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Executive Summary

Energy-efficient high performance computing extends beyond the use of energy-efficient low power processing hardware. With increasing variations in the power consumption depending on the workload of a high performance computing system, modern supercomputers need tighter integration with their surrounding data center infrastructure than ever before, causing new challenges for the design and operation of data centers and systems.

Main aspects covered in this document are the power supply chain and the cooling system of the data center and the supercomputer. Regarding the powering of the data center, the main goal for energy efficient operation is to avoid unnecessary conversion steps as they are inherently causing electrical losses, thus reducing overall energy efficiency. Also, the use of uninterruptible power supplies should be avoided if availability is only a minor concern like in most typical high performance computing systems. In the system itself, power saving features such as voltage and frequency scaling and power gating should be used to tune the system hardware according to the scientific workload’s needs.

With respect to cooling, water instead of air is becoming a increasingly accepted cooling medium for data centers. However, in a prototype like the Mont-Blanc system using air cooling can still be a viable option if its drawbacks are mitigated by using rear door heat exchangers in the racks.

Finally, optimized operation despite the increase in complexity of modern high performance systems and data centers can only be achieved by thorough and integrated monitoring of all parameters in the power supply chain, the cooling system and the IT system. In particular, per-node power monitoring should be implemented in order to enable energy based accounting on a per-job basis.
1 Introduction

One of the main motivations behind the Mont-Blanc project is to improve the energy efficiency of today’s high performance computing systems in order to overcome the imminent power consumption hurdles on the way to Exascale computing. For this, the Mont-Blanc project proposes novel approaches primarily in the area of system hardware by using mobile and embedded technology which is known to be designed for highest energy efficiency needs in order to maximize battery lifetime. The use of such energy saving hardware components is fundamental to an energy efficient HPC system. Yet, efficient operation of supercomputers extends beyond the system hardware into the areas of system software, the building infrastructure surrounding the HPC system and even the scientific applications themselves. In order to achieve significant improvements in the system’s energy efficiency, the actions taken in each of the mentioned areas need to be evaluated both individually as well as jointly. As supercomputers and data centers are getting extremely complex systems, only proper insight into the HPC system and its surrounding infrastructures during operation will highlight potential knobs where adjustments of operational parameters can lead to significant increases in performance or reduction of power consumption of the current system. Also, this knowledge should be used to identify further options for improving the design in future systems.

In this document, we will discuss the state of the art in powering and cooling of high performance computing systems, focusing on the details that need special attention during design as well as the points in the system where system monitoring should take place in order to optimize the system’s operational parameters during runtime. The two main topics, namely “power” and “cooling”, will be discussed at system hardware, system software and building infrastructure level. Where applicable, the related design decisions that have been made for the Mont-Blanc system will be explained in further detail or recommendations for the operation of the system will be given.
2 Power Aspects

Despite remarkable improvements in their energy efficiency, high performance computers are consuming significant amounts of electricity. Thus, powering data centers and the contained hardware has to be subject to major planning as different options exist for the building infrastructure and the IT equipment that are dependent on each other. Thus, in this section, we discuss the building infrastructure aspects, IT system aspects and recommend monitoring for optimizing the power supply chain.

2.1 Infrastructure

Generation, transmission, distribution and conversion of electrical power always cause unwanted losses of energy. According to a publication of the U.S. Department of Energy’s “Data Center Energy Efficiency Program”, out of 100 units of a fossil energy source only 35 units remain as electrical energy after power generation. As two more units vanish on the way through the power grid due to transformation and line losses, only 33 units are delivered to the data center [Sch09].

Then, inside the data center itself, not all electrical energy is delivered to the servers, but a large part is spent on the cooling infrastructure, and further losses occur during transformation and within uninterruptible power supply units. Since in some data centers, the cooling infrastructure is still responsible for almost half of the total energy consumption, the optimization of the cooling system is discussed in more detail in section 3.

2.1.1 Power Conversion

Most data centers are provided with power from the external power grid at a multiple kilovolts level. This is unavoidable since only high voltage levels allow transporting larger amounts of energy through reasonable wire diameters with acceptable losses. However, as the IT equipment in a data center requires low voltage levels, the high-voltage of the external power line to the data center has to be transformed to a low voltage level at least once within the data center.

Unfortunately, transformation of one voltage level to another involves electrical losses. Although modern transformer designs attempt to minimize such losses, a transformer’s efficiency typically decreases significantly at partial load levels. Data centers and high performance computing centers in particular experience large variations in their electrical demands according to the variations in their IT workload. For example, as part of the acceptance tests for SuperMUC [sup13], one of Europe’s current Tier-0 systems, a selection of 8 benchmark applications was run on the entire system and the average power consumed over the run was monitored. Despite the fact that all benchmarks occupied the entire machine, Figure 1 shows that their power consumptions varied by several hundreds of kilowatts. Therefore, data center designers and operators must take the varying electrical loads and the resulting transformer efficiencies into account during planning and operation of the center. A typical mitigation approach is to use multiple transformers connected in parallel that are switched on or off using a smart control scheme that ensures that all running transformers operate within the load range that they were optimized for.

2.1.2 Uninterruptible Power Supplies

Similar to transformers, uninterruptible power supply (UPS) systems are a source of electrical losses inside the data center power chain. While availability is a big concern for commercial
data center applications, it is debatable whether high performance computing applications need full power availability. Thus, where possible, the availability requirements should be carefully considered and uninterruptible power should only be delivered to services that are either business critical or where restoring after a power failure takes unacceptably long. This might, for example, be the case for storage systems where file system recovery on large volumes can take several days. High performance compute systems, however, can typically be restarted easily after a power failure and scientific applications can resume from their last checkpoint.

The most common types of UPS systems are static and rotary UPS systems. Static UPS systems use batteries for storing energy that can be supplied in case of a power failure. Rotary UPS systems contain flywheels that are accelerated using an electric motor. A generator on the other end of the flywheel turns the rotational energy back into electrical energy. Like transformers, rotary UPS systems typically achieve the highest efficiency when almost under full load. Thus, when using rotary UPS systems, multiple smaller units should be set up in parallel with a control system that turns on or off the flywheels depending on the electrical demand. Fortunately, many commercially available systems already provide support such setups [UPS12].

2.1.3 Direct Current instead of Alternating Current

Often discussed for supposedly higher efficiency, but rarely implemented, is the option of distributing power within the data center in the form of direct current (DC) instead of alternating current (AC). Yet, recent studies [RS13] show that both approaches are quite comparable with respect to their energy efficiency. As the market for DC components is small, and not many sup-

![SuperMUC Average System Power Consumption](image)

*Figure 1: Average power consumption of 8 different application benchmark runs in SuperMUC.*
pliers of DC powered data center components exist, business competition is limited and prices are higher. Consequently, a recommendation for DC power distribution at the data center level cannot be given.

2.2 Hardware

2.2.1 System-internal power distribution

While there is typically only few different voltage levels at the data center level, as of today, high performance computing systems require many different voltage levels internally. For example in Mont-Blanc, the main processing element, the Samsung Exynos 5 Dual System-on-Chip is supplied with a voltage around 1V DC. However, other components in the system (e.g. networking components or fans) typically require other voltages (e.g. 3.3-12V DC). The necessary power conversions typically take place in PCB mountable DC-DC converters. Thus, some vendors have proposed to use an intermediate DC distribution system at the rack level (e.g. by using a 230V AC to 48V DC power supply per rack). The on-board DC-DC converters then facilitate certain liquid cooling options such as coldplates. However, as the Mont-Blanc system will be air-cooled, high-efficiency AC-DC switching power supplies transforming directly from 230V AC to 12V DC are the recommended choice for system-internal power distribution as an additional conversion step would only lead to additional losses without any gained advantage.

2.2.2 Voltage and Frequency Scaling (VFS)

Voltage and frequency scaling (VFS) [DVF13] is a technique that allows for reducing the power consumption of a wide range of computing systems, from embedded devices and desktop computers to high-performance computing systems. VFS reduces the frequency at which the processor is clocked, which has an immediate effect on its power consumption. Additionally, the lower frequency allows for operating the CPU at a lower voltage which in turn reduces the power consumption further. Normally, lowering the processor frequency results in increased application runtimes. However, at least for memory bound applications, the impact is minimal [HM07].

The selection of an optimal CPU frequency that allows maximizing the system performance, while at the same time minimizing the energy consumption, can be a non-trivial task. Specifically, the impact in terms of energy consumption may change according to the system architecture. As a preliminary assessment of this behavior, we present results on experiments conducted on the Insignal Arndale board, the first development board designed around the Samsung Exynos 5 Dual SoC. The Exynos 5 comes with an ARM Cortex A15 Dual Core processor and the Arm Mali T-604 GPU. The board itself further comprises two 32-bit 800MHz DDR3(L)/DDR3 RAM modules, each providing 1GB of main memory. A picture of the experimental setup is depicted in Figure 2.

For our test, we used the HYDRO benchmark, which is a computational fluid dynamics code using a Riemann solver on a regular 2D mesh [TLdV12]. In contrast to synthetic CPU, memory or I/O intensive benchmarks, HYDRO represents the typical behavior of applications in the field of computational fluid dynamics and has been ported to a large number of platforms and programming models.

In this context, the impact of VFS on the time-to-completion (runtime) of a job and the energy-to-solution is of particular interest. The energy-to-solution of a job is defined as the aggregated energy consumed by all hardware components for completing the execution of a given job (in our scenario, a HYDRO benchmark run on a single processing unit of the board). The benchmark problem size is fixed and is equal for all the experiments.
As depicted in Figure 3, the system exhibits a predictable performance behavior, as the runtime significantly increases with decreasing CPU frequencies. Also, the power consumption is expectedly higher at higher frequencies (shown in Figure 4). Note that lowering the CPU frequency does not generally yield an energy-to-solution gain as the longer run time can render the lower power consumption futile. In fact, the HYDRO benchmark workload selected for the experiment turns out to be well balanced at higher frequencies, showing the lowest energy consumption at 1.6 GHz (see Figure 5). Nevertheless, a slight increase of the energy-to-solution at 1.7 GHz can still be observed, suggesting that the optimal operating frequency may be lower for other workloads. Additionally, it can be expected that the behavior of the system may be potentially different when running the same experiment with both CPU cores, multiple boards and when exploiting the Mali GPU accelerator programmed in OpenCL. However, these experiments were not yet possible to conduct as of this writing since the software stack for the Exynos 5 Dual SoC and the Insignal Arndale development board is still too immature. Yet, once the software stack further stabilizes, it is expected that running further experiments can give a better insight on how the Mont-Blanc prototype will behave at different operating CPU frequencies which will create opportunities for finding near-optimal points of operation. Also, we are aware that varying thermal conditions can change the power consumption of a CPU significantly even when running the same workload since higher temperatures increase the amount of leakage currents in the semiconductor. Thus, the behavior of the final Mont-Blanc system running the same experiment might also vary due to the chips being equipped with proper heat sinks.

Figure 2: Experimental setup for runtime and power consumption readings of the Arndale Board.
2.2.3 Power Gating

Despite offering significant improvements in terms of energy savings, VFS is still limited by the minimum voltage required to operate the transistors of the circuit. A more drastic approach for increasing the energy efficiency is offered by power gating [JMSN05]. Power gating allows for reducing the energy consumption by putting parts of the circuit that are not in use into standby or sleep modes. This is achieved by inserting a gate (or sleep transistor) between the power supply and the circuit block that needs to be deactivated. Gating the power supply results in virtually no power consumption in the gated block, thus containing the impact of leakage currents and reducing processor’s power consumption. However, special care must be taken when adopting this technique as it may introduce additional restrictions from the design perspective. For example, adding a sleep transistor to the circuit blocks that are intended to be deactivated may cause a large area penalty.

2.2.4 Clock Gating

Additional improvements can potentially be achieved with the adoption of clock gating [CLO13]. This is a well-established design technique for optimizing power, and can be applied at system level, register transfer level (RTL) and gate level. In order to save power, clock gating activates the clocks in a logic block only when there is work to be done (that is, allowing power consuming switching of flip-flops in selected portions of the circuit). Similarly to power gating, the granularity of clock gating and the impact it has on the overall energy consumption

![Arndale Board Hydro Benchmark Performance](image)

Figure 3: Runtime at different CPU frequencies of the Hydro benchmark.
strongly depends on the design stage. The impact of this technique on performance and energy consumption of the Mont-Blanc prototype can be investigated as the Samsung Exynos 5 Dual supports numerous options for clock gating.

2.2.5 Power Consumption Monitoring

As discussed so far, state-of-the-art technology offers several opportunities for energy efficiency, with different approaches potentially leading to multiple optimal solutions. In order to conduct all the experiments mentioned above and eventually determine the operating points reflecting the most power-efficient configuration of the Mont-Blanc prototype, it is of critical importance to develop an extensive monitoring infrastructure which can offer full awareness of the system status in terms of power consumption. Only with a complete description of the system status it is possible to effectively analyze the prototype behavior by identifying correlations between different system variables (e.g., temperature and power consumption of a core).

Since, as discussed in [PS12], the system packaging of the Mont-Blanc prototype will be based on the Bull daughterboard design, it is recommended that, in order to effectively monitor the power consumption of each node, sensors providing power readings should at least be employed at the daughterboard level. Having a complete picture of the system not only allows better understanding of the inter-dependencies between the different system variables (subsequently determining optimal operating points with the technologies described above), but also allows exposing the energy consumption concern at the user level. In this way, for example, it is possible to define user accounting policies on the basis of the energy consumption, as explained

Figure 4: Average power consumption at different CPU frequencies of the Hydro benchmark.
2.3 Software

At the top layer of the software stack, a resource management tool is needed in order to manage and monitor the HPC system at the cluster level. In addition to scheduling and dispatching MPI tasks to different processors, this tool should be responsible for monitoring the state of the cluster as well as managing the configuration of the nodes and of the network interconnect.

2.4 Energy-aware monitoring, scheduling and accounting

In order to integrate the support for energy consumption in the batch scheduling system, it is necessary to have the capability of predicting the total energy consumption associated with the execution of a job. This is only feasible via thorough power monitoring of the system, both at the compute unit level (e.g., processors, memory, switches,...) and at the infrastructure level (e.g., cooling). Different solutions exist in order to retrieve energy information for different architectures, such as the Running Average Power Limit (RAPL) interface counters for Intel Sandybridge chips [Int09] or vendor specific extensions to the Intelligent Platform Management Interface (IPMI) [IPM13].

However, as of today, cluster management and monitoring tools typically do not include energy consumption for user accounting and job batch scheduling, with the notable and recent exception of SLURM (Simple Linux Utility for Resource Management) [SLU08]. SLURM is
an open-source cluster monitoring tool offering the opportunity of defining power saving mode strategies with an integrated mechanism that allows for slowing down the performance of computing nodes or completely powering them off. In order to efficiently coordinate the sleep/awake state of computing nodes, SLURM provides a comprehensive set of parameters (e.g., total sleep time of a node, maximum number of nodes that can be simultaneously resumed from sleep mode in order to avoid rapid increases in power consumption, etc.). The advantage of having complete visibility on historical data of jobs in terms of their energy consumption, allows the data center operator to define new accounting policies and scheduling strategies with energy efficiency in mind. This may potentially include increasing the user awareness on the energy that is consumed when executing their jobs. Potentially, exposing power consumption data to users might also offer novel ways for energy savings. For example, new billing policies may be specified, where users can be charged on the basis of the energy consumption associated with the execution of their jobs, consequently encouraging them to optimize their code for increasing the energy savings.

2.5 Application tuning

Exploiting the full capability of the system hardware can be cumbersome due to the ever-increasing complexity of parallel architectures for HPC. Programmers need to appropriately tune their codes in order to obtain maximum performance. Increased application performance is also beneficial to energy efficiency as it yields shorter runtimes and hence improves the energy-to-solution. This will play an increasingly important role towards the path to Exascale. However, as performance optimization is severely time-consuming, it introduces undesired productivity gaps. Nevertheless, opportunities for automating the application tuning process exist and one notable example is provided by the European FP7 funded AutoTune project [AUT13]. The AutoTune project started in October 2011 and its objective is to develop a framework (the Periscope Tuning Framework, PTF) that allows code optimization by determining recommendations for application tuning runs. These tuning recommendations can then be applied to optimize the code for later production runs. The PTF is an extension of the Periscope distributed performance analysis tool developed by Technische Universität München. It has been claimed that the adoption of Periscope can increase the energy savings by up to 10% [AUT13] due to increased application performance.
3 Cooling Aspects

Powering the different components of an HPC system generates waste heat that has to be removed in order to keep the IT equipment temperature within acceptable thermal boundaries. Several heat removal methods exist for cooling down the IT environment and transport unwanted heat energy to the outdoors. In this section we will analyze different cooling solutions and present recommendations for improved cooling efficiency from hardware, infrastructure and software perspectives.

3.1 Hardware

Cooling can be responsible for up to 50% of the total power consumption of a data center. Hence, it is essential to evaluate the different available cooling solutions for IT systems in order to quantify their effectiveness in terms of cost, performance and energy savings. Generally, cooling strategies can be categorized into two different classes:

- Air cooling
- Liquid cooling

Air cooling is adopted in the vast majority of today’s data centers and HPC systems. In its simplest form, air cooling is performed by blowing air on the IT equipment and transporting the generated hot air to the outdoors by means of an air-conditioning system. We can further distinguish air-cooled strategies on the basis of different heat exchange mechanisms and heat transport fluids. For example, in chilled water systems the waste heat is removed in Computer Room Air Handling (CRAH) units where heat is exchanged between air and chilled water provided by the chilled-water circuit of the building. Heat absorbed by the chilled water production system is transported outdoors where it is removed with the aid of a cooling tower [coo13]. Cold production itself is typically performed using the same vapor-compression cooling that can be found in fridges, car air conditioners, etc. In smaller setups, there is no need to extend the hot and cold parts of the vapor-compression cooling infrastructure with additional water circuitry to respectively transport the waste heat outside and the cold into the computer room. Instead, the entire refrigeration cycle is contained inside a Computer Room Air Conditioner (CRAC) unit inside the data center and a dry cooler outside where the waste heat is finally rejected to the outdoors. Air cooling is currently the de-facto standard in most of today’s HPC systems.

In liquid cooling systems, a fluid different from air (typically water) is used as the main coolant. Similarly to air cooling, we can distinguish between different heat removal mechanisms, such as indirect or direct liquid cooling. Indirect-liquid cooled systems are almost equivalent to air-cooled ones (e.g., chilled water systems), with the difference that, as opposed to a CRAH unit, the heat transfer is performed in in-rack air-water heat exchangers. In direct-liquid cooling systems, the coolant is brought in close proximity of the IT components, resulting in eliminating air from the cooling chain. This is achieved by mounting “coldplates” or “cooling pipelines” on the computing units, guiding the fluid coolant over the main heat-emitting components of the node. Examples of both strategies are depicted in the node designs of Figures 6 and 7. Liquid cooling solutions gained significant attention over the past 5 years and are currently adopted in many Top500 supercomputers. Oak Ridge National Laboratory’s Titan system, for example, is indirect-liquid cooled [tit13]. Direct liquid cooling can be found in Leibniz Supercomputing Center’s SuperMUC [sup13] and in Riken’s K computer [kco13].

Generally, liquid cooling offers advantages over air cooling in terms of energy efficiency. Since the thermal capacity of water is much higher than that of air [wat13], it is possible to...
achieve lower energy consumption than with air cooled systems at the same coolant temperature. Furthermore, liquid cooling allows maximizing the computing package density of a node, consequently increasing the number of units that can be fit per rack and providing additional valuable floor space. Finally, liquid cooling offers better opportunities for free cooling. However, air cooling still is a viable solution for the Mont-Blanc prototype system from a hardware perspective for multiple reasons:

- **Heat dissipation profile**: there is a significant difference between the expected heat-dissipation profile of the Mont-Blanc prototype and that of an x86-based system. Typically, in high performance computing systems the number of heat emitting components, such as processors, RAMs and host channel adapters, is restricted. The produced waste heat is thus concentrated in specific active components and is comparably high, making direct-liquid cooling a remarkably efficient solution for heat removal. However, in Mont-
Blanc the emitted heat is distributed over several components, each of them contributing with relatively low heat intensity to the overall heat dissipation profile of the compute unit. Hence, in this scenario, the realization of a dedicated direct liquid cooling solution (or the utilization a preexisting one) would be unfeasible.

- **Daughterboard system packaging**: As discussed in [PS12], the Mont-Blanc prototype will be based on the Bull INCA chassis architecture. Each server unit is packaged according to the daughterboard design. Several daughterboards will then be vertically mounted on a motherboard responsible for their communication, power supply and status monitoring. Adopting a dedicated direct-liquid cooling solution to the system architecture under consideration would be impractical, leaving an air-cooling approach as the only reliable alternative. Nevertheless, the advantages from a maintainability and serviceability point of view outweigh the less effective cooling solution as increased maintenance has to be expected.

- **Air-cooled components**: as of today, there are components in HPC systems for which no direct-liquid cooled solution is applicable. For example, devices such as network switches or power supplies still require the adoption of air-based cooling. Even though the amount of waste heat emitted by these components is relatively small compared to direct-liquid cooled parts, still their aggregated heat at the scale of an HPC system can be significant. For this reason, extra care must be taken in order to ensure energy-efficient cooling of those components as well.

- **Maintenance costs**: as opposed to liquid cooled systems, an air cooling approach allows for lower maintenance costs. In liquid cooled systems it is of critical importance to periodically inspect the liquid coolant quality in order to avoid bacteria growth, responsible for corrosion of the plumbing material. Different alternatives exist for overcoming this issue, such as the use of deionized water or buffer substances. However, to this day, liquid coolant treatment is still a topic of debate and it is rather hard to identify a unique, efficient solution to the problem. Additionally, extra care must be taken for mitigating the risk of leaks, resulting in a more extensive sensor monitoring infrastructure (e.g., pressure monitoring, water flow monitoring and so on) and consequently increasing maintenance costs. Finally, further complications and delays can be experienced when substituting equipment in case of failure. For all these reasons and since increased maintenance will be expected for the Mont-Blanc prototype system, adopting an air-cooled solution would be the best approach for the scope of the project.

- **Adoption of rear-door heat exchangers**: despite its lower energy efficiency compared to direct-liquid cooled solutions, air cooling can still be improved with the adoption of rear-door heat exchanger as they can contribute to optimizing energy efficiency in a data center facility in several ways: First of all, once a rear-door heat exchanger is installed, it does not directly require electrical energy at the infrastructure level to operate. Second, rear door heat exchangers require less chiller energy since they perform well at warmer (higher) chilled water set-points. Finally, because of the improved cooling, more server units can be fit into a single rack, resulting in additional free floor space. These inherent features help reduce energy use while at the same time minimizing maintenance costs. Furthermore, components for which no direct-liquid cooling strategy exists (e.g., power supplies, network switches, etc.) can be easily integrated with the solution described above.
3.2 Infrastructure

From an infrastructure perspective, air cooling offers simpler requirements than direct-liquid cooling. Generally, direct-liquid cooled systems demand a dedicated plumbing infrastructure that is capable of guiding the liquid coolant to the main heat-emitting sources of the system, thus being limited by additional constraints in terms of flow and pressure of the coolant. This solution can be difficult and expensive to realize. On top of that, as discussed in the previous section, increased maintenance would be expected (e.g., liquid treatment, plumbing material conditions, etc.). In an air cooled solution, only the airflow through the racks and the building needs to be designed. However, large quantities of air have to be circulated, and the hot air has to be cooled by the air conditioning system of the data centre.

Several approaches are possible in order to improve the efficiency of air-cooling systems. For example, the adoption of hot and cold air enclosures isolating hot from cold air areas in the IT equipment room. The main objective is to avoid the mixing of hot air and cold air, allowing considerable improvements in terms of energy efficiency, as shown in [20211]. A proper choice of the inlet air temperature is also of critical importance for more efficient air cooling. As reported in the latest ASHRAE specification, the optimal inlet air temperature should be set at 27°C. Nevertheless, too high inlet temperature values may provoke undesired fan speed increasing and higher leakage currents, resulting in additional energy waste.

3.2.1 Free Cooling

Significant energy savings can also be achieved with the adoption of free cooling. In standard air cooled systems, free cooling consists into exploiting outside ambient air to lower the water temperature of the chilled water system, eventually eliminating the need of power-hungry water chillers. During fall, winter, and spring, a system’s cooling tower or closed circuit cooling tower can produce water which is cold enough to eliminate the need to operate a chiller. There exist 3 different options for free cooling:

- **Cooling Tower and Heat Exchanger**: in this solution, the system operates as a conventional cooling tower/chiller system during summer. On the other hand, during the winter, the chiller is bypassed, and the cold water produced by the cooling tower cools the chilled water through a heat exchanger. This kind of solution has been successfully operated in colder climates and can still provide significant energy savings in warmer climates as well.

- **Closed Circuit Cooling Tower**: in this system, the cooling tower and heat exchanger of the condenser water loop are substituted by a closed circuit cooling tower. During the summer, water from the tower is circulated in a closed loop through the condenser of the chiller. During the winter, cold water from the tower is circulated in a closed loop directly through the chilled water circuit. This system is the only one combining the operating simplicity of a single circuit with the reliability of a closed, chilled water loop. This type of application is feasible with closed circuit cooling towers because contaminants in the recirculating water are never in direct contact with the system water.

- **Refrigerant Migration**: in this system, the valves between the condenser and evaporator of the chiller are opened when the compressor is off. This allows free migration of refrigerant vapor from the evaporator to the compressor and of liquid refrigerant from the condenser to the evaporator. This system is limited to the phase change and requires the coldest possible water from the open tower or closed circuit cooling tower.
Air-side Free Cooling: instead of extending the existing chiller based cooling infrastructure with an operation mode for free cooling, another approach is to bring in large quantities of outside air to cool the IT equipment. The challenge of air-side free cooling is the air quality. Even clean air requires filtering. Filters reduce the airflow, they expend energy to pull the air through them, and they require cleaning and replacement, which adds labor to the price tag. Humidity also has to be controlled.

The HPC system location is determinant for an effective adoption of free cooling. Generally, the best locations for free cooling are lower-humidity and lower-temperature areas. High humidity requires dehumidification and consequently the adoption of power-hungry refrigeration systems that produce enough cold for condensing humidity out of ambient air.

3.3 Software

Similarly to what has been discussed for power, a cooling monitoring software solution is necessary to efficiently operate a data center. Extensive monitoring of the cooling infrastructure provides data center operators visibility of equipment status and potential failure notifications through real-time alerts and alarms. Principal functionalities of such solution should include sensing IT equipment temperatures in order to prevent failure, consequently improving the precision of the air flow control at the rack and increasing the cooling efficiency. Detecting fluid leakages is also of critical importance. Sensors should be strategically placed at every point in the data center where heat removal fluids are present. These include fluid piping, humidifier supply and drain lines, condensate drains and unit drip pans.

Real-time monitoring with a management software tool can further facilitate proper actions in case of equipment problems, while real-time monitoring data can be used to analyze the actual performance of the system and potentially optimize it. Specifically, proactivity is enhanced as data center personnel will have the capability of preventing potential failures and automatically shift computing resources in order to increasing resource utilization for optimizing efficiency across the data center.

An example of this kind of software solutions can be found in the cluster management tool adopted for monitoring the cooling infrastructure of the BADW-LRZ CoolMUC system. CoolMUC is a cluster of 178 compute nodes with 2.0 GHz AMD Magny Cours processors and 16 GByte of main memory. The main interconnect network follows a fat tree topology and is implemented with Infiniband QDR. CoolMUC is the first AMD processor based prototype worldwide to adopt a direct warm water cooling solution. The node components characterized by the highest heat emission are cooled with warm water guided through a pipeline infrastructure placed on the motherboard. Air cooling is also applied to remove waste heat of IT components for which a liquid cooled solution does not exist or is not applicable (e.g., power supply, network switches, etc.).

Real-time monitoring of CoolMUC’s cooling infrastructure is performed with ClustWare [clu13], a cluster monitoring tool provided by MEGWARE GmbH. ClustWare offers the data center operator full awareness of the status of a cluster in terms of monitoring and management of its different assets. Key features of ClustWare are a centralized view of IT equipment temperature, flow rates and external factors such as environmental humidity percentage. An example of ClustWare monitoring views is depicted in Figures 8 and 9. Since increased maintenance will be expected for the Mont-Blanc prototype, extensive monitoring and real-time awareness of the status of the system at the software level should be highly considered. On top of that, a complete knowledge of the system will help addressing research tasks such as investigating and identifying potential correlations between energy-to-solution of a job and temperature of the system.
Figure 8: An overview of the plumbing infrastructure of the CooLMUC system.

Figure 9: Temperature and flow rate monitoring of CooLMUC at the rack level.
References


