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A GROUND SOURCE ENERGY PLANT FOR THE NEW ASSEMBLY FOR WALES

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ABSTRACT

The new National Assembly for Wales in Cardiff Bay has been completed in September 2005. This event was not only a political achievement but also a milestone in environmentally friendly building.

Architect Lord Richard Rogers' key in the design formula were sustainability and innovation. The designers accomplished this by using local materials and bringing waste to a minimum. Another feature of this environmentally conscious building style is the natural ventilation and temperature control. The marked funnel on the roof is not only a defining feature of the architecture but also a functional design, as it enhances natural ventilation, rejecting warm air and allowing cooler air to be drawn in. As a source of heat and cool a system of ground source heat pumps is installed, that allow very efficient heating and cooling, making use of the earth beneath the building.

For the New Assembly for Wales building Groenholland developed a new approach of applying ground source heat pump technology. Often, when both heating and cooling are required, the heat pump is reversed, the function of the condenser and evaporator are changed. This means that the building is the "warm side" in winter and the "cold side" in summer. It also means that only heating or cooling is possible at any given time. While very efficient and practical in many situations, it is not possible to cool and heat concurrently. We therefore developed a system that primarily transfers heat from the air conditioning system to the heating system. The ground loops are coupled to the side that requires the lowest load at a given time. For instance, in summer the building will be dominated by cooling and the heat pumps will generate excess heat, the "warm"side of the heat pumps will then be connected to the building and the ground loops. The control software developed by us allows the system to operate completely autonomously, even a connection to the building control system is not needed.

An integrated design approach was followed, where a careful analysis of the interactions between the different components was made. The goal was to design a plant that can provide the full capacity needed, but that is optimized to provide the average capacity at the highest efficiency possible. Several novel approaches were implemented, both on the hardware level and in the control software. The final plant is of high efficiency and of very compact design, allowing significant space-savings as well.

1. INTRODUCTION

Wednesday 1th of March 2006 the new 'Senedd' (Assembly for Wales) building (figure 1) was inaugurated by Her Majesty the Queen. More than 500 guests from Europe and the commonwealth joined the Royal party, which included Prince Philip, Prince Charles and the Duchess of Cornwall.

This event was not only a political achievement but also a milestone in environmentally friendly buildings. Architect Lord Richard Rogers' key in the design formula were sustainability and innovation. The designers accomplished this by using local materials and bringing waste to a minimum. Another feature of this environmentally conscious building style is the natural ventilation and temperature control. The marked funnel on the roof is not only a defining feature of the architecture but also a functional design, as it enhances natural ventilation, rejecting warm air and allowing cooler air to be drawn in.

Figure 1. View of the Senedd building, Cardiff (Wales, United Kingdom) with rooftop funnel for enhanced natural ventilation (inset)

As a source of heat and cool a system of ground source heat pumps is installed, that allow very efficient heating and cooling, making use of the earth beneath the building. Groenholland provided consulting on the ground source system from the onset and installed the borehole heat exchanger system as well as the final integrated heat pump energy plant. The design of this integrated energy plant was quite a challenge, as it had to be built according to strict space limitations and was constructed completely off-site to be shipped and assembled on-site later. Moreover, the construction and design were for the largest part undertaken simultaneously.
In line with the general philosophy of the building, high quality materials and techniques were used, and a novel control strategy was developed to enhance overall plant efficiency.

2. BOREHOLE HEAT EXCHANGER DESIGN AND INSTALLATION

The design of the borehole heat exchanger was based on a number of test boreholes and Type II Geothermal Response Tests (van Gelder et al 1999, Witte et al 2002). In total four tests were performed on two separate borehole heat exchangers, one reaching to a depth of 100 meters and one reaching 60 meters. Test results clearly indicated more favourable heat transfer in the deep borehole. Moreover, a marked difference was found between the heat extraction and heat injection tests. In the heat injection tests, a 10% – 15% higher effective conductivity was encountered.

A dynamic energy simulation for the building was performed by BDSP partnership (London, UK). Total heating load (low temperature heating) is estimated at ± 75 MWh/year. Cooling loads are divided in space cooling and cooling needed for the IT- and broadcasting suites, total cooling load amounts to about 80 MWh/year. Peak loads are estimated to be around 80 kW, but with spike heating and cooling loads up to 130 kW.

Figure 3 Drilling and installation of a vertical borehole heat exchanger, National Assembly for Wales (Cardiff, Wales)

Based on this information, a design was made for the borehole heat exchanger system. The borehole heat exchanger system installed consists of 27 boreholes to a depth of 100 meters. The borehole heat exchangers are located beneath the building footprint. This meant that the drilling (figure 3) was executed before the building started and that the horizontal connections were made during the construction of the foundations. To ensure system integrity a full pressure test on all individual loops was performed after each horizontal subsection had been completed (figure 4).

Figure 4 Flushing and pressure testing individual heat exchangers, National Assembly for Wales (Cardiff, Wales).

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The individual Borehole Heat Exchangers are connected to a central flow- and return manifold in the technical room. In this way individual loops can be flow-balanced by the commisioning valves installed and, in the unlikely event of a leakage occuring, the individual heat exchanger can be isolated. The Borehole Heat Exchanger is connected to the heat pump array through a hydraulic block, that provides the different functions (heat rejection by free or mechanical cooling, heat extraction) based on the dominant building need.

3. HEAT PUMP ENERGY PLANT DESIGN

The design and construction of the heat pump energy plant was conducted in three phases. First a general concept of the plant and control strategy was defined. In this phase components were pre-selected and optimized using a TRNSYS (Klein et al 1976) dynamical simulation of the plant behaviour. Specific questions that were addressed involved for instance matching the heat pump capacity steps with building energy requirements and size of the inertia tanks, selection of primary heat exchangers, valves and fitting with respect to circulation pump selection and pressure loss. In principle, the heat pumps generate heat on one side and cool on the other side. Both heat and cool are stored in buffer tanks and transferred to the building by an heat exchanger. The building can use both heat and cool at the same time. The Borehole Heat Exchanger is switched to the side that is at a certain moment not the dominant side, meaning that during summer excess heat is rejected to the ground while during winter heat is extracted. In addition to the heat pumps (providing low temperature heat) there is a wood-chip boiler providing high temperature heat. This boiler also serves as a backup for the heat pump system, but is not part of the heat pump plant itself.

During the second phase of the project the design concepts were translated to a spatial plant design (figure 5), a hydraulic system design, electric and controls design. With the 3D construction and hydraulic system design the main focus was fitting the equipment in the relatively small space. Based on an overall plant-design, detailed 3D CAD drawings were produced and used to perform the actual construction, for a large part in parallel with the detailed design.

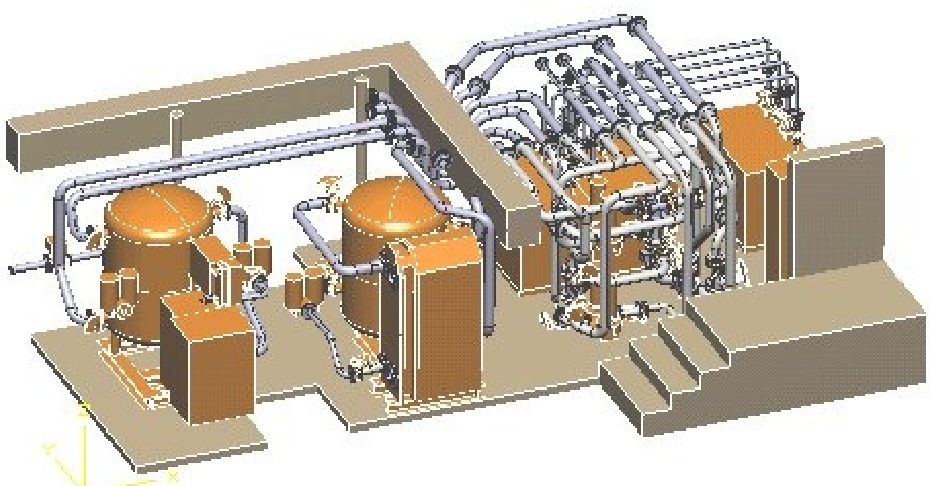

Figure 5 3D CAD drawing of heat pump energy plant design

In the last phase of the project the plant was de-assembled, shipped to Cardiff and assembled on site (figure 6).

Figure 6 Bird view of the heat pump energy plant during construction.

4. A NEW CONTROL STRATEGY

At the start of the project we defined two clear goals for the heat pump control system:

1. The system should operate completely autonomously.
2. The heat pump energy plant should run at high efficiency at average load, while at the same time be able to provide the anticipated peak loads.

That the system operates completely autonomously greatly eases the design and construction. Interface with the building management system is limited to volt free contacts used for a general start/stop command and main fault indication. The heat pump energy plant is able to "sense" the building requirements and reacts to them based on its internal control logic.

With respect to the efficiency of the plant it is first of all important to match the heat pump capacity steps to the building load profile. As the load distribution is rather skewed with high frequency of low loads, while at the same time peak loads can be quite high. From the frequency distribution it was calculated that 50% of the heating load hours are below 30 kW and 80% below 50 kW, for the cooling loads a similar distribution was observed. To match the capacity steps we chose to install three heat pumps, with two compressor stages each. Each compressor stage is sufficiently small to match well with the building energy demand. The complete heat pump array is slightly oversized, but this makes the system more robust as one heat pump can be serviced while the other two heat pumps will be able to generate sufficient capacity for the building. Further optimization concerned the pressure losses, circulation pump selection and operational flow characteristics of the system. It was decided to make the flow per heat pump variable, depending on the number of heat pumps in operation. This means that we allow the heat pumps to operate at lower flow (higher ΔT) when more heat pumps are active and at higher flow (lower ΔT) when fewer heat pumps are active. In practice this means that the heat pumps will run slightly less efficient at high capacity (but only for few hours). More importantly however, it allowed selecting overall smaller circulation pumps, that will need less energy to run at the lower speeds that occur for most of the time.

Although the system provides simultanous heating and cooling to the building, the heat pump system operates in one of three operational modes: free cooling, mechanical cooling dominated or mechanical heating dominated. Depending on the operational mode either the evaporator or condenser side of the heat pump array is connected to the borehole heat exchanger (in free cooling mode the heat pump array is by-passed). To control the system we defined a control strategy consisting of three tiers:

Tier 1 - component level. At this level the individual control loops of the components are defined. These include the PID (Proportional Integral Differential) controls for the primary and secondary circulation pumps using temperature or pressure measurements, the control loops for activating/deactivating heat pumps and, for instance, the compressor control set points of the individual heat pumps.

Tier 2 - operational level. At this level, depending on the mode of the system, the state of all Tier 1 controls is set. This includes the valve positions that activate a specific mode and the specific set points and even switching control-logic blocks used for the Tier 1 controls in that mode. This mode is in principle a state-change matrix with associated control set points.

Tier 3 - system level. This level controls the operational mode of the system. In the current heat pump system this is mainly limited to a decision of in which mode the system needs to run, based on the energy requirements of the building and temperature levels in the borehole heat exchanger system.

The different tiers can be represented in a hierarchy of operational level, but also in a hierarchy of intelligence and complexity, the number of control systems however decreases with the increased complexity (figure 7).

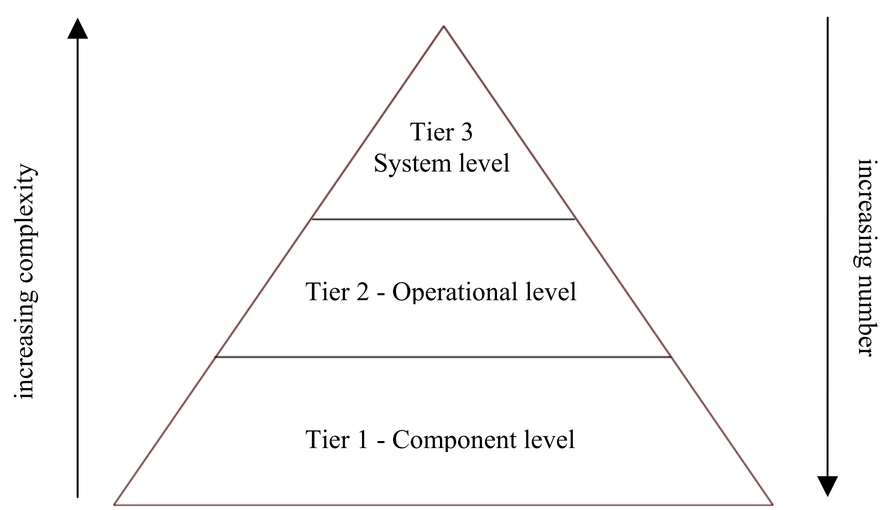

Figure 7 Three tiers of control levels showing increasing hierarchy and complexity and number of controled components.

5. DISCUSSION AND CONCLUSIONS

The new Senedd (Assembly for Wales) is a landmark building both from the point of view of architecture and sustainable design and engineering. For the heating and cooling that needs to be provided the concept of sustainable and environmentally friendly building was translated to the implementation of a highly efficient, low maintenance and long-lasting ground source heat pump energy plant. The ground source for this heat pump plant consists of 27 borehole heat exchangers installed beneath the building footprint.

State of the art techniques were used to design and built the actual energy plant. This included component optimization based on a dynamical analysis of plant behaviour, 3D CAD design and construction techniques to facilitate the off-site design and construction of the plant and the introduction of advanced control strategies.

From the point of view of control strategy, the Tier 1 controls (component level) are well known and understood. Problems at this level often have to do with inappropriately configured control loops and feedback between different components. The definition of the second tier is already more complex, especially as the selection of set points can change the dynamic behaviour of the system in unforeseen ways. Tier 3 is in principle most complex, especially when the evaluations involve choices between running different subsystems. Recent experience with hybrid ground source systems has shown that the selection of both the general strategy of running a hybrid systems as well as the selection of specific thresholds for changing between different subsystems are non-intuitive optimization problems. Hybrid heat pumps systems have additional heat rejection (or heat generation) capacity that can be controlled in several different ways. The straightforward approach would be to run the addional cooling capacity during peak demand. However, at those times the conditions for heat rejection to the air and the ground are usually unfavourable. It is therefore in general more efficient to generate cool during the end of winter and start of spring and store that cool in the ground for summer use. The optimal component sizing and implementation of control strategy for such a system is by no means trivial and will require more research (Yavuzturk & Spitler 2000, Spitler et al 2005). As the ground operates as a seasonal store, such a control system needs to be capable to predict future energy requirements and use that information in an intelligent way to decide to switch to cold generation and storage during the heating season. Furthermore, optimal set points for the Tier 2 state matrix need to be found. Depending on the current state of the system, even different set points may be optimal (no global minimum but several minima in the optimization, depending on the state of the system).

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