EoD Designer: A Computation Tool for Energy Optimization of Data Centers

Cyrill Grüt, Peter Gysel, Matthias Krebs and Christoph Meier
University of Applied Sciences and Arts Northwestern Switzerland FHNW
peter.gysel@fhnw.ch

Abstract—Total energy consumption in a data center is the sum of various components. We consider six main subsystems: Voltage transformer, uninterruptable power supply, IT equipment, computer room air handler, chiller and cooling tower. In this project a mathematical model for all five components was derived. Based on this model, a software tool was developed. It allows to simulate different variants of a data center and to minimize the total energy consumption by optimizing equipment and operating parameters. Thus potential energy savings can be evaluated. Finally the resulting reduction of operation expenses can directly be derived from the energy savings.

Keywords—energy efficiency, data center, power modeling

I. INTRODUCTION

According to the European Commission, data centers in Western Europe used 56 terawatt hours (TWh) in the year 2007 [1]. This number is expected to grow to 104 TWh by 2020. Optimizing the energy usage in data centers by e.g. 10% would result in savings of about 10 TWh per year. This corresponds to the production of about three nuclear power plants in Switzerland. Calculating with 0.2 $/kWh for refined electrical energy (uninterruptable power supply etc.) it also means savings of 2 billion $ in operational expenses. This is a considerable amount from the point of view of economics as well as of sustainability.

Today, many operators consider energy optimization in the data center as not profitable, since some capital investments are required. For these operators a quantitative and comprehensible evidence for savings in operation expenses might be helpful. Other operators put strong emphasis on energy optimization of their existing data centers. There are many helpful guide lines how to build an energy efficient data center, see e.g. the green grid [2]. However, these guide lines do not give a quantitative analysis of how much energy can be saved in a given data center. The wide-spread metrics for the energy efficiency of a data center is the Power Usage Effectiveness [2],

\[ PUE = \frac{\text{Total Facility Power}}{\text{IT Equipment Power}} \]  

Values between 1.8 and 1.5 for PUE are considered good. Best reported values are now below 1.2 [3]. Optimizing PUE, however, does not minimize total energy consumption. The more power a server uses, e.g. for ventilation, the better the PUE. This can obviously not be the goal.

A data center is a complex system with many degrees of freedom. Specialists in heating, ventilation and air conditioning, HVAC, are able to optimize computer room air handler (CRAH) and chiller. Electrical engineers can access the potential of savings in transformers, uninterruptable power supply (UPS) and power distribution. IT specialists know the advantage of the newest server and virtualization techniques. They all represent the interests of their equipment manufacturers. Professionals that are able to evaluate data center as a whole are rare.

Therefore, the goal of this project is to develop and parameterize a tool that can calculate the total energy consumption of a data center. With that tool it will be possible to simulate different implementation variants and calculate their respective return on investment. Thus, it should be possible to deploy the most effective improvements directly. The tool is intended to be a bridge between technicians and decision makers, who need simple figures.

The main requirement for such a tool is usability by non-experts. A person who is not a specialist in all three domains should be able to evaluate potential savings for a data center within a few hours. This means that the tool demands as few input parameters as absolutely needed to get the required accuracy.

To achieve this goal, we first need a mathematical model for the relevant contributions to power consumption in a data center. It must be as simple as possible. Therefore it is not a part of this project to simulate complicated air streams with computational fluid dynamics (CFD). In a second step an extensible software tool with an appropriate update concept is developed.

In part II we give a system overview and describe some related work which was used as basis for this project. Part III describes the mathematical approaches for the data center model. In part IV some features of the software tool are illustrated and in chapter V we offer our conclusions.

II. SYSTEM OVERVIEW AND RELATED WORK

An overview of the main energy-consuming components in a data center is given in Figure 1. Medium voltage from the power supplier is first transformed to low voltage. Due to high availability requirements, an uninterruptable power supply unit, UPS, is needed. It protects the IT equipment from voltage peaks and from short- and medium-term interruptions. IT equipment finally converts all supplied electrical energy into thermal energy. IT equipment comprises servers, switches and storage equipment. The task
of all subsequent components is to transport that thermal energy away from IT equipment. Today data centers use air to cool IT equipment. Directly water cooled data centers exist, but are still experimental. Computer room air handlers, CRAH, push "cool" air at temperature $\theta_{\text{outlet}}$, e.g. 20°C, to the server racks. When traversing the IT equipment the air is heated to a temperature $\theta_{\text{outlet}}$, e.g. 26°C, and takes the thermal energy to the heat exchanger in the CRAH. As we will see later, the higher the temperature $\theta_{\text{outlet}}$, the better. The heat exchanger transfers the thermal energy to a second cooling circuit with a liquid cooling medium at the temperatures $\theta_{\text{in}}$ (supply, e.g. 12°C) and $\theta_{\text{out}}$ (return, e.g. 18°C). Now we have to distinguish two cases. If the outdoor temperature is below 10°C, the water of this circuit can be cooled directly in the cooling tower. In this case, the chiller is bypassed and does not consume energy ("free cooling"). If the outdoor temperature however is higher than 10°C, the temperature level of the thermal circuit has to be transposed to a higher level in order to be cooled down in the cooling tower. This is the task of the chiller. It can be thought of like a refrigerator in the inverse sense. The compressor in the chiller consumes a considerable amount of energy. From that view it can be derived that the temperature of the air circuit should be chosen as high as possible. Thus, the supply temperature $\theta_{\text{in}}$ of the liquid cooling circuit can be raised to e.g. 18°C, which in turn allows much more free cooling.

A. Models for Servers

Several models have been proposed in the literature for the purpose of predicting the power consumption of servers. The goal of most of these models is to make predictions in order to control individual components of servers e.g. changing the operating frequency of the CPU or putting hard disks into idle state. These models are implemented by the equipment manufacturers in a power management software on the server itself.

The model of Jaiantilal et al. [4] is based on three components:

- CPU,
- memory and
- a bias (i.e. the sum of all other components).

It includes the most important factors but it has also some drawbacks. By changing the number of hard disks, the value for the component bias has to be adopted. This implicates many different values for the bias. However, the simplicity of this model is the reason why it will be partly the base for our own model.

Economou et al. [5] and Bohra and Chaudhary [6] are providing another way for predicting the power consumption of servers. Their approach is based on

- a static value (power consumption at idle state) and
- a dynamic value according to the load of the components.

This approach has the disadvantage for us that it is difficult to assess the power consumption at idle state.

The drawback of all currently existing models is that they ignored the impact of the server inlet temperature. As the American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE, mentioned in their guidelines [7], raising the inlet temperature from 15°C to 30°C may cause additional power consumption of up to 8% for a server. In a data center with 100 servers each consuming 150W at 15°C (in total 15kW), these servers will need additional 1.2kW when raising the inlet temperature to 30°C.

B. Models for Switches and Storage

For switches there is one widely used approach by Mahadevan et al. [8] for predicting the power consumption. It includes the power of the chassis, the line cards and the ports. The power consumed by a port differs according to the bandwidth (10Mbps, 100Mbps, 1Gbps, 10 Gbps) and the traffic. Measurements in [9] and [10] have shown that the effect of traffic is negligible (less than 2.5% difference between idle and full utilized ports). Hlavacs et al. [11] even included a distinction of traffic type (UDP and TCP).

The simplest approach for storage system power modeling is proposed by Allalouf et al.[12]. There the power consumption is split into a static part (power of the full system at idle state) and a dynamic part (additional power for the hard disks under load). This model has a huge drawback. When changing the number of hard disks the static part has to be adjusted and therefore many different values for this part will exist. Several more complex models have been proposed. The model of Liu et al. [13] uses a value for the power of the controllers (equals the chassis) and the power of the hard disks. It raises increases its accuracy (but also its complexity) by differentiating between five modes: Idle, sleep, sequential read/write operations, random read/write operations and accessing from the cache. Since this approach is too complex for our goals as stated in chapter one, we base our model on the approach of Liang et al. [14]. They include the power of the chassis, the hard disks at idle, the controllers and a dynamic value for additional power under load.

III. POWER CONSUMPTION MODEL

The key element for a simulation of the power consumption in a data center is an analytical mathematical model for all its components. Our full data center model is depicted in Figure 2. It is based on the models for five subsystems:

- Transformer and UPS
- IT equipment (servers, switches, storage)
- Computer room air handler, CRAH
- Chiller (Ch)
- Cooling tower (CT)

We ignore the consumption of the building (illumination, access control etc.) at this point. It is considered a constant without optimization potential.
A. Transformer and Uninterruptable Power Supply UPS

The efficiency of a transformer and the UPS are defined as a simple factor

\[
\eta = \frac{\text{Output Power}}{\text{Input Power}}.
\]  

(2)

The efficiency factors depend on the load and on the power factor. They are specified in the data sheet of the equipment. The power dissipated by the UPS is

\[
P_{\text{UPS}} = \frac{P_{\text{IT}}}{\eta_{\text{UPS}}} * (1 - \eta_{\text{UPS}})
\]

(3)

where:
- \(P_{\text{UPS}}\): power consumption of the UPS
- \(P_{\text{IT}}\): power consumption of the IT equipment
- \(\eta_{\text{UPS}}\): internal efficiency of the UPS

In our software tool (see chapter IV) the efficiency factor \(\eta\) is configurable. Depending on the requirements more than one transformer and UPS system may be required.

B. IT Equipment

The IT equipment is the source of energy dissipation. Here the energy flows start. We distinguish two cases: Designing a new data center and modifying an existing one. In the first case the user might use the software tool to estimate the power consumed by the IT equipment. In the second case, the total power consumed by IT is known to the operator. In that case, the user can simply enter the measured value for \(P_{\text{IT}}\) as an input parameter.

The consumption of one server is modeled as

\[
P_{\text{server}} = P_{\text{chassis}} + (N_{\text{HD}} * P_{\text{HD}})
\]

\[
+ \sum_{i} \left( P_{\text{CPU}} + m_{\text{CPU}} * P_{\text{CPU, load}} \right)
\]

\[
+ \sum_{j} \left( P_{\text{RAM}} + m_{\text{RAM}} * P_{\text{RAM, load}} \right) + P_{\text{fan}}
\]

(4)

where
- \(P_{\text{server}}\): power consumption of the server
- \(P_{\text{chassis}}\): power consumption of the chassis (including graphics, motherboard, network interface cards)
- \(N_{\text{HD}}\): number of harddisks
- \(P_{\text{HD}}\): power consumption of one harddisk
- \(i\): number of CPUs
- \(P_{\text{CPU}}\): power consumption of the CPU at idle state
- \(m_{\text{CPU}}\): load of the CPU
- \(P_{\text{CPU, load}}\): additional power consumption of the CPU under load
- \(j\): number of RAM modules
- \(P_{\text{RAM}}\): power consumption of one RAM module at idle state
- \(m_{\text{RAM}}\): load of the RAM module
- \(P_{\text{RAM, load}}\): additional power consumption of a RAM module under load
- \(P_{\text{fan}}\): power consumption of the fan

With that model we take into account the number of hard disks, the number of CPUs and the amount of RAM in a server. Thus we are able to reflect the expansion stage of a server. Furthermore we consider the load of the CPU and the RAM. The increase of power consumption with rising inlet temperature is due to the higher rotation speed of the cooling fans consuming \(P_{\text{fan}}\). Some of the values e.g. \(P_{\text{HD}}\) can be found in data sheets or in reports, e.g. [15]. Other values, e.g. \(m_{\text{RAM}}\) had to be measured.

For switches the following model was applied:

\[
P_{\text{switch}} = P_{\text{chassis}} + \sum_{i} N_{\text{ports, i}} * P_{\text{port, i}}
\]

(5)

where \(i\) is the index for the different port speeds (10 Mbps to 10 Gbps) and \(N_{\text{ports, i}}\) is the number of active Ports at speed \(i\).

Storage finally was modeled as

\[
P_{\text{storage}} = P_{\text{chassis}} + \sum_{i} P_{\text{disk, idle}} + \sum_{i} m_{\text{disk}} * P_{\text{disk, load}}
\]

(6)

where \(P_{\text{disk, load}}\) stands for additional power consumption at full load and \(m_{\text{disk}}\) represents the percentage of disk load. Thus a static and a dynamical part of power consumption of disks is taken into account.

C. Computer Room Air Handler CRAH

CRAH equipment must generate an air stream strong enough to convey the thermal energy produced by the IT equipment. A heat exchanger transfers that thermal energy to a cooling circuit with a liquid medium. If the temperature difference between the cooled air leaving the exchanger and the heated air entering the exchanger is \(\Delta \theta\), the basic physical equation is

\[
P_{\text{in}} = \rho \cdot q_{v} \cdot c_{p} \cdot \Delta \theta
\]

(7)

where \(\rho\) is the density of air, \(q_{v}\) the air stream by volume in m\(^3\)/s and \(c_{p}\) the heat capacity of air in Ws/kg. The thermal power in the air stream can be set equal to the electrical power consumed by the IT in good approximation. The needed air stream therefore is

\[
q_{v} = \frac{P_{F}}{\rho \cdot c_{p} \cdot \Delta \theta}
\]

(8)

The required electrical power to generate the air stream can be approximated with a cubic polynomial:

\[
P_{F} = \frac{P_{F, req}}{100} \left[ k_{0} + k_{1} \left( \frac{q_{v}}{q_{V, req}} \right) + k_{2} \left( \frac{q_{v}}{q_{V, req}} \right)^2 + k_{3} \left( \frac{q_{v}}{q_{V, req}} \right)^3 \right]
\]

(9)

where \(P_{F}\) and \(P_{F, req}\) are the electrical power needed by the Ventilator at load \(q_{v}\) and at full load and \(q_{V, req}\) is the air stream at full load. Numerical values for the constants \(k_{0}\) to \(k_{3}\) can be found in [16].
D. Chiller

The mathematical model for the chiller is quite complicated, therefore we refer to the document [16].

E. Cooling Tower

The power consumed by the cooling tower can be calculated with the same model as for the CRAH.

F. Comparison with Measurements

The three models for IT equipment were compared to measurements in our lab. The worst case differences over the full range of load were below 5% for a blade server, below 10% for a conventional older server, below 6% for switches and below 10% for storage.

The model for CRAH was compared to measurements in different data centers in Switzerland. One has to keep in mind that cooling equipment in general does not work in continuous mode, but at discrete power levels. Therefore distinct measurements can differ significantly from the model. However, measurements over a period of several hours average out this quantization noise. Given that there is no blockage in the air duct and the CRAH is operated at 30% of full load or above the error was less than 7%.

The chiller model was investigated in [17] for two types of chillers. The error was below 4%.

IV. THE SOFTWARE TOOL

The software tool EoD Designer acts both as a planning and optimization tool for data centers. The various components of a data center can be configured individually, which allows the simulation and thus the direct comparison of different data center variants. This enables an engineer to determine to which extent the different data center variants affect the total energy consumption of the data center. To our knowledge, such a software tool is not yet available on the market.

The key feature of the software is the graphical design of different data center variants. All the components can be placed appropriately using an intuitive graphical user interface, as shown in Figure 3. When designing a data center, one usually starts with the configuration of the IT equipment. After that, power supply components such as transformers and UPS are modeled. To dissipate the occurring thermal energy, different cooling components are configured as well. There may be multiple instances of each component, for example two redundant UPS, depending on the requirements of the data center variant. After placing the required components, their parameters have to be set appropriately. Some parameters are preset according to existing component data sheets, other parameters need to be defined manually. Furthermore, each component has specific properties defined as input or output. After setting the parameters, the inputs and outputs of the different components can be linked together, resulting in a computation tree. Within this computation tree, the parameter values are propagated across the data center components, and the total energy consumption can be calculated. Additionally, the operator is given the possibility of importing external data, for example weather information of a specific location, from prepared text files. EoD Designer already ships with many predefined components. However, the operator may create custom components or modify existing components by adding or modifying an XML specification file for the component. This specification file contains the default parameters according to its data sheet. If the existing component templates are not sufficient or require additional computation algorithms, the operator may also add new functionality through a sophisticated plug-in API.

After all the components have been placed and their parameters and inputs or outputs are configured, the total energy consumption of the data center variant can be simulated. Modification of the component parameters immediately shows what effect each parameter has on the total energy consumption. Instead of single values, parameter values can also be specified as series. This allows a data center simulation over a certain period of time, for example.

To evaluate a data center variant, reports can be generated from simulations. A report does not only show the total energy consumption, but also the energy consumption of all the sub-systems, such as IT equipment and cooling. Figure 4 shows an example of a generated report based on a one-year simulation. The values are shown as percentages as well as absolute values (kWh). For example, the energy consumption over the duration of one year can be simulated. The resulting report, besides showing energy consumption over time, shows the energy costs and the PUE value. Either an annual or monthly report can be displayed. The reports allow the comparison of simulated variants to existing data centers. The benefit for customers is that they immediately see the projected costs when a data center variant is simulated, as no further calculations are necessary.

V. CONCLUSIONS

In this article we have presented a mathematical model to compute the total energy consumed in a data center. The challenge was to keep the model simple in order to guarantee usability. We have shown that the model can be parameterized with only few variables. Although distinct power measurements may differ significantly from the calculated value, we found that the calculated total energy over a period of time results in adequate accuracy. The measurements of CRAH equipment in various data centers however showed that a parameter \( \Delta p \) for the pressure difference that is to be generated by the fan should be introduced to generalize the model.

We also presented a software tool that implements the mathematical model. It enables non-experts to estimate and to compare the energy usage of different implementation variants of a data center. Since the return on investment can
now be estimated in advance it is easier to judge the risk of capital investments for better equipment.

We developed a software architecture that allows easy extensions for new components as well as new models. It should be possible to implement a new model e.g. for water cooling, without changing the main part of the software.

In conclusion we advocate minimizing the total energy consumed in a data center instead of minimizing the PUE value.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the Commission for Technology and Innovation, CTI, for funding the project. We thank our project partners green.ch and R+B Engineering for their valuable help during our work.

REFERENCES


---

**Figure 1:** Overview of the energy consuming components in a data center. UPS: Uninterruptable Power Supply, CRAH: Computer Room Air Handler, θ: Temperature.
Figure 2: The data center model. At the top: Input parameters to define the subsystem. Horizontal: The flows of energy. Bottom: Dissipated power of each component. $\phi$: Thermal flow. $\theta$: Temperature.

Figure 3: Simulation of a data center variant in EoD Designer
Figure 4: Report of a data center variant for one year created in EoD Designer