$$ **Eq. 3.6.1-1**

where

$$a \equiv \frac{N_s n_i k T_c}{q}$$ **Eq. 3.6.1-2**

To evaluate the five parameters in **equation 3.6.1-1**, five independent pieces of information are needed. Reference values of these parameters are determined for a standard rating condition (SRC). Three current-voltage pairs are normally available from the manufacturer at SRC: the short circuit current, the open circuit voltage and the current and voltage at the maximum power point (MPP). A fourth piece of information results from recognizing that the derivative of the power at the maximum power point is zero. Although both the temperature coefficient of the open circuit voltage (β_{Voc}) and the temperature coefficient of the short circuit current (α_{Isc}) are known, only β_{Voc} is used to find the five reference parameters. α_{Isc} is used when the cell is operating at conditions other than reference conditions.

<u>The Reference Parameters</u>

To determine the values of the five parameters appearing in **eq. 3.6.1-1**, corresponding to operation at SRC, the 3 known I-V pairs at SRC are substituted into **eq. 3.6.1-1** resulting in the following equations.

For short circuit current: $I = I_{sc,ref}$, $V = 0$

$$I_{sc,ref} = I_{L,ref} - I_{o,ref}\left[e^{\frac{I_{sc,ref}R_{s,ref}}{a_{ref}}} - 1\right] - \frac{I_{sc,ref}R_{s,ref}}{R_{sh,ref}}$$ **Eq. 3.6.1-3**

For open circuit voltage: I = 0, $V = V_{oc,ref}$

$$0 = I_{L,ref} - I_{o,ref}\left[e^{\frac{V_{oc,ref}}{a_{ref}}} - 1\right] - \frac{V_{oc,ref}}{R_{sh,ref}}$$ **Eq. 3.6.1-4**

At the maximum power point: $I = I_{mp,ref}$, $V = V_{mp,ref}$

$$I_{mp,ref} = I_{L,ref} - I_{o,ref}\left[e^{\frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{a_{ref}}} - 1\right] - \frac{V_{mp,ref}+I_{mp,ref}R_{s,ref}}{R_{sh,ref}}$$ **Eq. 3.6.1-5**

The derivative with respect to power at the maximum power point is zero.

$$\left.\frac{d(IV)}{dV}\right|_{mp} = I_{mp} - V_{mp}\left.\frac{dI}{dV}\right|_{mp} = 0$$ **Eq. 3.6.1-6**

where $\left.\frac{dI}{dV}\right|_{mp}$ is given by:

$$\left.\frac{dI}{dV}\right|_{mp} = \frac{\frac{-I_o}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} - \frac{1}{R_{sh}}}{1 + \frac{I_oR_s}{a}e^{\frac{V_{mp}+I_{mp}R_s}{a}} + \frac{R_s}{R_{sh}}}$$ **Eq. 3.6.1-7**

The temperature coefficient of open circuit voltage is given by:

$$\beta_{Voc} = \left.\frac{\partial V}{\partial T}\right|_{I=0} \approx \frac{V_{oc,ref} - V_{oc,T_c}}{T_{ref} - T_c}$$ **Eq. 3.6.1-8**

To evaluate β_{Voc} numerically, it is necessary to know $V_{oc,Tc}$, at some temperature near the reference temperature. The cell temperature used for this purpose is not critical since values of T_c ranging from 1 to 10 [K] above or below T_{ref} provide essentially the same result. $V_{oc,Tc}$ can be found from **equation 3.6.1-4**, if the temperature dependencies for parameters I_o, I_L, and a are known. The shunt resistance is assumed to be independent of temperature. Therefore, in order to apply **equation 3.6.1-8**, it is necessary to obtain expressions for the temperature dependence of the three parameters a, I_o and I_L.

Dependence of the Parameters on Operating Conditions

From the definition of a, the modified ideality factor is a linear of cell temperature (assuming n_i is independent of temperature) so that:

$$\frac{a}{a_{ref}} = \frac{T_c}{T_{c,ref}}$$ **Eq. 3.6.1-9**

The diode reverse saturation current, I_o is related to temperature and reference conditions with the following relation:

$$\frac{I_o}{I_{o,ref}} = \left[\frac{T_c}{T_{c,ref}}\right]^3 e^{\left[\frac{1}{k}\left(\left.\frac{E_g}{T}\right|_{T_{ref}} - \left.\frac{E_g}{T}\right|_{T_c}\right)\right]}$$ **Eq. 3.6.1-10**

E_g exhibits a small temperature dependence which, for silicon, can be represented as indicated in the following equation, where $E_{g,Tref}$ = 1.121 [eV] for silicon cells.

$$\frac{E_g}{E_{g,T_{ref}}} = 1 - 0.0002677(T - T_{ref})$$ **Eq. 3.6.1-11**

The light current I_L for any operating conditions is related to the light current at reference conditions by:

$$I_L = \frac{S}{S_{ref}}\frac{M}{M_{ref}}\left[I_{L,ref} + a_{Isc}\left(T_c - T_{c,ref}\right)\right]$$ **Eq. 3.6.1-12**

The shunt resistance controls the slope of the I-V curve at the short circuit condition. Large shunt resistances result in a horizontal slope. Desoto et al (2005) empirically propose the following equation to describe the observed effect of solar radiation on the shunt resistance.

$$\frac{R_{sh}}{R_{sh,ref}} = \frac{S_{ref}}{S}$$ **Eq. 3.6.1-13**

The Incidence Angle Modifier, $K_{\tau\alpha}$

The incidence angle, θ, is directly involved in the determination of the radiation incident on the surface of the PV device. In addition, the incidence angle affects the amount of solar radiation transmitted through the protective cover and converted to electricity by the cell. As the incidence angle increases, the amount of radiation reflected from the cover increases. The effect of reflection and absorption as a function of incidence angle is expressed in terms of the incidence angle modifier, $K_{\tau\alpha}(\theta)$, defined as the ratio of the radiation absorbed by the cell at some incidence angle θ divided by the radiation absorbed by the cell normal incidence.

The angle of refraction is determined from Snell's law

$$\theta_r = arcsin(n * sin\theta) \quad \textbf{Eq. 3.6.1-14}$$

A good approximation of the transmittance of the cover system considering both reflective losses at the interface and absorption within the glazing is:

$$\tau(\theta) = e^{-(KL/\cos\theta_r)}\left[1 - \frac{1}{2}\left(\frac{\sin^2(\theta_r - \theta)}{\sin^2(\theta_r + \theta)} + \frac{\tan^2(\theta_r - \theta)}{\tan^2(\theta_r + \theta)}\right)\right] \quad \textbf{Eq. 3.6.1-15}$$

To obtain the incidence angle modifier **eq. 3.6.1-15** needs to be evaluated for incidence angle of 0^o and θ. The ratio of these two transmittances yields the incidence angle modifier:

$$K_{\tau\alpha}(\theta) = \frac{\tau(\theta)}{\tau(0)} \quad \textbf{Eq. 3.6.1-16}$$

Separate incidence angle modifiers are needed for beam, diffuse and ground-reflected radiation.

Air Mass Modifier

Air mass is the ratio of the mass of air that the beam radiation has to traverse at any given time and location to mass of air that the beam radiation would traverse if the sun were directly overhead. An empirical relation is used to account for air mass effects:

$$\frac{M}{M_{ref}} = \sum_0^4 a_i (AM)^i \quad \textbf{Eq. 3.6.1-17}$$

where $$AM = \frac{1}{\cos(\theta_z) + 0.5057(96.080 - \theta_z)^{-1.634}}$$ **Eq. 3.6.1-18**

a_0 = 0.918093 a_1 = 0.086257 a_2 = 0.024459 a_3 = 0.002816 a_4 = 0.000126 **Eq. 3.6.1-19**

Module Operating Temperature

Type 194 uses temperature data from the standard NOCT (Nominal Operating Cell Temperature) measurements to compute the module temperature at each timestep. The NOCT temperature ($T_{c,NOCT}$) is the operating temperature of the module with a wind speed of 1 [m/s], no electrical load and a certain specified insolation and ambient temperature. The values for insolation and temperature are usually 800 [W/m^2] and 20 [^{o}C]. Type 194 uses the NOCT data to determine the ratio of the module transmittance-reflectance product to the module loss coefficient:

$$\frac{\tau\alpha}{U_L} = \frac{\left(T_{c,NOCT} - T_{a,NOCT}\right)}{G_{T,NOCT}}$$ **Eq. 3.6.1-20**

Assuming that this ratio is constant, the module temperature at any timestep is:

$$T_c = T_a + \frac{\left(1 - \eta_{ref}/\tau\alpha\right)}{\left(G_T \tau\alpha / U_L\right)}$$ **Eq. 3.6.1-21**

The electrical calculations discussed for five-parameter PV model deal with a single module. Type 194 may be used to simulate arrays with any number of modules. The total number of modules in an array is the product of the modules in series (NS) and the modules in parallel (NP). Also the voltage supplied to type 194 is for the entire array and not just one module. Module mismatch losses are not considered in this model.

3.6.1.2 Parameters and Inputs

The parameters used in this model are the following:

1. Module short-circuit current at reference conditions: **table 3.6.1-1**
2. Module open-circuit voltage at reference conditions: **table 3.6.1-1**
3. Reference temperature: 298.15 [K]
4. Reference insolation: 1000 [W/m^2]

5. Module voltage at max power point and reference conditions: **table 3.6.1-1**
6. Module current at max power point and reference conditions: **table 3.6.1-1**
7. Temperature coefficient of Isc at (ref. cond): **table 3.6.1-1**
8. Temperature coefficient of Voc (ref. cond): **table 3.6.1-1**
9. Number of cells wired in series: **table 3.6.1-1**
10. Number of modules in series: **table 3.6.1-1**
11. Number of modules in parallel: 1
12. Module temperature at NOCT: 313 [K]
13. Ambient temperature at NOCT: 293 [K]
14. Insolation at NOCT: 800 [W/m^2]
15. Module area: **table 3.6.1-1**
16. tau-alpha product for normal incidence: 0.95
17. Semiconductor bandgap: 1.12 [eV]
18. Value of parameter a at reference conditions: **table 3.6.1-1**
19. Value of parameter I_L at reference conditions: **table 3.6.1-1**
20. Value of parameter I_0 at reference conditions: **table 3.6.1-1**
21. Module series resistance: **table 3.6.1-1**
22. Shunt resistance at reference conditions: **table 3.6.1-1**
23. Extinction coefficient-thickness product of cover: 0.008

The photovoltaic models, used in this simulation, were:

- A zone: "ASE-100-ATF/34 (92)"
- B zone: "ASE-100-ATF/34 (92)"
- C zone: "ASE-100-ATF/34 (100)"
- D zone : "ASE-100-ATF/34 (100)"

Parameters 1, 2, 5, 6, 7, 8, 9, 15, 18, 19, 20, 21, 22 were given or calculated with the use of the "EES" application of TRNSYS, which contained the aforementioned PV models in its library. The parameter values and the number of modules in series are given in **table 3.6.1-1**.

Table 3.6.1-1 Pararameter values of PV array model

Photovoltaic Array	Climatic Zone of Greece			
	A	B	C	D
Module short-circuit current at reference conditions [A]	3	3	3.2	3.2
Module open-circuit voltage at reference conditions [V]	41.6	41.6	42.2	42.2
Module voltage at MPP and reference conditions [V]	34	34	34.4	34.4
Module current at MPP and reference conditions [A]	2.7	2.7	2.9	2.9
Temperature coefficient of Isc at (ref. cond) [1/K]	0.00078	0.00078	0.00078	0.00078
Temperature coefficient of Voc (ref. cond) [V/K]	-0.152	-0.152	-0.152	-0.152
Number of cells wired in series	72	72	72	72
Number of modules in series	7	7	8	8
Module area [m^2]	0.828	0.828	0.828	0.828
Value of parameter a at reference conditions [V]	1.8704	1.8704	1.8826	1.8826
Value of parameter I_L at reference conditions [A]	3.0104	3.0104	3.2102	3.2102
Value of parameter I_0 at reference conditions [A]	$6.195 * 10^{-10}$	$6.195 * 10^{-10}$	$5.595 * 10^{-10}$	$5.595 * 10^{-10}$
Module series resistance [Ω]	0.7812	0.7812	0.7879	0.7879
Shunt resistance at reference conditions [Ω]	225.2	225.2	248.3	248.3

The inputs used in this model are the following:

1. Total incident radiation on tilted surface: taken from the weather module
2. Ambient temperature: taken from the weather module
3. Load Voltage: 220 [V]
4. Array slope: 30^o

5. Beam radiation on tilted surface: taken from the weather module
6. Sky diffuse radiation on tilted surface: taken from the weather module
7. Ground diffuse radiation on tilted surface: taken from the weather module
8. Incidence angle on tilted surface: taken from the weather module
9. Solar zenith angle: taken from the weather module
10. Wind speed: taken from the weather module

3.6.2 Type 48a

Type 48 models an inverter, which converts the DC power to AC and sends it to the load and/or feeds it back to the utility.

3.6.2.1 Mathematical Description

As it is explained in the models manual [21], the power output from the array P_A is simply multiplied by eff_i and sent to the load P_L, with any excess fed back to the utility ($P_U < 0$). When the load exceeds the array output, the utility furnishes the difference ($P_U > 0$). The present version places no limit on the inverter size.

3.6.2.2 Parameters and Inputs

The parameter used in this model is the efficiency, which was set equal to 0.94, as a typical value of an inverter's efficiency.

The inputs used in this model are:

1. Input power: taken from the PV array model
2. Load power: the summation of, GSHP power and liquid pump power.

4 Simulation Results

During the construction of the simulation, one of the main issues was the choice of the GSHP. The model type 504b needed to read the heating/cooling capacity and the power of the GSHP from data files in a certain format. In this format at least two values of the air flow-rate, liquid flow-rate and liquid temperature were needed (for the needs of interpolation), which could not be found in any water-to-air GSHP brochures or technical data catalogs. So the example data files were modified, in order to achieve the required results.

The modification of the data files was made so that the COP and the ratio of sensible to total capacity, of the GSHP, remain steady. Then, by reducing/increasing the total heating/cooling capacity in the respective data files, the GSHP power and sensible capacity were calculated. The step of the increase/decrease of the total capacity was 0.1 [kW].

The choice of the GSHP was made so that over-sizing or under-sizing is avoided. In the case of over-sizing the GSHP overheats/overcools, which means it heats/cools the house outside the defined limits leading to the operation of the heat pump in the opposite mode, that is cooling during heating period and heating during cooling period, in order to correct the air temperature and place it inside the limits. In the case of under-sizing the GSHP operates for more time, in order to achieve the necessary air temperature. According to the air and liquid conditions, entering the GSHP, the heating/cooling capacity is defined, from the corresponding data files.

The GHX was chosen to be a vertical U-tube, because it is easier to find a location to install it, since it needs less surface area. The clay/silt ground was chosen as a typical ground for easy drilling in Greece. The potassium carbonate (K_2CO_3) aqueous solution was chosen, as a circulating liquid for the GHX, to avoid the freezing of the fluid.

The PV array modules were selected and installed, so as to produce enough energy to cover the GSHP needs and have yearly “excess energy” as close as possible to zero with a positive gain for the owner of the house. In the simulation, the term “excess energy” is meant for the summation of energy traded with the grid, which has a positive sign (+)

for the energy bought from the grid and a negative sign (-) for the energy sold to the grid.

4.1 House in climatic zone A of Greece

The aim of the GSHP is to keep the air temperature inside the house between the limits of 20 [^oC] and 26 [^oC].

The GSHP operates in heating mode, from January to June and from October to December. More specifically it operates in an on/off mode, from the 1^{st} hour of the year (1:00, 1^{st} of January) until the 3847^{th} hour of the year (7:00 10^{th} of June) and then reinitiates in the 6557^{th} hour of the year (5:00, 1^{st} of October) until the end of the year. The GSHP operates in heating mode for 899 hours per year (10.26 [%] of the year), in total. The average sensible heating capacity given by the GSHP during the year is 6940.65 [kJ/hr], with a maximum of 7423.17 [kJ/hr], given at the 6920^{th} hour of the year (8:00, 16^{th} of October). In **table 4.1-1** the average sensible heat capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of heating mode operation, of the year and the month.

Table 4.1-1: Values of the GSHP sensible heat transfer to the house in climatic zone A of Greece

Sensible heating (from GSHP to house air) per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	6870.85	6848.07	6835.48	6925.08	7002.71	7120.16	0.00	0.00	0.00	7345.96	7187.58	7004.12
Maximum [kJ/hr]	7150.25	6969.64	6957.32	7104.32	7124.64	7130.95	0.00	0.00	0.00	7423.17	7329.52	7102.95
Minimum [kJ/hr]	364.45	6642.17	6639.39	6774.36	6868.77	7104.00	0.00	0.00	0.00	7281.27	6957.24	6798.36
[%] of the year	2.15%	1.82%	1.74%	1.03%	0.43%	0.06%	0.00%	0.00%	0.00%	0.30%	1.00%	1.75%
[%] of the month	25.30%	23.70%	20.46%	12.52%	5.11%	0.70%	0.00%	0.00%	0.00%	3.50%	12.24%	20.59%

The GSHP operates in an on/off, cooling mode from the 3351^{st} hour of the year (15:00, 20^{th} of May) until the 7025^{th} hour of the year (17:00, 20^{th} of October). It is also needed once in April, at the 2418^{th} hour of the year (18:00, 11^{th} of April). The GSHP operates in cooling mode for 200 hours per year (2.28 [%] of the year), in total. The average sensible cooling capacity transferred by the GSHP during the year is 6189.51 [kJ/hr], with a maximum of 6255.77 [kJ/hr], transferred at the 4833^{rd} hour of the year (9:00, 21^{st} of July). In **table 4.1-2** the average sensible cooling capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of cooling mode operation, of the year and the month.

Table 4.1-2: Values of the GSHP sensible energy transfer rate from the house in climatic zone A of Greece

Sensible cooling (from GSHP to house air) per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	0.00	0.00	0.00	-6202.15	-6203.90	-6196.48	-6200.64	-6189.55	-6163.21	-6164.68	0.00	0.00
Maximum [kJ/hr]	0.00	0.00	0.00	-6202.15	-6220.49	-6234.83	-6255.77	-6232.34	-6197.47	-6193.08	0.00	0.00
Minimum [kJ/hr]	0.00	0.00	0.00	-6202.15	-6183.36	-6165.95	-6140.95	-6143.86	-6127.10	-6130.42	0.00	0.00
[%] of the year	0.00%	0.00%	0.00%	0.01%	0.06%	0.27%	0.75%	0.75%	0.35%	0.08%	0.00%	0.00%
[%] of the month	0.00%	0.00%	0.00%	0.14%	0.67%	3.34%	8.88%	8.88%	4.31%	0.94%	0.00%	0.00%

The GSHP operates the 12.54 [%] of the year in total. During that time it produces 6240 [MJ] of sensible heating energy and 1238 [MJ] of sensible cooling energy. The total heating energy demand of the house is 6.97 [kWh/m^2], while the total cooling energy demand of the house is 1.83 [kWh/m^2]. In **table 4.1-3** the average sensible energy (cooling and heating) can be seen, as well as the percentage, of the GSHP operation, of the year and the month. The plus sign (+) means it operates in heating mode, while the minus sign (-) means the GSHP operates in cooling mode. Also in **diagram 4.1-1** the average sensible energy transfer rate from the GSHP to the house and vice versa, per month, can be seen.

Table 4.1-3: Sensible Energy transfer rate, during the operation of the GSHP in climatic zone A of Greece

Average Sensible cooling+heating (from GSHP to house air) per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
[kJ/hr]	6870.85	6848.07	6835.48	6780.82	5467.06	-3900.50	-6200.64	-6189.55	-6163.21	4480.07	7187.58	7004.12
[%] of the year	2.15%	1.82%	1.74%	1.04%	0.49%	0.33%	0.75%	0.75%	0.35%	0.38%	1.00%	1.75%
[%] of the month	25.30%	23.70%	20.46%	12.66%	5.79%	4.03%	8.88%	8.88%	4.31%	4.44%	12.24%	20.59%

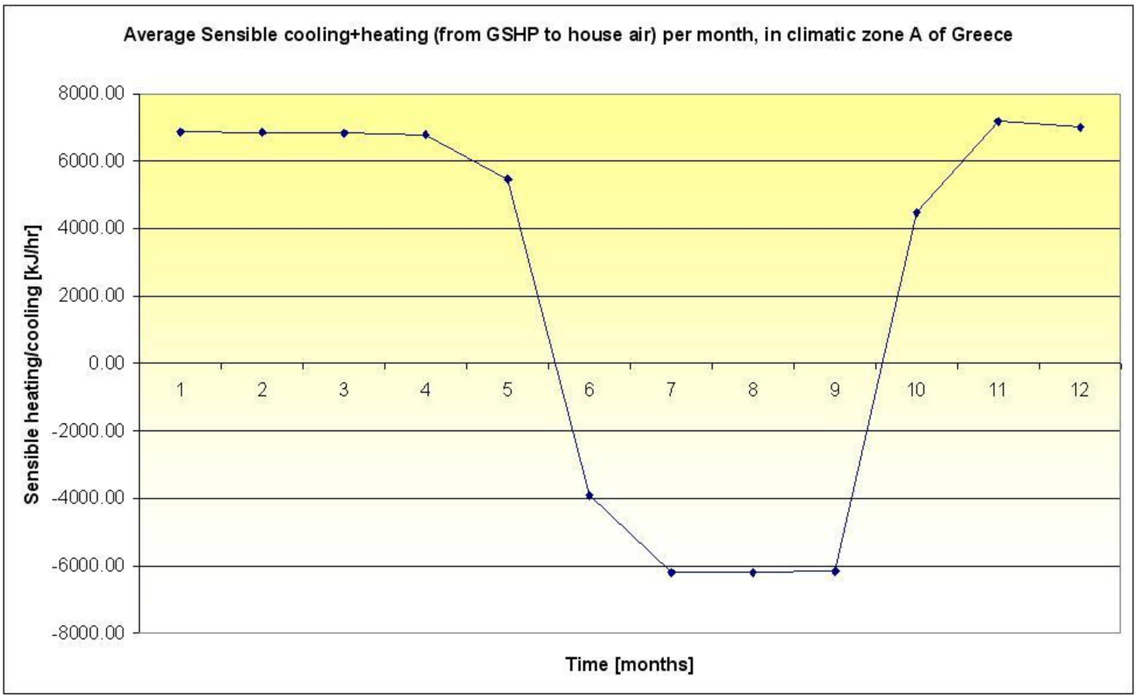

Diagram 4.1-1: Sensible Energy transfer rate per month, during the operation of the GSHP in climatic zone A of Greece

The average temperature of the house is 22.54 [^oC], on a yearly basis, with a maximum of 26.88 [^oC] at the 5009th hour of the year (17:00, 28th of July) and a minimum of 2.61 [^oC] at the 1st hour of January, when the GSHP is just beginning to operate. In **table 4.1-4** the average temperature per month is shown, with the maximum and minimum value. In **diagram 4.1-2** the average temperature per month is shown.

Table 4.1-4: Temperature values of the house air, in climatic zone A of Greece

House Air Temperature per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [°C]	21.40	21.39	21.49	21.86	22.66	23.42	24.16	24.10	23.38	22.98	21.93	21.61
Maximum [°C]	25.26	25.35	25.25	26.17	26.13	26.54	26.88	26.84	26.70	26.53	25.69	25.68
Minimum [°C]	2.61	17.77	17.94	18.56	18.86	19.69	20.70	20.78	20.01	19.22	18.72	18.30

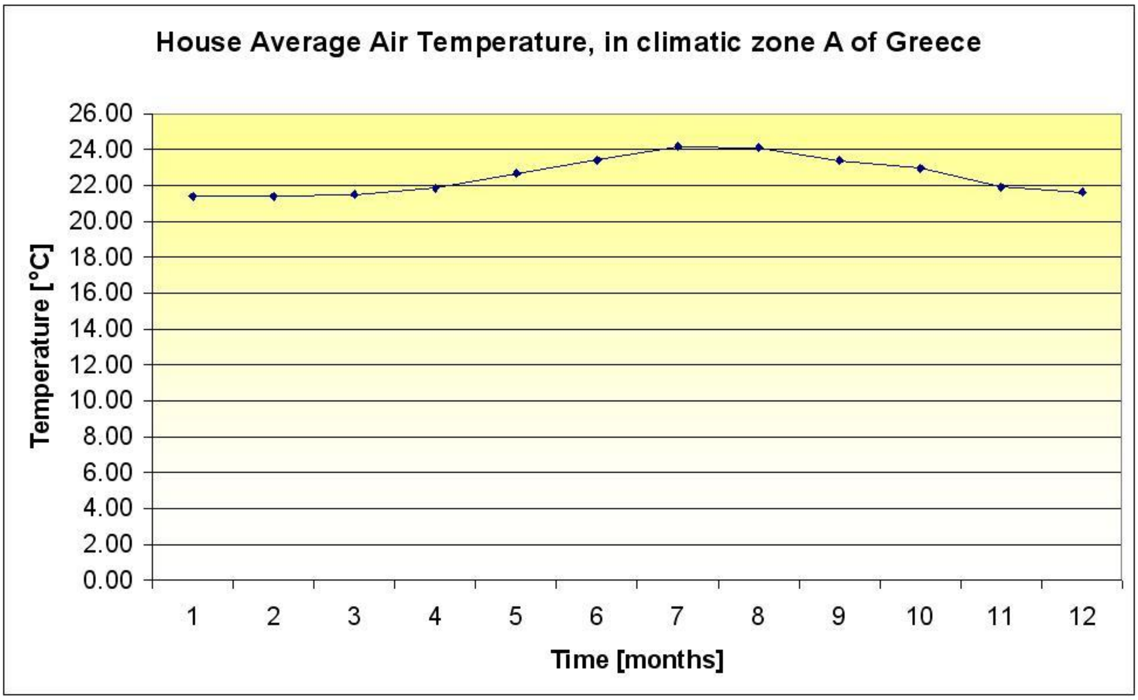

Diagram 4.1-2: Average air temperature of house, in climatic zone A of Greece

The COP of the GSHP has an average, on a yearly basis, of 5.32. The COP during the heating mode operation has an average of 5.31 and the COP during the cooling mode has an average of 5.36. In **table 4.1-5** the average COP per month is shown, with the maximum and the minimum value. In **diagram 4.1-3** the average COP, per month, is shown.

Table 4.1-5: COP values, per month, of GSHP operating in climatic zone A of Greece

COP (of operating GSHP) per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [-]	5.33	5.33	5.31	5.29	5.27	5.29	5.41	5.40	5.26	5.26	5.30	5.32
Maximum [-]	5.70	5.55	5.53	5.44	5.49	5.45	5.76	5.61	5.39	5.36	5.44	5.48
Minimum [-]	3.46	5.18	5.17	5.17	5.18	5.17	5.26	5.24	5.19	5.13	5.19	5.16

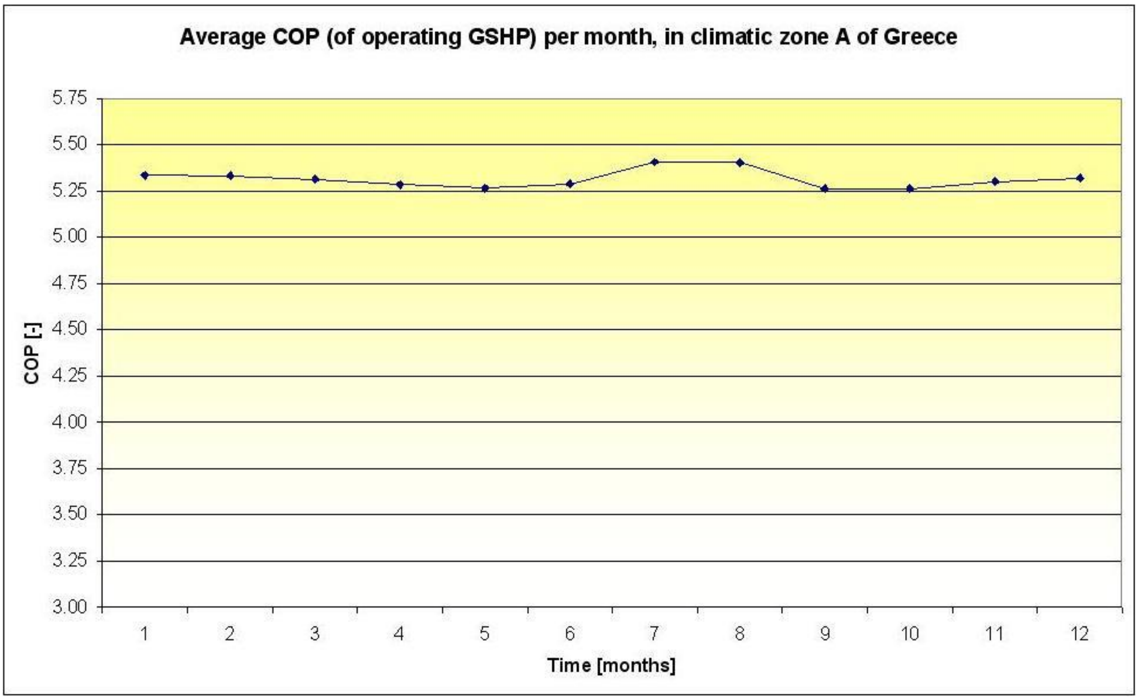

Diagram 4.1-3: Average COP, per month, of GSHP operating in climatic zone A of Greece

The GSHP electric power needed to operate has an average of 0.38 [kW], on a yearly basis. The average power needed during the operation of the GSHP in heating mode is 0.36 [kW] and in cooling mode is 0.43 [kW]. In **table 4.1-6** the average needed power of the GSHP, per month, is shown, as well as the maximum and the minimum value. In **diagram 4.1-4** the average needed power of the GSHP, per month, is shown.

Table 4.1-6: Values of GSHP electric power needed, per month, in climatic zone A of Greece

GSHP electric power per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [kW]	0.36	0.36	0.36	0.37	0.38	0.42	0.43	0.42	0.43	0.40	0.38	0.37
Maximum [kW]	0.38	0.37	0.37	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.39	0.38
Minimum [kW]	0.03	0.34	0.34	0.35	0.36	0.38	0.41	0.41	0.42	0.38	0.36	0.35

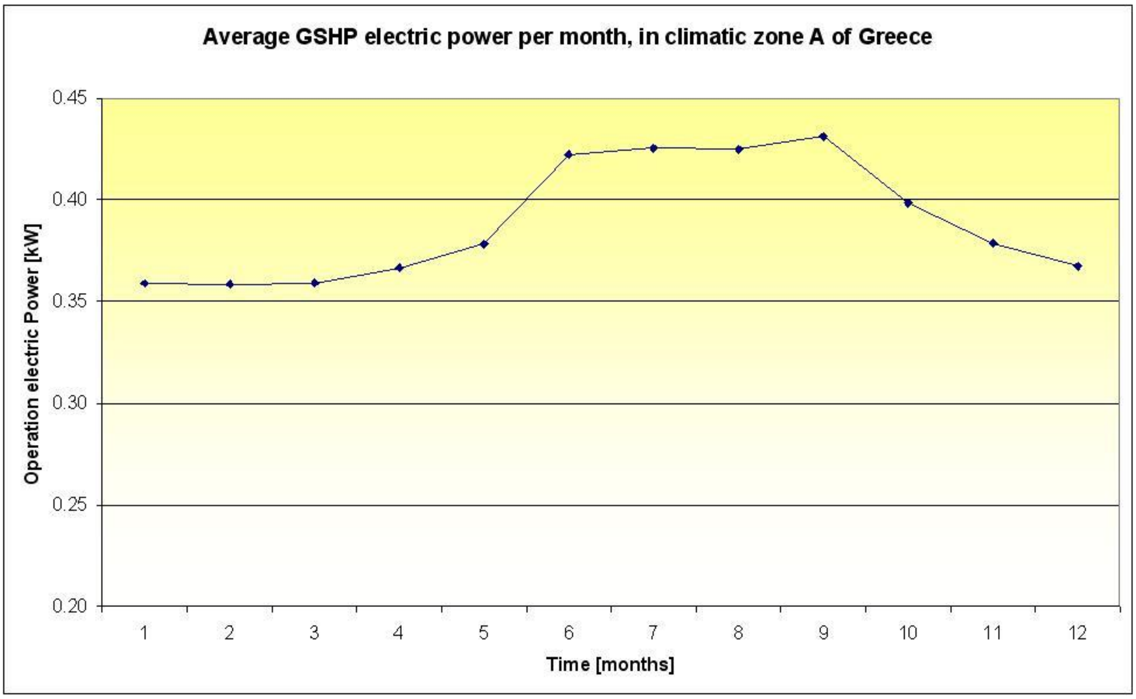

Diagram 4.1-4: Average GSHP electric power needed, per month, in climatic zone A of Greece

The liquid pump operates constantly with 8 [W].

The PV array, with a MPP tracker, produces an average power of 0.3 [kW] on a yearly basis, with a maximum of 0.68 [kW] produced at the 1452nd hour of the year (12:00, 2nd of March) and a minimum of 0.89 [W] produced at the 1735th hour of the year (7:00, 14th of March). The PV array produces energy for 4347 hours per year (49.62 [%] of the year). The peak capacity of the PV array is 0.64 [kW].

While the PV array produces less average energy than the average energy needed from the GSHP, it produces that energy for more hours than the GSHP operation. As a result the excess energy, on a yearly basis, is equal to –501.27 [kWh] (the minus sign meaning gain for the owner of the house). In **table 4.1-7** the excess energy per month is shown, the maximum energy given (-) to the grid and the maximum energy taken (+) from the grid. In **diagram 4.1-5** the excess energy per month is shown.

Table 4.1-7: Values of excess energy per month, of the house in climatic zone A of Greece

Excess Energy per month, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy [kWh]	2.38	0.89	-19.41	-55.73	-68.46	-72.53	-57.29	-54.18	-79.35	-69.48	-35.08	6.98
Maximum bought from the grid [kWh]	0.39	0.38	0.38	0.41	0.40	0.43	0.43	0.44	0.44	0.43	0.40	0.39
Maximum sold to the grid [kWh]	-0.55	-0.59	-0.60	-0.58	-0.55	-0.53	-0.52	-0.53	-0.56	-0.56	-0.57	-0.53

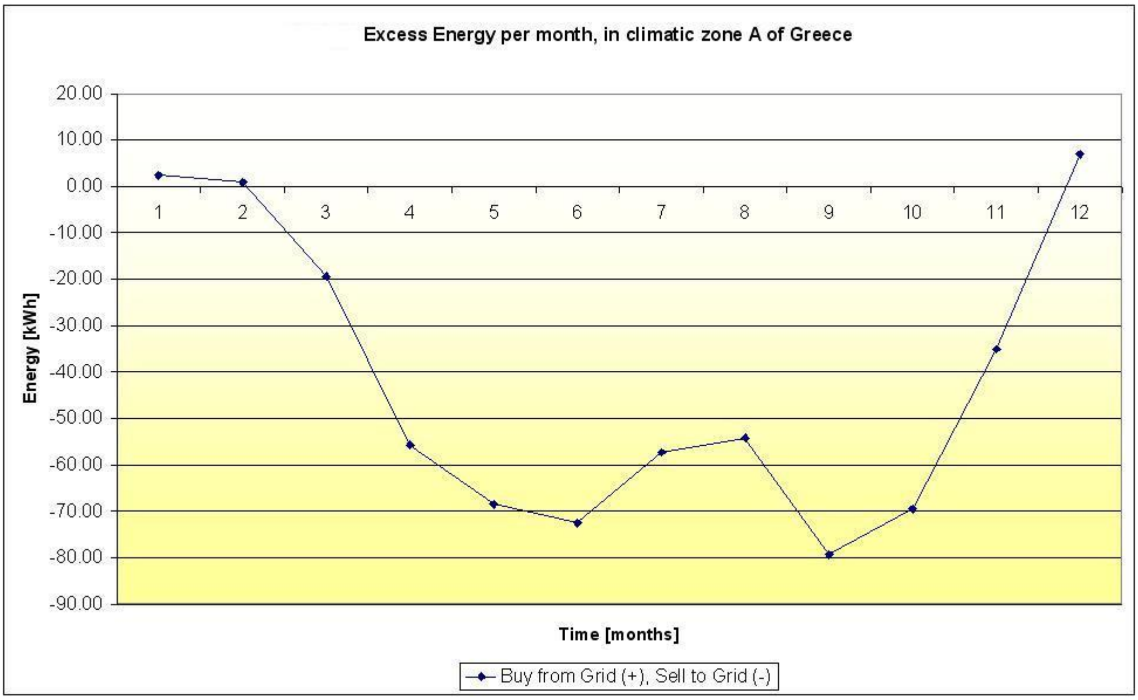

Diagram 4.1-5: Excess energy per month, of the house in climatic zone A of Greece

4.2 House in climatic zone B of Greece

The aim of the GSHP is to keep the air temperature inside the house between the limits of 20 [^oC] and 26 [^oC].

The GSHP operates in heating mode, from January to May and from October to December. It is also sporadically needed during June and September. More specifically it operates in an on/off mode, from the 1st hour of the year (1:00, 1st of January) until the 3316th hour of the year (4:00 19th of May) and then reinitiates in the 6560th hour of the year (8:00, 1st of October) until the end of the year. The GSHP operates in heating mode for 1060 hours per year (12.11 [%] of the year), in total. The average sensible heating capacity given by the GSHP during the year is 6992.60 [kJ/hr], with a maximum of 7612.98 [kJ/hr], given at the 6080th hour of the year (8:00, 11th of September). In **table 4.2-1** the average sensible heat capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of heating mode operation, of the year and the month.

Table 4.2-1: Values of the GSHP sensible heat transfer to the house in climatic zone B of Greece

Sensible heating (from GSHP to house air) per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	6927.80	6867.25	6863.23	6970.28	7085.02	7261.39	0.00	0.00	7574.75	7404.27	7229.86	7046.20
Maximum [kJ/hr]	7239.51	7024.29	7008.65	7088.04	7132.94	7283.13	0.00	0.00	7612.98	7587.60	7355.25	7199.22
Minimum [kJ/hr]	401.80	6655.59	6661.13	6825.03	7028.11	7225.97	0.00	0.00	7543.90	7269.00	7112.42	6797.32
[%] of the year	2.47%	2.16%	1.97%	1.19%	0.37%	0.03%	0.00%	0.00%	0.05%	0.55%	1.30%	2.02%
[%] of the month	29.07%	28.17%	23.28%	14.46%	4.31%	0.42%	0.00%	0.00%	0.56%	6.46%	15.86%	23.82%

The GSHP operates in an on/off, cooling mode from the 3352nd hour of the year (16:00, 20th of May) until the 6546th hour of the year (18:00, 30th of September). It is also needed twice during October. The GSHP operates in cooling mode for 237 hours per year (2.72 [%] of the year), in total. The average sensible cooling capacity transferred by the GSHP during the year is 6407.33 [kJ/hr], with a maximum of 6512.7 [kJ/hr], transferred at the 4075th hour of the year (19:00, 19th of June). In **table 4.2-2** the average sensible cooling capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of cooling mode operation, of the year and the month.

Table 4.2-2: Values of the GSHP sensible energy transfer rate from the house in climatic zone B of Greece

Sensible cooling (from GSHP to house air) per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	0.00	0.00	0.00	0.00	-6455.10	-6447.02	-6409.27	-6389.56	-6391.26	-6404.88	0.00	0.00
Maximum [kJ/hr]	0.00	0.00	0.00	0.00	-6507.84	-6512.70	-6471.98	-6469.91	-6440.93	-6428.98	0.00	0.00
Minimum [kJ/hr]	0.00	0.00	0.00	0.00	-6409.69	-6395.24	-6335.27	-6319.73	-6333.20	-6380.78	0.00	0.00
[%] of the year	0.00%	0.00%	0.00%	0.00%	0.07%	0.41%	0.97%	0.94%	0.30%	0.02%	0.00%	0.00%
[%] of the month	0.00%	0.00%	0.00%	0.00%	0.81%	5.01%	11.44%	11.04%	3.62%	0.27%	0.00%	0.00%

The GSHP operates the 14.83 [%] of the year in total. During that time it produces 7412 [MJ] of sensible heating energy and 1519 [MJ] of sensible cooling energy. The total heating energy demand of the house is 8.27 [kWh/m^2], while the total cooling energy demand of the house is 2.22 [kWh/m^2]. In **table 4.2-3** the average sensible energy (cooling and heating) can be seen, as well as the percentage, of the GSHP operation, of the year and the month. The plus sign (+) means it operates in heating mode, while the minus sign (-) means the GSHP operates in cooling mode. Also in **diagram 4.2-1** the average sensible energy transfer rate from the GSHP to the house and vice versa, per month, can be seen.

Table 4.2-3: Sensible Energy transfer rate, during the operation of the GSHP in climatic zone B of Greece

Average Sensible cooling+heating (from GSHP to house air) per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
[kJ/hr]	6927.80	6867.25	6863.23	6970.28	4947.11	-5392.53	-6409.27	-6389.56	-3591.62	6851.90	7229.86	7046.20
[%] of the year	2.47%	2.16%	1.97%	1.19%	0.43%	0.45%	0.97%	0.94%	0.34%	0.57%	1.30%	2.02%
[%] of the month	29.07%	28.17%	23.28%	14.46%	5.11%	5.42%	11.44%	11.04%	4.17%	6.73%	15.86%	23.82%

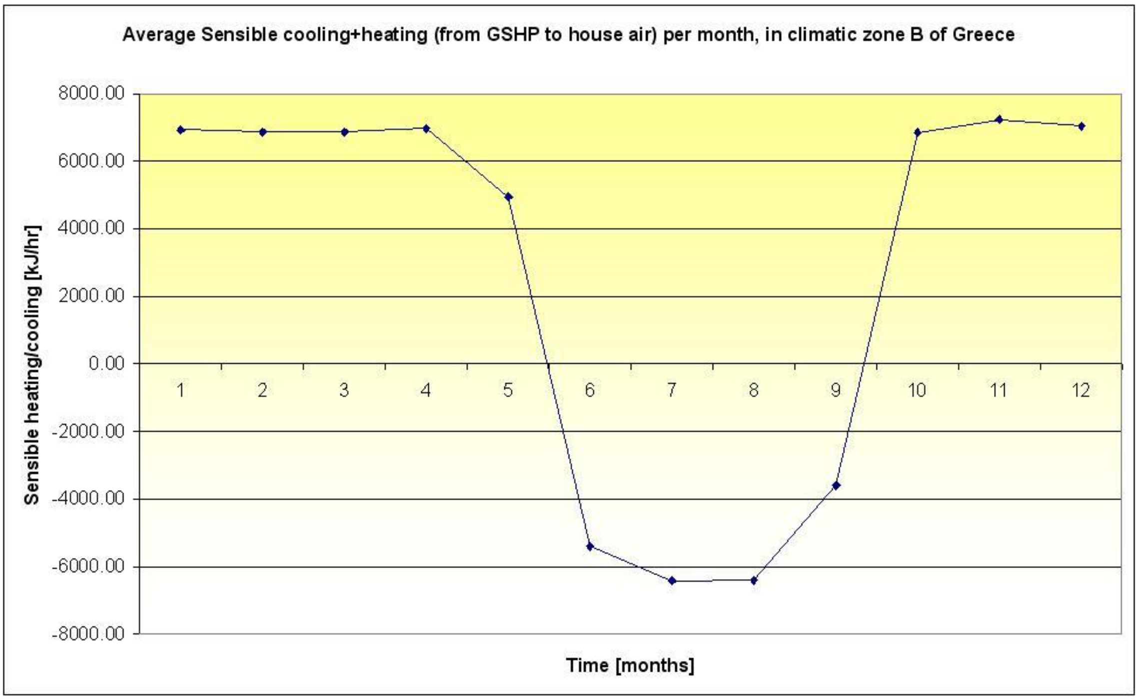

Diagram 4.2-1: Sensible Energy transfer rate per month, during the operation of the GSHP in climatic zone B of Greece

The average temperature of the house is 22.49 [^oC], on a yearly basis, with a maximum of 27.45 [^oC] at the 5511th hour of the year (15:00, 18th of August) and a minimum of 2.44 [^oC] at the 1st hour of January, when the GSHP is just beginning to operate. In **table 4.2-4** the average temperature per month is shown, with the maximum and minimum value. In **diagram 4.2-2** the average temperature per month is shown.

Table 4.2-4: Temperature values of the house air, in climatic zone B of Greece

House Air Temperature per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [^oC]	21.27	21.26	21.48	21.78	22.56	23.66	24.31	24.23	23.49	22.41	21.77	21.54
Maximum [^oC]	25.21	25.15	25.08	25.51	26.32	27.17	27.24	27.45	26.63	26.38	25.56	25.49
Minimum [^oC]	2.44	17.85	17.89	18.56	19.20	19.89	20.72	20.72	19.75	18.75	18.41	17.72

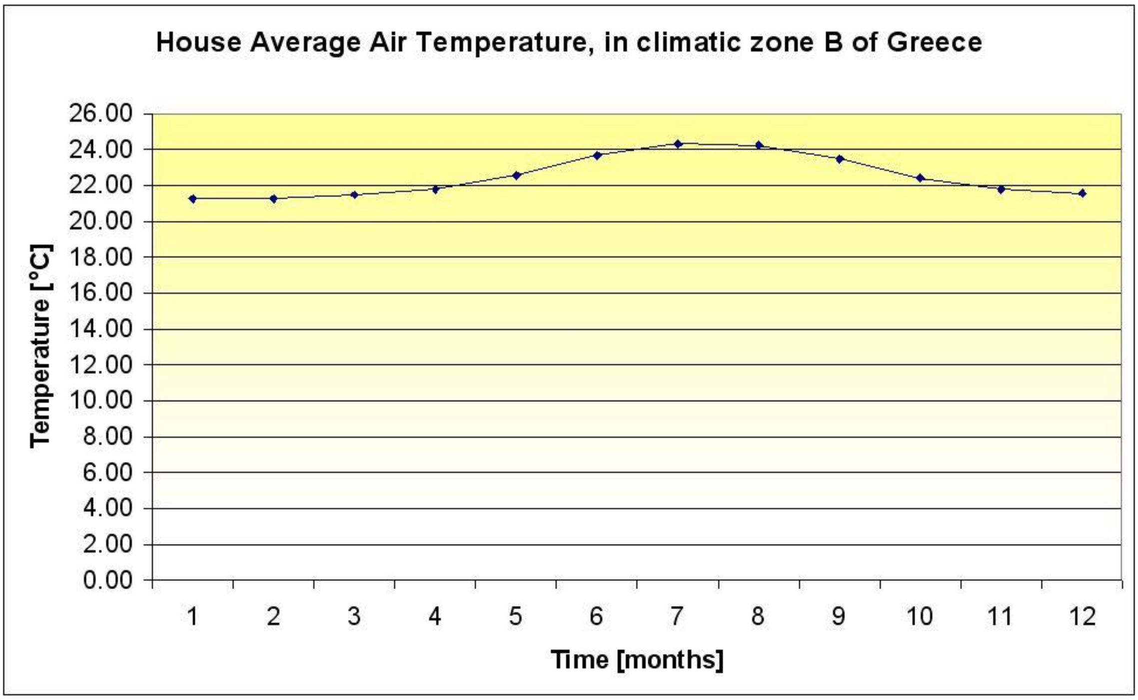

Diagram 4.2-2: Average air temperature of house, in climatic zone B of Greece

The COP of the GSHP has an average, on a yearly basis, of 5.23. The COP during the heating mode operation has an average of 5.29 and the COP during the cooling mode has an average of 4.95. In **table 4.2-5** the average COP per month is shown, with the maximum and the minimum value. In **diagram 4.2-3** the average COP, per month, is shown.

Table 4.2-5: COP values, per month, of GSHP operating in climatic zone B of Greece

COP (of operating GSHP) per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [-]	5.33	5.32	5.28	5.25	5.20	5.09	4.93	4.89	5.01	5.25	5.28	5.31
Maximum [-]	5.67	5.52	5.50	5.40	5.35	5.35	5.32	5.26	5.25	5.39	5.44	5.53
Minimum [-]	3.81	5.16	5.16	5.14	4.90	4.74	4.60	4.62	4.68	5.01	5.17	5.15

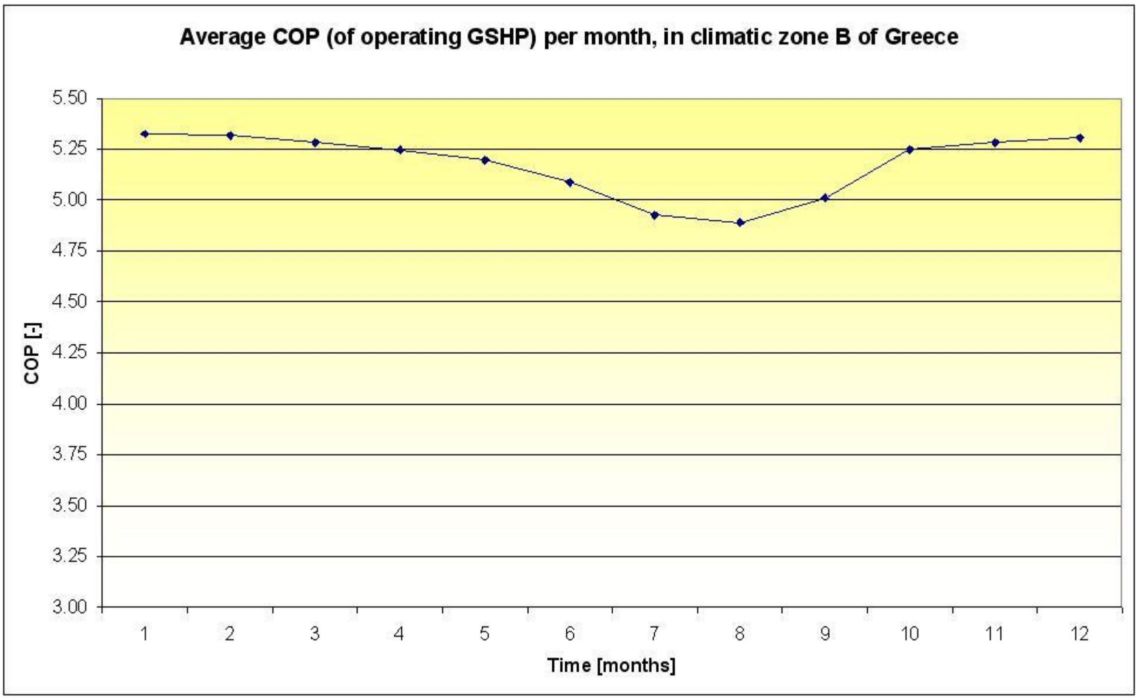

Diagram 4.2-3: Average COP, per month, of GSHP operating in climatic zone B of Greece

The GSHP electric power needed to operate has an average of 0.39 [kW], on a yearly basis. The average power needed during the operation of the GSHP in heating mode is 0.37 [kW] and in cooling mode is 0.47 [kW]. In **table 4.2-6** the average needed power of the GSHP, per month, is shown, as well as the maximum and the minimum value. In **diagram 4.2-4** the average needed power of the GSHP, per month, is shown.

Table 4.2-6: Values of GSHP electric power needed, per month, in climatic zone B of Greece

GSHP electric power per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [kW]	0.36	0.36	0.36	0.37	0.39	0.46	0.48	0.48	0.46	0.40	0.38	0.37
Maximum [kW]	0.38	0.38	0.38	0.38	0.47	0.49	0.50	0.50	0.49	0.46	0.39	0.39
Minimum [kW]	0.03	0.34	0.35	0.36	0.37	0.39	0.45	0.45	0.40	0.38	0.37	0.35

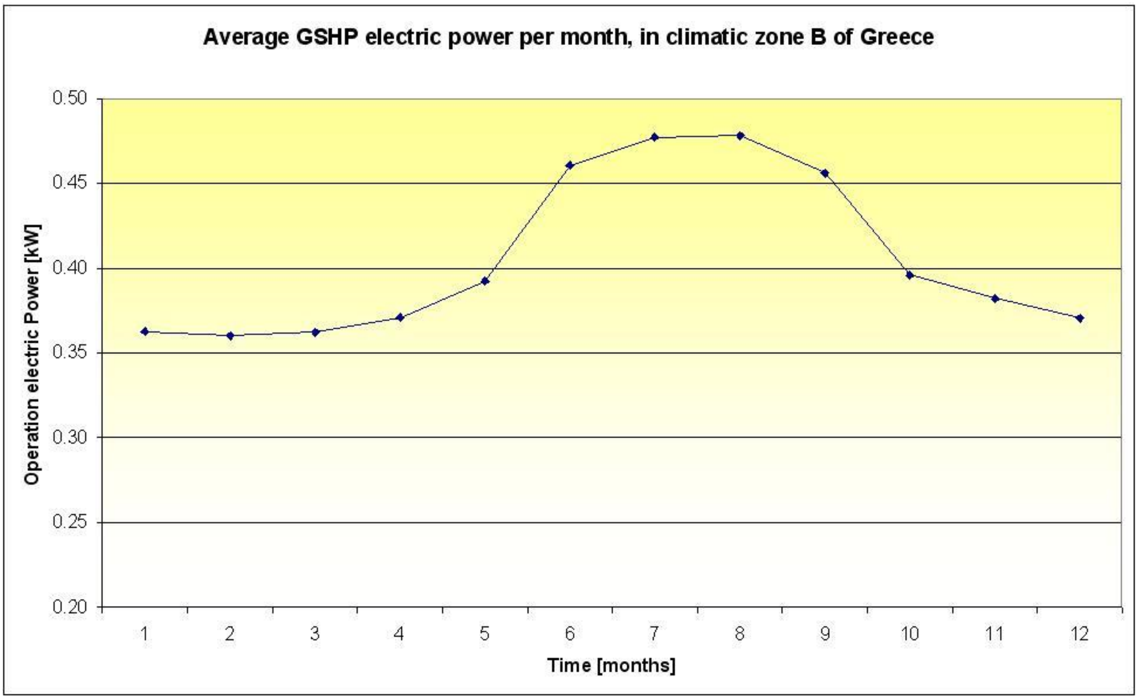

Diagram 4.2-4: Average GSHP electric power needed, per month, in climatic zone B of Greece

The liquid pump operates constantly with 8 [W].

The PV array, with a MPP tracker, produces an average power of 0.24 [kW] on a yearly basis, with a maximum of 0.66 [kW] produced at the 2077th hour of the year (13:00, 28th of March) and a minimum of 0.57 [W] produced at the 7074th hour of the year (18:00, 22nd of October). The PV array produces energy for 4351 hours per year (49.67 [%] of the year). The peak capacity of the PV array is 0.64 [kW].

While the PV array produces less average energy than the average energy needed from the GSHP, it produces that energy for more hours than the GSHP operation. As a result the excess energy, on a yearly basis, is equal to –196.54 [kWh] (the minus sign meaning gain for the owner of the house). In **table 4.2-7** the excess energy per month is shown, the maximum energy given (-) to the grid and the maximum energy taken (+) from the grid. In **diagram 4.2-5** the excess energy per month is shown.

Table 4.2-7: Values of excess energy per month, of the house in climatic zone B of Greece

Excess Energy per month, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy [kWh]	40.63	29.32	14.89	-27.35	-59.58	-61.32	-45.98	-49.35	-60.21	-31.44	11.61	42.25
Maximum bought from the grid [kWh]	0.39	0.38	0.39	0.39	0.45	0.47	0.50	0.50	0.48	0.45	0.40	0.39
Maximum sold to the grid [kWh]	-0.49	-0.54	-0.58	-0.57	-0.54	-0.52	-0.51	-0.51	-0.54	-0.52	-0.49	-0.47

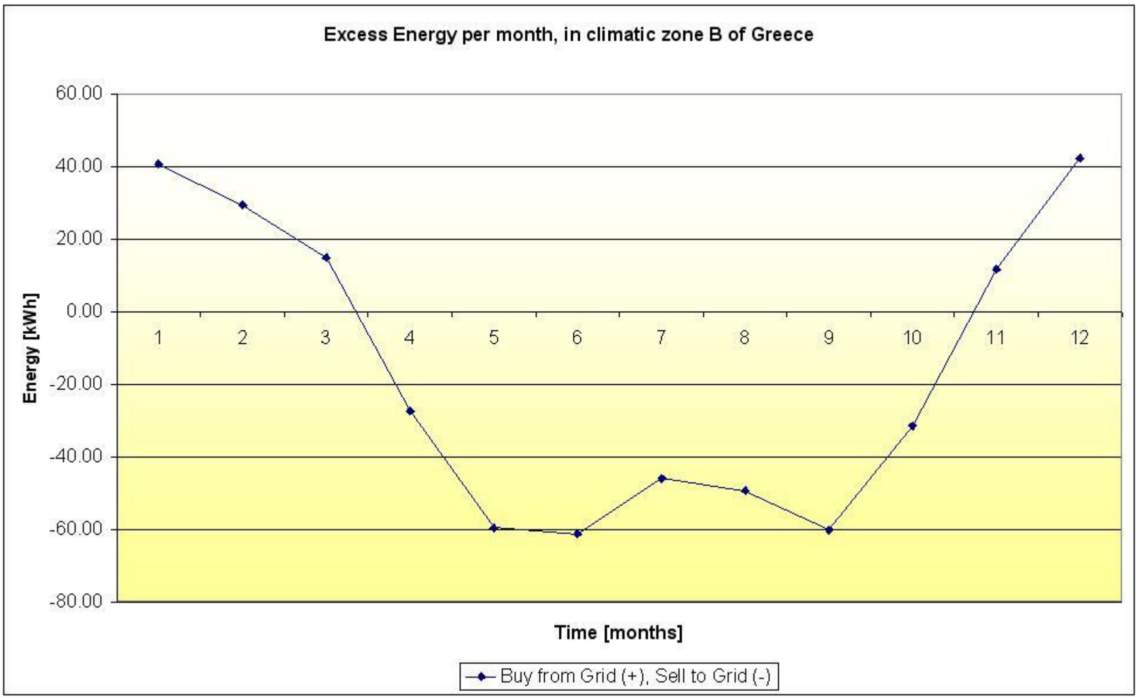

Diagram 4.2-5: Excess energy per month, of the house in climatic zone B of Greece

4.3 House in climatic zone C of Greece

The aim of the GSHP is to keep the air temperature inside the house between the limits of 20 [^{o}C] and 26 [^{o}C].

The GSHP operates in heating mode, from January to June and from September to December. It is also sporadically needed during August. More specifically it operates in an on/off mode, from the 1st hour of the year (1:00, 1st of January) until the 4279th hour of the year (7:00 28th of June) and then reinitiates in the 6005th hour of the year (5:00, 8th of September) until the end of the year. The GSHP operates in heating mode for 1703 hours per year (19.44 [%] of the year), in total. The average sensible heating capacity given by the GSHP during the year is 6359.42 [kJ/hr], with a maximum of 7156.74 [kJ/hr], given at the 6029th hour of the year (5:00, 9th of September). In **table 4.3-1** the average sensible heat capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of heating mode operation, of the year and the month.

Table 4.3-1: Values of the GSHP sensible heat transfer to the house in climatic zone C of Greece

Sensible heating capacity of GSHP in climatic zone C of Greece												
Month	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
Average [kJ/hr]	6269.89	6184.74	6224.75	6391.72	6564.06	6827.84	0.00	7090.73	7025.67	6830.78	6564.49	6298.22
Maximum [kJ/hr]	6704.22	6368.70	6451.45	6557.05	6848.04	7001.67	0.00	7106.43	7156.74	7087.45	6759.89	6561.98
Minimum [kJ/hr]	476.55	5853.14	5888.51	6173.85	6394.86	6725.79	0.00	7075.03	6961.55	6546.46	6307.93	5913.71
[%] of the year	3.85%	3.15%	2.77%	1.66%	0.66%	0.11%	0.00%	0.02%	0.29%	1.16%	2.34%	3.42%
[%] of the month	45.36%	41.13%	32.71%	20.17%	7.81%	1.39%	0.00%	0.27%	3.48%	13.73%	28.51%	40.38%

The GSHP operates in an on/off, cooling mode from the 3351st hour of the year (15:00, 20th of May) until the 6544th hour of the year (16:00, 30th of September). The GSHP operates in cooling mode for 173 hours per year (1.97 [%] of the year), in total. The average sensible cooling capacity transferred by the GSHP during the year is 7113.87 [kJ/hr], with a maximum of 7239.68 [kJ/hr], transferred at the 4839th hour of the year (15:00, 21st of July). In **table 4.3-2** the average sensible cooling capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of cooling mode operation, of the year and the month.

Table 4.3-2: Values of the GSHP sensible energy transfer rate from the house in climatic zone C of Greece

Sensible cooling (from GSHP to air of house in climatic zone C of Greece)												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [kJ/hr]	0.00	0.00	0.00	0.00	-7106.13	-7115.97	-7118.97	-7110.66	-7101.64	0.00	0.00	0.00
Maximum [kJ/hr]	0.00	0.00	0.00	0.00	-7197.85	-7186.56	-7239.68	-7190.59	-7149.91	0.00	0.00	0.00
Minimum [kJ/hr]	0.00	0.00	0.00	0.00	-7063.24	-7019.17	-7036.66	-7023.90	-7024.24	0.00	0.00	0.00
[%] of the year	0.00%	0.00%	0.00%	0.00%	0.13%	0.39%	0.72%	0.62%	0.13%	0.00%	0.00%	0.00%
[%] of the month	0.00%	0.00%	0.00%	0.00%	1.48%	4.73%	8.48%	7.27%	1.53%	0.00%	0.00%	0.00%

The GSHP operates the 21.41 [%] of the year in total. During that time it produces 10830 [MJ] of sensible heating energy and 1231 [MJ] of sensible cooling energy. The total heating energy demand of the house is 12.08 [kWh/m^2], while the total cooling energy demand of the house is 1.82 [kWh/m^2]. In **table 4.3-3** the average sensible energy (cooling and heating) can be seen, as well as the percentage, of the GSHP operation, of the year and the month. The plus sign (+) means it operates in heating mode, while the minus sign (-) means the GSHP operates in cooling mode. Also in **diagram 4.3-1** the average sensible energy transfer rate from the GSHP to the house and vice versa, per month, can be seen.

Table 4.3-3: Sensible Energy transfer rate, during the operation of the GSHP in climatic zone C of Greece

Average Sensible cooling+heating (from GSHP to air of the house in climatic zone C of Greece)												
Month	January	February	March	April	May	June	July	August	September	October	November	December
[kJ/hr]	6269.89	6184.74	6224.75	6391.72	4384.75	-3946.92	-7118.97	-6603.47	2709.00	6830.78	6564.49	6298.22
[%] of year	3.85%	3.15%	2.77%	1.66%	0.79%	0.50%	0.72%	0.64%	0.41%	1.16%	2.34%	3.42%
[%] of month	45.36%	41.13%	32.71%	20.17%	9.29%	6.12%	8.48%	7.54%	5.01%	13.73%	28.51%	40.38%

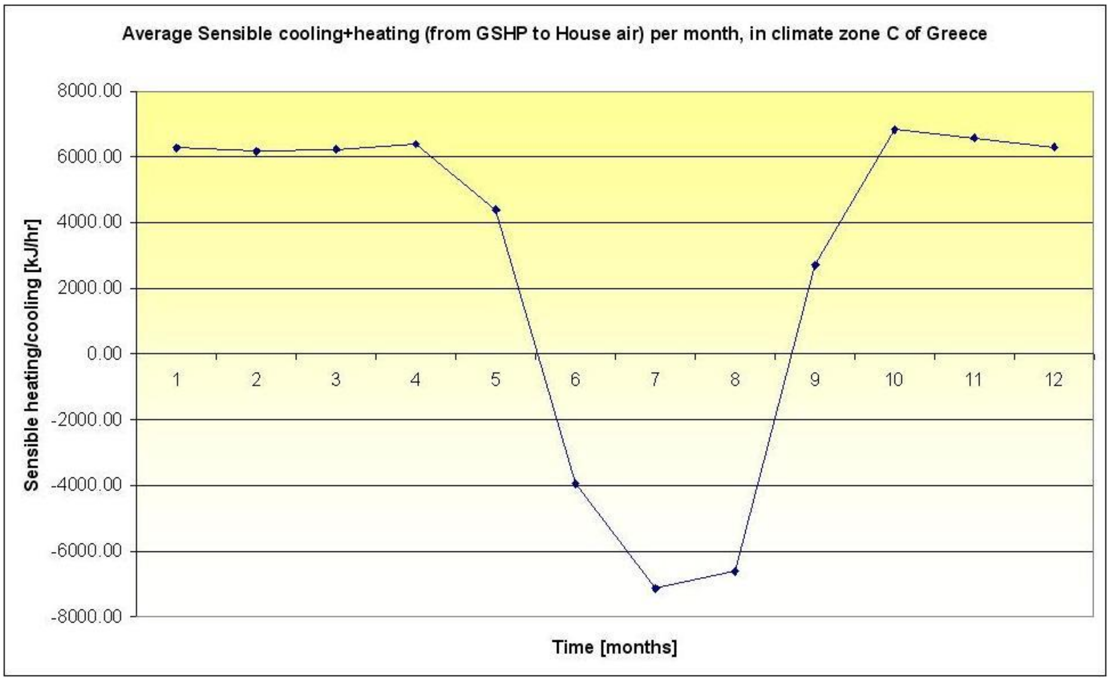

Diagram 4.3-1: Sensible Energy transfer rate per month, during the operation of the GSHP in climatic zone C of Greece

The average temperature of the house is 21.87 [^{o}C], on a yearly basis, with a maximum of 27.36 [^{o}C] at the 4838th hour of the year (14:00, 21st of July) and a minimum of 1.59 [^{o}C] at the 1st hour of January, when the GSHP is just beginning to operate. In **table 4.3-4** the average temperature per month is shown, with the maximum and minimum value. In **diagram 4.3-2** the average temperature per month is shown.

Table 4.3-4: Temperature values of the house air, in climatic zone C of Greece

House Air Temperature per month, in climatic zone C of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [^{o}C]	20.28	20.59	20.90	21.48	22.25	23.13	23.74	23.66	22.87	21.75	21.14	20.57
Maximum [^{o}C]	23.80	24.07	24.78	24.96	26.54	27.05	27.36	27.10	26.96	25.90	24.86	24.95
Minimum [^{o}C]	1.59	17.03	17.12	17.96	18.96	19.45	20.13	19.56	19.20	18.16	17.02	16.93

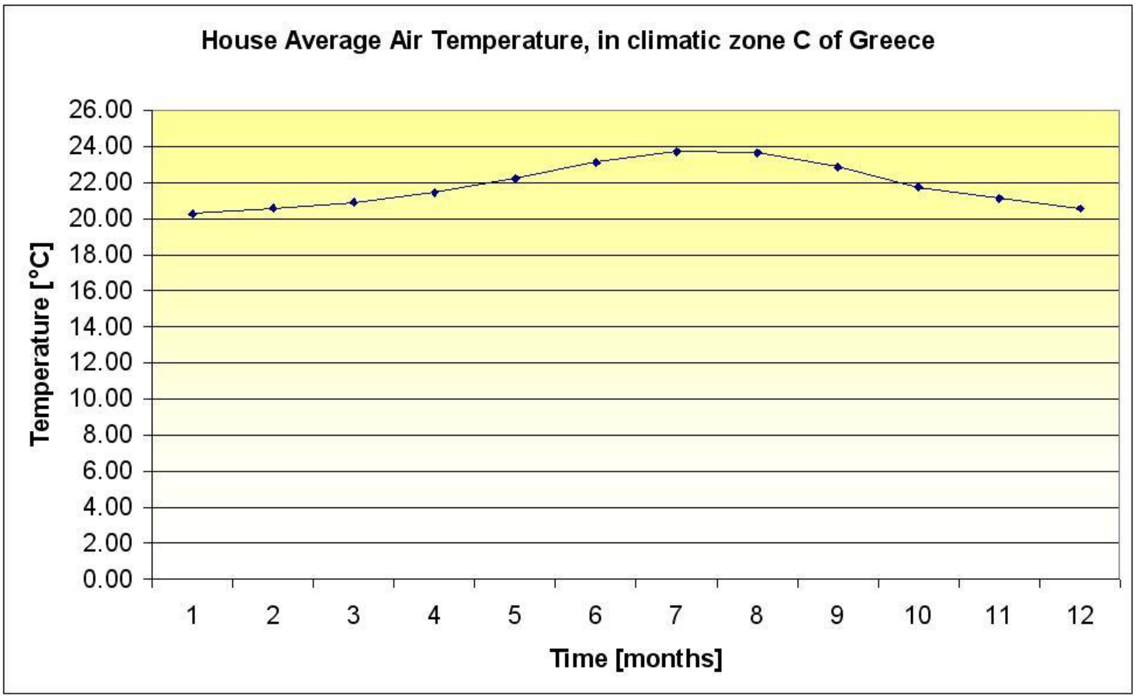

Diagram 4.3-2: Average air temperature of house, in climatic zone C of Greece

The COP of the GSHP has an average, on a yearly basis, of 5.21. The COP during the heating mode operation has an average of 5.21 and the COP during the cooling mode has an average of 5.26. In **table 4.3-5** the average COP per month is shown, with the maximum and the minimum value. In **diagram 4.3-3** the average COP, per month, is shown.

Table 4.3-5: COP values, per month, of GSHP operating in climatic zone C of Greece

COP (of operating GSHP) per month, in climatic zone C of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [-]	5.27	5.22	5.18	5.14	5.10	5.18	5.26	5.30	5.18	5.17	5.21	5.24
Maximum [-]	5.58	5.48	5.44	5.34	5.47	5.85	5.73	5.74	5.83	5.37	5.52	5.50
Minimum [-]	4.52	5.03	4.99	5.00	4.95	4.92	4.87	4.88	4.87	5.06	5.04	5.01

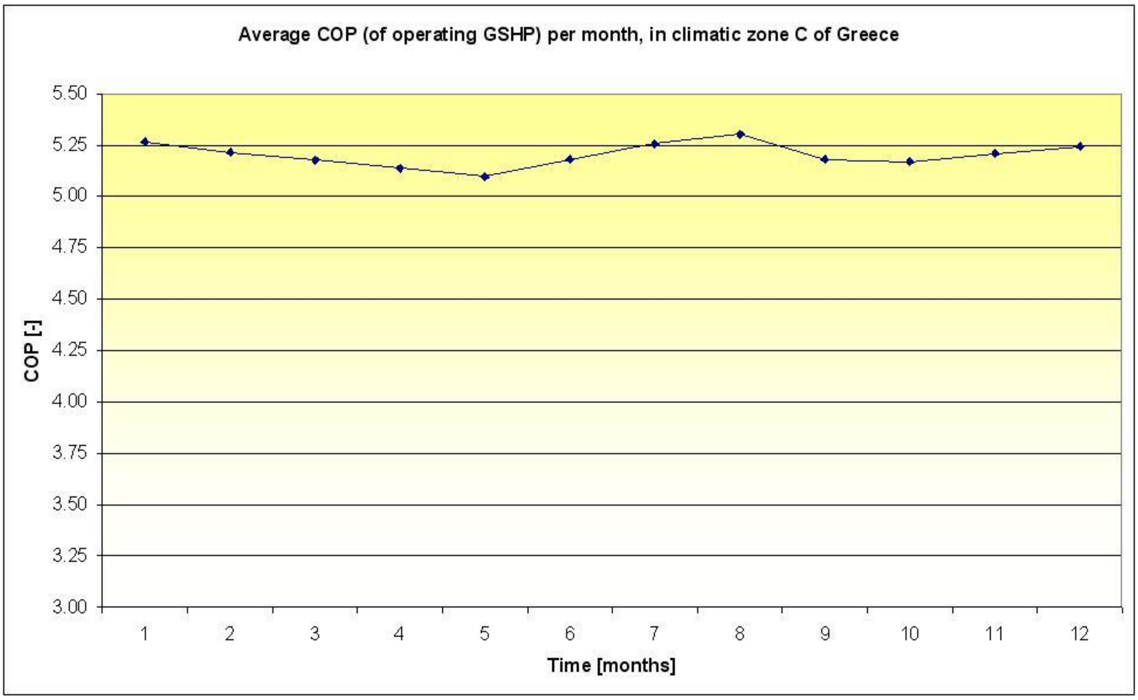

Diagram 4.3-3: Average COP, per month, of GSHP operating in climatic zone C of Greece

The GSHP electric power needed to operate has an average of 0.36 [kW], on a yearly basis. The average power needed during the operation of the GSHP in heating mode is 0.34 [kW] and in cooling mode is 0.50 [kW]. In **table 4.3-6** the average needed power of the GSHP, per month, is shown, as well as the maximum and the minimum value. In **diagram 4.3-4** the average needed power of the GSHP, per month, is shown.

Table 4.3-6: Values of GSHP electric power needed, per month, in climatic zone C of Greece

GSHP electric power per month, in climatic zone C of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [kW]	0.33	0.33	0.34	0.35	0.38	0.48	0.50	0.49	0.42	0.37	0.35	0.34
Maximum [kW]	0.36	0.35	0.35	0.36	0.52	0.53	0.54	0.53	0.53	0.38	0.37	0.36
Minimum [kW]	0.03	0.31	0.32	0.33	0.35	0.37	0.47	0.39	0.38	0.35	0.33	0.31

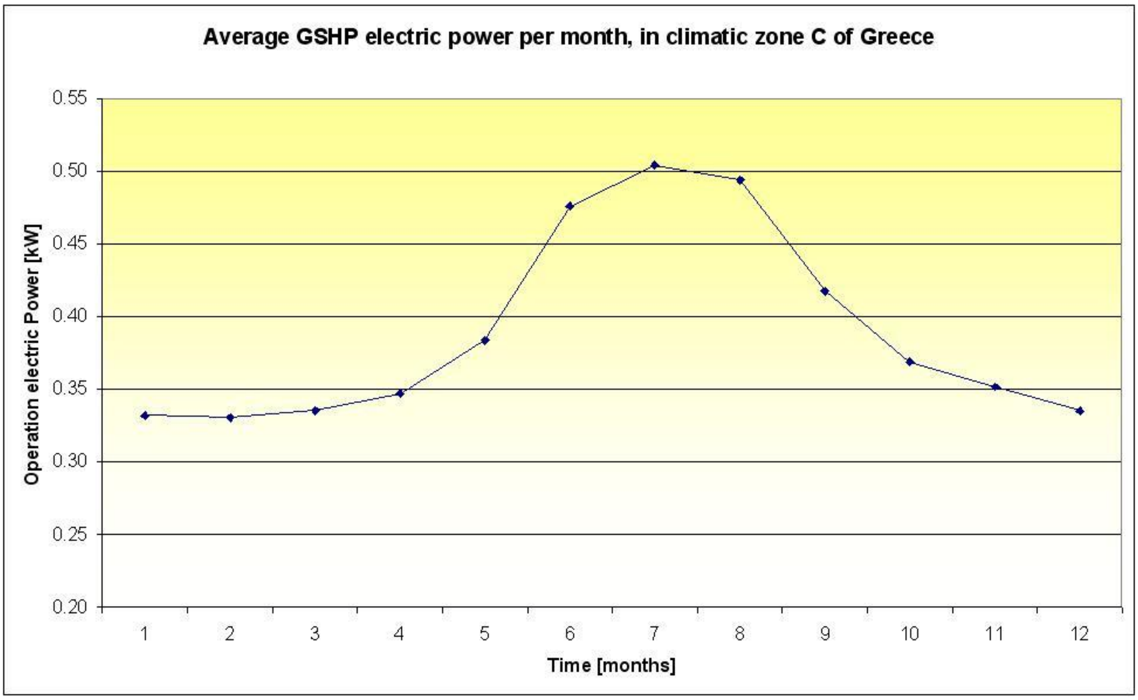

Diagram 4.3-4: Average GSHP electric power needed, per month, in climatic zone C of Greece

The liquid pump operates constantly with 8 [W].

The PV array, with a MPP tracker, produces an average power of 0.24 [kW] on a yearly basis, with a maximum of 0.82 [kW] produced at the 1573rd hour of the year (13:00, 7th of March) and a minimum of 0.66 [W] produced at the 5108th hour of the year (20:00, 1st of August). The PV array produces energy for 4353 hours per year (49.69 [%] of the year). The peak capacity of the PV array is 0.8 [kW].

While the PV array produces less average energy than the average energy needed from the GSHP, it produces that energy for more hours than the GSHP operation. As a result the excess energy, on a yearly basis, is equal to –36.27 [kWh] (the minus sign meaning gain for the owner of the house). In **table 4.3-7** the excess energy per month is shown, the maximum energy given (-) to the grid and the maximum energy taken (+) from the grid. In **diagram 4.3-5** the excess energy per month is shown.

Table 4.3-7: Values of excess energy per month, of the house in climatic zone C of Greece

Excess Energy per month, in climatic zone C of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy [kWh]	82.56	56.58	28.06	-22.43	-57.37	-65.93	-58.35	-58.74	-55.75	-8.07	43.91	79.25
Maximum bought form the grid [kWh]	0.37	0.36	0.36	0.37	0.50	0.52	0.53	0.52	0.51	0.39	0.38	0.37
Maximum sold to the grid [kWh]	-0.64	-0.71	-0.74	-0.65	-0.65	-0.65	-0.65	-0.65	-0.67	-0.65	-0.66	-0.65

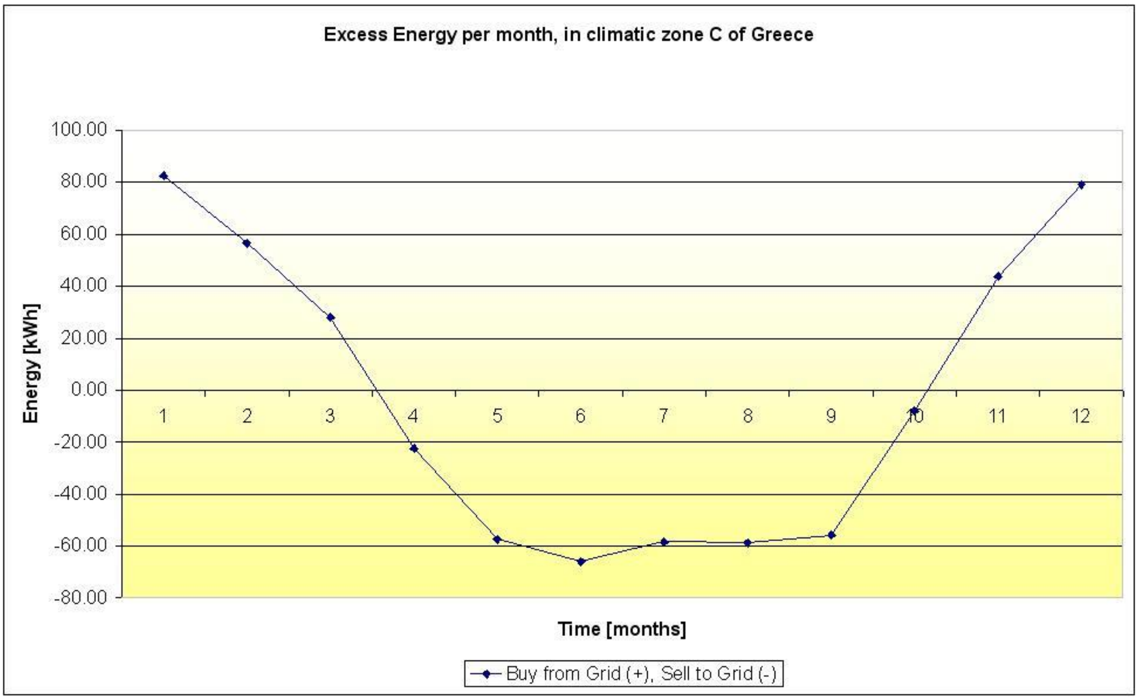

Diagram 4.3-5: Excess energy per month, of the house in climatic zone C of Greece

4.4 House in climatic zone D of Greece

The aim of the GSHP is to keep the air temperature inside the house between the limits of 20 [^{o}C] and 28 [^{o}C]. The thermostat's upper limit has been increased in comparison with the other climatic zones, because of the cold climate of zone D. When the 26 [^{o}C] limit was used, overcooling phenomena appeared while trying to cover the cooling needs of the house. The GSHP, with a low enough power so that it did not present any overcooling phenomena, could not cover the heating needs of the house during the winter and the months March, April and November. In climatic zone D of Greece the heating is most needed, while the cooling, with a 26 [^{o}C] limit, is needed for 57 hours per year (0.65 [%] of the year).

The GSHP operates in heating mode, throughout the year, for 2265 hours (25.86 [%] of the year. The average sensible heating capacity given by the GSHP during the year is 6435.95 [kJ/hr], with a maximum of 7160.95 [kJ/hr], given at the 5839th hour of the year (7:00, 1st of September). In **table 4.4-1** the average sensible heat capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of heating mode operation, of the year and the month.

Table 4.4-1: Values of the GSHP sensible heat transfer to the house in climatic zone D of Greece

Sensible heating (from GSHP to house air) per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	6385.76	6214.14	6244.83	6449.55	6594.70	6795.27	6957.17	7018.57	6970.99	6806.15	6537.93	6278.68
Maximum [kJ/hr]	6840.52	6494.28	6523.41	6628.40	6819.08	6966.57	7090.27	7151.23	7160.95	6972.54	6756.63	6535.83
Minimum [kJ/hr]	1903.63	5767.44	5878.62	6215.19	6303.43	6635.17	6847.18	6878.81	6817.42	6574.64	6099.17	5808.30
[%] of the year	4.18%	3.79%	3.38%	2.25%	1.20%	0.61%	0.33%	0.40%	0.91%	1.84%	3.00%	3.97%
[%] of the month	49.26%	49.48%	39.84%	27.40%	14.13%	7.37%	3.90%	4.71%	11.13%	21.67%	36.58%	46.84%

The GSHP operates in an on/off, cooling mode from the 4073rd hour of the year (17:00, 19th of June) until the 5826th hour of the year (18:00, 31st of August). The GSHP operates in cooling mode for 24 hours per year (0.27 [%] of the year), in total. The average sensible cooling capacity transferred by the GSHP during the year is 8674.20 [kJ/hr], with a maximum of 8779.03 [kJ/hr], transferred at the 4840th hour of the year (16:00, 21st of July). In **table 4.4-2** the average sensible cooling capacity per month can be seen, with the maximum and minimum value, as well as the percentage, of cooling mode operation, of the year and the month.

Table 4.4-2: Values of the GSHP sensible energy transfer rate from the house in climatic zone D of Greece

Sensible cooling (from GSHP to house air) per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average[kJ/hr]	0.00	0.00	0.00	0.00	0.00	-8679.65	-8684.30	-8659.43	0.00	0.00	0.00	0.00
Maximum [kJ/hr]	0.00	0.00	0.00	0.00	0.00	-8720.88	-8779.03	-8727.03	0.00	0.00	0.00	0.00
Minimum [kJ/hr]	0.00	0.00	0.00	0.00	0.00	-8655.63	-8637.97	-8601.82	0.00	0.00	0.00	0.00
[%] of the year	0.00%	0.00%	0.00%	0.00%	0.00%	0.05%	0.13%	0.10%	0.00%	0.00%	0.00%	0.00%
[%] of the month	0.00%	0.00%	0.00%	0.00%	0.00%	0.56%	1.48%	1.21%	0.00%	0.00%	0.00%	0.00%

The GSHP operates the 26.13 [%] of the year in total. During that time it produces 14571 [MJ] of sensible heating energy and 208 [MJ] of sensible cooling energy. The total heating energy demand of the house is 16.24 [kWh/m^2], while the total cooling energy demand of the house is 0.31 [kWh/m^2]. In **table 4.4-3** the average sensible energy (cooling and heating) can be seen, as well as the percentage, of the GSHP operation, of the year and the month. The plus sign (+) means it operates in heating mode, while the minus sign (-) means the GSHP operates in cooling mode. Also in **diagram 4.4-1** the average sensible energy transfer rate from the GSHP to the house and vice versa, per month, can be seen.

Table 4.4-3: Sensible Energy transfer rate, during the operation of the GSHP in climatic zone D of Greece

Average Sensible cooling+heating (from GSHP to house air) per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
[kJ/hr]	6385.76	6214.14	6244.83	6449.55	6594.70	5709.31	2655.76	3811.71	6970.99	6806.15	6537.93	6278.68
[%] of the year	4.18%	3.79%	3.38%	2.25%	1.20%	0.65%	0.46%	0.50%	0.91%	1.84%	3.00%	3.97%
[%] of the month	49.26%	49.48%	39.84%	27.40%	14.13%	7.93%	5.38%	5.92%	11.13%	21.67%	36.58%	46.84%

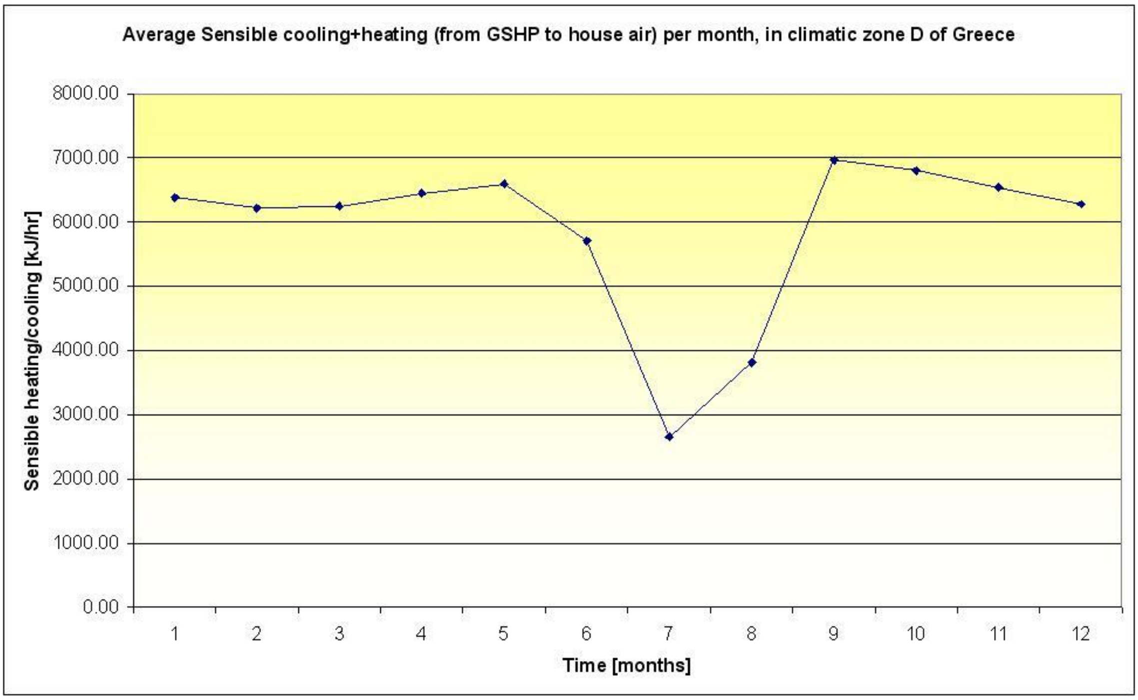

Diagram 4.4-1: Sensible Energy transfer rate per month, during the operation of the GSHP in climatic zone D of Greece

The average temperature of the house is 21.57 [^oC], on a yearly basis, with a maximum of 28.92 [^oC] at the 4839th hour of the year (15:00, 21st of July) and a minimum of 2.63 [^oC] at the 1st hour of January, when the GSHP is just beginning to operate. In **table 4.4-4** the average temperature per month is shown, with the maximum and minimum value. In **diagram 4.4-2** the average temperature per month is shown.

Table 4.4-4: Temperature values of the house air, in climatic zone D of Greece

House Air Temperature per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [^oC]	20.05	20.06	20.58	21.29	22.01	22.95	23.61	23.37	22.20	21.58	20.86	20.18
Maximum [^oC]	24.08	24.42	24.89	25.36	27.53	28.42	28.92	28.67	26.12	25.96	25.16	24.48
Minimum [^oC]	2.63	15.94	16.49	17.18	17.88	18.72	18.81	18.99	18.34	17.57	16.90	16.28

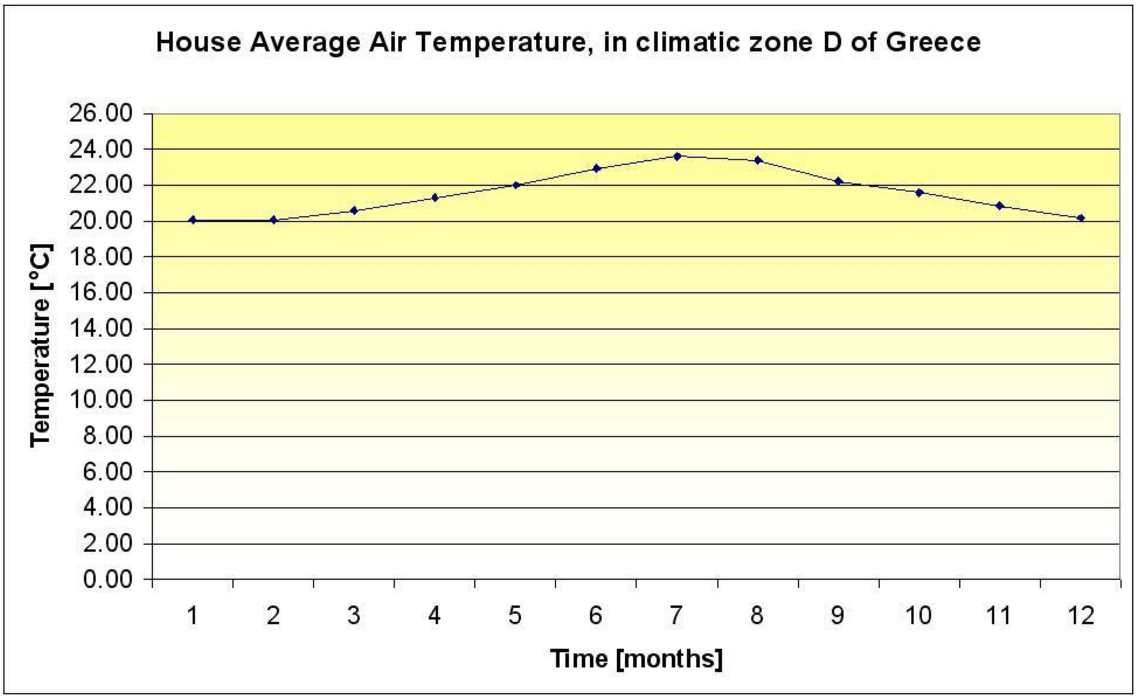

Diagram 4.4-2: Average air temperature of house, in climatic zone D of Greece

The COP of the GSHP has an average, on a yearly basis, of 4.84. The COP during the heating mode operation has an average of 4.84 and the COP during the cooling mode has an average of 5.27. In **table 4.4-5** the average COP per month is shown, with the maximum and the minimum value. In **diagram 4.4-3** the average COP, per month, is shown.

Table 4.4-5: COP values, per month, of GSHP operating in climatic zone D of Greece

COP (of operating GSHP) per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [-]	4.90	4.89	4.83	4.76	4.72	4.77	4.90	4.87	4.79	4.80	4.83	4.87
Maximum [-]	5.20	5.19	5.14	5.01	4.89	5.32	5.47	5.37	4.94	5.04	5.13	5.18
Minimum [-]	4.60	4.63	4.62	4.59	4.59	4.64	4.65	4.68	4.66	4.65	4.64	4.65

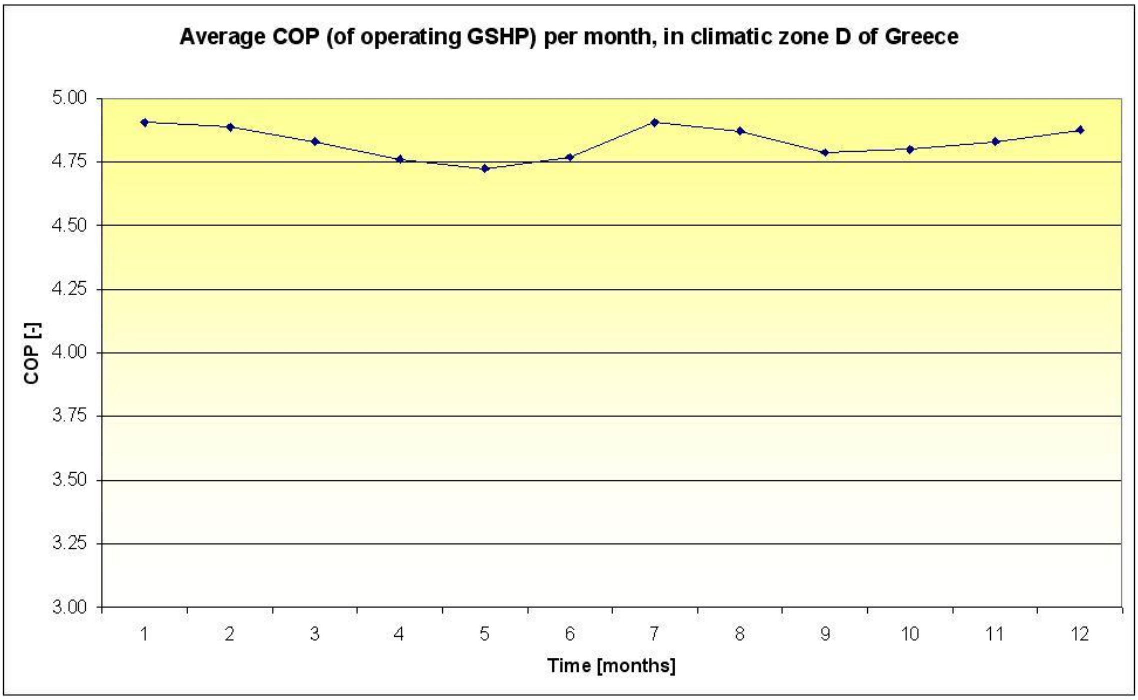

Diagram 4.4-3: Average COP, per month, of GSHP operating in climatic zone D of Greece

The GSHP electric power needed to operate has an average of 0.37 [kW], on a yearly basis. The average power needed during the operation of the GSHP in heating mode is 0.37 [kW] and in cooling mode is 0.62 [kW]. In **table 4.4-6** the average needed power of the GSHP, per month, is shown, as well as the maximum and the minimum value. In **diagram 4.4-4** the average needed power of the GSHP, per month, is shown.

Table 4.4-6: Values of GSHP electric power needed, per month, in climatic zone D of Greece

GSHP electric power per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Average [kW]	0.36	0.35	0.36	0.38	0.39	0.42	0.47	0.45	0.41	0.40	0.38	0.36
Maximum [kW]	0.40	0.38	0.39	0.40	0.41	0.63	0.63	0.63	0.42	0.42	0.40	0.39
Minimum [kW]	0.11	0.32	0.34	0.35	0.37	0.39	0.40	0.40	0.39	0.38	0.35	0.33

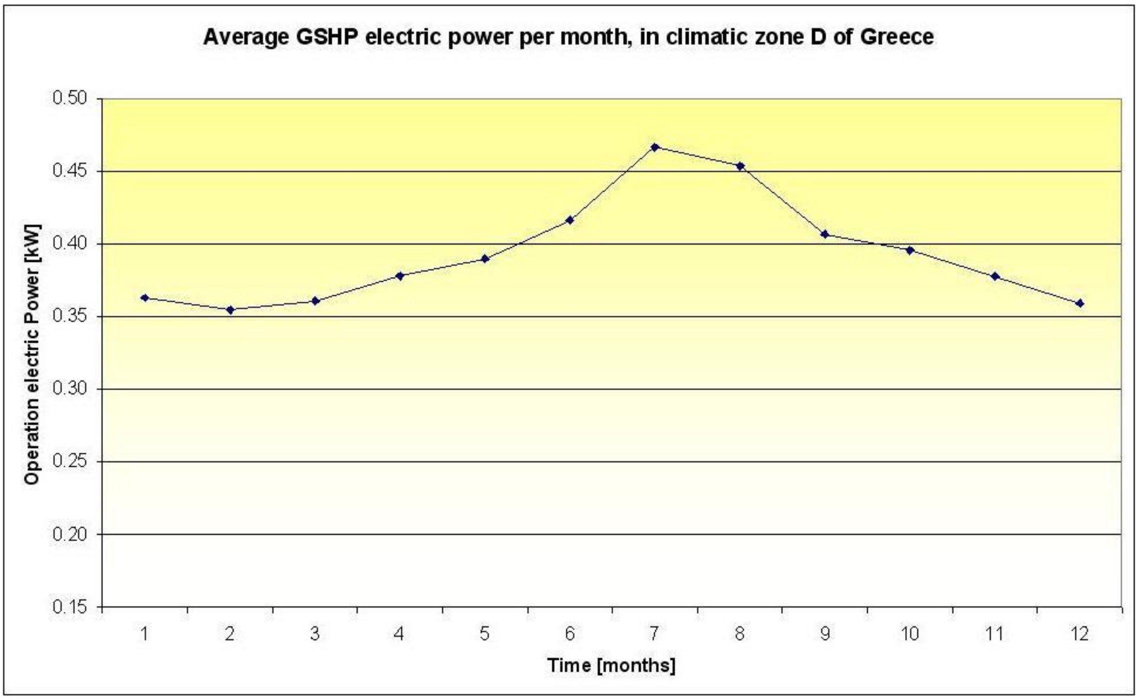

Diagram 4.4-4: Average GSHP electric power needed, per month, in climatic zone D of Greece

The liquid pump operates constantly with 8 [W].

The PV array, with a MPP tracker, produces an average power of 0.31 [kW] on a yearly basis, with a maximum of 0.85 [kW] produced at the 2509th hour of the year (13:00, 15th of April) and a minimum of 1.53 [W] produced at the 6343rd hour of the year (7:00, 22nd of September). The PV array produces energy for 4364 hours per year (49.82 [%] of the year). The peak capacity of the PV array is 0.8 [kW].

While the PV array produces less average energy than the average energy needed from the GSHP, it produces that energy for more hours than the GSHP operation. As a result the excess energy, on a yearly basis, is equal to –158.09 [kWh] (the minus sign meaning gain for the owner of the house). In **table 4.4-7** the excess energy per month is shown, the maximum energy given (-) to the grid and the maximum energy taken (+) from the grid. In **diagram 4.4-5** the excess energy per month is shown.

Table 4.4-7: Values of excess energy per month, of the house in climatic zone D of Greece

Excess Energy per month, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy [kWh]	82.36	58.53	19.19	-25.88	-66.86	-85.39	-98.73	-92.95	-68.70	-7.53	52.49	75.38
Maximum bought from the grid [kWh]	0.40	0.39	0.40	0.41	0.41	0.57	0.62	0.62	0.42	0.42	0.41	0.40
Maximum sold to the grid [kWh]	-0.65	-0.74	-0.75	-0.76	-0.71	-0.70	-0.66	-0.70	-0.72	-0.70	-0.69	-0.64

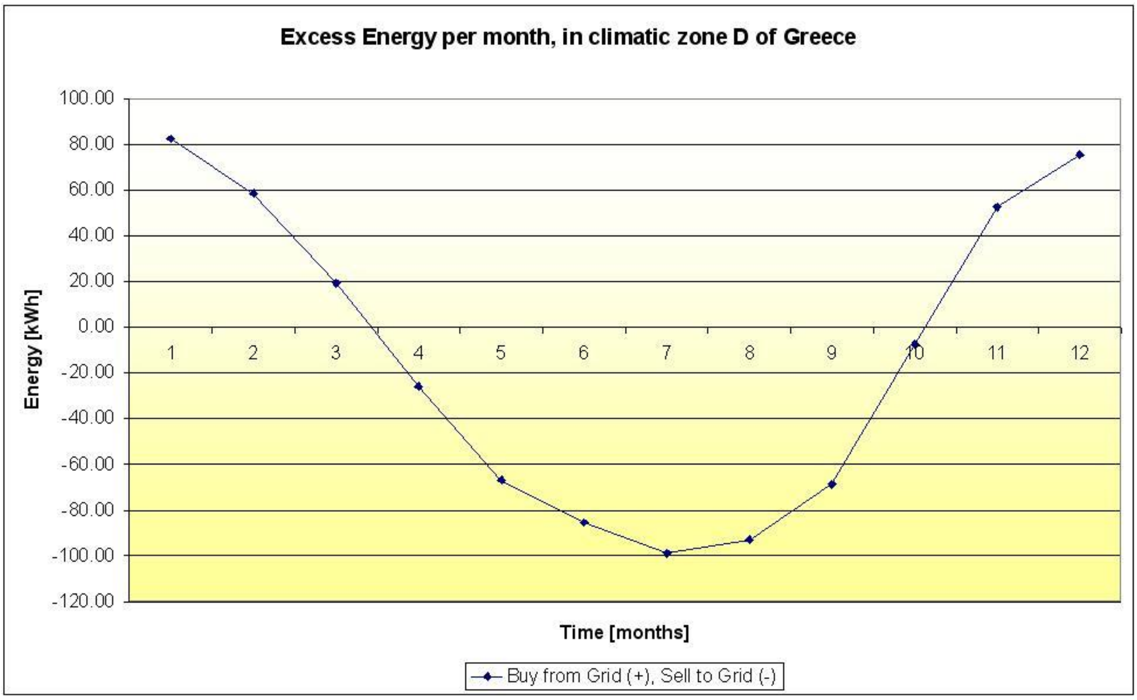

Diagram 4.4-5: Excess energy per month, of the house in climatic zone D of Greece

5 PV Array Sensitivity Analysis

In the PV array sensitivity analysis the PV array nominal power is increased/decreased by adding/removing PV panels. So the increase/decrease of the power is by 92 [W] (in the case of the A and B climatic zones of Greece), and 100 [W] (in the case of the C and D climatic zones of Greece). The MPP voltage of each panel is 34 [V] so the minimum number of panels per string is 7 (7*34=238 [V]) for a load with a voltage of 220 [V]. In climatic zones A and B of Greece 7 modules have been installed on the respective houses, so a decrease of the panels is not possible, but for the sake of the analysis, the panel is removed.

5.1 PV array in climatic zone A of Greece

The increase/decrease of the PV array by one panel, of nominal power 92 [W], changes the average power it produces, on a yearly basis, by 42.3 [W]. The maximum changes by 97.3 [W] and the minimum changes by 0.13 [W]. The average power production, on a yearly basis, for three different numbers of PV panels is shown in **diagram 5.1-1**.

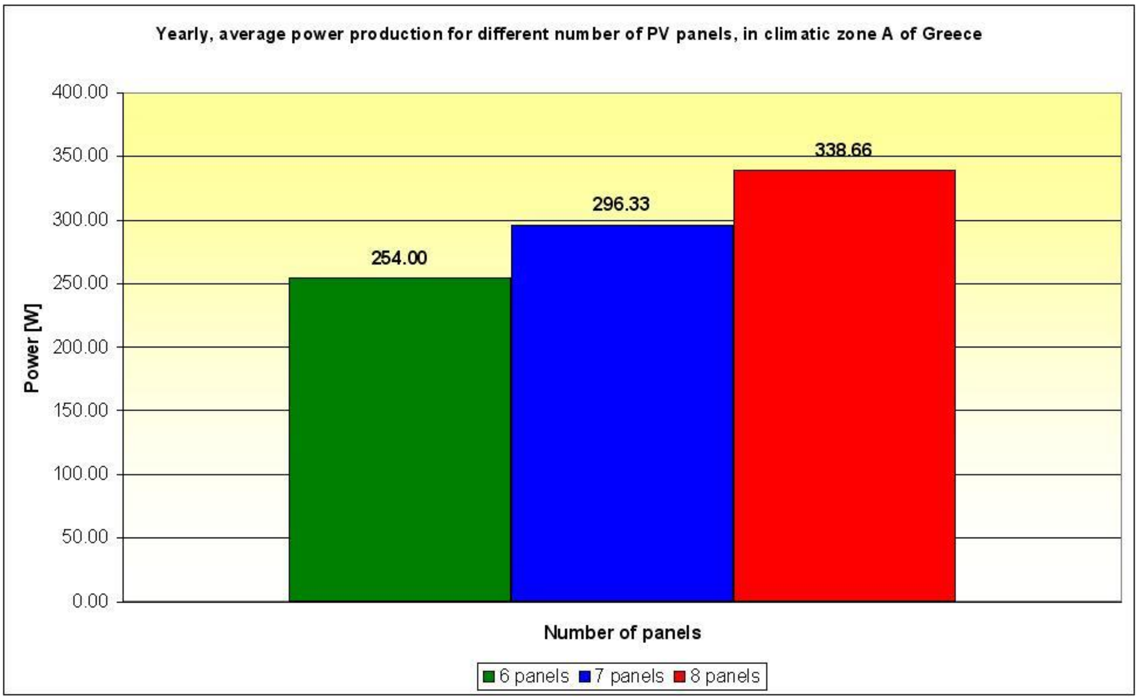

Diagram 5.1-1: Yearly average power production for different number of PV panels, in climatic zone A of Greece

The change in the excess energy, on a yearly basis, from the addition/subtraction of a PV panel, is equal to 172.98 [kWh]. The results of the increase/decrease of the number of PV panels on the house are shown in **diagram 5.1-2**.

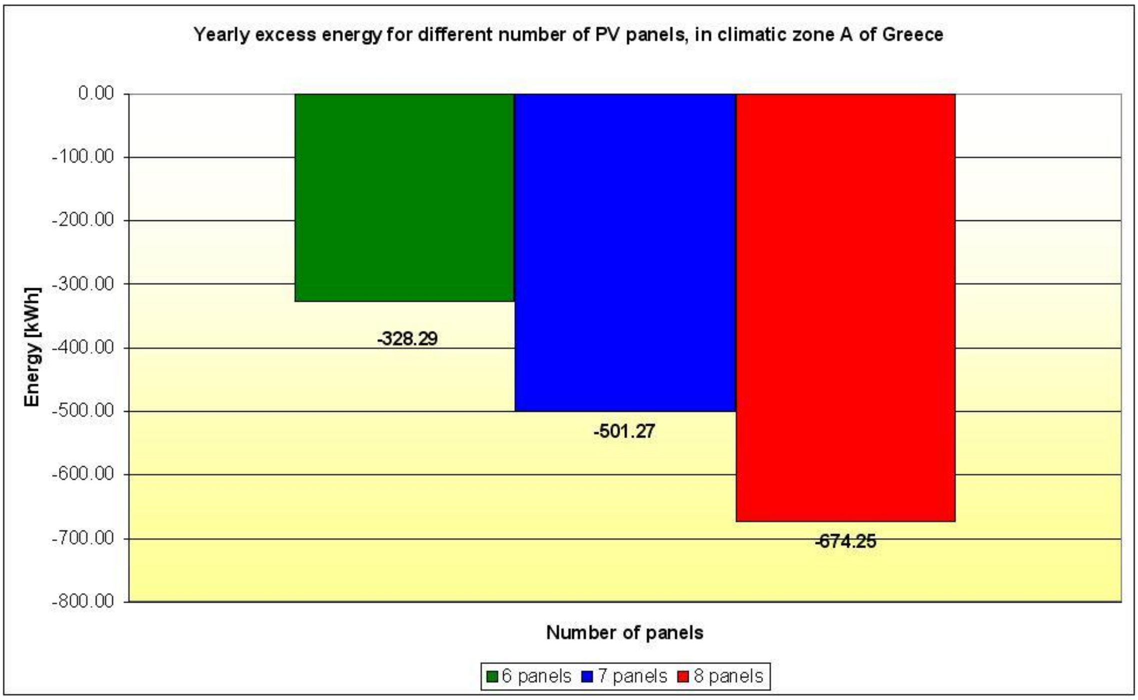

Diagram 5.1-2: Yearly excess energy for different number of PV panels, in climatic zone A of Greece

The change in the number of PV panels has a greater impact during the summer months than in the winter months, since the excess energy change during summer is about 16 [kWh] and during winter is about 11 [kWh]. The excess energy per month for 6, 7 and 8 panels can be seen in **diagram 5.1-3** and **table 5.1-1**.

Table 5.1-1: Excess energy per month for different number of PV panels, in climatic zone A of Greece

Excess Energy per month for different number of PV Panels, in climatic zone A of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy of 6 panels [kWh]	14.88	11.85	-5.49	-39.53	-52.55	-56.69	-41.38	-38.73	-62.37	-53.83	-21.82	17.36
Excess Energy of 7 panels [kWh]	2.38	0.89	-19.41	-55.73	-68.46	-72.53	-57.29	-54.18	-79.35	-69.48	-35.08	6.98
Excess Energy of 8 panels [kWh]	-10.13	-10.06	-33.33	-71.49	-84.37	-88.38	-73.19	-69.64	-96.32	-85.13	-48.34	-3.41

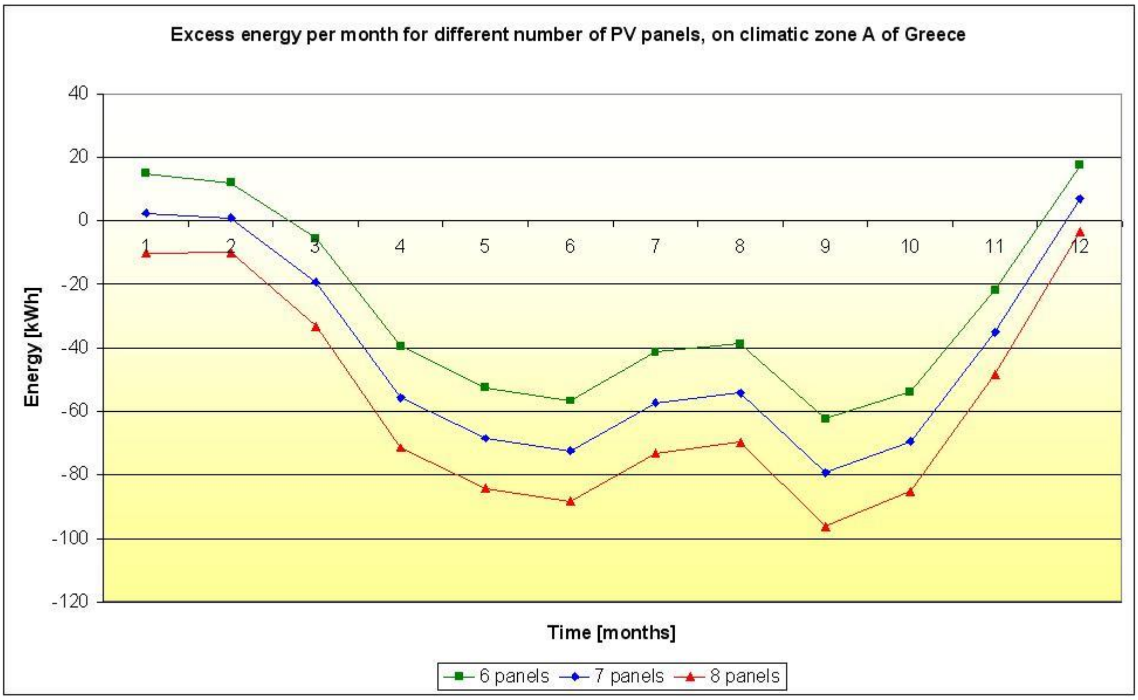

Diagram 5.1-3: Excess energy per month for different number of PV panels, in climatic zone A of Greece

5.2 PV array in climatic zone B of Greece

The increase/decrease of the PV array by one panel, of nominal power 92 [W], changes the average energy it produces, on a yearly basis, by 34.6 [W]. The maximum changes by 94.5 [W] and the minimum changes by 0.08 [W]. The average power production, on a yearly basis, for three different numbers of PV panels is shown in **diagram 5.2-1**.

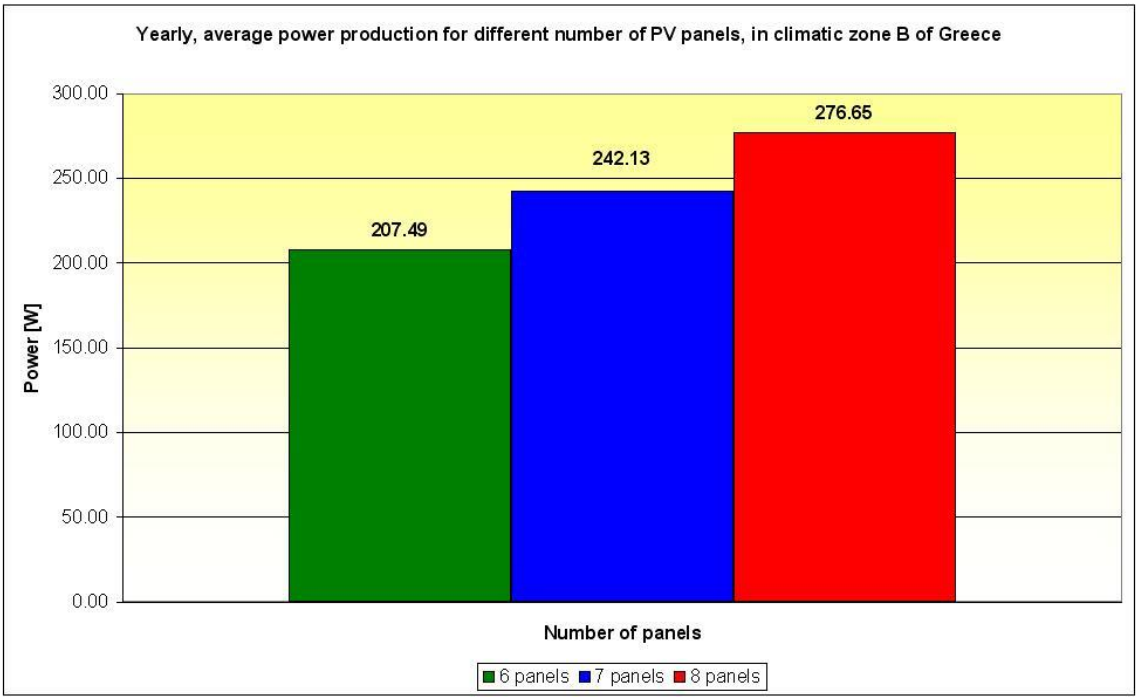

Diagram 5.2-1: Yearly average power production for different number of PV panels, in climatic zone B of Greece

The change in the excess energy, on a yearly basis, from the addition/subtraction of a PV panel, is equal to 141.22 [kWh]. The results of the increase/decrease of the number of PV panels on the house are shown in **diagram 5.2-2**.

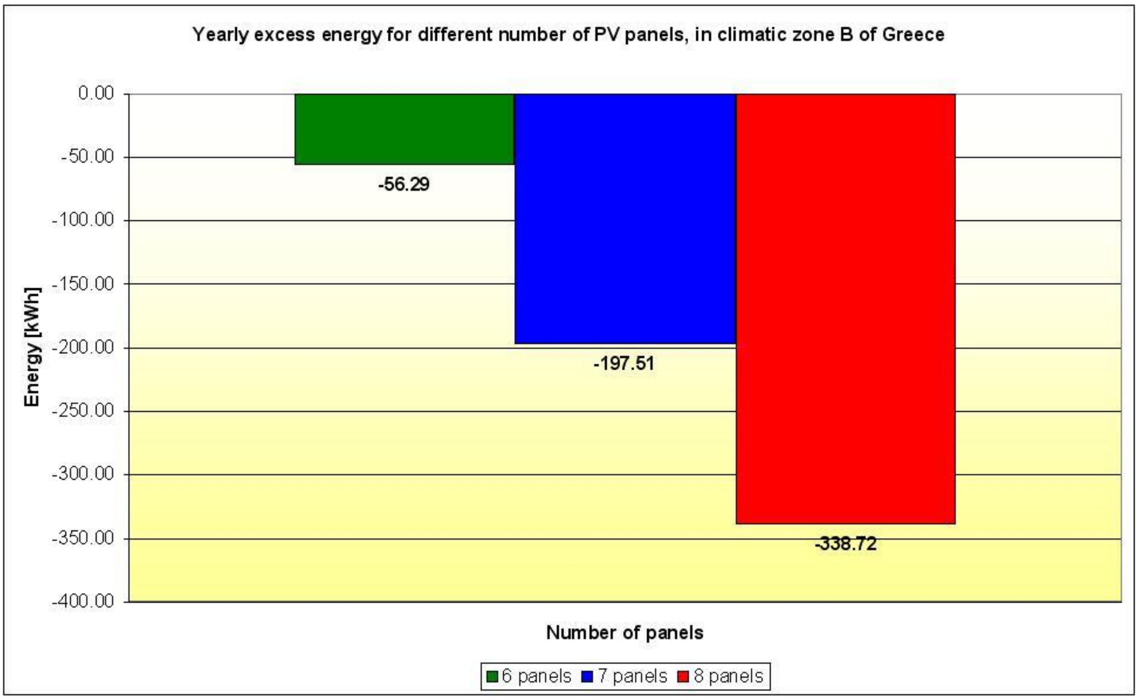

Diagram 5.2-2: Yearly excess energy for different number of PV panels, in climatic zone B of Greece

The change in the number of PV panels has a greater impact during the summer months than in the winter months, since the excess energy change during summer is about 16 [kWh] and during winter is about 8 [kWh]. The excess energy per month for 6, 7 and 8 panels can be seen in **diagram 5.2-3** and **table 5.2-1**.

Table 5.2-1: Excess energy per month for different number of PV panels, in climatic zone B of Greece

Excess Energy per month for different number of PV Panels, in climatic zone B of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy of 6 panels [kWh]	49.10	37.67	24.98	-14.51	-45.11	-46.30	-29.99	-33.06	-45.90	-20.35	19.55	48.83
Excess Energy of 7 panels [kWh]	40.63	29.32	14.89	-27.35	-59.58	-61.32	-45.98	-49.35	-60.21	-31.44	11.61	42.25
Excess Energy of 8 panels [kWh]	32.16	20.97	4.79	-40.19	-74.05	-76.34	-61.97	-65.65	-74.51	-42.54	3.66	35.67

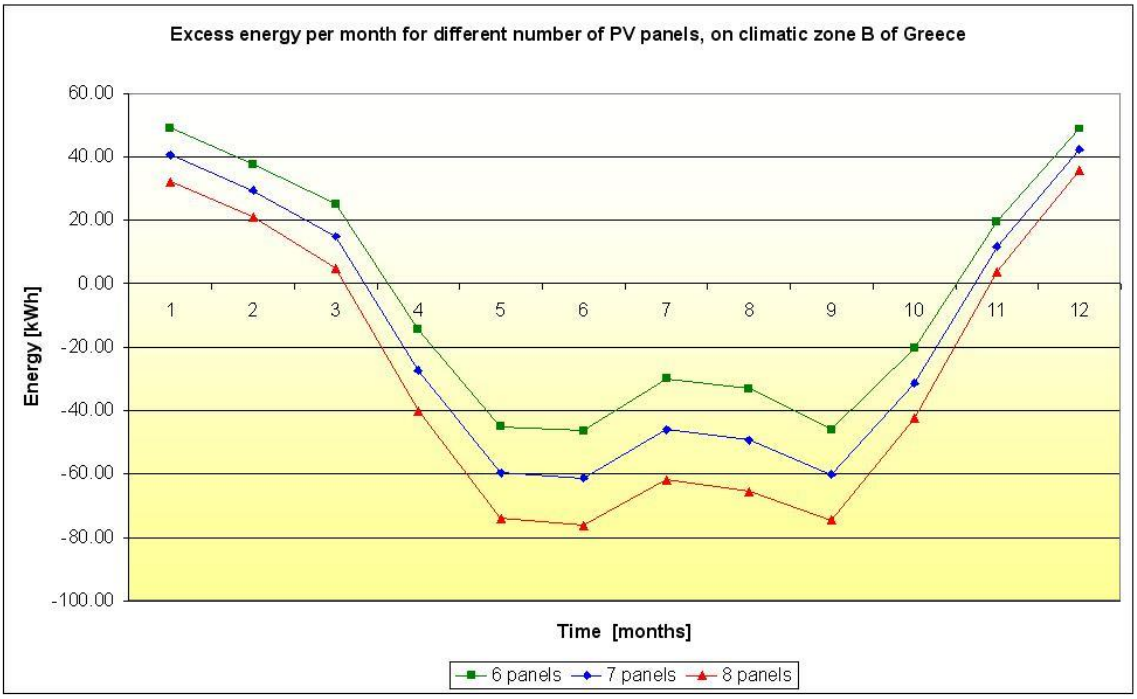

Diagram 5.2-3: Excess energy per month for different number of PV panels, in climatic zone B of Greece

5.3 PV array in climatic zone C of Greece

The increase/decrease of the PV array by one panel, of nominal power 100 [W], changes the average energy it produces, on a yearly basis, by 29.85 [W]. The maximum changes by 102.9 [W] and the minimum changes by 0.08 [W]. The average power production, on a yearly basis, for three different numbers of PV panels is shown in **diagram 5.3-1**.

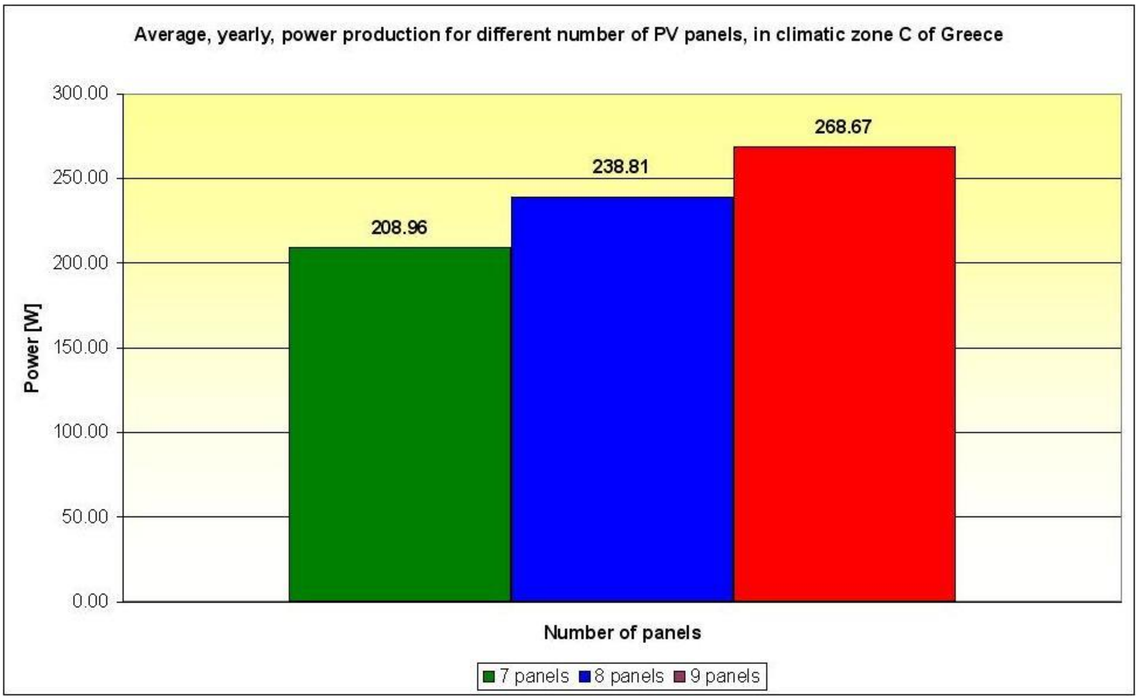

Diagram 5.3-1: Yearly average power production for different number of PV panels, in climatic zone C of Greece

The change in the excess energy, on a yearly basis, from the addition/subtraction of a PV panel, is equal to 122.15 [kWh]. The results of the increase/decrease of the number of PV panels on the house are shown in **diagram 5.3-2**.

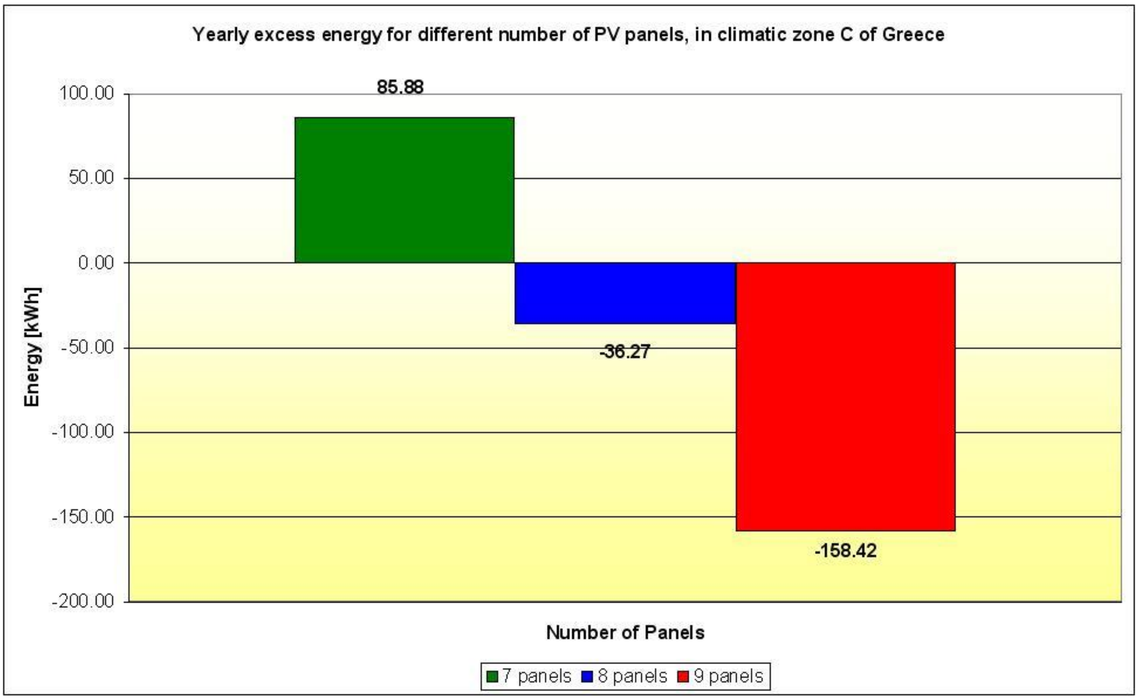

Diagram 5.3-2: Yearly excess energy for different number of PV panels, in climatic zone C of Greece

The change in the number of PV panels has a greater impact during the summer months than in the winter months, since the excess energy change during summer is about 14 [kWh] and during winter is about 6 [kWh]. The excess energy per month for 7, 8 and 9 panels can be seen in **diagram 5.3-3** and **table 5.3-1**.

Table 5.3-1: Excess energy per month for different number of PV panels, in climatic zone C of Greece

Excess Energy per month for different number of PV Panels, in climatic zone C of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy of 7 panels [kWh]	88.48	63.06	37.34	-10.48	-43.65	-51.86	-43.83	-44.66	-43.66	0.76	50.07	84.31
Excess Energy of 8 panels [kWh]	82.56	56.58	28.06	-22.43	-57.37	-65.93	-58.35	-58.74	-55.75	-8.07	43.91	79.25
Excess Energy of 9 panels [kWh]	76.64	50.10	18.77	-34.37	-71.08	-80.00	-72.87	-72.83	-67.84	-16.90	37.76	74.20

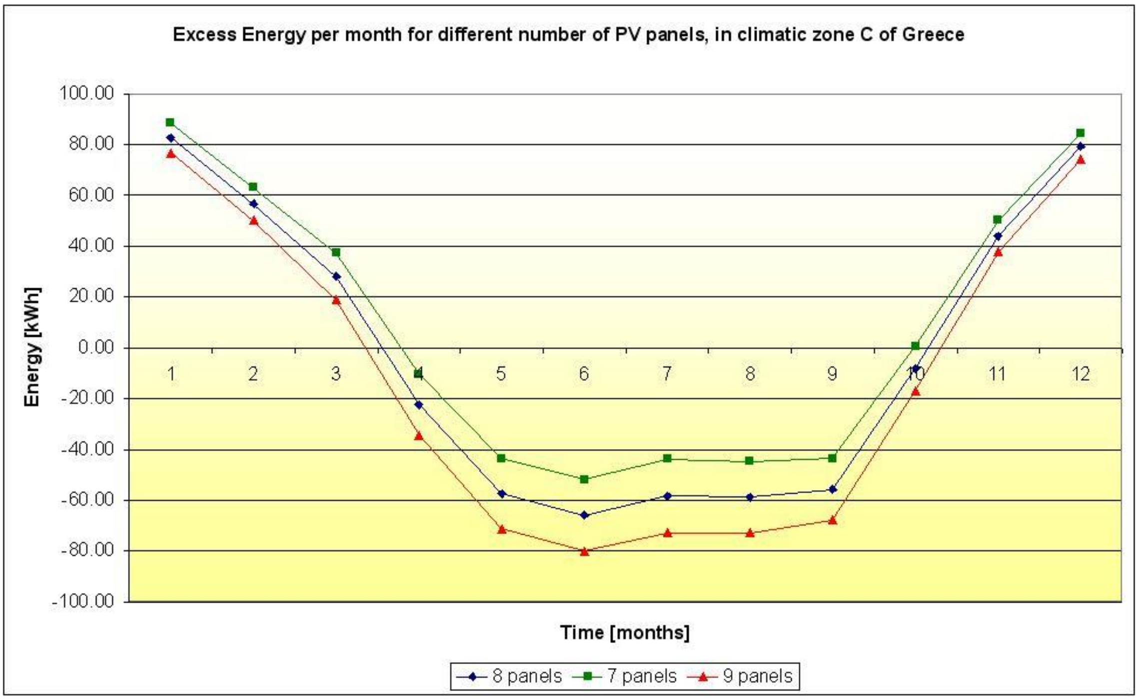

Diagram 5.3-3: Excess energy per month for different number of PV panels, in climatic zone C of Greece

5.4 PV array in climatic zone D of Greece

The increase/decrease of the PV array by one panel, of nominal power 100 [W], changes the average energy it produces, on a yearly basis, by 38.87 [W]. The maximum changes by 105.8 [W] and the minimum changes by 0.09 [W]. The average power production, on a yearly basis, for three different numbers of PV panels is shown in **diagram 5.4-1**.

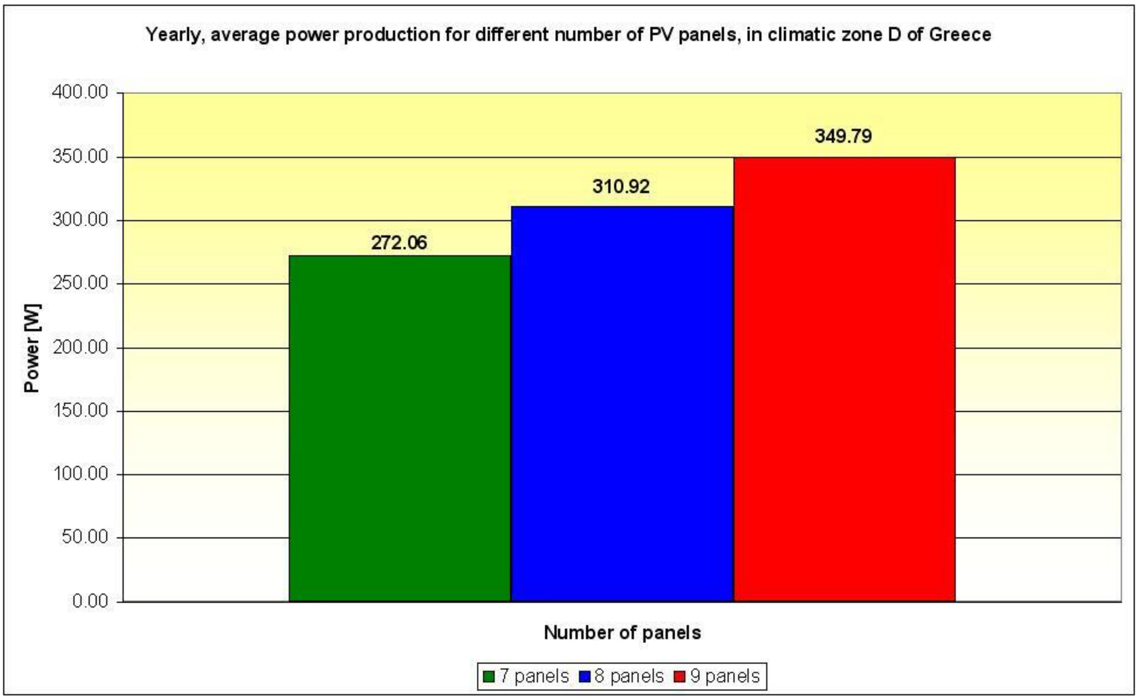

Diagram 5.4-1: Yearly average power production for different number of PV panels, in climatic zone D of Greece

The change in the excess energy, on a yearly basis, from the addition/subtraction of a PV panel, is equal to 159.43 [kWh]. The results of the increase/decrease of the number of PV panels on the house are shown in **diagram 5.4-2**.

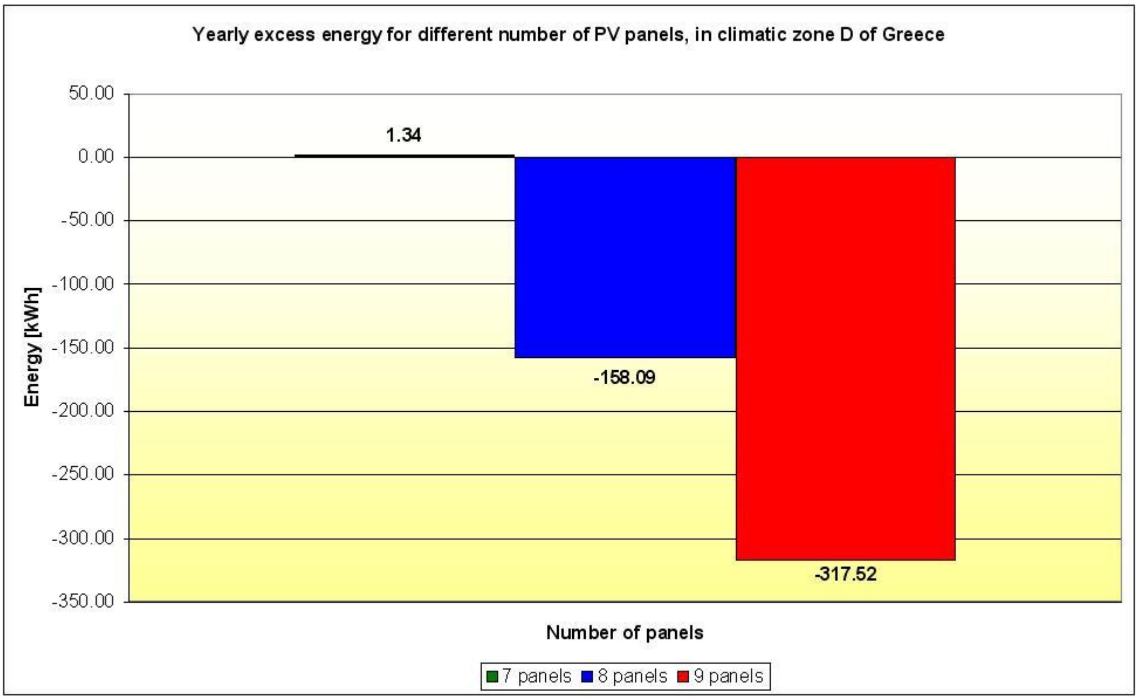

Diagram 5.4-2: Yearly excess energy for different number of PV panels, in climatic zone D of Greece

The change in the number of PV panels has a greater impact during the summer months than in the winter months, since the excess energy change during summer is about 17 [kWh] and during winter is about 9 [kWh]. The excess energy per month for 7, 8 and 9 panels can be seen in **diagram 5.3-3** and **table 5.3-1**.

Table 5.4-1: Excess energy per month for different number of PV panels, in climatic zone D of Greece

Excess Energy per month for different number of PV Panels, in climatic zone D of Greece												
Month	January	February	March	April	May	June	July	August	September	October	November	December
Excess Energy of 7 panels [kWh]	90.86	67.87	32.54	-10.69	-50.29	-68.58	-80.72	-75.51	-52.97	4.28	60.75	83.79
Excess Energy of 8 panels [kWh]	82.36	58.53	19.19	-25.88	-66.86	-85.39	-98.73	-92.95	-68.70	-7.53	52.49	75.38
Excess Energy of 9 panels [kWh]	73.87	49.20	5.84	-41.08	-83.44	-102.20	-116.75	-110.39	-84.44	-19.33	44.23	66.97

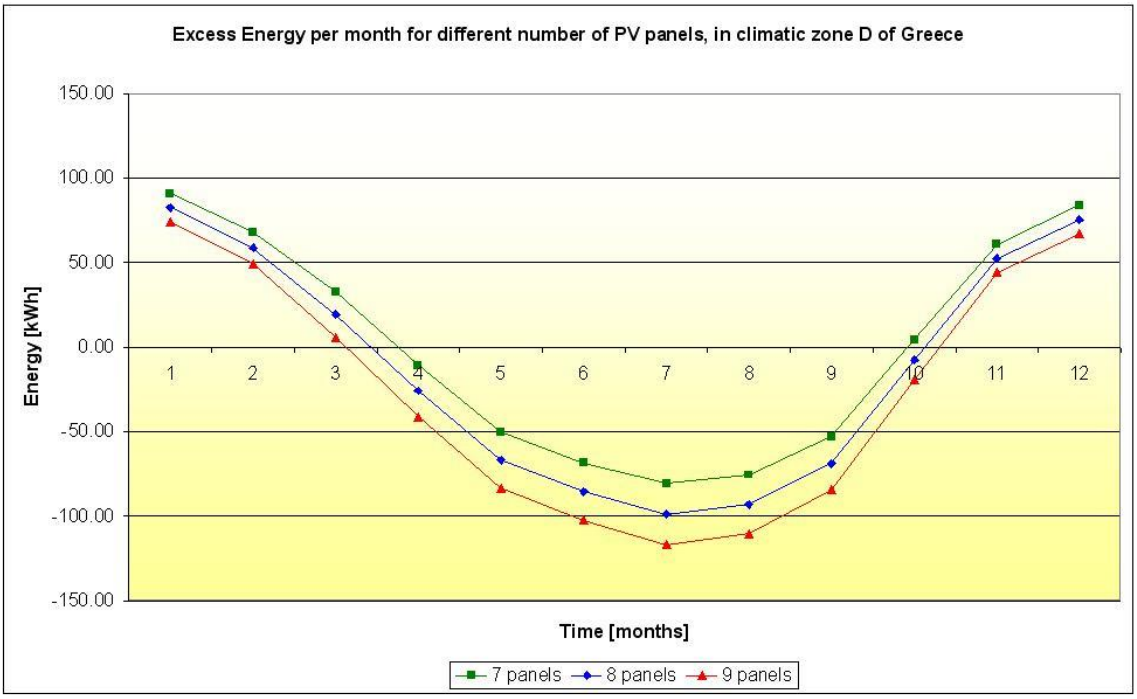

Diagram 5.4-3: Excess energy per month for different number of PV panels, in climatic zone D of Greece

6 Pre-feasibility study

In this simple pre-feasibility study the cost analysis and the financial analysis of the GSHP-PV system is made in the four climatic zones of Greece. In the financial analysis the net present value (NPV) rule is used.

6.1 Cost analysis

The initial cost of the GSHP-PV system consists of four parts, the feasibility study cost, the GSHP cost, the PV cost and the transportation cost.

The feasibility study cost depends on the engineer conducting it and is assumed equal to 700 [€]. The transportation costs are estimated equal to 300 [€].

For the PV array the costs concerning the PV panels are different for each climatic zone, while the costs concerning the equipment for the transaction with the grid and the operation and maintenance of the PV array are the same for all the houses. The PV panels used in the simulation could not be found so the prices of, 100 [W] nominal capacity, panels of another company were used, with the appropriate price reduction for the 92 [W] nominal capacity panels [27]. The solar cable cost is equal to 1.68 [€/m] [32]. In **table 6.1-1** the different costs concerning the PV panels are shown. The inverter cost is equal to 800 [€] [31]. The AC control panel cost is estimated equal to 160 [€] and the DC control panel cost is estimated equal to 250 [€]. The PV array mounting and installation cost is estimated equal to 400 [€]. The energy meter costs 13.20 [€] [26]. The transmission line, connecting the inverter with the PPC transformer, installation cost is estimated equal to 200 [€]. The annual cost for the operation and maintenance of the PV array is estimated equal to 200 [€].

Table 6.1-1: PV panel array's different costs in each climatic zone of Greece

PV panel array cost	Climatic Zone of Greece			
	A	B	C	D
PV nominal capacity [W]	92	92	100	100
Cost per PV panel [€]	140	140	145	145
Number of PV panels	7	7	8	8
PV panels cost [€]	980	980	1160	1160
Solar cable cost [€/m]	1.68	1.68	1.68	1.68
Solar cable length [m]	14	14	15	15
Solar cable total cost [€]	23.52	23.52	25.20	25.20

The cost for the installation of the GSHP system is estimated equal to 800 [€/kW] [7]. The GSHP nominal capacity and cost, in each climatic zone of Greece, are shown in **table 6.1-2**.

Table 6.1-2: GSHP nominal capacity and cost, in each climatic zone of Greece

GSHP nominal capacity and cost	Climatic Zone of Greece			
	A	B	C	D
GSHP nominal capacity [kW]	2.50	2.50	3.00	3.50
GSHP cost [€]	2000	2000	2400	2800

The cost for the drilling and installation of the GHX is estimated equal to 50 [€/m] [7]. So for two boreholes of 60 [m] each the total drilling cost is 50 [€/m]*120 [m]=6000 [€]. The liquid pump costs 82 [€] [25].

The installation of ventilation system transferring the conditioned air from the GSHP to the house is estimated to cost 1000 [€] [28]. The thermostats cost 10 [€] each, so for five thermostats the total cost is 50 [€] [25]. The annual cost for the operation and maintenance of the GSHP system is estimated equal to 400 [€] [24].

In total the annual expenses for the operation and maintenance of the GSHP-PV system are equal to 600 [€]. The initial cost of the whole system for each climatic zone of Greece is shown in **table 6.1-3**.

Table 6.1-3: Capital cost of the GSHP-PV system in each climatic zone of Greece

Initial cost of GSHP-PV system	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
Feasibility study cost [€]	700.00	700.00	700.00	700.00
Transportation cost [€]	300.00	300.00	300.00	300.00
PV initial installation cost [€]	2826.72	2826.72	3008.40	3008.40
GSHP initial installation cost [€]	9132.00	9132.00	9532.00	9932.00
System total cost [€]	**12958.72**	**12958.72**	**13540.40**	**13940.40**

6.2 Financial analysis

The net present value of the GSHP-PV system is the sum of the present values of each of the cash flows, positive as well as negative, that occur over the life of the system. The general formulation of the NPV rule is as follows:

$$NPV = \sum_{t=1}^{t=N} \frac{CF_t}{(1+r)^t} - Initial\_Investment \quad \textbf{Eq. 6.2-1}$$

The cash flow in each year is calculated from the following equation

$$CF_t = PV_{it} + AS_{it} - C_{OMt} \quad \textbf{Eq. 6.2-2}$$

The inflation rate is taken into account in the calculation of AS_{it} and C_{OMt}.

PV_{it} is calculated by subtracting the cost of electricity, bought from the grid, from the profit from the electricity, sold to the grid, during the operation of the system. The profit from electricity is calculated by multiplying the exported energy to the grid, produced from the PV array, with the price of electricity sold to the grid, which is equal to 0.25 [€/kWh] [30]. To calculate the cost of electricity, the imported energy from the grid, for the operation of the GSHP, is multiplied with the price of electricity bought from the grid, which is equal to 0.08 [€/kWh]. In **table 6.2-1** the income from the energy trade with the grid is shown.

Table 6.2-1: Values for the calculation of the electricity income, in each climatic zone of Greece

Annual electricity income calculation	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
Annual income from electricity traded with the grid [€]	**204.09**	**141.92**	**125.11**	**176.57**

A common practice in Greece is the use of an oil boiler for heating and an air condition (A/C) device for cooling. Another practice could be the coverage of the heating/cooling load only with the use of an air HP.

The extra cost not spent in case the GSHP replaces an oil boiler is the fuel cost. To calculate the annual fuel cost, the price of oil for heating is needed [29] as well as the quantity of the fuel. The annual quantity of the oil needed, is calculated by the ratio of the energy needed from the fuel [kWh] to the net calorific value of oil [kWh/kg]. The fuel energy is calculated from the following equation:

$$E_{oil} = P_{oil} * heating\ hours * 0.75 \qquad \textbf{Eq. 6.2-3}$$

Where P_{oil} is the maximum power needed from the fuel of the boiler and as *heating hours* are used the hours the GSHP operates in heating mode. Since the house does not always need the maximum heating power, P_{oil} is multiplied by the correction factor 0.75. For the P_{oil} calculation the following equations are used [12], [13]:

$$P_{oil} = \frac{P_{gen}}{n_b} \qquad \textbf{Eq. 6.2-4}$$

$$P_{gen} = A * U_m * \Delta T * 2.5 \qquad \textbf{Eq. 6.2-5}$$

The factor 2.5 includes the increased load because of infiltration, the intermittent operation of the boiler, losses of the distribution network etc.

$$U_m = \frac{\sum_{j=1}^{n} A_j * U_j}{\sum_{j=1}^{n} A_j} \qquad \textbf{Eq. 6.2-6}$$

The aforementioned values for each climatic zone of Greece are shown in **table 6.2-2**. The efficiency of the boiler is considered equal to 93.5 [%] [12]. The net calorific value of oil, for heating, is equal to 11.92 [kWh/kg] [12]. The oil density is equal to 0.827 [kg/lit].

Table 6.2-2: Values for the calculation of the annual oil cost, in each climatic zone of Greece

Annual oil cost calculation	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
U_m [W/(m^2*K)]	0.43	0.37	0.32	0.30
ΔT [^{o}C]	18.00	20.00	23.00	28.00
P_{gen} [W]	13953.20	13181.21	13319.92	14850.39
P_{oil} [W]	14923.21	14097.55	14245.90	15882.77
Heating hours per year	899	1060	1703	2265
E_{oil} [kWh]	10061.98	11207.55	18195.58	26980.85
Oil quantity [liters]	1020.71	1136.92	1845.80	2736.99
Oil cost per liter [€]	1.30	1.27	1.27	1.30
Annual oil cost [€]	**1326.92**	**1443.89**	**2344.16**	**3558.09**

The A/C or HP extra cost in comparison with the GSHP-PV system is the cost of the electricity needed to operate the device, which is paid at the grid. For the calculation of electric energy needed for the cooling/heating energy generation the following equations are used [12]:

$$E_{el,c} = \frac{E_c}{COP} \qquad \textbf{Eq. 6.2-7}$$

$$E_{el,h} = \frac{E_h}{COP} \qquad \textbf{Eq. 6.2-8}$$

The heating and cooling energy needed for the house, in the case of the HP, have been already calculated during the simulation. The COP is chosen equal to 3 for the cooling mode of the HP and 3.7 for the heating mode. The cost of electricity is equal to 0.08 [€/kWh]. The cost of heating with a HP is shown in **table 6.2-3** and for cooling is shown in **table 6.2-4**, for each climatic zone of Greece.

Table 6.2-3: Annual electricity cost for the heating operation of a HP, in each climatic zone of Greece

Annual heating cost of HP	Climatic Zone of Greece			
	A	B	C	D
E_h [kWh]	1741.49	2068.25	3020.61	4060.85
$E_{el,h}$ [kWh]	470.67	558.99	816.38	1097.53
Cost of HP heating [€]	**37.92**	**45.03**	**65.77**	**88.42**

Table 6.2-4: Annual electricity cost for the cooling operation of a HP, in each climatic zone of Greece

Annual cooling cost of HP	Climatic Zone of Greece			
	A	B	C	D
E_c [kWh]	457.84	555.82	455.91	78.5
$E_{el,c}$ [kWh]	152.61	185.27	151.97	26.17
Cost of HP cooling [€]	**12.29**	**14.93**	**12.24**	**2.11**

The NPV of the GSHP-PV system depends on the annual cash flow, which in turn depends on the alternative heating/cooling source that is compared with. The inflation rate is taken equal to 2 [%] and the discount rate of the NPV is chosen equal to 5 [%]. The life of the system is 25 years.

In the case the GSHP-PV system is compared with an oil boiler for heating and an A/C for cooling, the AS_{it} is equal to the summation of the annual oil cost and the annual HP cooling cost. The NPV in this case is positive and the system is considered economically feasible. The NPV of the system and the equity payback year, in each climatic zone of Greece are shown in **table 6.2-5**.

Table 6.2-5: NPV of GSHP-PV system and equity payback year, in each climatic zone of Greece. (Comparison with oil boiler and A/C)

Financial analysis of GSHP-PV (comparing with oil boiler and A/C)	Climatic Zone of Greece			
	A	B	C	D
NPV [€]	2874.55	4094.59	19008.89	40434.07
Equity payback year	13	12	7	5

In the case the GSHP-PV system is compared with a HP for heating and cooling, the AS_{it} is equal to the summation of the annual HP heating and cooling cost. The NPV in this case is negative and the system is economically rejected. The NPV of the system, in each climatic zone of Greece is shown in **table 6.2-6**.

Table 6.2-6: NPV of GSHP-PV system, in each climatic zone of Greece. (Comparison with HP)

Financial analysis of GSHP-PV (comparing with Heat Pump)	**Climatic Zone of Greece**			
	A	**B**	**C**	**D**
NPV [€]	-19718.88	-20424.28	-20926.45	-27541.99

7 Conclusions

The simulation of the GSHP-PV system has different results in each climatic zone of Greece. The main reason is, of course, the different weather conditions. In climatic zone D we have the lowest average ambient air temperature, leading to the construction of a house with the greatest insulation. While in the house in climatic zone A, where the average ambient air temperature is the highest, the insulation is the lowest. That is because the main issue in each climatic zone of Greece is the heating of the house, as it can be seen by the duration of the heating mode operation of the GSHP.

The maximum sensible heating capacity of the GSHP is equal to 2 [kW]. The reason for this is the insulation of the house, which leads to a thermal transmittance of half the value of the recommended from the Greek legislation. Also the recirculation of the air plays an important role, since only 15 [%] of the outside air enters through the ventilation. Because of this recirculation the temperature of the air entering the GSHP is close to the limits of air temperature set by the thermostat, so a limited amount of work is demanded from the HP.

The average ambient air temperature during the cooling period is greater in climatic zone B of Greece (26.11 [^{o}C]) than in climatic zone A (25.61 [^{o}C]). Because of this fact, the duration of the GSHP cooling mode operation is longer in climatic zone B than in climatic zone A, although in climatic zone A cooling is needed from April until October while in climatic zone B it is needed from May until October. Moreover, the average sensible cooling capacity of the GSHP in climatic zone B is larger than the average cooling capacity in zone A.

The COP of the GSHP, in each climatic zone, is close to 5. The lowest COP is in zone D, because of the low temperature of the liquid inside the GHX.

The PV arrays produce electric energy approximately 50 [%] of the year, in each climatic zone of Greece. The most excess energy is produced in climatic zone A, which is reasonable since the GSHP operates for fewer hours in this zone than in the others.

The PV array in climatic zone D produces more electricity than the one in climatic zone C, probably because of the ambient air low temperatures during summer. As a result the excess energy produced in climatic zone D is more than in zone C, even though the GSHP operates for more hours in climatic zone D than in the other zones.

The most sensitive in the increase/decrease of the PV panels is the PV array in climatic zone A. This changes though for the summer period, when the PV array in climatic zone D is more sensitive.

The excess energy, produced from the PV array and sold to the grid, does not produce enough income to cover the operation and maintenance costs of the GSHP-PV system, in the case of a NZEB. The NPV is positive only when comparing it with an oil-A/C system, since heating is needed most in Greece and oil is expensive. The more heat needed the greatest the benefit from not buying oil, which is why the house in zone D has the greatest NPV in this case, even though it has the greatest initial cost.

The NPV situation is reversed when the GSHP-PV system is compared with an air-HP system. The gain from the electricity not paid for the operation of the HP is not enough to give a positive NPV. And the less negative NPV is that of the house in climatic zone A, where the most excess energy is sold and the capital cost is lowest.

So the NZEB could be economically reasonable in both cases if the excess energy income could cover the costs of the operation and maintenance of the system plus a reasonable profit.

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