The ground source heat pump project at Lakeshore, Bristol (UK)

– an example of a commercial turn-key heat pump project

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Introduction

The Lakeshore development[1] of eco homes is being realized in Bristol (UK), see **Figure 1**. The project converts the Grade II listed building, former home of Imperial

1 http://www.urbansplash.co.uk/residential/lakeshore

Tobacco to modern apartments set over it's own lake and in 10 acres of green space.

The design of the building and building services are ambitious, the energy efficiency meets the best 'A' low energy criteria (BREEAM rating). One of the key systems to achieve this ambitious energy rating is the ground source heat pump system which, together with a biomass boiler, will provide the thermal energy for space heating and tap water production. When operational it will be among the largest residential installations in the UK.

As with any ambitious project, and especially with a project that retrofits an existing building, there are many design challenges and issues that need to be considered. One of these challenges is the fact that originally the ground source heat pump system would be used to provide a certain amount of cooling to the apartments, which could unfortunately not be realized due to limitations of the system. This means that the additional thermal regeneration of the ground will not be available. Another issue with the system was that the borehole heat exchanger system was already installed and could not be increased in size.

Figure 1. The Imperial Tobacco building during refurbishment (2011).

Groenholland Geo-Engineering was contracted to provide a turnkey heat pump system for this development. To be able to achieve the goals of energy efficiency within the boundaries of the existing borehole heat exchanger system and functioning as a heating-only system, a new design study was undertaken. This study first of all calculated the energy use of the building, on an hourly basis, with a dynamical building simulation. This model was created in TRNSYS (Klein et al 1976) and was used to carry out a number of sensitivity analyses on different important parameters affecting energy usage profiles. Also, the model results were used to select the appropriate capacity and capacity steps of the heat pump system. Subsequently, the model results were used to calculate the possible thermal use of the ground store under different scenarios, for this analysis the standard program EED (Earth Energy Designer, Eskilson et. al 2000) was used.

The modelling we present here has been carried out more from an engineering point of view and not from a scientific point of view. Therefore different approaches have been used and combined in a practical way:

- A very detailed energy simulation study to correctly calculate the overall energy performance of the building, needed for the capacity selection and borehole heat exchanger thermal performance.
- A standard approach to the thermal analysis of the borehole heat exchanger system, allowing the rapid evaluation of different scenarios.
- A simple spreadsheet based approach to performance analyses and achieved energy savings.

After the design studies had been completed the heat pump plant was designed and constructed as a pre-manufactured turnkey plant room system. This system was adapted from the highly modularized Groenholland standard plant room modules, using sophisticated but standardized controls and control algorithms. This pre-manufactured and pre-commissioned system means only little time is spent in construction of the plant room on site while at the same time a high standard of manufacturing quality can be delivered. In this case for instance, full commissioning of the completed plant was carried out in less than one day.

In this paper we present these three aspects of the Lakeshore system in more detail: the building energy simulation, heat pump plant design and evaluation and some impressions of the turnkey plant room system.

Dynamical building energy simulation

The design of a borehole heat exchanger, or the thermal performance of an existing borehole heat exchanger system, depends to a large extent on the thermal load. One

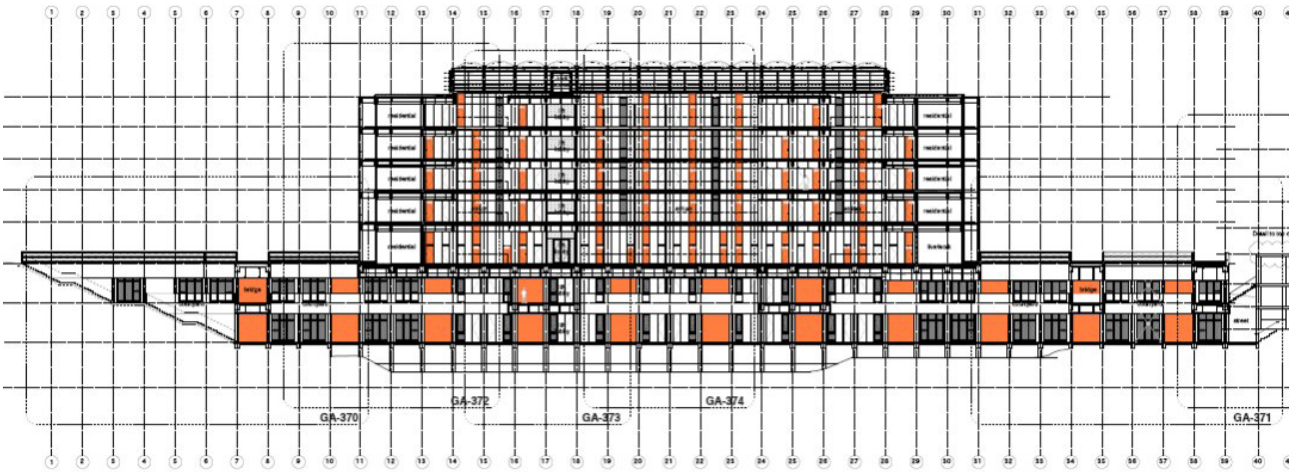

Figure 2. Vertical (side) view of the development.

of the main challenges in ground source heat pump design is the fact that the source water temperature (the water entering the heat pump from the ground) is dynamically linked to the heat pump operation (capacity and running time in a typical cycle) as well as to the long-term cumulative loading.

The long-term thermal loading (seasonal loads during the complete operational life span of the system) affect the store temperatures in the whole ground volume. During winter, when heat is extracted, the total store will cool down, while in summer (during cooling operation or natural regeneration) the store will heat up. On top of this, during each operational cycle of the heat pump, the local temperature in and around the borehole will react to the heat being injected or extracted by that specific pulse.

It is therefore essential to have accurate energy use information. Usual practice, to design the plant on capacity needed for a transmission loss at one set of specific conditions, is not sufficient. Ideally hourly heating and cooling loads, or at least monthly loads and capacity, need to be available. The hourly heating and cooling loads can be used to select the total capacity of the heat pump system, the size of the individual heat pump stages and the size and configuration of the borehole heat exchanger ground source system.

To create a complete model of each space in the building would be very time consuming and expensive. In the simulation model therefore the building is structurally represented by different zones, where each zone represents a distinct unit (zone) made up of several spaces, which is defined by exposition and location in the building, size and boundaries with the environment or other spaces. In this way not every individual space needs to be modelled. The total load of the building is then calculated by multiplying the number of units of that specific type with the results from the model.

For every zone the following factors influencing the loads are considered:

1. Structural make-up of zone: floors, walls, roof, windows (materials and orientation).
2. External climate: temperature, irradiation, and relative humidity.
3. Boundaries with other spaces.
4. Infiltration and ventilation schedule.
5. Heating and cooling schedule.
6. Heating and cooling gains (persons, computers, lighting, other).

The model calculates the hourly heating and cooling demand for each zone. The building total demand is calculated by multiplying the load of each zone type by the number of times this zone occurs in the building.

The building (**Figure 2**) comprises seven floors, with a total of 286 apartments

The apartments are distributed over the different levels as follows:

Level 1: .... 72 apartments
Level 2: .... 87 apartments
Level 3: .... 31 apartments
Level 4-6: .... 25 apartments
Level 7 (top):... 21 apartments

The smallest apartment measures 28.7 m², the largest 115.4 m². Average size is 61.5 m², total apartment floor area is 17598 m².

For each floor 1, 2-4 (which are identical), 5, 6 and 7 several different zones have been defined in such a way that a representative sample of apartments has been obtained. In essence all different apartment types with different boundaries and different expositions have been selected. In total 67 distinct types have been defined.

For each modelled space the constructive data were taken from the architects drawings and translated to floor, wall, ceiling types, windows etc. The resulting thermal characteristics were compared with the building-specification of U-values as a check on the input.

The model uses the ambient conditions from the climate record of Cardiff (UK). The parameters ambient temperature, relative humidity, solar zenith and azimuth angle, total and beam radiation on the horizontal as well as total radiation and incidence angles on tilted surfaces are used. Minimum ambient temperature in the record is -4.78°C, maximum ambient temperature in the record is 24.6°C. The temperature graph for the model-year is given in **Figure 3**. Another important aspect of the simulation are the temperature set points and internal gains, these are summarized in **Table 1**.

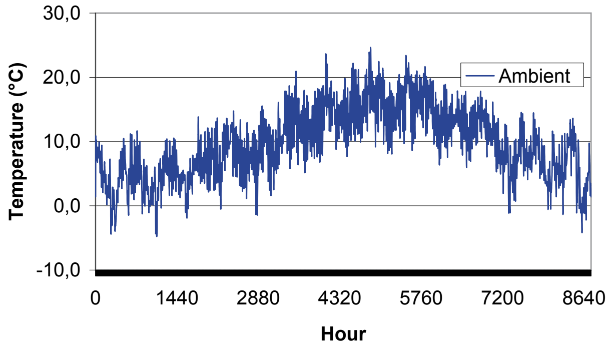

Figure 3. Ambient temperature TRY record Cardiff (Wales, UK).

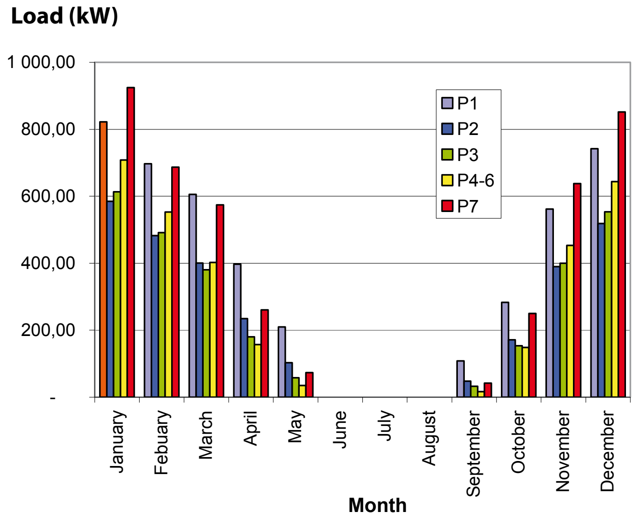

Figure 4. Average monthly apartment load per level.

Table 1. Internal load schedules used for the TRNSYS simulation.

Internal gain or set point	Value	Schedule	
Temperature set point heating (occupied spaces)	21°C	No heating June, July & August	
Temperature set point heating (unoccupied spaces)	16°C	No heating June, July & August	
Temperature set point cooling	-	-	
Infiltration	*Calculated from the ventilation and infiltration rates provided (VENTILATION PART F)*	-	
Ventilation			
People (low activity rate)	depends on apartment size & bedrooms (2, 3 or 4 persons)	between 7:00 and 17:00 only one person present	8.5 hours/day
Electrical gains	230 W	11 hours/day	
Lights	5 W/m²		

Based on the calculations, the total heating load of the building is 831 MWh/year, with a maximum peak load of 570 kW. Average apartment load for each level is shown in **Figure 4**.

Loads per apartment for the lowest (P1) and highest (P7) levels are higher due to higher losses across the (unheated) foundation and roof boundaries. Also the size of the apartments plays a role.

Figure 5 shows the yearly load demand curve, we can see that the load curve is not very steep towards the higher capacities. Nevertheless, with only 200 kW capacity already over 70% of the load is covered, with 400 kW 98% of the total yearly demand is covered.

The maximum demand (peak capacity) per apartment type has also been extracted from the model results, a summary is presented in **Table 2**. Peak capacities range between 1 kW and 4.3 kW. As is to be expected with apartments differing significantly in size and exposition the range of capacities if fairly large. At the same time however, one may conclude that the average capacity is not very big, attributable to the energy efficient design. With apartment sizes varying between about 40 and 115 m² the heating load varies between 20 W/m and 31 W/m.

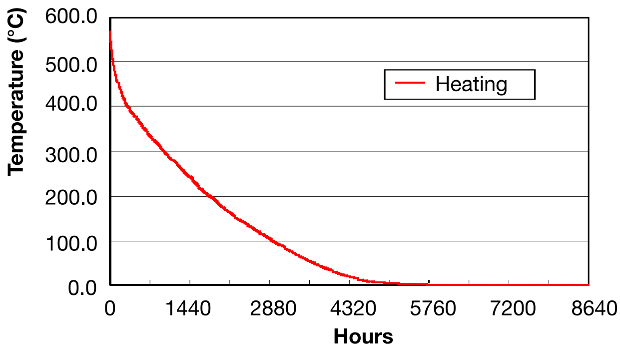

Figure 5. Load demand curve, space heating load.

The sensitivity of the model to certain boundary conditions has been investigated by running a number of simulations for the apartment with the lowest (level 3, zone 5

Table 2. Maximum heating demand (peak capacity) per apartment type.

Level 1			Level 2			Level 3			Level 4-6			Level 7		
Zone	**Type**	**kW**	**Zone**	**Type**	**kW**	**Zone**	**Type**	**kW**	**Zone**	**Type**	**kW**	**Zone**	**Type**	**kW**
ZI	B1	**2.01**	ZI	B1	**1.83**	ZI	H	**3.29**	ZI	N	**3.06**	ZI	N	**3.55**
	B2	**1.82**		B2	**1.65**	ZII	J1	**1.53**	ZII	K	**1.15**	ZII	R	**2.42**
	E	**1.20**		E	**1.07**		J1	**1.58**		M	**1.79**		M	**1.73**
ZII	C	**2.18**	ZII	C	**1.87**	ZIII	H	**3.34**	ZIII	N	**3.10**	ZIII	P	**4.31**
	C	**2.23**		C	**2.31**	ZIV	H	**3.26**	ZIV	N	**3.10**	ZIV	P	**3.74**
ZIII	B2	**1.81**	ZIII	B2	**1.53**	ZV	J	**1.48**	ZV	K	**1.03**	ZV	R	**2.31**
	B1	**1.77**		B1	**1.61**		J	**1.53**		M	**2.68**		M	**2.27**
	B1	**1.84**		B1	**1.66**	ZVI	H	**3.39**	ZVI	N	**3.00**	ZVI	N	**3.47**
	B2	**2.03**		B2	**1.64**									
	D	**1.77**		D	**1.57**									
ZIV	B2	**1.63**	ZIV	B2	**1.60**									
	B1	**1.71**		B2	**1.68**									
	B1	**1.77**	ZV	B2	**1.53**									
	B2	**1.93**		B2	**1.65**									
	D	**1.72**	ZVI	B2	**1.59**									
ZV	A	**2.40**		B1	**1.55**									
	A	**2.76**		B1	**1.61**									
ZVI	S	**2.09**		B2	**1.59**									
	S	**2.19**		D	**1.57**									
			ZVII	A	**1.67**									
				A	**1.94**									
			ZVIII	S	**1.79**									
				S	**2.01**									

apartment type K) and highest (level 7, zone 3 apartment type P) heat loss. Results are given in **Table 3**.

Infiltration (leakage) has little effect on the total or peak loads, using aluminium frames on the outside instead of insulated frames clearly has a larger effect. If a night setback to 18°C is simulated large changes in load results, with lower total loads but higher peak demand (due to the need for warming up the spaces in the morning).

Although the sensitivity study performed is very limited in scope it does indicate that effects of constructive changes are relatively small, while changes in user behaviour may affect loads much more.

In addition to the space heating loads, also the domestic hot water (DHW) loads need to be covered by the system. These loads are not calculated by the dynamical TRNSYS model, but have been estimated based on a report issued by the BRE (June 2005). This report indicates that a household in the higher income range will use about 50 litres of hot water per person per day. The hot water demand for 286 apartments with, on average, 2 adults per apartment (574 persons in total), can be calculated by a further assumption of the temperature difference. Assuming source water supply is 10°C and needs to be heated to 60°C the total load is: 50 * 572 * 0.9998 * 4192 * 50 = 1.67 MWh/day.

Table 3. Sensitivity results, percentage total yearly load and peak load change.

Parameter	App. level 4, Zone V (K)		App. level 7, Zone III (P)	
	Load	Peak load	Load	Peak load
Infiltration +30%	+4	+1.9	+2.5	+1/5
Window frame insulation	-14.5	-4.7	-11.8	-5.5
Night-setback (23:00 - 8:00 - 18°C)	-34	+6.5	-26.5	+23.6

Table 4. Space heating, domestic hot water and total load profile (MWh).

	Space Heating (MWh)	Domestic Hot Water (MWh)	Total (MWh)
January	180.11	51.77	231.88
February	140.41	46.76	187.17
March	113.51	51.77	165.28
April	54.56	50.10	104.66
May	17.78	51.77	69.55
June	0	50.10	50.10
July	0	51.77	51.77
August	0	51.77	51.77
September	6.36	50.10	56.46
October	40.30	51.77	92.07
November	115.00	50.10	165.10
December	163.11	51.77	214.88
Total	**831.14**	**609.55**	**1440.69**

Adding these loads to the previously calculated space heating demands results in the following total load profile (**Table 4**).

Normally the DHW load is met in a few hours per day, if additional capacity needs to be added to the base (heat pump and biomass boiler) capacity resulting from the space heating load profile analyses remains to be discussed.

Borehole heat exchanger model

The essence of the borehole design is to size the borehole heat exchanger so that it is able to maintain the required operating temperature bandwidth given the energy profile (heating and regeneration operation) and the associated heat pump equipment. This can be achieved by either changing the size of the BHE system to the full load profile or, in the case of a hybrid heat pump system, by balancing the amount of thermal energy exchanged with the ground, or by a combination of both.

For the present case the size (number of loops & installed depth) of the borehole heat exchanger system was fixed, therefore the design focused at optimizing the energy exchange with the earth, the amount of regeneration and heat pump capacity.

The operational temperature bandwidth selected will affect performance of the heat pump significantly. Running at low evaporating temperatures during heating should be limited, as the drop in performance (both efficiency and total output) is significant. At the same time, the heating system of the building should be configured for low temperature heating to achieve the highest performance rates from the heat pump equipment.

The installed borehole heat exchanger is made up of 88 standard single U-loop heat exchangers installed in boreholes of about 100 meters depth.

Table 5. Energy savings (Co₂ Emission Factors 0.204 for gas, 0.543 for electricity, DEFRA 2009).

Scenario	MWh		COP-SPF	MWh expended	%	CO_2 factor (kg/kWh)	ton CO_2	%
Gas boiler	Heating	1,440	0.85	1,694		0.204	346	
	TOTAL			**1,694**	**100**		**346**	**100**
Heat pump	Heating 50%	720	3.2	225		0.543	122	
Gas boiler	Heating	720	0.85	848		0.204	173	
	TOTAL	**1,440**		**1,073**	**63**		**295**	**85**

The target of the ground source heat pump installation was to provide about 50% of the total heating load with the ground source heat pump system, and achieve a reduction of CO_2 emissions of 15%. Using these data we can calculate the design parameters for the ground source heat pump system, including the required minimum performance factor. **Table 5** shows the energy savings calculation for the total load of 1441 MWh by comparison with a standard gas-fired boiler system (conversion factors based on DEFRA 2009 data).

From this table we can see that, with a heat pump system supplying 50% of the total heating load (720 MWh) the target of 15% savings on emissions is realized if the Seasonal Performance Factor of the heat pump system (including circulation pumps) is at least 3.2.

The performance of the heat pump depends typically on the source and sink temperatures. Typical data is given in **Table 6**, to achieve the required performance level the source temperature should, on average, be above 1°C when the sink (heating) temperature is 35°C and above about 5°C when the sink (heating) temperature is 45°C.

Table 6. Indicative heat pump Co-efficient of Performance (COP) for different source and load side temperature conditions.

COP efficiency	Evaporator in / out Water (°C)		Condenser in / out Water (°C)	
2.9	-5	-10	30	35
3.7	1	-4	30	35
5.4	7	2	30	35
1.9	-5	-10	40	45
2.2	1	-4	40	45
3.4	7	2	40	45

The temperature of the heating system, as the same loop is used for the DHW production, is required to be 45°C, therefore the design temperature for the ground source heat exchanger was set at an source temperature for the heat pump of 5°C, as the heat pump operates at a temperature difference of 5K this means the average fluid temperature is about 2.5°C.

The temperature response of the existing borehole heat exchanger was calculated with Earth Energy Designer (EED, Eskilson et. al. 2000). This response was calculated for several energy scenarios until the required result was obtained. In **Figure 6** the average monthly temperature in year 1, 2, 5, 10 and 25 for three energy scenarios is depicted. The general trends are indicated by a polynomial fit. The reference case (1440 MWh total load) quickly shows very low temperatures, already in year 2 the temperatures drop well below 0°C. Using the ground source heat exchanger for only half the total energy load results in average fluid temperatures just around 0°C in year ten, while when at least 200 MWh of heat is injected into the ground during summer, the temperatures remain above 0°C even after 25 years of operation. The heat needed to regenerate the ground

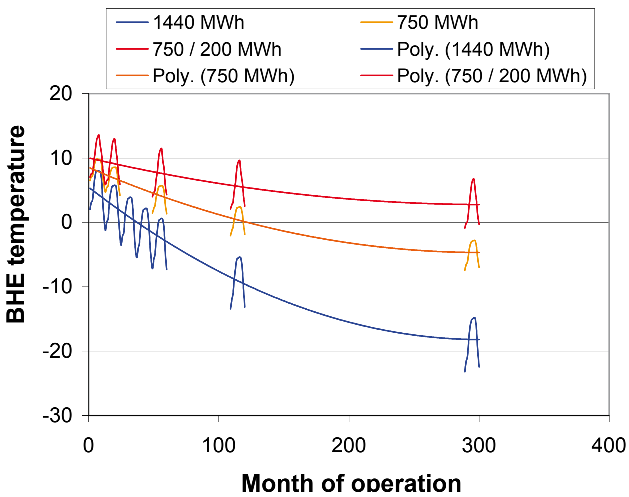

Figure 6. Temperature response of the ground source heat exchanger with different energy scenario's.

temperature will be delivered by a solar thermal panel array, the design of this array is still to be finalized.

Even though this is not an exact fit to the design requirement, it does indicate that even with a limited amount of regeneration the design specifications can be met. Taking into account the fact that the climate will vary from year to year and that any system installed for regeneration will operate more efficiently when the source temperatures are lower, it was considered that the thermal response of the borehole heat exchanger was sufficiently well understood to proceed to design the ground source heat pump system.

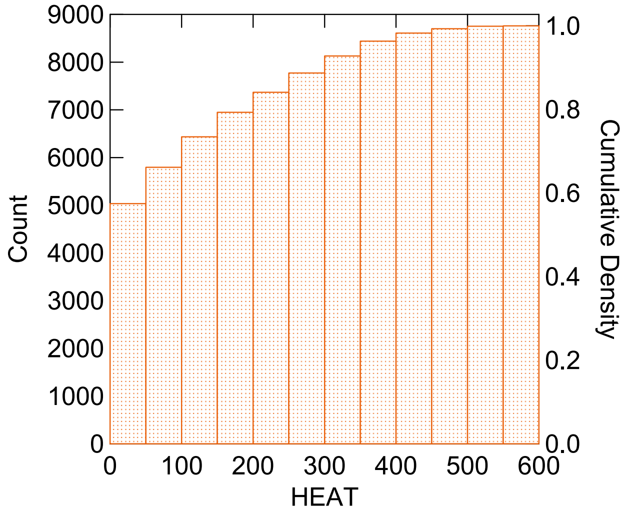

Figure 7. Cumulative frequency of heating capacity.

Ground source heat pump plantroom design

The technical specifications for the heat pump plant room can now be finalized. Based on the total energy specification and the hourly load profile (**Figure** 7) taken from the TRNSYS simulation.

A 350 kW heat pump installation is selected, this will mean that the heat pump system will have about 2150 full load hours per year. There are also a number of considerations with regard to the Domestic Hot Water Supply (in essence the heat pump heats the system to 45°C after which the boilers raise the temperature further to 55°C), therefore a fairly large buffer capacity (3 m³) was selected as well to provide sufficient buffer capacity for combined heating / DWH peak loads.

For the system two heat pumps were selected. Together these heat pumps provide about 355 kW capacity, with a total of 8 compressor stages. Therefore the system not only provides the peak capacity but is also able to modulate down to fairly small loads for efficient running in part load conditions. Using two heat pumps in stead of one allows some optimization of pumping strategy as well as providing a more robust system as failure (or maintenance) on one heat pump will still leave the system with about 180 kW of base capacity.

The design was finished by calculating pressure losses across the different system circuits and selecting the appropriate pumps. Each heat pump has been fitted with individual circulation pumps for the evaporator and condenser circuit. These are connected to the heating buffer and to the low loss header of the Borehole / Solar array control unit.

The ground source plant room system has been designed and constructed according to the general philosophy developed by Groenholland. We have developed several standardized control units, complete with sensors, valves, pumps and controls that can be combined in different ways. The units are standardized, pre-fabricated and pre-commissioned off-site. On site, only a power and network cable needs to be provided between the different units to make them work together as a whole. An example of such a unit, a Heat Transfer Unit, is given in **Figure 8**, **Figure 9** shows the BHE/Solar unit during its construction.

In the case of Lakeshore the plant room consists of:

- Two heat pump units
- One main heat pump control unit with sensors, valves for the heat pumps and the main control panel.
- One heat transfer unit with secondary pump and plate heat exchanger
- One Borehole Heat Exchanger/Solar skid with circulation pumps, valves, heat exchanger.
- Pressurization units and expansion facilities.

The complete plant room was pre-manufactured and transported (**Figure 10**) to site where it was piped-up, connected to the heat pumps and commissioned.

Conclusions

In this paper we describe a case study of the design and actual implementation of a ground source heat pump system for a large apartment building that is being completely refurbished. We have used several design techniques and approaches that are not fully "scientifically" accurate, but allow a robust and efficient system to be designed and constructed.

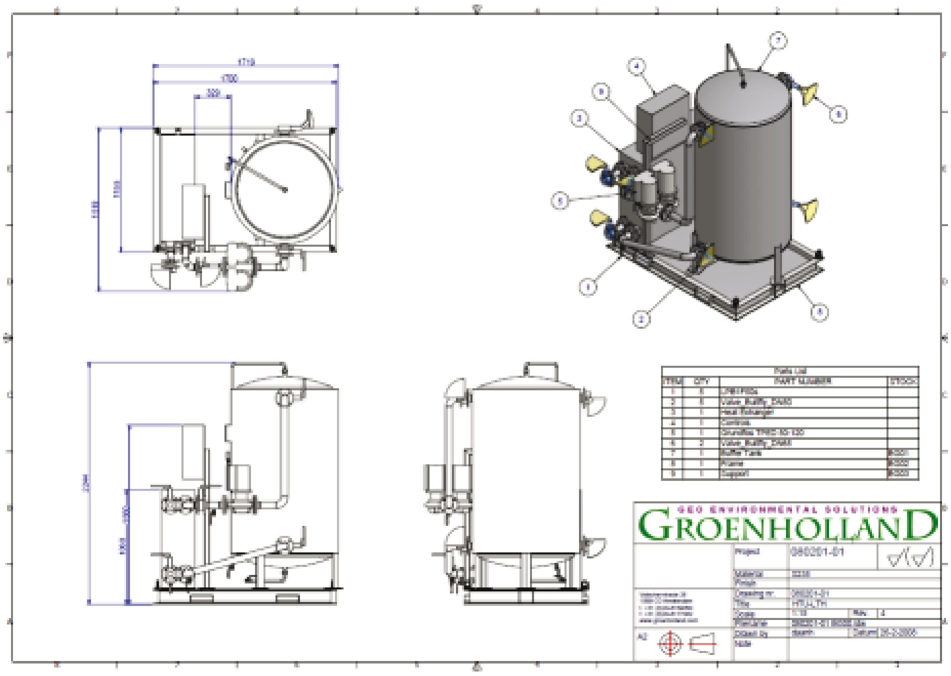

Figure 8. Example of a modularized Groenholland control unit: a Heat Transfer Unit.

One of the main points that the design study needed to address was the calculation of the thermal loads of the building. For a successful ground source heat pump installation at this scale it is essential to have high-quality data on the projected energy use of the building. One of the main caveats with GSHP design is the fact that it cannot be designed on capacity alone, but actual total energy use is needed. In addition, over sizing the capacity will result in very poor performance of the system as the electrical consumption of compressors and pumps will not be matched by sufficient load from the building.

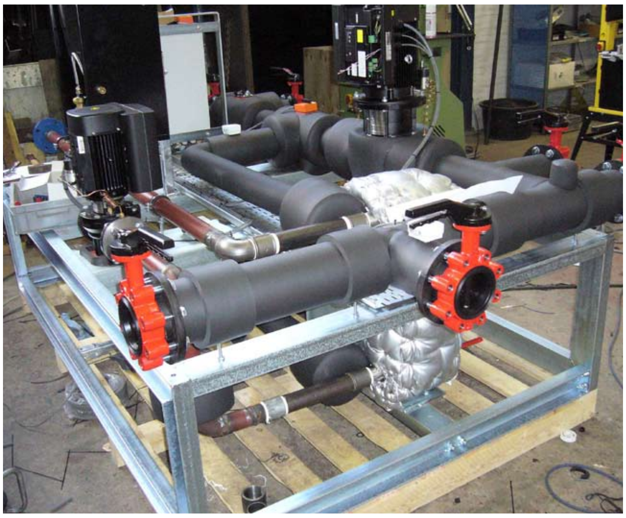

Figure 9. BHE/solar array control unit during its construction.

The strategy of using pre-designed and standardized design units that can be easily adapted to different uses has proven its worth on many occasions. The standard design allows the development of several sophisticated control algorithms without excessive cost as the development and testing time can be shared between many projects. The off-site construction allows a high level of quality control and efficient manufacturing as the work can be carried out in a workshop with all tooling and which is always accessible. The pre-commissioning and proven control strategy and software means that the "turn-key" quality of the system is real: if all components have been integrated in the plant room, the final commissioning is very quick and usually achieved in less than a day.

Figure 10. Plant room packed and ready for transportation.

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