Solar assisted ground source heat pump performance assessment for residential energy supply in southern European climates

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Abstract

The awareness about environmental problems due to fossil fuel consumption is increasing widely; therefore, efforts are being made to develop energy efficient and environmentally friendly systems by utilisation of non-polluting renewable energy sources. Ground source heat pumps (GSHPs) belong to this category. Many variations of geothermal system typologies exist, with different configurations suitable in different situations and most locations around the world. One emergent configuration is the solar assisted GSHP (SAGSHP). The paper focuses on different control strategies of a solar assisted ground source heat pump (SAGSHP) for different Italian locations. Dynamic simulation approach has been used through TRNSYS software. The impact of the considered strategies on the seasonal performance factor has been evaluated. Results have shown that the strategy strongly affects the system consumption; therefore, it needs to be chosen appropriately in the design phase. Furthermore, when solar energy is driven into the ground, the temperature difference between solar collectors and the ground, which has to be a positive value to charge the ground, plays a fundamental role. In particular, solar thermal energy injected into the ground decreases to zero moving from a humid sub-tropical (Cfa) to a dry-summer subtropical (Csa) climate. Therefore, a compromise between the operation of the circulation pumps used for supplying free cooling energy and for driving solar thermal energy into the ground has to be found for each climate.

1. Introduction

The 2010/31/EU Directive of the European Parliament and the Council of 19 May 2010 have set, as a priority under the "20-20-20" objectives, the reduction of the energy consumption of the building sector, which represents 40% of the European Union's (EU) total energy consumption [1]. Solar thermal systems are key technologies to achieve this goal, indeed they are spreading in the European countries [2]. They receive particular interest from southern European countries, in particular from Italy and Spain, which have high solar heat generation targets accordingly to their National Renewable Energy Action Plans [3]. Indeed, in Italy, which has been considered in this study, solar thermal technology is mandatory in new and in renovated buildings [4]. Three different climates have been taken into account: humid subtropical climate (Cfa, in accordance with the Köppen climate classification [5]), Mediterranean climate with mild, humid winters and hot, dry summers and hot-summer (Csa) Mediterranean climate (Csa). They refer respectively to the cities of Milan, Rome and Palermo and they can be considered representative of many southern European locations. Solar thermal energy can be used also unconventionally. In fact with regard to ground source heat pump (GSHP), solar thermal collectors can also supply heat directly to the ground, increasing the temperature of the evaporator in the GSHP, in addition to providing building heating energy. Since one machine is able to provide heating and cooling building energies, they could play a significant role in reducing CO_2 emissions [6]. The GSHP systems have been investigated by many scientists for many applications, from residential to public buildings, affirming that they effectively make use of renewable energy stored in the ground to supply building thermal energy in a new and clean form [7-13]. They are particularly indicated for low environmental impact projects around the globe. Indeed, heat pumps utilize significantly less energy than alternative heating systems in various climatic contexts, from cold to mild temperate conditions [7, 8, 10, 12- 16]. One promising configuration is the solar assisted GSHP (SAGSHP) [17]. In such systems, the solar collectors may supply heat directly to the domestic hot water systems, the building heat distribution systems, increasing the temperature of the evaporators in the heat pumps, recharging the boreholes or combinations of all [18]. The effective use of these systems might play a leading role in the world in the foreseeable future [19]. Moreover, a free ground cooling (FGC) loop can be implemented easily in the same machine, using the ground as a thermal cooling source; therefore, the building space cooling (SC) requirements can be satisfied only consuming a small amount of electricity if the thermal condition of the ground are suitable [20]. Many scientists [16-29] have investigated the design, the modelling and the testing of SAGSHP solutions. The efficiency of SAGSHPs can be further increased, thus supplementary research on solar thermal system operation strategy and control is needed [18]. The aim of this research is to assess the long-term performance of a SAGSHP in southern European climates for residential thermal energy supply; therefore, results refer to the 21st year of analysis. In particular, the final energy consumption and the seasonal performance factor (SPF) have been evaluated. A FGC system for supplying the building cooling requirement, as the good practice suggests, and a PV system, as the Italian law imposes [4], have been considered. The study is performed with a simulation approach due to the complexity of the proposed system, as suggested by C. Montagud [23]. In addition, TRNSYS v.17® [30] has been used in accordance to many scientists [25, 29]. The first part of the paper concentrates on the building and heating/cooling system configurations. The second part regards the results of the considered systems, while the last the conclusions.

2. Case study

2.1 Building

The analysed building is a four-storey building (Figure 1) consisting of two flats of about 110 m² per floor. The pitched roof has a tilted angle of 20°. General information about the building can be seen in Table 1. Internal and external superficial thermal resistances have been assumed accordingly to UNI EN ISO 6946 [31], while the infiltration rate and the envelope thermal properties for the considered localities respectively refer to the standard UNI 11300 – Part 1 [32] and Italian Presidential Decree of April, 2009 N°59 [33].

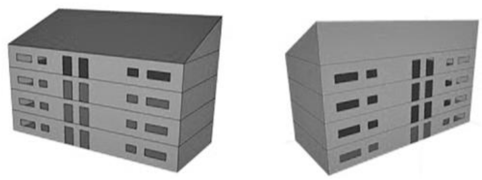

Fig. 1 – Building front and back views

Table 1 – Thermal features of the building envelope elements: external wall, roof and window and main data of the building

Building thermal data [33]				
	U Value [W/m²K]			g factor
	Milan	Rome	Palermo	
External Wall	0,3	0,4	0,45	-
Roof	0,3	0,35	0,4	-
Window	2,2	2,2	2,2	0,701

Building general data	
Location	Milan, Latitude 47° 27' N and longitude and 9° 10' E Rome, Latitude 41° 54' N and longitude and 12° 27' E Palermo, Latitude 38° 7' N and longitude and 13° 22' E
Floor surface	880 m² -two flats of about 110 m² per each floor(4-strorey building)
Internal - external superficial thermal resistances	0,2 - 0,05 m²K/W [39]

Mechanical exhaust air ventilation rate	0,3 ACH [40]
Cooling - heating set point temperatures	26°C - 21°C
DHW set point	45 °C
Heating supply inlet temperature	40 °C
Cooling supply inlet temperature	17 °C
Water network temperature	7 °C
Storage tank set point	55 °C

The DHW hourly profile shown in Figure 2 has been implemented [34] into the building thermal model. The building model has been built in TRNBuild [35], which is a TRNSYS subroutine able to generate the thermal loads profile of a building.

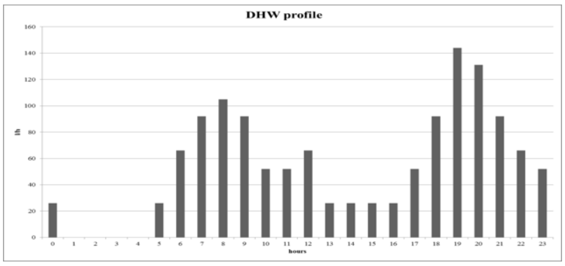

Fig. 2 – DHW hourly profile [34]

The design features of the solar thermal system, including the storage tank are shown in Table 2. An auxiliary system, consisting of a gas boiler, of 11 kW has been connected to the hot tank (Figure 3); it works if heating building energy is requested and temperature of the storage tank is below 55 °C.

Table 2 – Solar thermal system design

Rotex V26P, Flat plate collector [37]	
Net surface (one panel)	2,6 m^2
Number of panels connected in series – number of rows	6 – 3 (Milan, 46,8 m^2) 6 – 0 (Rome, 15,6 m^2) 4 – 0 (Palermo, 15,6 m^2)
ECO COMBI 2 VC Cordivari [38]	
Capacity	1500 l (Milan) – 600 (Rome , Palermo)

2.2 Borehole heat exchanger (BHE)

BHE plays a key role in GSHP systems as a thermal source for the heat pump and the FGC loop. Usually for a single-family dwelling one BHE is enough. Therefore, since the considered building is a multi-family house, a specific procedure has been used in order to design the nominal borehole field in case of absence of solar thermal system [39]. It has to be pointed out that the designed borehole field parameters are similar to each city. Precisely, the results achieved for Milan and Palermo were almost the same in terms of borehole configuration features. However, with regard to Rome, the borehole configuration slightly differs from Palermo. Therefore, the authors preferred to consider the same configuration for all the cities for the sake of comparison and so the biggest BHE nominal configuration calculated with the aforementioned methodology has been considered. Table 3 shows the main BHE and soil characteristics and the undisturbed temperature has been assumed as the yearly average external air temperature of each location. BHE thermal behaviour has been simulated utilizing Type 557 available in the TESS library of TRNSYS [40].

Table 3 – Main BHE and soil characteristics

BHE, single U tube system	
Pipe Outer radius	0,025 m
Pipe Inner radius	0,020 m
Centre to centre half distance	0,0265 m
Pipe thermal conductivity	0,42 W/mK
Distance between boreholes	5 m
Number of BHE	5
Depth	100 m
Soil	
Conductivity	2 W/mK
Storage heat capacity	2400 kJ/m^3K
Undisturbed temperature	13,72 °C (Milan) 15,54 °C (Rome) 18,60 °C (Palermo)

2.3 Heat pump

The considered heat pump refers to the SI 10MR model manufactured by Dimplex® [41]. The heat pump supplies heating load networks by means of the storage tank, while cooling loads have been directly supplied. Therefore, storage tanks supply both DHW and heating loads.

3. System configurations

Three system configurations have been evaluated. Particularly, the first configuration is a conventional GSHP without a solar thermal system and with a FGC loop, which has been taken as a reference. The second one is a SAGSHP with solar thermal system used only conventionally, for the building's heating energy supply. The latter is a SAGSHP, where solar thermal energy can be used conventionally or unconventionally. In particular, the solar thermal energy is used principally to supply building heating energy and its surplus is driven into the BHE accordingly to the implemented controlling temperature difference between solar collectors and BHE. A schematic representation of the SAGSPH is shown in Figure 3. PV panels feed the battery pack by means of the inverter, which extracts electricity from the batteries to supply the heating and cooling system or it drives the PV produced electricity to the grid, in case of full battery. The system carrier fluid is a mixture of water and glycol, it has a specific heat capacity of 3,795 kJ/(kgK) [42]. The circulation pumps work only when the heat pump run [24].

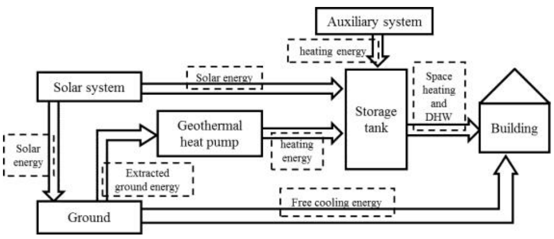

Fig. 3 – SAGSHP simplified scheme.Generic diagram

3.1 GSHP

Four main connections can be identified within Figure 3:

1. Ground – Geothermal heat pump;
2. Ground – Building (FGC);
3. Geothermal heat pump – Storage tank;
4. Storage tank – Building.

In particular, GSHP configuration does not include the solar thermal system but is connected to the hot tank and to the BHE and directly to the heating and cooling building loads loop.

3.2 SAGSHP_C

SAGSHP_C configuration consists of the aforementioned connections and it also includes the connection between the solar thermal system and the storage tank (Figure 3). Precisely, the solar circulation pump drives the carrier fluid through the solar thermal fluid driven collectors and the hot tank when a temperature difference between the bottom part of the hot tank and the solar thermal collector outlet is higher than 4 °C.

3.3 SAGSHP_U

SAGSHP configuration adds the connection between the solar thermal system and the ground to the SAGSHP_C configuration (Figure 3). Control strategy between solar thermal field, BHE and hot tank is hierarchical. The solar circulation pump draws the carrier fluid through solar collectors when the solar collector outlet temperature is higher than the BHE outlet temperature and the hot tank does not require solar energy. The strategy used in this configuration maximises the use of solar heat. Indeed, it is used primarily for DHW and SH supply through the storage tank and secondarily for charging the ground. In particular, when the storage tank does not require solar heat and a specific temperature difference between ground and solar thermal field occurs solar heat is driven into the ground (Figure 3). Furthermore, many temperature differences between solar thermal field and BHE have been evaluated; only the best cases have been reported in the result session as regard Milan.

4. Result

Table 4 – Cases summary

Simulation case	Concept	Free ground cooling	Solar heat injected to ground
Case1, ref.	GSHP	X	
Case 2	SAGSHP_C	X	
Case 3	SAGSHP_U	X	X

Results regard the cases listed in Table 4 and they refer to the last year of the simulation period (21 years). Table 4 lists the simulation cases giving a brief description of their main features, especially how and if solar thermal energy is used. Simulations were carried out for three different Italian locations with BHE depths of 100 m Results in terms of SPF, SF and FGC fraction indexes have been calculated. They are stated respectively as:

SPF = $Q_u/E_{tot} = (Q_{SH}+Q_{SC}+Q_{DHW}+Q_{FGC})/(E_{P1}+E_{P2}+ +E_{P3}+E_{P4}+E_{GSHP}+E_{aux})$ (1)
SF = $Q_{sol} / Q_{SH} = Q_{sol} / (Q_{SH}+Q_{DHW})$ (2)
FGC = Q_{FGC} / Q_{SC} (3)

Moreover, the final energy balance:
Final energy balance = $E_{tot}-PV_{consumed}$ (4)

The results refer to the building energy needs showed in Table 5.

Table 5 – Building cooling - heating loads and DHW energy.

Building thermal loads [kWh]			
	Milan	Rome	Palermo
Q_{SH}	29529	12157	2866
Q_{SC}	8250	11725	18074
Q_{DHW}	18366	18366	18366

Clearly, the building loads are heating dominated in Milan, balanced in Rome and cooling dominated in Palermo (Table 5). Firstly the ground injected and extracted energy, the solar fraction (SF) and the free ground cooling (FGC) fraction have been analysed for all the considered solutions and, then, the final energy consumption and balance.

4.1 Ground energy balance and solar fraction

SAHGSP configurations strongly impact on the extracted and injected ground energy (Figure 4). The link between SF and injected/extracted ground energy is evident. Indeed, Case 2 systems have a solar fraction which is slightly higher than Case 3 systems. It is worth noticing that this happens because the controlling temperature difference between solar collectors and BHE of Case 3 systems have been optimized. In fact, the lower this temperature difference is, the lower the SF of Case 3 systems. Obviously, Case 2 and Case 3 systems show a ground extracted energy less than Case 1 systems, since in the first solutions solar thermal energy is also used to supply building heating energy. Due to the higher ground temperature of the dry-summer subtropical (Csa) climate (Rome and Palermo), the free ground cooling is difficult to attain during the summer. Only for the Case 1 solution in Rome is the FGC fraction around 40%. In such a case, the FGC is possible because of the high extracted ground energy. However, in a humid sub-tropical (Cfa) climate, a suitable method to cover the building cooling demand is the FCG. Indeed, the FGC fractions for all the solution are almost 100% (Figure 4). With regard to Milan and the Case 3 solution, it is extremely important to find a good balance between solar conventional and unconventional operations to have also a high FGC fraction and, therefore, to maximize the energy saving. The controlling temperature difference between solar collectors and BHE is again crucial in this case and the optimum controlling temperature difference, set to 29 °C in Milan, allows us to achieve high SF and FGC fraction.

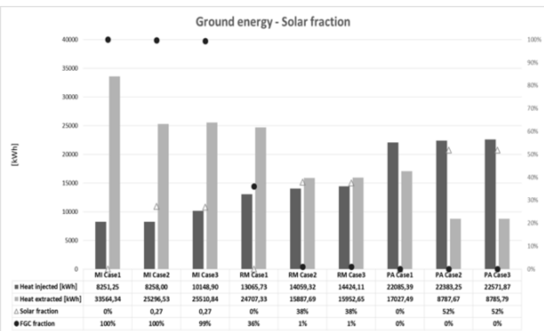

Fig. 4 – Annual ground extracted - injected energy and solar fraction of Case 1, Case 2 and Case 3 solutions for Milan, Rome and Palermo

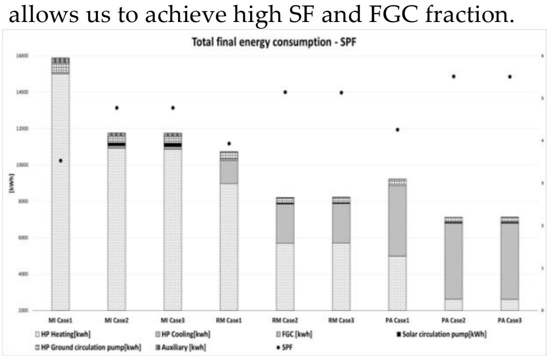

Fig. 5 – Total final energy consumption and SPF of the analysed cases for the considered localities

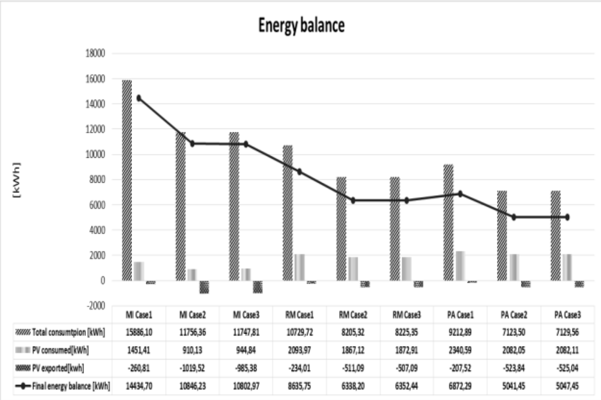

Fig. 6 – Annual final energy consumption, PV consumed and exported energy and energy balance of the considered cases.

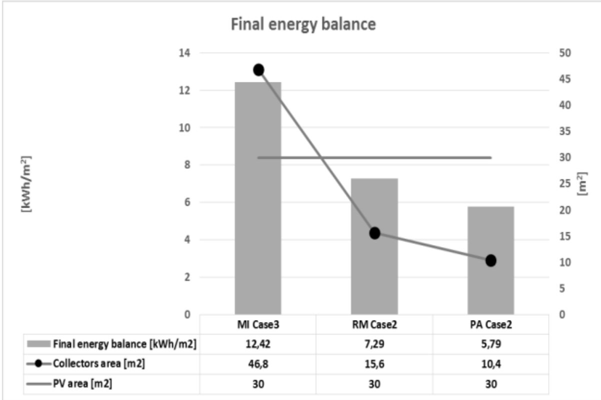

Fig. 7 – Final energy balance referred to m2 of floor area. The best solution for Milano, Rome and Palermo.

On the other hand, the use of low controlling temperature difference values causes a lower FGC fraction, since more solar thermal energy is driven into the ground. As far as Rome and Palermo are concerned, the controlling temperature difference of Case 3 systems has been set respectively to 54 °C. This confirms that using solar thermal energy to load the ground is not appropriate as stated in section 2.2. The performances of Case 3 systems are almost the same as the related Case 2 system, since almost the whole solar thermal energy is used for supplying building heating energy.

4.2 Final energy consumption and balance

Obviously, the Case 1 solutions (Figure 5) have the highest final energy consumption in all the considered localities. Consequently, the SPF of Case 1 systems are the lowest. The Case 3 solution is effective in Milan, while it is not in Rome and in Palermo. In fact, the final energy consumption of Case 3 systems is slightly higher than the related Case 2 system in Rome and Palermo (Figure 5), because of the high controlling temperature difference between the solar thermal collectors and the BHE (see the section 5.2 for more detail). However, with regard to Milan, the Case 2 system has a similar final energy consumption to the Case 3 system. GSHP are able to reach high value of SPF in both Csa and Cfa climates. Indeed, Case 1 systems show a SPF value of 3.53, 3.94 and 4.27 respectively for Milan (Cfa), Rome (Csa with mild, humid winters and hot, dry summers) and Palermo (Csa with hot summer). It is worth noticing that the performances of the GSPHG are higher than that of an air-to-water heat pump used in a building with the same thermal features, which shows an annual SFP of 2.78, 3.47 and 3.6 respectively for Milan, Rome and Palermo [43]. The use of the solar thermal system leads the system to higher SPF.

The SFPs of the best solutions are 4.78 for Milan (Case 3), 5.14 for Rome (Case 2) and 5.52 for Palermo (Case2). With regard to the same locality, Case 3 and Case 2 systems have very close SPF.

The use of a PV system has been considered to assess the final energy balance. Indeed, figure 6 shows the final energy consumption, the PV consumed, through the battery pack, and exported energy and the final energy balance, calculated as stated in (4), of the best cases of each location. As expected, going from Milan to Palermo, the produced PV energy increases. With regard to Case 1 solutions, the battery pack allows it to consume almost all the PV produced energy, reducing the energy fed into the electricity national grid. However, with regard to the SAGSHP systems (Case 2 and Case 3), the PV exported energy is less in Csa locations (Rome and Palermo) than in the Cfa. This is due to the matching of the cooling load and the PV production. The authors have also carried out simulations without the battery pack, finding that the PV exported energy is much higher than a system with battery pack. Solar energy plays a fundamental role in the SAGSHP systems. It leads to low energy consumption especially in localities reached by a lot of solar irradiance like Rome and Palermo; where the use of a PV and a small solar thermal systems create high energy savings (figure 7).

5. Conclusion

Serious environmental problems due to fossil fuel consumption are an increasing world issue. Today, efforts are being made to develop energy-efficient and environmentally friendly systems by utilising non-polluting renewable energy sources. Solar technologies play a fundamental role in achieving these goals, especially in southern European countries, such as Italy, which has been considered in this study. In particular, three different climates have been taken into account: humid subtropical climate (Cfa, in accordance with the Köppen climate classification), Mediterranean climate with mild, humid winters and hot, dry summers and hot-summer (Csa) Mediterranean climate (Csa). They refer respectively to the cities of Milan, Rome and Palermo. A promising technology is the solar assisted GSHP (SAGSHP). In such systems, the solar collectors may supply building heating energy directly, conventional operation, or loading the ground, unconventional operation.

The aim of this research is to assess the long-term performance of a SAGSHP in southern European climates for residential thermal energy supply. In particular, the final energy consumption and the seasonal performance factor (SPF) have been evaluated. Moreover, a free ground cooling (FGC) system for supplying building cooling requirement, as good practice suggests, and a PV system, as the Italian law imposes, have been considered. Furthermore, a PV system with batteries has been considered, since their usage allows higher self-consumption rates of the PV produced energy. The analysed systems configurations are listed in Table 4. It has to be mentioned that solar thermal energy has to be used only conventionally in semi-arid climates (Rome and Palermo). Results show that in Milan almost the whole building cooling demand is satisfied by the FGC, while in the other cities it has not been used. Only in Rome does the FGC fraction assume 40% for the Case 1 system and very small values during the transitional months for the Case 2 system. The lowest energy consumption is achieved by the Case 3 solution in Milan and by the Case 2 solution in both Rome and Palermo. Moreover, with regard to the Case 3 solution in Milan, it is extremely important to find a good balance between solar conventional and unconventional operations to have high FGC fraction and SF. Indeed, the optimum controlling temperature difference has been set to 29 °C. On the other hand, the use of low controlling temperature difference values causes a lower FGC fraction, since more solar thermal energy is driven into the ground. GSHPs are able to reach higher values of SPF in both Csa and Cfa climates than an air-to-water heat pump. As expected, going from Milan to Palermo, the produced PV energy increases. With regard to Case 1 solutions, the battery pack allows it to consume almost all the PV produced energy, reducing the energy fed into the electricity national grid. However, with regard to the SAGSHP systems (Case 2 and Case 3), the PV exported energy is less in Csa locations (Rome and Palermo) than in the Cfa one. This is due to the matching of the cooling load and the PV production. Finally, the use of SAGSHP with PV system show a final energy balance (4), of 12.42 kWh/m², 7.29 kWh/m² and 5.79 kWh/m² respectively for Milan, Rome and Palermo.

6. Nomenclature

Symbols

E_{aux} [kWh]	auxiliary heater consumption
E_{GSHP} [kWh]	GSHP energy consumption
E_{P1} [kWh]	solar circulation pump energy consumption
E_{P2} [kWh]	solar boost pump energy consumption
E_{P3} [kWh]	GSHP - BHE circulation pump energy consumption
E_{P4} [kWh]	FGC – BHE pump energy consumption
E_{TOT} [kWh]	total energy consumption
EER	energy efficiency ratio [-]
FGC	free ground cooling
GSHP	ground source heat pump
PER	primary energy ratio [-]
Q_{DHW} [kWh]	DHW supplied energy
$Q_{heating}$[kWh]	heating supplied energy
Q_{SC} [kWh]	space cooling supplied energy

Q_{SH}	[kWh]	space heating supplied energy
Q_{sol}	[kWh]	solar hot tank supplied energy
Q_u	[kWh]	useful supplied energy
Q_{FGC}	[kWh]	FGC supplied energy
SAGSHP		solar assisted ground source HP
SAGSHP_C		ground source HP with solar thermal system used only for building heating energy (conventional operation)
SAGSHP_U		ground source HP with solar thermal system used for building heating energy and for loading the ground (unconventional).

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