CIC Start Online

Report on

Achieving Higher Heat Pump COP through the use of roof-top thermal solar collectors

By

Professor Tariq Muneer
Lorraine McCauley

School of Engineering and Built Environment
Edinburgh Napier University, Merchiston Campus
10 Colinton Road, Edinburgh EH10 5DT

A report carried out for the
European Energy Centre (EEC)

Acknowledgements
The authors are grateful to CIC Start Online for providing funding to this project. CIC Start Online is funded by European Regional Development Fund and Scottish Government SEEKIT programme that is managed by Scottish Funding Council.

Thanks also due to the European Energy Centre Ltd for their support.

Table of Content

Executive summary

This project investigates the feasibility of achieving higher COP for the Ground Source Heat Pumps (GSHP) through the use of roof-top thermal solar collectors. The report may be divided into four main development areas; a review of the on-site solar and ground energy resource, an analysis on the influence of the solar collector in achieving higher heat pump COP, a development of a simulation tool for the performance of the solar-assisted GSHP and conclusions.

A collection of manufacturers' data from various heat pumps and solar collectors was carried out in order to test the performance of the different technologies.

This study shows that the use of solar collector in northern latitude country has little impact on the heat pump performance improvement in winter. However, the system works slightly better in spring/autumn. The system is more suitable for cold countries with high irradiance.

It has also been shown that using gas boiler for space heating emits nearly twice more CO2 than a heat pump. However, when counting all the costs through the lifetime of each system, a heat pump overall running cost is nearly 50% higher than a gas boiler.

1. The CIC-Start project

CIC Start Online is a joint project of seven Scottish universities, led by Glasgow Caledonian University in collaboration with Edinburgh Napier University, Glasgow School of Art, Heriot Watt University, The Robert Gordon University, University of Edinburgh and University of Strathclyde Glasgow. The project supports collaboration between academia and Scottish small to medium size enterprises (SMEs) in developing, testing and disseminating innovations for sustainable building design and refurbishment. The collaboration is undertaken through joint academic/industry feasibility studies and academic consultancy. Dissemination of the outcomes is provided through seminars, interactive webinars, video recordings, quarterly online magazine Innovation Review and website. The project is funded by ERDF and SEEKIT programmes from 01/09/2009 to 31/08/2012.

The project will deliver 50 feasibility studies and 19 academic consultancies whose outcomes are presented at seminars/webinars (12 held to date). Two online conferences (Sustainable Refurbishment in June 2010 and Resilience of Buildings, Neighbourhoods and Cities in 2011) delivered 15 videos filmed in collaboration with the academics involved in the project. The searchable Knowledge Base within the project website enables easy access to the webinar recordings, videos and articles classified under the headings Decision making, Planning, Design, Construction, Refurbishment and Performance.

The project partners will host six live conferences from February to June 2012. The conference themes will address strategic or technical aspects for the development of low carbon built environment. By December 2011, the project has attracted over 1,030 members from over 790 organisations of which over 540 members represent over 460 Scottish SMEs. In total, there were over 6,000 viewings of seminars/webinars and conference videos.

CIC Start Online was included in the Scottish Green List 2010 of Scottish Sustainable Development Forum as one of the top 20 projects and initiatives for sustainable development. The project was shortlisted by European Structural Funds for Best Practice Awards 2010 in two categories: Best Partnership working and Best contribution to a “Greener” Scotland.

The present feasibility study has been funded by CIC-Start.

2. The European Energy Centre

Centro Studi Galileo (CSG) was established in 1975 to train and educate professionals and technicians in renewable energy, refrigeration and heat pumps. Centro Studi Galileo works with all the 19 leading Italian Universities and the major worldwide associations - such as the leading American ASHRAE, the European AREA, the intergovernmental International Institute of Refrigeration IIR representing 61 countries worldwide - and the leading experts to promote best practice and ensure high standards in the industry are always met. The latest technologies in the sector are showcased at the CSG’s European conferences, next year it will be the 15th European Conference in refrigeration and air conditioning, organised by Centro Studi Galileo, the European Energy Centre and the United Nations Environment Programme (UNEP). CSG’s magazine Industria & Formazione – which is also the official magazine of CSG’s Association of Refrigeration ATF - is a leading tool for delivering the latest technological news to professionals in those sectors. Special issues of this magazine are also published with the United Nation (UNEP) periodically.

The heat pump is an important technology that Centro Studi Galileo teaches and promotes to professionals and technicians working in the heating, air conditioning and related sectors. Such technology has increased in importance especially in recent years. Like all energy technologies, the more efficient they become the more important they are in helping to meet national and European energy efficiency targets. Centro Studi Galileo, as a leader in Italy, and with its strong presence in Europe with the European Energy Centre based in Edinburgh (UK), is always keen to promote and publish important new technologies to share with its large network of professionals, leading experts and technicians.

3. Motivation

The need for an energy performance improvement in Ground-Source Heat Pumps (GSHP) for the residential and commercial sectors has historically been identified as a result of regular project work undertaken by European Energy Centre Ltd. It is clear that there is a dearth of in-situ measured data that is available on COP of GSHP and their equivalent performance. In order to achieve higher heat pump COP through the use of roof-top thermal solar collectors, the Edinburgh Napier University team has been commissioned to undertake research and investigate the performance of such systems. Heretofore such systems shall be called as 'Solar-assisted Ground-Source Heat Pumps (SGSHP)'. Figure 1 provides an illustration of a SGSHP system.

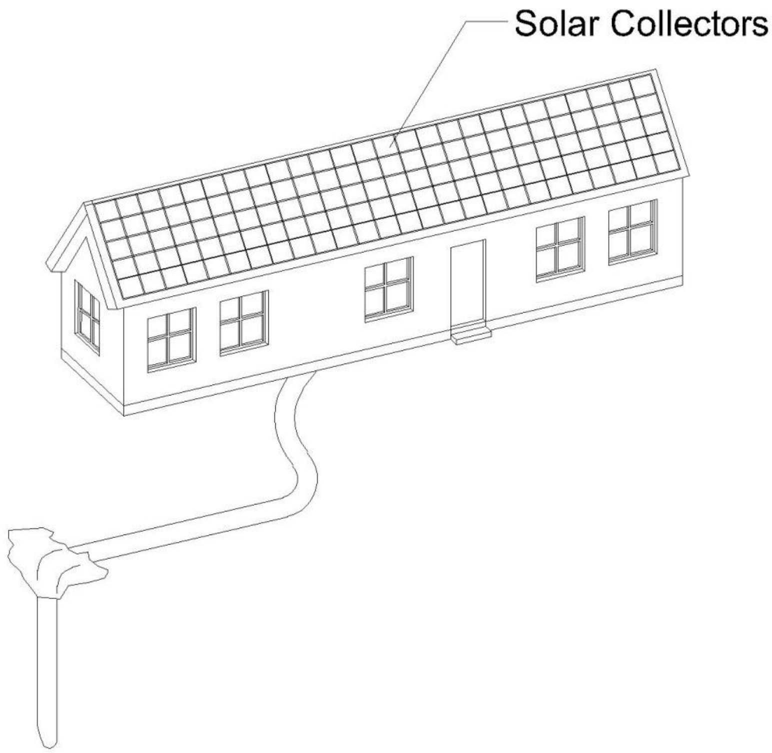

Figure 1 Schematic of a Solar-assisted Ground Source Heat Pump (SGSHP)

It is hoped that the outcome of this study will lead to a rigorously researched and unbiased set of results for GSHP and SGSHP heating systems. Potentially, such systems may be commercialised by the European Energy Centre in future and the product promoted online through the EEC's website www.EUenergycentre.org.

4. Objectives

The feasibility study is directed to explore the potential increase in COP of a heat pump by using roof-top thermal solar collectors. As part of this work the threshold coefficient of performance required to make the financial and environmental break-even point, compared to a conventional heating system shall be found for two scenarios, i.e. (a) space heating only, and (b) space heating combined with hot water heating. Furthermore, the performance of three systems, i.e. gas-boiler based space heating systems for buildings, electrically-operated GSHP and SGSHP shall be compared with respect to the following three parameters:

- energy use
- emissions
- financial costs

This feasibility study is based on commercially available products from manufacturers such as Daikin, Dimplex, Mitsubishi (for GSHP), AES solar (for solar thermal collectors), and Worcester (for gas-boiler).

Data used for this study:

- Air-source heat pump COP is 1.5 – 2 (Source: Energy Saving Trust, March 2004)
- Gas boiler efficiency over its life-time is around 80-85% (Source: NIFES Handbook)
- Running costs: gas = 3.21- and electricity = 11.53 p/kWh. Cost/kWh ratio of electricity-to-gas = 3.6.
- Approximate capital cost ratio of heat pump-to-boiler = 3.5, i.e. Boiler costs £6000, Heat pump costs £15000.
- Life span ratio = 2, i.e. Gas-boiler based system: 20 years, GSHP: 10 years
- Cost for boreholes are about £40 - £60/m
- Cost of trenches are about £15 - £20/m
- Approximate ground heat transfer rate of 50 W/m

5. Overview of Heat Pump technology and its use within the building sector

GROUND HEAT EXCHANGERS

A Ground Source Heat pump is a combination of a heat pump and a system exchanging heat with the ground. It consists of a closed loop system (ground heat exchanger) or an open loop system (ground water).

Following the guidance of ASHRAE (1995), three categories can be identified:

- Ground Coupled Heat Pump (GCHP)
- Ground Water Heat Pump systems (GWHP)
- Surface Water Heat Pump systems(SWHP)

GCHP

Ground coupled heat pump use a buried coil with a circulating fluid in a closed loop of horizontal or vertical pipes to transfer the thermal energy from the ground. The fluid used can be pure water or an antifreeze solution. It is typically circulated through pipes installed in vertical boreholes or coils and horizontal trenches.

GCHP has been used extensively as it eliminates the problems associated with ground water quality and availability. Moreover, they require less pumping energy than the water well systems.

The vertical mode of the GCHP has a heat exchanger that consists of vertically buried pipes or vertical heat exchanger coil. A borehole heat exchanger can contain a U-shaped pipe or a spiral shaped vertical coil heat exchanger. Boreholes are drilled approximately 45m to 150m deep and 4.5 to 6m apart to allow minimum interference between the pipes. Typical U-tubes have a diameter of 20mm to 40mm. The borehole is generally backfilled with a material that prevents de-bonding.

The horizontal mode of the GCHP has a heat exchanger that consists of using a series of parallel pipe arrangements laid out in trenches or horizontal borehole. The pipes are buried in trenches spaced a minimum of 1.5m apart and from 1.2m to 1.8m deep. This distance allows the minimum thermal interference between the pipes. Pipes have a diameter in the range of 20mm to 40mm and about 35m to 50m is installed per kW of heating and cooling capacity, ASHRAE (1995).

Horizontal collectors require relatively large areas free from hard rock or large boulders and a minimum soil depth of 1.5m. Multiple pipes (up to six, placed either side by side or in an over/under configuration) can be laid in a single trench. The amount of trench required can also be reduced if the pipe is laid as a series of overlapping coils, placed vertically in a narrow trench or horizontally at the bottom of a wider trench. Trench lengths are likely to be 20% to 30% of those for a single pipe configuration but pipe lengths may be double for the same thermal performance.

Vertical collectors are used where land area is limited and for larger installations. They are inserted as U-tubes into pre-drilled boreholes generally 100 mm to 150 mm diameter and between 15 m and 120 m deep.

The length of trenches and boreholes greatly depends on the soil conditions including temperature, moisture content, particle size and shape and the thermal performance of the material covering the vertical GCHP.

GWHP
Ground water heat pump systems also called open-loop systems are the origin of GSHP. The majority of open loop systems rely on one or more wells.

Water well ad well pumps are used to supply ground water to a heat pump directly. Water is withdrawn from the well or other source and disposed of through the use of injection wells. The main advantage of GWHP is their low cost, simplicity and small amount of ground area relative to GSHP. On the other hand, the problems are inadequate flow in the production well, plugging that causes pressure build-up in the injection well and failure of the pump.

SWHP
Surface water heat pump systems can either be a closed or an open loop. In the closed loop, heat is being rejected or extracted by circulating a heat exchange fluid through a heat exchanger sized adequately and positioned at the right depth within a lake, pond reservoir or any open channel. On the other hand, in the open loops, water is pumped from the source and discharged to a suitable receptor.

SWHP uses the heat transfer mechanisms and the thermal characteristics of surface water bodies which are different from those of soils and rocks. The closed loop design involves a selection of the right depth, sufficient coil length, pipe diameter and number of loops to have an adequate thermal capacity.

GSHP AND ASHP
GSHP are systems combining a heat pump with a ground heat exchanger (closed or open loop systems). ASHP are systems using a heat pump and ambient air as a heat exchanger. A fan is generally used to create a forced convection and increase the heat transfer capacity of the condenser or evaporator.

Efficiencies of GSHP are much greater than ASHP. Higher COP can be achieved because the temperature of the ground is relatively constant. Additionally, heat is rejected using water which is a better heat transfer medium due to its higher heat capacity.

Table 1 provides details of the load side performance.

Table 1 Typical delivery temperatures for various heating distribution systems (EST, 2004)

Distribution system	Delivery temperature C
Underfloor heating	30-45
Low temperature radiators	45-55
Conventional radiators	60-90
Air	30-50

GSHP PERFORMANCE
The performance data should provide the coefficient of performance (COP), measured as the heat output (kWth) divided by the electrical input (kWel), at standard test conditions for brine/water heat pumps of B0W50, B0W35 and B5W35 (i.e. brine input temperature of 0°C and water output temperature of 50°C, etc).

Figure 2 shows coefficients of performance (COP) measured under test conditions for a typical GSHP. The efficiency for a specific installation will also be dependent on the power required by the ground loop circulating pump and this should be kept as low as possible.

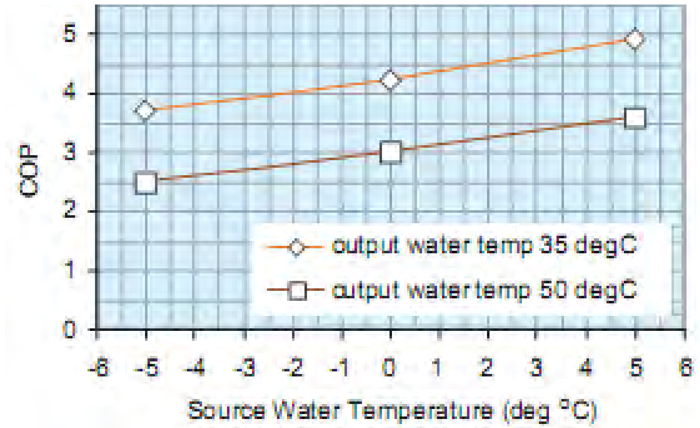

Figure 2 Coefficients of performance of typical small GSHP's (EST, 2004)

WORLDWIDE STATUS OF GSHP

GSHP have been used for over 50 years. Despite this fact, the market penetration is still in its infancy, with gas-boiler and ASHPs largely dominating the space heating market. Germany, Switzerland, Austria, Sweden, Denmark, Norway, France and USA are the countries that have a large number of heat pumps already installed. Table 2 shows the GSHP market size in different countries.

Table 2 Worldwide Geothermal Heat Pump Installations in year 2000 John W, Lund, 2001

COUNTRY	**Installed capacity of GSHP (MWth)**	**Annual Energy Use (GWh/year)**	**Equivalent number of installed GSHP units of 12kW capacity**
Australia	24	16	2000
Austria	228	303.9	19000
Bulgaria	13.3	45	1108
Canada	360	147.5	30000
Czech Republic	8	10.6	663
Denmark	3	5.8	250
Finland	80.5	134.5	6708
France	48	70.8	4000
Germany	344	319.2	28667
Greece	0.4	0.9	33
Hungary	3.8	5.6	317
Iceland	4	5.6	333
Italy	1.2	1.8	100
Japan	3.9	17.8	323
Lithuania	21	166.3	1750
Netherlands	10.8	15.9	900
Norway	6	8.9	500
Russia	1.2	3.2	100
Poland	26.2	30.1	2183
Slovenia	2.6	13	217
Sweden	377	1146.8	31417
Switzerland	500	550	41667
Turkey	0.5	1.1	43
UK	0.6	0.8	53
USA	4800	3333.6	400000
TOTAL	6875.4	6453.1	572949

6. The Renewable Heat Initiative in UK

The Renewable Heat Incentive (RHI) for non-domestic generators was thrown open for applications on Monday 28 November 2011 (DECC, 2012). The start of the scheme was delayed due to the fact that DECC resolved the scheme's compatibility with EU state aid rules. Hopefully, the supporting payments will be made on a quarterly basis for heat generated over the next 20 years. A £2,000 interest free loan from the government was cited in the now dated documentation. Table 3 gives the breakdown of the RHI support that was promised earlier on.
On the 6th of January 2012, Umbrella company and holiday cottages were the first two successful applicants to low carbon heating incentive by installing heat pumps. Note that the revised RHI policy is about to be replaced by mid-2012.

Table 3 UK RHI scheme

Technology	RHI Voucher Value
Solar Thermal Hot Water	£300
Air Source Heat Pump	£850
Ground Source or Water Source Heat Pump	£1,250
Biomass boiler	£950

7. Ground characteristics

The principle of GSHP relies on the near stability of the temperature of ground at medium to large depths (<10m). The temperature difference between the ground and the fluid in the ground heat exchanger drives the heat transfer so it is important to determine the ground temperature. At depths of less than 2m the ground temperature will show marked seasonal variation above and below the annual average air temperature. As the depth increases the seasonal swing in temperature is reduced and the maximum and minimum soil temperatures begin to lag the temperature at the surface. At a depth of about 1.5m the time-lag is approximately one month. Below 10m the ground temperature remains effectively constant at approximately the annual average air temperature (i.e. between 10°C and 14°C in the UK depending on local geology and soil conditions). Figure 3 shows the annual variation in ground temperatures at a depth of 1.7m and is compared to the daily average air temperature measured at Falmouth. It also shows the ground temperature at a depth of 75 m.

Figure 3 Air and ground temperatures, Falmouth 1994 (Geoscience Ltd)

Figure 4 presents ground temperature as function of depth.

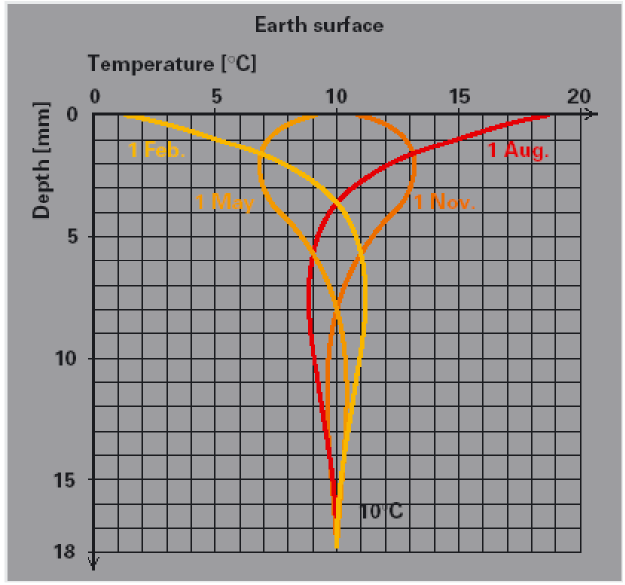

Figure 4 Earth Temperature versus soil depth

Table 4 presents the relevant thermo-physical data.

Table 4 Material characteristics (BSRIA guide, 1999)

Material	**Conductivity**	**Specific heat**	**Density**	**Diffusivity**
	W/(m K)	**kJ/(kg K)**	**kg/m3**	**m2/day**
Granite	2.1 to 4.5	0.84	2,640	0.078 to 0.18
Limestone	1.4 to 5.2	0.88	2,480	0.056 to 0.20
Marble	2.1 to 5.5	0.8	2,560	0.084 to 0.23
Sandstone				
Dry	1.4 to 5.2	0.71	2,240	0.074 to 0.28
Wet	2.1 to 5.2			0.110 to 0.28
Clay				
Damp	1.4 to 1.7	1.3 to 1.7		0.046 to 0.056
Wet	1.7 to 2.4	1.7 to 1.9	1,440 to 1,920	0.056 to 0.074
Sand				
Damp		1.3 to 1.7		0.037 to 0.046
Wet	2.1 to 2.6	1.7 to 1.9	1,440 to 1,920	0.065 to 0.084

8. GSHP costs

For all types of ground collector, setting up costs (design, equipment mobilisation and commissioning) are a significant part of the total cost therefore the capital cost measured in £/m of borehole or £/m of trench will fall as the collector size increases.
For example, for a group of 5 houses on a single site, the collector costs per house are likely to be between 10% and 15% lower than for an individual house.

9. Costs and benefits

Four heating options can be compared. Electric storage heating provides a substantial energy cost saving of £500 per year over the original heating. Oil gives a slightly greater saving of £600 per year, but at a capital cost around £4000 higher. The heat pump options may deliver much higher energy cost savings than either, but at much higher capital costs. Table 5 shows the total costs for GSHP.

Table 5 Indicative capital costs including installation and commissioning for ground-to-water heat pump systems (as cited in literature)

System type	Ground coil costs (£/kW)	Heat pump costs (£/kW)	Total system costs (£/kW)
Horizontal	250-350	350-650	600-1000
Vertical indirect	450-600	350-650	800-1250

10. Review of the Scottish Renewables heating pilot report from the Scottish Government

The installation of renewable central heating systems improved National Home Energy Rating (NHER) scores in all households. The average NHER score of properties in the pilot before installation was 2.8. After installation of renewable, the average NHER score was 5.5, slightly below the national average of 6.1. However, current NHER software is considered to under-estimate the effectiveness of modern models of heat pumps.
NHER–based projections suggest that, before improvements, pilot households emitted on average 11.7 tonnes of carbon per year. The installation of renewable heating systems was projected to reduce this to an average of 4.9 tonnes, a better projected outcome than for oil or electric storage.
Electric storage was found to have a higher benefit to cost ratio (BCR) than the heat pump or oil-based systems.

Table 6 Heat pump design related information (Energy Saving Trust, March 2004)

Type	Description
Sizing	The length of pipe required depends upon the building heating load, soil conditions, loop configuration, local climate and landscaping. The costs associated with the ground coil typically form 30% to 50% of the total system costs, oversizing will be uneconomic. The specific thermal power that a loop can extract (usually measured in: w/metre pipe length for horizontal loops, w/m trench length and W/m of borehole for vertical loops) will be dependent on the temperature difference between the circulating fluid and the 'far field' ground temperature. Sizing is complex and usually performed using specialised software programs the accuracy of which have been verified using monitored data.
Layout, depth	Health and Safety Regulations do not allow personnel to enter unsupported trenches if they are more than 1.2 m deep. Vertical boreholes should be at least 3 m and preferably 5 m apart. Multiple pipes laid in a single trench should be at least 0.3 m apart and to avoid interference between adjacent trenches there should be a minimum distance of 3 m between them.
Piping	For indirect systems high-density polyethylene is most commonly used. It is flexible and can be joined by heat fusion. Pipe diameters between 20 mm and 40 mm are usual. For direct expansion systems copper pipe (12 to 15 mm diameter) is usually used. Depending on soil conditions, a plastic coating may be necessary to prevent corrosion.
Fluid	The freezing point of the circulating fluid should be at least 5°C below the mean temperature of the heat pump. As the mean operating temperature of the heat pump may be as low as – 4°C it is usual to add antifreeze solution to prevent freezing to below –10°C.
Pump	In general the pumping power should not exceed 50W per kW installed heat pump capacity. The pump must be suitable for the minimum design water temperature.

Tables 6 and 7 respectively summarise design guidance and the overall costs and benefits of the four heating options – ASHP, GSHP, electric storage, and oil. A Satisfactory Heating Regime is assumed, and June 2008 energy prices were used as the basis of energy price calculations. These tables were reported in the Energy Saving Trust, March 2004 and the Scottish government social research, 2008.

Table 7 Summary of costs and benefits of different heating options (Scottish government social research, 2008)

Heating technology	Estimated near future installation cost, £	Mean annual energy cost, £	CO2 emissions (T CO2/year)	Carbon value vs original heating, £	Net present value, £	Benefit cost ratio
Electric storage	2850	1800	10.1	730	11500	4.9
Oil Boiler	6890	1700	7	2160	6300	1.9
ASHP	9000	1210	5.1	3030	12200	2.4
GSHP	14500	1170	4.9	3120	9600	1.7

11. Analysis

The initial research work focused on the estimation of different COP depending on the different evaporating and condensing temperatures. The information detailed in Table 8 has been used to provide the first assumptions.

Table 8: UK Housing Data in 2005

Item	Description
Number of households (most constructed <1970)	23 million
Number of households with central heating	20 million
Home ownership	68%
Ownership period for a given property	7.5 years
UK average floor area	85m²
heat loss index	50 Wh/m² Degree Day
Annual loads for space heating	18 MWh
Annual loads for space heating	5 MWh
Annual loads for electricity	3.5MWh
Heating demand	2,000 – 4,000 hours
Annual boiler market (replacement)	1.2 Million units sold
Annual boiler market (new systems in existing buildings)	0.1 Million units sold
Annual boiler market (new systems in new homes)	0.2 Million units sold
Annual boiler market (total)	1.5 Million units sold
Scottish total energy consumption for year 2005 (Domestic)	52TWh
Domestic Energy consumption (% of total energy consumption)	31%

Refer to Tables 9 and 10 that respectively show the sensitivity of COP and space heating costs.

The Figure 6 shows the P-h flows of the refrigerant R410a.

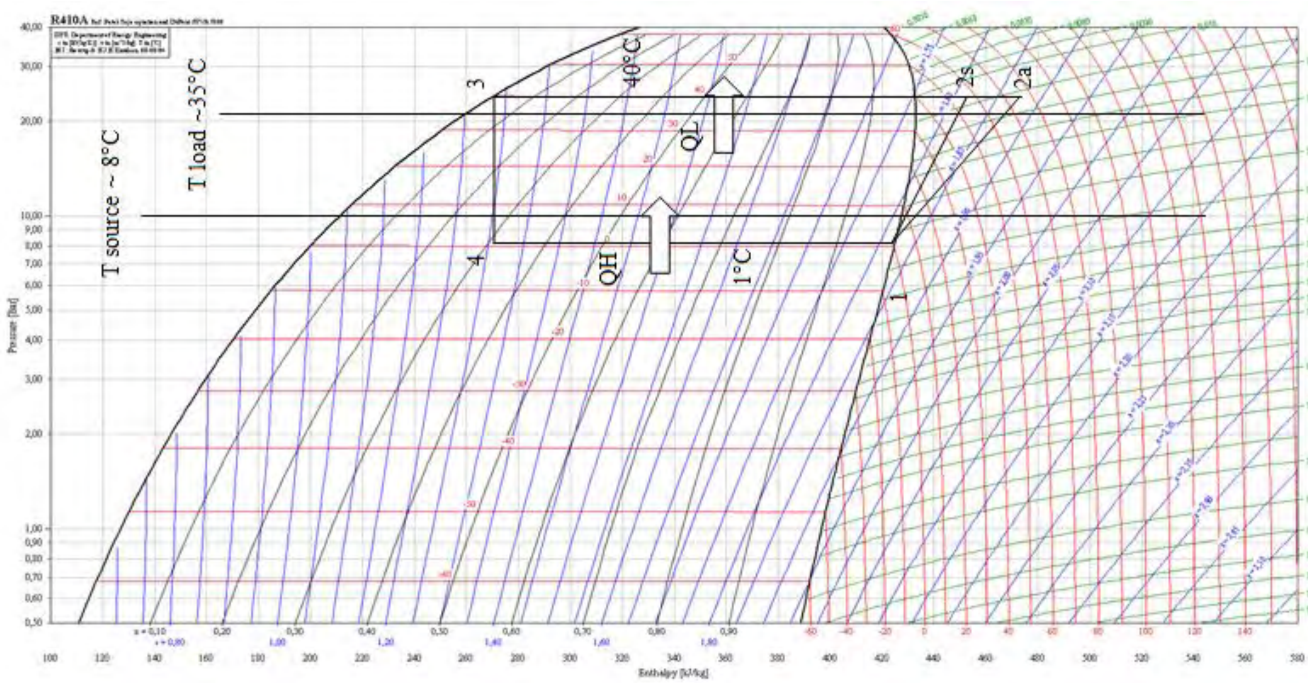

Figure 6 Pressure-enthalpy chart for the heat pump cycle using R410a as the refrigerant.

Table 9 shows the COP variations of the refrigerant R410a.

Table 9: Heat pump COP as a function of temperature (Celcius) of evaporator (1st column) and condenser (1st row)

COP	30	35	40	45	50	55	60
2	8.238	6.9553	5.9995	5.256	4.6578	4.1627	3.7432
4	8.9221	7.443	6.3663	5.5415	4.8858	4.3483	3.8967
6	9.7131	7.999	6.7764	5.8565	5.1348	4.5496	4.062
8	10.653	8.6375	7.2388	6.2063	5.4081	4.7684	4.2405
10	11.81	9.3977	7.776	6.6058	5.7163	5.0128	4.4381
12	13.161	10.25	8.3631	7.0343	6.0423	5.2685	4.6434
14	14.888	11.288	9.0561	7.5297	6.4135	5.556	4.8719
16	17.115	12.55	9.8681	8.0959	6.8301	5.8747	5.1225
18	20.078	14.104	10.825	8.7443	7.2976	6.2271	5.3965
20	24.231	16.076	11.977	9.4985	7.8291	6.6209	5.6989

Figure 7 shows the information from Table 9 in graphical format.

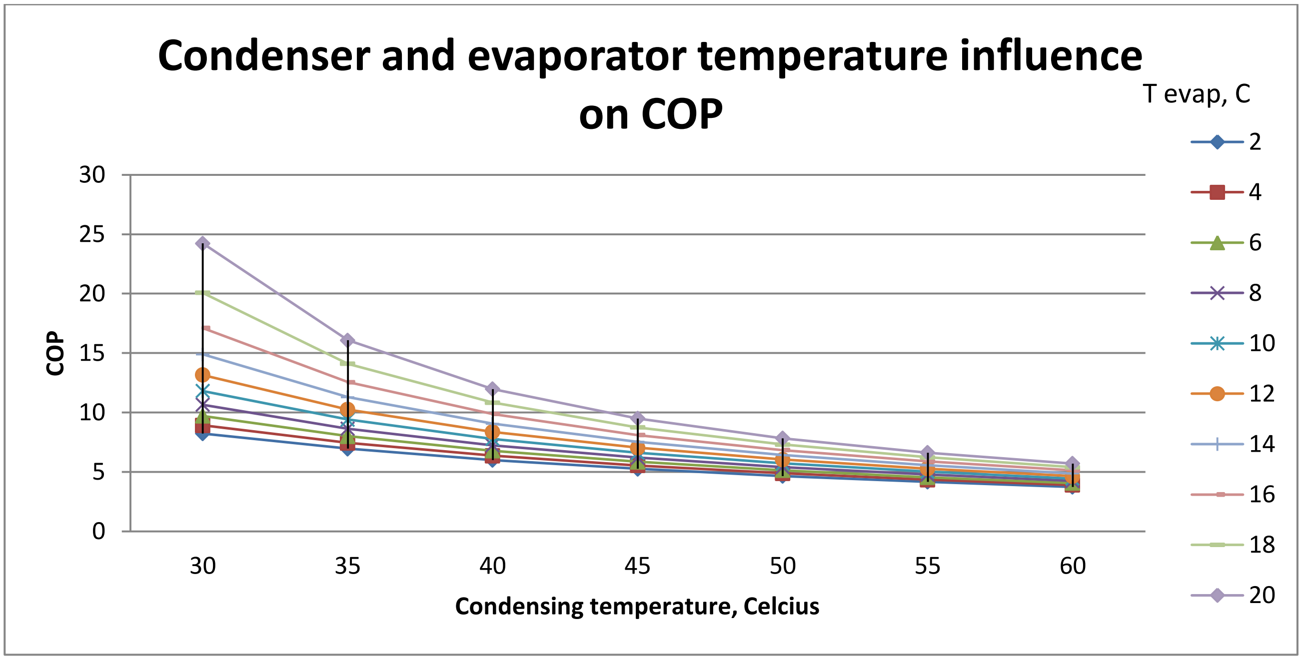

Figure 7 Evolution of COP versus condensing and evaporative temperatures

Table 10 shows the different electrical consumption for space heating depending on the COP

Table 10 Space heating cost as a function of COP – An annual space heating consumption of 15750kWh is assumed

	Cost (£)	Heat pump COP
Cost of electricity for space heating/annum	2575.32	1.5
Cost of electricity for space heating/annum	2066.85	2.5
Cost of electricity for space heating/annum	1848.93	3.5
Cost of electricity for space heating/annum	1727.87	4.5
Cost of electricity for space heating/annum	1650.83	5.5
Cost of electricity for space heating/annum	1597.49	6.5
Cost of electricity for space heating/annum	1558.38	7.5
Cost of electricity for space heating/annum	1528.47	8.5
Cost of electricity for space heating/annum	1504.85	9.5
Cost of electricity for space heating/annum	1485.74	10.5

The second part of the analysis focused on the characteristic estimation of each point of the refrigerant cycle.

Evaporator side:

BSRIA guide states ‘The Geothermal Heat Pump Consortium suggest as a rough guide that a horizontal 2-pipe system may require 17 m to 26 m of trench per kW of nominal capacity. Laying more than 2 pipes per trench or using a spiral configuration would reduce the overall area’.

Pipe diameters between 20 mm and 40 mm are usual. Larger diameter pipe is more expensive, requires a larger fluid volume and is more difficult to handle and install than smaller diameter pipe.

Table 11 shows Glasgow, London and Aberdeen ground temperatures at 1.22m depth.

Table 11 Temperature of the ground at 1.22m depth (°C), Page J and Lebens R, 1986

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Soil type
Aberdeen (Craibstone)	4.4	3.8	4.1	5.6	7.4	10	12	12.8	12.2	10.2	7.6	5.6	7.9	Light soil with hardpan beneath
Glasgow (Paisley)	6.4	5.9	6.1	7.3	9.1	11.3	13.1	13.7	13.2	11.5	9.3	7.6	9.6	Dark garden loam, boulder clay
London (Kensington Palace)	7	6.6	6.6	8.2	10.5	13.2	15.2	16.1	15.6	13.6	10.6	3.2	10.9	Light loam, gravel

Using the following equation, $Q=UA\Delta T$

For the purpose of this study, the following was assumed:

$\Delta T = 3$ °C

A design value of 50 W/m has been assumed as the load of ground buried piping to provide for evaporator load

Electricity tariff: £0.12 / kWh

Electricity CO_2: 0.543kg/kWh

Condenser side

For the purpose of this study, a maximum heating demand of 5.82kW is assumed for the property considered (a two bedroom apartment).
Figure 8 shows the number of households using different amount of energy. It highlights that 3 million use 18MWh of gas per year.

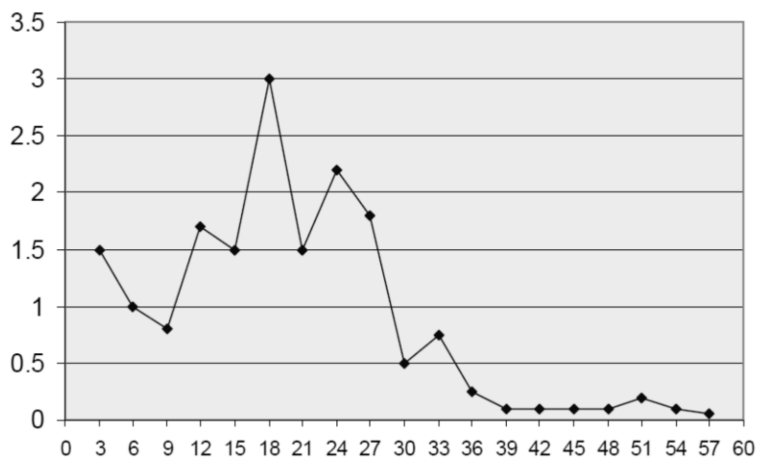

Figure 8 Households in millions (Y-axis) with a given annual gas consumption, MWh

Average UK home with a floor area of 85m²

$Q_{H, peak}$ = 5.82kW

Heating schedule: 6 -10 am and 3 – 9pm

Month: 1st October to 30th April

Degree Day, DD = 2700

UA = 50 Wh / m².DD = 50.3 MJ/DD

Area of walls = 133m²

Design internal and external temperatures are respectively 19 and -2°C

Table 12 Manufacturer's specification for selected heat pumps (Water furnace)

Specifications	
Heat capacity, kW	5.82
COP	3.9
Wcompressor, kW	1.49
Qevaporator, kW	4.342
∆Pevap pump, kPa	20
∆Pcond pump, kPa	30.3
Evaporator mass flow rate, m_e, l/s	0.27
Te,i, °C	10
Te,o, °C	6.06
Area evaporator, m²	0.8
Condenser mass flow rate, m_c, l/s	0.394
Tc, i, °C	37.8
Tc,o, °C	41.3
Area condenser, m²	0.456

12. Simulation

Refer to Figure 9 that shows the three fluid flow loops: (a) hot water circuit on the condenser side, (b) ground /solar-collector heated water circuit on the evaporator side, and (c) refrigerant – flow loop.

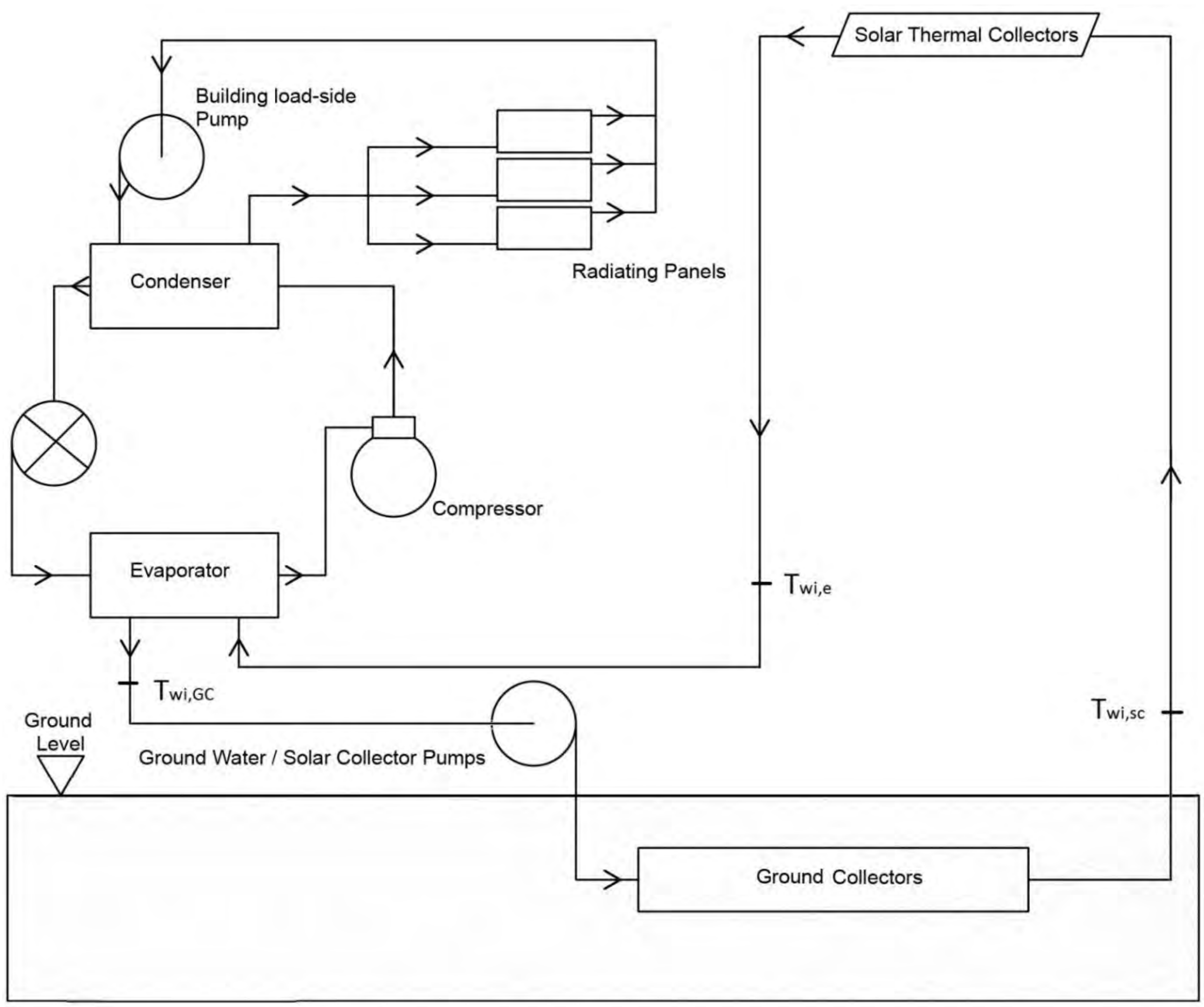

Figure 9: Flow circuits considered in the present simulation exercise

The COP variation shown in Figure 7 has been modelled as follows:

$$COP = (a_0 + a_1 Te + a_2 Te^2) \exp[-b_0 + b_1 Te + b_2 Te^2) T_c]$$

Where:

$a_0 = 11.929$

$a_1 = 1.5964$

$a_2 = 0.07526$

$b_0 = 0.019235$

$b_1 = 0.002291$

$b_2 = -5.29 .10^{-5}$

The temperature / energy calculations for the evaporator and condenser are as follows:

1. Assume $T_{evap} = T_{wei} - 8$
2. Calculate Q_{evap} from P- h chart

3. T_{wei} – (Q_{evap} / mCp)
4. Calculate new Tevap from the following equation (Two – Tevap) / (Twi – Tevap) = exp (-UAs / mCp)
5. Repeat steps 1 to 4 until Tevap convergence is achieved

Assumptions:

a. Tcondenser = 45C; Twci = 35C; Twco = 40C (variable flow rate)
b. From P-h chart, with Tevap / Tcond given, find Qcond

The analysis described in the above section has been written in a Visual Basic for Applications program within MS Excel software.

Sample simulation results for one day each, in January and April are shown in Tables 13 and 14. Table 15 provides the required nomenclature.

Table 13 Simulation results for the first day of January

Month	Day	Hour	SG	DBT, C	Twei	Tevap	Qevap	Ncount	COP	Qcond	Wcomp	Wpump
1	1	1	0.00	2.30								
1	1	2	0.00	2.50								
1	1	3	0.00	2.60								
1	1	4	0.00	2.70								
1	1	5	0.00	2.50								
1	1	6	0.00	2.50	5.76	-0.43	4.58	2.00	4.69	4.57	0.97	0.02
1	1	7	0.00	2.50	5.76	-0.43	4.58	2.00	4.69	4.57	0.97	0.02
1	1	8	0.00	1.90	5.76	-0.43	4.58	2.00	4.69	4.74	1.01	0.02
1	1	9	0.81	2.60	5.76	-0.43	4.58	2.00	4.69	4.55	0.97	0.02
1	1	10	14.58	2.90	5.76	-0.43	4.58	2.00	4.69	4.46	0.95	0.02
1	1	11	48.45	2.90								
1	1	12	38.93	3.50								
1	1	13	29.36	3.70								
1	1	14	27.16	3.70								
1	1	15	4.86	3.70	5.76	-0.43	4.58	2.00	4.69	4.24	0.90	0.02
1	1	16	0.00	3.50	5.76	-0.43	4.58	2.00	4.69	4.30	0.92	0.02
1	1	17	0.00	3.40	5.76	-0.43	4.58	2.00	4.69	4.32	0.92	0.02
1	1	18	0.00	3.40	5.76	-0.43	4.58	2.00	4.69	4.32	0.92	0.02
1	1	19	0.00	2.90	5.76	-0.43	4.58	2.00	4.69	4.46	0.95	0.02
1	1	20	0.00	3.20	5.76	-0.43	4.58	2.00	4.69	4.38	0.93	0.02
1	1	21	0.00	2.50	5.76	-0.43	4.58	2.00	4.69	4.57	0.97	0.02
1	1	22	0.00	2.80								
1	1	23	0.00	3.00								
1	1	24	0.00	3.30								

Table 14 Simulation results for the first day of April

Month	Day	Hour	SG	DBT, C	Twei	Tevap	Qevap	Ncount	COP	Qcond	Wcomp	Wpump
4	1	1	0.00	6.40								
4	1	2	0.00	5.90								
4	1	3	0.00	6.20								
4	1	4	0.00	5.80								
4	1	5	0.00	4.00								
4	1	6	9.81	3.70	6.57	0.34	4.60	2.00	4.78	4.24	0.89	0.02
4	1	7	59.88	4.00	8.76	2.45	4.66	2.00	5.02	4.16	0.83	0.02
4	1	8	107.10	5.00	11.16	4.77	4.72	2.00	5.30	3.88	0.73	0.02
4	1	9	155.80	6.90	14.17	7.68	4.80	2.00	5.68	3.35	0.59	0.01
4	1	10	281.68	9.40	22.48	15.68	5.03	2.00	7.34	2.66	0.36	0.01
4	1	11	445.27	11.50								
4	1	12	734.89	13.60								
4	1	13	543.27	13.50								
4	1	14	193.20	13.60								
4	1	15	271.25	14.50	27.10	20.10	5.18	2.00	9.04	1.25	0.14	0.01
4	1	16	154.83	14.60	21.83	15.05	5.01	2.00	7.15	1.22	0.17	0.01
4	1	17	94.91	14.10	18.56	11.92	4.91	2.00	6.40	1.36	0.21	0.01
4	1	18	27.43	11.30	12.64	6.21	4.76	2.00	5.48	2.13	0.39	0.01
4	1	19	0.81	9.70	9.80	3.46	4.69	2.00	5.14	2.58	0.50	0.01
4	1	20	0.00	9.70	9.80	3.46	4.69	2.00	5.14	2.58	0.50	0.01
4	1	21	0.00	9.40	9.50	3.17	4.68	2.00	5.11	2.66	0.52	0.01
4	1	22	0.00	8.90								
4	1	23	0.00	9.20								
4	1	24	0.00	9.00								

Table 15 Nomenclature for Tables 13 & 14

Acronym	**Definition**
SG	Slope Global Radiation in W/m²
DBT	Dry Bulb Temperature, Celcius
Twei	Temperature water entering evaporator
Tevap	Temperature evaporator
Qevap	Energy evaporator, kWh
Ncount	Number of iteration
COP	Coefficient of performance
Qcond	Energy condenser, kWh
Wcomp	Energy used by compressor, kWh
Wpump	Energy used by pumps, kWh

13. Discussion

The Table 16 compare the performance of three systems, i.e. gas-boiler based space heating systems for buildings, electrically-operated GSHP and SGSHP following three parameters:

- energy use
- emissions
- financial costs

Table 16 Comparison between the 3 sources of heating

	GSHP (0m² of solar)	SGSHP (63m² of solar)	Conventional gas boiler
W compressor, kWh	1760	1662	-
W pumps, kWh	28	37.5	-
Energy space heating, kWh	8,632	8,632	8,632
Average yearly COP (efficiency for gas boiler)	4.9	5.2	0.9
Total electricity, kWh	1,788	1,699.5	-
Total gas used, kWh	-	-	9495
Cost of energy, £ / year	217	206	345.62
Overall cost, £ / year Fuel usage + fuel standing charge + maintenance cost + equipment replacement cost	1517	In view of the quoted solar collector prices this option is uneconomical on a monetary basis.	1,055
CO2 emission, kg	971	923	1747

The costs and CO2 emissions of each system have been calculated using Table 17.

Table 17 Details of costs used for the financial analysis

Gas price (usage)	3.64	p/kWh
Gas standing charge	31.47	p/day
Gas CO2 emission	0.184	kg/kWh
Installed cost of condensing gas boiler	5,000	£
Gas boiler monthly maintenance charge	10	£
Service life for gas boiler	15	Years
Gas boiler monthly replacement cost	39.54	£
Electricity price (usage)	12.11	p/kWh
Electricity standing charge	20.66	p/day
Electricity CO2 emission	0.543	kg/kWh
Installed cost of heat pump	10,389	£
Heat pump monthly maintenance charge	20	£
Service life for heat pump	15	Years
Heat pump monthly replacement cost	82.08	£

Table 18a Hurlstones prices for energy technologies

Fully installed prices	
Air source	£650 - £800 per kW
Ground source horizontal	£1,100 - £1,500 per kW
Ground Source Borehole	£1,500 - £2,000 per kW
Solar Thermal	£1,500 / m2 for 1st 4m2 £1,000 / m2 for anything larger
London installations towards the higher end for GSHP	up to £3,000 per kW in central London.

Table 18b Independent check for prices provided in Table 18a

Item code	Model No.	Heating capacity, kW	Price (incl. VAT), £	Accessories, £	Delivery, installation, and commissioning, £	Trenching, £	Borehole cost, £	Total cost, £	Cost, £/kW
031914	SIH6ME (GSHP)	6	4030.95	2754.25	1661.63	1942.50	4725.00	10389.32	1731.55
360040	LAB7M (ASHP)	7	2425.57	1377.12	830.81			4633.51	661.93
NIBE	F1145 (GSHP)	12	6858.6525	5508.50	3323.25	3885.00	9450.00	19575.40	1631.28

14. Conclusions

The results of this feasibility study demonstrate that the use of solar collectors combined with ground-source heat pump helps in achieving only marginally higher COP. The other main conclusions are:

- Using gas boiler emits nearly twice more CO2 than a heat pump.
- Using heat pump is a third cheaper to run than a gas boiler (only counting the cost of energy).
- When counting all the costs through the lifetime of each system, a heat pump overall running cost is nearly 50% higher than a gas boiler.
- Solar assisted heat pump (SGSHP) system is more suited for cold regions but those that have a high irradiance income. For Scotland, in view of the low irradiance during winter and bearing in mind the excessive costs quoted by the solar collector manufacturers SGSHP is not an economical option.
- Decarbonising the grid will make heat pump a very attractive low carbon solution compared to the other presently popular sources of heating.

15. References

Daikin, 2011. Technical Data: Heating. Daikin Altherma. EEDEN10 - 721. Accessed online from: http://daikin.mcquay.hu/3_H%C5%91szivatty%C3%BAk%20%C3%A9s%20napkollektorok/1_Daikin%20Altherma/1_Alacsony%20h%C5%91m%C3%A9rs%C3%A9klet%C5%B1%20osztott/3_Kieg%C3%A9sz%C3%ADt%C5%91k_%C3%A9s_Opci%C3%B3k/Documents/EKHTS_Haszn%C3%A1lati_Melegviz_tart%C3%A1ly/Data_Books/EEDEN10-721_EKHTS-AC_tcm135-168665.pdf on December 11th 2011

Dimplex renewable, 2011. Project planning manual: Heating and cooling with heat pumps. Accessed online from http://www.dimplex.de/fileadmin/dimplex/downloads/planungshandbuecher/en/dimplex_phb_kuehlen_gb_122008.pdf. on December 10th 2011

Energy Saving Trust, March 2004. Energy Efficiency Best Practice in Housing. Domestic Ground Source Heat Pumps: Design and installation of closed-loop systems. Accessed online from: http://gshp.org.uk/documents/CE82-DomesticGroundSourceHeatPumps.pdf on December 2nd 2011

GSR, 2008, The Scottish renewable heating pilot, Scottish Government Social Research, 2008

John W, Lund, 2001 Geothermal Heat Pumps, Geo-Heat Centre Quarterly Bulletin, Vol 22, No. 1, Geo-Heat Centre, Oregon Institute of Technology, Klamath Falls, OR.

Mertzios C. 2006. A solar driven cooling system using innovative ground heat exchangers. PhD thesis. Nottingham University

Mitsubishi, 2011. Design, Installation & Servicing Instructions. Ecodan® Air Source Heat Pump and Flow Temperature Controller 2 Accessed online from: http://domesticheating.mitsubishielectric.co.uk/files/library/files/ecodan/Technical%20Brochures/FTC1%20Design,%20Installation%20&%20Servicing%20Instructions.pdf on December 12th 2011

Page J, and Lebens R, 1986. Climate in the United Kingdom: a handbook of solar radiation, temperature and other data for thirteen principal cities and towns

Pehnt M. et al, Micro Cogeneration, Towards Decentralized Energy System

Pennycook K, 2008, The illustrated guide to renewable technologies, BG 1/2008, BSRIA

Rawlings R, 1999, Ground Source Heat Pumps a technology review. A Technology review, TN18/1999, BSRIA