Green Room: A Giant Leap in Development of Green Datacenters

Charles El Azzi

Roozbeh Izadi

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	Charles El Azzi	
	Roozbeh Izadi	
Approved 08/03/2012	Examiner Hans Havtun	Supervisor Hans Havtun (KTH) Anders K.Larsson (TeliaSonera)
	Commissioner Hans Havtun	Contact person Hans Havtun

Acknowledgments

Abstract

In a world that is slipping towards a global energy crisis as a result of a heavy dependence on depleting fossil-based fuels, investment in projects that promote energy efficiency will have a strong return on investment not only economically but also socially & environmentally. Firms will directly save significant amounts of money on their energy bills and besides, contribute to slowing down the environmental degradation & global warming by diminishing their carbon footprint. In the global contest to achieve high levels of energy efficiency, IT sector is no exception and telecommunication companies have developed new approaches on how to develop more efficient data centers and cooling systems in the past decades.

This paper describes an ambitious project carried out by TeliaSonera to develop a highly-energy-efficient cooling approach for data centers called "Green Room". It is important to realize that Green Room approach is not specifically limited to data centers. It is designed to support any sort of "technical site" in need of an efficient cooling system. As a result, the word "datacenter" repeatedly used in this paper is expandable to a huger category of technical sites. As the hypothesis, Green Room was expected to generate appropriate temperature level accompanied with effectual steady air flow inside the room while using considerably lower amount of electricity compared with other cooling methods in the market.

To begin with, an introduction is given to familiarize the readers with the concept of "data center" and immediately preceded a concise discussion in Chapter 2 providing convincing reasons to promote energy-efficient projects like Green Room from economic, social and environmental points of view. The chapter is complemented by a comprehensive part attached to this paper as Appendix I. In Chapter 3, the different cooling approaches currently available for datacenters is looked into. Chapter 4 describes how it is possible to assess the efficiency of a data center cooling system by introducing critical values such as PUE (power usage effectiveness) and COP (Coefficient of performance). Understandably, it is of great significance to determine how accurate the measurements carried out in this project are. Chapter 5 provides useful information on measurements and describes uncertainty estimation of the obtained results.

Chapter 6 explains the test methodology and continues by touching on the components of Green Room and their technical specifications. Subsequently, it compares the Green Room approach to other cooling systems and identifies five major differences making the Green Room a distinctive cooling method.

Chapter 7 explains the measurement requirements from the point of view of sensors, discusses the calibration process and finally represents the uncertainty calculations and their results. Chapter 8 broadly describes the five different categories of 25 independent tests carried out within a period of almost two weeks. It provides the readers with all the necessary details for each test and includes

thorough description of conditions, numerical results, calculations, tables, charts, graphs, pictures and some thermal images.

Ultimately, the last two chapters summarize the results of this project and assess its degree of success based on the hypothesis of this paper. Consequently, a number of questions have been raised and relevant suggestions made to modify this approach and improve the results. Surprisingly, the values obtained for efficiency of this cooling system are as expected. However, some part of calculations to achieve the total power load of the whole cooling production system is based on estimations acquired from software simulations. Overall, this is considered as a successful project fulfilling the primary expectations of the founders.

Contents

1. Introduction

In the beginning, it seems to be necessary to describe what it is meant with a "data center" and why it is crucial to establish an efficient cooling system for it. A broad definition suggests that "a data center is a centralized repository, either physical or virtual, for the storage, management, and dissemination of data and information organized around a particular body of knowledge or pertaining to a particular business". (Tech Target, 2011). However, the concept which is referred to as a data center in this report is a facility that accommodates computer systems and a wide range of components and devices such as routers, servers, power conditioners, backup systems & etc.

In particular, in the past, when data centers' energy consumption was in the range of 75-100 W/ft^2 (0.8-1 kW/m^2), a complicated solution was not required for cooling purposes. A dramatic increase in computing capabilities in data centers has resulted in a corresponding increase in rack and room power densities. Nowadays, data centers' energy consumption can rise to 1000 W/ft^2 (10 kW/m^2). As Figure 1 shows, the heat load of Data center devices will continue increasing.
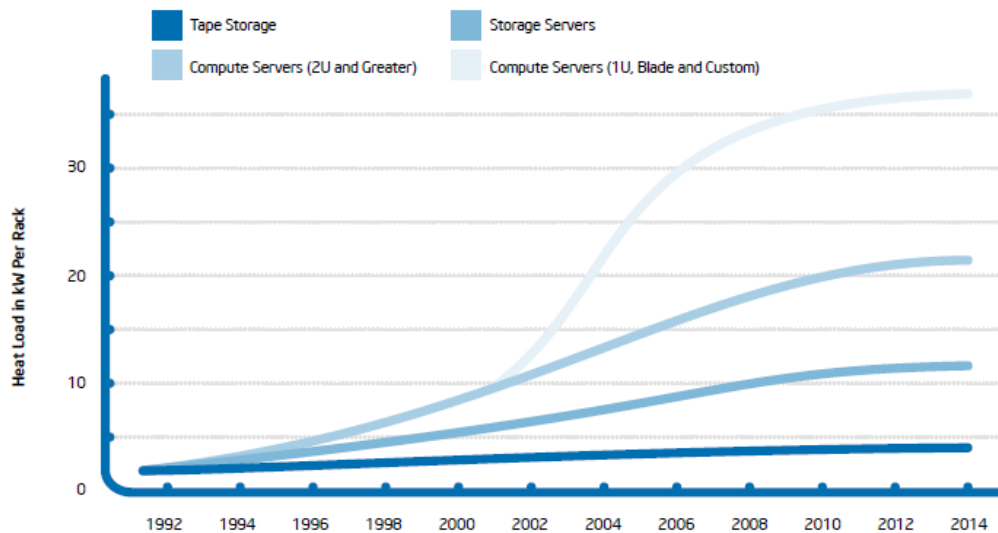
Figure 1: Heat Load per Rack Trend for Datacenter Component (ASHRAE, 2008)

Due to this certain increase in power demand of IT datacenters, Green Room technology must have a much higher cooling capacity than the current one in the company. Using specific measurement techniques described in next chapters, capability of "Green Room" to provide the promised energy efficiency will be analyzed & evaluated.

The rising demand for IT services accompanied with the increased density of equipment and devices resulting from Moore's law have obligated the IT companies to invest in new innovations representing more efficiency in energy consumption. This demand for connectivity and digital information as a result of increased reliance on information is increasing so rapidly that the

performance of IT devices cannot catch up with it on its own and quantity of such devices (modems e.g.) in data centers should be increased too. On the other hand, the rising concerns about the environmental impact of unsustainable use of energy resources and the consequent carbon footprint have raised the alarm for IT sector to move towards green energy management.

To add insult to injury, the excessive dependence of industries on fossil-based resources has lead to over-extraction of fossil fuels in recent decades and estimates by scholars suggest that a global energy crisis is on its way. Data centers are the vital parts of IT organizations providing them with their necessary services such as data storage, networking and computing. Consequently, In terms of energy consumption of an IT company, the data centers have a big share too.

As Schulz (2009) have discussed, IT organizations need to support their business growth but simultaneously, have to deal with the impacts of their PCFE especially their footprint. (Power, cooling, floor space & environmental health and safety) He later acknowledges that in general, IT firms have not prioritized environmental sustainability in connection to their PCFE. First of all, the rapid growth in density of IT equipment in data centers simply means more electricity is needed to power them up. Although this increased density helps the companies to more efficiently use the floor space but their associated heat load literally outstrips the conventional cooling systems. To exemplify this growth, according to Datacom (2005), rack power density (kW/rack) has been up more than five times from 1995 until 2005.

In addition to the growing power costs, the other significant issue in a data center is to provide a strong cooling system to keep the mean temperature of the room below the recommended level to prevent mal-function. Donowho believes that more than eighty percent of datacenter managers have identified thermal management as their greatest challenge. It has not been impossible for companies to install powerful cooling systems capable of meeting the primary cooling needs but the major problem has been inefficiency of those cooling solutions. For instance, if the functional capability (including storage & processing) of a data center needs to be increased by 10%, the same percentage improvement is needed for the efficiency.

The unreasonable cooling costs are easily capable of increasing the total cost of ownership and operation to the point that it surpasses the primary cost of the IT equipment itself. Energy costs (including cooling and thermal management) make up a great portion of a datacenter operational cost. In typical IT data centers, nearly half of the electrical power is consumed for cooling purposes and consequently, nearly half of the power consumption cost for data centers is spent on cooling. (Schulz, 2009) To raise the energy efficiency of data center, both the power and cooling systems need to be focused upon, improved and the layout of the racks in the room as well as the components inside the racks must be taken into careful consideration.

TeliaSonera's "Green Room" is purposely designed to promote the financial, environmental and operational aspects of the company's operations. Since the datacenter is literally the heart of an IT firm, any progress within its structure means general improvements in the whole system. Green

Room will significantly reduce the carbon footprint and interestingly improve the public image of the company which is of great importance particularly in Swedish culture.
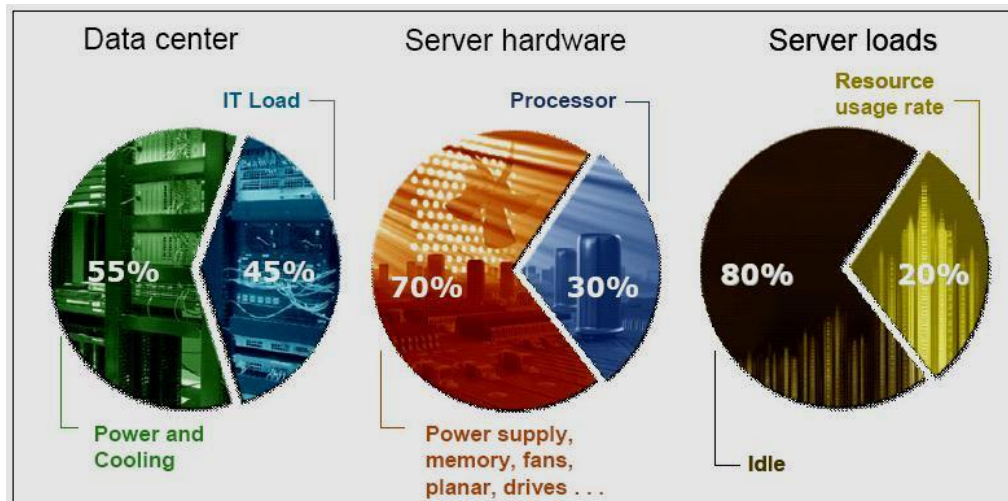
Figure 2: Distribution of Energy Consumption in a Typical Datacenter

More contribution to the green movement in industries will open new possibilities for collaborations with other IT firms from around the world and this certainly will accelerate the movement towards sustainable development. The main focus of this paper will be on the operational improvement and savings in energy consumption as well as progress in computational performance & finally, extending the lifetime of the devices.
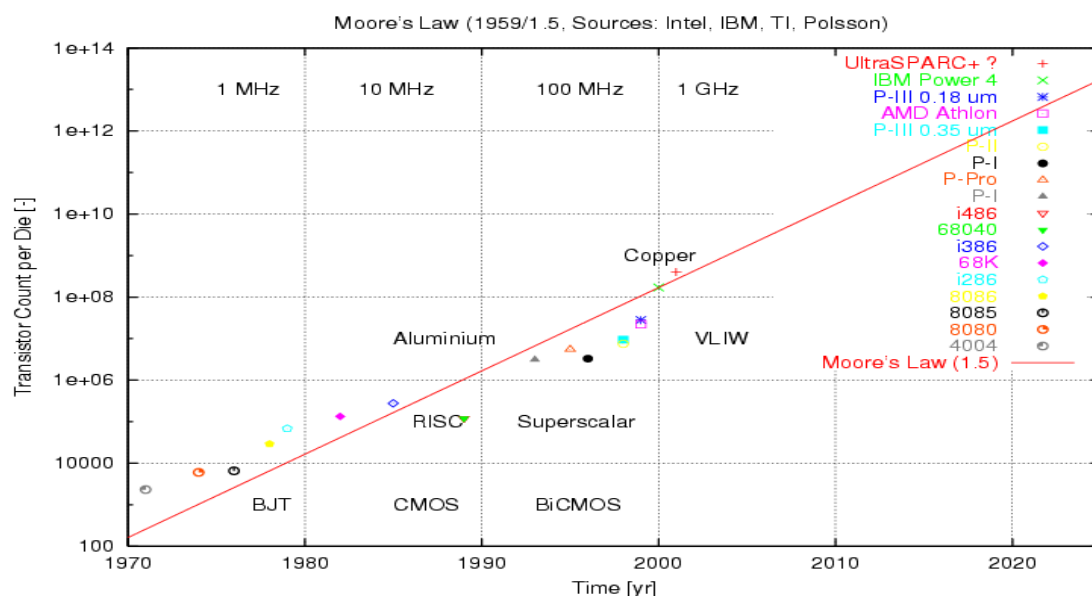
Figure 3: Moore's Law (Available at: http://www.ausairpower.net/OSR-0700.html)

2. Major Reasons for Promotion of Energy Efficiency in 21st Century

It is obviously necessary to thoroughly discuss the importance of Green Room from TeliaSonera's perspective but first, it seems interesting to briefly point out to different aspects of this project from a higher vantage point. On their agenda, TeliaSonera has paid particular attention to be as environmentally-friendly as possible. Interestingly, achieving a sustainable development in IT sector not only benefits the environment but is also advantageous from economic and social points of view. Importance of providing an efficient network access and green telecommunication in TeliaSonera's strategic business planning obligates to take other consequences of energy policies into serious consideration.

In fact, besides the likely huge economic savings of a super-efficient cooling system like Green Room, other positive impacts of such projects will be touched upon in this paper. As it has been widely debated nowadays, global environmental changes accompanied with an unprecedented population growth and heavy dependence on fossil-based energy resources, have raised serious concerns about the future of energy.

Continuous use of energy especially when the main energy resources are non-renewable, have significant environmental and economic impacts on the companies and the environment they are working in. These impacts are likely to be worsened mostly by three significant factors which are climate change, energy scarcity and population growth. In his book, Peter Newman (2000) points out to three unwanted "black swans" which need to be responded to: Climate change, peak oil and the crash.

It seems necessary to provide evidence for huge global changes occurring at the moment and which are expected to have even more intense effects in the not too distant future. These changes will occur both in urban and rural areas but since most of IT service providers and clients are city-dwellers, the main concentration of this chapter regarding the motivation for energy-saving will be on urban areas. In other words, the global issues concerning energy consumption are narrowed down to the cities unless their occurrence in rural and uninhabited locations perceptibly affects the urban life.

The other reason for concentrating mostly on cities is that because of higher concentration of firms providing energy-hungry services, the cities represent a higher capacity of energy consumption compared with rural areas. It should not be forgotten that due to the fact that most of IT headquarters and data centers are located in cities, expansion of IT is widely considered as an urban phenomenon.

On the other hand, the main purpose of this paper is to focus on Green Room and it is not supposed to be a comprehensive guide on the outcomes of current global trends affecting the availability of energy resources. Hence, this chapter has been summarized into a few pages to avoid diversion from the core topic. However, the thorough version of this part has been represented in

this paper as Appendix I to provide the readers with a higher viewpoint regarding green projects like this.

Four significant reasons are identified to promote energy efficient projects like Green Room in all possible sectors:

1. Population Growth, Urbanization & Skyrocketing Demand For Services & Energies
2. Climate Change, Environmental Degradation & Increasing Carbon Footprint
3. Energy Insecurity
4. Economic Savings & Financial Profitability.

The first three are considered as undesirable global trends which each of them alone are enough to trigger intense universal problems if not immediately dealt with. Unfortunately, the simultaneous occurrence of all these issues has set the alarm bell ringing earlier than expected. The immediate advantage of a project like this for companies will be the considerable amount of money saved for them.

In the last part of Appendix I, a rough financial study is carried out to estimate the amount of money expected to be saved as the result of implementation of Green Room concept in most TeliaSonera datacenters in Sweden and around the globe. Some assumption were made including an average PUE of 1.68 in Sweden and 2 in other parts of the world which TeliaSonera is operating in.

Calculations were made based on TeliaSonera's electricity consumption and on the cost of electricity in Sweden alone and worldwide. As a result of these primary calculations, it is concluded that more than 64 millions SEK will be saved per year if a PUE of 1.1 is achieved by implementation of Green Room in TeliaSonera datacenters in Sweden. In addition, approximately 24 million USD can be saved if this technology is applied to all TeliaSonera datacenters all over the world. However it must be reminded again that these calculations were not supposed to provide exact figures and are solely carried out to prove the profitability of Green Room concept.

For more details about the financial study and the assumptions and rate used, refer to Chapter 4 of Appendix I (Economic savings & Financial Profitability).

3. An Overview of Data Center Cooling Methods

3.1. Cold Aisle/Hot Aisle Approach

After the discussion on importance of cooling systems in datacenter from the point of view of energy-saving and risk-reduction, it is sensible to touch upon these cooling systems in more details. Today, most of the advanced datacenters use some sort of cold aisle/hot aisle approach to segregate the cold and hot exhaust air. Basically, the aim is to cool down the hot exhaust air produced by the devices, sufficiently deliver it back to all devices so the internal temperature of the equipment remain below the maximum safe temperature. Transformation of hot exhaust air into cold air is performed by Computer Room Air Conditioning (CRAC) units or simply air conditioners (AC). Theoretically, this system works very well but in practice, it encounters problems such as integration of cold and hot airflow which reduce the efficiency of the energy consumption. The most known problems occurring to cold aisle/hot aisle system are hot-air recirculation and hotspots.

Recirculation is the condition when hot exhaust air flows back into the equipment intake air stream. (Donowho) It is obvious that higher operating temperature of the room simply means waste of energy. Another problematic condition which usually occurs at conventional Cold Aisle/Hot Aisle systems is bypassed cold airflow and it happens when the cold air which is supposed to cool down the equipment, bypasses them and directly goes to the hot aisle.

Since usually the cold air is delivered to the devices from the tiled raised access floor between the two rows of racks, insufficient supply of it leaves the devices close to the top of the cabinets considerably warmer. The perforation in the tiles might be problematic due to the pressure differential they cause. It should not be neglected that although most of the datacenters use a raised floor approach consisting of vented tiles, a similar ceiling based approach is not uncommon.

All the problems mentioned above can be generally addressed as "mal-provisioning" and lead to waste of energy. To create enough sufficiently-cold air to all devices in the cabinets, several factors play the prominent role:

1. Strong AC units capable of extracting enough hot air and then cooling it down to generate a sufficiently-low-temperature cold air.

2. The size of the tiles and the amount of perforation in them must be optimal. It means the perforation in the vented tiles in plenum must allow enough momentum for the cold air to be delivered to the cabinets. It is recommended to fully remove the vented tiles from hot aisles, high-heat and open areas. In low heat areas, dampers can be used in helping to deliver lower amounts of air through the vented tiles.

3. The overall layout of the datacenter is of considerable significance and an improper layout leads to inefficient utilization of air conditioners. In fact, geometrically-asymmetrical

distribution of racks with respect to the air conditioners will dramatically disturb the airflow pattern leading to inefficiency. This disturbance happens because the pressure in the aisles drops, while pressure goes high at the end of the aisles leading to recirculation and creation of hot spots. The condition worsens when recirculation zones forces the hot exhaust air back to the devices. (Patel, Bash, 2002)

Unfortunately most of the times, fulfilling all the requirements mentioned above in datacenters is not achievable and besides, their fulfillment does not guarantee an energy-efficient result. In practice, there is still one other problematic issue which seems to be far more difficult to be dealt with. Due to the heterogeneous mix of hardware in the racks, the heat load of the devices is not uniform imposing non-uniform cooling loads on CRAC units in the data center.

To be more specific, non-uniform heat load of devices is likely to impose over-capacity cooling loads on one or more CRACs in the room and this make the air conditioner unable to meet their primary cooling specifications. As Patel & Bash (2002) have touched upon it, the serious problem is that heat load distribution in a conventional datacenter unpredictably changes both in time and space. The design of the room can add insult to the injury by limiting the air distribution contributing to further complication in heat load distribution.

This changing heat load manipulates the hot air flow patterns inside the room and finally causes unwanted under- or over-provisioning by CRAC units. Under-provision happens when the CRAC unit supplies air flow with unacceptably-high temperature leading to hot spots and further waste of energy. On the contrary, over-provision occurs when CRAC operates below its capacity and because it is technically designed to take more loads with the same power consumption, it is literally wasting energy too. As a result, two major problems which datacenter air conditioners face are under- and over-provisioning both wasting energy and contributing to inefficiency of the cooling system.

Since usually heat loads in the racks are impossible to be uniformed (due to the inevitable heterogeneous mix of devices), an offered solution to reduce the CRAC energy consumption is to design air conditioners with variable capacities. (There are sites that have exceptionally managed to have an even distribution of devices in the racks. Google e.g.) This variability enables them to provide the proper amount of cool air consistent with the momentary energy flow pattern of the room. It also seems to be a good idea to help the cool air bypass the generated heat by considering big openings in the racks. It is noteworthy to say that the air always takes the path of least resistance (Reliable Resources, 2010), and the perforated doors can provide more resistance than the open space around the equipment and this simply lets the exhaust hot air to be forced towards the devices again which is certainly not favorable. In addition, due to the air-pressure reduction they cause, cut-outs in the raised floor are not favorable either and it is strongly suggested to block them for more efficient air flow in the system. Recirculation of the exhaust air can be significantly reduced by considering partitions in ceiling of the room.

To achieve a higher efficiency, several general strategies have been recommended and adapting them in the right way can dramatically help data centers to function more efficiently and hence, less costly. As the first simple step and at a smaller scale, choosing the latest technology providing energy-efficient components like power-saving multi-core processors, high-efficiency power supplies and power regulators seems to be an obviously good beginning.

As the next stage, it is highly recommended to identify the equipment categorized as "high density" and nearly isolate them from rest of the devices and then apply additional cooling tools specifically to these equipments. Later it will be discussed that due to the asymmetrical distribution of heat and the cold air in the room, many areas of the aisles enjoy the right functional temperature and devices adjacent to them will not face overheating. As a result, increasing the cooling burden of the whole room will unnecessarily add energy consumption.

3.2. Major Components Used for Cooling: CRACs, RDHXs, HVACs & AHUs

CRAC and HVAC equipment can be implemented in many different ways depending on the cooling strategies in datacenter. For instance, they can be deployed around the edges of a room, at the edges and in the middle of a room, and in lines, with equipment arranged in hot and cold aisles. Some companies install the cooling equipment on top of the cabinets specifically if the floor space is shorter than usual. "Forced air" or liquid cooling is another approach insisting on inside-the-cabinet cooling. (Schulz, 2009) In addition to the main cooling units in datacenter, supplemental cooling options like water or refrigerant heat exchangers are proved to be useful if managed in the proper way.

There is another solution in the market called the Rear Door Heat Exchanger (RDHX) which can be used as a replacement for or alongside with CRAC systems. When the chilled water infrastructure is installed, RDHX can be a favorable solution because the dissipated heat bypasses the CRAC unit and will be more efficiently sucked up by the chillers. To touch upon the HVACs a little bit, they generally tend to be more efficient than CRAC units if they are centrally installed. The reason why is that systems are larger and more amenable to taking advantage of no-cost cooling when outside air temperatures are satisfactorily low to provide some or all of the cooling obligations. (Ebbers, 2008)

Another cooling unit which is proved to be useful is AHU or Air Handling Unit. Its primary job is to deal with the outside temperature and whether to cool or heat it. The recent low-energy AHUs can increase the efficiency by reclaiming a portion of the already-conditioned air.
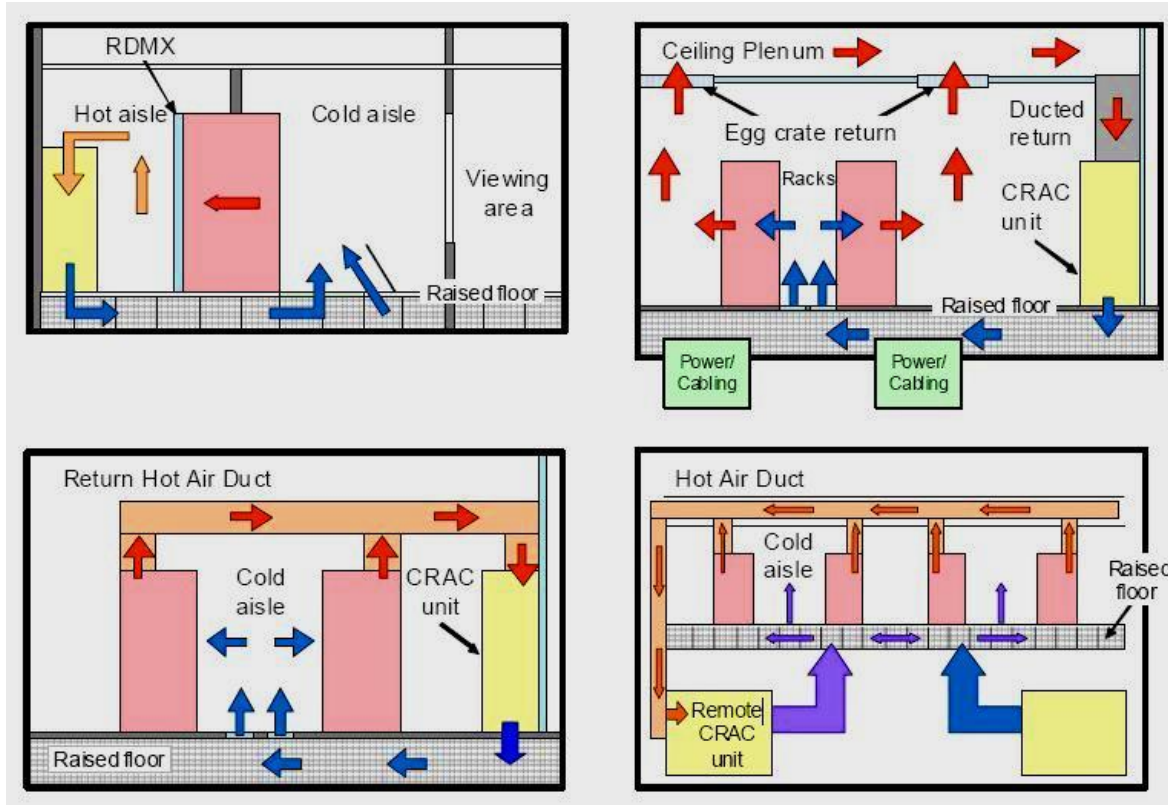
Figure 4: Typical Raised-floor-based layouts for data centers (Ebber, Galia, 2008)

3.3. Effective Cable Management & Its Impact on Cooling Efficiency

The main impact of a proper cable management on the cooling conditions in a datacenter is definitely provision of a better airflow. In addition, there are other benefits rewarded by a good management which are simplified maintenance and time saving. By keeping cables grouped together, airflow beneath the floor is less blocked and the resulted better air flow increases the efficiency of CRAC and HVAC systems. Implementation of effective cable management is not confined to the raised floor and it preferably includes inside the cabinets and equipment racks too. In general, obstructions beneath the raised floor (including cables) are likely to increase the static pressure and it has a negative effect on the way the airflow pattern is designed to function. Cable management is certainly not spatially limited to under-the-raised-floor cabling and it also suggests using overhead and vertical trays to reduce the number of cables which means reduced obstruction beneath the floor as well.

4. "Greenness Assessment" & Efficiency Calculation

To assess how much improvement the Green Room will award Teliasonera, it is definitely needed to evaluate the current situation to precisely calculate the progress. Basically, there are four important efficiency indicators primarily used to evaluate the progress which are:

1. The data center infrastructure efficiency (DCiE)

   DCiE = (IT equipment power / total facility power) x 100%

2. The power usage effectiveness (PUE)

   PUE = Total facility power / IT equipment power

3. The Coefficient Of Performance (COP)

   COP = IT equipment power / total cooling power

4. The Rack Cooling Index (RCI)

DCiE is the reciprocal of PUE: DCiE = 1/PUE

"IT equipment power includes the load that is associated with all of your IT equipment (such as servers, storage, and network equipment) and supplemental equipment (such as keyboard, video, and mouse switches; monitors; and workstations or mobile computers) that are used to monitor or otherwise control the data center." (Ebbers, Galea, 2008, P8)

As simply as its name tells us, Total Facility Power includes everything including the IT equipments themselves and their supportive components like Uninterruptible Power Supply (UPS), generators, Power Distribution Units (PDU), batteries, CRACs, pumps, storage nodes, lighting & etc.

It is interesting to know that the average DCiE does not exceed 44%. In great conditions, it reaches 60% (Ebbers, 2008) but going higher than that, requires extraordinary measures to reduce waste of energy & one of the main purposes of this paper is to find out if Green Room's DCiE rises higher or not. It is crystal clear that DCiE indicates the efficiency of the total facility and does not provide an insight into efficiency of the IT components. The main concern of this project is to efficiently deal with the heat naturally produced as the system is operating. For some reasons, it is believed that air is a very inefficient cooling medium and liquid cooling should be sensibly preferred over air cooling. (Ebbers, 2008)

In fact, when liquid is used to cool the server or the rack by letting it crossing their interface, higher amounts of heat will dissipate compared to air cooling. The simple scientific explanation is that one liter of water is capable of absorbing nearly 4000 times more heat than the same volume of air. On the other hand, it adds significant costs and complexity to the data center, due to the fact that piping system need to be constructed. Moreover, what adds more complicity is the need to switch or

transport IT equipments to another places and replace them with new equipment in the racks with different specifications. This becomes very hard and complicated when using fluid cooling due to the fixing and inflexibility of the implemented pipes. And even more concerning point is that liquid cooling can raise safety concerns due to proximity of fluid to the IT devices and possible risk of leakage. For all these reasons, liquid cooling is usually not preferred and its usage is limited to special high density conditions lacking other solutions.

It is noteworthy to mention that sometimes for particular cases, liquid cooling can be a good idea especially when dealing with an existing data center with a limited cooling capacity because of its infrastructure. In the Green Room project, a totally new solution for these high density racks will be developed and it might indirectly use liquid for better cooling. Air that air will be the heat removal fluid from the rack but additionally, liquid may be used to remove the hot exhaust flow out from the room. This will be discussed in further chapters in this paper. (Patterson & Fenwick 2008)

Cooling an IT data center is basically a thermodynamic problem. There is a heat source which is the server (or router) and a heat sink which is typically the outdoor environment. In real life, there are other sources of heat in a data center but they are very small & negligible compared to the heat from the servers and other IT equipments. In many cases where the heat sink temperature is too high or very unstable for efficient energy transfer, a chiller system is used. It can create a low temperature intermediate sink (such as chilled water) and will transfer the heat eventually from low temperature intermediate sink into the final sink (This is often done with a refrigeration cycle).

In the Green Room design, a chiller system might be needed. But more importantly, more efficient cooling production of the chilled water will be given much higher priority. Systems such as geothermal cooling and free cooling that will have much higher efficiency than chillers but with much higher limitations of using them (usually geographic limitations). Refer to Chapter 6.2.2.3 for more about cooling production methods.

As discussed before, a way to express the efficiency of the system is to find the power usage effectiveness. The closer PUE is to 1, the more efficient the system. In other words, the amount of additional energy needed to accomplish adequate transfer of the heat energy from the server to the outdoors must be calculated. As mentioned, the total facility power includes the IT equipment power and everything else. To be more specific, the remaining power is used mainly for cooling but also as electricity loss in UPSs, switchboards, generators, power distribution units, batteries and etc. For simplification, these power losses are combined and referred to as UPS power loss in this report. In addition, other components' load is included and it consists of lighting, fire protection system, air purifier and so on. In this report, only the consumption of the air purifier will be considered as other power losses in PUE calculations, and the other facters are delieberately neglected.

Therefore,

$$PUE = \frac{Total\ facility\ power}{IT\ equipment\ power} = \frac{P_{IT} + P_{cooling} + P_{Losses,UPS} + P_{other}}{P_{IT}}$$

In the overall system, the additional energy (or cooling energy) is demanded by the following processes:

1) Energy used for cooling production in order to produce the chilled water used by the system. This is done by chillers in most parts of the world but can be done in a much efficient ways such as using geothermal system or simply free cooling (refer to Chapter 6.2.2.3).

2) Energy used by the pump rack (refer to Chapter 6.2.2.2), which is mainly the power used by the pumps in order to pump the cold water for heat exchange to take place.

3) Energy used in order to move the fluids (air in this case) that will be used to carry the heat between the source and the sink. This will be done using fans, thus there is a need to find how much power the fans are using.

Summing up, PUE can be now expressed as follows,

$$PUE = \frac{P_{IT} + P_{cooling\ production} + P_{Pumps} + P_{Fans} + P_{Losses,UPS} + P_{other}}{P_{IT}}$$

The Coefficient of performance is also another way to see the cooling efficiency of the whole system. It is generally used for heat pumps efficiency, but in data centers it is expressed as the total computers power to be cooled divided by the total cooling power required, therefore,

$$COP = \frac{P_{IT}}{P_{cooling\ production} + P_{Pumps} + P_{Fans}}$$

From the above formula it can be seen that the lower cooling is needed, the larger the value of COP and the higher the efficiency.

Another important metric measuring the efficiency of the cooling system in data centers is The Rack Cooling Index (RCI). RCI determines how effectively the equipment in the room are cooled by using thermal guidelines and standards. It is of great siginficance to measure the cooling efficiency in a data center because it provides valuable data leading to a better thermal management. An effective

thermal management reduces the waste of energy and also prevents hot spots capable of harming the equpment and causing downtime.

The interesting point about this index is that it can be applied to many thermal standards for data centers. In fact, RCI is a measure of compliance with ASHRAE/NEBS temperature specifications. The RCI is also addressed in ANSI/BICSI Standard 002-2011 and The Green Grid (2011) Data Center Maturity Model. These data center standards suggest recommended and allowable inake temperatures to make sure all the equipment in the room are fuuctioning in the proper conditions.

To develop this index, some key characteristics have been included in the formula to achieve a high compliance. This includes a meaningful measure of rack cooling having a potential to be represented graphically, easily understood numerical scale in percentage, avoiding giving undeserved credit for over-cooling, indication of potentially harmful thermal conditions and being suitable for both computer modeling and direct measurements. This metric squeezes the temprature into two values RCI (Hi) and RCI (Low). These two numbers are represented in percentage and if they both equal 100%, it is verified that all temperatures are within the recommended range which is referred to as "Full compliance".

Table 1: Rating for RCI values

Rating	RCI
Ideal	100 %
Good	≥ 96 %
Acceptable	91-95 %
Poor	≤ 90 %

The basic formulas to measure the RCI_{HI} & RCI_{LOW} are:

$$RCI_{HI} = \left[1 - \frac{Total\ Over\ Temp}{Max\ Allowable\ Over\ Temp}\right] \times 100\%$$

$$RCI_{LO} = \left[1 - \frac{Total\ Under\ Temp}{Max\ Allowable\ Under\ Temp}\right] \times 100\%$$

Achieving a RCI_{HI} of 100% means no temperature above the maximum recommended level has been recorded. Similarly, RCI_{LOW} of 100% indicates that no temperature below the minimum recommended level has been noted. Interpretation of both 100% RCIs is that all the recorded temperature points in the room have been within the safe recommended range. Understandably, an

RCI_{HI} =96% means that 4% of the recorded temperatures have been above the maximum recommended level which is a disadvantage.
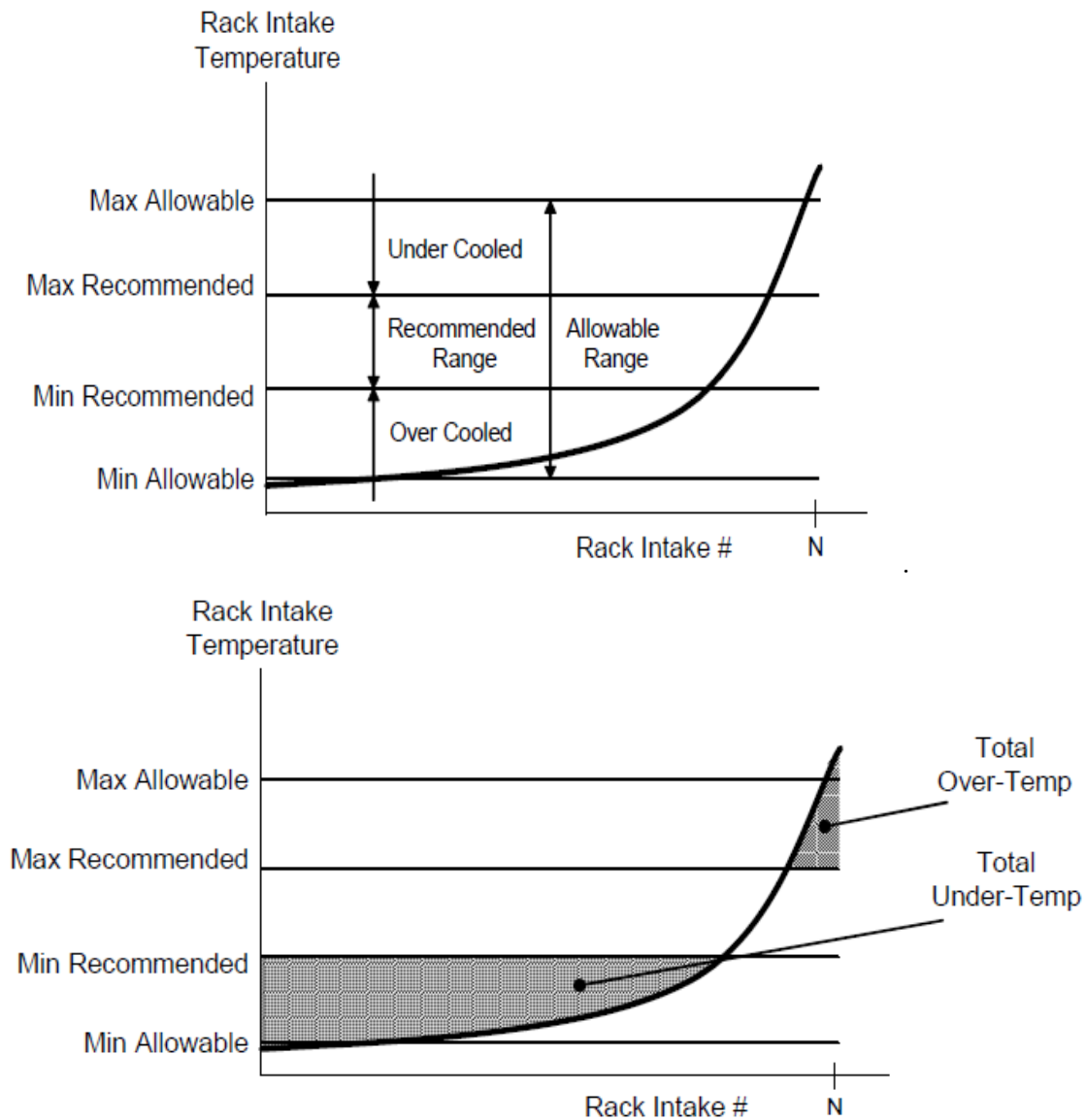
Figure 5: Diagrams illustrating the concept of RCI

5. An Overview of Measurement

5.1. Introduction

Measurement by definition is the process of estimating or determining the magnitude of a quantity. Measurement analysis comes from the need of experimentation. Experimentation is very important in all phases of engineering thus the need for the engineer to be familiar with measurement methods as well as analysis techniques for interpreting experimental data. Experimental techniques have been improving with the development of electronic devices, and nowadays more measuring methods with better precision are available. Moreover, further development in instrumentation techniques is expected to be very fast due to the increasing demand for measurement and control of physical variables in a wide variety of applications. Due to the existence of this wide range of experimental methods, the engineer should have a fair knowledge of many of them as well as the knowledge of many other engineering principles in order to perform successful experiments.

He must be able to specify the physical variables to be investigated, then designing and using the proper instrumentation for the experiment, and finally he should be able to analyze the data by having knowledge about physical principles of the processes being investigated and of the limitation of the data. Furthermore, measuring skillfully certain physical variables is not enough. The engineer should calibrate his instrument to make sure he is receiving correct data. Also, for the data to have maximum significance, the engineer should be able to specify the precision and accuracy of his measurements. Possible errors that may occur should be as well specified.

Statistical techniques can be used to analyze the data and to determine the expected errors and the deviations from the true measurements. Finally, the engineer must take enough data but should not waste time and money by taking more than enough. For all these reasons, experimentation is considered to be very difficult. (Holman, 2007)

5.2. Definition of Some Terms (UNIDO, 2006)

Hysteresis
A devise is said to exhibit hysteresis when it gives different readings of the same measured quantity, sometimes by simply changing the angle of approach. This can be the result of mechanical friction, magnetic effects, elastic deformation, or thermal effects.

Accuracy
How close the result of a measurement is to the true value of the measured quantity.

Precision

How close the results of successive measurements are to each other if the measurement is performed under the same conditions of the same measured quantity?

These conditions are called repeatability conditions and include the following:
- ✔ The same measurement procedure
- ✔ The same operator
- ✔ The same measuring instrument, used under the same conditions
- ✔ The same location
- ✔ Repetition over a short period of time
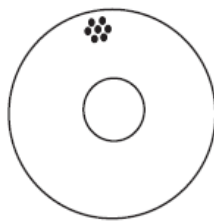
Case 1	Case 2	Case 3
Case 1 is an example of precise but not accurate	Case 2 is an example of accurate but not precise	Case 3 is an example of both precise and accurate
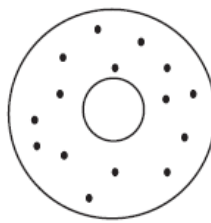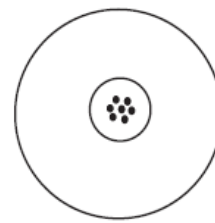
Figure 6: Precision vs. accuracy

Reproducibility

How much the result of a measurement is close to the successive measurements of the same measured carried out under changed conditions

The changed conditions of measurement may include:
- ✔ Different measurement principle
- ✔ Different method of measurement
- ✔ Different operator
- ✔ Different measuring instrument
- ✔ Different reference standard
- ✔ Different location
- ✔ Different conditions of use at a different time
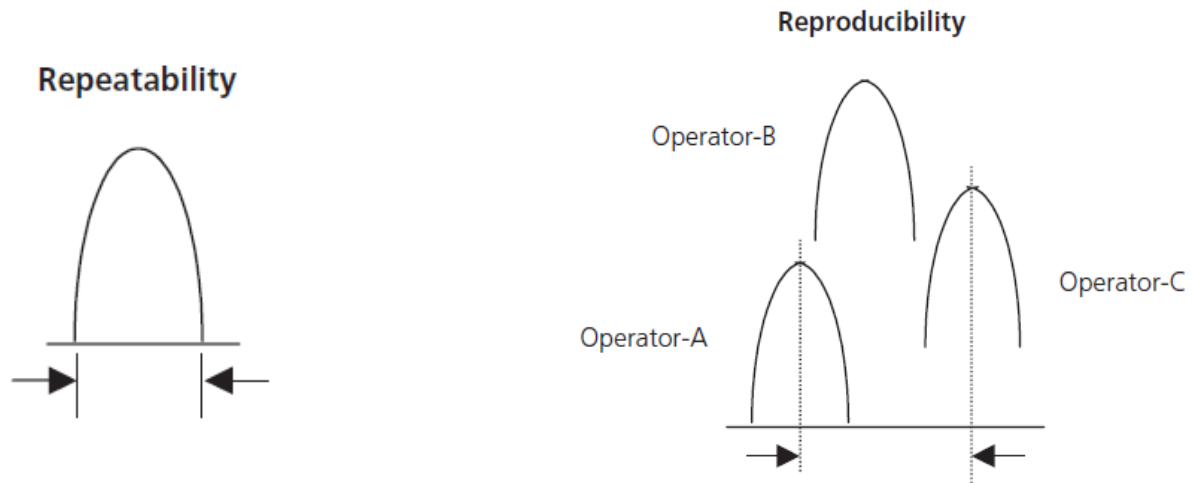
Figure 7: Repeatability & reproducibility

Least count
The least or the minimum value of a unit that can be read in a displaying devise

Resolution
The smallest difference between indications of a displaying device that can be meaningfully distinguished

Uncertainty
It represents a range associated with the result of measurement which characterizes the dispersion of an infinite number of values inside this range. Its numerical value is as $x = \pm \Delta x$, where $\pm \Delta x$ is the assigned uncertainty of the value of the measured x. For example, if the uncertainty of a devise reading temperature is $\pm 0.5°C$. If the measured temperature is read as 4°C, this means that the actual or true value of the temperature is somewhere between 3.5 and 4.5°C. Uncertainty is slightly different from error even though in some contexts they are considered the same. Uncertainty Δx is always a positive value; error can be positive or negative. Also, error indicates the knowledge of the correct value and uncertainty the lack of knowledge of the correct value.

5.3. Selection of Measuring Instruments

The measuring instrument is considered the most important part of the measurement process, and thus, careful selection of an accurate instrument is of great significance in any experimentation. Wrong selection can lead us to wrong results that will lead us again to incorrect decisions. Having in mind that the selection of measuring instruments depends on the measurement to be performed, three general characteristics are provided and considered to be used as selection criteria. First, the

selected instrument should have the range to cover the range and magnitude of the parameter to be measured.

Secondly, the resolution of the measuring instrument should be small enough in a way to be smaller than the minimum unit of measurement of the parameter. Finally and most importantly, the range of accuracy or uncertainty of the measuring instrument should fulfill the required accuracy of the parameter to be measured. In order to check this, an uncertainty analysis will be done for different measuring instruments and the best instrument will be selected to be used based on how much error or uncertainty can be allowed and based as well on the cost of the instrument. Usually, the smaller the uncertainty for an instrument, the better and more expensive it is. More about uncertainty analysis will be discussed later in this report.

5.4. Calibration

Calibration is an essential process to be done in any measurement process. It is done to make sure that the value of the quantity being measured displayed on a measuring instrument is accurate and reliable, by checking the instrument against a known standard. The procedure involves comparing the instrument with either a primary standard, a secondary standard with a higher accuracy than the instrument to be calibrated, or a known input source. Note that a primary standard establishes the value of all other standards of a given quantity; therefore a secondary standard is when the value has been established by comparing it with a primary standard.

To have a better idea about calibration, here comes an example of calibrating a temperature indicator. The temperature measuring system will be composed normally of a sensor (thermocouple, thermistor, etc), a compensating cable and an indicator or scanner. Or it can be simply mercury or an alcohol thermometer. In both cases, calibration is done by creating a stable heating source then comparing the temperature reading of the unit under calibration with a standard thermometer. The stability of the heating source in this case is very important and it should be checked as well.

5.5. Uncertainty analysis

As mentioned before, the need to calculate the uncertainty is necessary to ensure the reliability of the data captured by checking that the accuracy requirements are met. Reasonably, experimental uncertainty is defined as the possible value the error may have. This uncertainty may vary a lot depending on the errors and the conditions of the experiment. The following are some of the types of errors that may cause uncertainty in an experimental measurement with some basic solutions. (Holman, 2007)

Causes, Types and Solutions of Experimental Errors: (Holman, 2007)

1) Error caused from misconstruction of the instrument. Most of these errors should be caught and eliminated by the experimenter easily.

2) Random errors that may be caused by personal fluctuations, random electronic fluctuations in the equipments, friction influences, etc. These errors are hard to avoid and they will either increase or decrease a given measurement. They usually follow a certain statistical distribution, but not always. Performing several trials and averaging the results can reduce their effect.

3) Fixed errors causing repeated readings to be in error by about the same amount, usually for an unknown reason. These errors are sometimes called systematic errors or bias errors. Sometimes, the experimentalist may use theoretical methods in order to estimate the magnitude of the fixed error. As an example, a miss-calibrated instrument can cause a fixed error. Since this error always pushes the result in one direction, the problem won't be solved by repetition and averaging. Its effect can be reduced by changing the way and condition the experiment was carried out, such as using better equipment, changing laboratory conditions, etc.

It is worthy to mention as well the human error which is not a source of experimental error, but it is rather an experimenter error. Human error can include misreading an instrument, not following proper directions, wrong calculations, etc. These errors must be avoided taking into consideration that the experimentalist is skilled and familiar with the process.

Uncertainty Estimation and Calculation:

Estimating the measurement uncertainty will need a detailed knowledge about the measurement process and its source of variation, and knowledge about the accuracy and precision of the measurements performed.

Now suppose a set of measurements is made and the uncertainty of each measurement is estimated. If these measurements are used to calculate some desired result, then the result R will be function of independent variables $x_1, x_2, x_3, \ldots, x_n$.

Thus: $R = R(x_1, x_2, x_3, \ldots, x_n)$.

Let w_R be the uncertainty of the result and $w_1, w_2, \ldots, w_n$ be the uncertainties of the variables. If the uncertainties of the independent variables are given with same odds, then the uncertainty of the result can be calculated using the following formula,

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2}$$

6. Test Preparation & Technical Overview of Green Room

6.1. Methodology

To evaluate the accuracy of TeliaSonera's hypothesis regarding the capability of this cooling system to reach the expected efficiency level, it was inevitable to build a test room to assess the technology from all the possible aspects. In this chapter, necessary information regarding the construction of the room and its components such as the cabinets, racks and cooling system will be provided.

Green Test Room has been built to simulate a real-life high-density datacenter with all its sophistications. As Figure 8 demonstrates, two rows of racks each consisting of 10 identical cabinets are installed in room. In addition, two rows of SEE coolers have been set up parallel to the equipment racks and they represent a distinctive approach to the datacenter cooling methods compared to the conventional designs in other datacenters. This distinctiveness will be thoroughly discussed in the chapter completely dedicated to the cooling components of the system.

Right beside the datacenter, another room containing the power consumption indicators and some other measurement devices has been built. The complete list of these measurement devices plus the sensors they use to determine the power load, temperature & pressure will be provided in Chapter 7 (Pre-Measurement Requirements & Uncertainty Analysis). It seems to be necessary to mention that both AC & DC electricity supplies are needed to run all the components of the Test Room. Moreover, a "Power Room" containing the switchboards controlling the provided electricity for the whole system & also UPSs (Uninterruptible Power Supply) responsible for back-up electricity for AC- & DC-run components of the system has been separately constructed.

Finally, a room specifically dedicated to the system's pump-rack system is built and it is responsible not only for pumping the cold water to the SEE coolers but also as a central unit communicating with and connecting all the other temperature sensors (or devices) in the system. Later on in this report, the pump rack itself will be talked over more in details.

After construction of the Test Room, there are several crucial steps to be taken before starting the test and acquiring the necessary data. The first step is to make sure that all the sensors & devices indicating the values for temperature, power load and pressure will work with the desired accuracy and consequently, high reliability. As a result, a phase of calibration to achieve the maximum correctness in the measurement process was completed. Afterwards, an uncertainty analysis evaluating the accuracy of the data acquired throughout the test has been conducted. Both uncertainty Analysis & calibration will be comprehensively touched upon in a separate chapter and it will also list all the devices and sensors used in the measurement process.
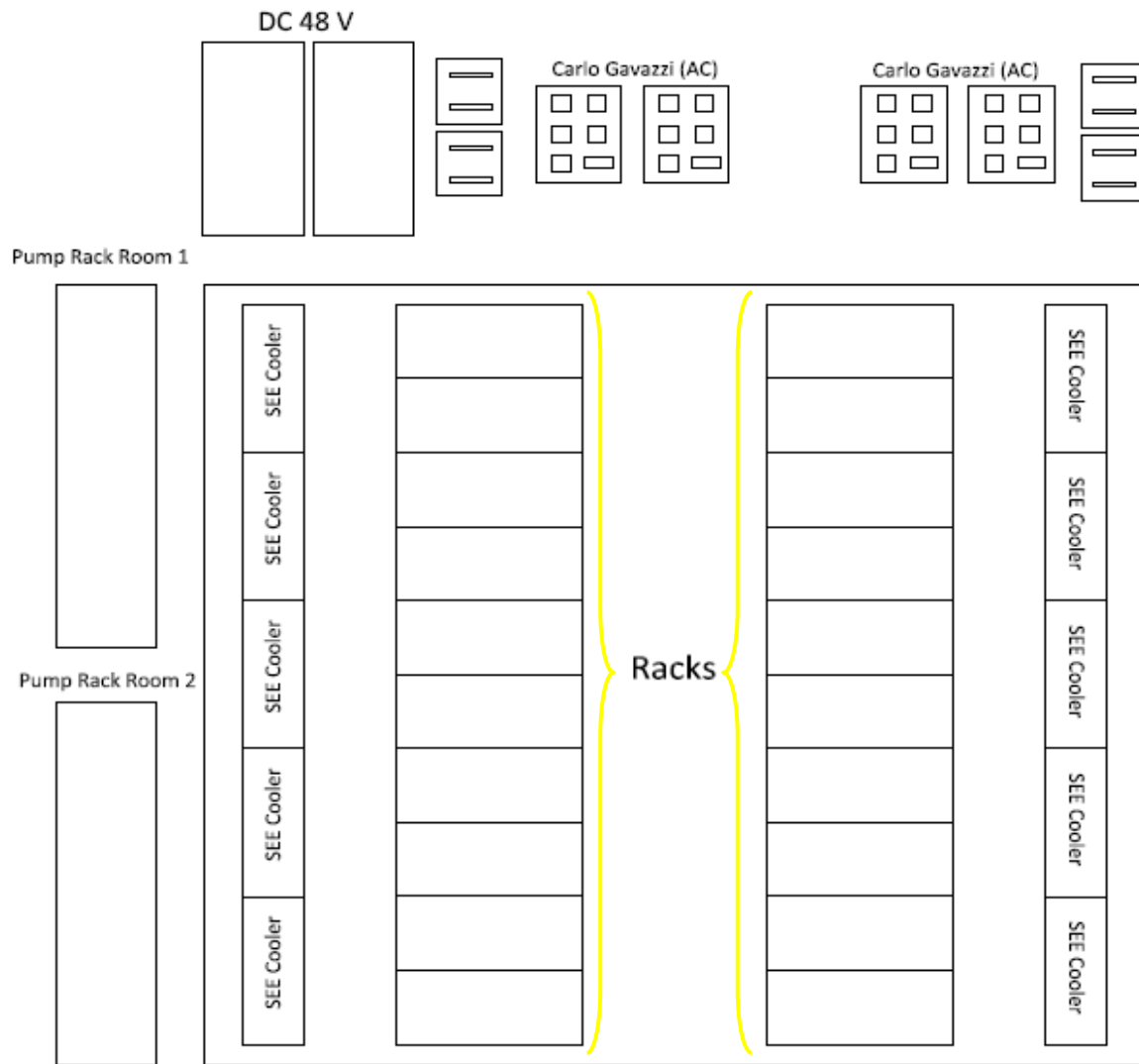
Figure 8: Green Room's Rough Layout

Subsequently, the major differences between the Green Test Room & a conventional datacenter especially in terms of the physical construction and the cooling methods will be detected. Chapter 6.3 will provide a comprehensice description on what makes the Green Room distinctive from the other common datacenters.

The power supply system of Green Test Room and its components including the switchboards, the generators & UPSs will be described in this chapter later. Additionally, the Control System of the room responsible for monitoring the environment in the racks and the aisles as well as the exact list of the equipment used (e.g. routers, modems, dummy loads etc) and their specifications will be discussed in the same chapter.

6.2. Test Room Components

The Test Site is located in Stockholm, TeliaSonera has designed & constructed a complete datacenter providing the necessary conditions to have a real-life test environment. The main part of the construction is the main room mostly consisting of the server racks, the coolers & optical fiber distribution frames. In addition, several other rooms have been built to provide supplementary space for installation of the pump rack, the switchboards, DC batteries, UPSs & other indispensible elements necessary for running the test.

Besides, to get the instant temperature, pressure & power-load data to control the datacenter environment & also to properly run the test, numerous sensors & measurement devices have been put in place in different parts of the system. These sensors & devices make up a "Datacenter nervous system" providing the crucial information needed for determining the efficiency level of the Green Room. These components have been categorized & thoroughly touched upon in 4 major groups of server racks, the cooling system, the power system & the control system.

6.2.1. Server Racks

In total, two rows of racks have been symmetrically set up in the main room. Each row consists of 10 cabinets to keep the routers, servers & the dummy loads. On the first row, the first three cabinets are similar to each other and taller than the rest of the cabinets in the room. Other 17 cabinets are identical and the dimensions for each of them are 197 cm (height), 79 cm (width) & 120 cm (depth). These cabinets have four stands generating approximately 4 cm of gap between their bodies and the floor. To minimize the cold air escape from the cold aisles to the hot one, this gap will be sealed with rectangular plates specifically designed for this purpose.

The distance between the rows is 1.5 meters. As the Figure 9 displays, in the first row of racks, the 1st, 2nd & the 10th cabinets are equipped with real devices. 16 of the remaining racks are each equipped with 2 heaters (Dummy loads) and each consuming up to 12 kW of electricity. The only remaining rack (number 1:2) is exceptionally provided with 4 dummy loads which totally generate up to 48 kW of power load. In fact, the dummy loads are put in place to simulate the role of the real telecommunication devices in terms of power consumption and heat generation.

The advantage of using dummy loads compared with real devices in the test is the considerable reduced cost of test set up. It is crystal clear that if the company were using the real devices like servers and routers in all the cabinets, the cost of test would rise probably to the point that it would make it economically unreasonable. The drawback of using dummy loads is that their power and heat load are unrealistically alike. In reality, due to usage of the different equipment in the racks, the heat load of racks in a datacenter is not identical and sometimes noticeably different.

Each of these dummy loads consists of 6 heating plates inside them and one fan in their front parts. Every single of these heating plates are capable of generating power load up to 2 kW and each of them can be manually turned off/on using a dedicated switch on the front part of the dummy's body. In fact, each heater can reach the maximum heat generation in 6 phases from 0 to 12 kW. To obtain the temperature data from the heaters, each of them are equipped with two sensors on in the inlet and the other one in the outlet. The outlet sensor is similar to the inlet one except the fact that it is not covered with a plastic coating. Thus, the inltet sensor can tolerate temperatures up to 70 °C but the other one bears the temperatures as high as 130 °C thanks to the removed plastic coating.

The other point concerning the real equipment used in the racks is that comparing their power loads, heat generation and efficiency in this test is inevitable. In the first rack, a modern Core Router (sized 54.4 x 132 x 91.9 cm) is used and consumes up to 8616 W of electricity, is powered by 47 V DC & safely function in temperatures between 0 to 40° C. In the second rack adjacent to the first one, another model of Core Router is employed (with theoretical power consumption of almost 7 kW, safe operational temperature range as same as the other mode and recommended ambient temperature of 40 °C.

In the tenth rack from the same row, four Blade Servers enclosures are used to hold multiple servers. Blade servers are used to save space and reduce the power consumption of the servers. This model is powered up by single-phase, three-phase or a -48V DC power subsystem for flexibility in connecting to datacenter power. C7000 can securely function in temperatures between 10 to 35 °C. The c7000 enclosure is divided into 4 quadrants by the vertical support metalwork and within each quadrant a removable divider is used to support half height devices. Two of these blade-systems hold 16 Blade Server (8 ones each) and the other two hold 8 Blade Server of a different model each. The system inlet temperature for all these 32 Blade Server is between 10 to 35 °C.As it was mentioned, in all of the other 17 remaining cabinets, dummy loads are used to simulate the real devices. Inside the cabinets, numerous "blind panels" have been used below and above the heaters to minimize the fresh-air loss and unnecessary air flow. Inside the cabinets and on the very top of them, 4 major electricity outlets are installed to satisfy the need of the dummy loads for power. Inside the cabinets on the sides, special cable holders are installed to minimize the exposure of cable to the air flow and consequently reduce the air blockage. Each server rack has a smaller cabinet placed between the main body and the ceiling.

This small compartment contains a control box, switches, LCD display, electricity outlets and cable trays close to the ceiling. The control boxes on the top of the server racks own 4 inputs on the body to meet the communication connections needs. These boxes are designed and produced by Honeywell™ and they connect the server racks to each other and also to the SEE coolers (Described in Chapter 6.2.2.1) in the cold aisles. In terms of connectivity between the server racks, From every 5 of these control boxes, one plays the role of "Master" and the remaining four are slaves (Figure 10 displays master and slave control box, including connections). As a result, there are totally four server-rack masters in the room controlling 16 slaves. The way these server racks are

connected to each other and also to the coolers will be thoroughly touched upon in part 6.2.2 of the same chapter.

Between the top of the cabinets and the ceiling, special rectangular metal plates are designed and tightly put in place to fully isolate the hot and cold aisles from each other. Finally, the doors of the server racks are sufficiently perforated to let the cold air in with optimal flow rate.
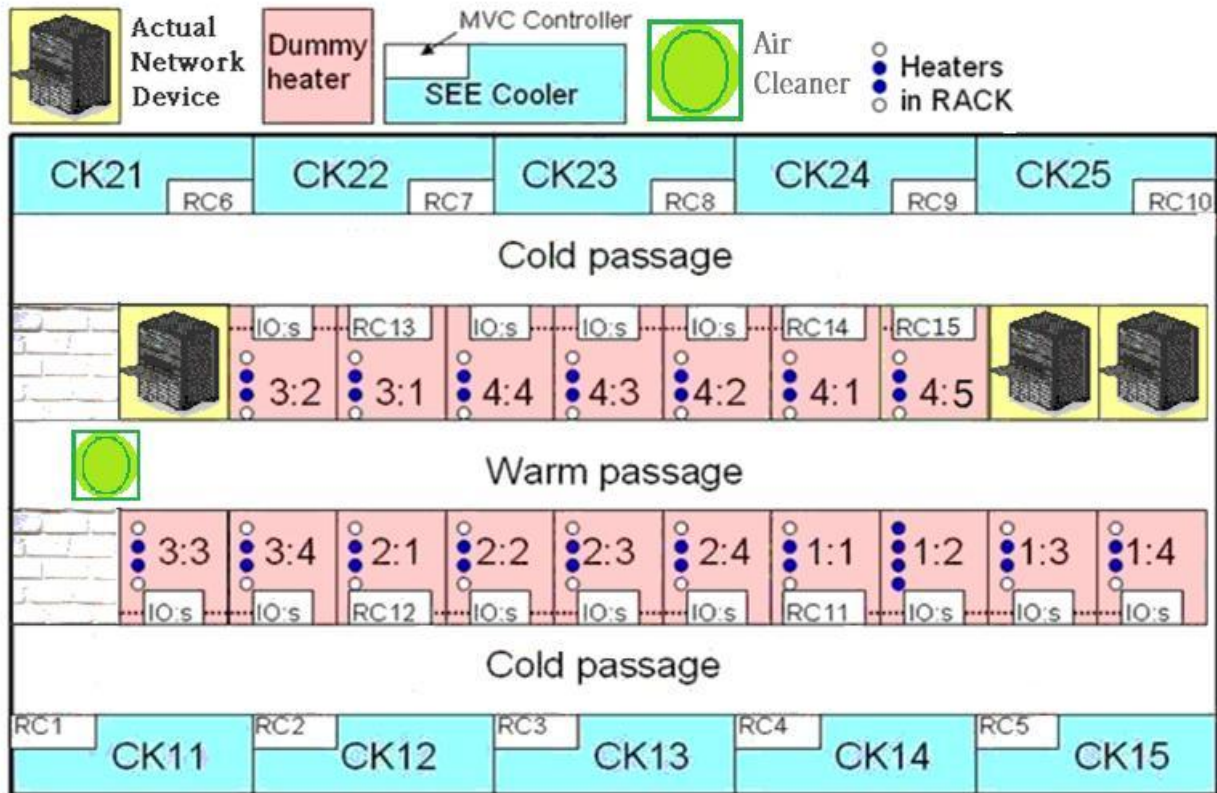
Figure 9: Rack components in Green Room

Figure 10: Control box for dummy heaters

6.2.2. Cooling System

Green Room's cooling system is made up of several components which need to be discussed both separately and coonectedly. First of all, the CRAC units in the room which are referred to as SEE coolers and are manufactured by collaboration of the company itself will be discussed. Afterwards, the pump rooms containing the pump racks, heat exchangers and control system will be touched upon. The cooling system inside the room must be supported by a cooling production system providing the coolant. Cooling production can be entirely based on chillers or supported by green methods such as free cooling or geothermal cooling.

This chapter also portrays the whole image of the cooling system by describing the cooling cycle and the way it functions. Finally, some formulas are provided to familiarize the reader with effieciency of the heat exchangers and their significance in the cooling cycle.

6.2.2.1. SEE Coolers

The cooling system used in Green Room project comprises two rows of coolers in the main room & a pump rack in a room specifically designed for it. Each row is consisted of 5 identical SEE HDZ-3 coolers which are considered as one of the most efficient coolers specifically designed for high-density datacenters in the world. Figure 11 illustrates a graph comparing the SEE coolers with some of the most common CRAC units in the market from the point of view of cooling capacity and power consumption. It is clearly noticeable that SEE coolers provide a high cooling capacity by consuming much less electricity compared to its rivals. These coolers are developed and manufactured through the cooperation between both TeliaSonera and AIA™. They have played a significant role in the development of this technology and remarkably contributed to its effective design for higher energy efficiency.

These coolers have very low levels of carbon footprint and at the same time, are capable of generating great amount of cold air by consuming a considerably low level of electricity. Other advantages of SEE coolers are built-in redundancy & the minimum moving parts making them ideal for producing high cooling effects.

Temperature of coolant varies between +5 and 20°C and it provides a cooling capacity of 18-56 kW. According to the information provided by the company, HDZ-3 has a height of 326 cm and it includes coil with the fan unit, "Top" & "Top Base". It employs condensation pump & pump brackets & has 3 connections on both sides. Its three fans generate airflow of 3.27m3/s & 62 dBA of noise at 5 meters distance from the unit in a typical environment.
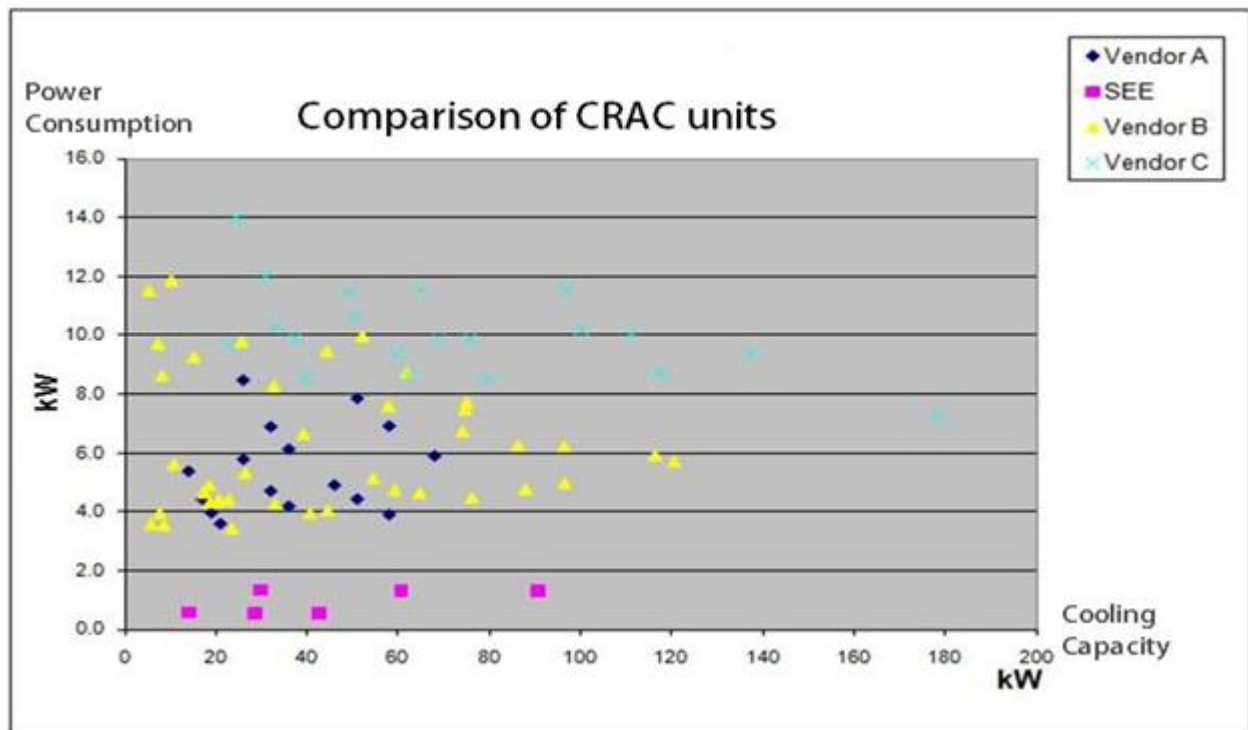
Figure 11: Comparison between SEE coolers and three common CRAC units
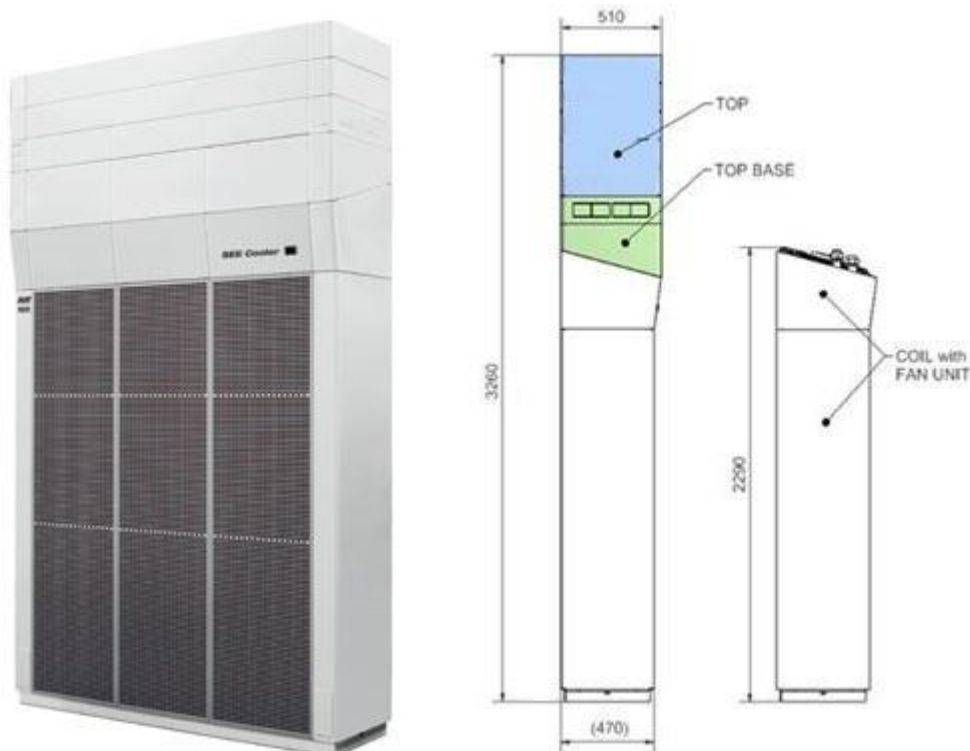
Figure 12: SEE HDZ-3 Front Image & Sidebar

The main control logic unit is integrated into the SEE rack and it controls all functions and manages all optional add-on products in the installation. To facilitate controlling the cooler, an integrated control unit supplied with different levels of functionality is placed inside the cooler. These two rows of coolers are located 120 centimeters away from their adjacent rows of racks. (The widths of the cold aisles are 1.2 meters)

To have the exhaust hot water in the coolers cooled down, all of them are connected to a pump rack system in another room and this pump rack system itself is backed up by an identical redundant one in an adjacent room to support the cooling system in case of malfunction of the first one. These pump racks are more energy efficient than the average racks globally used because they do not use any chillers to cool down the water and instead, they consist of the pumps, heat exchangers, control valves, valves, filters and control logic unit delivering a cooling capacity of 60-750 kW. In addition, it also boasts a COP (Coefficient of performance) of 73, including peak load cooling during the summer. These pump racks are managed by a Siemens control system installed on them in the same rooms.

6.2.2.2. Air Purifier

One of the reasons for high efficiency of SEE coolers is the absence of a built-in filter to purify the tiny particles in the environment. However, absence of such a filter inside the coolers needs to be compensated by utilizing a separate air purifier in the room. In this project, a highly-efficient air purifier referred to as "CamCleaner" has been used to meet the needs for air purification.

CamCleaner is capable of eliminating the tiniest particles in the room atmosphere by drawing air from two directions. This device consumes up to 400 watts and is included in P_{other} in relevant power calculations in this paper. Figure 13 displays two images of this air purifier one while operating in Green Room. This air purifier was placed in the hot aisle during the tests and is included in Figure 9 as "Air cleaner".

Figure 13: CamCleaner Air Purifier

6.2.2.3. Pump Rack Rooms

To cool down the equipment in Green Room, it is indispensible to pump the coolant (fresh water) to the SEE coolers at an appropriate momentum. To achieve so, two pump rack rooms are designed and constructed in the vicinity of the server room. Each of these two adjacent rooms mainly contains a pump rack and a Siemens™ Control system in charge of connecting and processing the thermal data from the whole system. To describe the components of these two identical pump rooms more comprehensively, they will be broken down into 2 major groups:

1. Pump System
2. Control System

6.2.2.2.1. Pump System

The pump system designed for Green Room is a combination of different components manufactured by several vendors. The main body of this system is a Pretec HDZ01-300kW™ pump rack which is complemented by two Grundfos™ pumps, Ahlsell™ Ball valve, Alfalaval™ heat exchanger, Ahlsell™ manometer, and finally butterfly valves, check valve, lever, actuators, strainer and filters manufactured by Ventim™. Each pump rack includes one in-operation pump (A or TPE 100-130) and a backup one (B or TPE 100-130).

Pump A is a three-Phase, Single-stage, centrifugal, in-line and single-headed pump. Its shaft seal is a corrosion resistant maintenance-free mechanical seal and the pump is fitted with an IEC-flanged three-phase MGE motor with frequency converter and PI-controller integrated in the motor terminal box. It means that no additional motor protection is required as both motor and electronics are protected by integrated overload and temperature protection.

External sensor can be connected if controlled pump operation based on for example flow, differential pressure or temperature is required. A control panel enables setting of required set point as well as setting of pump to MIN or MAX operation or to STOP. Communication with the pump is possible by means of Grundfos R100 Remote Control enabling further settings as well as reading out of a number of parameters such as Actual value, Speed, Power input and total Power consumption.

Pump B is a single-staged centrifugal pump which is single-headed and wear rings made out of bronze. The pump motor is a three-phase AC-run one and it enjoys a top-pull-out principle for easier maintenance. The only difference between these two kinds of pumps is that Pump A enjoys an electronically speed-controlled motor with a built-in frequency convertor.

Figure 14: Pump A & pump B

Threaded	6 bar, EN 1092-2	Rp 4	579901
For welding	6 bar, EN 1092-2	100 mm, nominal	579902
Threaded	10 bar, EN 1092-2	Rp 4	579801
For welding	10 bar, EN 1092-2	100 mm, nominal	579802
Threaded	16 bar, EN 1092-2	Rp 4	579801
For welding	16 bar, EN 1092-2	100 mm, nominal	579802

TP, TPE 100

Figure 15: Pump Accessories

Each of the pump racks in the system enjoys a dedicated CB200 brazed plate heat exchanger manufactured by Alfa Laval™. The brazing material seals and holds the plates together at the contact points ensuring optimal heat transfer efficiency and pressure resistance. In addition, the plate design guarantees the longest possible life. The heating surface consists of thin corrugated metal plates stacked on top of each other. Channels are formed between the plates and corner ports are arranged so that the two media flow through alternate channels, usually in countercurrent flow for the most efficient heat transfer process.
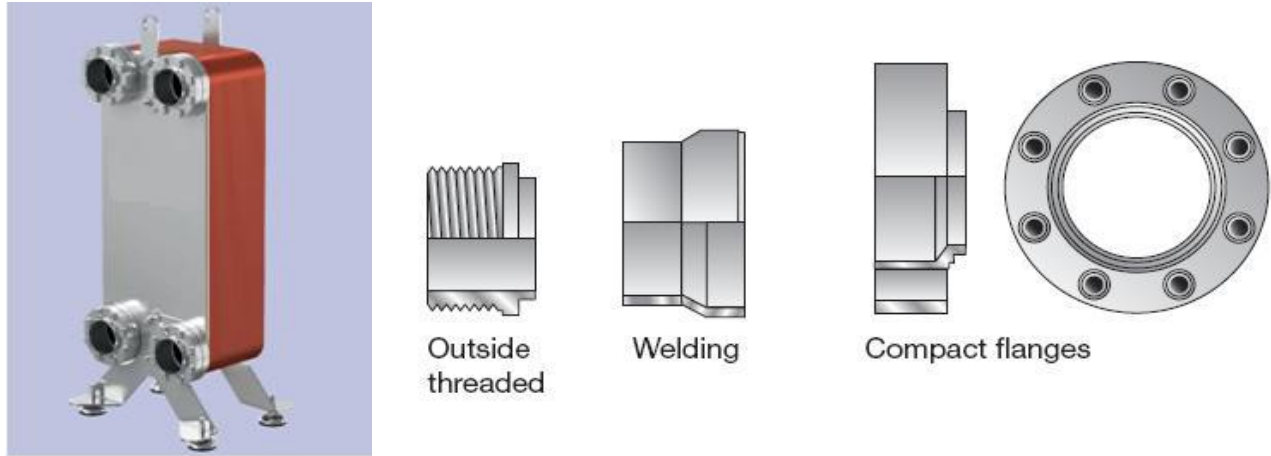
Figure 16: CB 200 Brazed-plate Heat Exchanger with example of connections

6.2.2.2.2. Control System

The 2 central control units mounted in pump rooms are manufactured by Siemens™ and comprehensively discussed in chapter 6.2.4.2.

6.2.2.3. Cooling Production

It is noteworthy that the whole cooling system of the green room (including the coolers and the pumps) is supplied by a huge cooling production system dedicated to the whole building where the test room is located. To calculate the key values of this test including the COP and PUE, it is necessary to cover all the components contributing to Green Room's cooling system. To achieve this objective, the electricity consumption of the coolers and the pump racks will be precisely measured during the test.

On the other hand, the total cooling production for the whole building is available but unfortunately, it is not feasible to accurately measure how much of the total load is dedicated to the Green Room alone. To solve this issue, estmations have been made in order to calculate Green Room's cooling production load from the available total electricity consumption of the test site for 2010 & 2011. In addition, TeliaSonera has developed software capable of simulating the cooling production of its different datacenters according to their power loads and other determining factors. In this report, this software has been used to estimate the cooling production backed up by chiller-based system and geothermal.

In addition, the total amount of electricity needed to back up Green Room's cooling system will be estimated based on three different production methods resulting in three different estimated values

for consumption. In practice, the Test Site facility which Green Room has been built in utilizes a both chiller-based system and "Free Cooling" as the cooling production method. During Summer, building is totally dependent on the chillers because the current free cooling technique gifted by the nearby lake does not provide sufficient potential to support the whole building's cooling needs. However, during winter, temperature of the lake's water is low enough to be utilized as a coolant. As a result, the cold water coming directly from the lake is taken advantage of and employed to support the cooling production.

It is crystal clear that free cooling is way more energy efficient, environmentally friendly & economical than using chillers. Nevertheless, utilization of efficient non-chiller-based systems to back up the datacenters around the world is tremendously limited to certain geographical locations and climatic conditions. Therefore, many datacenters around the globe still have to use chillers as the backbone of their cooling systems. In the best case scenario, free cooling will be both the greenest and the most energy efficient method if the natural conditions are provided. However, if free cooling alone is not sufficient, a combination of free cooling and geothermal is also a sustainable method if the right climatic and geographical conditions are provided. (For instance, one of TeliaSonera's datacenter located in Stockholm utilizes this ideal cooling production system thanks to its proximity to required natural elements to implement such systems). Since TeliaSonera's Green Room is supposed to be a universal solution, it is necessary to calculate the required electricity to back it up from both points of view of chiller-, free-cooling-, & Geo-based systems.

First of all, the current cooling production method adopted in the Test Site will be studied and afterwards, a cooling system reliant entirely on the most efficient chillers in the market will be simulated and its power consumption will be estimated. Finally, a cooling system utilizing a geothermal cooling method will be simulated in a separate part and all the calculated values will be compared to each other in the end. To clarify this part, the table below will concisely describe the details of all simulations to be carried out:

Table 2: Different cooling methods to be considered for efficiency calculations and/or simulations

Cooling Method	Cooling Production Based on:	Internal Cooling System	Related Chapters	
			Description	Calculations
Entirely Chiller-based	Chillers	CRAC Units	*6.2.2.3.2.*	*8.1.4*
Test Site Summer	Chillers	SEE Coolers (Green Room)	*6.2.2.3.1.*	*8.1.4*
Test Site Winter	Free Cooling	SEE Coolers (Green Room)	*6.2.2.3.1.*	*8.1.4*
Geothermal Cooling	Geothermal Cooling	SEE Coolers (Green Room)	*6.2.2.3.2.*	*8.1.4*

6.2.2.3.1. Current Cooling Production State in Test Site

Although TeliaSonera is currently conducting researches in order to see the potential of using an underground geothermal cooling production in the Test Site, this section was made using information on current cooling production of the Test Site both in summer and winter. Another purpose is to find out about the exact cooling production load during the test period. As it was mentioned before, the presented data will be used to calculate COP of the green room as the current state in the Test Site.

Necessary data were provided and an estimation method was applied in order to assess the cooling production used for operating only the Green Room in full load (around 350 kW) and half load (around 160 kW).

As already discussed, Test Site cooling production is supplied with the free cooling provided by a nearby lake in most of the year. However during summer, free cooling is not a possible option and therefore cooling production is supported by conventional chillers. Therefore, in order to estimate the cooling production, the total electricity consumption of the site for years 2010 and 2011 as well as the total IT equipments load were provided.

It should be considered that total energy comsumption will includes total computers load, total cooling production, ventilation, lighting, personal usage and etc. However, due to the fact that electricity will be used mostly for cooling and IT equipments (computers) usage, all other factors can therefore be skipped in order to estimate the cooling power usage for the Green Room.

The following chart originate from the total site electricity consumption versus time throughout the year. It is seen clearly from the below chart that the period that free cooling was not available, the cooling production increases dramatically.
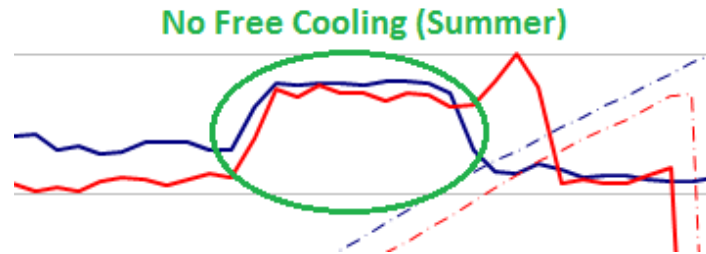
Figure 17: Test Site electricity consumption chart summer highlighted

Also, a sudden increase in production in Weeks 37, 38 and 39 is quite noteacble. In fact, during those weeks the test took place (test period from 13 to 29 September 2011) and this increase in production is obviously a result of the extra load imposed by the Green Room test.
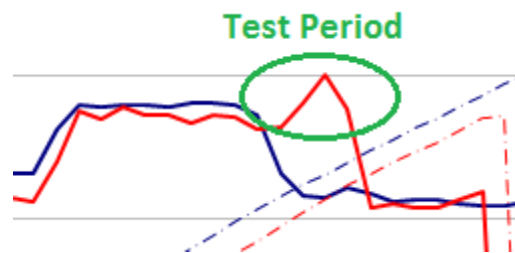
Figure 18: Test Site electricity consumption chart, test period highlighted

In order to predict the extra cooling production for operating the green room in kW, two cases need to be taken into consideration. First case considers the fact that the Green Room is operated in cold outdoor conditions and thus free cooling is applicable. And the second case considers operation in warm or hot outdoor conditions and thus free cooling cannot be applicable.

In order to find the best estimation, data of cooling load and cooling production per hour are retrieved for different months. Having all data required, the following table was deduced,

Table 3: Test Site cooling production estimation for Green Room on full and half load

	Cooling production Green Room Full Load (350 kW)	Cooling production Green Room Half Load (160 kW)
Free Cooling (Winter)	31.612	14.451
Chiller (Summer)	101.493	46.397

6.2.2.3.2. Entirely Chiller-based Cooling Production System

As it was talked over before, most datacenters around the globe are dependent on industrial chillers to remove the heat from the exhausted water. Principally, most of these datacenters utilize chillers both to support the Cooling production & to use inside the rooms as CRAC units. It is generally agreed on that using an entirely chiller-based cooling system is the least energy efficient option if compared with other cooling methods such as geothermal cooling. However there is another approach for such datacenters incapable of replacing their chiller-based system with a more energy-efficient one.

These datacenters can still maintain the chiller-based system for cooling production but instead of employing CRAC units inside the room, the "Green Room" approach (including utilization of SEE coolers) can be adopted. The current Green Room in the Test Site is a notable example of a datacenter utilizing Chiller-based cooling production system and "Green Room" approach.

However to compare the results acquired from Green Room Test to the dominant cooling method in the market which is an entirely chiller-based cooling solution, it is inevitable to simulate the current room's conditions for CRAC units instead of SEE coolers.

Based on a study conducted by TeliaSonera in 2010, the most efficient chiller which could be used as the CRAC unit inside the room was manufactured by Liebert Emerson™. There are basically two main types of chillers in the market: air-cooled and water-cooled chillers. Air-cooled chillers consumes more power than water-cooled ones and are not proper choices for large-capacity datacenters. Water-cooled chillers absorb heat from process water and transfer it to a separate water source such as a lake or river.

6.2.2.3.3. Combination of Geothermal and Free Cooling

Both Geothermal and free cooling are considered as renewable sources for cooling datacenters and provide the operators with much lower operational costs by reduction or elimination of mechanical cooling methods. Geothermal cooling is considered as a low impact alternative method to replace the conventional chiller-based systems in geographical locations capable of supporting this technology. The simple fact that it is categorized as a renewable resource, speaks of a sustainable solution to be considered for datacenter cooling purposes. Geothermal cooling is a non-consumptive system which means it not only uses the temperature gradient to provide cooling but also minimizes the environmental footprint of the data centers.

In fact, the underground temperature of the earth tends to remain at a constantly low level which creates a closed-loop cooling system waiting to be harnessed by construction of suitable pipes and heat pumps. For large energy-hungry infrastructure such as a high-intensity datacenter, a "ground-coupled" system made up of vertical wells under the ground is common to be used. These wells

should be spaced anywhere from nearly 4.5 to 9 meters apart from one another and have a vertical depth of up to 244 meters. . (Heilman, 2011)

To avoid freezing during the winter, these pipes are buried below the frost line and create what the experts refer to as a "bore field". Utilization of geothermal cooling achieves the most favorable results if the datacenter is located in areas enjoying moderate climatic conditions. As Don Betty (2011) from the ASHRAE claims, "as long as the geology and geography on the data center site is appropriate, paybacks on the differences in system costs can be realized in energy savings in as little as four or five years depending on the critical load".

There are two down sides to geothermal cooling which both are avoidable with a proper management. The first one is the heavier initial cost which is proved to be offset by the strong return on investment thanks to considerably reduced maintenance and operational costs. The second disadvantage is a potential thermal contamination happening when a constant load of a data center space places the bore field in a constant heat sink mode. The consequent dead bore field is unable to absorb more heat from the datacenter because the ground temperature has risen to a point which cannot support any heat transfer.

As a result, geothermal potential does not exit everywhere and there are certain requirements to be considered for establishment of this cooling method:

1. Geographical location & climatic conditions proving a suitable geological state
2. Datacenters with plenty of space surrounding them

Geothermal cooling systems use the earth as a source of coldness. A series of pipes, commonly called a "loop," carry the coolant fluid used from the datacenter to the earth. From the point of view of loops, Geothermal cooling system for datacenters can be implemented in different ways. Based on the conditions, they can be open or closed and the latter can be constructed vertically or horizontally. Open loop systems are generally simpler than closed ones but suffer from certain disadvantages.

In open loop systems, cold water is drawn from an aquifer through one well and after being utilized in heat transfer process at heat exchangers, will be discharged into the same source of water. The drawback of this system is that in some areas, ground water chemical conditions can gradually damage the heat exchangers. To prevent this from happening, it is usual to add certain chemical compounds to the aquifer which raises serious environmental concerns due to ground water contamination.

On the other hand, closed loop systems are not only more environmentally friendly but also more economical, efficient and functionally reliable. In this system, water is circulated totally through the pipes and is not streamed into the aquifer. Hence, there is no risk of chemical contamination and it makes these systems environmentally sustainable. The length and depth of pipes in closed systems

might vary depending on ground temperature, thermal conductivity of the ground, soil moisture, and system design. (Finger Lake Institute, 2011)

For small sites enjoying sufficient available land, closed loop systems are often constructed horizontally due to its cost-effectiveness. However, since many datacenters have a limited land availability, vertical closed loop systems are preferable. Figure 19 schematically portrays three major types of geothermal looping to be used for datacenter cooling purposes.
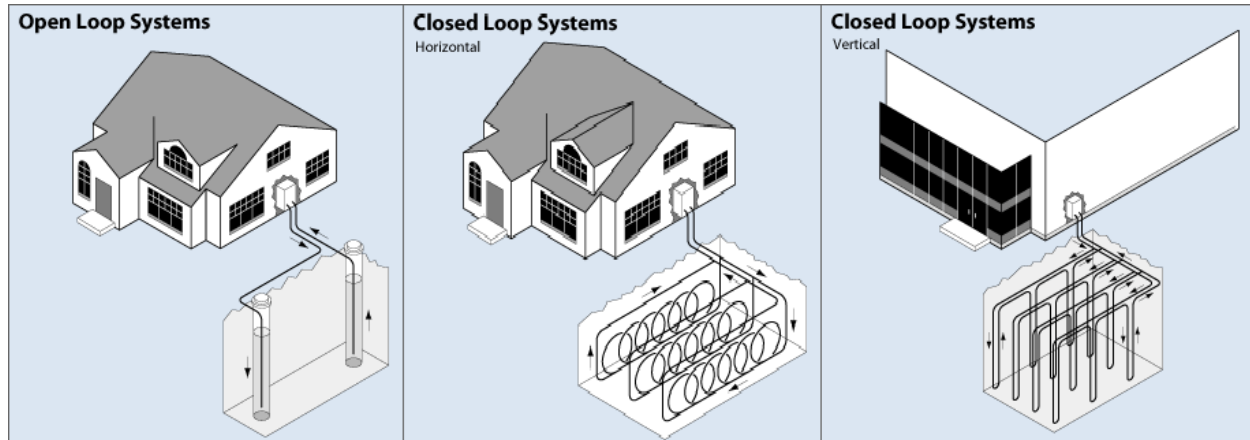
Figure 19: Three dominant approaches to geothermal cooling

6.2.2.4. Cooling System's Cycle

Since this paper is primarily aimed at studying the efficiency of an innovative cooling system, a clear and concise explanation of this cooling system's mechanism is of considerable significance. The cycle begins with the main coolant which plays a prominent role in most of heat cycles in cooling systems. In Green Room, the main coolant is cold water which comes directly from the building's major cooling production. It is noteworthy that there are basically two ways to build a cooling production to provide the system with a proper coolant.

The most common one is to utilize chillers to remove the heat from the gas or liquid in the refrigeration cycle. The common coolants used in various chiller-based applications are usually ammonia, sulfur dioxide, and non-halogenated hydrocarbons such as methane.

There is a wide diversity of industrial chillers which can be used but since the purpose of this chapter is not focusing on the chillers, they are touched upon very briefly in this part. The other cooling production system (which is currently employed by Green Room) is called Geo Cooling and

is not only more economical than the chiller-based systems but also more environmentally sustainable. In should be considered that geothermal cooling system uses the earth as the heat sink transferring the generated heat from the datacenter.

In this case, the proximity of the datacenter to a lake has been taken advantage of by employing its cold water as the main coolant. Due to Stockholm's climatic conditions and geographical location, lake's water experiences low temperatures throughout most of the year. This natural condition provides a great opportunity for building a cooling production system free of chemical coolants and more affordable in terms of energy transfer costs.

As it is quite conspicuous in the sketch below, Green Room has utilized 2 pump racks working simultaneously to pump up the cold water to the SEE coolers inside the room. Although only one of these pump racks are sufficiently strong to support the whole room, they are employed at the same time to avoid a complete cessation of cooling cycle as a result of an unpredicted failure of one of them. As the picture shows, each pump rack includes two pumps called A (The main pump) & B (The backup pump).

Right next to each pump rack, a heat exchanger is mounted to cool down the exhaust hot water coming from the SEE coolers and direct it forward to the pumps as the fresh cold water to be delivered to the SEE coolers again. These Plate Heat Exchangers are principally working based on a straightforward but effective principle. As Figure 20 displays, each of these heat exchangers consists of numerous frame plates to form channels. The heat coming from the SEE Coolers is transferred through the plate between the channels and to achieve the highest feasible efficiency, a complete counter-current flow is created between those plates.

The fans installed on the SEE coolers inhale the hot exhaust air from the datacenter and forward it to the cooler's built-in heat exchanger which is generally called "Finned Coil Heat Exchangers" (Water to Air Heat Exchangers). Figure 21 shows a typical water-to-air heat exchanger manufactured by AIA™. This exchanger transfers the heat from the return hot air inhaled by the fans to the fresh cold watered arrived pumped into the cooler. As a result there are two products of the process.

Firstly, the newly refreshed air which is blew back to the cabinets, cools down the equipment, becomes the exhaust warm air and returns to the exchanger by the fans to lose enough temperature. Secondly, the once-fresh exhaust water which has become considerably warmer after obtaining the warmth of the inhaled exhaust air. This hot water is redirected to the plate heat exchangers close to the pump racks to be cooled down and pumped back to the SEE coolers again.

This cooling cycle continues as long as the datacenter requires to be cooled down and the highest cooling efficiency can be achieved by finding the optimal values for pumps' speed and SEE coolers' fan speed.
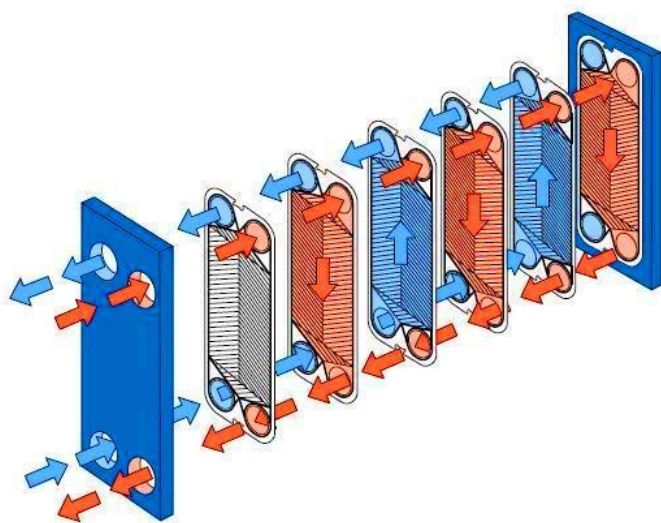
Figure 20: Flow principle of a plate heat exchanger (Available at: http://local.alfalaval.com/en-us/key-industries/fluid-power/oil-coolers/Documents/M10%20PHE%20-%20product%20data%20sheet.pdf)

Figure 21: Finned coil heat (water to air) exchanger manufactured by AIA^{TM} (Available at: http://www.aia.se)
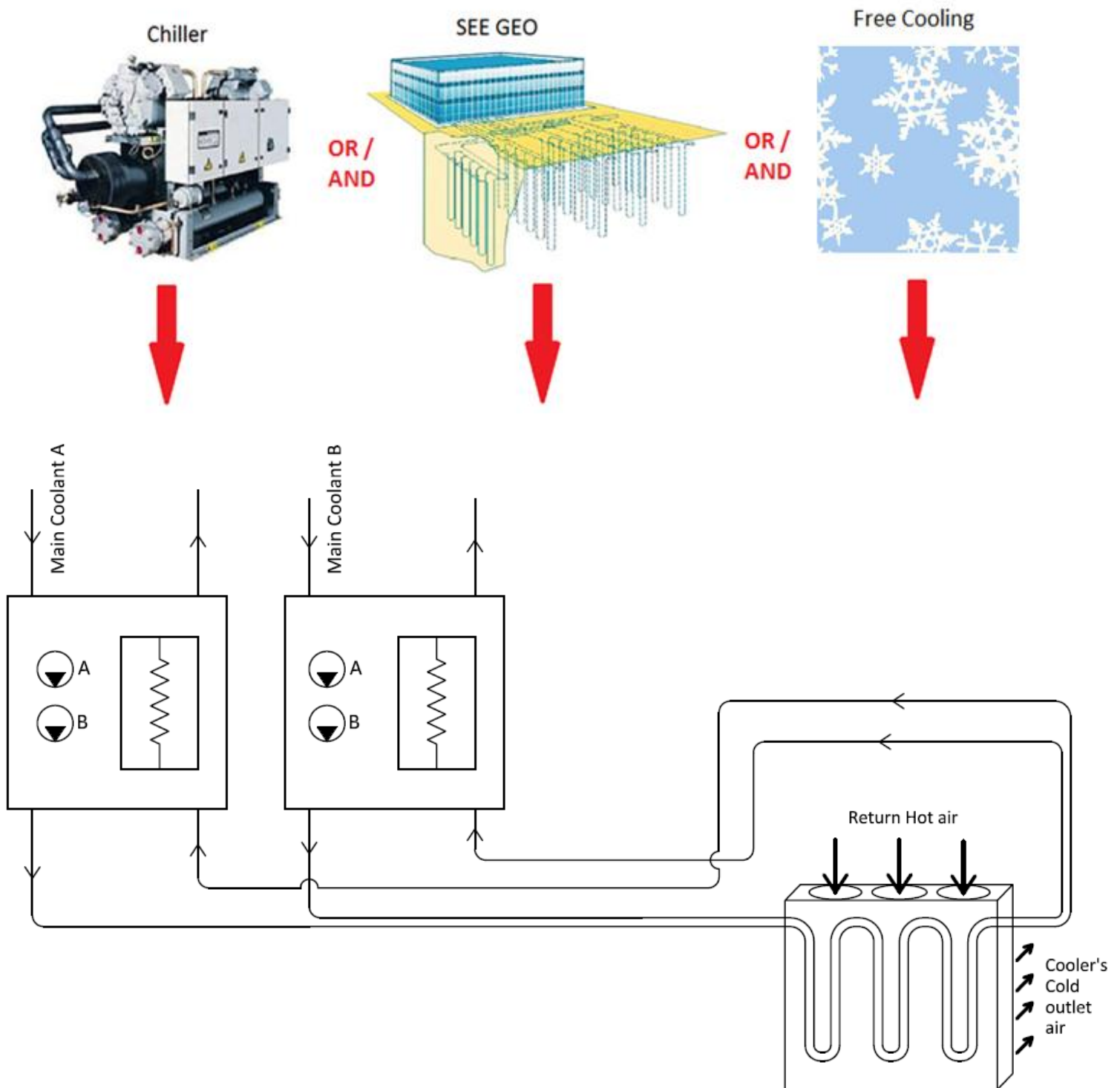
Figure 22: Green Room's cooling cycle & three different options for cooling production

6.2.2.4.1. Efficiency of a Heat Exchanger

Overall Efficiency

In order to determine or estimate the overall efficiency of a heat exchanger, firstly the heat transfer for both hot and cold fluid needs to be calculated and therefore used to determine the heat loss to the surrounding environment (or heat gain from the surrounding). In fact, if the average cold fluid temperature is above the ambient room temperature, heat will be lost to the surrounding, and if it is below the room or surrounding temperature, heat will be gained from the surrounding.

In heat exchangers used in Green room's cooling system, the average cold fluids temperature will be lower than the surrounding temperature resulting in a heat transfer from the surrounding towards the fluid. In addition, it is noted that the temperature difference between the cold fluid and the surrounding is not considerably high (Max 8°C) resulting in a relatively low and probably negligible heat gain. Let $\dot{Q}_h$ be the heat power emitted by the hot fluid and $\dot{Q}_c$ is the one absorbed by the cold fluid, then,

$$\dot{Q}_h = \dot{m}_h(h_{h,i} - h_{h,o}) = \dot{m}_h \times Cp_h(T_{h,i} - T_{h,o})$$

$$\dot{Q}_c = \dot{m}_c(h_{c,i} - h_{c,o}) = \dot{m}_c \times Cp_c(T_{c,i} - T_{c,o})$$

Where,

$\dot{m}_h, \dot{m}_c$: Mass flow rate of hot and cold fluid

$h_{h,i}, h_{h,o}$: Inlet and outlet enthalpies of hot fluid

$h_{c,i}, h_{c,o}$: Inlet and outlet enthalpies of cold fluid

$T_{h,i}, T_{h,o}$: Inlet and outlet temperatures of hot fluid

$T_{c,i}, T_{c,o}$: Inlet and outlet temperatures of cold fluid

Cp_h, Cp_c: Specific heat of hot and cold fluid

The heat power gain from the surrounding is therefore the difference of the heat transfer between the hot and cold fluid.

$$\dot{Q}_{gain} = |\dot{Q}_c| - |\dot{Q}_h|$$

The heat gain can also be expressed as a percentage using the following formula,

$$P_{Gain} = \frac{|\dot{Q}_c|}{|\dot{Q}_h|} \times 100 \ (\%)$$

Note that in the above formula, the percentage will be higher than 100% for this specific case of heat gain, but in case heat loss occurred, the percentage value would be less than 100%.

Moreover, in a perfectly isolated heat exchanger, all the heat emitted by the hot fluid will be absorbed by the colder one, and thus the heat loss to the environment (or heat gain from the environment) will be zero.

Temperature Efficiency

Finding the temperature efficiency of each fluid stream is also a proper way to evaluate and compare the performance of a heat exchanger. To achieve so, the temperature difference in each fluid stream is compared to the maximum temperature difference in both fluid streams; therefore, the temperature efficiency of the hot and cold fluid is respectively,

$$\eta_h = \frac{T_{h,inlet} - T_{h,outlet}}{T_{h,inlet} - T_{c,inlet}} \times 100 \ (\%)$$

$$\eta_c = \frac{T_{c,outlet} - T_{c,inlet}}{T_{h,inlet} - T_{c,inlet}} \times 100 \ (\%)$$

Mean temperature efficiency,

$$\eta_m = \frac{\eta_h + \eta_c}{2}$$

Since the purpose of the heat exchangers in the green room is to cool the hot fluid, thus in this report only hot fluid thermal efficiency will be calculated in order to compare different tests with different variables. Refer to Chapter 8 for more details and calculation and data comparison.

6.2.3. Power Supply, Backup & Distribution Units

Most of the elements of Green Room engaged in the test process run on AC power. However, both Core Routers located in first two racks of the second row are supplied with DC power. The main power room contains the electricity-supply devices distributing the power to SEE coolers, Dummy loads and Blade Server. Adjacent to the AC-Power room, another room is located which a small area of it is dedicated to a DC-Power generator feeding the Core Routers. Following a comprehensive list of all the power-related devices is provided and each unit will be separately discussed in detail.

6.2.3.1. AC Power

1.   *HT-ställverk Nässjö™ AC Power Switchboard (including Janitza™ Measurement Devices):*
To ensure reliable electricity supply to Green Room, a T2H™ switchgear panel has been placed in the power room. This large panel enjoys 9 UMG96S & one UMG508 Janitza™ measurement devices installed on it and enhances system availability by letting more than one source to feed a load. In addition to the measurement device, this switchgear includes a couple of components such as "Automatic Transfer Switches" and "current limiting fuses".

Figure 23: T2H™ Switchgear supplying electricity to Green Room

2. Elcam AB Spectra IP54™ Power Distributor (including Carlo Gavazzi™ Measurement devices):

In proximity to the Green Room, 8 power distributor cabinets of this kind have been installed to ensure steady supply of 230 V AC to the SEE coolers and dummy loads inside the room. These cabinets include fuses and quick-shut-down handles to increase the safety of the system.

Each of these cabinets enjoys an additional accurate EM24 DIN measurement device manufactured by Carlo Gavazzi™. These Three-phase energy analyzers enjoy built-in configuration joystick and LCD displaying the current electricity load of the connected devices. IP 54 is managed by time periods (t1-t2) and utilizes an automatic synchronization program. These measurement units have been the main reference for collecting the power consumption of the server cabinets inside the Green Room in this project.

Figure 24: Two Spectra cabinets (left) & IP 54 measurement units on them (right)

3. Eaton™ PW9395 UPS supporting pump racks:

This UPS supports up to 225 kW of load and its capacity is 25 minutes on full load.

4. Eaton™ PW-9355 UPS supplying the Blade Server:

This unit supports up to 36 kW of load and can store power for 25 minutes with 1005 kW of load.

6.2.4. Control System

Perhaps, one of the most significant components of Green Room is the control system which connects the different parts of the structure to each other and provides detailed data necessary for monitoring purposes. This control system is made up of different individual units, communication protocol and central control units collecting the data. Basically, the control system of Green Room operates in two main ways. First of all, different units in the system collect the data regarding the temperature, pressure; fan speed and power load. Finally, these units present the data on their displays and/or send it to the administrative control units using the communications protocol used for the system.

To fully understand the Green Room's control system, it seems to be necessary to first provide a list of all the components involved and then, a picture demonstrating the overall scheme.

All components of the Control System can be categorized in three main groups:

1. Collecting Units
2. Central Processing Units
3. Communications Protocol

Each group will be carefully touched upon and their responsibilities will be clearly identified.

6.2.4.1. Collecting Units

To control the environment of the room, it is necessary to collect the data from different components of it. In Green Room, several devices and sensors are put in place to measure, store and transmit the data mainly contributing to temperature, power usage and pressure. Besides, there are several additional sensors installed specifically for the test purposes. A complete list of the sensors used in the room is provided in Table 5 in Chapter 7 of this report.

Each SEE cooler used in the room enjoys having a dedicated control panel with switches and LCD display on it. These control panels are designed and developed by Honeywell™ and they are in charge of several tasks:

1. To identify the temperature and adjust the proper fan speed accordingly.
2. To notify the operators of unusual conditions by a warning system.
3. To allow the operators to set the different values like the fan's speed manually
4. To send the data to computers for monitoring & controlling purposes

As it was discussed before, each pump room is comprised of one main pump (A) and one backup pump (B). To regulate the desirable airflow inside the room, it is necessary to set the right pump

speed for the pumps. To achieve so, one pump control unit manufactured by Siemens™ has been mounted in each pump room. These control units are not only responsible for adjusting the pump speed but also collecting the necessary data from the SEE coolers and all the sensors used in both SEE coolers and pump racks. In fact, this unit is playing the role of the brain of the nervous system of the whole sensor-based network in this project.

Finally, all the dummy loads & hot-aisle ceiling sensors are controlled using the control panels mounted in the two rows of cable racks above the cabinets. Totally, 16 Honeywell control units are installed in the whole room. However, only 4 of these units are considered as "Masters" and each master unit supports three "Slave" ones. Since the way these control units are connected to one another is not straightforward, the description about them will be accompanied by a few tables for better understanding.

6.2.4.2. Central Processing Units

All the data collected from the SEE coolers, pumps, hot aisle temperature sensors and the heaters are sent to a dedicated software which makes the monitoring possible outside of the room. This software is directly connected to two Siemens™ central control units in the pump rack rooms. These control units are considered as the brains of the Green Room's nervous system and collect required data by connecting different parts of the system to each other.

These units are programmed not only to receive and transmit the data to the operators but also to act automatically if something serious unexpectedly happens.

There are five "extreme conditions" in the room which the control unit will take immediate action in response to them. To control these undesirable conditions, respective values have been calculated and programmed in the unit. The table below provides a list of the critical values, the area which they will act and the exact response of the control unit to alleviate or stop them.

Table 4: Some of the control system's signals, functions and description

Code	Represented Value	Description
V1_1A_BV_T2_MAX	Max Coolers' outlet Temp	Manually set, it is continuously compared with the data received from the temperature sensors of each cooler. If any cooler's outlet temp exceeds this value, the unit orders the respective fans to speed up to cool it down until it drops below V1_1A_BV_T2_MAX again.
V1_MEAN_TR V1_1A_RV_DIFFT V1_1A_CAIEF_S	Mean Temp in Hot Aisle Hot Aisle Temp Minus Heaters' Inlet Temp Signal Sent From the Control Unit to Fans	V1_1A_RV_DIFFT is manually set (12° C) and if the actual thermal differential between hot aisle & heaters' inlets exceeds it, the unit orders the heaters' fans to speed up resulting in a sufficient reduction in this ΔT.
V1_1A_FAN_MIN	Min Fan Speed	The set value for minimum percentage of the heaters' fan speed. Based on the intensity of the datacenter, this value is estimated and does not allow the fans to automatically reduce their speed to lower than it.
V1V2V3B_FAN_S	1st Cold Aisle Heaters' fan speed	This value provides the opportunity to set all fans of the first cold aisle function at the same speed if desired.
Heater Deactivation Values	Max Temp of Hot Aisle, All Heater's outlet & Inlet	Control Unit will automatically switch off the heaters if one of these limits are exceeded: 130°C < Heaters' outlet temperature 35°C < Heaters' inlet temperature 58°C < Hot aisle temperature
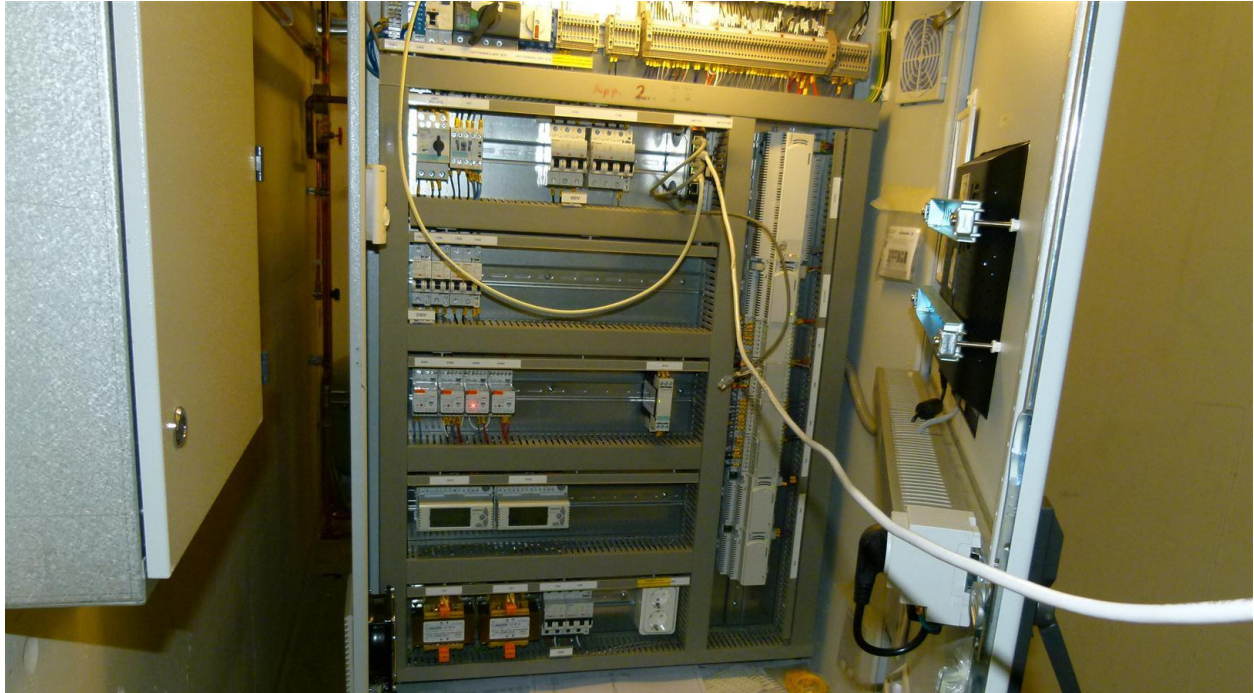
Figure 25: One of the two Siemens Central Control System in the Pump rack room

6.2.4.3. Communications Protocol

Electronic devices of Green Room are connected to each other using a serial ModBus for its simplicity, availability and also lack of restrictions on transfer of raw bits, values and words. ModBus connects all the sensors and value-collecting devices in the system to the supervisory computers known as the Control Units in this paper.

6.3. Major Differences between Green Room & Conventional Datacenters

Before demonstrating the test process and its results, it is quite essential to compare the Green Room to other conventional datacenters and detect the tangible differences in terms of the structure of the room, rack layout, cable management and other determining factors.

If the Green Room accomplishes its mission to deliver a highly-efficient cooling method compared to other cooling solutions in the market, it owes some considerable part of its success to the structural features described below.

6.3.1. A Better Air Distribution System

Unlike most of the datacenters constructed by the IT firms in the world, the Green Room design surprisingly skips the conventional raised floor to deliver the cool air to the racks in hot aisles. Instead of having a perforated floor to deliver the fresh cold air up to the racks from the bottom of the corridor, the designers of the Green Room have preferred to utilize a normal floor with three rows of ceramic tiles in each hot aisle.

There are some major reasons to make such a decision in construction of the room:

1. The conventional raised floors usually fail to deliver an optimal amount of cold air to racks due to the disordered cable layout underneath the perforated tiles blocking the air flow path up to the cabinets. In fact, the raised floors are also used to carry cables and electrical wirings and overuse of them as a cable-management device certainly limits its cooling effectiveness. "Overhead cable management typically presents less of a disruption to the delivery of cooled air to the critical equipment, and the visibility of the cabling system aids in identifying and rectifying cable-management challenges, such as cable abandonment." (C.A. McKinnon, 2009)

    The other typical disadvantage of the raised floor is that depending on the density of the devices in the cabinets, the amount of perforation on the tiles might not be enough to let out sufficient cold air to the racks.

2. Since the raised floor delivers the fresh air from the bottom of the aisles, it is not surprising to have higher temperatures at the top of the cabinets. In other words, the distribution of cold air to the devices inside the racks is not even and it seems that equipment on the top receive less cold air than the ones adjacent or closer to the floor. It is obvious that uneven distribution of cold air is inefficient by its nature and must be avoided as much as it is possible. In the Green Room, the parallel layout of the coolers to the cabinets at least theoretically guarantees a more equal delivery of cold air to the racks.

3. Using a slab floor instead of raised one can maximize the available space and increase the accessibility of maintenance devices and cables if they are mounted along the ceiling. In addition, the slab floor with ceramic tiles is more stable and easier to keep clean while the perforated floors are much likelier to let in the dirt and dust over time.

In fact, the Green Room's design provide a considerably better air distribution in the room which leads to a more efficient cooling cycle and the consequent cut in energy consumption.

6.3.2. Aisle Sealing & Fluid-Mix Prevention

As it was discussed earlier in this report, one of the serious issues the datacenters face is the unwanted mixture of hot and cold air. This problem usually occurs because hot/cold isle isolation is often neglected during the construction of these datacenters. Theoretically, to minimize the undesirable effects of mixture between the exhaust and fresh air, it is crucial to seal any gap in the cabinet rows. This total isolation can be achieved by sealing:

1. Open spaces between the bottom of the cabinets and the floor
2. Gap between the top of the cabinets and the roof
3. Openings between the adjacent cabinets
4. First and last cabinets in each row with their neighboring walls
5. All the empty spaces left inside the cabinet after installation of devices
6. Any gap between the top of the coolers (where the fans are located) & the cold aisles

It should not be neglected that not all the sealing options mentioned above applies to all datacenters operating nowadays. In many cases, depending on the approach of the datacenter designers, the construction of the rooms can be quite different from the Green Room. For instance, some designers do not consider any roof over the cold aisles or any walls tightly surrounding the operational area of the datacenter. However, almost all the datacenter constructed based on cold/hot aisle approach share many same similarities.

Green Room enjoys an acceptable sealing of the noticeable gaps leading to unwanted leakage of the exhaust or cold air. However, to evaluate the effectiveness of having a 100% sealed system, different degrees of sealing in the room will be examined during the test. To be precise, some parts of the room will be intentionally left unsealed during specific tests to record the results, compare them and reach realistic conclusions regarding the extent of the sealing really needed. After carrying out these tests, the optimal amount of sealing and the exact places demanding the careful attention will be discovered.

Figure 26 demonstrates the removable sealing parts of the system including the covering lids and under-cabinet covers. In addition, after installing the devices inside the cabinets, there are always empty spaces left uncovered. In this project, to cover most of these empty spaces over and under the dummy loads, a considerable number of "Blind Panels" have been used on both sides of the racks. Nevertheless, there are still noticeable gaps left uncovered on the sides of the heaters and surrounding the upper/lower blind panels. There are also narrow linear gaps between the blind folds themselves and they definitely contribute to cold air leakage during operation of the coolers.
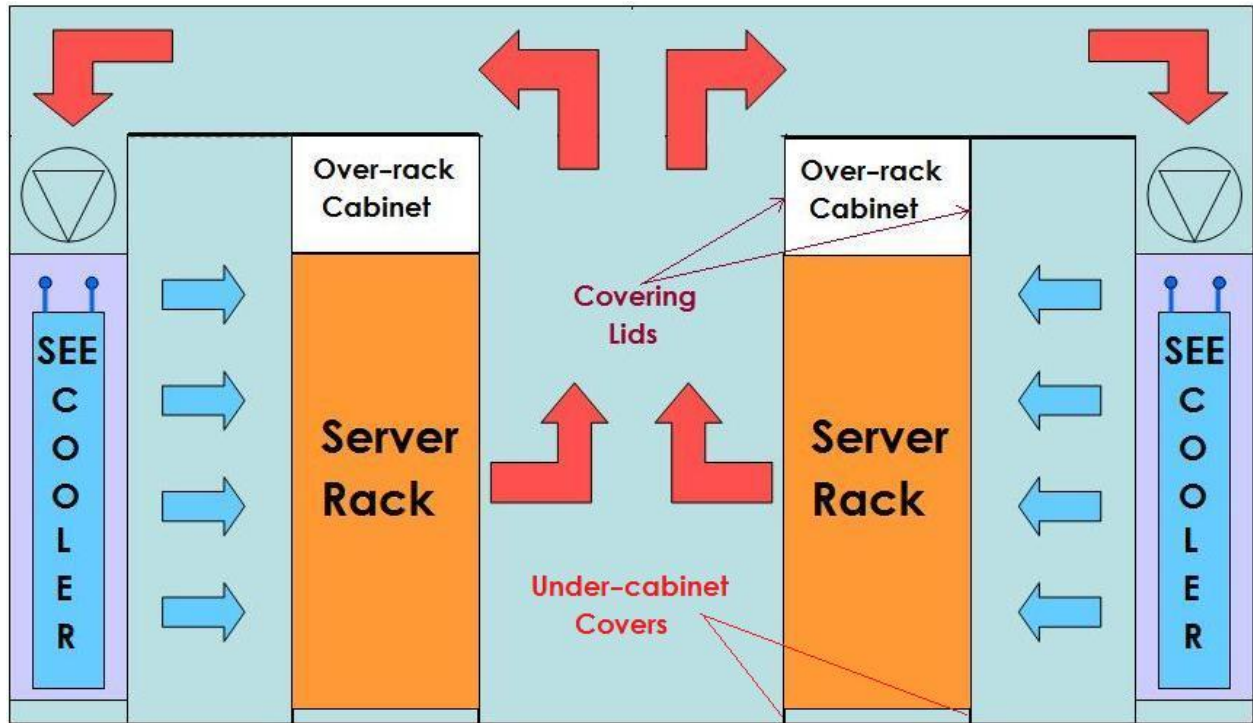
Figure 26: The air flow inside Green Room & position of the sealing covers

At first glance, these small gaps might look unimportant but when multiplied by the total number of racks in the room, their negative effect on energy efficiency of the system might be fairly large. Here, the hypothesis is that covering all these remaining gaps will significantly reduce:

1. the adequate cooling load resulting in higher energy efficiency
2. ΔT between the coolers' outlet and heaters' inlet
3. ΔT between the heaters' inlet and outlet inside the cabinets

During the test, different combination of sealed and unsealed parts will be tried out and the results will be compared to each other. On the two extreme conditions regarding the sealing, once all the removable covers in the system will be removed to record the results under "minimum sealing" and then, the room will experience a "100% sealing" by taping up all the remaining gaps inside, under and between the cabinets.
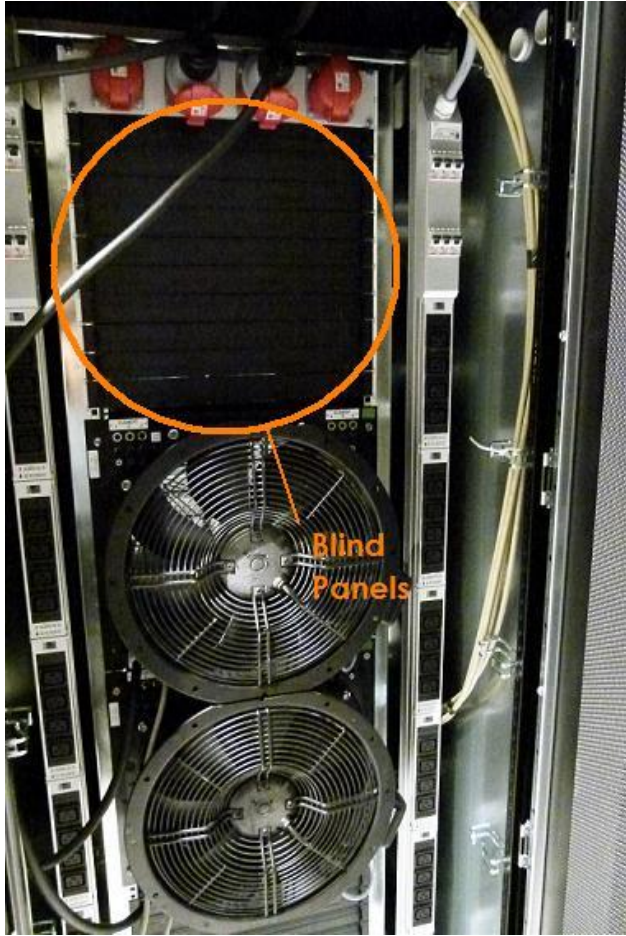
Figure 27: Front Picture of a cabinet and position of the blind panels in it

6.3.3. Distinctive Layout of Coolers inside the Room

Unlike most of the hot/cold aisle approaches which place the coolers either along the width of the datacenter or sometimes all 4 sides, in Green Room, SEE coolers are installed along the length of the room parallel to the cabinet rows. There are several reasons making this decision, it is wise from an air-flow perspective and affordable from a financial point of view:

1. Since the energy consumption of SEE coolers is remarkably lower than conventional coolers on the market, it seems to be economically affordable to pay the lower electricity bill associated with them.

2. Placing the coolers in a face-to-face position in front of the cabinets will minimize the air flow complications in the cold aisle. This method delivers the coolest air to the cabinet due to a minimized distance resulting from the straight path which the cold air travels on to the racks.

3. Since the cold-air generation in the SEE cooler is evenly distributed all over its surface, different areas of the cabinet in the bottom, middle and top receive the same air flow in terms of temperature and velocity. As was discussed before, an even supply of cold air to the cabinets is of great significance to achieve the desirable energy efficiency.

4. Due to the high density of equipment and the consequent high level of heat generation, the designers have allocated one cooler for every two cabinets which ensures the cabinets will receive an adequate amount of cold air. In addition, this layout highly contributes to an overall symmetry in the room reducing the heat loss by equal circulation of cold air.

6.3.4. Highly-Efficient Cable Management

One of the main issues which the designers of Green Room have paid enough attention to is effective cable management. While many conventional datacenters face numerous problems as the result of messy cablings both inside and outside of the cabinets, the Green Room concept has managed to resolve these issues thanks to consideration of cable holders, trays, ladders and other devices necessary to tidily fix the position of cables and cords in the system.

In terms of cable management, there are numerous areas which have been taken into account while constructing the Green Room:

1. Usage of proper products providing effective cabling routes. Power cables & Data cords have been separately grouped together to prevent electromagnetic interference. Inside the cabinets and using sufficient number of holders, the cables have been mounted on the sides of rack to minimize the blockade of cold air blown into devices and exhaust air coming out of them. On the top of the cabinets, all cables are neatly mounted on a horizontal cable tray (inside the cable racks) which starts from the first cabinet in each row and continues all the way to last one at the end of rows. This approach hugely increases the accessibility of the cables and reduces the confusion and complexity when access to the right cable is needed for maintenance, replacement or other purposes.
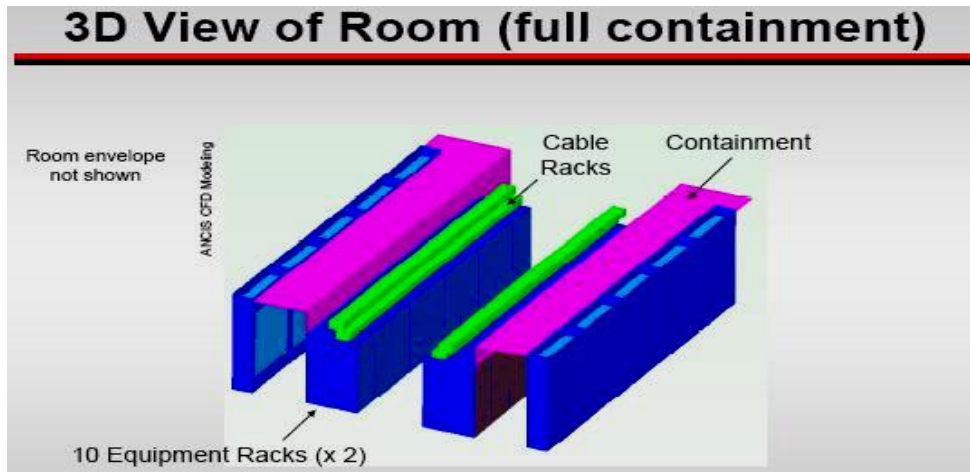
Figure 28: 3D view of Green Room including the position of cable racks (ANCIS, 2011)

2. Together with the position of the cables, the proper size of them facilitates better air flow and reduces the heat inside the cabinets through optimized space utilization. Based on the introduction given about cabling earlier in this paper, choosing more compact cables will definitely ensure better results during the test period and will later enhance a more reliable networking.

3. Cable labeling is another important factor which the developers of Green Room have been aware of. It not only facilitates the cable documentation through orderly organization" but also looks "easy to deal with" which simplifies trouble-shooting.
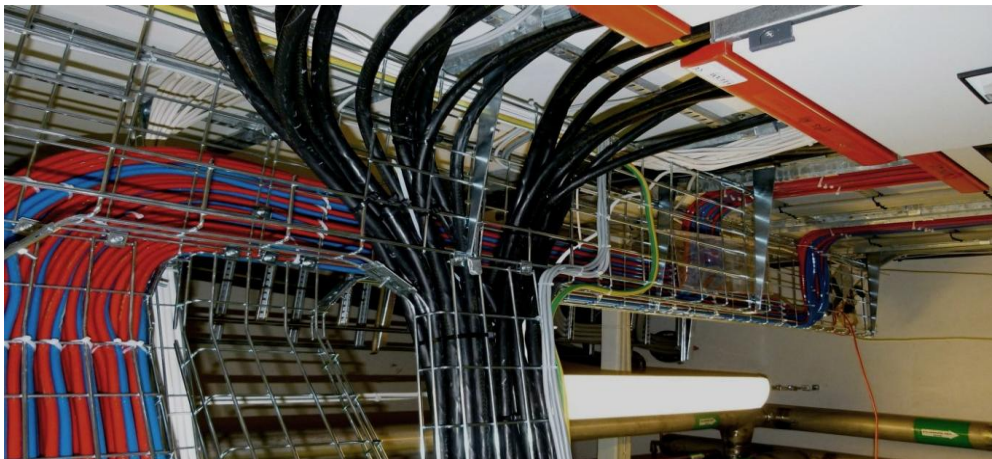
Figure 29: A demonstration of effective cable management in Green Room

7. Pre-Measurement Requirements & Uncertainty Analysis

In this chapter, the necessary steps needed to be taken in order to achieve reliable measurement accuracy have been explained. The very first step was to choose the right sensors & measurement devices in the market suitable for this test. Subsequently, a Calibration process seemed to be inevitable to adjust the accuracy of different sensors used in the project. Finally, an uncertainty analysis was carried out to determine the accuracy and therefore, reliability of all the data collected during the test.

7.1. Description of Sensors & Measurement Devices

There are two major categories of components used for measurement in the test process. The first group consists of all the sensors displaying the temperature & pressure in the Test Room. The temperature sensors are located in different locations inside the room to make sure that adequate temperature-related data will be gathered during the test period. Temperature sensors are installed on the roof over the hot aisle, the outlet of middle chillers & inlet/outlet of the dummy loads. In addition, the real equipment in the racks (Core Router and Blade Server) have their own built-in temperature sensors & displays. Each SEE cooler in the room has 12 inlet built-in sensors, 1 outlet sensor and finally one room sensor which they make up totally 14 sensors per each cooler.

Pressure sensors in the room are confined to 4 Siemens sensors installed in outer corners of the room adjacent to the control room. Regarding the power load measurement, it must be taken into consideration that some components of the system (Routers) run on DC power. As a result, power measurement devices are needed both for AC- & DC-run equipment. Measurement of power load has been done individually for each cabinet using "Carlo Gavazzi" energy analyzer device. In the Switchboard Room, "Janiza AC power measurement device" has been specifically set up for calculating the total AC power load of the whole system.

Below, a complete list of the sensors & measurement devices has been complied and it indicates the necessary information including the vendor's name, quantity, installation location & accuracy range of each. It is obvious that for convenience, it has been categorized into two main groups of "Sensors" & "Measurement Devices" which the latter indicates the installed telecommunication devices having the built-in temperature sensors.

Table 5: Temperature & Pressure Sensors Specifications Used in the Test Room

Sensor/ Device	Vendor	Quantity	Type & Installation Location	Accuracy Range
Room Pressure Sensor	Siemens	4	Kimo CP301-BOP, 2 Corners of the datacenter, adjacent to the control room	±1 Pa ±0.5%
Temperature Sensors	Siemens	6	QAA2012 , QBE2002-P10, QBM65.1-1, QAE2112.015 2 on middle chiller row 1, 2 on middle chiller row 2 and 2 as roof sensors in middle position hot aisle	From 0…50 °C: ±0.6 °C ± 0.4 % FS (Full scale) ±3 % FS From -30…130 °C: ±0.95 °C
Core Router Temperature Sensor		48	(Assumption): IC *(integrated circuit)* Temperature Sensors (Example: LM75, DS1631), Built-in sensors inside the Core routers	± 3°C Max
Blade Server Temperature Sensor		16	(Assumption): IC Temperature Sensors, Built-in sensors inside the Blade Servers	± 3°C Max
Dummy Load Temperature Sensor	Honeywell	60	C7068A1007, Thermistor, Inlet & outlet of all dummy loads inside the racks	± 0.3° C at 25° C
Room Cold Aisle Temperature Sensor	Honeywell	10	Thermistor, Cold aisle , roof position, facing each of the 10 coolers in both rows	
Roof Temperature Sensor	Honeywell	16	RTD (resistance temperature detector), TD series, On roof of the Test Room over the hot aisle	± 2.5 °C

Rack Power Load Measurement Device	CARLO GAVAZZI	20	EM24 DIN	± 1.5 %
AC Power Measurement Device	Janitza	8-10	Power Analyzer, UMG508	± 0.5 %
AC Power Measurement Device	Fluke	1	Three-Phase Power Logger (Fluke 1735)	± 0.5 %
DC Power Measurement Device	Delta (Current)	1	48 V DC Measurement device	± 0.5 %
	Delta (Voltage)	1	48 V DC Measurement device	± 0.2 %
Wireless Thermo Recorder	T&D	40	RTR-51A, Primarily set up inlet & outlet of heaters. Will be used in various locations inside the room.	Avg. ± 0.5℃
Cooler Built-in Temperature sensor	Honeywell	140	Thermistor, 12 inlet built-in sensors for return air (4 for each fan), 1 outlet sensor & 1 room sensor for each cooler, facing each cooler and placed on a upper ceiling position	Avg. ± 0.3℃ at 25℃

7.2. Calibration Process

It is obvious that in order to get the most reliable result from the sensors, they need to be calibrated first. To calibrate the sensors used in inlet and outlet of the heaters, the used standard device with the assigned correctness is RTR-5 Wireless Thermo Recorder (also known as radio loggers). These data collectors are designed to be accurate in collecting, managing and monitoring the thermal data.

The whole calibration process can be categorized into two phases:

1. "Standard Device" Calibration: Calibration of the wireless Thermo recorders to ensure the desired accuracy & correctness.
2. "Unit Under Test" Calibration: The second phase of the calibration process was to evaluate the accuracy of all the sensors involved in Green Room's test period and consequently, adjust them by obtaining and applying the right correctness value if necessary.

7.2.1. Standard Device Calibration

Before starting the tests, 38 of these Wireless Data Loggers had been taped up together for 24 hours to make sure that they were calibrated to each other in the first place. These T&D RTR-5™ wirelessly collect the thermal data and record it in their memory. Another interesting usage of these loggers was real-time monitoring of a favorable number of them on the screen in the control room. Using their exclusive software, the current readings of any selected Remote Unit was possible to be monitored and viewed at fixed interval in a simplified graph form. Since these loggers are tremendously accurate, the plan was to optimally take advantage of them and use them as temperature sensors in different parts of the aisles and at different heights as well.

In addition, the recording interval of these loggers could be set to satisfy different needs for different tests. For instance, if one of the tests required a more intense data collection process in terms of time, the interval could be set to "every 5 seconds" instead of 10 or 15 seconds. It is obvious that smaller intervals meant more thermal data and more precise thermal graphs. Since the purpose of this part is not describing the functionality of the radio loggers, this issue will be comprehensively touched upon later.

The loggers were divided up in different groups and then had their sensors taped up and insulated from the environment by carefully wrapping a special kind of foam around them. In addition to this 2-layered insulation, the whole groups were placed inside a vacant room with ambient atmosphere to ensure that they would enjoy the minimum disturbance in terms of temperature, humidity and pressure. After approximately 24 hours, all the insulation was removed from the loggers all the recorded values form the devices were downloaded and compared. First of all, the average temperature value from all the devices was calculated and expectedly, most of the loggers were functioning within the desirable accuracy range close to this mean value. The loggers with

unexpected values were calibrated using and the base unit by applying their correction values in the exclusive software.

7.2.2. Unit under Test Calibration

The data loggers were taped up with the sensors inside the racks and thermal data was obtained from both groups and compared together to make sure the test sensors were as accurate as possible within their functional specifications. The sensors calibrated using Radio loggers include the heater's inlet/outlet sensors, pump racks' sensors, SEE coolers' fan sensors & the ceiling's temperature sensors located inside the hot aisle. Since the to-be-calibrated sensors outnumbered the Radio loggers, this phase of calibration was completed in 2 rounds.

Totally, 18 loggers were used to calibrate each SEE coolers. 9 were symmetrically mounted on the cooler's surface and the rest were employed to calibrate the triple-fan system. All the loggers were taped up together with the sensors and carefully insulated for one hour. The average temperature acquired from both the sensors and loggers were recorded and compared to each other to determine the correction value for each of them. Finally, these correction values were applied to the devices to obtain the required accuracy. More specifications regarding these loggers (including the accuracy range) has been previously pointed out in Table 5 (wireless thermo recorder).

Figure 30: A group of Radio loggers used for calibration & during the test

7.3. Uncertainty Analysis

Most of the uncertainty ranges can be determined directly from the equipments characteristics and manuals, refer to Table 5.

Moreover, since the required accuracy range or uncertainty of the different sensors used for measurement was obtained, the uncertainty of all the required secondary data can now be calculated from the primary data found from measurement.

Recall the formula that was mentioned previously in this report, assuming independent variables,

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1}w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n}w_n\right)^2}$$

7.3.1. Uncertainty Calculation for the power usage effectiveness (PUE)

As mentioned before, PUE is a way to calculate the efficiency of the system.

$$PUE = \frac{Total\ facility\ power}{IT\ equipment\ power} = \frac{P_{IT} + P_{cooling} + P_{Losses,UPS} + P_{other}}{P_{IT}}$$

$$PUE = \frac{P_{IT} + P_{Fans} + P_{Pumps} + P_{other}}{P_{IT}}$$

In order to predict the uncertainty of PUE, some assumptions need to be made. Assuming that the room is operated at maximum capacity (around 380 KW of total IT load), and neglecting P_{other} and $P_{Losses,UPS}$ and assuming a value of PUE = 1.1 would be reached, and then the maximum cooling capacity $P_{cooling}$ can be calculated. It should be considered that $P_{cooling}$ includes both cooling production and cooling load of the equipments inside the room. In addition, both Janitza and Fluke devices were used to measure the AC power inside the Green Room, and it is assumed that the total cooling production will be measured using instruments with similar accuracy range.

For the total IT load, both Carlo Gavazzi and Janitza measurement instruments are used, and therefore, for PUE uncertainty calculations, the instrument with larger accuracy range is assumed to be used (worst case scenario). Referring to Table 5, the accuracy range for both Janitza and Fluke devices is 0.5 % and for Carlo Gavazzi is 1.5 %.

Having all these assumptions, the maximum uncertainty of PUE will be estimated.

$$PUE = \frac{P_{IT} + P_{cooling}}{P_{IT}}$$

$$\frac{\partial PUE}{\partial P_{IT}} = \frac{-P_{cooling}}{P_{IT}{}^2}$$

$$\frac{\partial PUE}{\partial P_{cooling}} = \frac{1}{P_{IT}}$$

$$w_{P_{IT}} = 0.015 \times P_{IT}$$

$$w_{P_{Cooling}} = 0.005 \times P_{Cooling}$$

$$w_{PUE} = \pm\, 0.0015811388$$

$$PUE = 1.1 \pm 0.0015811388$$

7.3.2. Uncertainty Calculation for the coefficient of performance (COP)

Coefficient of performance (COP) is another way to calculate the efficiency of the system. It is expressed as the total load produced by all the IT equipments divided by the load used to cool them, therefore,

$$COP = \frac{P_{IT}}{P_{Cooling}}$$

Same assumptions as PUE are taken in order to predict the uncertainty of COP.

$$\frac{\partial COP}{\partial P_{IT}} = \frac{1}{P_{Cooling}}$$

$$\frac{\partial COP}{\partial P_{Cooling}} = \frac{-P_{IT}}{P_{Cooling}{}^2}$$

$$w_{P_{IT}} = 0.015 \times P_{IT}$$

$$w_{P_{Cooling}} = 0.005 \times P_{Cooling}$$

$$w_{COP} = \pm\, 0.15811$$

$$COP = 10 \pm 0.15811$$

7.3.3. Uncertainty Analysis Conclusions

It is concluded from this basic pretesting uncertainty analysis that all uncertainty ranges found either from instrument manual or calculated are acceptable for the purpose of the tests driven. The approximate uncertainty of COP found can be considered a bit high, but it is to be mentioned that the green room is a global technology which can be used into many cooling production cases. This means that cooling production can be generated using totally free cooling, or using geothermal energy, or by conventional chillers (refer to chapter 6.2.2.3). For each of these cases, different system efficiency with a different COP or PUE will be obtained.

For instance, both a worse case with a COP much lower than 10 for a conventional chiller system, or a better case with a COP reaching 20 with a geothermal or free cooling system can be obtained. But for the current state at the actual test site, the error range of COP driven from measurement can be considered as acceptable. For more about calculations for each case cooling production case, refer to chapters 8.1.4.

8. Test Methodology & Results

Tests were carried out during a three-week period. In this period, many criteria were changed in order to get wide variety of data leading to the best conclusions. In general, 25 tests were performed and they can be categorized into 5 major groups.

1) **Pre-testing: Test 1 – 2**

   The purpose of these two tests was to ensure the well-functioning of the whole system. For that reason, these tests were run at 0 power load and thus not much importance will be given to them in this report.

2) **Efficiency testing: Test 3 – 14 and Test 25**

   In total, 13 tests were carried out to specifically evaluate the efficiency of the cooling system by applying different values for pumps' speed, SEE coolers' fan speed & heaters' load. In addition, before beginning Test 13, all the gaps, empty spaces, holes & openings in inside the room were carefully taped up to ensure the minimum air leakage and fluid mixture. This sealing process took almost half a day and actually accomplished the ultimate sealing condition referred to as "total isolation" in chapter 6.3.2.

3) **Flow leakages and temperature distribution testing: Test 12**

   Test 12 was exclusively conducted to determine which parts of the room were suffering from air flow leakage as a result of sealing imperfections or unwanted hot/cold air mixture. To achieve so, an infra-red camera was employed to provide accurate thermal images of different parts of the room including back & front of the cabinets, cable trays, SEE coolers, hot aisle ceiling, containments & finally the whole cold aisles themselves.

   The outstanding accuracy of FLIR SC-640™ thermo camera accompanied with expertise of the volunteer cameraman provided an essential documentation of illustrated thermal data for Green Room. Later in this report, a selection of interesting thermal images taken during this test will be presented and sufficiently analyzed to pinpoint the leakage areas and find out the solutions.

4) Temperature rise testing: Test 15 – 16 and Test 23 – 24

The pre-conditions for these 4 tests were engineered to evaluate the thermal tolerance of the dummy loads and also the time it takes to reach the maximum safe temperature according to heaters' safety instructions. To accomplish this objective, the heaters were turned on while the whole cooling system including the pumps and SEE coolers was off.

Meanwhile, the temperature of different parts of the room was being recorded and to obtain even more accurate charts, the logging time of the wireless thermo recorders was reduced to every 5 seconds. The maximum temperature reached inside the room relied on thermal tolerance of the heaters' safety clickers mounted inside them. The primary job of these clickers was to cut off the electricity supply to the heaters' plates in order to prevent over-heating. The maximum temperature which these clickers would bear was approximately between 50° to 60° C but due to the variable proximity of them to the plates inside different heaters, they did not have the same thermal tolerance.

As a result, when the room temperature rose to a certain point, clickers begun functioning and turning off the heater plates resulting in a gradual drop in room's temperature. All the data during these tests including the precise thermal graphs provided by the radio loggers was documented and will be demonstrated later in this chapter.

5) Containment effect testing: Test 17 – 22

This series of tests were particularly carried out in order to determine how much the hot/cold air mixture prevention would be effective compared to a half-sealed or entirely unsealed room. To achieve this, certain coverings including the cable racks' cover plates & the cardboard-made vertical and horizontal stripes used on the walls of the room (adjacent to the two coolers' rows) were all removed. The information obtained from these tests will be used to investigate how effective the sealing was in terms of energy efficiency.

Note that in Test 17 the room was still fully sealed and thus this test can be also considered and studied as an Efficiency test.

Table 6: All the tests' manually set values & power loads

Date	Test #	Room load (kW)	Pump speed (%)	Coolers row 1 fan speed (%)	Coolers row 2 fan speed (%)	Heaters fan speed (%)
13/09/11	1	0	30	85	50, 60	25
	2	0	30	85	50, 60	55
	3	160	30	85	50, 60	55
14/09/11	4	160	30	50	50	48
15/09/11	5	355	30	75	50, 60	48 - 53
20/09/11	6	355	30	75	50, 60	48 - 53
	7	355	30	75	50, 60	48 - 53
	8	355	30	85	50, 60	48 - 53
21/09/11	9	355	30	100	50	48 - 57
	10	360	100	100	50, 60	48 - 57
	11	360	160	100	50, 60	48 - 57
22/09/11	12	360	80	85	50	48 - 52
23/09/11	13	330	30	75	50	48 - 53
27/09/11	14	340	80	75	50, 60	48 - 58
	15	340	0	0	0	48 - 58
	16	160	0	0	0	48 - 58
28/09/11	17	310	80	100	60	48 - 58
	18	320	80	90	45	48 - 58
	19	320	80	90	45	48 - 58
	20	320	80	85	45	48 - 58
	21	320	80	80	45	48 - 58
	22	320	80	92	45	48 - 58
29/09/11	23	320	0	0	0	67
	24	160	0	0	0	67
	25	330	60	82	45, 50	52

Notes from the above table:

➢ In Test 11, 160% pump speed percentage means that in addition to the main pump, the backup one was in operation as well. This pump is principally installed as a backup unit to immediately replace the main one in case of any breakdown but the aim of this test was to run both pumps simultaneously. The main pump was functioning at 100% operational speed while the backup one was running at 60% of the full speed.

> In a couple of tests, having 2 percentages for coolers' fan speed in the second row (ex: 50, 60) means that CKF to CKI were operating at 50%, but CKJ facing the Router_Server_Vendor2 racks were operating at 60% of its full speed (refer to Appendix IV).

> In some tests, instead of having one specified value representing the heater's fan speed, a certain range was shown the table. Due to the non-identical design of the heaters, the best percentage for every heater was manually found and set to continuously keep all the heaters on below the clicking point. (This was achieved by increasing the fan speed on the heaters which clicked to reduce the temperature inside the heater).

8.1. Analyzing Efficiency tests

8.1.1. Plate Heat Exchanger Efficiency (Effect of Pump Speed)

In order to study the effect of the pump speed on its own, a variety of tests with different pump speed was compared. In fact, 4 groups of tests were carefully compared to each other and it is noteworthy that each group contains tests with the similar pump speed.

Moreover, since the purpose is to exchange the maximum possible heat in order to cool the hot fluid, therefore the temperature difference between the fluids and the thermal efficiency of the hot fluid was the reference in this analysis (refer to Chapter 6.2.2.4.1, Efficiency of a Heat Exchanger).

First, from the test data obtained, the following table shows the inlet and outlet temperature of the fluids in each heat exchanger for each pump rack, for different tests.
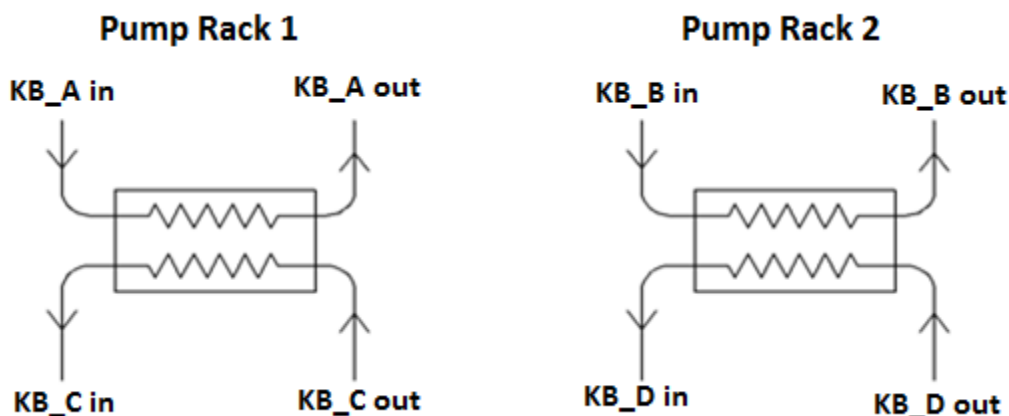

Figure 31: The heat exchangers of each pump rack

Table 7: Set values for pumps' speed & resulted temperature for all pump sensors

Pump Speed	Test #	Pump rack 1				Pump rack 2			
		KB_A in (°C)	KB_A out (°C)	KB_C out (°C)	KB_C in (°C)	KB_B in (°C)	KB_B out (°C)	KB_D out (°C)	KB_D in (°C)
30 %	4	16.9	19.5	17.4	20.5	16.8	19.9	17.2	21.5
	5	17.6	21.8	18.1	24	17.5	22	18.1	24.7
	6	17.5	22	18	24.8	17.3	22.5	18	25.4
	7	16.5	21.5	17.2	24.2	16.5	21.9	17	24.7
	9	17.6	21.8	18	24.2	17.4	21.7	17.9	24.6
	13	16.7	21.1	17	23.5	16.5	21.3	17.1	24.2
60 %	25	14.7	18.7	16.3	18.8	14.5	19.3	16.7	19.6
80 %	14	15.1	19.6	16.7	20.1	14.9	20.3	17.1	20.8
100 %	10	16.8	21.5	19.4	21.3	16.5	22.3	20.1	22.4
	11	16.8	21.5	18.9	21.8	16.6	22.3	19.2	22.7

Note that while testing, these values were only recorded for the efficiency tests. Also note that test 8 is missing in the above table due to data absence.

The following formula can be recalled from Chapter 6.2.2.4.1: $\eta_h = \frac{T_{h,inlet}-T_{h,outlet}}{T_{h,inlet}-T_{c,inlet}} \times 100$ (%)

Therefore the following table,

Table 8: Hot fluid thermal efficiency for both pump rack's plate heat exchanger at various pump speed tests

Pump Speed	Test #	Pump rack 1		Pump rack 2		Average	
		ΔT (KB_C out / KB_A/B in) (°C)	η_h (%)	ΔT (KB_D out / KB_A/B in) (°C)	η_h (%)	ΔT (KB_C/D out / KB_A/B in) (°C)	η_h (%)
30 %	4	0.5	86.11	0.4	91.49	0.45	88.80
	5	0.5	92.19	0.6	91.67	0.55	91.93
	6	0.5	93.15	0.7	91.36	0.6	92.25
	7	0.7	90.91	0.5	93.90	0.6	92.41
	9	0.4	93.94	0.5	93.06	0.45	93.50
	13	0.3	95.59	0.6	92.21	0.45	93.90
60 %	25	1.6	60.98	2.2	56.86	1.9	58.92
80 %	14	1.6	68.00	2.2	62.71	1.9	65.36
100 %	10	2.6	42.22	3.6	38.98	3.1	40.60
	11	2.1	58.00	2.6	57.38	2.35	57.69

It is concluded from the above table that the best results were obtained for a 30% pump speed, giving an average temperature difference between the hot fluid out and the cold fluid in of around 0.5 °C and a thermal efficiency of around 92 %.

8.1.2. Finned Coil Heat Exchanger Efficiency

8.1.2.1. Effect of Pump Speed

In order to study the effect of pump speed on the build in liquid to air coolers heat exchanger, also called as finned coil heat exchanger, more or less same procedure was done as Chapter 8.1.1.1 but in a more complex environment. This is because not only the pump speed is a variable in these tests but also the fans speed of the coolers that control the flow of the hot return air. Both of these variables are essential for the efficiency study of the finned coil heat exchanger. In this chapter, only the effect of pump speed is studied therefore tests are compared in a way that they have different pump speeds but similar cooler fan speed.

Note that for this study, temperature values of the inlet and outlet of both KB_C and KB_D for each row are obtained from the Siemens temperature sensors in the pump room. It is true that the real temperature value of KB_C and KB_D at the inlet and the outlet of the coolers will be slightly different than the one taken in the pump room due to the heat exchange with the environment while the fluid is transported through pipes, but for the sake of this study, this difference won't have much effect on determining the best efficient speed and such an assumptions will have to be taken.
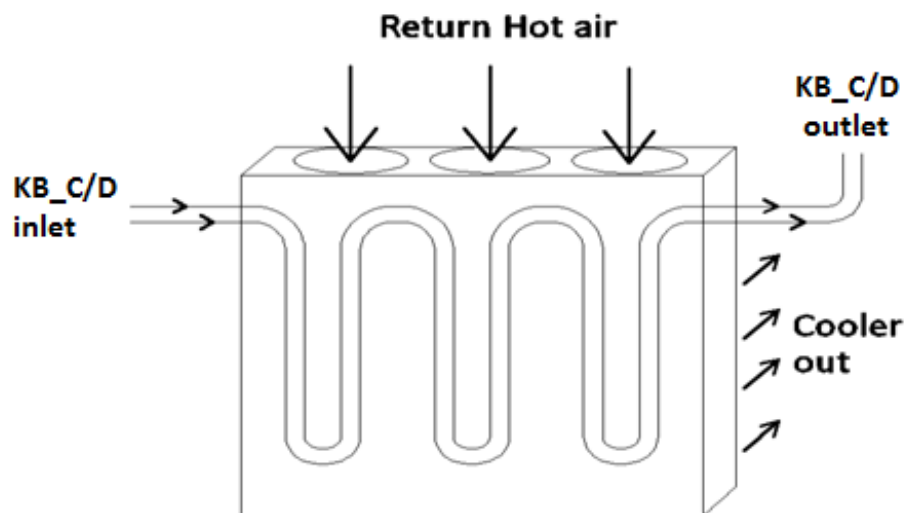

Figure 32: Liquid to air SEE cooler heat exchanger

The following table shows the average of both fluids KB_C and KB_D inlet and outlet and average hot fluid return air and coolers outlet for 2 chosen sets of tests, where each set has 2 tests with different pump speed but similar coolers fans speed in both rows.

Table 9: Thermal data for tests sets including same coolers fans speed but different pump speed

Set #	Pump Speed (%)	Test #	KB_C/D inlet (°C)	KB_C/D outlet (°C)	Return (°C)	Coolers out row 1 (°C)	Coolers out row 2 (°C)
1	30	7	17.1	24.45	35.25	21.04	19.22
	80	14	16.9	20.45	33.50	17.83	17.44
2	30	9	18.45	24.4	33.32	22.09	18.26
	100	10	19.75	21.85	32.95	20.43	20.02

Now for each test, the temperature difference between cooler's outlet air and average KB_C and KB_D is found as well as the hot fluid thermal efficiency for each test. This will allow comparing the effect of pump speed on the finned coil heat exchanger.

The results for both sets are illustrated in the following table.

Table 10: Hot fluid thermal efficiency for the liquid to air heat exchanger SEE coolers for tests sets including same coolers fans speed but different pump speed

Set #	Pump Speed (%)	Test #	ΔT (Coolers out / KB_C/D in) (°C)	η_h (%)
1	30	7	3.03	83.31
	80	14	0.735	95.57
2	30	9	1.725	88.40
	100	10	0.475	98.41

It is concluded from the above table that for each set, a higher pump speed results in a slightly higher thermal efficiency for the hot fluid and a lower temperature difference. This is taking into consideration the finned coil heat exchanger alone.

But since this is a whole system bases on two types of heat exchangers, and since previous results have shown that the best heat efficiency was obtained for a lower 30 % pump speed, then more analyses should be done in the future studies on this system.

Therefore, the temperature difference between cooler's outlet air and the main coolant (KBA/B) inlet fluid is also calculated in addition to the total thermal efficiency (assuming that both heat exchangers works as one, and thus finding the thermal efficiency of the whole system). This will give

us an idea of the thermal efficiency of the total system. In this sense, the thermal efficiency of the total system is calculated as,

$$\eta_{h,total} = \frac{T_{return,inlet} - T_{return,outlet}}{T_{return,inlet} - T_{KB13,inlet}} \times 100 \ (\%)$$

And thus comes the results,

Table 11: Hot fluid thermal efficiency taking the whole system (both heat exchangers) for tests sets including same coolers fans speed but different pump speed

Set #	Pump Speed (%)	Test #	ΔT (Coolers out / KB_A/B in) (°C)	$\eta_{h,total}$ (%)
1	30	7	3.63	80.64
	80	14	2.635	85.76
2	30	9	2.675	83.09
	100	10	3.575	78.07

It is now concluded from the total thermal efficiency results that as a total system, there is not much effect of the pump speed of the system since it works in opposite effect on both heat exchanger. This gives more stability and flexibility to the system, and thus the best pump speed is the lowest one possible giving us the required Cooler's outlet temperature needed.

Furthermore, the lower the pump speed, the less cooling load in the system, and thus higher COP and lower PUE, which means better efficiency of the whole system.

As a result of all the above, it is concluded that the best pump speed to use is 30%. More studies should be done to see if 30% is in fact the lower possible pump speed to be used, but for this stage, it is believed so. In addition, since the pumps are utilized on only 30% of their capacity, it can be concluded that they are unnecessarily oversized for this size of the room and this power load.

All the values above suggest that the results have been contradictory to what was theoretically designed before the actual measurements conducted. It was believed that increasing the pump speed would lead to a reduction in coolers' operational temperature which is proved to be wrong based on the analysis above. Moreover, the automatic control system of the room for future operation was set in a way that if a lower operation temperature was needed, the control system would order the pumps to speed up.

If this had occurred, it would force the pumps to run on full speed and therefore enormous amount of energy would have been wasted. As a result, more studies should be conducted on this issue in two directions. Firstly, the minimum allowed pump speed should be found. Based on measurement

and calculations, it was true that a 30 % pump speed gave us approximately the same average coolers' operational temperature. However, based on the CAD drawing templates of the tests, it can be noticed that a higher pump speed provides a more stable temperature values if outlet temperature values of coolers are compared (comparison included different positions of a specific cooler as well as different coolers between each other).

Thus this effect should be studied and the minimum allowed pump speed must be set and introduced to the control system. Furthermore, it is now believed that the pump rack heat exchanger was inefficient and need to be changed or optimized for a better heat transfer at high pump speed. In fact, a better heat exchanger of pump racks will lead to lower operational temperature when increasing the pump speeds as it was established originally in the control system.

8.1.2.2. Effect of Coolers' Speed

In order to study the effect of coolers speed alone on the efficiency of the finned coil heat exchanger, and based on the previous results, tests will be studied with fixed pump speed of 30% (refer to Chapters 8.1.1.1 and 8.1.2.1) and different coolers fan speed.

Therefore, the chosen tests for this study and their coolers fan speed and other data recorded needed for the study are presented in the following table,

Table 12: Data on the tests carried out with similar pump speed of 30%

Test #	Coolers row 1 fan speed (%)	Coolers row 2 fan speed (%)	KB_C/D inlet (°C)	KB_C/D outlet (°C)	Return (°C)	Coolers out row 1 (°C)	Coolers out row 2 (°C)
4	50	50	17.3	21	31.17	18.53	17.38
5	75	50, 60	18.1	24.35	35.70	20.90	18.96
6	75	50, 60	18	25.1	35.13	20.58	18.84
7	75	50, 60	17.1	24.45	35.25	21.04	19.22
9	100	50	18.45	24.4	33.32	22.09	18.26
13	75	50	17.05	23.85	34.49	20.50	18.44

Due to the fact that the cooler's speed was the same in row 2, temperature difference and thermal efficiency calculations were performed for row 1.

Table 13: Temperature efficiency at different coolers fan speed percentage tests with similar pump speed of 30%

Test #	Coolers row 1 fan speed (%)	ΔT (Coolers out / KB_C/D in) (°C)	η_h (%)
4	50	1.23	91.13
5	75	2.8	84.09
6	75	2.58	84.94
7	75	3.94	78.29
9	100	3.64	75.52
13	75	3.45	80.22

As seen in the above table, the best temperature range and higher efficiency were obtained for the lower fan speed value of 50%.

Note also that there is not a big difference between the highest efficiency value obtained and the lower one due to the design of the heat exchanging where hot air share a relatively large area with the cold fluid.

From the results obtained, it can be said that the whole system is in homogeneous. That means that lowering the fans speed will increase the efficiency of the heat exchanger as well as it will reduce the cooling production, increasing COP and thus the efficiency of the whole system. And therefore, finding the appropriate cooler fan speed is totally dependent on the heat load of the computers that need to be cooled as well as on the air flow inside the room. In fact, the air flow provided by the coolers should be enough taking into consideration how much of this air is allocated to cooling of the computers.

8.1.3. Green Room Efficiency

8.1.3.1. Undesired Heat Transfer vs Air Flow

Perhaps one of the most problems that affect the efficiency of the cooling system in a data center is the unwanted heat transfer in the room between the cooling fluid and the environment before reaching the computer cabinets. This heat transfer or heat gain is highly dependent on the condition inside the room. This includes how the room is sealed and isolated from the outer environment, but more important, how the air flow is controlled inside the room, and how much hot and cold air are isolated from each other. Consequently the better the flow is controlled and the better cold air is isolated from hot air, the less undesired heat transfer will take place between both air flows. As a result, a better and more efficient system is achieved.

From here comes the main idea of the green room. The green room is perfectly closed and sealed from the outer environment as well as fluid flow is controlled separating and isolating both fluids (refer to Chapter 6.3.2).

In order to show how well cold fluid is isolated in the green room, temperature difference between coolers' outlet and cabinets' inlet was found for each test. This was done by installing radio loggers on both coolers outlet and cabinets inlet in a way that most points are covered (horizontally and vertically) inside each row.

Radio loggers are high efficient temperature measuring instrument, that can record and store in memory all recorded value based on a time interval set by the user. Temperature values can be later extracted either wirelessly (through radio signals from each radio logger to a universal receiver, covering a certain range of area) or manually by connecting this receiver to each radio logger by itself. The extracted time base temperature values can be then saved both as graphs and as numerical values. For more, refer to Chapter 7.2.1.

Figure 33: Wireless and manual extraction of radio loggers' temperature stored values
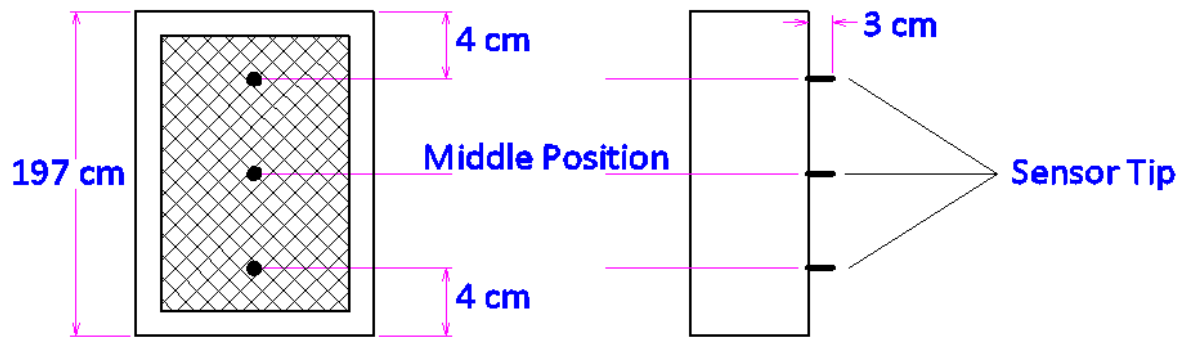
Figure 34: Different positions of radio loggers on the coolers (left) & cabinets (right)

To see radio loggers positioning in the coolers and cabinets in the whole room, the following picture illustrate all positions with radio loggers' numbers and temperature values chosen from one random

test. Keep in mind that positioning can differ between one test and another; in some tests all radio loggers are used to study one single row rather than both of them at the same time.
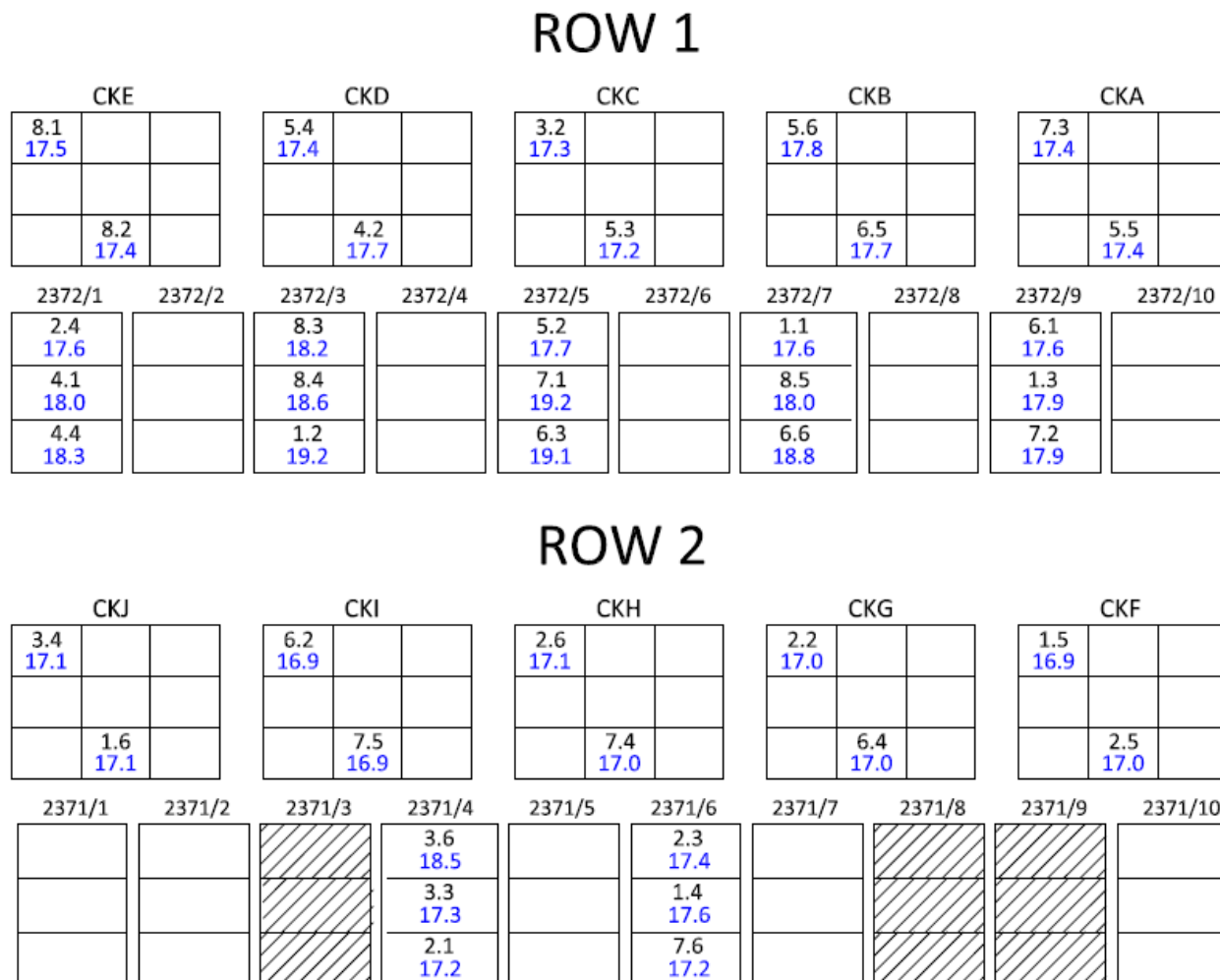
ROW 1

CKE	CKD	CKC	CKB	CKA
8.1 / 17.5	5.4 / 17.4	3.2 / 17.3	5.6 / 17.8	7.3 / 17.4
8.2 / 17.4	4.2 / 17.7	5.3 / 17.2	6.5 / 17.7	5.5 / 17.4

2372/1	2372/2	2372/3	2372/4	2372/5	2372/6	2372/7	2372/8	2372/9	2372/10
2.4 / 17.6		8.3 / 18.2		5.2 / 17.7		1.1 / 17.6		6.1 / 17.6	
4.1 / 18.0		8.4 / 18.6		7.1 / 19.2		8.5 / 18.0		1.3 / 17.9	
4.4 / 18.3		1.2 / 19.2		6.3 / 19.1		6.6 / 18.8		7.2 / 17.9	

ROW 2

CKJ	CKI	CKH	CKG	CKF
3.4 / 17.1	6.2 / 16.9	2.6 / 17.1	2.2 / 17.0	1.5 / 16.9
1.6 / 17.1	7.5 / 16.9	7.4 / 17.0	6.4 / 17.0	2.5 / 17.0

2371/1	2371/2	2371/3	2371/4	2371/5	2371/6	2371/7	2371/8	2371/9	2371/10
		(hatched)	3.6 / 18.5		2.3 / 17.4		(hatched)	(hatched)	
		(hatched)	3.3 / 17.3		1.4 / 17.6		(hatched)	(hatched)	
		(hatched)	2.1 / 17.2		7.6 / 17.2		(hatched)	(hatched)	

Figure 35: Detailed position of radio loggers on the coolers and cabinets in both rows

In Figure 35 it is quite noticeable that no radio loggers were positioned on the right side of the coolers (under fan 3) due to the lack of radio loggers (around 40 available) and to the fact that each cooler contain temperature sensors at that particular side that can be read from the digital display of the cooler.

Logging was done at an interval of 1 or 2 minutes for most of the tests, and value were extracted and used to illustrate charts showing average coolers' temperature as well as average cabinets' temperature at each row based on time.

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For the purpose of this study, only the average temperature difference will be presented for every test. Moreover, some charts from particular tests will be also illustrated. For full radio-logging time base values and all available charts for all tests, please refer to Appendix II.

Also note that in this section only the efficiency tests are dealt with. More precise temperature difference between coolers and cabinets will be seen later in this report when studying efficiency versus Containment effect testing (Test 17 to 22), Chapter 8.4.

Table 14: Lowest, highest & average ΔT for all efficiency tests

Test #	Row 1 (CKA-CKE)			Row 2 (CKF-CKJ)		
	Average ΔT	Min ΔT	Max ΔT	Average ΔT	Min ΔT	Max ΔT
2	0.140	0.106	0.321	NA		
3	1.068	0.835	1.580			
4	0.205	0.097	0.319			
5	0.321	0.252	0.405	0.490	0.284	0.805
6	NA			0.169	≈ 0	0.380
7	0.375	0.187	0.560	NA		
9	0.193	0.056	0.305			
10	0.440	0.359	0.576			
11	0.457	0.359	0.579			
13	0.449	0.330	0.537			
14	0.362	0.302	0.435			
17	0.288	0.213	0.430	0.118	0.060	0.200

It is seen from the above table that the maximum temperature difference was obtained for Test 3 (1.068 °C) which is more than the double of the second max value obtained (Test 11, 0.457 °C). This is probably due to the fact that Test 3 was the first test with load and therefore continuous manual supervision was necessary for safety reasons. This has caused the green room doors to be continuously opened during the test which has allowed more heat exchange with the outside environment which explain the higher temperature difference obtained.

As a general view, it is then concluded from the above table that the green room provides an average temperature difference between coolers and cabinets inlet of around 0.5 °C which is way better than most other technologies. Based on data from other TeliaSonera sites, a regular raised floor cooling system working at its best can provide a temperature difference at hot spots up to 12 °C. More about comparing with other measured values from real sites can be seen (refer to Table 16 and Figure 38).

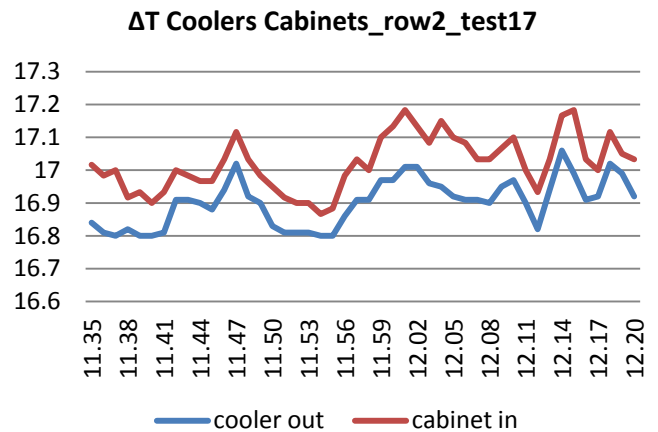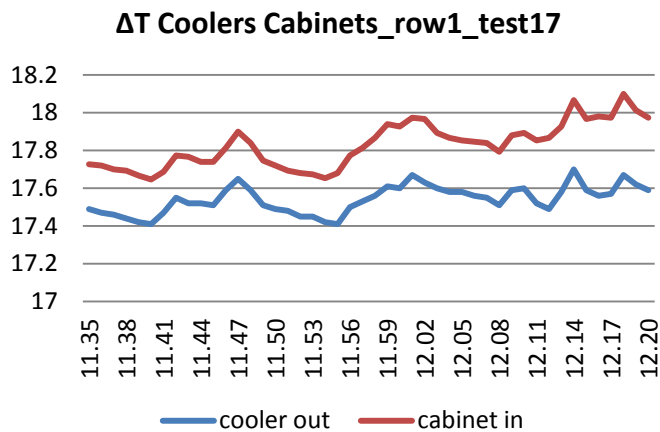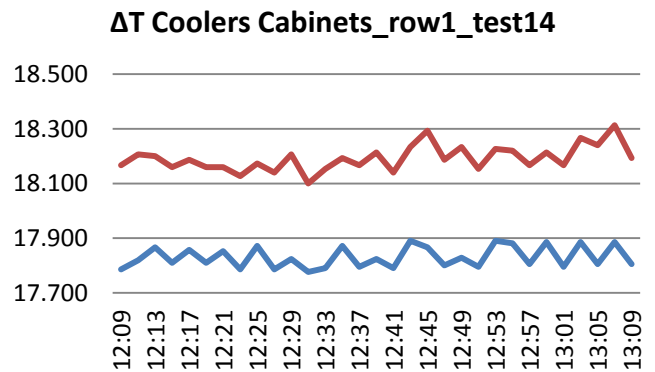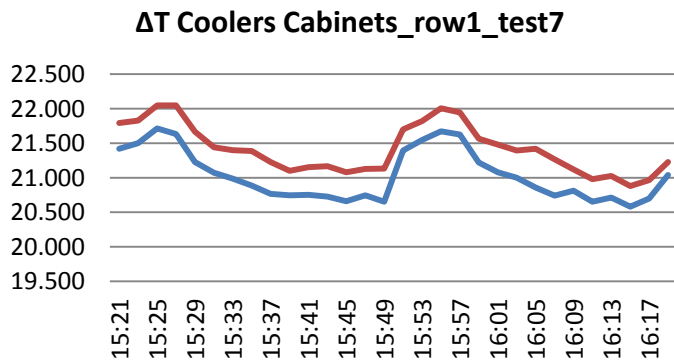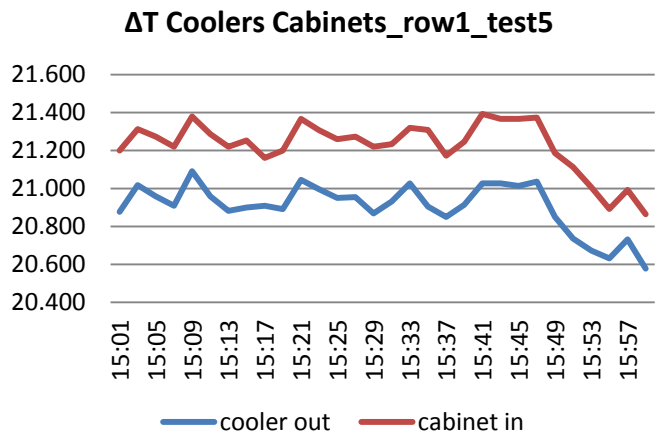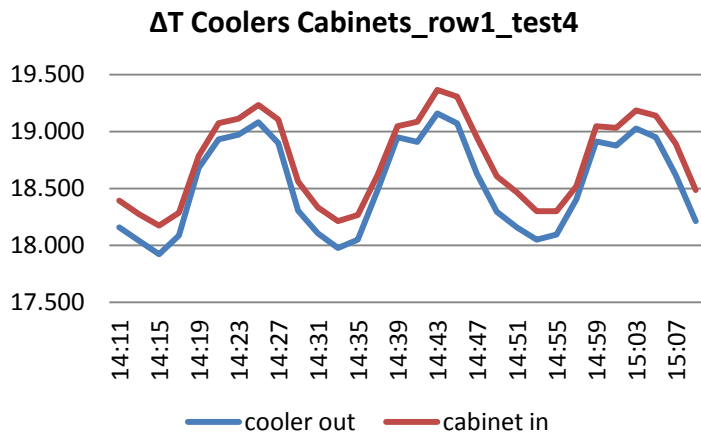Here come temperature difference charts of some tests based on time.

Figure 36: A selection of thermal differential graphs versus time

Note that in order to see all time based values with all the charts for every test refer to Appendix II.

Also note from some charts the fluctuation up and down of the cooler's temperature causing same fluctuation of the cabinet inlet (mostly seen in the chart of Test 4). This is because of the fluctuation of the initial main coolant temperature that is supplied from the cooling production of the site. The most stable temperatures obtained were for Test 14.

More precise view was made for some tests by finding the temperature difference between coolers and each position of the cabinets (high, middle and low). As said before, radio loggers were positioned at 3 different positions in the cabinets and therefore it was possible to extract data and calculate temperature difference between coolers and average high cabinet's position, middle cabinet's position and low cabinets position.
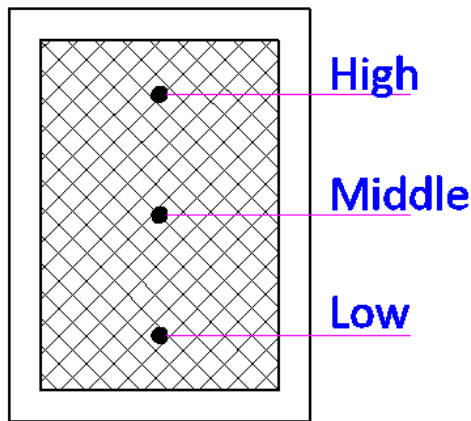

Figure 37: Sketch of the three vertical positions of radio loggers on cabinets' inlet

The results are illustrated in the following table,

Table 15: Associated ΔT with position of Radio loggers on the coolers & cabinets

Test #	Row 1 (CKA-CKE)		
	ΔT high	ΔT middle	ΔT low
9	≈ 0	0.777	0.068
10	0.391	0.629	0.301
11	0.274	0.751	0.345
13	0.152	1.086	0.108
14	0.271	0.652	0.163
17	0.135	0.297	0.433

It is concluded from all the data presented in this section the relatively small temperature gain of the cooling air before it reaches the cabinets (a max value of about 1 °C). But more importantly, the rough symmetry in the different vertical positions in the racks, which is one of the main advantages of the green room design. In fact taking into consideration vertical positions, the max difference between lowest ΔT and highest ΔT was for Test 13 were the lowest was at high position (0.108 °C) and the highest at middle position (1.086 °C).

It is noted also that the maximum ΔT for almost all test is at the middle position. This can be clearly noticed also in one infrared picture presented later in this report, refer to Figure 40. The reason for this is unknown, and no more investigations were carried out for this case because of the excellent values of ΔT obtained. (Allowing the cold air reaches the cabinets with an almost intact temperature).

To see more the advantages of this symmetry, it is convenient to refer to the results of TeliaSonera´s Sauna report written by Svante Enlund on 18 May 2009. According to the Sauna report, measurements were done on 5 data centers sites that have raised floor cooling system which is considered the standard solution for many data centers around the world. Due to this high unsymmetrical cooling method, temperature measurements were done in order to identify the hottest spot which indicate the highest temperature difference ΔT and compare it with the best or lowest temperature difference position.

The following table and chart illustrate the results obtained from the Sauna report adding to it the worst result obtained from measurement (Test 13) and one of the best results (Test 17). It should be considered that both the poorest and finest values are achieved by combining the two factors, value of ΔT and symmetry between the positions.

Table 16: Hottest spots and temperature difference at real measured sites compared with Green Room

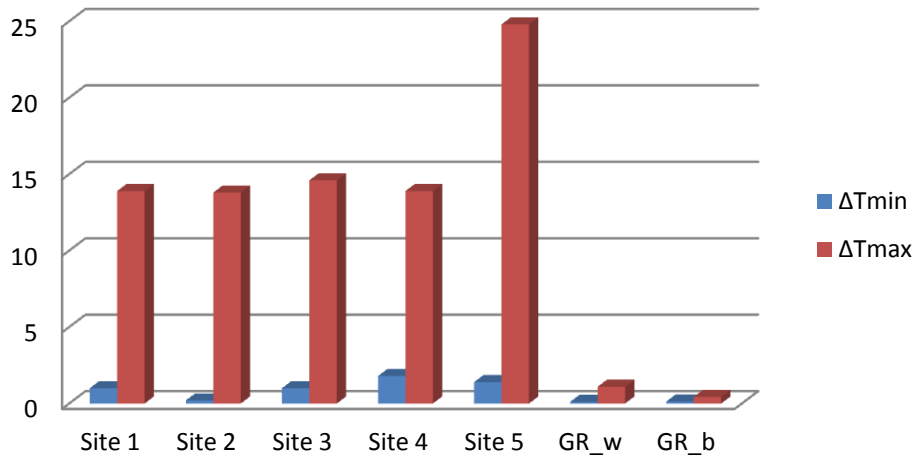|	Site 1	Site 2	Site 3	Site 4	Site 5	Green Room (worst test)	Green Room (best test)
ΔT_{min} (°C)	1	0.2	1	1.8	1.4	0.11	0.13
ΔT_{max} (°C)	13.9	13.8	14.6	13.9	24.8	1.1	0.43
$\Delta T_{min} - \Delta T_{max}$	12.9	13.6	13.6	12.1	23.4	0.99	0.3

ΔT, Green RoomVs Raised Floor

Figure 38: Comparison between ΔT achieved in Green Room & raised-floor-based layouts

It is clearly noticed the huge difference between the green room values obtained and other data centers with raised floor. It would have been also good to compare the green room values with other cooling technologies, but unfortunately this was not possible due to lack of available data. Even though, it is clearly concluded from the green room results that the cold air reaches the cabinets with almost an intact temperature which is one of the most important advantages of the green room regarding efficiency. Effectively, this allows us to operate in a higher coolers outlet air temperature, which means that the max main coolant fluid temperature value that is used to supply cooling for the coolers is also increased, which allows us in its turn to use free cooling at higher outdoor temperature. This means that more free cooling along the year will be used or at worst less cooling production occurs for warm weather countries all over the year. This will increase more and more the efficiency of the whole system and decreases the cooling cost.

8.1.4. COP and PU Calculations

8.1.4.1. Test Site

Referring to Table 3, interpolation was done to find the cooling production in summer and winter for every efficiency test having its total load which was obtained through measurement.

Referring to Chapter 4, the coefficient of performance and the power usage effectiveness can be calculated for every test of the efficiency tests category.

It should be noted that due to lack of data or suspicious data resulted from human error in reading the values, some tests were eliminated from this list.

Table 17: Resulted COP & PUE values for the conducted tests based on cooling production in Test Site in both cases, summer and winter

Test #	Total Load (kW)	IT Load (kW)	Cooling within room (kW)	Cooling production		COP		PUE	
				Winter (kW)	Summer (kW)	Winter	Summer	Winter	Summer
3	160.0	157.9	1.9	14.5	46.4	9.80	3.31	1.119	1.322
4	159.3	157.6	1.6	14.4	46.2	9.99	3.34	1.114	1.316
5	353.4	346.6	3.2	31.9	102.5	10.06	3.34	1.122	1.326
6	355.6	350.7	3.2	32.1	103.1	10.07	3.34	1.116	1.318
7	351.3	348.5	3.2	31.7	101.9	10.05	3.34	1.109	1.311
8	356.9	350.5	4.2	32.2	103.5	9.81	3.32	1.123	1.327
9	355.9	349.2	5.9	32.1	103.2	9.36	3.26	1.129	1.333
10	355.3	350.7	9.5	32.1	103.0	8.54	3.16	1.133	1.335
13	324.8	302.5	6.0	29.3	94.2	9.20	3.24	1.192	1.406

It must be noted from this table that the total load means the total measured load obtained from the Janitza measurement device. This unit measures the power load at an early location of the circuit where the losses referred to as "UPS power losses" has not taken place yet. In other words, the IT load is obtained from measurements taken by Carlo Gavazzi unit where the UPS power losses has already taken place. As a result, in the PUE calculation, the $P_{Losses,UPS}$ is the difference between total load and IT load. In addition, it is important not to forget that the air purifier consumes 400 W which goes under P_{other} in PUE calculation, while neglecting all other power consumption factors such as lighting.

8.1.4.2. Conventional Chillers

A software created by TeliaSonera is able to estimate the cooling production load produced from one of the finest and most efficient chillers found in the market. Based on these estimations, the cooling production needed for every test is calculated relating to the total load inside the room. From these values, COP and PUE were calculated for all the tests.

Table 18: Estimated COP & PUE values based on software simulation of best chillers available in the market

Test #	Total Load (kW)	IT Load (kW)	Cooling within room (kW)	Cooling production (kW)	COP	PUE
3	160.0	157.9	1.9	76.0	2.05	1.509
4	159.3	157.6	1.6	75.7	2.06	1.503
5	353.4	346.6	3.2	167.9	2.07	1.515
6	355.6	350.7	3.2	169.0	2.07	1.506
7	351.3	348.5	3.2	166.9	2.07	1.497
8	356.9	350.5	4.2	169.6	2.05	1.515
9	355.9	349.2	5.9	169.1	2.03	1.521
10	355.3	350.7	9.5	168.8	1.99	1.522
25	324.8	302.5	6.0	154.3	2.03	1.605

8.1.4.3. Geothermal

Using the same software, cooling production supported by geothermal technology is estimated. Due to the incredibly low temperature losses between coolers outlet and cabinets inlet as discussed in Chapter 8.1.3.1, operation can be done in a higher cooling outlet temperature, and thus a big question is raised. What is the maximum coolers outlet temperature that can be reached in the Green Room and still satisfying the need of the computers and servers to be cooled?

According to ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.) and NEBS (Network Equipment-Building System) standards, the coolers temperature inside a data center is recommended to be between 18 and 27 °C. Whereas the maximum allowable equipment inlet temperature is 32 °C according to ASHRAE and can reach up to 40 °C according to NEBS. For these reasons, COP and PUE in this section were estimated considering two cases of coolers temperature outlet.
The first one is 22.5 °C which is a value close to the ones obtained while operating the tests and the second is 27 °C which is the maximum recommended value according to ASHRAE and NEBS. However, it is believed that due to the low temperature loss in room, operation at values higher than 27 °C may be possible, and thus giving potentials of increasing even more the efficiency. Therefore, more studies should be conducted to expand the knowledge about servers and routers used in the

real operation of the Green Room. This will provide reliable answers to the question of the maximum temperature giving the best optimization of the cooling consumption.

Taking into consideration 22.5 °C operation temperature, the estimated values COP and PUE for a geothermal cooling production system for every efficiency test are presented in the following table,

Table 19: Estimated COP & PUE for geo cooling production with operational temp of 22.5 °C

Test #	Total Load (kW)	IT Load (kW)	Cooling within room (kW)	Cooling production (kW)	COP	PUE
3	160.0	157.9	1.9	4.8	23.94	1.058
4	159.3	157.6	1.6	4.8	25.12	1.054
5	353.4	346.6	3.2	10.6	25.55	1.061
6	355.6	350.7	3.2	10.7	25.59	1.055
7	351.3	348.5	3.2	10.6	25.50	1.049
8	356.9	350.5	4.2	10.7	23.97	1.062
9	355.9	349.2	5.9	10.7	21.48	1.068
10	355.3	350.7	9.5	10.7	17.60	1.072
25	324.8	302.5	6.0	9.8	20.62	1.127

And for 27 °C coolers outlet, the results are as follows,

Table 20: Estimated COP & PUE for geo cooling production with operational temp of 27 °C

Test #	Total Load (kW)	IT Load (kW)	Cooling within room (kW)	Cooling production (kW)	COP	PUE
3	160.0	157.9	1.9	4.2	26.49	1.054
4	159.3	157.6	1.6	4.2	27.94	1.049
5	353.4	346.6	3.2	9.2	28.48	1.057
6	355.6	350.7	3.2	9.3	28.53	1.051
7	351.3	348.5	3.2	9.2	28.41	1.045
8	356.9	350.5	4.2	9.3	26.54	1.058
9	355.9	349.2	5.9	9.3	23.52	1.064
10	355.3	350.7	9.5	9.3	18.94	1.068
25	324.8	302.5	6.0	8.5	22.49	1.123

8.1.4.4. Analysis and Conclusions

Based on COP and PUE calculations for different cooling production technologies, the following conclusions have been achieved:

✓ Best efficiency is obtained for Geothermal cooling production, with a COP reaching up to 28 (considering 27 °C operation) and a PUE as low as 1.05.

✓ Green Room Test Site's PUE in winter (Free cooling) is about 1.12 which verifies more or less the pre-tests estimations made in earlier stages. It is believed that utilization of a free-cooling system can result in even a better efficiency than a geothermal system. Therefore, it is likely that the PUE value can even fall to a much lower level than values obtain from geothermal. This is mainly for two reasons.

Firstly, the cooling operation temperature in real test was between 17 to 21 °C (Refer to Appendix IV for operation temperatures for every test). This range was heavily dependent on the main coolant's temperature which was fixed and set by Test Site's operators. In addition, it is also reliant on other factors involving heat exchanging but they do not seem to be important for the purpose of this analysis. Therefore, by knowing the maximum allowed operating temperature, lower PUE values can be achieved and more free cooling operating time will be available per year (Site can be free-cooled at higher outdoor or lake temperature).

Secondly, it is very likely that the free cooling option has not been adequately studied to be utilized as effectively as possible. Although free cooling in Test Site is saving energy and money comparing to Chillers used in the summer, this should not be the only target. It is also of great significance to study how much this system can be optimized and apply sufficient changes to acquire the best results leading to even a more economical and efficient system.

✓ Even with the worst case of using conventional chillers, estimated values are way better compared to the most data centers of the world where PUE goes usually up to and sometimes beyond 2, whereas for the green room the estimated values of PUE are around 1.51. But it is to be noticed that chillers cooling production estimation is made only for comparison purposes because while using the software, a completely chiller based system cooling is considered, not only for cooling production but as well for cooling within the room by using a conventional CRAC unit, eliminating the advantages of using the SEE coolers. Therefore, calculations done for the Test Site summer case can be a better reference for a chiller cooling production system combined with Green Room cooling system; the system that is clearly described in Figure 22. Therefore the PUE for Test Site in summer is around 1.32, which is still much better than a system operated completely on chillers.

✓ Comparing values between tests, it was clear that the best values obtained are for the tests with less cooling production within room measured, and this is obviously for the tests operating at 30 % pump speed, which meens less load of cooling equipments inside the room.

8.1.5. RCI Calculations

Referring to Chapter 4, the rack cooling index high and low (RCI$_{HI}$ & RCI $_{LO}$) can be calculated for every test. ASHRAE Class 1 (2008) standard is used for the calculations, where:

Table 21: Recoomended & allowable temperatures according to ASHRAE Class 1 standard

ASHRAE Class 1 (2008) Standard	
Max Allowable	32 °C
Max Recommended	27 °C
Min Recommended	18 °C
Min Allowable	15 °C

Refer to Figure 5.

Based on the chosen standard and referring to Chapter 4 and having temperature values at inlet of the racks from radiologgers, therefore the rack cooling index for every test is calculated.

$$RCI_{HI} = \left[1 - \frac{Total\ Over\ Temp}{Max\ Allowable\ Over\ Temp}\right] \times 100\%$$

$$RCI_{LO} = \left[1 - \frac{Total\ Under\ Temp}{Max\ Allowable\ Under\ Temp}\right] \times 100\%$$

Table 22: RCI values for Green Room tests

Test #	RCI_{HI} (%)	RCI_{LO}
3	100	100
4	100	100
5	100	100
6	100	100
7	100	100
8	100	100
9	100	100
10	100	100
13	100	100
14	100	95.61
17	100	85.56
18	100	90.79
19	100	92.06
20	100	91.59
21	100	91.27
22	100	92.70
23	100	89.68

Please refer to Appendix III for a chart illustration of the different thermal points for every test used for RCI calculation.

Using ASHRAE standard and based on the above table, It is concluded that all temperature values taken at the inlet of the racks fall into the recommended range, except for Tests 17 to 23 where some values were under the minimum recommended range. This means that these tests were operated under colder conditions than recommended while it was possible to increase the operational temperature and save energy.

8.2. Analysis of Flow leakages & Temperature Distribution Test

As it was briefly explained in the beginning of this chapter, Test 12 was exclusively conducted to determine which parts of the room were suffering from air flow leakage as a result of sealing imperfections or unwanted hot/cold air mixture. To achieve so, an infra-red camera was employed to provide accurate thermal images of different parts of the room including back & front of the cabinets, cable trays, SEE coolers, hot aisle ceiling, containments & finally the whole cold aisles themselves.

In addition, to evaluate the effectiveness of "Total Isolation", one cabinet was completely taped up to seal all the gaps and afterwards, thermal images were taken to be compared to the images of the same cabinet without additional sealing. The whole test process will be broadly described in two parts representing the main thermal test phases:

8.2.1. General Thermal Images of the Whole Room

To conduct this test, all the devices inside the room were running on full load which provided a total consumption of 360 kW. The pump speed was set to 80% of the total power which is a high value. The fan speed of the coolers in the first & second rows was adjusted to 85% & 50% respectively. To evaluate the cold-air dissipation along the cold aisles (from the coolers to the cabinets), a few nets were mounted between them at the right angle to hold the tapes revealing the temperature.

According to the thermal images taken from different parts of the room and at different angles, there were certain areas experiencing higher temperatures. These areas include:

1. Area between the cable tray lids and the cold-aisle containment tiles.
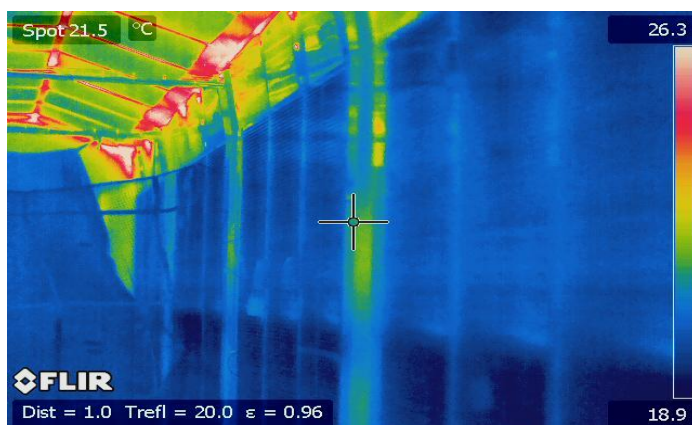
Figure 39: Thermal image of one of the cold aisles

As the image above demonstrates, this horizontal area along the top of the lids was experiencing a much higher temperature. (Upper left portion of the photo)

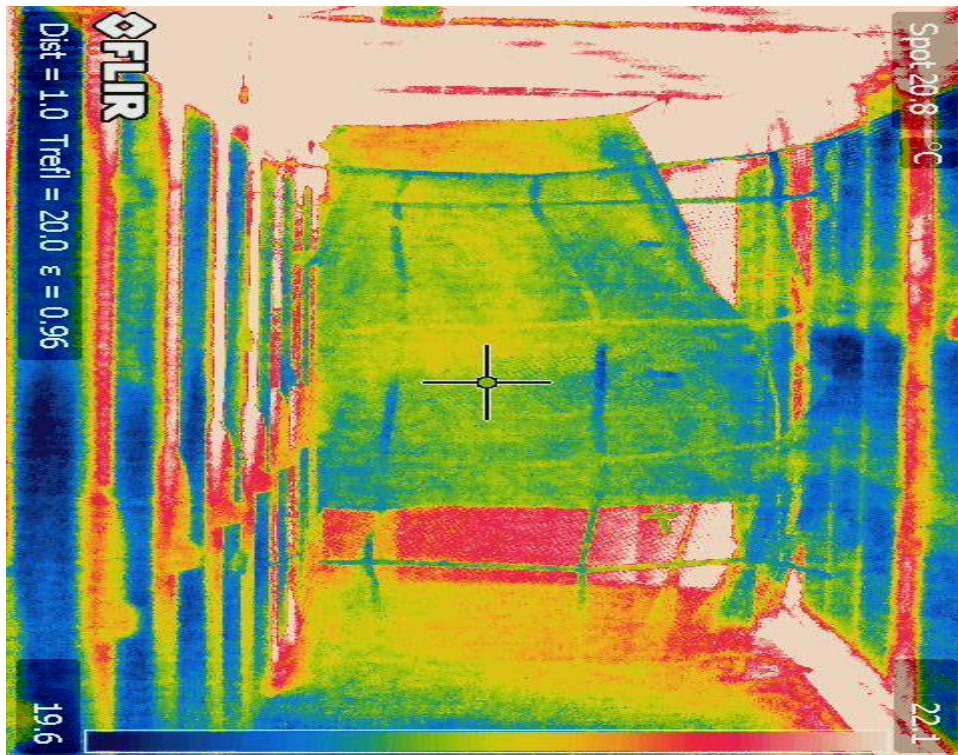2. Long gap between the body of the coolers and the floor

Figure 40: Thermal image of one of the cold aisles. The net hanging along the aisle between the parallel cooler and cabinet is conspicuous in this picture

According to the image, it is noticeable that the gap between the bottom of the SEE coolers and the floor was experiencing higher temperature compared to rest of the room (lower right portion of the image).

3. Steel-made frame of the containment holding the tiles
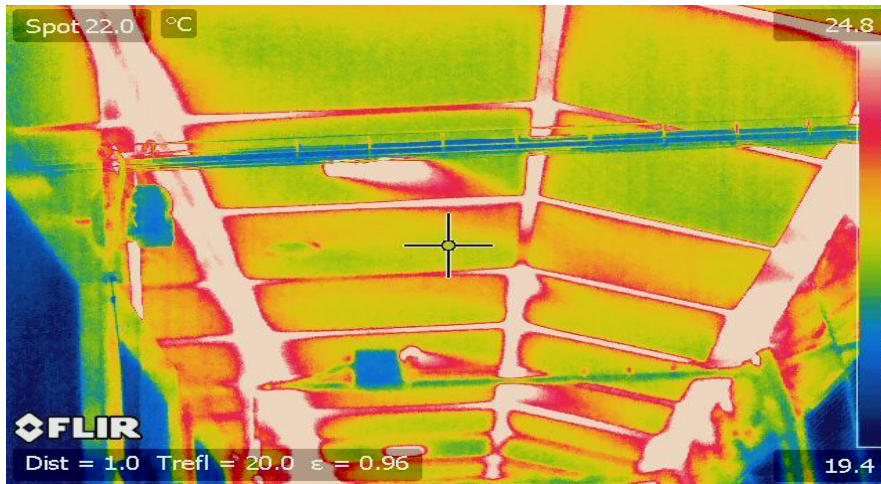
Figure 41: Thermal image of the ceiling in one of the cold aisles

The higher temperature experienced by the metal frame in the cold aisles is quite conspicuous in this image. This happened as the result of the heat leakage from the return air duct from the hot aisle to the SEE coolers.

4. Vertical gap between the adjacent coolers
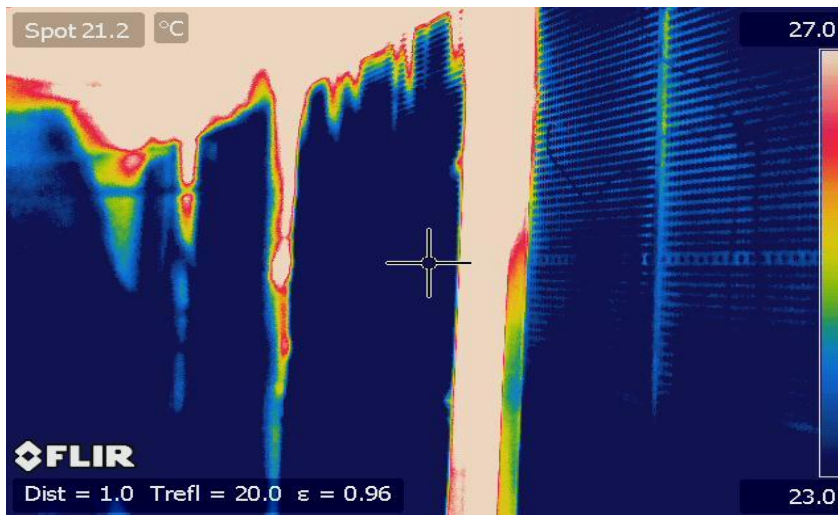
Figure 42: Thermal image of one of the cold aisles focusing on the gap between the adjacent SEE coolers

The vertical open area between adjacent SEE coolers was perceptibly obtaining more warmth than the coolers themselves. It is due to heat leakage from the hot return air coming out of the hot aisle.

5. Higher part of the cold aisles
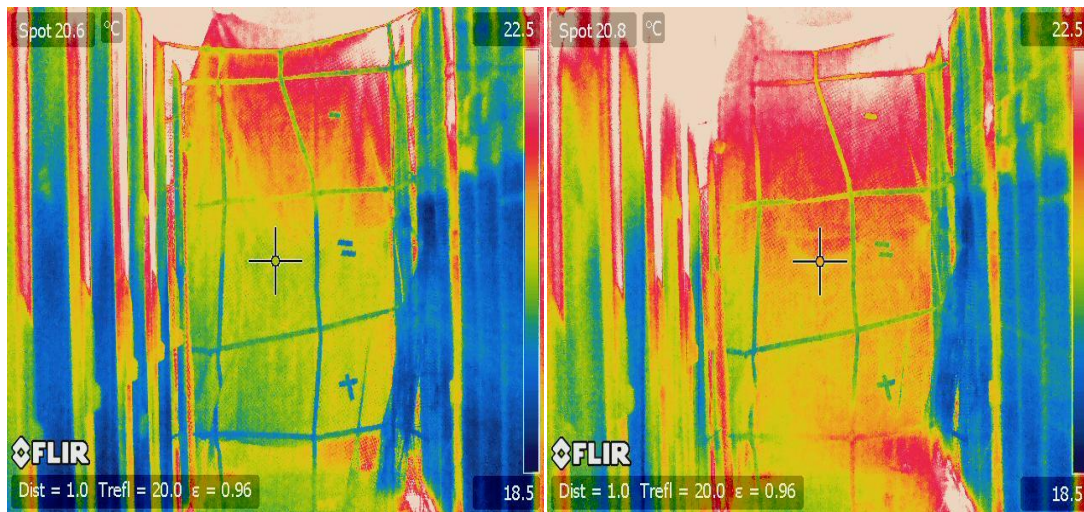
Figure 43: Thermal images of the 1ˢᵗ cold aisle captured at 2 different moments

As these two selected images display, generally the higher part of the cold aisle receives more warmth compared to the bottom. To be more specific, the net was perpendicularly mounted between one of the coolers and its opposite cabinet. To achieve the highest possible thermal accuracy, 5 horizontal and 2 vertical rows of tape were attached to this net at different distances. The surprising point is that the distribution of heat seemed to be uneven and hence unpredictable at the bottom of the net close to the floor. For instance, the first horizontal tape from the bottom in the left image is noticeably colder than in the right one. The second and third horizontally-mounted tapes are having almost the same temperature distribution in both images (tapes are slightly warmer in the right photo) while the two upper tapes have different Thermal conditions.

These two tapes are obviously warmer in the right image than in the left one. These thermal images approve that in certain circumstances, the bottom of the aisle might be the coolest part but there are some exceptions which it is warmer than the middle of the aisle.

8.2.2. Specific Images of one Cabinet Before & After the Sealing

After taking general thermal images, it was decided to seal one of the cabinets completely and observe the differences by taking thermal images of different parts of it. The sealing was carried out using different kinds of tape to cover both the front and back of this cabinet. The hypothesis was that "total isolation" would make a considerable difference making it worthy to do the same thing to all other cabinets in the room. Below, the thermal images of the cabinet without the additional sealing reveal some of the areas which suffered from heat leakages:

1. The narrow horizontal gap between the blind folds on both front and back of the cabinets
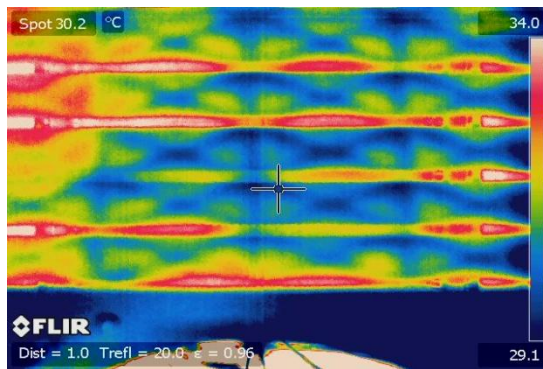

Figure 44: Thermal image of front of a cabinet focusing on the gaps between blind panels

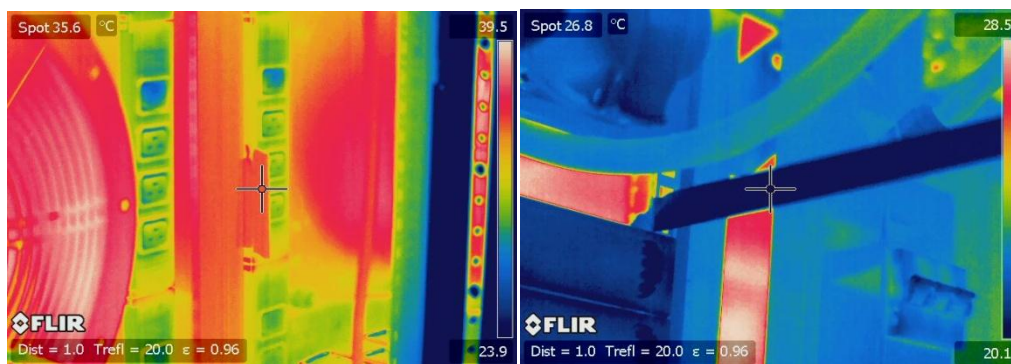2. The vertical gaps at both ends of the cabinet on the sides.

Figure 45: Thermal image of front of a cabinet focusing on the sides

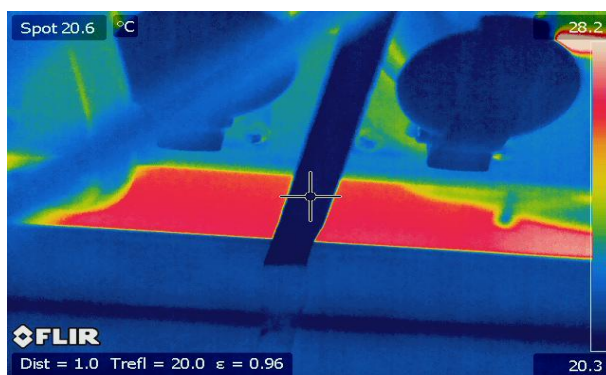3. The gap between the highest blind panel and the cable plug board.

Figure 46: Thermal image of top front of a cabinet

4. Inside the cabinets

As the image from the back of the cabinets in the hot aisle displays, one of the cabinets (the circled one in the image) is suffering from a high level of leakage. The reason for this is probably the mistakenly-left-lids on two sides the cabinet which caused a direction of cold air flow from the sides of the rack to the hot aisle. Moreover, more or less identical leakage behavior was observed above each heater (blue color above most of heaters in figure below). This can be due to a small gap above and between the heaters. The gap was too small to be covered with a blind panel which caused high cold air leakage toward the hot aisle (the side lids and all the gaps between the coolers were totally sealed after this test as shown in Figure 48).
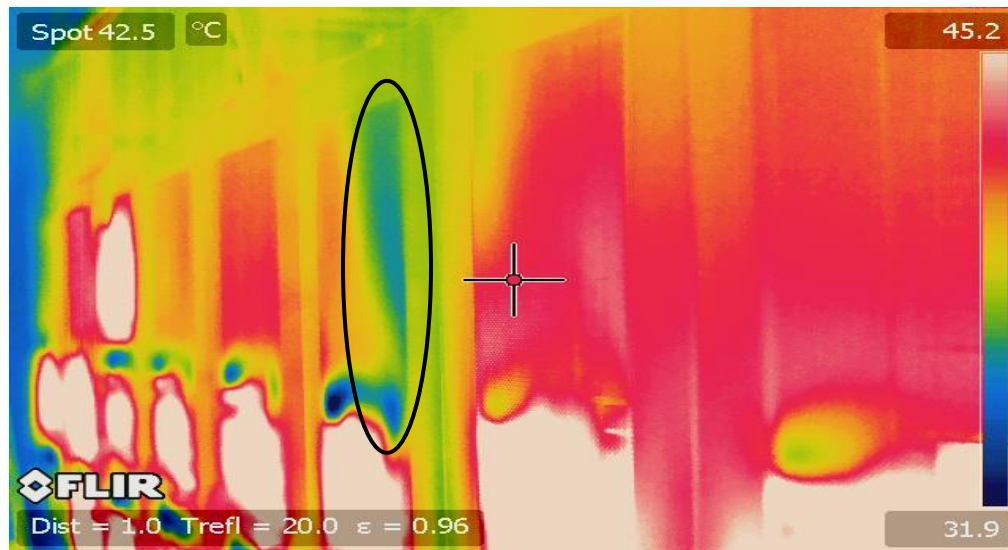

Figure 47: Thermal image of back of the cabinet row in the hot aisle

After Test 12 and based on the desirable result of sealing and proof of its noticeable effectiveness on the efficiency, it was decided to carry out what is referred to as "total isolation" described in part 6.3.2. All the areas sealed in this phase of the project were comprehensively discussed in part 6.3.2 and below, a couple of photos are selected to visualize this phase of the project:

Figure 48: Random pictures of the areas sealed up for "total isolation"

8.3. Analysis of "Temperature Rise" Tests

8.3.1. Introduction

As was briefly discussed in the introduction part of this chapter, these series of tests were carried out to evaluate the thermal tolerance of the dummy loads and also the exact time it takes to reach the highest safe temperature. To achieve this, all dummy loads were switched on while the whole cooling system including the pumps and SEE coolers was kept off.

Among these four thermal tests, two of them were conducted with the heaters running on 50% of the total load while the other two performed with heaters on full load. Basically, two types of graphs were provided to monitor the test and determine the critical points including the exact beginning time of the temperature rise & the maximum thermal capacity:

1.   Thermo-chronological graphs provided by Radio loggers
2.   Power-load graphs provided by Siemens™ "control system" software

In respect of the Thermo-chronological graphs, only one out of eight utilized groups of radio loggers have been used to demonstrate the conditions throughout the tests. Each of these groups includes several loggers which can be distinguished by different colors on the graphs. The process of each test and the way each graph was utilized to reach final conclusions will be thoroughly discussed in the following parts.

8.3.2. Tests with Lower Heaters' Fan Speed (Sealed)

Table 23: Room's power load and set values in Test 15 & 16

Test #	Room load (kW)	Pump speed (%)	Coolers row 1 fan speed (%)	Coolers row 2 fan speed (%)	Heaters fan speed (%)
15	340	0	0	0	48 - 58
16	160	0	0	0	48 - 58

The first two tests were conducted with setting the heaters' fan speed around 50% of the full rate which had been the average fan speed set for most of the previous tests. Test 15 was carried out with heaters running on the full load (340 kW). Test 16 was performed under the same conditions but with the heater half loaded (160 kW).

The first graph covers both tests chronically and provides a broad point of view on the critical moment during the tests. As it is quite conspicuous on the graph, the recorded maximum

temperature for the first test is slightly higher than the second test's. The obvious reason for this lies in the different power loads of the heaters. To specifically analyze each of these tests, they will be studied in separate parts.
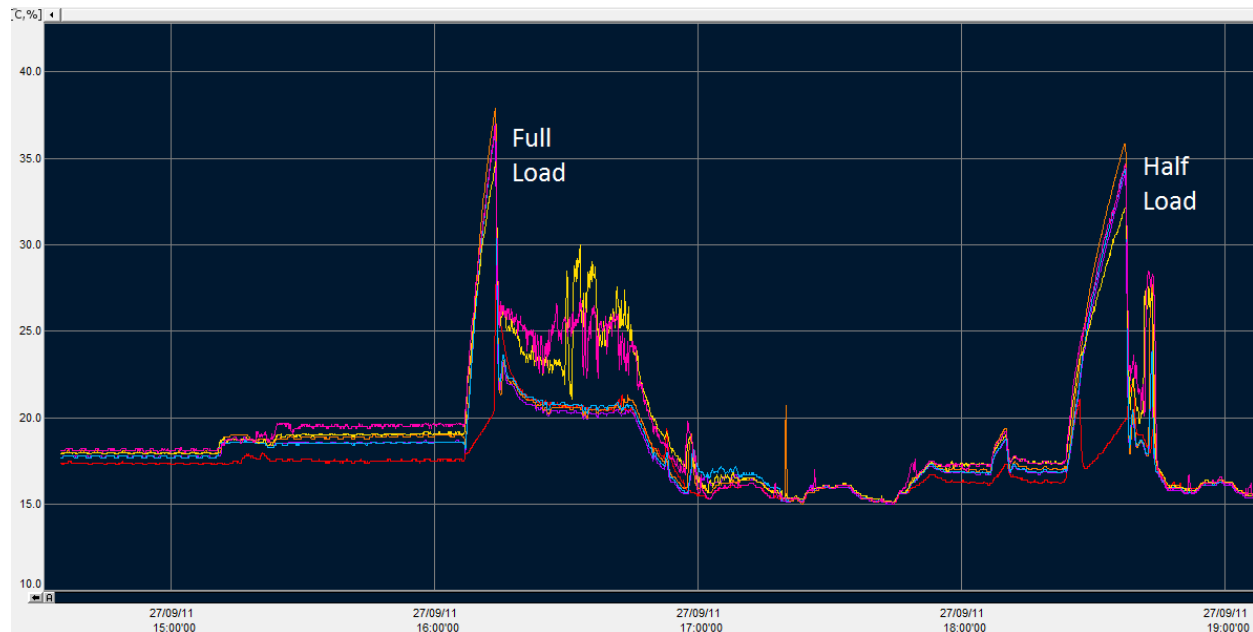

Figure 49: Thermal-chronological graph of "temperature rise" tests

8.3.2.1 Fully-loaded Heaters (Test 15)

As it is shown in Figure 50, two critical points (A & B) have been determined for this test. Point A is the exact time when the whole cooling system (including SEE coolers & pumps) is turned off and therefore, the temperature inside the room begins to rise gradually. This increase surge continues to point B which is the "Breakdown" point. At point B, the temperature in the racks increases to the point that triggers the clickers mounted inside the heaters.

As was touched upon before, the responsibility of clickers are to cut off the electricity supply to the heater's plates when reaching a certain temperature. Due to slight differences in installation of these clickers on different heaters, not all of them act at the same time. In other words, point B is the instant that the first clicker goes off, turns off one heater and consequently reduces the overall temperature of the room. After a while and gradually, more & more clickers go off and the total number of running heaters dramatically reduces and reaches zero in the end.

The significant value expected to be acquired as the result of the test was the exact length of A→B. In fact, this is the time which Green Room takes to reach a breakdown point in case of a total

cooling system collapse. According to Figure 50, it takes 7 minutes and 10 seconds from when the cooling system stops working to when the temperature reaches its maximum safe limit.
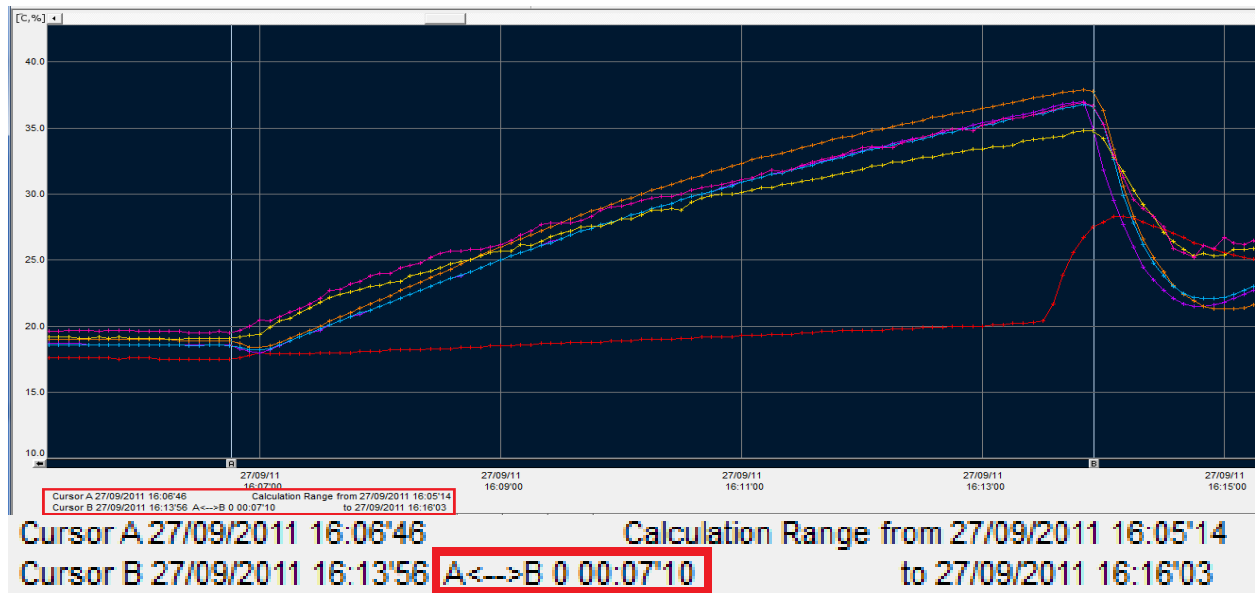

Figure 50: Thermal-chronological graph of Test 15

Figure 51 demonstrates the power load of the system chronologically and acknowledges the values extracted from the radio loggers. As it is noticeable on this graph, the total power load dramatically drops to less than 330 kW which is a sign of beginning of clicking.
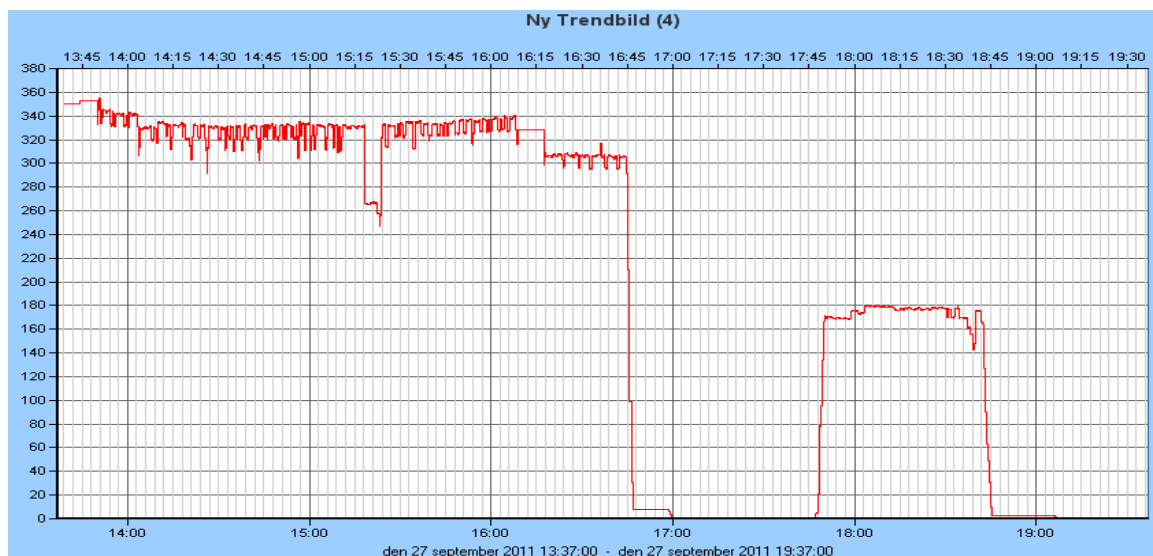
Figure 51: Power-chronological graph of Test 15

8.3.2.2. Half-loaded Heaters (Test 16)

Interpretation method of this test's graphs is completely as same as the previous one. As it was mentioned before, the only difference between this test and the previous one is the reduced total power load. (160 kW) Figure 52 displays the total temperature transmitted by radio loggers chronologically.
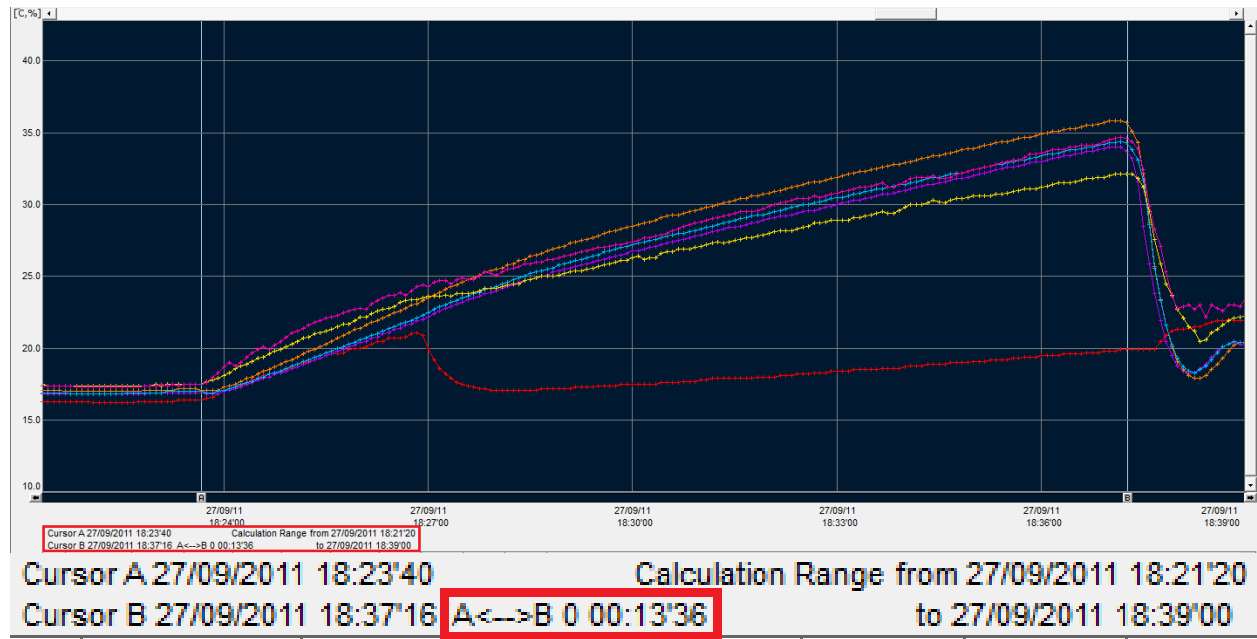

Figure 52: Thermal-chronological graph of Test 16

As the graph demonstrates, point B happens 13 minutes and 36 seconds after point A this time. The reason for a longer A→B compared to the previous test is that the heat generated in the room considerably less and therefore it takes a longer time to reach the maximum safe temperature and set off the clickers. Surprisingly, a 50% reduction in power load resulted in a 47% increase $(\frac{(816\ secs - 430\ secs)}{816\ secs} \times 100 = 0.473)$ in the length of A→B.

This shows an extremely high linearity rate between "Power Load Reduction" & "Thermal Tolerance Length" in Green Room.

Rate of Linearity = $(1 - \frac{(50 - 47)}{50}) = 0.94$

This linearity rate is very close to the ideal and it shows that if the heaters' load is doubled, the length of rescue time for Green Room will be reduced to half. This rate provides an interesting insight to how to design the automatic safety system regarding the available time.

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8.3.3. Tests with Higher Heaters' Fan Speed (Unsealed)

Table 24: Room's power load and set values in Test 23 & 24

Test #	Room Load (kW)	Pump Speed (%)	Coolers Row 1 Fan speed (%)	Coolers Row 2 Fan speed (%)	Heaters Fan Speed (%)
23	320	0	0	0	67
24	160	0	0	0	67

The second group of tests was conducted a few days later and it was decided to increase the fan speed to 67% of the total for all of the heaters. Similarly, the first test was carried out with the full power load (320 kW) & the second one was conducted with half power load (160 kW).
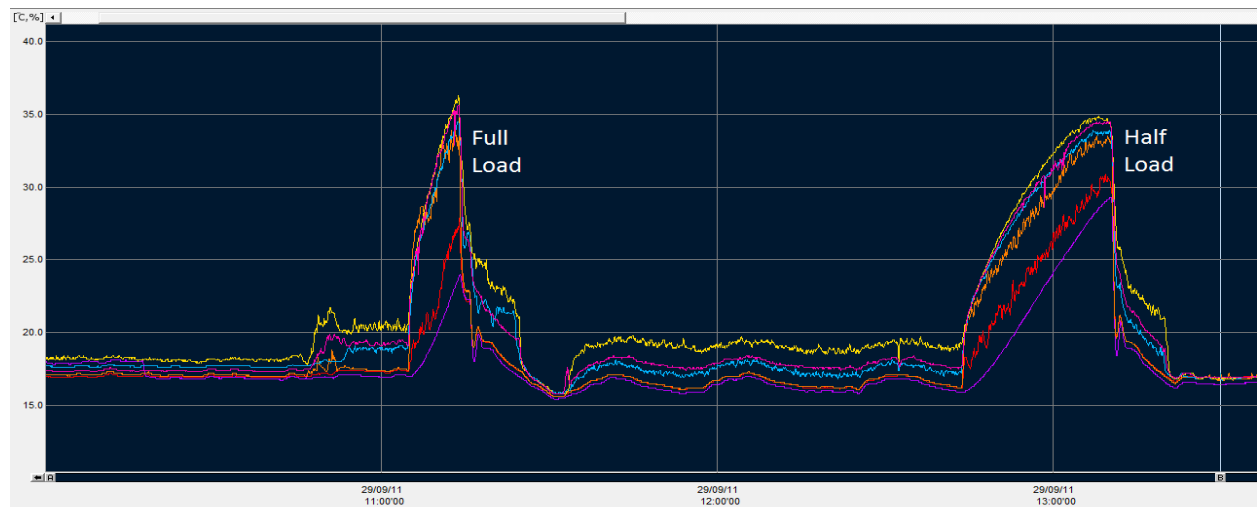

Figure 53: Continuous thermal-chronological graph of Tests 23 & 24

8.3.3.1. Fully-loaded Heaters (Test 23)

This test was carried out while the heaters were running at full load creating a total of 320 kW. Just like previous tests, points A & B were recorded using the online logging graphs based on the transmitted data by the radio loggers. The reliability of these critical points is approved by the "Total Power Load" graph shown right after the first one. According to these the first graph, the exact length of A→B for this test is 9 minutes and 10 seconds.

Compared to Test 16 & thanks to the increase in the fans' speed, length of A→B is extended exactly by 2 more minutes. Since the fan speed for heaters in Test 16 was not quite the same, it is

impossible to determine exactly how much the fan speed was increased in Test 23 but generally, 9-19% of increase in fan speed of the heaters resulted in 28% of increase in length of A→B.
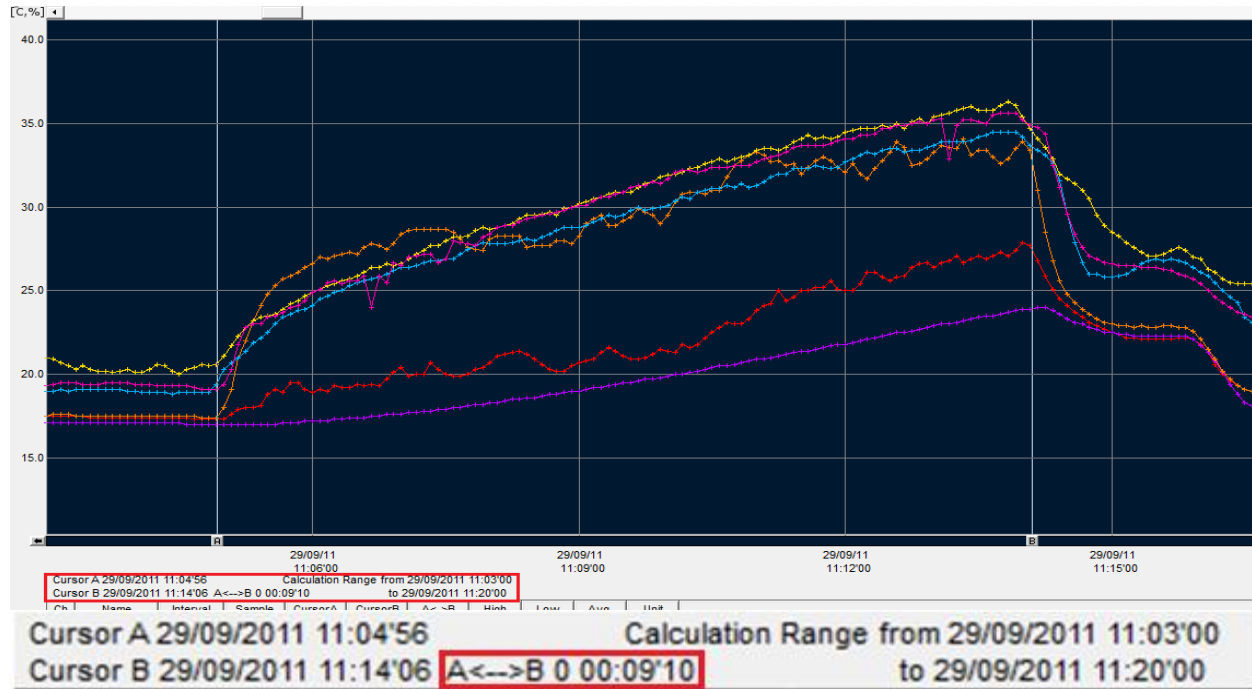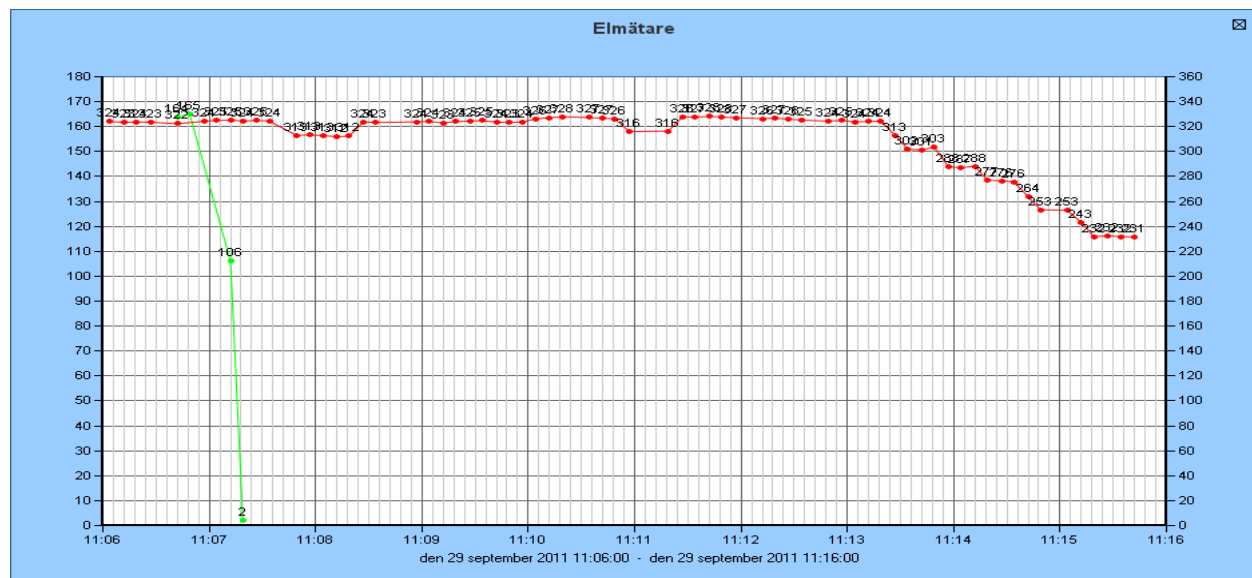

Figure 54: Thermal-chronological graph of Test 23

Figure 55: Power-chronological graph of Test 23

8.3.3.2. Half-loaded Heaters (Test 24)

Test 24 was carried out under the same conditions as Test 23 while the total power load of the heaters was reduced to half (160 kW). It is crystal clear that this reduction led to a much longer A→B which is 26 minutes and 42 seconds for this test.
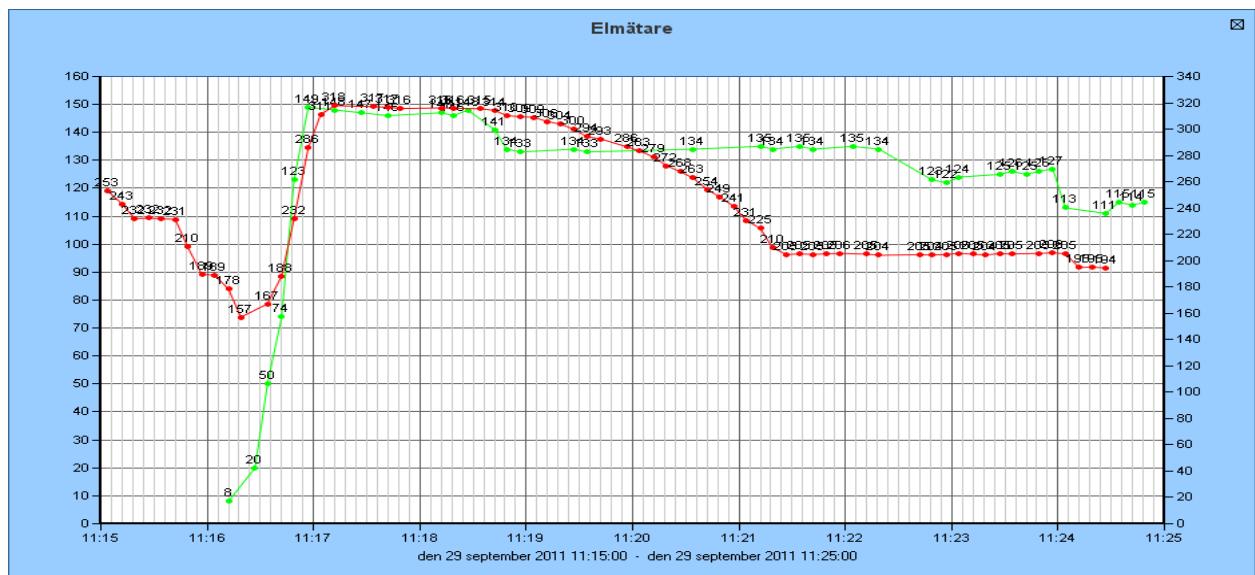

Figure 56: Thermal-chronological graph of Test 24

Figure 57: Power-chronological graph of Test 24

Surprisingly, a 50% reduction in power load resulted in a 47% increase $(\frac{(1602\ secs - 550\ secs)}{1602\ secs} \times 100 = 0.657)$ in the length of A→B.

This shows 76% rate of linearity between "Power Load Reduction" & "Thermal Tolerance Length" in Green Room which is considerably lower than the same value resulted from the tests with lower fan speed for heaters.

Rate of Linearity $= (1 - \frac{(66 - 50)}{66}) = 0.76$

8.3.4. Conclusions

Theoretically, it is necessary to conduct more tests at different fan speeds & power loads to get close to a reliable conclusion but based on the limited number of tests carried out, it can be concluded that:

1. It is likely that by increasing the fan speed of the heaters, the effectiveness of the fans to cool down the room and consequently lengthening A→B will decrease.
2. The less the power load of the heaters, the less heat they generate and therefore, the longer A→B will be.
3. While the room is unsealed, the exhaust air has the chance to partially escape from the room and therefore, it takes a considerably longer time to reach the maximum temperature.

8.4. Analysis of Containment Effect Testing

8.4.1. Introduction

One of the determining factors affecting the efficiency of Green Room's cooling system is the sealing conditions. In Chapter 6.3.2, it was discussed that theoretically, a perfect sealing condition is likely to deliver the highest efficiency by minimizing the unwanted air flow mixtures and undesirable leakages. To prove this hypothesis in practice, a couple of tests were conducted with the aim of changing the different insulation components of the room's sealing step by step.

The removable covering parts in the system include:

1. Cable tray lids over the cabinets (In cold aisles)
2. Cable tray lids over the cabinets (In hot aisle)
3. Wall coverings between the SEE coolers
4. Wall coverings under the SEE coolers
5. Wall covering plates above the SEE coolers

8.4.2. Comprehensive Description of Removal Process

The sealing removal process was performed in three general phases each associated with at least one complete test. In the beginning, Test 17 was carried out by placing the Radio loggers in hot aisle and both cold aisles. The detailed explanation on position of radio loggers for this group of tests has been already visualized in part 8.1.3.1. In actual fact, Test 17 served as the primary test with primary sealing conditions which all the coverings were in place without any intervention.

Test 17 was carried out as usual and the results were recorded. Images below illustrate the initial sealing conditions inside and outside the Room which this test was performed under.

Figure 58: Initial sealing conditions inside the room

Figure 59: Initial sealing conditions outside the room

In the next phase, the steel-made lids covering the cable trays were removed in all aisles. In fact, the intention of this phase was to determine the effectiveness of covering the gap between the top of the cabinets and the ceiling. By doing so, fluids from hot aisle and cold will get together through this passage above the cabinets and therefore hot air is allowed to mix with the cold one highly reducing the efficiency of the system. Only one test (Number 18) was performed under these conditions and the necessary data was acquired.
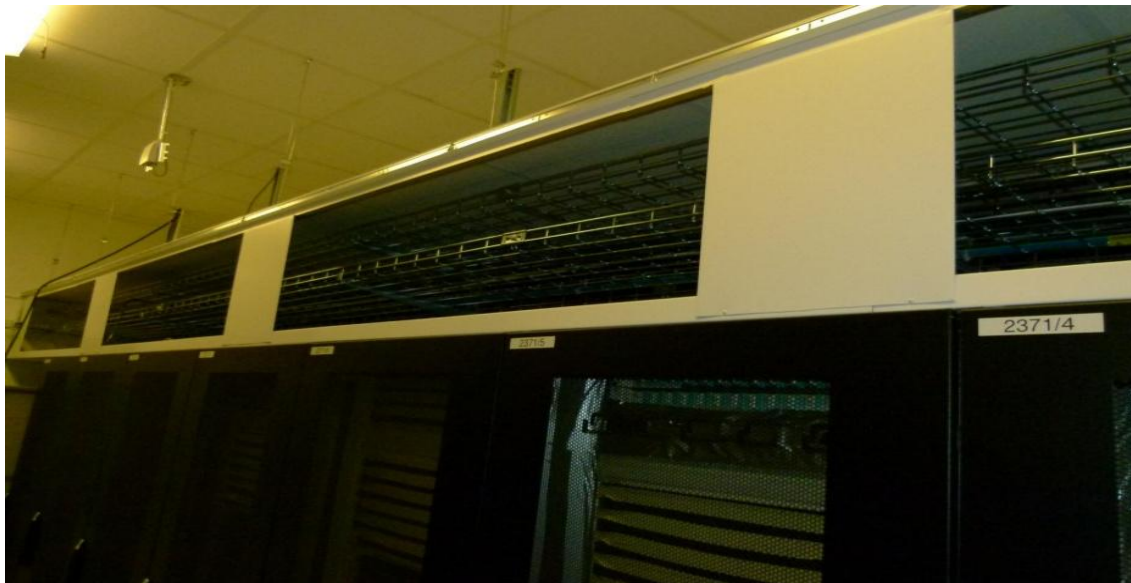

Figure 60: Naked cable tray after removal of steel-made lids over the cabinets

This group of tests proceeded with the next phases of sealing removal which is associated with Test 19. In this test, all the paper covering used under and between the SEE coolers in both rows were removed. These covering served the room as the outer walls and removing them meant direct uninterrupted contact between the air flow inside the Green Room and the surrounding air outside of it. Note that the plates removed at the previous test were put back again in order to study only the effect of mixture with the outer environment, and not with both cold and hot fluid together as in the previous test.

Figure 61: Back of SEE coolers after removal of paper-made covers from beneath and between them. (Picture was taken from outside of the room)

In the final phase of this group of tests, the remaining covering plates above the SEE coolers which were basically functioning as the upper parts of the outer walls were removed. As a result, it was expected to experience a lower efficiency compared to the previous test as a result of a high mixture between the return hot and surrounding cold air, which will also exchange heat with the cold aisle through the gaps in between and under the coolers. Three tests were performed in these conditions, Tests 20, 21 and 22. The difference between them was the coolers' fan speed in row 1 in order to see how much it can affect fluid mixing and cabinet's inlet temperature (refer to Table 6).

Figure 62: Back of SEE coolers after removal of all covers surrounding them

8.4.3 Results and Analysis

In order to study the effect of a properly-sealed room versus a poor one, once again the temperature difference between coolers outlet and cabinets inlet are found and studied using radio loggers (refer to Chapter 8.1.3.1). But more, due to the fact that while unsealing fluid mixing with environment is allowed at different positions of the room, a more precise view is by finding temperature difference between coolers at different vertical positions of the cabinets in the room (refer to Figures 34 and 37).

The results obtained are illustrated in the following table,

Table 25: Temperature difference at different vertical positions between coolers and cabinets

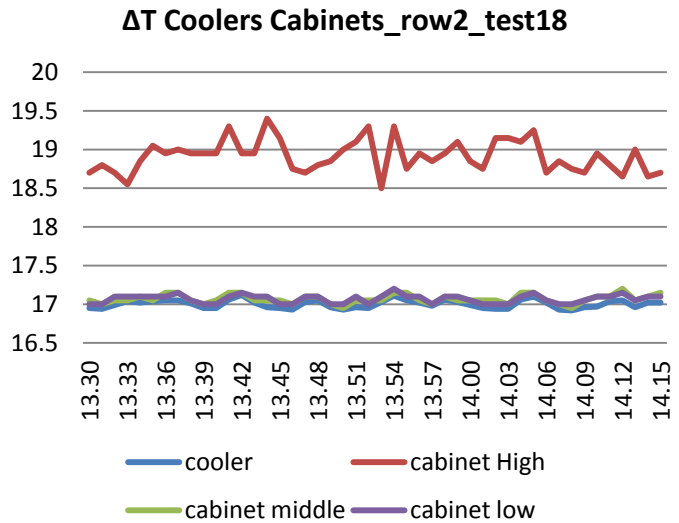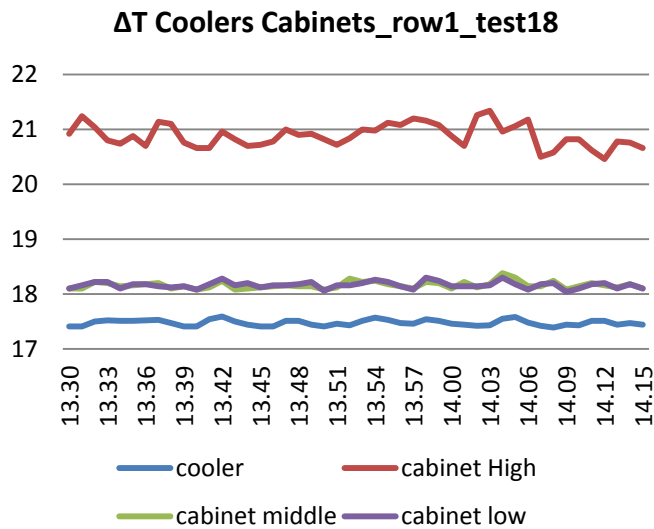| Test #	Row 1 (CKA-CKE)				Row 2 (CKF-CKJ)			
	ΔT High	ΔT Middle	ΔT Low	ΔT Average	ΔT High	ΔT Middle	ΔT Low	ΔT Average
17	0.135	0.297	0.433	0.288	0.164	0.076	0.115	0.118
18	3.412	0.687	0.689	1.596	1.914	0.067	0.067	0.683
19	0.359	0.829	1.101	0.763	0.820	0.080	0.110	0.337
20	0.742	1.010	1.299	1.017	1.006	0.061	0.091	0.386
21	0.935	1.129	1.463	1.176	1.164	0.045	0.135	0.448
22	0.632	1.128	0.941	0.900	3.410	0.010	0.146	1.189

Figure 63: Temperature difference charts of coolers and cabinet's different position, Test 18, both rows

Removing the plates above the cabinet in Test 18 made an air passage mixture between the air from the hot aisle and the one from the cold aisle, affecting most the top position of the cabinets. This is clearly seen in the above charts of Test 18 where the temperature difference between coolers and high position of the cabinets is around 3.4 °C, and only 0.7 °C for the middle and lower position considering row 1.
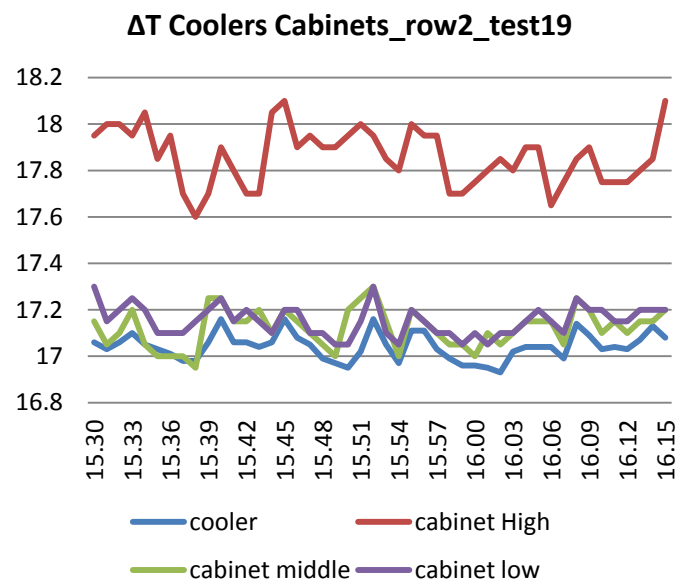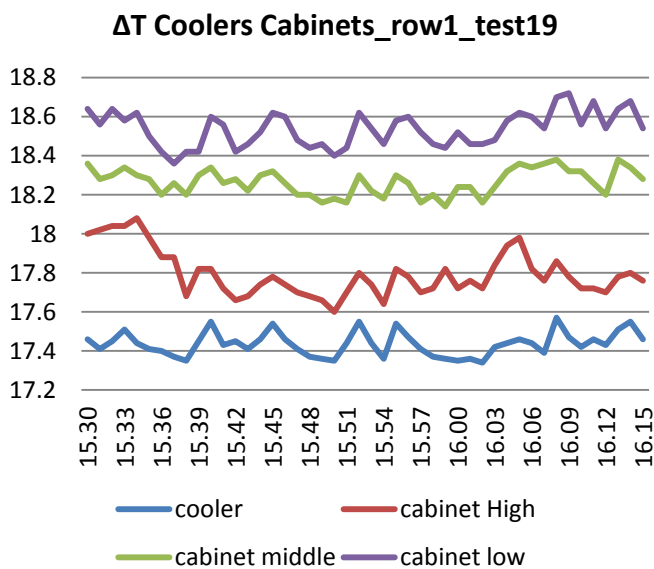

Figure 64: Temperature difference charts of coolers and cabinet's different position, Test 19, both rows

Removing covers in between and under coolers in Test 19 has caused mixing between cold aisle air and the surrounding air from outside the room. This mixing was done from all directions (air penetration between coolers) but larger mixing was done in the lower position of the room (air penetration under coolers). This is clearly seen in the above chart for Test 19, row 1, where the maximum temperature difference is between coolers and cabinet low position (1.1 °C), followed by the one between coolers and cabinet middle position (0.83 °C) and therefore the minimum difference is between the coolers and the cabinet high position (0.36 °C).

It is obvious as well from the charts of Test 19 that what was just explained doesn't apply for row 2. This is estimated to be caused by the fact that row 2 has a much lower coolers fan percentage speed (45%) than row 1 (90%). Therefore, fluid is in row 2 is much better mixed and hot fluid mixture has enough time to rise upwards while its way to reach the cabinets, and therefore cold fluid drop downwards (cold fluid has higher density then hot fluid). This explains the high temperature difference between coolers and cabinet's high position, and the very low difference for the middle and low position (around 0.1 °C).
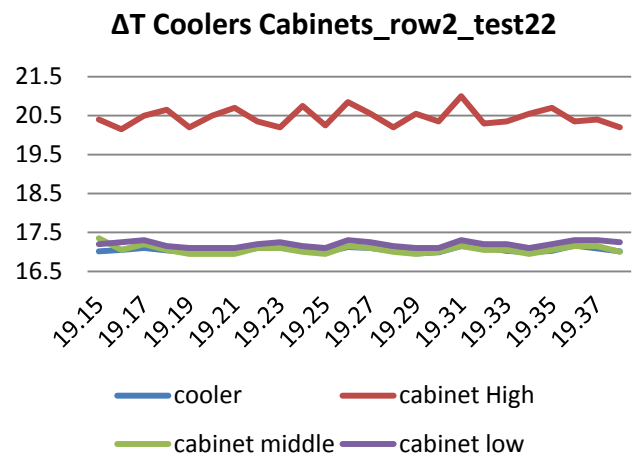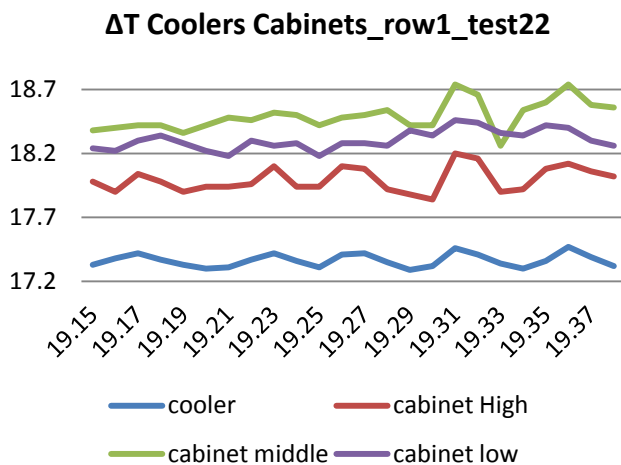
ΔT Coolers Cabinets_row1_test20

ΔT Coolers Cabinets_row2_test20

ΔT Coolers Cabinets_row1_test21

ΔT Coolers Cabinets_row2_test21

ΔT Coolers Cabinets_row1_test22
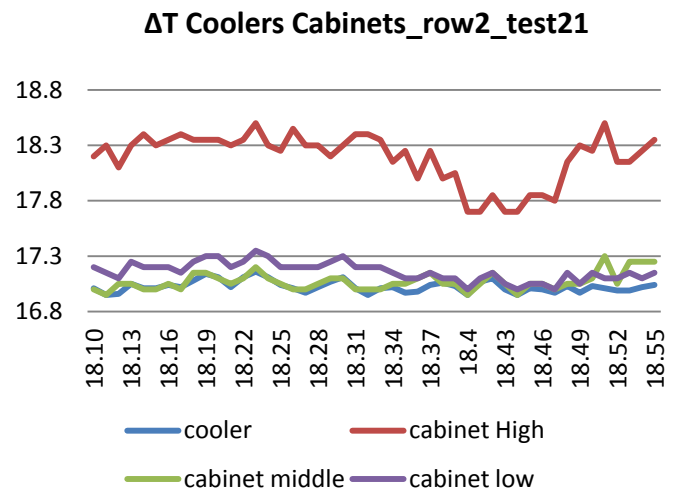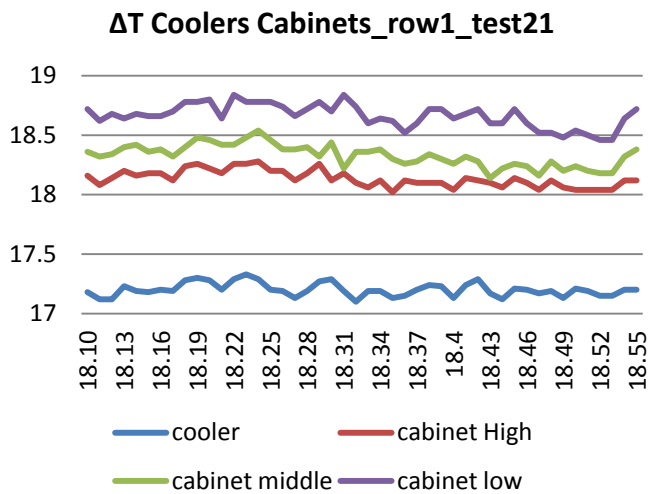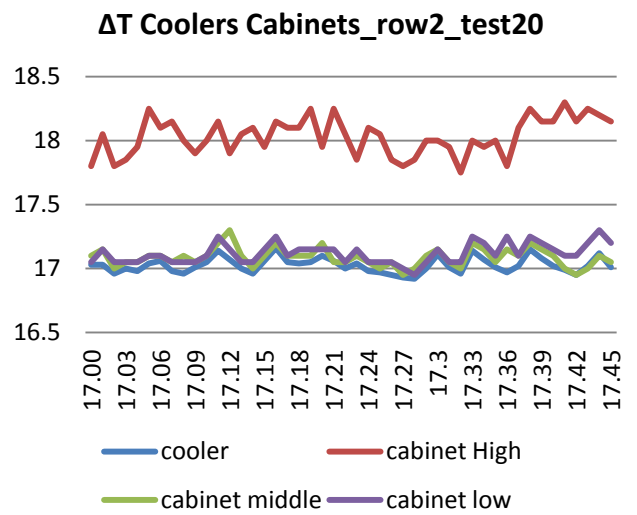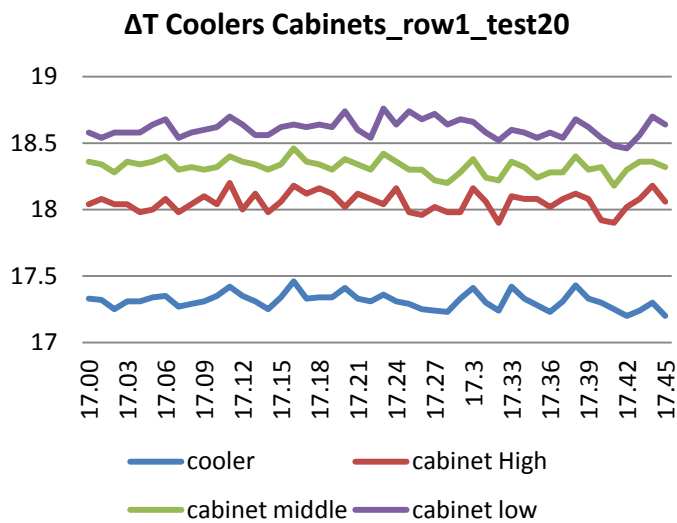
ΔT Coolers Cabinets_row2_test22

Figure 65: Temperature difference charts of coolers and cabinet's different position, Tests 20, 21, 22, both rows

In Tests 20 to 22, the same scenario as Test 19 has repeated itself but with slightly higher temperature difference. This is because the surrounding air exchanges heat with the hot return air and the cold aisle at the same time. It therefore acts as a heat carrier from the hot aisle to the cold aisle. Same scenario is also noticed in row 2 of each test since the coolers fan speed remained unchanged.

Referring to Tables 7 and 25, and looking at row 1 of each test, it is also concluded a higher coolers fan speed will results in a less heat transfer rate between cold air and surrounding outlet air which results in an average lower temperature difference between coolers and cabinets. Test 22 has the lowest of these 3 tests with an average temperature difference of 0.9 °C and coolers fans speed of 92%.

For a complete time base data and additional charts, please refer to appendix II.

As a general conclusion, even though it is shown that a completely covered or sealed green room is much better than an unsealed one in both symmetry and value; it is also noticed referring to Table 15 and Figure 38 that an unsealed green room is still much better than a common raised floor cooled room.

9. Conclusions

The main purpose of this paper has been to describe all different phases of this project, obtaining the results and analysis them to approve (or reject) the hypothesis explained in the first chapter. In addition, it was crucial to stress on the importance of an efficient cooling technology for data centers from different perspectives. Different categories of tests with different purposes were carried out but the main aim of most of them was to examine the efficiency of the system through performing COP and PUE calculations.

In addition, another group of tests was conducted to determine the characteristics of the air flow inside the room and locate the leakage areas and hot spots (Using infrared images). "Temperature rise" tests were carried out to determine how long it takes the room's temperature to exceed the safe level and other group of tests provided valuable data regarding the effectiveness of a complete sealing inside the room versus un-sealed condition. In many occasions, the results were compared with available data acquired from other cooling solutions in the market.

As a result, it is expected that readers can easily compare TeliaSonera's Green Room with other cooling systems in the market and judge the results. The Green Room was proven to have many advantages which have helped it to outpace many of its market rivals in terms of efficiency. For instance, COP estimated in this paper can rise to 28 if the Green Room concept is combined with geothermal cooling production. In one word, the hypothesis of "Green Room: a highly-efficient cooling system for data centers" has been approved based on the observations, calculations, analysis and a degree of estimations.

The advantages of the Green Room concept over many of its rival approaches in the market are effective aisle sealing, lack of a raised floor, fluid-mix prevention, distinctive layout of SEE coolers inside the room, efficient cable management and finally, considerably lower power consumption of SEE coolers thanks to their effectual design.

Although the technology described in this paper is still recent and results are highly satisfactory, it still can be expected that the Green Room including real devices instead of dummy loads will be different. As was described in the paper, the way the dummy loads were allocated to the cabinets was close to a symmetrical pattern. In the real world, it is not always possible to mount the devices inside the cabinets in the way that a symmetrical power load or air flow is achieved. Due to technical restrictions, companies are often obligated to place similar devices (Based on functionality or power requirements) close to each other which makes it hard to achieve an even air flow distribution inside the datacenter.

One of the main advantages of the Green Room over typical raised floor approach is that the flow rate of each SEE cooler can be controlled and desirably manipulated. This feature is advantageous because a higher air flow rate can be directed towards high-heat-dissipating equipment in the racks.

In fact, different equipment with different cooling needs have the chance to receive appropriate levels of air flow rather than being delivered equal amounts of fresh air.

A couple of recommendations have been made in order to improve the Green Room approach and boost its efficiency and they are included in the next chapter. Other important issue to be considered by cooling-system developers is that even if the same conventional chiller-based approach is adopted for the cooling production, Green Room still achieves a far better COP than a raised-floor-based cooling system using chillers. According to the calculation, COP of "Green Room backed up by chiller-based cooling production" is almost twice as large as an "Entirely chiller-based cooling system". This simply means that Green Room technology is likely to have an operational cost of at most half of the conventional systems in the market in terms of energy consumption for cooling purposes.

This difference will become larger if sustainable technologies like free- or geothermal-cooling are employed as the cooling production. By today's standards, the Green Room is both an economical and environmentally-friendly technology and this remark is backed up by sufficient scientific evidence provided in this paper.

10. Recommendations & Future Tasks

In this chapter, a list of the areas which need to be further investigated or improved has been provided. It should not be neglected that an ambitious approach like this always has the potential to be tested with more diverse variables to reach a higher certainty for the ultimate conclusions. As it was discussed before, other studies must be carried out to reach a wider range of calculated values and even more precise conclusions.

1. Detailed heat transfer calculations associated with flow rate calculation of air through the cabinets. Flow rate calculation inside the cabinets is important in order to make sure that the air flow absorbed by the computers inside the racks is slightly higher than the air flow provided by the coolers. This is necessary to make sure that the room runs in under-pressure conditions resulting in reduction of any form of air recirculation, which will decrease the total efficiency of the system. Therefore, there is a need to study the best way to calculate this flow rate; more measurement on site tests can be needed to be done.

2. Based on the analysis done in Chapters 8.1.1 and 8.1.2, it is concluded that more studies should be done in order to identify the minimum allowed pump speed used in the pump rack rooms. In addition, the efficiency of the current heat exchanger used in the pump racks need to be studied an improved to discover the optimal values leading to a better heat transfer.

3. Determine the exact maximum temperature of coolers' outlet air allowed (is it 27 °C? can it be more?). This value is dependent of the maximum inlet temperature allowed for the computers and servers to be cooled down. Moreover, after calculating this value, the maximum thermal value for main coolant fluid used to supply cooling for the SEE coolers can be also determined. Afterwards, it will be possible to calculate the maximum outdoor temperature at which free cooling becomes a feasible option. This eventually allows a better "free cooling" throughout the year or at least less cooling production for locations with warmer climate. Ultimately, this will gradually increase the efficiency of the whole system and reduces the cooling cost subsequently.

4. More research should be conducted in order to predict minimum power loss inside UPSs, Switchboards and etc value. It is necessary to find the lowest possible value especially while building a new data center because this value affects the PUE of the data center. The more the losses, the higher the PUE and the lower the efficiency of the system.

5. It is needed to conduct more temperature measurement studies (especially in the hot aisle) while the room is operating with real devices. For this purpose, it is recommended to use a highly sensitive infrared camera device similar to the one used in the Analysis of Flow leakage & Temperature Distribution Tests. Using the infrared camera, studies will be carried out in the cold aisles as well as in the hot one. Since in this project all dummy loads were identical and only 2 real servers were used, there is still more to be studied.

In real operation, infrared pictures in hot aisle (such as Figure 47) are not expected to be that homogeneous simply because some servers will be hotter in the outlet and it might be needed to increase the cooling supply. In order to be more efficient, studies can be conducted to see if higher amount of cold air can be diverged towards that particular sensor, keeping the overall cooling supply inside the room constant. The other problem likely to occur and needs to be investigated is that devices start stealing the fresh air from each other leading to a more dramatically uneven distribution of air and formation of hot spots.

6. It is believed that free cooling at the Test Site in winter should have provided even better values in COP and PUE calculations made. As a result, free cooling system at this site should be carefully studied and if possible, optimized. The purpose is not to reach lower figures but rather to optimize the system and push it to its limit and determine how much energy it is capable of saving. This can enormously increase the efficiency and lower the cost.

7. To conduct a precise study of Geothermal cooling system including the cooling production calculations and determining the advantages, drawbacks, suitable conditions and restrictions of using it. It is also necessary to study the universality of geothermal cooling system and feasibility of its establishment in different geographical locations both inside Sweden and around the globe. Finally, it should be compared with all other available efficient technologies in the market.

8. To carry out a detailed financial study including investment cost, return on investment and money saved per year for investing on the best possible cooling technology for chosen sites. For example, if it is found that both geothermal and free cooling are available for a specified site, a financial study will be of great importance to determine which one to choose. The final decision must take into account that although geothermal technology is the costliest in terms of initial cost but instead, it is a very efficient solution compared to a chiller-based system.

9. A thorough study needs to be conducted in order to determine exactly how much electricity will be saved after applying the Green Room technology in a certain TeliaSonera site. Based on the results, it will be possible to precisely determine the amount of carbon dioxide saved from emitting per year.

10. It seems to be economically profitable to sell the excess heat from data centers enjoying the Green Room approach to neighboring residential areas or a district heating system if possible. The feasibility of selling the heat to another facility or utilizing it for domestic heating purposes hugely varies depending on the location of the data center. However, there are data center facilities utilizing an advanced mechanism in which they can choose whether to use this excess heat for their own offices or feed it to the district heating network as energy input.

Although practice of selling heating energy or trading it with cooling energy is not dependant on the internal cooling system approach, it is certainly worthy to be considered as an option to save operational costs for facilities utilizing Green Room in the future.

11. To improve the design of some components of the room. For instance, the cable-tray lids over the cabinets can be designed in a way that provides both a great insulation and fine accessibility. The tiles used in the ceiling can become more resistant to over pressure by adding additional weight over them or fixing them in place.

12. During the tests, it was noticed that the cabinets were suffering from numerous leakages due to its poor design. The design was so inefficient that air was easily allowed to re-circulate between the edges and blinds inside the racks. This became clearly noticeable in the infrared images captured in Test 12 (Figures 44, 45 and 46) and afterwards it was decided to manually tape up all air leakage passages especially inside the racks (Figure 48). Therefore, it is crucial to search for best available racks in the market enjoying an appropriate design guarantying minimum leakage. It is also needed to conduct a study on how much the design of the cabinets effect the total efficiency of the system.

13. It is important to remember that this project is considered as a High-Density Green Room with up to 350 kW of power load. TeliaSonera has serious plans to adopt the same approach for its mid- and low-density data centers too. The design of the room as well as the layout of quantity of SEE coolers for such data centers are different from this project. Similar studies should be carried out to study different aspects of Green Room approach for mid- and low-density data centers.

11. Glossary

AHU……………………………………Air-handling unit for cooling and HVAC systems

Cooling ton……………………………..12,000 BTU to cool 1 ton of air

Economizer…………………………….Cooling device that utilizes outside cool air for cooling

PCFE………………………………..Power, cooling, floor space, and environment

Precision cooling……………………….Pinpointing cooling closest to heat sources for efficiency

Raised floor…………………………….Elevated floor with cabling located under the floor

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