Diplomarbeit

Fakultät für Wirtschaftswissenschaften, Universität Karlsruhe (TH)

Energy System Analysis of a University Campus

Energy consumption and efficiency measures for the ***E****cole* ***P****olytechnique* ***F****ederal* ***L****ausanne (EPFL)*

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Cover picture:

EPFL campus, seen from northwest; source: EPFL

Abstract

The goal of this Diploma Thesis is to deliver an integrated view on EPFL as an energy system. It shall support future decision making about further steps towards increased sustainability and efficiency at EPFL, regarding the energy system. The results of the Thesis allow the comparison of different measures with respect to costs and energy savings. Beginning with the current status, the largest energy consumers are identified, and the energy consumptions are categorized in order to show the *flash points* of possible actions. Subsequently, an efficiency analysis is conducted over three different stages. First, the main *services* related with significant energy consumption are examined for possible efficiency measures, and significant saving potentials for the different services are identified. The greatest savings pertains to the ventilation system. In the second stage, the options for *energetic integration* are investigated to reveal synergies between thermal streams. The *conversion system* is the focus of the last stage. Here, the CO_2- intensity and the effects of the heat distribution network extension on the existing heating system are analyzed.

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Abbreviations

- **ENERGIS:** A geographical information based system for the evaluation of integrated energy conversion systems in urban areas, developed at LENI- EPFL, implemented in MATLAB.

- ***EPFL- Pl- DII_E***: ***EPFL*** = ***P****lanification et* ***L****ogistique-* ***D****omaine* ***i****mmobilier et* ***i****nfrastructures-* ***E****xploitation*: provided the energy data for EPFL used in this study.

- **Grid** ***F****: **F**orce;* ***F-S****: **F**orce-* ***S****ervice;* ***L+ M****: **L**ighting +* ***M****easuring*

- **HDN**: **H**eat **D**istribution **N**etwork

- **IW** = *Industrial Water*: Lake water for cooling purposes at EPFL. As soon as the pumped up lake water enters the cooling cycle, it is called *Industrial Water.*

- **PV** = ***P****hoto****v****oltaic*

- **SFR** = ***S****wiss* ***F****rancs*: Swiss currency

- **SIA** = ***S****chweizer* ***I****ngenieur- und* ***A****rchitektenverein*. Editor of technical standards in Switzerland for buildings and civil constructions

- **SIA limit values**: (energy consumption) standard values, which have to be observed in new or refurbished buildings

- **SIA target values**: (energy consumption) standard values, technologically possible ideal values

- **TCO = T**otal **C**osts of **O**wnership: summed up lifecycle costs, including all aspects of the usage of an object

1. Introduction and approach

1.1 Introduction and motivation of the study

Sustainability plays an important role at EPFL. The energy conversion system can, without a doubt, be described as exceptional. Heat pumps supply heat in a very efficient way, using the nearby lake as the main heat source. The lake provides around 75 % of the heat load of EPFL. Other measures have been and will be undertaken to further promote the sustainable use of energy and resources at EPFL. The awarding of the *ISCN Sustainable Excellence Campus Award* for EPFL this year represents an official appreciation of the great efforts of EPFL in this field.

This study shall assist with the decision-making of further steps towards increased sustainability and efficiency at EPFL, with an integrated view on EPFL as energy system. The main goal is to identify the most promising near term measures to increase energy efficiency and reduce the energy consumption at EPFL. Therefore, the main consumers at EPFL shall be revealed. Adequate measures to increase the efficiency of the services which are required for the operation of a university campus shall be demonstrated. To answer the question of "where to act first", an initial magnitude of the related costs for the different measures is estimated.

1.2 Approach and contents

Before beginning with the analysis of energy efficiency potentials, the **chapter 2** shall give a first overview over the energy sources for EPFL, and list up the main consumer categories and consumers. The total energy consumption of EPFL is composed of the energy categories heat, electricity and cooling. Each building can be seen as a single consumer, consuming a certain amount within the mentioned energy categories. The focus is on electricity and heat consumption, as cooling at EPFL is provided very efficiently with lake water, and is related only with small energy consumptions. Within the electric consumption one can further separate between the categories *Force*, *Force- Service* and *Lighting + Measuring* (further explained in chapter 2.1). These categories are a consequence of the existing measurement at EPFL: each of these consumption categories is measured separately on an own counter in each building. The collection and illustration of these values can give a first glance and overview about the existing situation.

For the efficiency analysis an approach in the style of the so called *onion diagram* is chosen, which is very often applied in process integration, e.g. in plants, but also represents a suitable sequence for the analysis of buildings or building complexes:[1]

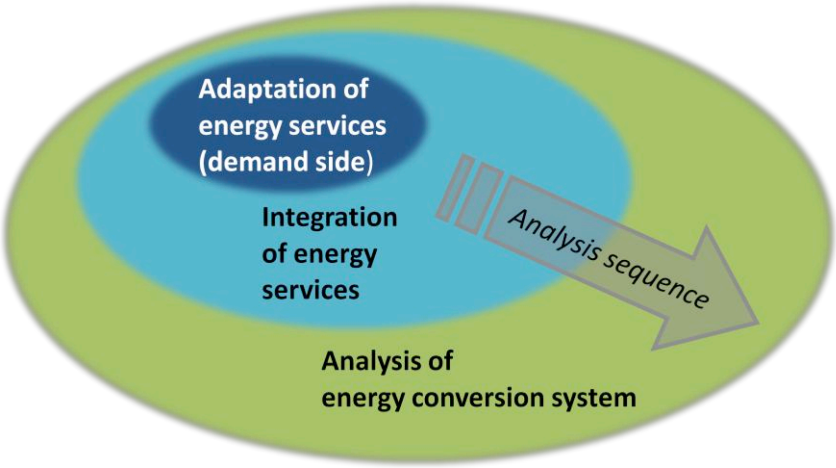

Figure 1: Onion diagram for process analysis and integration (based on BFE (Ed.) (2006), own illustration)

In the first phase (**chapter 3**) it is generally analyzed whether the energy services, which satisfy specific demands, e.g. heating or ventilation, are adapted to the real needs, or whether efficiency potentials can be realized through adaptation of the processes. In the second phase (**chapter 4**), synergies between processes shall be revealed, for example through the re- use of waste heat. Finally, after the processes have been optimized and synergies have been utilized, it is essential to adapt the conversion system, so that the remaining requirements in heat, electricity and cooling are supplied in an efficient way (**chapter 5**). This approach assures that, especially in industrial process integration, the resulting conversion system suits the real demand and is not over dimensioned. Furthermore, it can be assumed that, along these different steps, the required investments progressively increase. So a process analysis should always forego considerations about the conversion system or the infrastructure. Additionally, an extension of the conversion system or the infrastructure - without a proper analysis of the processes - would fix eventual inefficiencies on the process level.

When applied to building technology, this framework can be interpreted in many ways. The main goal of the framework is to keep a certain order and sequence for the efficiency analysis. Under the **first level** (chapter 3), one could understand measures that are completely “for free” and directly realizable, for example, behavior changes of the occupants.[2] In this case, where a very big building complex needs to be analyzed, another option is chosen: The different *services* to be supplied in the buildings, for example lighting, ventilation etc. are understood as processes. Their improvement in terms of efficiency and adaptation to the real needs represents the first phase of the analysis, or the innermost skin of the onion diagram. This includes also possible investments and change of the technology. It is of course not possible to categorize and analyze all electric consumers on campus. Therefore, the main consumers within the implied categories *Force*, *Force- Service* and *Lighting + Measuring*, shall be identified an analyzed.

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[1] Kemp (2007) p. 6 + BFE (Ed.) (2006), p. 39 ff.

[2] BFE (Ed.) (2006) p. 39 ff.

In the **second phase** (chapter 4), it is examined whether synergies between different services exist, and if options exist to "recycle" energy streams. This part concerns thermal streams, as it does in industrial process integration. For electrical consumption, subjects such as load or demand side management for this level of the analysis are imaginable, when they are aimed for a more regular load distribution along a certain period. As the basic goal of this work is the identification of saving potentials, issues concerning the electrical load distribution were not explicitly examined.

In the **final phase** (chapter 5) - the analysis of the conversion system - the focus is on the effect of the campus expansion on the conversion system, namely the heating system. A short cost analysis about the future photovoltaic plant is executed to make it comparable to the efficiency measures in terms of costs and energy savings.

Other important general points concerning this analysis that should be mentioned:

- The focus of this work is on the evaluation of *energy* saving potentials. Whenever possible, a related cost for the implementation for the efficiency measures is estimated. Numerous assumptions and hypotheses need to be made to arrive to a conclusion for a heterogeneous building complex as large as the EPFL campus. Therefore, the cost analysis can only display a magnitude For more exact estimations, the costs should be validated in a more detailed building- by- building analysis.
- "Grey energy and emissions", which represent energy consumption and emissions through the production and the setup of a new installation, e.g. a new building envelope, are not considered to restrict the complexity of the analysis. One can assume that for most efficiency measures with significant energy savings, these "grey emissions" are amortized within a relatively short period through the resulting energy savings. For example: The "grey emissions" for the energetic retrofit of an older laboratory building are amortized within 5-6 months. [3] An exception represents the chapter about *Thin Clients*: the emission savings over the full lifecycle are additionally mentioned. It is here reasonable to consider emissions during production, distribution etc. due to the very short lifecycles (5 years), compared to other efficiency measures.
- All savings in energy, for example heat savings are, for reasons of comparison, basically transformed in savings of electricity. Electricity can be considered as the only form of energy consumed at EPFL, as also heat is produced almost completely with electricity. The comparatively small amounts of natural gas and fuel oil entering the system limits are neglected.
- Whenever possible, written documents were cited as the source of information for this work. Much of the information about energy consumptions and the energy system at EPFL could only be gathered through numerous personal discussions with responsible persons and experts from the department "*EPFL- Planification et Logistique- Domaine immobilier et infrastructures- Exploitation" (EPFL- Pl- DII_E)".* In this case,"*EPFL- Pl- DII_E*" is quoted as source.

[3] Birnbaum et al. (2007), p. 259- 262

2. Energy system and energy balance

2.1 The energy system EPFL

The energy system of EPFL is strongly related to the nearby Lake Geneva. In winter time, the lake serves as a heat source for two heat pumps, and simultaneously provides cooling throughout the year for technical or scientific installations, as well as for room acclimatization.

In 2008, 11.325.907 $m^3$of water were extracted and pumped up from the lake to the campus, which would represent a cube of more than 100 m x 100 m x 1000 m! From this amount, 4.003.711 m^3 (35 %) were used for cooling purposes, for which the expression *industrial water* will be used in the following. 7.322.196 m^3 (65 %) served as a heat source for the two heat pumps.[4]

The water is extracted at a depth of 68 m from the lake where the water has a constant temperature of about 7 °C throughout the year. The industrial water is warmed up to around 12 °C during the cooling processes.

The lake water enters the vaporizer of the heat pumps at 7 °C and loses around 2-3 Kelvin due to the heat exchange. Both water flows are then, in most cases, directly re- injected into the Lake Geneva.[5]

The campus can generally be separated into three buildings categories by their age of construction: buildings from the first construction period (1975- 1985), the second period (1985- 1999) and the last construction period (since 2000). Buildings from the same construction period are mostly built with a comparable or equal technology and energy standards. The buildings on the EPFL campus are – except for a few smaller or special buildings - all connected to the EPFL heat distribution network (HDN). An important difference between the construction phases is the supply and return water temperature of the heat distribution network: the buildings from the first construction period are supplied with a maximal supply temperature of 65 °C and a return temperature of 45 °C; this represents the *medium temperature (MT) network*. The newer buildings are connected to the *low temperature (LT) network*, and are supplied with maximal supply and return temperatures of 50/35 °C (further information about network temperatures in chapter 5.3 and 5.4).

[4] Data from *EPFL- Planification et Logistique- Domaine immobilier et infrastructures- Exploitation" (EPFL- PI-DII_E),* specifically *Diagr_flux_2008.pdf*
[5] Data from *EPFL- PI- DII_E*, specifically Schmid (2005)

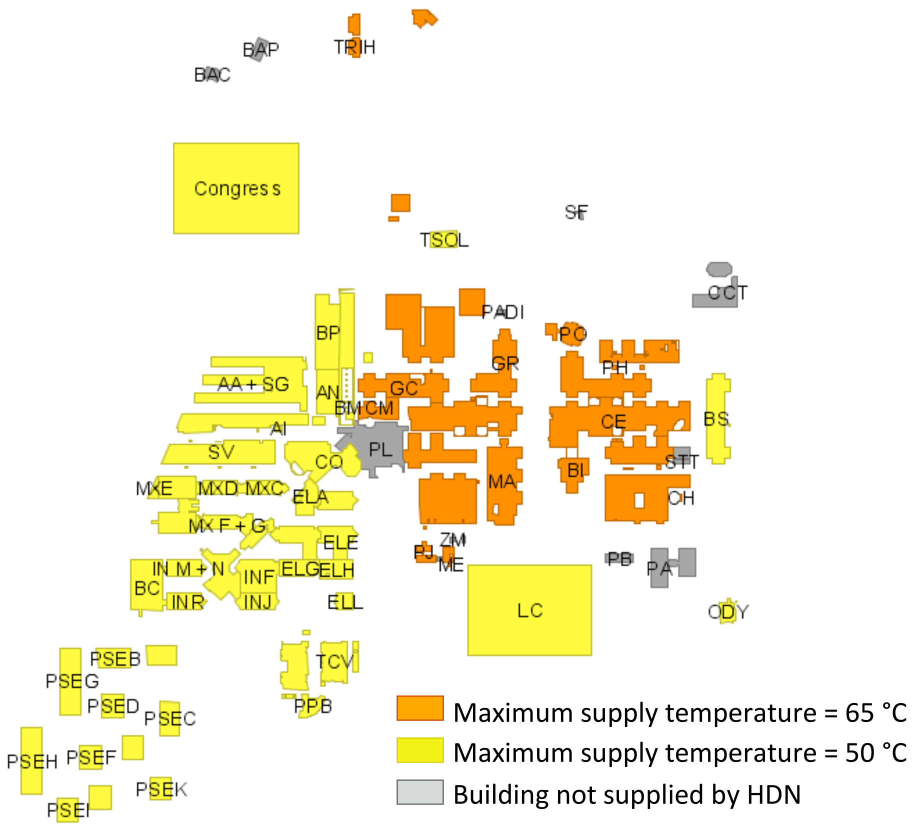

Figure 2: EPFL buildings with HDN sizing supply temperatures (extracted from ARCGIS; the future buildings PSE, LC and Congress Center were manually added to the GIS data; own illustration)

The heating conversion system consists of the two heat pumps, with a thermal peak load of 4,5 MW each, and two gas turbines with a thermal peak load of 5 MW and 3 MW electrical peak load. The condensing temperature in the heat pump cycles is around 50 °C, the vaporization temperature at 2 °C, so the maximum supply temperature the heat pumps can provide is around 50°C. The heat pumps operate constantly at full load when heat needs to be produced. The excessive heat is then stored in thermal water tanks; the heat pumps are stopped, when the tank is filled. As the heat pumps always provide hot water at 50 °C, the returning water from the buildings is mixed with the hot water from the heat pumps, to obtain the adequate supply temperature, and then sent back to the buildings.

The heat pumps achieve throughout the year an average COP[6] of 4, 56. If one considers also the energy which is required to pump the water from the lake to the campus, one obtains a total COP of around 3,6. This value is later on also used to transform heat consumptions into electricity consumptions (see chapter 4.3.1 for calculations).

The gas turbines are only operated when the heat pumps cannot satisfy the heat requirement anymore. This is the case when the required heat load of EPFL exceeds 9 MW, or when the required supply temperature for the medium temperature network rises over 50 °C. In the actual building constellation, both of these conditions are complied at around 0 °C exterior temperature (compare

[6] Coefficient of performance

with heat signatures in chapter 5.3). So the gas turbine operation is strictly *heat- led*. The additional produced electricity then supplies directly the heat pumps. The gas turbines are operated with fuel oil.[7]

The analysis of the optimal operation strategy for heat pumps, gas turbines and the heating system in general at EPFL, has been already extensively examined in other studies. It is therefore not analyzed deeper within this work. It shall only be mentioned at this point, that the variation of the operating strategy is often limited due to technical restrictions, which are partly not visible on the first view. Therefore one has to be careful to draw conclusions about an improvement of the operation strategy, which seem to be obvious at first glance.

The electricity demand of EPFL is almost completely provided from exterior electricity sources. A 50 kV/ 20 kV transformation station connects EPFL to the transmission grid. Only a very small share of electricity consumption is produced in the gas turbines on the campus.

The following figure shall give a first overview about the energy system and the important energy flows at EPFL:[8]

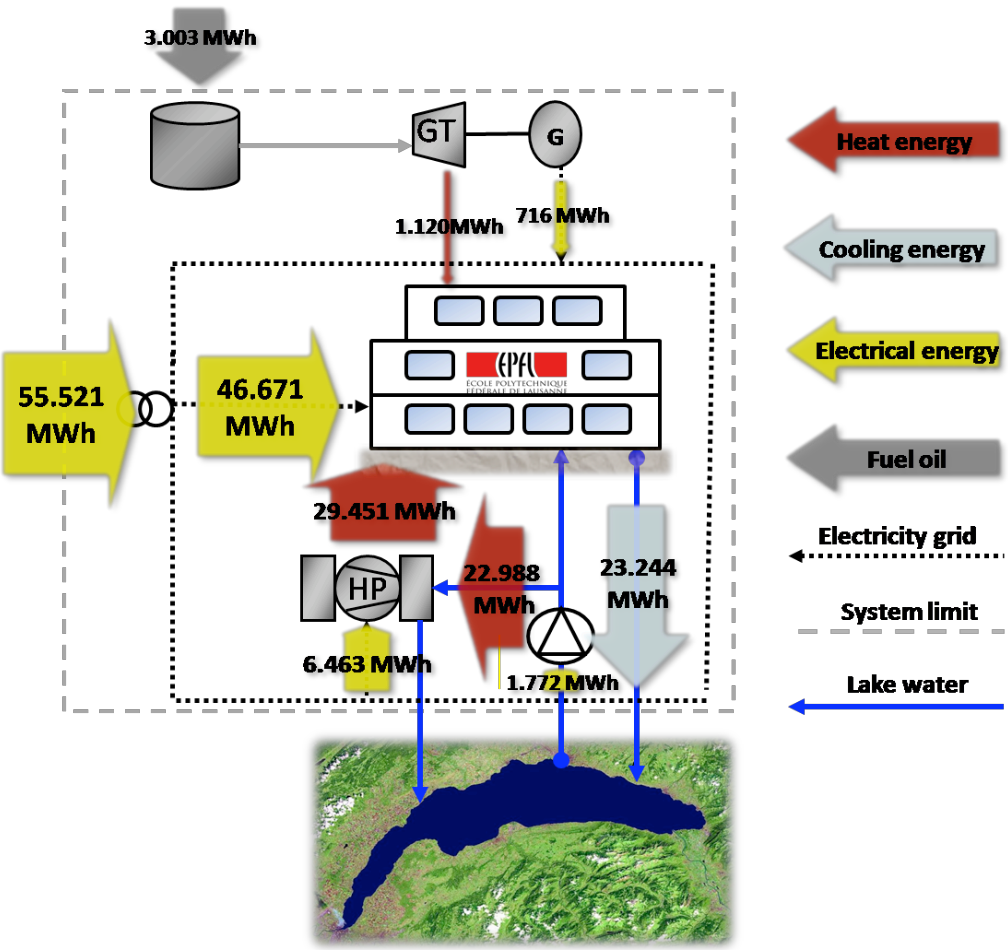

Figure 3: Simplified diagram of the energy system of EPFL (own illustration)

[7] Data from *EPFL- PI- DII_E*, specifically Schmid (2005) + Pelet (1997)

[8] values from *Diagr_flux_2008.pdf*, *chaleur_batiments_2008_v1.xls*, *Elec_EPFL_2008_v4.xls*

2.2 Balance of energy consumption for EPFL

In this chapter the basic energy consumption categories of EPFL shall be presented. This balance shows the demand side of the energy streams, and is the starting point for the analysis of energy efficiency at EPFL. The energy values represent the effectively used *net energy*. These values are, if not mentioned differently, the measured values for the year 2008. They were measured on the different counters of the university throughout the year, by the department *"EPFL- Planification et Logistique- Domaine immobilier et infrastructures- Exploitation" (EPFL- Pl- DII_E).*

2.2.1 Characteristic of electrical consumptions

The figure below shows the measured load curve for a typical week summer week for EPFL, measured at the transformation station 50/20 KV in June 2005. Since then the total electrical consumption has slightly risen due to some new buildings, but the characteristic of the load curve has not been significantly affected.

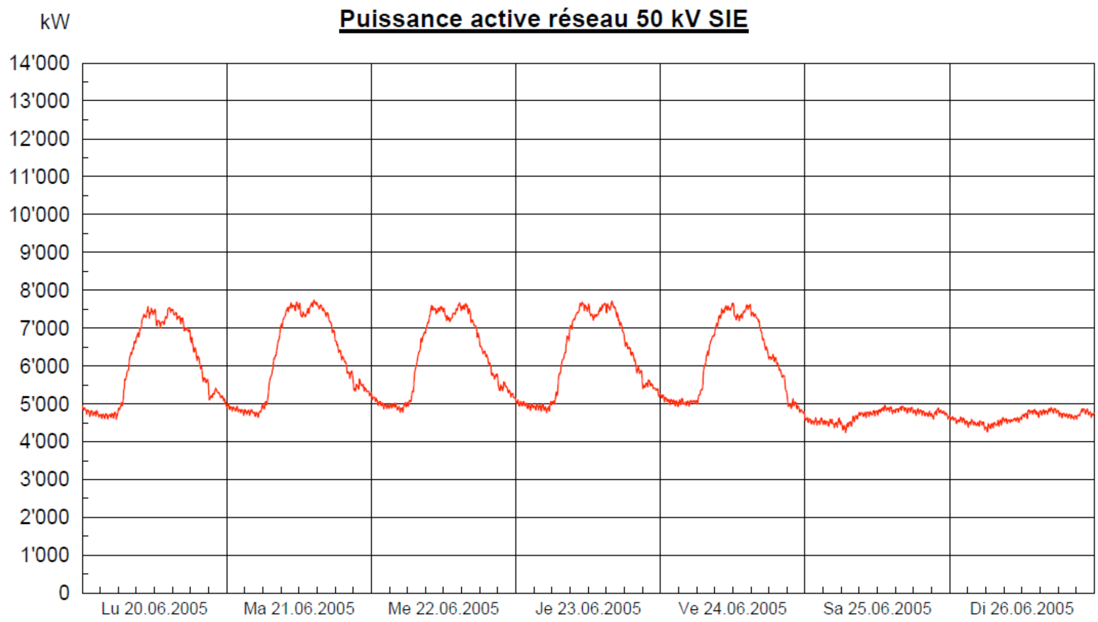

Figure 4: Electrical load curve EPFL for a typical summer week

The following observations can be made:

- The daily consumptions consist of a significant base load, representing obviously more than 70 % of the total energy consumption, and an additional peak load on working days. During the working hours around 8 am and 6 pm, the consumption rests pretty stable. On weekends the peak load disappears.
- In winter, the profile is less regular due the volatile operation of the heat pumps, which contributes significantly to the total electricity consumption, and the gas turbines, which

feed electricity into the campus grid when operated (see appendices B and C). The profile is occasionally affected due to the operation of big electricity consumers like the TOKAMAK experimental reactor.

- Further figures from the *EPFL- Pl- DII_E,* which are not shown here, illustrate that the consumption profile is not affected by the presence of students. The profiles during academic holidays are the same as within the lecture periods. The effects of the seasons on the electric loads are also marginal, except for the consumptions of the heat pumps and gas turbines. [9]

Further issues concerning the electric load profiles were not treated within this work.

2.2.2 Categorization of electrical consumptions

The overall electrical consumption in 2008 amounts to 55.520.709 kWh_{el}. Included in this amount is the consumption of 6.462.900 kWh_{el} by the two heat pumps, which deliver the heating energy for the campus. Also included is the consumption of the industrial water supply pumps of 1.772.060 kWh_{el}, and 615.104 kWh_{el} for the 4 booster pumps for the operation of the heat distribution network. These elements basically represent the heating system of the campus, but also the energy used to pump cooling lake water to the campus is included in these values. After the subtraction of these elements, one obtains a sum of 46.670.644 kWh_{el} for the electrical consumptions for the buildings, and the technical and scientific processes at EPFL.

Overall electrical consumption EPFL 2008	**55.520.709 kWh_{el}**
Consumption of 2 heat pumps	6.462.900 kWh_{el}
Lake water supply pumps	1.772.060 kWh_{el}
4 booster pumps (heating system)	615.104 kWh_{el}
EPFL buildings and processes	**46.670.644 kWh_{el}**

To make the buildings and their efficiency comparable, it is now necessary to further split up the energy consumptions of the buildings into different categories. Furthermore the consumptions, which are not really related to the operations of the building, or which deliver services for the operation of the whole campus, need to be separated.

Most of the buildings have three separated internal grids to deliver the electricity to the different consumers:

- **Grid Force:** delivers electricity for the power sockets, the office equipment, the scientific processes etc.
- **Grid Lighting + Measuring:** provides electricity for all lighting systems, sensible measuring equipment (the frequency of the current is therefore specifically stabilized), and all the equipment required for the electricity distribution.
- **Grid Force- Service:** provides electricity to all buildings services related to **h**eating, **v**entilation, **a**cclimatization and **c**ooling (HVAC). Among others, the ventilation fans, the cooling units, and the pumps for the industrial water and heating circulation are supplied from this grid.

[9] Information according to *EPFL- Pl- DII_E*

Each of these grids has a proper counter to measure the electricity consumption, and represents a first category for the energy balance of EPFL.

Several big consumers within the buildings have their own distribution grids with own consumption counters. The most important ones are:

- the central calculation center within the *MA* building (*DIT*) (3.301.725 kWh_{el})
- the *"TOKOMAK"* experiment, a thermonuclear fusion reactor with connected *Gyrotrons* (electromagnetic wave emitters for plasma heating) in the *TCV* building (658.560 kWh_{el})
- the steam production in the *AN* building (834.732 kWh_{el})
- the supersonic wind channel in *ME* building with the *PLUTO* compressor (379.300 kWh_{el})
- the *"Krios"*- compressor in the *ME* building (70.900 kWh_{el})

These consumption values will appear in the energy balance category "other processes".

Furthermore, there are processes with substantial consumptions, which are not directly related to the operation of the building, but they do not have proper counters, and their consumptions are recorded on one of the three basic grid counters (*Force*, *Lighting + Meas*uring, or *Force- Service*) in the building. These are mainly server rooms in the buildings *ME, AI, BC, IN j,* and the smaller server room in the *MA* building. In these cases, the consumptions of these processes must be estimated , as they are not exactly known, and must be subtracted from the measured value on the relevant counter. The approach to estimate the annual electrical consumption of these servers is the following: There exist punctual measurements for the power demand of these servers $p_{el,server}$ and for the central calculation center *(DIT)* in the *MA* building. Also the annual electrical consumption $C_{el,DIT}$ of the *DIT* is known. The annual electrical consumption $C_{el,server}$ of the servers is calculated by comparing the power demand of a server with the one from the *DIT*, and the annual consumption is deduced:

- $C_{\ server} = \frac{P_{server}}{P_{\ DIT}} \times C_{\ DIT}\ in\ [kWh_{el}]$

The following consumptions for the servers can be calculated:

Server in building:	**Power (in kW):**	**Consumption (in kWh_{el}):**	**Recorded on grid:**
MA	400	Measured: 3.301.725	Own counter
BC	120	Calculated: 990.518	Force
IN j	20	Calculated: 165.086	Force
ME	80	Calculated: 660.345	Lighting + Measuring
MA ext.	120	Calculated: 990.518	Force
AI	80	Calculated: 660.345	Force
sum	820	6768.537	

These values are now subtracted from the consumption records of the corresponding grids, and are added to the category "other processes".

The energy balance for electrical consumption at EPFL now consists of 5 main categories. The distribution is shown in the following figure:

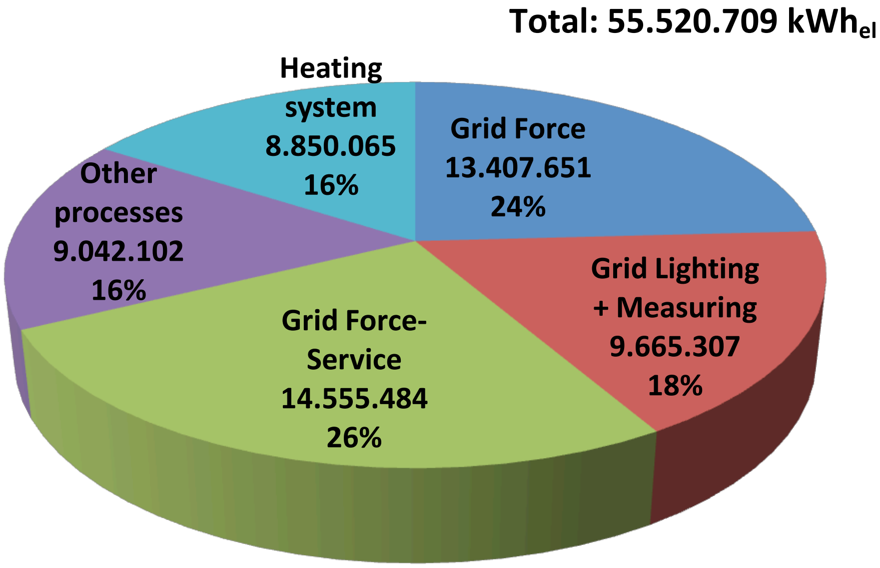

Figure 5: Distribution of electrical consumption at EPFL, in kWh for 2008

2.2.3 Electric consumptions for the different buildings

It is now possible to further analyze the consumption characteristics of the different buildings. The next graphic shows the absolute consumptions values for each building and the grid *Force (F)*, grid *Lighting + measuring (LM)* and grid *Force- Service (FS)*. These values represent a total of 36.072.951 kWh$_{el}$. This is not the total consumption for the grid *Force*, grid *Force- Service*, and grid *Lighting+ Measuring* (37.628.442 kWh$_{el}$). To preserve the clarity of the figures, a few consuming buildings are not included anymore, when they are either situated outside the campus, or have a very small consumption, or the consummation cannot really be allocated to one of the 3 above mentioned categories.[10]

[10] Values from *Elec_EPFL_2008_v4.xls*

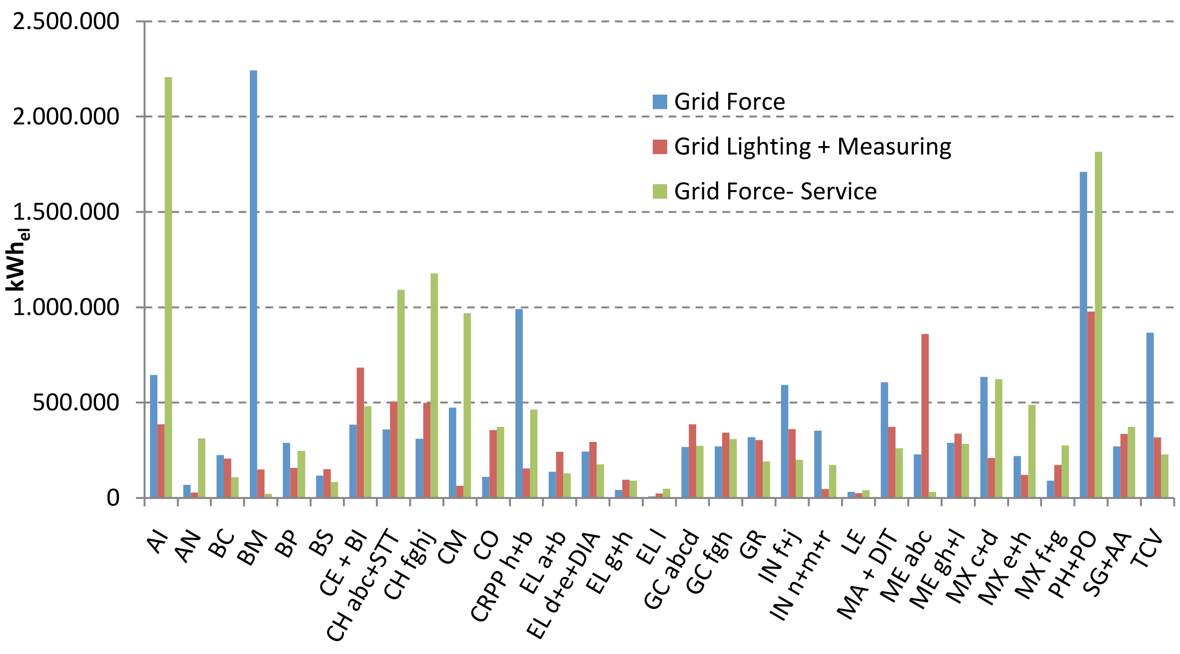

Figure 6: absolute consumptions of buildings at EPFL in 2008, in kWh$_{el}$

In the next step, one can calculate the relative or *specific* consumptions, by dividing the total consumptions through the heated surface of the corresponding building. This makes it later on possible to compare the energetic efficiency or performance of the buildings with other buildings, standards or benchmarks:[11]

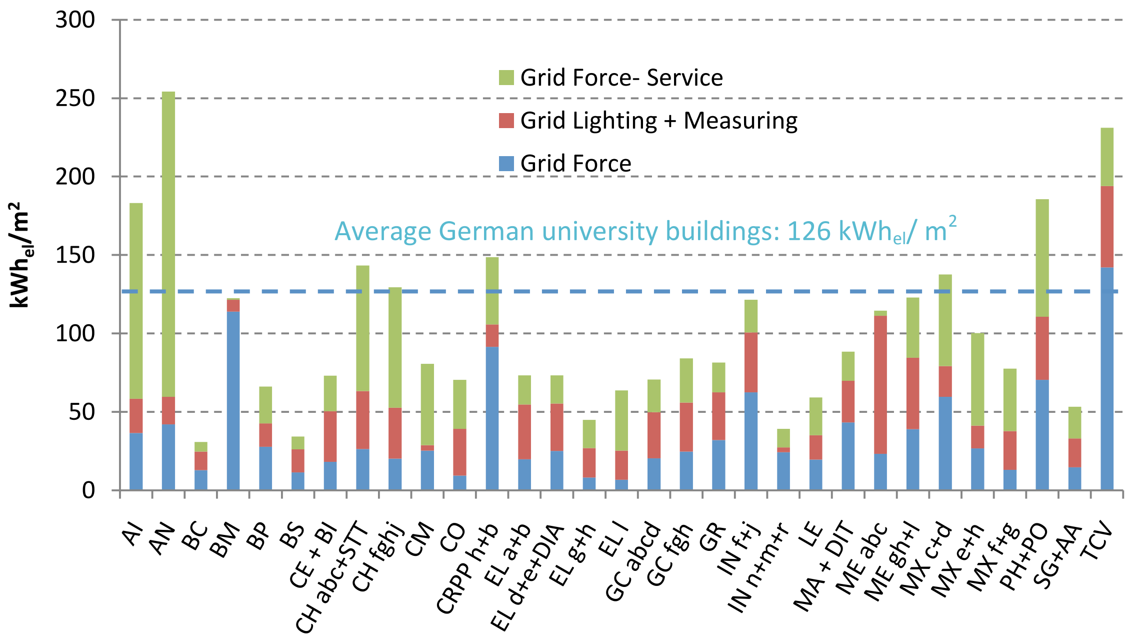

Figure 7: specific consumptions of buildings at EPFL in 2008, in kWh$_{el}$/m^2

[11] Values from *Elec_EPFL_2008_v4.xls*

At this point a few very characteristic building consumptions in the figures above shall be basically explained (more detailed analysis in the next chapters):

Building *AI*: houses the School of Life Sciences. In the laboratories (37 % of surface in the building), an air renewal of 10x the volume per hour is necessary. This explains the extremely elevated absolute and specific values for the consumptions for the ventilation system (*Force- Service*)

Building *AN* ("Animalerie"): The research conducted in this building requires a very specific and adapted heating system. Therefore heating is mainly supplied by an electric heating system, which leads to the very high specific consumption on the grid *Force- Service*.

Building *BM* ("Batiment Microelectronique"): The scientific processes in the Microelectronics labs (30 % of surface in the building), causes a considerable electric consumption, which is recorded on the grid *Forc*e. But consumptions for the category *Force- Service* are obviously also recorded partly on the counter of the grid *Force*, which explains the extremely elevated consumptions on this counter, and the extremely low recording on the counter *Force- Service*.

Building *CH* ("Chimie"): The chemistry building houses a considerable fraction of laboratories (20 % of surface in the building) and is also one of the biggest buildings on the campus (together with *CH + STT* around 29.000 m^2). Toxic fumes need to be evacuated from the laboratories, which require high air streams and air renewal rates. This results in very high absolute and specific electrical consumptions for the grid *Force- Service*.

Building *PH* ("Physique"): the Physics building houses a considerable fraction of laboratories (21 % of surface in the building) and is one of the biggest buildings on campus (24.273 m^2). This results in high consumptions on the grid *Forc*e (many experimental installations), and as well as in the *CH* building, a high air renewal rate is necessary, which causes high consumptions recorded on the grid Force-Service.

Building *TCV* ("TOKAMAK à Configuration Variable"): this building houses the thermonuclear fusion reactor TOKAMAK. Its consumption is recorded on a separate grid, but the high specific consumption can be ascribed to the auxiliary units of this installation. The spec. consumption does therefore not serve as an indicator for energy efficiency of the building.

Building *CRPP* ("Centre des recherché en Physique des Plasmas"): As the name already indicates, this building contains other experimental or scientific installations for the Plasma Physics Research, which leads to high specific consumptions. The spec. consumption does therefore not serve as an indicator for energy efficiency of the building. [12]

[12] All surface information provided by *EPFL- Pl- DII_E,* treated in *EPFL_room_distribution_working.xls*

2.2.4 Heat consumption of EPFL buildings

Almost all buildings on the campus are provided with heat from the heat distribution network. Exceptions are the buildings *PA* and *PB*, which are heated by gas. For these buildings, no consumption values are available. Their consumptions are small, and they are not taken into account in the following figures for the moment. Also other buildings, which are not situated on the campus or where no data is available yet, like the building *SV*, are not displayed in the following figures.

The next figure shows the absolute values for the heating energy consumption for buildings on the campus connected to the heat distribution network. The buildings are given different colors which stand for the construction period of each building: red for the first construction period (1975- 1985), orange for the second period (1985- 1999) and yellow for the last construction period (since 2000):[13]

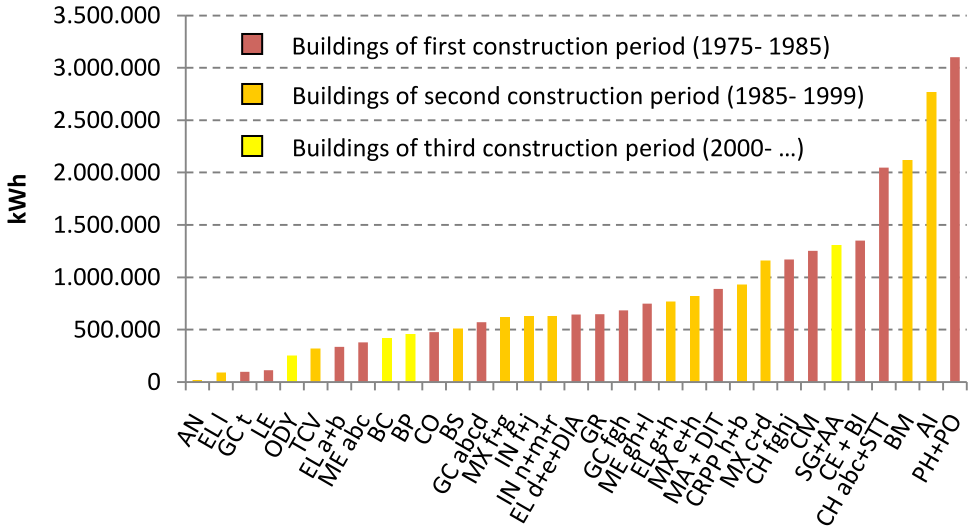

Figure 8: absolute heating energy consumptions for EPFL buildings, in kWh for 2008

The following figure now shows the specific consumptions (the absolute consumption divided by the heated surface of the building):[14]

[13] Values from *EPFL_Chal_Elec_06-08_enerstat_v2_withGraphics.xls*
[14] Values from *EPFL_Chal_Elec_06-08_enerstat_v2_withGraphics.xls*

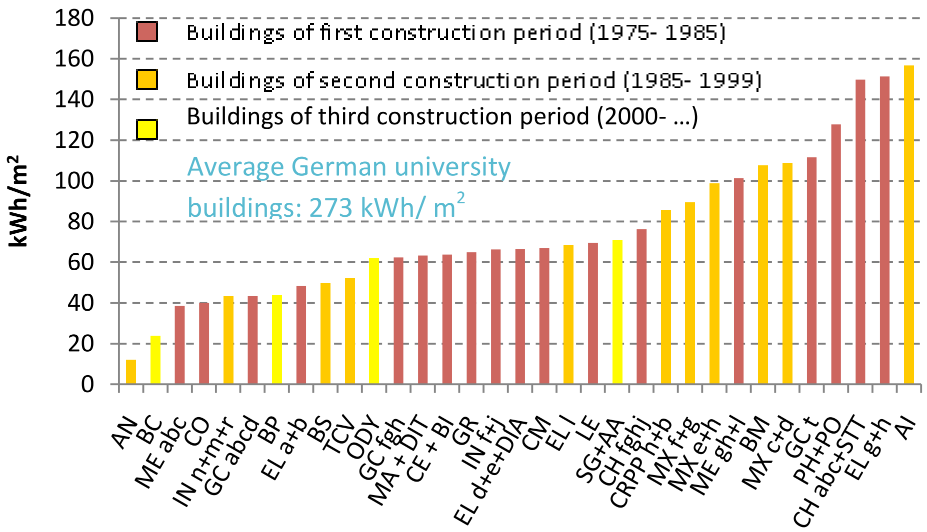

Figure 9: specific heating energy consumptions for EPFL buildings, in kWh/m² for 2008

One can observe big differences between the different specific heat consumptions. This results once more, as mentioned above, from the different usage characteristics of the buildings, which has always to be taken into account when comparing different buildings on campus. A high air renewal rate in laboratory buildings, for example, also results in elevated specific consumptions of heat energy, due to heat losses through the air renewal streams. The best example is the *AI* building with a very high electric consumption on the grid *Force- Service*, which is also resulting in very high specific heat consumptions. All the buildings with a high fraction of laboratories can be found at the upper end of the specific heat energy consumption scale: The buildings *AI, EL, CH, PH, MX c* and *d*, and *BM*. The *AN* building is found at the lower end of the scale, as it is mainly heated with electrical and gas heating (as mentioned above, due to the very specific needs and safety requirements for research in Life Sciences). These heating consumptions are not recorded. The *BC* building is the one with the highest energy standards on the campus and its consumptions are comparable to those specified by the Swiss MINERGIE standard.[15]

2.2.5 A first look on efficiency at EPFL buildings

At this level of aggregation, it is very difficult to compare or measure the efficiency of university buildings. These buildings represent a very special category, which are not really comparable to other common buildings like office buildings or school buildings, as the very specific use of the university buildings has a high impact on the energy consumptions, as one can observe on the variety of values in the figures shown before. To make these buildings more comparable to other buildings, the energy consumptions need to be further split up and the very specific demands for the different energy services need to be evaluated. This will be part of the next chapters. At this level of aggregation, only

[15] According to *EPFL- PI- DII_E,* namely *Bilan des Energies EPFL (2007)*

the comparison with other university buildings makes sense and can give a first idea about energy efficiency and performance on the campus.

In the study of Kluttig (2001), the specific energy consumptions of 303 university buildings in Germany were examined: the average electrical consumption was 126 $\frac{kWh_{el}}{m^2}$. It is not specifically expressed in the study which consumptions were exactly taken into account. But one can assume that all consumptions within the buildings were included. If one calculates this overall average specific value for the buildings at EPFL, which were also listed up in the figures above, and which represent more than 95 % of the electric consumption at EPFL (consumption for heating system not included, but consumptions for server rooms included), the following value is derived:[16]

- $\frac{45.657.458\ kWh_{el}}{362.234\ m^2} = 126\ \frac{kWh_{el}}{m^2}$

This is exactly the same value as the overall average for German university buildings.

Furthermore, the average heating energy consumptions were evaluated in the study. An average of 273 $\frac{kWh}{m^2}$ was derived. The calculated average value for the buildings at EPFL shown in the previous figures, amounts to:

- $\frac{28.324.865\ kWh}{362.234\ m^2} = 78\ \frac{kWh}{m^2}$

The colder climate in Germany compared to Lausanne must be taken into account. Anyway, this fact alone does not justify the more than 3 times higher specific heating consumptions in the German university buildings, and it must be assumed, that the analyzed building stock in Germany does not keep up with the relatively good insulated buildings et EPFL.

In the study of Kluttig (2001), specific consumption values for different building categories at universities were evaluated. A few shall be presented here, without being further analyzed:

Building category	**Specific annual electric consumption in [$\frac{kWh_{el}}{m^2}$]**	**Standard deviation**	**Specific annual heating consumption in [$\frac{kWh}{m^2}$]**	**Standard deviation**
Medicine, Biology, Chemistry	267.7	+-151.7	454.8	+- 106.4
Engineering and Natural Sciences	116.1	+-91.9	206.5	+-137.0
Lecture halls	84.6	+-57.2	249.5	+-92,.0
Administration and Libraries	114.8	+-107.3	237.8	+-164.3

The great variety of the values is also mentioned in the study and can be observed in the high standard deviations. It shows once more the complexity of comparison and benchmarking for university building consumptions. Consumption values for other universities are shown in appendix A.

[16] Values calculated in *Elec_EPFL_2008_v4.xls*

3. Adaptation of energy services

3.1 Introduction

3.1.1 General procedure

The first goal is to identify and analyze the services with the highest energy consumptions. The starting point is always the total consumption on the grids: *Force*, *Force- Service* and *Lighting+ Measuring*. The challenge is then to clearly identify the consumption for a single service, for example like ventilation. In the following the consumptions can be compared with benchmarks. As university buildings have very specific energy consumption characteristics, specific benchmark values need to be created for each service, e.g. from the application of SIA standard target and limit values for energy consumptions in different room categories. From this information one can then derive a possible saving potential for the different services. Cost estimations for the according measures are conducted, to give a first magnitude of the economic viability of the measure, and to make the different measures comparable to each other. When cost estimations are impossible, the maximum investment, which could be completely financed by the expected monetary savings through energy consumption reduction, is calculated.

As mentioned before, energy savings are finally transformed into electricity savings to make the different measures comparable. Electricity is basically the only energy source for EPFL; the small amounts of gas and fuel oil consumed at EPFL are negligible.

Finally the specific annual capital costs per saved energy unit $\left(\left[\frac{SFR}{kWh_{el}}\right]\right)$ are calculated, which allows for the economical comparison of the different efficiency measures among each other; one can then derive a sequence of "where to act first", when a certain reduction of energy consumptions or emissions shall be achieved.

A similar approach is applied in chapter 4.

3.1.2 Important aspects for the economical calculations

3.1.2.1 Economical calculations for energy relevant refurbishment projects

This chapter shall give an overview, how the *profitability* of an energetic refurbishment can be generally determined.

The goal is to compare the costs of the energy relevant refurbishment with the achieved energy savings. This is difference between the energy consumption before and after the refurbishment. The costs consist of the annual ***capital costs*** for energy related refurbishment measures, and eventually ***additional fixed operational costs*** (or savings). The related investments are passed on the amortization period, and the annual capital costs are derived. Only the ***energy relevant additional costs*** should be considered here. Of course, the big challenge is to clearly identify the *energy relevant additional costs* and to separate them from the *basic costs* for a refurbishment (extensively explained in chapter 3.1.2.2).

The monetary savings due to energy consumption reduction represent the income side of the calculation.

The possible economical annual benefit of an energetic refurbishment can be determined as follows:[17]

- $Benefit = Saved\ energy\ costs - Capital\ costs - Add.fixed\ operational\ costs$

Assuming that the building and the installations had been completely amortized before the refurbishment, the ***actual annual operational costs*** would be:

- $K_{ante} = \sum_{j=1}^{n} p_j \times C_{ante,j} + O_{ante} \quad [SFR]$
    - $n = energy\ sources$
    - $p_j = energy\ cost\ for\ energy\ source\ j\ in\ [\frac{SFR}{kWh}]$
    - $C_{ante,j} =$ $annual\ energy\ consumption\ of\ energy\ source\ j\ before\ refurbishment\ in\ [kWh]$
    - $O_{ante} = fixed\ operational\ cost\ before\ refurbishment\ [SFR]$

The annual ***after- refurbishment operational costs*** are then determined as follows:

- $K_{post} = \sum_{j=1}^{n} p_j \times C_{post,j} + O_{post} \quad [SFR]$
    - $C_{post,j} =$ $annual\ energy\ consumption\ of\ energy\ source\ j\ after\ refurbishment\ in\ [kWh]$
    - $O_{post} = fixed\ operational\ cost\ after\ refurbishment\ [SFR]$

[17] Birnbaum et al. (2007), p. 215- 220

The average costs for energy source *j* during the considered amortization period of the efficiency measure can be derived with the following simplifying approach:[18]

- $p_j = 0{,}5 \times p_{j,actual} \times (1 + (1 + r)^n \quad [SFR])$
  - $p_{j,actual} = actual\ costs\ for\ energy\ source\ j\ in\ [\frac{SFR}{kWh}]$
  - $p_j = average\ costs\ for\ energy\ source\ j\ in\ [\frac{SFR}{kWh}]$
  - $r = assumed\ annual\ price\ increase\ for\ energy\ source\ in$ [%]
  - $n = amortization\ period\ in$ [years]

With the annuity method one can transform investments *I* into annual capital costs *A:*

- $A = a * I \quad [SFR]$

The annuity factor is determined as followed:

- $a = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad [-]$
  - $i = interest\ rate\ in$ [%]
  - $n = amortization\ period\ in\ [years]$

These values are explicitly defined in chapter 3.1.2.4.

The ***total annual costs*** after refurbishment amount then to:

- $K_{total} = A + \sum_{j=1}^{n} p_j \times C_{post,j} + O_{post} \quad [SFR]$
  - $A = annual\ capital\ cost\ for\ refurbishment\ in\ [SFR]$

The difference between energy consumption for different energy resources *j,* before and after refurbishment, is defined as follows:

- $E_j = C_{ante,j} - C_{post,j} \quad [kWh]$

The ***additional fixed operational costs*** are defined as:

- $O_\Delta = O_{ante} - O_{post} \quad [SFR]$

Operational cost after refurbishment might be relatively high due to a higher complexity of installations. This is accompanied by the high operational costs caused by bad conditions of the un-refurbished building and installations. The operational costs before and after the refurbishments are therefore assumed to be equal, as they are difficult to determine due to missing data.[19]

The overall yearly benefits (or expenditures) through the energetic refurbishment measures are then calculated as follows:[20]

[18] Birnbaum et al. (2007), p. 219
[19] Birnbaum et al. (2007), p. 228
[20] Birnbaum et al. (2007), p. 215- 220

- $B = \sum_{j=1}^{n} p_j \times E_j - A - O_{\Delta} \quad [SFR]$

This is equivalent to the relation introduced in the beginning of this chapter:

- $Benefit = Saved\ energy\ costs - Capital\ costs - Add.fixed\ operational\ costs$

One can observe that when the *fixed operational costs* are not considered, then energetic refurbishment is only *profitable* when the monetary savings through reduction of the energy consumption are higher than the annual capital costs (when capital costs consist only of *energy relevant additional costs*!).

Once more it shall be pointed out here which costs were considered in the following analyses:

- For all examined efficiency measures only the *annual capital costs* are considered. These are derived from the estimated investment for the efficiency measure. For the investment only the *energy relevant additional costs* are considered, but these can make up to 100 % of the total investment (see chapter 3.1.2.2). Other operational costs are neglected, and could be further examined in subsequent studies.
- An exception is the calculation for *Thin Clients* (chapter 3.5): Very detailed information about the differences in TCO (T*otal Costs of Ownership*) between PCs and *Thin Clients* was available, which is incorporated in this study. Therefore the *costs* consist not only of capital costs, but include also other fixed operational costs.
- For PV, additionally to the capital costs, a small fraction of maintenance costs is considered.

These costs for each efficiency measure can then be compared with the possible electricity savings of each measure.

3.1.2.2 Definition of energetic relevant additional costs

The study of Birnbaum et al. (2007) about the refurbishment project of the laboratory building *Phytosphäre* at the *Forschungszentrum Jülich* in Germany shall serve as a reference concerning the definition of *energetic relevant additional* costs. Specific cost approximations from this study for different refurbishment measures will be also partly used in the following chapters.

The total costs of an *energetic relevant refurbishment* consist basically of two elements:

- $Total\ refurbishment\ costs = basic\ costs\ +\ energetic\ relevant\ additional\ costs$

Basic costs or *anyway costs* are costs for the replacement of old installations or renovation of buildings, which are not directly related to energy consumption reduction. This could be reparation and replacement works, which are required to assure the operation of the system or the installation in the future. By contrast the *energetic relevant additional costs* are directly related to energy savings. In reality it is in some cases difficult, if not impossible, to separate these two costs types, and compromises have to be accepted.[21]

Some examples, how different refurbishment measures are considered in the *Phytosphäre* report:

- **Removal of heat bridges:** total refurbishment costs are accounted as *energetic relevant additional costs*.
- **Roof and envelope:** only material and installation costs for insulation are *energetic relevant additional costs*.
- **Windows:** total refurbishment costs for renewal are accounted as *energetic relevant additional costs*
- **Lighting:** total refurbishment costs for renewal are accounted as *energetic relevant additional costs*
- **Air treatment system:** total refurbishment costs for renewal are accounted as *energetic relevant additional costs* (cost separation difficult or impossible).
- **Installation of a heat distribution network connection:** full installation costs are accounted as *energetic relevant additional costs*.[22]

One could also define the e*nergetic relevant additional costs* as the extra costs for a more efficient system or technology compared to that of a less efficient system. This requires fairly exact price information for different systems which provide the same service or serve the same purpose. The monetary savings through energy consumption reduction for the more efficient system can then be compared with the price difference of both systems and technologies. This definition is applied in chapter 3.4, where desktop PCs and *Thin Clients* are compared in terms of costs and energy consumptions.

This study will stick to the considerations in the *Phytosphäre*- report, so costs for ventilation and lighting refurbishment are to 100 % considered as *energetic relevant additional costs.* For the building envelope, only the additional costs for insulation and the full costs for windows exchange are considered. Price differences between less and more efficient systems could not be evaluated within this work, as a very detailed price analyses would be necessary.

The costs for the most efficient system are generally evaluated in this study. Subsequent to this work, more exact price analyses for different systems, especially for lighting and ventilation, might be conducted and the derived results of this work can be applied anyway. For example, if a system needs to be exchanged due to aging, and it is known that the efficient system is only 40 % more expensive than the cheaper alternative, then only 40 % of the costs evaluated here per kWh of saved energy could be considered.

As shown later in this work, the calculated cost per saved electricity unit $[\frac{SFR}{kWh_{el}}]$ reaches in most cases values above the electricity price, which would be the limit of profitability, when only the *energy relevant additional costs* are entered in the investment calculation. The reasons are the following:

[21] Birnbaum et al. (2007), p. 221 ff.
[22] Birnbaum et al. (2007), p. 223- 225

- For a fair comparison, a strict differentiation needs to be established between:
    - the costs of replacing the existing system with a new system of the same efficiency (the same energy consumptions) as the old system, called *basic costs*
    - the additional costs for a more efficient system, the *energy relevant additional costs*.

  This is, in many cases, difficult or impossible to determine. A new HVAC system will almost always be more efficient as one being thirty years old. Therefore the total refurbishment costs for a HVAC installation need be considered and annualized as energy relevant additional costs.[23] This leads then to the high calculated costs per saved electricity unit. That applies also to new lighting installations. For the refurbishment of building envelope, one can consider only the costs for additional insulation as energy relevant costs if a refurbishment of the envelope would be anyway necessary. Also, the costs for the replacement of desktop PCs through more efficient *Thin Clients* or laptops are easier to split up, as both costs for "business as usual" (buy new desktop PC) and for the more efficient option (Thin Clients or Laptop) are known.

- Another important point is that, for new systems, e.g. HVAC systems, lower maintenance costs are possible, which would further affect the outcome of the investment calculation. For a proper determination of reduction in operational costs (additional to energy savings), a very particular cost analysis for the existing and a possible new system would be necessary. This issue could not be further treated in the course of this work.

3.1.2.3 Considering an efficiency measure as an "advanced replacement investment": does it make a difference?

In this chapter it shall be demonstrated, how the cost calculation is affected when an efficiency measure- such as the installation of a new, more efficient HVAC system- is considered as an *advanced replacement investment*. This is, for example, the case when an installation reaches the end of its lifecycle in 5 years, but could already be replaced today. The following figure compares the effects, when it needs to be decided at point in time t= 0, whether an existing installation will be replaced before it reaches its technical end of the lifecycle, or not:

[23] Birnbaum et al. (2007), p. 223- 224

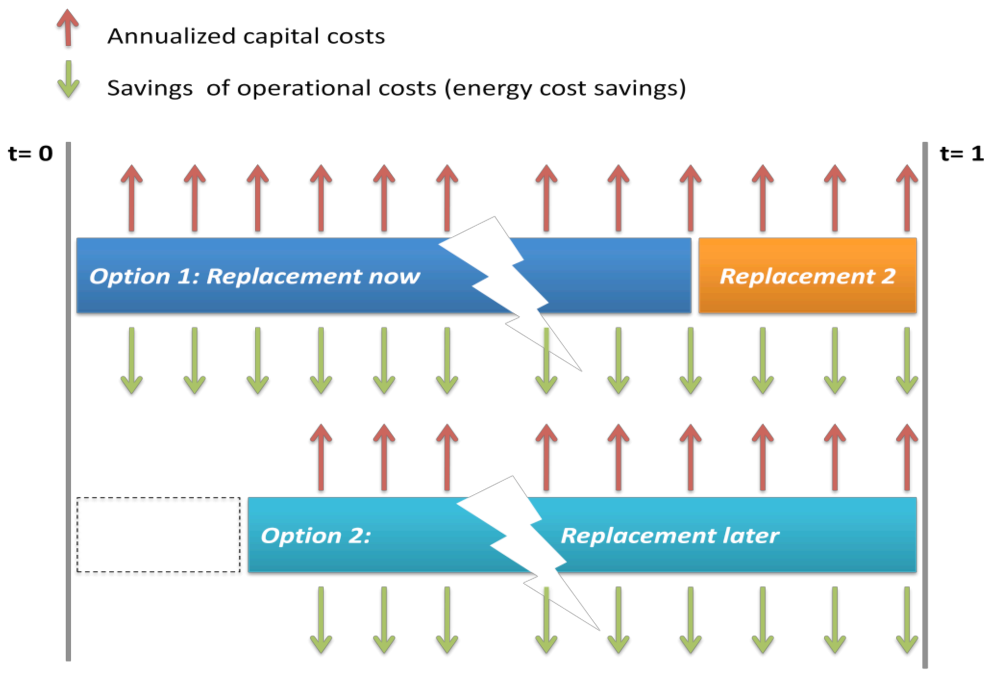

Figure 10: Comparison of payment effects for different replacement options (own illustration)

All investments can be transformed into an annual capital cost. Both options need to be compared over an equivalent period of time. Therefore it needs to be considered, that an earlier replacement also results in an earlier second replacement (*Replacement 2*). One could for example assume that the existing system needs to be replaced in no later than five years, and the new installation has an estimated lifetime of 20 years. Investing today and not in 5 years means that in 20 years the installation has to be replaced again, so it needs to be accounted for the costs for the first five years following the replacement. The end of the comparison period is then in 25 years. One can observe now, that the only difference in capital costs and operational cost savings (energy cost savings) of both options is within the first 5 years. From a pure economic point of view, the savings of operational costs need to exceed the total capital costs during the first five years to justify investing today instead of in five years.

As a result of the mentioned points the following conclusions can be drawn:

- When the refurbishment of an installation is considered as an advanced replacement investment, the *total annual capital costs* (considering the *total costs* of the refurbishment, not only *energy relevant additional costs)*) need to be compared with the savings of operational costs, which are in this case basically the energy cost savings. From a pure economic point of view, an *advanced* replacement (replacement *now* and not in 5 years) should only be carried out, when the savings in operational costs are bigger than the *total annual capital costs* for the new system.
- When the estimated specific costs in $[\frac{SFR}{kW\,h_{el}}]$ in this study for an efficiency measure like an HVAC refurbishment exceed the electricity price, it cannot be automatically assumed that the investment is not profitable. This would only be correct if only the exact *energy related*

additional costs were considered, which is very difficult in many cases (see previous chapter 3.1.2.2).

- For these reasons, the calculated costs for a saved electricity unit are not suited to answer the question whether a measure is profitable or not; they should not be regarded as *absolute* values, as the fraction of *basic costs and energy related additional costs* is not absolutely clear. Nevertheless, they represent a good *relative* benchmark value for the comparison between the different efficiency measures. When a certain amount of money is available to increase the energy efficiency, they serve as an indicator of "where to act first".

3.1.2.4 Energy price assumptions, amortization time and interest rate

For the investment calculations, the following is assumed:

- The interest rate is fixed at *i = 5 %*
- The actual electricity price $p_{elec,act}$ is assumed to be 0, 20 $\frac{SFR}{\text{kWh}_{el}}$, increasing 2 % annually. The average price over a certain amortization period is then:[24]
  - $p_{elec,aver} = 0{,}5 \times p_{elec,act} \times (1+(1+0{,}02)^n)$ $[\frac{SFR}{kWh_{el}}]$

For 20 years one derives an average electricity price of 0, 249 $\frac{SFR}{kWh_{el}}$, for 25 years 0,264 $\frac{SFR}{kWh_{el}}$.

Heat consumptions can be transformed into electricity consumptions by applying the total COP of 3,6 of the heat pump system at EPFL (see chapter 4.3.1). Monetary savings through heat consumption reduction are then derived in the same manner as for electricity consumption reductions. The calculation of electricity prices leads to directly realizable savings, as heat at EPFL is produced in the existing electrically operated heat pumps. If one wants to calculate the total costs of a produced unit of heat, the capital costs, maintenance costs, etc. for the conversion system must be included. This number represents then the realizable monetary savings through heat consumption reduction in the long term. Unfortunately, such a total cost for a produced unit of heat is not available at EPFL. Therefore the price for a heat unit from the heat distribution network Lausanne serves as a reference, which is common practice at the *EPFL- PI- DII_E* as well. One can assume that the heat price already contains all related costs for the heat production including capital costs for the conversion system, the network, etc. The actual heat price from the HDN Lausanne is 91 $\frac{SFR}{MWh}$.[25] This amount, reduced by an assumed 10 % rate of return for the distributor, serves as reference value for the costs of heat, when supplied over a HDN:[26]

- $p_{heat,act} = 91\ \frac{SFR}{MWh} \times \frac{0{,}9}{1000} = 0{,}082\ \frac{SFR}{kWh}$

The average heat price over a certain period with an annual 2 % increase is:

[24] Birnbaum et al. (2007), p. 219
[25] According to *EPFL- PI- DII_E*
[26] Approach according to *EPFL- PI- DII_E*

- $p_{heat,aver} = 0{,}5 \times p_{elec,act} \times (1+(1+0{,}02)^n) \quad \frac{SFR}{kWh_{el}}$

For 20 years one derives an average heat price of 0, 102 $\frac{SFR}{kWh}$, for 25 years 0, 108 $\frac{SFR}{kWh}$.

The energy cost saving calculation is only conducted over heat prices, when only heat is saved due to certain efficiency measure. When heat and electricity are saved, energy cost savings are only calculated over electricity prices, to avoid confusion.

The amortization period for refurbishment project is fixed in the *Phytosphäre* – report at 20 years; also in this study a general amortization period of 20 years for refurbishments concerning the buildings shall be assumed. Furthermore, the economic calculation is always executed for one more value (e.g. 15 years for lighting, 25 years for building envelope refurbishment), to cope with the different expected lifetimes for a building envelope and a technical installation.[27]

For the PV- plant, an amortization period of 30 years is assumed, to cope with the long lifecycles of photovoltaic installations.

For more precise cost calculations, sensitivity analyses for different amortization periods, interest rates etc. could be conducted.

[27] Birnbaum et al. (2007), p. 227

3.2 Heating and building envelope

3.2.1 Introduction

In this chapter, the heat consumption at the EPFL and the performances of the building envelopes shall be examined. The renovation of the building envelope is classical measure to reduce the energy consumption of a building, and the effects of such a measure shall be determined for the older EPFL buildings. The outcome serves also as a benchmark for other possible efficiency measures.

The following graph shows the general heat flows into and out of a building:

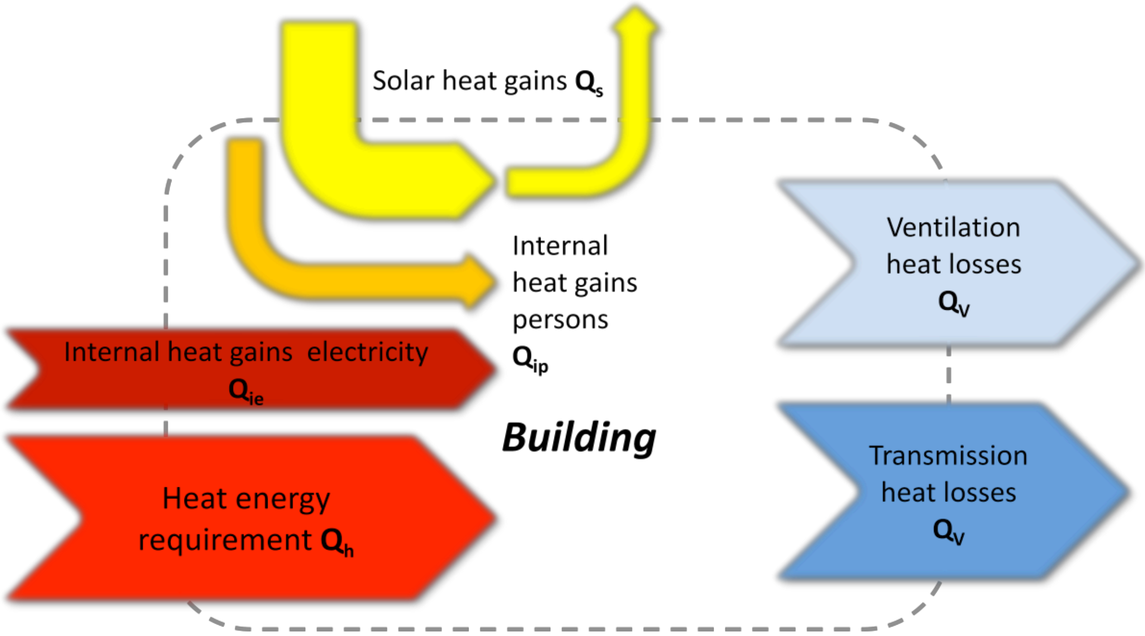

Figure 11: heating balance of a building (without sanitary water, according to SIA 380/1, p. 8; own illustration)

Heat is lost either through transmission losses or ventilation losses. Heat requirement for sanitary water is not regarded here, as sanitary water at EPFL is mostly not heated anymore, in some cases it is done by decentralized electrical boilers.

Transmission losses are caused by heat transfer through the building envelope. The energy lost over the building envelope is a linear function of the exterior temperature, considering the interior temperature is kept constant.[28] The indicator for the quality of the thermal insulation of a building envelope is in literature often called *U- value*. Its unit is $[\frac{W}{m^2 \times K)}]$, which is the heat transmission between interior and exterior space per square meter of the building envelope and temperature difference in Kelvin. The overall U- value of a building envelope is made up of the specific U- values

[28] Girardin (2009), p. 5

for the walls, windows, existing heat bridges, air tightness and other elements in the building elements. It makes quite sense to separate between U- values for windows and walls, as those for windows can be 4 -10 times higher than those for walls.[29] The U- values for windows depend not only on the glazing used, but also on the used frame. [30]

According to the SIA Norms the following values should be achieved for refurbished buildings: [31]

Refurbished buildings:	**Limit value in** $[\frac{W}{m^2 \times K}]$	**Target value in** $[\frac{W}{m^2 \times K}]$
Roofs	0,25	0,15
Walls	0,25	0,15
Floor to basement	0,30	0,2
Windows	1,3	0,9

The heat losses through ventilation are caused through the air exchange with the exterior, which is necessary to assure healthy and hygienic air conditions. As it will be shown in the chapter 3.3, the required air renewal rate depends highly on the use and the occupancy of the building. The renewal rates should be calculated according to the requirements of the different room categories. For naturally ventilated buildings without mechanical ventilation units and with standard utilization, one can assume average hourly air renewal rates for different building categories, which includes for example air renewal for kitchens, WC, etc. Some examples (values per heated surface):[32]

Building category	**Single family house**	**Apartment building**	**Adminis-tration**	**School**	**Hospital**	**Storehouse**
Exterior air renewal rate in $[\frac{m^3}{h \times m^2}]$	0,7	0,7	0,7	0,7	1,0	0,3

These values will be of importance to determine heat losses through transmission and ventilation. Heat losses also occur through infiltration, or leakages in the building envelope. When calculating mechanically induced air flows, one can additionally assume an air flow of infiltration through the building envelope of 0, 1 $\frac{m^3}{h \times m^2}$. [33]

3.2.2 Introduction to the heat curve model

The heat curve shows the required heat load for a building depending on the exterior temperature, which assures a comfortable interior temperature, in the case of EPFL at 21, 5 °C. When the heat curve is known, the consumptions can be further split up in losses caused by *transmission* (U_T) and

[29] Mroz (Ed.) (2003), p. 10
[30] Mroz (Ed.) (2003), p. 12-13
[31] SIA 380/1 (2009), p. 21
[32] SIA 380/1 (2009), p. 32
[33] SIA 2024 (2006), p.15

losses caused by *ventilation* (U_V) ; it can then be derived what impact a refurbishment and additional insulation would have on the building's heat requirement.

To derive the heating curve of a building, the following values are necessary:

- the annual specific heat consumption of a building q_h in $[\frac{kWh}{m^2}]$
- the indoor comfort temperature T_{in} in [°C] (at EPFL: 21,5 °C)
- the cut- off exterior temperature T_{cut},. Above of T_{cut}, no heating is provided (at EPFL: 16 °C)
- the exterior temperatures T_{ext} in [°C]. In this case, hourly temperatures for 2008 from the weather station *Pully* -close to EPFL- were used.

The thermal load requirement for a building is a linear function of the exterior temperature. The actual heat load requirement is given by the following equation:[34]

- $\dot{q}_t = \begin{cases} S \times T_{ext} + b & if\ T_{ext} < T_{cut} \\ 0\ otherwise \end{cases} \quad [\frac{W}{m^2}]$
    - $S = slope\ of\ heating\ curve\ in\ [\frac{W}{m^2 \times °C}]$
    - $b = corection\ factor\ in\ [\frac{W}{m^2}]$

The annual specific heat energy requirement is given by:

- $q_h = \int_Y \dot{q}_t \times dt \quad \left[\frac{kWh}{m^2}\right]$

The cut- off temperature and the slope define the heating curve. The slope of the heating curve is calculated as followed:

- $S = \dfrac{q_h}{\int_{Y:T_{ext} < T_{cut}} T_{ext,t}\, dt - \int_{Y:T_{ext} < T_{cut}} T_{cut}\, dt} \quad [\frac{W}{m^2 \times °C}]$

Furthermore:

- $b = S \times T_{cut} \quad [\frac{W}{m^2}]$

Additionally, at EPFL (and also in other buildings), an exterior temperature is defined where the maximum heat power is provided. At EPFL this is -10 °C. This value defines the size or maximum load of the system. The ENERGIS Tool, implemented in MATLAB and developed at the *LENI- Institute* at EPFL, calculates the heat curve for buildings executing the above mentioned calculation steps. As an example, the results for EPFL- buildings shall be presented here. The annual specific heat consumption for each building at EPFL is known, and the following heat curves can be derived:

[34] Girardin (2009), p. 4

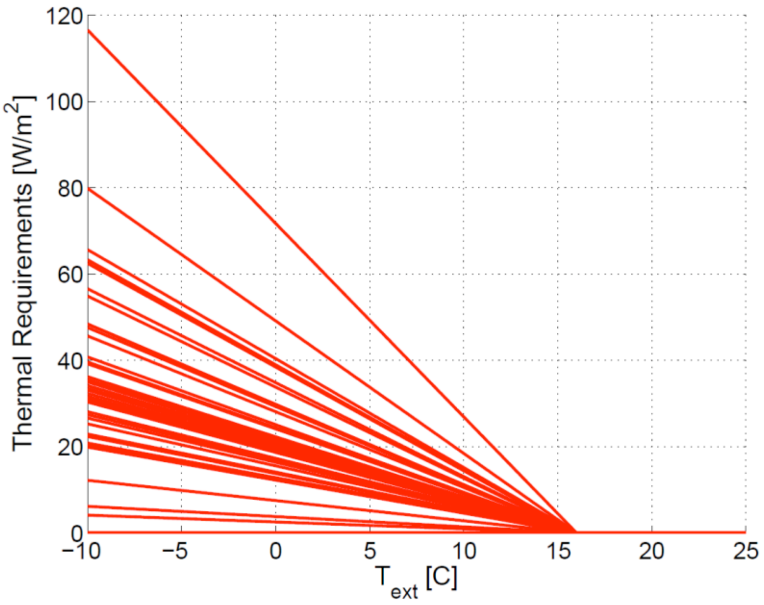

Figure 12: heating curves of EPFL buildings

The topmost heating curve is the one from the building with the highest specific heat consumption, which results in the steepest slope of the heat curve.

The slope S of the heat curve in $[\frac{W}{m^2 \times °C}]$ consists of losses due to ventilation or air exchange, and losses due to heat transmission through the building envelope:[35]

- $S = U_V + U_T \quad \left[\frac{W}{m^2 \times °C}\right]$
    - $U_V = heat\ losses\ through\ ventilation\ in\ \left[\frac{W}{m^2 \times K}\right]$
    - $U_T = heat\ losses\ through\ transmission$ in $\left[\frac{W}{m^2 \times °C}\right]$

The following figure shall illustrate the possible heat losses of a building:

[35] Annotation: S is originally defined in $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \times °\mathrm{C}}\right]$ in ENERGIS, where as U- values in literature are mostly defined in $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \times \mathrm{K}}\right]$. $\mathrm{U_T}$ shall here be defined in $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \times °\mathrm{C}}\right]$. S, $\mathrm{U_V}$ and $\mathrm{U_T}$ all represent slopes of a heating curve. It is possible to add and subtract these values, as the slope has on both the °C scale and the K scale the same value.

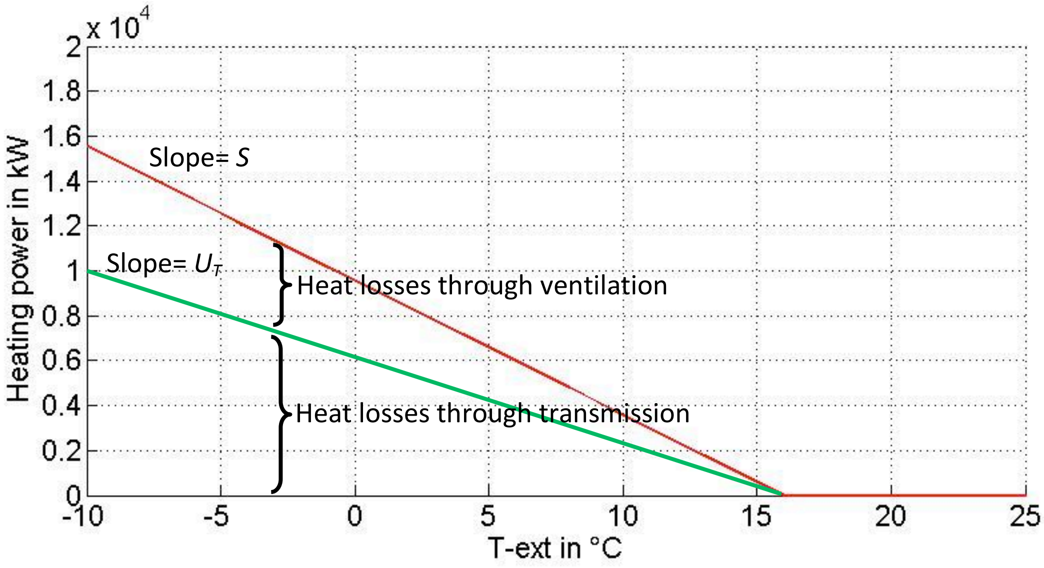

Figure 13: example of heat losses for a building

It is important to keep in mind at this point, that these values are referred to the heated building surface (heated surface) and *not* yet to building envelope surface, as it is mostly the case in literature.

The losses through ventilation can be calculated as followed: [36]

- $U_V \;= \frac{n \times V_{bat} \times 0{,}32 \,\frac{W \times h}{K \times m^3}}{A_h} \;\left[\frac{W}{m^2 \times K}\right]$
  - $n =$ air exchange rate per hour in $[\frac{1}{h}]$
  - $0{,}32 \,\frac{W \times h}{K \times m^3}$ is the specific heat capacity for air in 400m meters above sea level
  - $A_h =$ heated building surface

Equivalent to the equation above is

- $U_V \;= R \;\times 0{,}32 \,\frac{W \times h}{K \times m^3}$
  - $With\ R = \ specific\ air\ exchange\ rate\ in\ [\frac{m^3}{m^2 \times h}]$

When the air exchange rate R is known it is possible to derive:

- $U_T = S - U_V \left[\frac{W}{m^2 \times °C}\right]$

This represents the U- value per m^2 of heated building surface. If the relation between building surface and building envelope surface is known, one can calculate the U- value per envelope surface, $U_{T,\ Env}$.

[36] According to SIA 384.201 (2003), p. 22, see also Rager (2009), p. 42

3.2.3 Model application to EPFL

The goal is to determine the U- values for buildings at EPFL, focusing on the buildings of first construction period (1975- 1985), as they are due to their age the first candidates for possible refurbishment measures. It is sufficient to determine the U –value $U_{T,\ Env,}$ (referred to building envelope surface) for one building of this period, as the technology of the buildings' envelopes (including walls, windows, doors etc.) for all buildings of this period is generally the same. Once the specific U- value is known, the heat losses for other buildings can be calculated by multiplying the U-value with its building envelope surface.

As reference building to determine the U- values serves the Building *BS*. Although constructed in 1994 (already in the second building phase of EPFL), it was added to the existing building compound, using the same technology for the building envelope as buildings from first construction period. It is chosen as reference building, because it is used exclusively as administrative building and is only naturally ventilated (except for toilets, etc.); therefore the SIA approximations for air renewal rates in naturally ventilated buildings can be applied. In other buildings, where mechanical ventilation units supply the building with fresh air due to partial use as labs, lecture halls etc., it is not possible to determine air renewal rates without detailed measurements, as the ventilation units might deliver highly elevated air flow rates (see chapter 3.3).

ENERGIS allows now to calculate the signature of the building, according to the equations in chapter 3.2.2. For the *BS* building (heated surface 10.267 m^2, annual heat consumption 509.183 kWh), one obtains a slope for the signature of:

- $S_{BS} = -0{,}937 \quad [\frac{W}{m^2 \times °C}]$

To obtain the U- value for transmission, specific heat losses through ventilation need to be subtracted:

- $U_v = R \times 0{,}32 \frac{W \times h}{K \times m^3} \quad \left[\frac{W}{m^2 \times K}\right]$
  - With R= specific air exchange rate in $[\frac{m^3}{m^2 \times h}]$.

As explained in chapter 3.2.1, an air renewal rate of $0{,}7 \frac{m^3}{m^2 \times h}$ is assumed for naturally ventilated buildings. Then one obtains the following heat losses through ventilation:

- $U_v = R \times 0{,}32 \frac{W}{K \times m^3} = 0{,}7 \frac{m^3}{m^2 \times h} \times 0{,}32 \frac{Wh}{K \times m^3} = 0{,}224 \quad \left[\frac{W}{m^2 \times K}\right]$

$U_{T,\ BS}$ amounts then to:

- $U_{T,BS} = S_{BS} - U_{V,BS} = 0{,}713 \quad \left[\frac{W}{m^2 \times °C}\right]$

In a next step, the building envelope surfaces of the building need to be determined. As now exact values are available, the building envelope surface is approximated with the following approach:

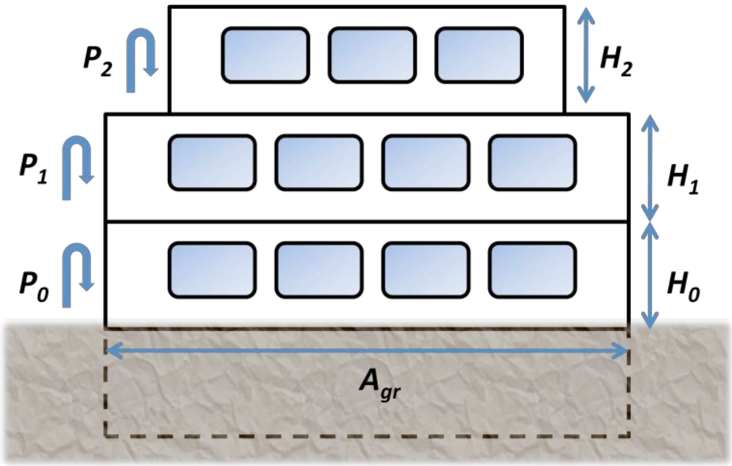

Figure 14: used Building measures

- P_n = $Perimeter\ of\ floor\ n\ in\ [m]$
- H_n = $Height\ of\ floor\ n\ in\ [m]$
- A_{gr} = $Surface\ over\ ground\ in\ [m^2]$

The bottom plate of 0th floor is treated as a boundary to a unheated space, as basements are basically not heated. The thermal relevant building envelope surface is then derived according to the equation in the SIA Norms:[37]

- $A_{th} = \sum_j A_{e,j} + \sum_k b_{uk} A_{uk} + \sum_I b_{GI} \times A_{GI} \quad [m^2]$
  - A_{th} = $thermal\ relevant\ building\ envelope\ surface\ in\ [m^2]$
  - $A_{e,j}$ = $Surfaces\ against\ exterior\ in\ [m^2]$
  - b_{uk} = $Reduction\ factor\ for\ surfaces\ against\ unheated\ spaces$
  - A_{uk} = $Surfaces\ to\ unheated\ spaces\ in\ [m^2]$
  - b_{GI} = $Reduction\ factor\ for\ heat\ losses\ to\ soil$
  - A_{GI} = $Surfaces\ to\ soil\ in\ [m^2]$

The surfaces against unheated rooms (in this particular case surface to unheated basement) are weighted with the reduction factor 0,7, and the following approximating equation for EPFL buildings is derived:[38]

- $A_{th} = 1 \times A_{gr} + 0{,}7 \times A_{gr} + \sum_0^n P_n \times H_n \quad [m^2]$
  - $(1\ x\ A_{gr}\ for\ roof\ surfaces, and\ 0{,}7\ x\ A_{gr}\ for\ floor\ over\ basement) in\ [m^2]$

The following results are obtained for the buildings from first construction phase:[39]

[37] SIA 380/1 (2009), p. 24
[38] SIA 380/1 (2009), p. 35
[39] calculated in *surf_vol.xls* and *Chaleur_batiments_V1.xls*

Building	BI	BS	CE	CH	CM	GC	GR	MA	ME	PH
Therm. rel. build. env. A_{th} in [m^2]	4.717	8.642	21.179	26.237	18.553	31.295	9.682	12.240	24.117	22.187
Heated surf. A_h in [m^2]	4.496	10.267	16.655	28.986	18.663	26.586	9.997	14.018	17.151	23.581

The specific U- value referred to the building envelope surface can be now obtained from the before calculated U-value referred to the building's heated surface:

- $U_{T,Env} = U_T \times \frac{A_{h,n}}{A_{th,n}} \quad [\frac{W}{m^2 \times °C}]$
    - $A_{th} = \textit{thermal relevant building envelope surface in } [m^2]$
    - $A_h = \textit{heated ground surface in } [m^2]$

With the data for the building *BS* the following value is obtained:

- $U_{T,Env,BS} = 0{,}713 \frac{W}{m^2 \times °C} * \frac{10.267\ m^2}{8.642\ m^2} = 0{,}847 \quad [\frac{W}{m^2 \times °C}]$

This value can now be regarded as a real indicator for the average performance of the whole building envelope; it is valid for all the buildings with the same envelope technology.

U_T and U_V, which are the specific values referred to the building's heated surface, can then be derived for the other buildings, which shows then the amount of heat lost by transmission or ventilation. U_T is derived for each building *n* as followed:

- $U_{T,n} = U_{T,Env,BS} \times \frac{A_{th,n}}{A_{h,n}} \quad [\frac{W}{m^2 \times °C}]$

U_V is then determined for each building *n* by:

- $U_{V,n} = S_n - U_{T,n}$

S_n for the buildings is calculated with ENERGIS, according to the previously described equations. The results of these calculations for the examined buildings are:

Building	BI	BS	CE	CH	CM	GC	GR	MA	ME	PH
S in $[\frac{W}{m^2 \times °C}]$	1,453	0,937	1,139	2,098	1,267	1,042	1,227	1,453	1,242	2,433
U_T in $[\frac{W}{m^2 \times °C}]$	0,889	0,713	1,078	0,767	0,842	0,998	0,821	0,740	1,192	0,797
U_V in $[\frac{W}{m^2 \times K}]$	0,564	0,224	0,061	1,331	0,425	0,045	0,406	0,713	0,050	1,636

The following figure illustrates the relation between heat losses causes by transmission and ventilation for the different buildings:

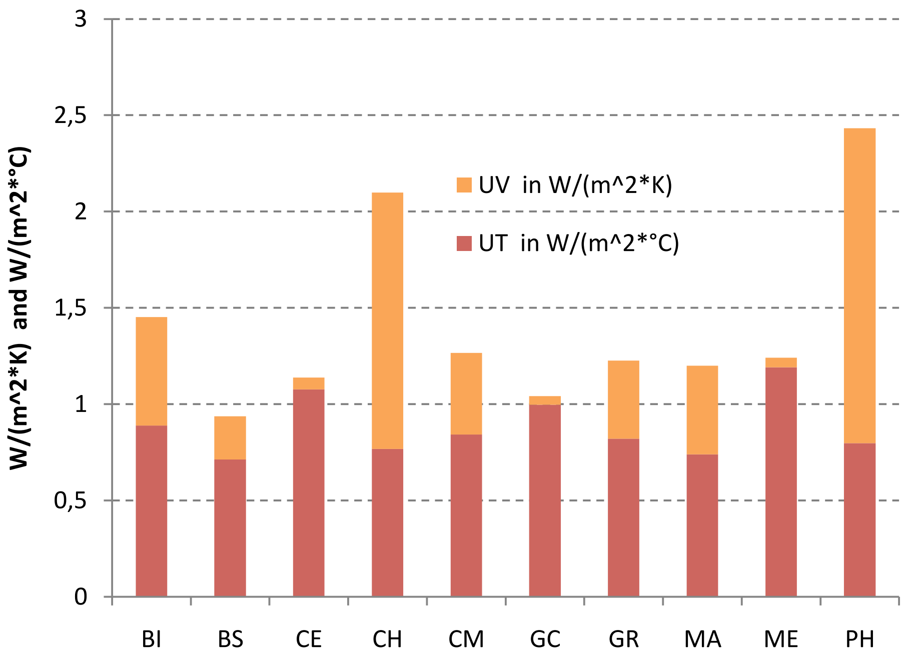

Figure 15: U- Values for buildings of 1st building construction phase at EPFL

The relation S/U_T and S/U_V equivalent to the relation Q_h/Q_T and Q_h/Q_v respectively, where Q_V and Q_T are the total heat losses of the building through ventilation and heat transmission, and Q_h is the annual heat consumption of the building. The heat losses can now be calculated. An example:

- $Q_{V,CH} = \frac{U_V}{S_{CH}} \times Q_{h,CH} = \frac{1{,}331}{2{,}098} \times 3.217.870\ kWh = 2.041.388\ \frac{kWh}{year}$

Building	BI	BS	CE	CH	CM
Heat cons. Q_h in [kWh]	345.679	509.183	1.003.313	3.217.870	1.251.411
Q_T in [kWh]	211.516	387.616	949.227	1.176.482	832.056
Q_V in [kWh]	134.163	121.567	54.086	2.041.388	419.355

Building	GC	GR	MA	ME	PH
Heat cons. Q_h in [kWh]	1.465.755	649.081	889.271	1.126.830	3.036.870
Q_T in [kWh]	1.403.176	434.156	452.856	1.081.103	995.215
Q_V in [kWh]	62.579	214.925	436.415	45.727	2.041.655

The following figure illustrates the total heat losses per building:

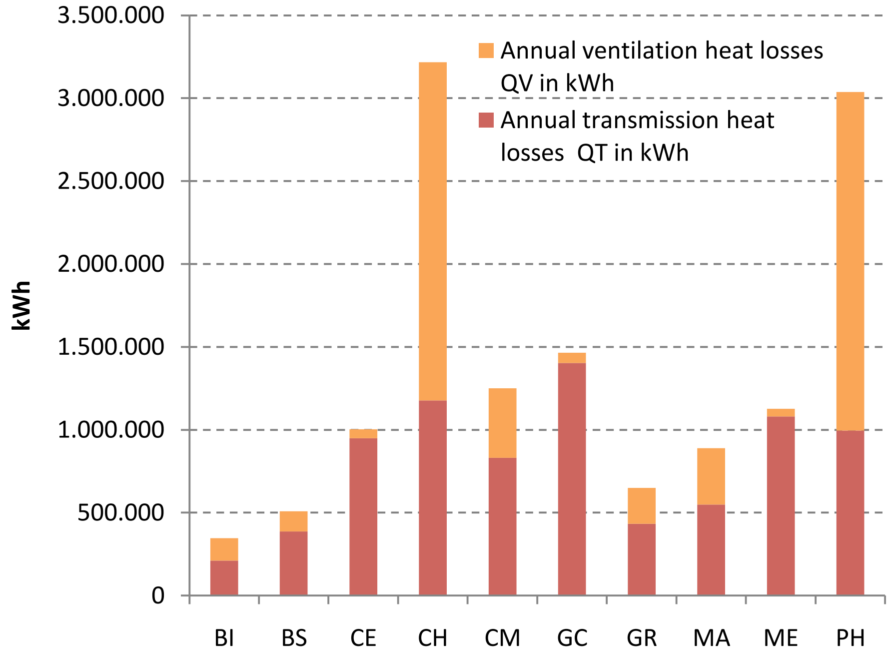

Figure 16: Heat losses for buildings of 1st building phase at EPFL, in kWh/

3.2.4 Calculation of reference values

It shall now be examined, how heat consumption of the buildings would change, if their building envelope was refurbished, and the SIA limit or target U-values for the building envelope were achieved. A refurbishment of the building envelope will reduce the U_T - value of the building and will reduce the losses through heat transmission. The limit and target values for the different envelope surfaces according to SIA are: [40]

Refurbished buildings:	**Limit value $U_{T,Env,lim}$ in $[\frac{\mathbf{W}}{\mathbf{m^2 \times K}}]$**	**Target value $U_{T,Env,tar}$ in $[\frac{\mathbf{W}}{\mathbf{m^2 \times K}}]$**
Roofs	0,25	0,15
Walls	0,25	0,15
Floor to basement	0,30	0,2
Windows	1,3	0,9

The reduction factor for the floor over basement is again 0, 7, and it is assumed that 40 % of the building facades consist of windows (incl. frames) and doors. The new total average U_T - value can be calculated as average over all the building envelope surfaces.

[40] SIA 380/1 (2009), p. 21

Meeting the SIA limit values:

- $U_{T,Env,lim} = \frac{1 \times A_{gr} \times 0{,}25 + 0{,}7 \times A_{gr} \times 0{,}3 + \sum_0^n (0{,}6 \times P_n \times H_n \times 0{,}25 + 0{,}4 \times P_n \times H_n \times 1{,}3)}{A_{th}} \quad [\frac{W}{m^2 \times K}]$
  - $P_n = Perimeter\ of\ floor\ n\ in\ [m]$
  - $H_n = Height\ of\ floor\ n\ in\ [m]$
  - $A_{gr} = Surface\ over\ ground\ in\ m^2$
  - $A_{th} = thermal\ relevant\ building\ envelope\ surface\ in\ m^3$

Meeting the SIA target values:

- $U_{T,Env,tar} = \frac{1 \times A_{gr} \times 0{,}15 + 0{,}7 \times A_{gr} \times 0{,}2 + \sum_0^n (0{,}6 \times P_n \times H_n \times 0{,}15 + 0{,}4 \times P_n \times H_n \times 0{,}9)}{A_{th}}$

The calculated values for all buildings are:[41]

Building	**BI**	**BS**	**CE**	**CH**	**CM**	**GC**	**GR**	**MA**	**ME**	**PH**
$U_{T,Env,lim}$ in $[\frac{W}{m^2 \times K}]$	0,484	0,457	0,448	0,480	0,464	0,474	0,489	0,453	0,475	0,489
$U_{T,Env,tar}$ in $[\frac{W}{m^2 \times K}]$	0,320	0,301	0,295	0,317	0,306	0,313	0,323	0,298	0,313	0,324
U_T in $[\frac{W}{m^2 \times °C}]$	0,889	0,713	1,078	0,767	0,842	0,998	0,821	0,740	1,192	0,797

The original $U_{T,Env}$ was calculated to be 0,847 $\frac{W}{m^2 \times K}$ for all the buildings with the same envelope technology. It shall also be mentioned here, that one makes no big mistake by assuming the same average $U_{T,Env}$- *for* building with the same technology, which can be observed for example regarding the calculated $U_{Env,\ limit}$ which are all in the range between 0,45 and 0,49 W/(m²*K). It is evident, that a refurbishment, which lowered the $U_{T,Env}$ - Value of a building by a certain percentage, would lower losses of the building through heat transmission by the same percentage, as $U_{T,Env}$ is nothing else as the indicator for heat transmission losses per m² of building envelope surface. The new annual transmission losses after building envelope refurbishment according to SIA limit values are:

- $Q_{T,limit,n} = \frac{U_{T,Env,limit,n}}{U_{T,Env,n}} Q_{T,n}$
  - $Q_{T,limit,n} = new\ transmission\ losses\ after\ refubishemnt\ in\ [kWh]$
  - $Q_{T,n} = transmission\ losses\ before\ refubishemnt\ in\ [kWh]$
  - $U_{T,Env,limit,n} = new\ envelope\ U -\ value\ after\ refurbishment\ in\ [\frac{W}{m^2 \times K}]$

The equation for the target values is obtained equivalently.

[41] calculated in *building_envelope.xls*

The following table represents the new transmission losses, when limit and target values are achieved through building envelope renovation:[42]

Building	BI	BS	CE	CH	CM
Q_h in $[\frac{kWh}{year}]$	345.679	509.183	1.003.313	3.217.870	1.251.411
Q_T in $[\frac{kWh}{year}]$	211.516	387.616	949.227	1.176.482	832.056
$U_{T,Env}$ in $[\frac{W}{m^2 \times K}]$	0,84742	0,84742	0,84742	0,84742	0,84742
Applying SIA limit values, transmission losses drop to… [%]	57,14	53,95	52,88	56,67	54,76
Applying SIA target values, transmission losses drop to… [%]	37,76	35,53	34,79	37,44	36,10
new $Q_{T,Env,limit}$, applying SIA limit values in [kWh]	120.850	209.117	501.970	666.728	455.607
new $Q_{T,Env\ target}$, applying SIA target values in [kWh]	79.873	137.734	330.206	440.448	300.358

Building	GC	GR	MA	ME	PH
Q_h in $[\frac{kWh}{year}]$	1.465.755	649.081	889.271	1.126.830	3.036.870
Q_T in $[\frac{kWh}{year}]$	1.403.176	434.156	452.856	1.081.103	995.215
U_{Env}	0,84742	0,84742	0,84742	0,84742	0,84742
Applying SIA limit values, transmission losses drop to… [%]	55,93	57,72	53,49	56,03	57,76
Applying SIA target values, transmission losses drop to… [%]	36,92	38,17	35,21	36,99	38,20
new $Q_{T,Env,limit}$, applying SIA limit values in [kWh]	784.765	250.580	242.244	605.692	574.818
new $Q_{T,Env\ target}$, applying SIA target values in [kWh]	518.018	165.712	159.469	399.855	380.153

[42] calculated in *building_envelope.xls*

The following figure displays the savings per building:

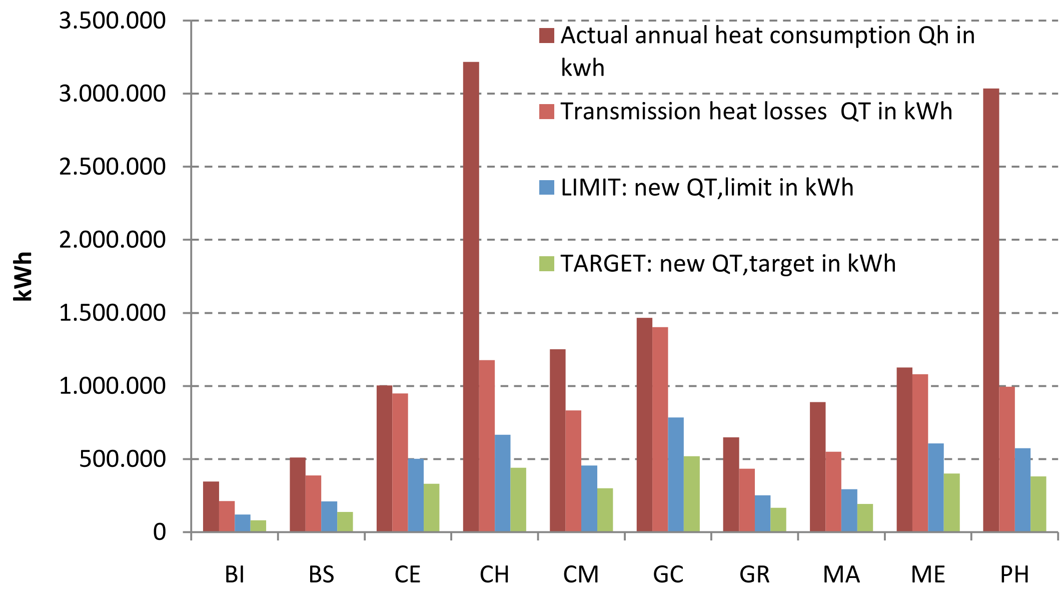

Figure 17: annual consumption before and after a possible building envelope refurbishment, in kWh

3.2.5 Comparison of actual heat demand with reference values

The regarded buildings of the 1st construction phase have an annual heat consumption of 13.495.263 kWh; 7.923.403 kWh are transmission losses. By renovation and if SIA limit or target values were applied, these transmission losses could be reduced to 4.412.373 kWh or 2.911.826 kWh respectively. This would result in annual heat energy savings of 3.511.030 kWh or 5.011.577 kWh. The heat is produced with heat pumps, with an overall COP of 3, 6 (see chapter 4.3.1) throughout the year; heat savings are transformed into savings of electricity:

- $E_{elec} = \frac{E_{heat}}{3{,}6} \quad [kWh_{el}]$

The following table illustrates the summed up results for the examined buildings:

	Actual annual heat cons. Q_h in [kWh]	*Q_T in [kWh]*	*new $Q_{T,lim/tar}$ in [kWh]*	*Savings heat E_{heat} in [kWh]*	*Annual Savings electricity E_{elec} [kWh_{el}]*
Meeting SIA limit values	13.495.263	7.923.403	4.412.373	3.511.030	975.286
Meeting SIA target values			2.911.826	5.011.577	1.392.105

3.2.6 Economic analysis

The heat savings can be transformed into monetary savings with the according electricity prices. As illustrated before, one can assume an average electricity price of 0, 249 $\frac{SFR}{kWh_{el}}$ for the next 20 years, and 0,264 $\frac{SFR}{kWh_{el}}$ for the next 25 years.

The price for heating can be considered, as 0,102 $\frac{SFR}{kWh}$ for the next 20 years and 0,108 $\frac{SFR}{kWh}$ for the next 25 years.

The direct monetary savings due to electricity consumption reduction amount to:

- $G_{elec} = E_{elec} \times p_{elec,aver}\ [SFR]$
  - $G_{elec} = electricity\ cost\ savings\ in\ [SFR]$
  - $E_{elec} = annual\ electricity\ savings\ \ [kWh_{el}]$
  - $P_{elec,aver} = average\ electricty\ price\ [\frac{SFR}{kWh}]$

The annual monetary savings calculated over the heat consumption reduction are:

- $G_{heat} = E_{heat} \times p_{heat,aver}$

With the introduced annuity equation, one can now calculate the maximal investment, which is justified by these savings and which leads to an NPV of zero for the investment. The equations are:

- $A = a \times I_{max} = G_{elec}$
- $I_{max} = \frac{G_{elec}}{a}$
  - $A = annuity\ or\ annual\ capital\ costs\ for\ an\ Investment\ in [SFR]$
  - $a = annuity\ factor\ \ [-]$
  - $I_{max} = maximum\ justified\ Investment\ in\ [SFR]$
- $a = \frac{i \times (1+i)^n}{(1+i)^n - 1}$
  - $i = interest\ rate\ [\%]$
  - $n = amortization\ period\ [years]$

One obtains the following results for the regarded buildings:

	Annual savings electricity E_{elec} in [kWh$_{el}$]	**Annual monetary savings over 20 years [SFR]**	**Annual monetary savings over 25 years [SFR]**	**Max. justified Investment over 20 years in [SFR]**	**Max. justified Investment over 25 years in [SFR]**
Meeting SIA limit values	975.286	242.451	257.535	2.789.054	3.629.678
Meeting SIA target values	1.392.105	367.600	392.105	3.981.043	5.180.935

Executing the same calculation over the saved heat, one derives:

	Annual Savings heat E_{heat} in [kWh]	**Annual monetary savings over 20 years [SFR]**	**Annual monetary savings over 25 years [SFR]**	**Max. justified Investment over 20 years in [SFR]**	**Max. justified Investment over 25 years in [SFR]**
Meeting SIA limit values	3.511.030	357.421	379.658	4.454.259	5.350.873
Meeting SIA target values	5.011.577	510.176	541.916	6.357.924	7.637.733

To get a first raw approximation for the building envelope renovation costs at EPFL, the well documented report about renovation of the laboratory *Phytosphäre (Forschungszentrum Jülich)* building shall be consulted.[43] Through building envelope renovation, the specific transmission losses were reduced from an average 0, 97 $\frac{\mathrm{W}}{\mathrm{m}^2\times\mathrm{K}}$ before refurbishment to 0, 49 $\frac{\mathrm{W}}{\mathrm{m}^2\times\mathrm{K}}$ after refurbishment. These values are close to the actual situation for the older buildings at EPFL in presence ($U_{T,Env}$*~0,85)* and the resulting average transmission, if SIA target values were applied in an eventual refurbishment (0,45 $<U_{T,\ Env,\ limit} < 0{,}49$).[44] The isolation is slightly better as it was at *Phytosphäre* before refurbishment.

As part of the study about the refurbishment, specific costs were determined in $\left[\frac{€}{m^2}\right]$ (relative to envelope surface) for all the envelope refurbishment measures. These costs for the *Phytosphäre* from the middle of 2003 shall now be applied for EPFL. The costs are transferred to present by assuming an average inflation rate of 1 %, and an exchange rate of 1 € = 1, 50 SFR. Furthermore a price adaption of +5 % is applied to the German costs to account for slightly higher prices in the Suisse construction sector.[45] One obtains: [46]

- $P_{SUI\ 2009} = P_{GER\ 2003} \times 1{,}05 \times 1{,}5 \times 1{,}01^6$
  - $P_{SUI\ 2009} = estimed\ price\ level\ in\ SUI\ in\ 2009\ in\ [SFR]$

For the refurbishment of the *Phytosphäre* building the following specific renovation costs were determined:

	Roof insulation	**Envelope insulation for opaque for surfaces**	**Window exchange**
Specific costs in 2003 in $[\frac{€}{m^2}]$	91	152	385
Specific costs today for full refurbishment in $[\frac{SFR}{m^2}]$	152	254	643

The *energy relevant additional costs* for roof and walls consist only of additional costs for insulation material, the other costs (removal of old layers, plastering etc.) are considered as *basic costs*.

[43] Birnbaum et al.(2007)
[44] Birnbaum et al.(2007), p. 145
[45] Prices in construction sector in Switzerland are only slightly higher as in other EU countries, see Eichler et al. (2003), p. 12
[46] Birnbaum et al.(2007), p. 240

Windows replacement costs are considered as 100 % energy relevant additional costs. The fraction of *energy relevant additional costs* on the different measures is given in the *Phytosphäre* documentation.[47] With this information the *specific energy relevant additional costs* can be calculated:[48]

	Roof insulation	Envelope insulation for opaque surfaces	Window exchange
Fraction of *energy relevant additional costs* in total refurbishment costs	20 %	20 %	100 %
Specific *energy relevant additional costs* in [$\frac{SFR}{m^2}$]	30	51	643

To derive the total costs of renovation for the considered EPFL buildings, the specific costs with the referring surfaces of the examined building park need to be multiplied. It shall be mentioned, that in the *Phytosphäre*- refurbishment, the floor to basement was not further insulated, as no economical solution was found.[49] Two calculations are therefore executed, one where the floor to basement is not refurbished **(1)**, and one where it is refurbished, and specific costs identical to roof refurbishment are considered **(2)**. Again, it is assumed that 40 % of the buildings' facades consist of windows, and 60 % are opaque surfaces. The resulting investment costsfor all *n* buildings are: [50]

- $I_{Env} = \sum_0^n 1 \times A_{gr} \times c_{roof} + P_n \times H_n \times (0{,}4 \times c_{windows} + 0{,}6 \times c_{opaque})$ **(1)**
- $I_{Env} = \sum_0^n 2 \times A_{gr} \times c_{roof} + P_n \times H_n \times (0{,}4 \times c_{windows} + 0{,}6 \times c_{opaque})$ **(2)**

The *surfaces over ground* for all buildings amount to 52.238 m², the facades surfaces to 90.045 m² for the considered buildings.[51] This leads to the following investment costs for renovation:

Total renovation investment excl. floor to basement **(1)** in [SFR]	44.861.518
Energy relevant additional costs excl. floor to basement **(1)** in [SFR]	**27.515.531**
Total renovation investment incl. floor to basement **(2)** in [SFR]	52.809.199
Energy relevant additional costs incl. floor to basement **(2)** in [SFR]	**29.075.978**

The energy related annual capital costs for 20 or 25 years amortization period are then:

- $A_{env} = I_{env} \times \frac{i \times (1+i)^n}{(1+i)^n - 1}$
  - $I_{env} = Energy\ relevant\ additional\ investment\ costsfor\ envelope\ refurbishment\ in\ [SFR]$
  - $A_{env} = annual\ capital\ costs\ in\ [SFR]$
  - $i = interest\ rate\ in\ [\%]$
  - $n = amortization\ period\ in\ [years]$

[47] Birnbaum et al.(2007), p. 225
[48] calculations in *Fin_calculations.xls*
[49] Birnbaum et al.(2007), p. 144
[50] calculated in *Build_envelope.xls*
[51] *see building_envelope_v2.xls and surf_vol.xls*

For I_{Env} = 27.515.531 SFR, i = 5 % and n = 20 years, one obtains:

- $A_{env,EPFL} = I_{env} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} = 27.515.531 \times \frac{0,05 \times (1+0,05)^{20}}{(1+0,05)^{20} - 1} = 2.207.917\ SFR$

	20 years amort. period	**25 years amort. period**
Energy rel. add. capital costs excl. floor to basement **(1)** in [SFR]	2.207.917	1.952.295
Energy rel. add. capital costs incl. floor to basement **(2)** in [SFR]	2.333.132	2.063.012

3.2.7 Interpretation of the result and conclusion

The result is a bit sobering: all calculated costs are far away from a value which would be justified by the annual monetary savings. As shown in the table above, the achievement of limit values would lead to monetary savings of max. 541.916 SFR. A positive NPV would be achieved if investments were not higher than the economically maximum justified amount of 7.637.733 SFR. In short words: The renovation of the building envelope is far away from being economic. Investment costs can by far not be amortized by the returns through energy savings, not even if only energy relevant costs are taken into account.

The result gets another taste, when the reasons for the high costs are further analyzed: The costs for the window exchange of 643 $\frac{SFR}{m^2}$ were fully considered as *energy relevant additional costs*. The costs for the windows exchange with the considered surface amount to 23.184.058 SFR. If 20 % of the total costs for the windows refurbishment would be considered as *energy relevant, energy relevant additional costs* for windows would only amount to 4,6 million SFR. The energetic relevant refurbishment costs of the building envelope would then amount to 8.968.285 SFR instead of 27.515.531 SFR. This amount could almost be financially amortized by the related energy savings, when SIA target values were met. If the exchange costs of the windows were 100 % considered as *anyway* or *basic costs*, the refurbishment investment would amount to 4.331.473 SFR.

So the chosen consideration of the windows exchange costs has a significant effect on the calculation results.

One could also draw the conclusion not to renew the windows. To determine the energy savings of the other buildings envelope measures, the exact actual U- values of windows, walls etc. for EPFL needed to be determined.

Further reasons, why the building envelope refurbishment turned out to be not economic in this case, are:

- The building envelope of the examined buildings is already relatively good. They were constructed after the oil crisis in the middle of the 70s, and the adapted isolation standards were quite high for their time.
- The heat at EPFL is produced on a very efficient way, mostly by the heat pumps with an overall COP of 3,6 throughout the year, so savings in the heat demand of the buildings are not reflected as high monetary returns.
- As the figures above show, a big fraction of heat is lost through ventilation mainly in the buildings also used as laboratories. This is for example not the case in casual administrative buildings. A building envelope refurbishment has no effects on these ventilation losses. When a higher fraction of heat is lost by transmission, refurbishment measures have a more significant impact.

Finally the costs per saved kWh of electricity shall be calculated. The most economic scenario (U-value reduction to SIA target values (25 years amortization period, no refurbishment of floor to basement) is therefore chosen:

	Investment for envelope renovation in [SFR]	**Annualized capital costs in [SFR]**	**Annual electricity savings in [kWh$_{el}$]**	**Costs in [$\frac{SFR}{kWh_{el}}$]**
Windows considered 100% as energy relevant costs	27.515.531	1.952.295	1.392.105	1, 40
Windows considered 0% as energy relevant costs	4.331.473 SFR	307.329	1.392.105	0, 22

Annotation: The chosen approach represents a simplification. A lower U- value for the building envelope will not only lower the slope of the heat curve of a building, but will also further reduce the cut- off temperature. This effect is not yet considered in the chosen approach. To include this effect, the new U- value for transmission after refurbishment needs to be evaluated, and the heat signature must be re- calculated, with the equations shown in chapter 3.2.2. With this approach, a more precise result will be obtained. The heat savings estimated in this chapter represent therefore a "pessimistic" approximation, as it is not yet considered, that reduced transmission heat losses will result in less hours of operation per year for the heating system. Theoretically this applies also to heat savings due to a refurbishment of the ventilation system, which will be evaluated in chapter 3.3.

3.3 The ventilation system

3.3.1 Ventilation as important factor of energy consumption

The energy consumption of ventilation systems represents a very substantial fraction of the overall energy consumption of many buildings, especially of non- residential buildings.[52] At EPFL, its consumption is represented on the grid *Force-Service*, on which a consumption of more than 14 million kWh per year was recorded in 2008. Ventilation is supposed to be the biggest consumer on the grid *Force- Service*, and therefore one of the main electricity consumers at EPFL. Hence, a closer analysis of the ventilation system at EPFL will be conducted.

An air treatment system has to fulfill the following functions, according to the DIN- Norms:

- Supply rooms with the necessary external fresh air, when natural ventilation is insufficient or not possible
- Discharge pollution and contaminations in the air
- Discharge of heat and cooling loads, as well as air humidity loads
- Eventually providing a pressure protection in laboratories, kitchens, clean rooms etc.[53]

Air treatment systems can generally include installations for heating, cooling, humidification units, de- humidification units, and the ventilation fans. The energy for the fans for air renewal and air transportation itself is in milder climates the most important fraction. When a high air renewal rate is necessary, the specific energy consumption for ventilation can be even bigger than heating consumption.[54] Furthermore, the ventilation strategy has an important impact on the heating energy consumption of a building. A high air renewal rate causes a higher heat demand. This effect can be observed in the buildings' energy statistics in the chapter 2.2, where the highest specific heat demands can be found in buildings with a high fraction of laboratories and therefore a high air renewal rate, like the buildings *AI*, *PH*, and *CH*. This work will therefore focus on the improvement of the ventilation or *air transport* function within the air treatment system.

In literature, the air treatment system plays an important role in improving buildings energy efficiency. As described, efficiency measures on the air treatment system have substantial impacts on the total energy efficiency of the building and can very often be achieved with low costs and small investments.[55]

The *Informationszentrum Energie (BW)* states that the 10- year- lifetime costs of a ventilation fan are composed of only 5 % of investment costs for the ventilator, 5 % of maintenance and operations costs and an overwhelming 90 % of energy costs.[56] These figures show what impact the right choice of the fan has on the lifetime costs, and that the efficient operation of a fan is also economically seen

[52] Birnbaum et al.(2007), p. 9
[53] Informationszentrum Energie (Ed.) (2002), p. 3
[54] SIA 2024 (2006), e.g. p. 49
[55] Birnbaum et al. (2007), p. 19
[56] Informationszentrum Energie (Ed.)(2002), p. 4

of highest importance. A few points shall now be mentioned here which influence significantly the consumption and efficiency of an air treatments system:

- Accordance of effectively provided air streams and the real needs of the supplied rooms, also after the usage characteristic of the room has changed
- The need of special services like (de-) humidification
- The need of room cooling devices
- The additional energy needed through pressure losses in inefficient air supply channels
- Existence of heat recovery
- Part load operation possible, when no full load operation of the system is necessary (e.g. nights, weekends).[57]

Some main reasons can be identified, why many air treatment installations in older buildings do not provide their services in an efficient way anymore, in today's understanding:

- Electronic systems to effectively control the air volume flow for single rooms were not yet available in the 70s
- Frequency converters to control the motor rotation to deliver an appropriate variable air stream, were also not available
- The usage of rooms has changed over time, ventilation was not adapted
- The controls of the system were mostly analog, and a flexible volume stream was too complicated to implement. The focus was on delivering a sufficient air stream, and not on energy management issues.[58]

3.3.1 The ventilation system at EPFL

At EPFL, the basic ventilation strategy is natural ventilation, which means that rooms shall be ventilated just by opening windows. According to the EPFL standards, mechanically induced ventilation may only be used if absolutely necessary and when natural ventilation does not suffice.[59] This is for example the case for the laboratories, but as well in many lecture halls. Heat recovery units are installed wherever technically feasible.

One can basically identify four different ventilation systems at EPFL:

- Double flow high pressure systems: system can be found in the CH, GR and GC buildings.
- Standard- monoblock low pressure ventilation systems, installed in most of the buildings.
- More complex ventilation systems acclimatization units. This system can be found for example in the buildings BI, MA, BM, AN.
- Systems designed for very high air flows in the buildings AI, MA.[60]

[57] Birnbaum et al.(2007), p. 19- 20
[58] Birnbaum et al.(2007), p. 21
[59] *EPFL- Pl- DII_E* (2008), p.25
[60] According to *EPFL- Pl- DII_E*

Especially the double flow systems have an elevated consumption in comparison to other systems. Hot and cold air is continuously produced and supplied to the room over two separated air ducts. Each room has then a mixing box, where the hot and cold air streams are mixed, according to the specific demand of the room. Due to the low specific thermal capacity of air (compared to water), high air flows are necessary to provide heat and cooling, which results in high energy consumptions. Furthermore hot and cold air is continuously produced, although not necessarily needed. Finally, the two necessary air ducts require higher energy consumptions as a single duct for air distribution. High pressure systems are often installed, when space for the ventilation system is limited. The air is then provided over small diameter ducts under high pressure and with very high air flow speeds around 10 m/s, whereas low pressure systems work with speeds around 2 m/s. The high flow speed results in elevated energy consumptions for the air distribution. It is in some cases possible to replace a high pressure system with a low pressure system.[61,62,63,64]

General propositions about efficiency measures on the ventilation system will be made in the chapter 3.3.8.

3.3.2 Approach to determine the performance of EPFL's ventilation system

University buildings are very specific buildings concerning energy consumptions. This was shown in chapter 2.2 where similar buildings from the same age and with a similar building envelope have a completely different energy signature. So the way a building is used - for example if it inherits laboratories - has a big impact on its energy consumption. To cope with this fact, it is necessary to find a specific, adapted and fair comparison value for each building.

For every building at EPFL the surfaces for different room categories according to *DIN 277/ 2* are known, such a list was provided by the *EPFL- Pl- DII_E.* The SIA provides specific limit (maximum acceptable) and target values for consumption of ventilation for each room category. With this information, the limit and target values for the consumption of the building can be derived. In the following, this approach is further explained.

In a first step, the consumptions for ventilation in each building need to be evaluated. As mentioned before, the consumptions for the air treatment system are recorded on the grid *Force- Service*, and the *Force- service* consumptions are known for most of the buildings. For reasons of a simplified presentation of the results, only the important buildings on the campus will be presented, which stand for more than 13.5 million kWh_{el} of the 14.5 million kWh_{el} consumed at EPFL in the category *Force- service*.

[61] ENERGHO (Ed.)(2000), p. 4
[62] ASHRAE (Ed.) (2004), chapter 2.10
[63] Informationszentrum Energie (Ed.) (2002), p.20
[64] Joos (Ed.)(2004), p.191 ff.

Four main consuming elements can be generally found within the category *Force- Service*:

- The ventilation aggregates, providing the air flow into, within, and out of the buildings
- The cooling aggregates
- The industrial water pumps, providing water for cooling for the servers, for the scientific processes which need to be cooled, and for the room cooling units to discharge the heat loads
- The pumps for the heating water circulation in the building, provided by the heat distribution network.

Humidifying units have mostly been taken out of service at EPFL for energy saving reasons.

The first challenge is now to determine the consumption fractions for the different elements on the grid *Force- Service*. Therefore several approximations need to be made:

- According to the SIA- Norms, the consumptions of the heating water circulation for bigger buildings can be approximated with a tenth of a percent of the building's heat consumption:[65]
    - $C_{heat.circ.pumps} = 0{,}001 \; x \; Q_h \quad [kWh_{el}]$

- The energy required for the industrial water circulation pumps needs to be approximated by the following approach: for all the buildings the flows of industrial water are known, but not the energy consumptions for the circulation pumps in the buildings.[66] But the annual consumption has been measured within the DIAGELEC project in 1999 for the building *PH* (259.721 kWh_{el}).[67] The specific energy consumption for the industrial water circulation can now be derived by dividing the energy consumptions through the according industrial water flow (building PH: 660.000 m^3 per year). The specific consumption results in:
    - $\frac{259.721 \; kWh_{el}}{660.000 m^3} = 0,39 \; \frac{kWh_{el}}{m^3}$

  The industrial water circulation pump consumption for each building can then be derived by multiplying the water flows with the specific consumption:
    - $C_{IW.pumps} = 0,39 \; \frac{[kWh_{el}}{m^3} \; x \; f_{IW \; flow} \quad [kWh_{el}]$
        - $f_{IW,flow} = annual \; IW \; flow \; per \; building \; in \; [m^3]$

- Contrary to conventional cooling installations, there is little energy consumption for cooling at EPFL. Only in exceptional cases conventional cooling units with compressors are used. This amount is negligible. In general the cooling is provided by cold lake water, cooling down the ventilation air in heat exchangers. So the only cooling related energy consumption is the consumption of the lake water pump (which is separately recorded) and the distribution pumps in the buildings.

[65] SIA 380/4 (2006), p. 56
[66] *EPFL- PI- DII_E* (2007)
[67] *EPFL- PI- DII_E* (2006), p. 44

After having determined for each building the consumptions for heat circulation pumps and industrial water circulation pumps, one obtains the consumptions for the ventilation as follows:

- $C_{venti\ ,actual}\ = C_{F-S} - C_{heat\ .circ\ .pumps}\ - C_{IW.pumps}\ [kWh_{el}]$
  - $C_{F-S} = consumption\ recorded\ on\ grid\ F-S\ in\ [kWh_{el}$

The next step is to define for each building the comparison values according to the standards SIA. As mentioned before, a list was provided by the *EPFL- Pl- DII_E,* containing surfaces of all room categories according to standard DIN 277/ 2, "classification of net ground areas" for each building. This list is transformed into a matrix, showing the different buildings on one axe and the room categories on the other axe. The matrix then contains for each building and each room category the according surface (e.g. building *PH*, room category "electronic and physical laboratories": 4.308 m^2; building *PH*, room category "lecture halls": 1.133m^2, etc.). This allows a characterization of the usage of the buildings, which is necessary to find values for comparison.

Unfortunately, the room categories in the DIN standards are not equivalent to those in the SIA standards. It is therefore necessary to relate each existing room category at EPFL according to DIN-standards with a similar room category in the SIA standards.

The SIA technical bulletin *"Standard- Nutzungsbedingungen für die Energie- und Gebäudetechnik"* gives limit and target values for the specific energy consumption in the categories lighting, ventilation, cooling, humidification, heating, and sanitary water for different room categories like lecture halls, libraries, kitchens, restaurants, etc. The values are evaluated by considering typical room conditions like room climate, facades etc. Furthermore, estimations are made about the occupancy of the different room categories, namely on a daily basis, as well as on a monthly basis. From these basic assumptions, the maximum acceptable limit values, as well as aspired target values are derived. The method shall be quickly demonstrated here with the example of the room category "lecture halls":[68]

For the ventilation, the starting point for the calculation is the necessary specific volumetric air flow, which is also specified in the SIA standards. For some room categories, a value "per person", is initially determined, the "per surface" value is then derived by applying the occupancy assumptions. For other categories, where the occupancy does not play the dominant role, for example in kitchens, the value is directly determined per m^2. For lecture halls a value of 15 $\frac{\mathrm{m}^3}{\mathrm{h}\times\mathrm{m}^2}$ is given for the full load hours. The next step is the choice of the ventilation system for the room category according to SIA 382/1, chapter 1.5. A typical system for the according room category is assumed. The choice of the control system is also of importance (1 step, 2 step, step- less), and is also specified by the SIA standards according to the necessary air flow rates.[69] In the case of the lecture halls, a *simple* ventilation system is assumed, together with a 2- step control (to achieve the limit value), or a step-less control (to achieve the target value). For this system a specific fan power of 0,55 $\frac{\mathrm{W}}{\mathrm{m}^3\times\mathrm{h}}$ is given as limit value, the target value is 0,34 $\frac{\mathrm{W}}{\mathrm{m}^3\times\mathrm{h}}$. Multiplied with the values for the specific volumetric air

[68] SIA 2024 (2006), p. 48
[69] SIA 2024 (2006), p. 15

flow rates, one obtains a specific electrical fan power in [$\frac{W}{m^2}$]. Then the annual operating hours need to be evaluated. Part load hours are transformed into full load hour equivalents, considering also the changing efficiency of the fan in part load operation. For the lecture halls, a *full- load- operating-hour- equivalent* of 1770 hours as limit values is obtained, the target value is 1040 hours per year. One can then calculate the annual electrical consumptions for ventilation (in [$\frac{\mathrm{kWh}_{\mathrm{el}}}{\mathrm{m}^2}$]), by multiplying specific electrical fan power (in [$\frac{\mathrm{W}}{\mathrm{m}2}$]) and the full load hours, and dividing by 1000. The resulting limit value for lecture halls is 15 $\frac{kWh_{el}}{\mathrm{m}^2}$, the target value results in 5 $\frac{kWh_{el}}{\mathrm{m}^2}$.

So the specific limit consumption for ventilation for a certain room category *i* is defined as:

- $c_{vent,limit,i} = f_{SIA,i} \times p_{vent,limit,i} \times t_{vent,limit,i}$ [$\frac{kWh}{m^2}$]
    - $i = room\ category\ according\ to\ Norm\ SIA$
    - $f_{SIA,i} = specific\ volumetric\ air\ flow\ for\ room\ category\ in$ [$\frac{m^3}{m^2 \times h}$]
    - $p_{vent,limit,i} = specific\ fan\ power\ in$ [$\frac{W}{m^3 \times h}$]
    - $t_{vent,limit,i} = annual\ full\ load\ operating\ hoursequivalent\ in\ [h]$
- the equation for target consumption is equivalent

Unfortunately, the SIA norms do not give values for all room categories. For the laboratories, alternative values need to be evaluated: according to the *EPFL- PI- DII_E,* the air stream for laboratories needs to be around 10 times the room volume per hour or bigger. Assuming a room height of 3 m, this would result in an air volume stream of 30 $\frac{m^3}{h \times m^2}$, which shall be considered here. The standard DIN 1947- 7 proposes a flow rate of at least 25 $\frac{m3}{h \times m2}$ for laboratories. The biggest specific electrical fan power found in the SIA- *"Nutzungsbedingungen"* are those for Kitchens, which are specified as 0,91 $\frac{W}{m^3 \times h}$ (limit value) or 0,55 $\frac{W}{m^3 \times h}$ (target value), and shall serve as a reference for laboratories. In other scientific reports about laboratory retrofits, similar values are given.[70] The SIA standard calculates with 2040 full load hours (limit value) or 1230 hours (target value) for kitchens. These values seem pretty low for a laboratory; therefore these values are for this examination replaced by 6000 hours and 3000 hours respectively. 6000 full load hours equivalents per year are for example obtained, if the system runs for around 60 % of the time (nights and weekends) with 50 % of its full load electrical consumption, and the rest of the time with full load consumption.[71] With the mentioned values, an annual specific consumption for ventilation in laboratories of 164 $\frac{kWh_{el}}{m^2}$ as limit value and 46 $\frac{kWh_{el}}{m^2}$ as target value is calculated. It shall be mentioned here, that the comparison values for labs have been chosen rather high for this work. The laboratories have very specific demands for ventilation, and their needs shall not be underestimated for a fair comparison.

As for all room categories the limit and target values for the specific annual consumption for ventilation are defined now, one obtains the absolute comparison values for ventilation for each building, by multiplying the specific values for the different room categories with the respective

[70] Birnbaum et al.(2007), p.25
[71] Birnbaum et al.(2007), p.156

surfaces in the different buildings. The limit consumption for ventilation for a building b amounts then to:

- $C_{vent,limit,b} = \sum_{i=1}^{n} c_{vent,limit,i} \times a_{i,b} \quad [kWh_{el}]$
  - $a_{i,b} = surface\ of\ room\ category\ i\ in\ building\ b\ in\ [m^2]$
  - $c_{vent,limit,i} =$ $specific\ consumption\ for\ ventilation\ for\ room\ category\ i\ in\ \frac{[kWh_{el}]}{m^2}$
- $target\ values\ are\ calculated\ equivalently$

In some cases limit and target values are given in the standards, but it is known that the corresponding room category at EPFL is generally not mechanically ventilated. In this case the consumption for the corresponding room category is set to zero. [72]

3.3.4 Comparison between actual consumption and reference values

The following figure shows the result of the comparison, illustrating the real consumptions for ventilation, as well as the determined limit and target values:[73]

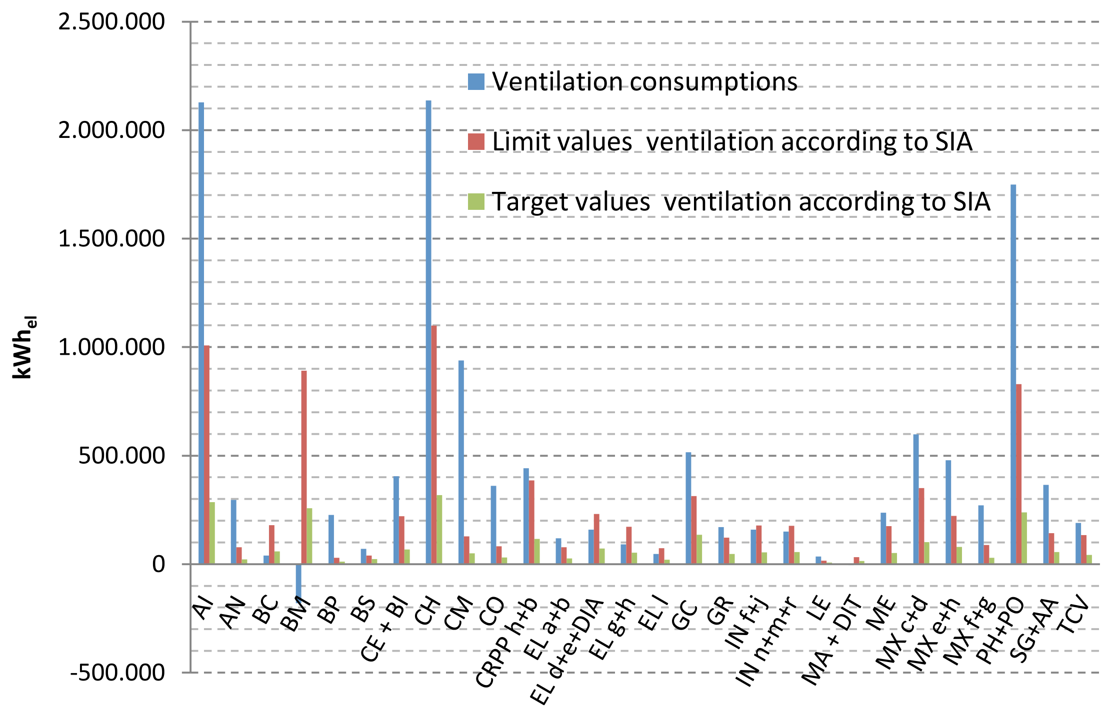

Figure 18 : Consumptions of ventilation at EPFL, compared to limit and target values

[72] calculated in *Ventilation_Calculation_EPFL_v2.xls*
[73] calculated in *Ventilation_Calculation_EPFL_v2.xls/ selected_buildings*

The total consumption for ventilation amounts to 12.188.895 kWh_{el}. The values for the building *BM* are obviously not really correct, it is assumed (as already mentioned in the chapter 2.2), that consumers in the category *Force- Service* in this building are recorded on another grid. The first impression is that the buildings *AI* (life sciences), *PH* (physics) and *CH* (chemistry) are the key buildings for a substantial energy consumption reduction. Their consumptions are very high compared to the reference values, although very high comparison values for the room category "laboratories" were chosen, due to their usage as laboratories and the resulting higher consumption for ventilation. Another important building with a high potential for efficiency improvement in cooling and ventilation is obviously the building *CM*, where the very big consumption cannot be explained by its usage characteristics. Most of the other buildings perform acceptably and are close to, sometimes below the limit values in the SIA norms. This is for example the case for the *EL* and *IN* buildings. The *BC* building even beats the target values according to these calculations.

The possible savings can be evaluated for each building, assuming that ventilation consumption is reduced to SIA limit values:

- $E_{venti,limit} = C_{venti,actual} - C_{venti,limit} \quad [kWh_{el}]$
    - $E_{venti,limit} = savings\ for\ a\ building\ after\ reduction\ to\ limit\ values\ [kWh_{el}]$
    - $C_{venti,limit} = consumption\ of\ ventilation\ when\ limit\ values\ are\ met \quad [kWh_{el}]$
    - $C_{venti,actual} = actual\ cosnumption\ ventilation \quad [kWh_{el}]$
- *Equation for target values accordingly*

By summing up the savings for the different buildings, one derives the total savings: If all buildings, which have a consumption above the limit value, could reduce their consumption to the limit values, the overall savings for EPFL would amount to 6.189.282 kWh_{el} per year, which represented a saving of 55 % on ventilation consumptions; if the target value could be achieved, even 10.341.601 kWh_{el} (85 %) per year could be saved.

A reduction to a value in between limit values and target values seems to be an ambitious but realistic scenario. The savings for each building are then:

- $E_{venti,lim/tar} = C_{venti,actual} - \frac{(C_{venti,limit} + C_{venti,target})}{2}$
    - $E_{venti,b} = savings\ for\ building\ b\ after\ reduction$

If ventilation consumptions in all the buildings were lowered to this reference value, energy savings would amount to 8.173.827 kWh_{el} (67 %) at EPFL.

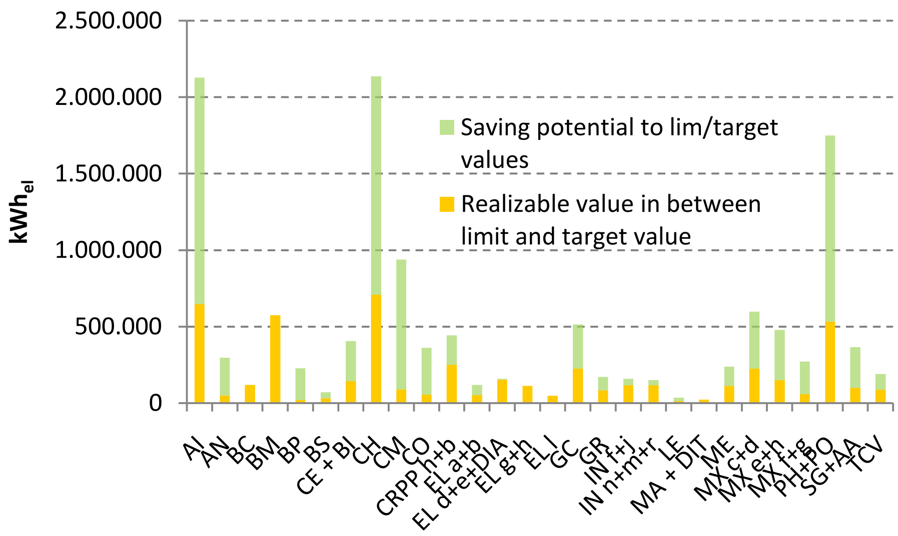

Figure 19: reduction potential for each building assuming reduction to consumption between limit and target values

It is now also possible to calculate the annual air flow rates for the buildings according to the SIA standards, by multiplying the specified volume streams per m^2 with the surfaces and the full load equivalent hours per year. The following values are obtained:

- 13.971.626.978 m^3 of air per year as limit value
- 8.010.173.065 m^3 per year as target value

The actual value will possibly be above these calculated values according to SIA.

A last interesting point shall be mentioned here. The buildings *LE* has no mechanical ventilation system installed and is only naturally ventilated. Therefore it serves as a reference for other buildings from the same construction period. It has a specific annual heat consumption of 70 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$ (see the chapter 2.2). There are buildings from the same construction period with a lower specific heat consumption, where mechanical ventilation is installed. The lower heat consumptions possibly result from the heat recovery units, which can only be installed together with mechanical ventilation. At the same time, there are buildings with specific heat consumptions of around 140 $\frac{\mathrm{kWh}}{\mathrm{m}^2 \times \mathrm{year}}$, where a high air renewal rate causes also big heat losses. These numbers show once more the significance of a ventilation system which is adapted to the real needs, as not only the electrical consumption, but also the heating consumption of a building is influenced significantly.

3.3.5 Thermal "fine" for electric consumption reduction

The reductions in electric consumption will also reduce the internal heat gains. Many of the fans (where electricity is transformed into heat) in the ventilation system are placed in the exhaust air ducts, so their heat emissions are directly lead to the exterior. Due to this fact not all of the electric consumptions are counted as internal heat gains, but will only be considered with a factor of 50 %. As the buildings are heated during 5 months, the additional heat to be provided by the heating system, assuming electricity savings of 8.173.827 kWh_{el}, amounts to:

- $Q_{fine\,,vent} = 8.173.827\ kWh_{el} \times 50\% \times \frac{7}{12} = 2.384.033\ kWh$

This amount will be considered in the next chapter. The reduction of electric consumptions will also reduce cooling loads (not quantified), and increase the indoor climate in summer.

3.3.6 Heat savings through ventilation refurbishment

The ventilation rate has a big impact on the heat consumption of the building. This can be observed in the chapter 3.2, where the heat consumptions for each building are separated into transmission losses and ventilation losses. Above it was observed, that the ventilation system operates inefficiently in many of the buildings. Without detailed measurements for the different buildings it's not possible to tell whether these inefficiencies are caused by a system which is working inefficiently but which transports an appropriate air volume flow, or if the system is transporting too much air, especially in non working hours. The real situation will be a combination of both cases. As the actually transported volume flows cannot be evaluated for the moment, reference values from comparable retrofits have to be regarded. Again the *Phytosphäre*- report shall serve as a reference here: the volume flows in the table represent the volume flows before and after the retrofit:[74]

	Operation time	**Volume flow $[\frac{m^3}{h}]$**	**Volume stream reduction compared to original state**	**Annual flows [Mio. $\frac{m^3}{h}$]**	**Annual flow reduction compared to original state**
Original state:	**Day**	**50.300**	**-**	**441**	**-**
	Night/ weekend	**50.300**	**-**		
Retrofitted System:	**Day**	**~22.900**	**54%**	**167**	**62%**
	Night/ weekend	**~17.250**	**66%**		

[74] Birnbaum et al. (2007), p. 200

In the chapter 3.2 the heat losses through ventilation for the building of the 1st construction phase were evaluated. To get a first indication of savings in heating consumption through ventilation refurbishment, it shall be assumed for this work, that the retrofit of the EPFL ventilation system would also lead volume streams to reduce by 62 % as in the *Phytosphäre* retrofit. For a more detailed analysis, actual volume streams needed to be measured. The following figures show the evaluated heat losses at EPFL through transmission and ventilation:[75]

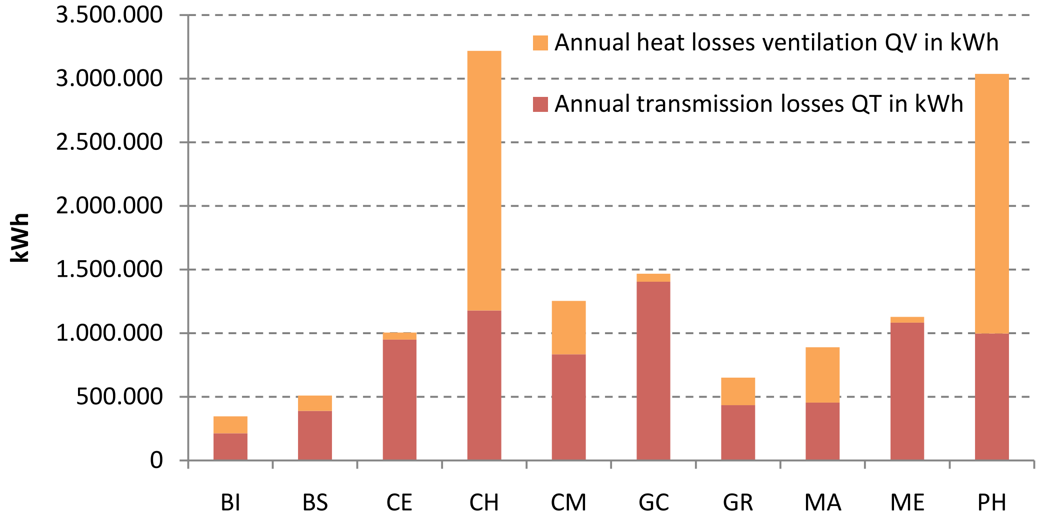

Figure 20 : Heat losses through ventilation and transmission for EPFL buildings, in kWh

The specific heat losses are:

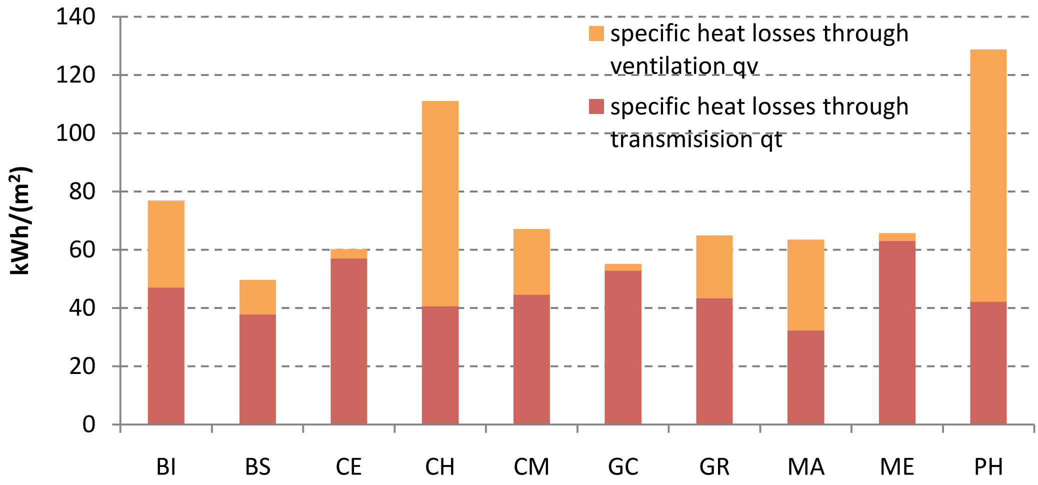

Figure 21: Specific heat losses through ventilation and transmission for EPFL buildings, in kWh/(m^2)

[75] see chapter 3.2, calculations in *building_enevlope.xls/gen_calc*

In chapter 3.2*,* the ventilation losses in building *BS* are defined as losses through natural ventilation. So it must be assumed that these losses are not touched by a possible reduction of the mechanical ventilation rates. The specific heat losses of the *BS* building serve therefore as reference value for the part which stays untouched in all buildings with mechanical ventilation. For each building *b* the following heat savings through air volume flow reduction are derived:

- $E_{Q_{vent},b} = (Q_{v,b} - A_{h,b} \times q_{v,BS}) \times 62\ \%\ \ [kWh] \quad if\ q_{V,b} > q_{V,BS}$
- $E_{Q_{vent},b} = 0\ \ [kWh] \quad else$
    - $E_{Q_{vent}} =$ $savings\ in\ heat\ energy\ for\ building\ b\ through\ vent.reduction\ in\ [kWh]$
    - $Q_{v,b} = heat\ losses\ through\ ventilation\ in\ building\ b\ in\ [kWh]$
    - $A_{h,b} = heated\ surface\ building\ b\ in\ [m^2]$
    - $q_{v,b} = specific\ ventilation\ heat\ losses\ building\ b\ in\ [kWh]$

The following figure shows the annual heat losses before and after the retrofit of the ventilation system:[76]

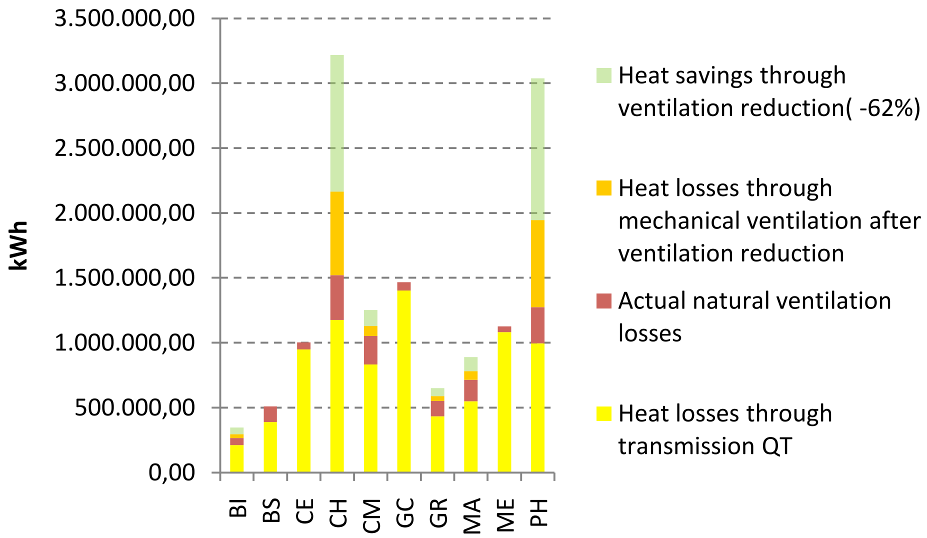

Figure 22 : Heat losses of building before and after ventilation retrofit and air flow reduction

For the buildings of the 1st construction the savings in heat demand amount to:

- $E_{Q_{vent},EPFL1st} = \sum_{b=1}^{10} E_{Q_{vent},b} = 2.486.804 \frac{kWh}{\text{year}}$

For the buildings of the 2nd construction phase, the explicit calculation about transmission and ventilation heat losses was originally not executed, so it is not known for these buildings how much heat per building is lost through ventilation and transmission respectively. Anyway, to get a first

[76] calculation in *building_envelope_v3.xls/heat_losses_vent*

impression about heat losses reduction through ventilation reduction, the same approach was also used for the buildings of 2nd construction phase, knowing that it is not absolutely correct to assume the same U- value for these buildings as for the *BS*- building (which is one of the core assumptions to determine transmission and ventilation heat losses for the building of the 1st construction phase in chapter3.2).

The approach was applied for the buildings *CO*, *SG+ AA*, *MX*, *TCV* and *AI*. The building *AI* is still relatively new (2001), so the very high consumptions in ventilation might also have other reasons than ventilation inefficiency (Life Science research), anyway it shall be assumed here that also in this building it is possible to significantly reduce the air flows (-61%).

Following buildings were not considered:

- *SV*: very new (2008), no values available yet.
- *CRPP, EL, IN*: ventilation consumptions already in acceptable area, so low reduction potential assumed.
- *ODY*: no data available.
- *BM*: data for grid *F- S* is obviously wrong, so no calculation possible.

This leads to the following results for the buildings of 2nd construction phase:[77]

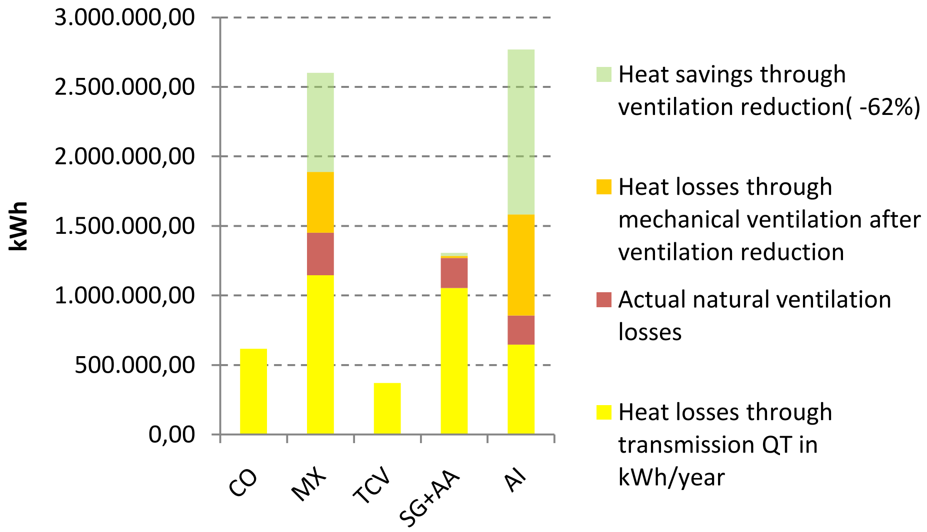

Figure 23: Heat losses of buildings of 2nd construction phase before and after ventilation retrofit and air flow reduction

The fact, that for the newer buildings the same specific transmission heat losses were assumed, leads obviously to slight mistakes: the ventilation losses for buildings *CO* and *TCV* cannot be zero. Anyway the model is further used to approximate the heat losses due to ventilation.

When air flow rate reduction is also considered for the buildings of the 2nd construction phase the savings for all buildings with the mentioned hypotheses amount to:

[77] calculation in *building_envelope_v3.xls/heat_losses_vent*

- $E_{Q_{vent},EPFL} = \sum_{b=1}^{15} E_{Q_{vent},b} = 4.407.655 \frac{kWh}{\text{year}}$

Furthermore a *thermal fine* of 2.384.033 kWh of heat from electricity consumption reduction was determined, increasing the heat demand of the system. So the total heat savings amount to:

- $E_{Q_{vent},EPFL} - Q_{fine,vent} = 4.407.655 \frac{kWh}{\text{year}} - 2.384.033 \frac{kWh}{\text{year}} = 2.023.622 \frac{kWh}{\text{year}}.$

Applying the COP of 3,6 on the 2.023.622 kWh of heat, one derives an electrical consumption reduction of 562.117 kWh_{el}.

3.3.7 Economic analysis

The financial calculation is conducted assuming that ventilation consumptions could be reduced to the value exactly in between limit and target values. This is an ambitious but realistic target. Savings were predicted when applying the lim/target- scenario in ventilation for the buildings *AI, AN, BP, BS, BI+CE , CH, CM , CO, CRPP, EL a+b , GC , GR , IN , ME, MX, PH, SG+AA,TCV*. For the electrical savings a sum of 8.173.827 kWh_{el} was evaluated. The heat savings amount to 4.407.655 kWh, reduced by the thermal fine of 2.384.033 kWh, which results in a total of 2.023.622 kWh of heat saved. The cost for an energetically optimized retrofit of the ventilation of the considered buildings shall be calculated now. As the cost reference serves a specific retrofit cost, which has been determined in the *Phytosphäre* refurbishment report: it is directly related to the size of the system. A cost of 20 $\frac{EUR}{m^3/h}$ as reference value lets one derive a first cost indication of the retrofit cost for the ventilation system. Transformed with the before described factor of 1,67 $\frac{SFR}{EUR}$ (see chapter 3.2.6), one derives a cost of 33,44 $\frac{SFR}{m^3/h}$. For the considered buildings, the appropriate dimensions of the systems need to be evaluated now. This is done with the well known approach of applying SIA standard values, in this case for air flow rates in $[\frac{\text{m}^3}{\text{h}\times\text{m}^2}]$, for different room categories, and multiplying these values with the according room category surface per building. The appropriate dimensioning of the ventilation system for each building amounts to:

- $F_{venti,SIA,b} = \sum_{i=1}^{n} f_{SIA,i,b} \times a_{i,b} \quad [\frac{m^3}{h}]$
  - $With\ i\ =\ room\ category\ according\ to\ standard\ SIA$
  - $f_{SIA,i,b} = specific\ air\ flow\ need\ in\ [\frac{m^3}{m^2\times h}]\ for\ room\ category\ i$
  - $a_{i,b} = surface\ of\ room\ category\ i\ in\ building\ b\ in\ [m^3]$

The investment costs for the ventilation retrofit per building *b* can then be derived:

- $I_{vent,b} = F_{venti,SIA,b} \times 33,44 \ \frac{\text{SFR}}{\frac{m^3}{h}}$

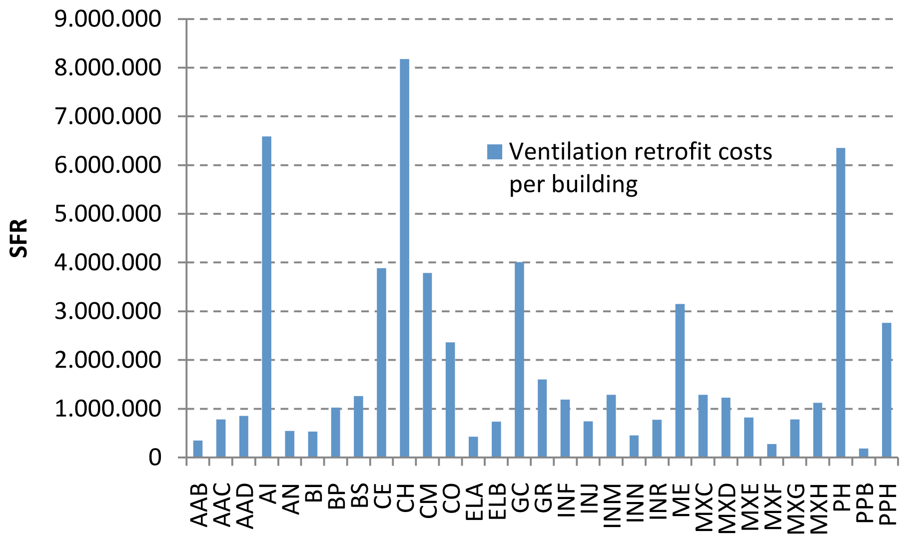

Figure 24: Investment for considered ventilation retrofit per building, in SFR

The total investment for EPFL is then:

- $I_{vent} = \sum_{b=1}^{n} I_{vent,b}$

The total retrofit investment for the considered buildings at EPFL amounts to 62.473.619 SFR.

The investment is annualized, and amortization time and interest rate are considered to be 20 years and 5 %. Then the annual capital costs amount to:

- $A_{vent} = I_{vent} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} = 62.473.619 \text{ SFR} \times \frac{0,05 \times (1+0,05)^{20}}{(1+0,05)^{20} - 1} = 5.013.045 \text{ SFR}$

For a 25 year amortization period one derives annual capital costs of 4.432.657 SFR.

The monetary savings are calculated assuming an electricity price of 0,20 SFR, increasing 2 % annually over the next 20 years (25 years). The average electricity price for 20 (25) years is 0,249 SFR (0,264 SFR).Then one derives the following monetary savings:

- $G_{vent} = P_{elec,aver} \times E_{vent} = 0.249 \frac{SFR}{kWh_{el}} \times (8.173.827 + 562.117)\ kWh_{el} = 2.171.708\ SFR$

For a 25 year amortization period one derives average annual savings of 2.306.817 SFR (due to the higher average electricity price).

Investment in [SFR]	Amort. period	Annual savings in electrical energy in [kWh_{el}]	Average electricity price in [SFR]	Monetary savings in [SFR]	Annual capital costs for investment in [SFR]
62.473.619	20 years	8.173.827 + 562.117 = **8.735.944**	0,249	2.171.710	5.013.045
	25 years		0,264	2.306.817	4.432.657

3.3.8 Options to improve the performance

In the previous chapter, a complete refurbishment and exchange of the ventilation system was considered for the buildings, where substantial savings can be expected. It is especially in the newer buildings not mandatory necessary to exchange the whole system. In the following chapters, the main options to improve the efficiency of a ventilation system shall be listed.

3.3.8.1 Minimization of pressure losses

The hydraulic power of a fan is determined by:[78]

- $P_{v,out} = \dot{V} \times \Delta p_{tot} \ \ [W]$
    - $\dot{V} = air\ volume\ flow\ in\ [\frac{m^3}{s}]$
    - $\Delta p = total\ pressure\ difference\ in\ [Pa]$

In many older ventilation installations, significant reductions of pressure losses can be achieved. In most cases it is difficult to improve the ventilation channels in the building. But very often, it is already sufficient to optimize the flow channels in the central ventilation units itself, as 50% percent of the pressure losses are caused there. All equipment which is not absolutely necessary should be abandoned to minimize pressure losses.[79] The reduction of pressure losses and air flow speeds results therefore in substantial energy savings. An enlargement of the duct and aggregate diameters is another option to decrease air flow velocity. Additional cost for higher aggregate diameters can usually be amortized within 4- 6 years.[80]

[78] ENERGHO (Ed.)(2000), p. 34
[79] ENERGHO (Ed.)(2000), p. 37
[80] Birnbaum et al.(2007), p. 57- 58

3.3.8.2 Improvement of efficiency of fans

Another aspect is the renewal of fans and electronic drives themselves. Especially for big ventilation systems with a power of 100 kW and more, together with long annual operation times of 3000 hours per year or more, very short amortization times of 1-2 years for the exchange and renewal of the fans are realistic.[81] Case studies give examples of retrofits, where by the simple exchange of fans, energy savings of 40 % for the ventilation system were achieved. The investments were amortized within 1-2 years. [82, 83] Also other sources specify an efficiency potential for the exchange of fans around 30 %. [84] Important for the fan's overall efficiency is the power transmission system from motor to fan and the efficiency of the electrical drive itself. [85, 86]

3.3.8.3 Limitation of operation hours and adapted volume streams

An important option to improve the efficiency of a system is to limit the operation of the system to times when the room is occupied. In times when the rooms are not occupied like nights or weekends, the air flows can be reduced or the system can even be switched off. Nights and weekends represent already 64% of the overall operation time per year. Even in laboratories, the air flows can be reduced up to 80% in these times.[87] It needs to be taken into account that a reduction of air streams theoretically leads to a cubic reduction of hydraulic work:[88]

- $\frac{P_{hydr.1}}{P_{hydr.2}} = \left(\frac{n_1}{n_2}\right) = \left(\frac{\dot{V}_1}{\dot{V}_2}\right)^3$
  - $With\ P = \ hydraulic\ power\ in\ [W]$
  - $n = \ revolutions\ per\ minute\ [\frac{1}{min}]$
  - $\dot{V} = \ volume\ stream\ in\ [\frac{m^3}{s}]$

Although the efficiency factor of the system, e.g. the electrical drive, might degrade when operating in part load, the equation shows the potential energy savings through reduction of the rotation speed of the fan when the system does not need to operate under full load conditions.[89] According to examinations in different countries, the adjustment of the operation time of the ventilation results in the greatest and fastest savings for the ventilation system.[90]

[81] Informationszentrum Energie (Ed.)(2002), p. 14
[82] Informationszentrum Energie (Ed.) (2002), p. 34
[83] Informationszentrum Energie (Ed.)2002), p. 4
[84]Birnbaum et al.(2007), p. 59
[85] Informationszentrum Energie (Ed.) (2002), p. 5
[86] ENERGHO (Ed.)(2000)o, p. 13- 15
[87] Birnbaum et al.(2007), p. 60
[88] ENERGHO (Ed.)(2000), p. 21
[89] ENERGHO (Ed.)(2000), p. 21
[90] Mroz (2003), p. 100

There are different ways to control power of the fans: it can be controlled by throttling of the fans, adjustment of the fans' blades or by bypass regulation. The most efficient way though is the control of the rotation speed of the fan, regulated by an electric drive with a frequency converter. This is the most economic solution, when big differences exist between full and part load, and when the systems works a substantial fraction of time in part load, which should be the case for laboratories[91,92] If the volume stream is variable over time, different control systems are possible:

- For irregularly occupied rooms either manual switches or movement detectors (initial cost around 100 SFR).
- For regularly occupied rooms, with fixed occupancy hours: time switches (initial cost around 100 – 200 SFR).
- Rooms with variable usage: CO_2 or other mixed gas sensors measure air contamination and adjust ventilation accordingly (CO_2 Sensors initial cost: around 1000 SFR).[93]

The SIA Norm SIA 380/4 and SIA 382/1 regulate, that systems with an air flow rate >5 $\frac{\mathrm{m}^3}{\mathrm{h}*\mathrm{m}^2}$ need to be regulated by a two- speed or step- less drive, combined with air quality sensors.[94]

Evidence suggests that the operation of ventilation at EPFL is not really adapted to the real needs over time. In the course of the DIAGELEC project, the power load in the physics building was measured on a 15 min basis, over a period of one month. The result for the 24 hours of a day is shown below. The red points represent the grid *Force- Service*.

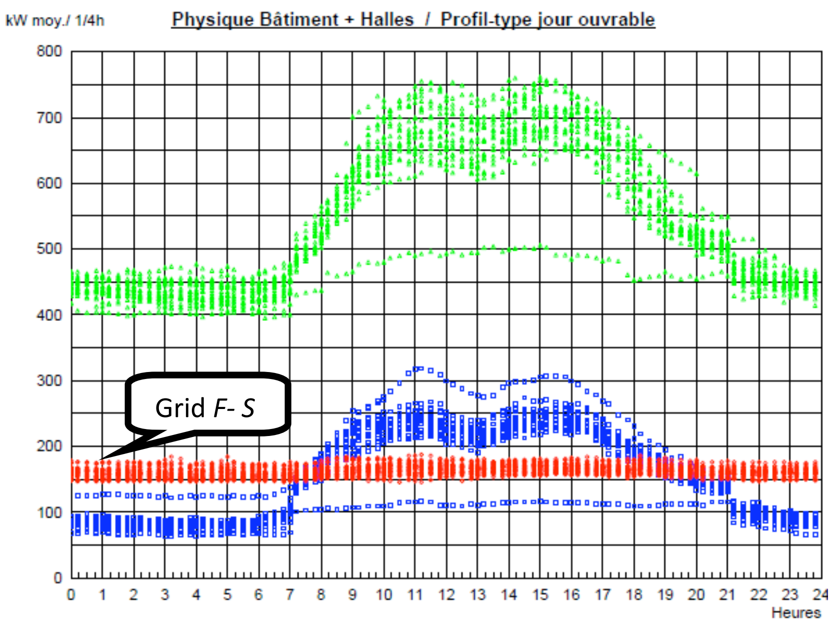

Figure 25: Load curves for grids F, F-S and L + M in PH building (source: EPFL- Pl- DII_E (Ed.)(2006))

[91] ENERGHO (Ed.)(2000), p. 5- 6
[92] Birnbaum et al.(2007), p. 59
[93] ENERGHO (Ed.)(2000), p. 5
[94] SIA 2024 (2006), p. 15

The consumption on the grid Force- Service shows no reduction at all during the night. Although a variable speed of the ventilation fans is foreseen, this has obviously no influence on the energy consumption.[95] One must therefore assume that the speed regulation either does not work correctly, or the efficiency of the fans drops extremely in part load operation, so no energy savings can be achieved in part load. No significant changes have been undertaken on the ventilation system since the measurements were taken.[96] Similar problems possibly exist in other buildings.

In general, it must be assured that the air flows are -around 30 years after the installation of the system- still adapted to the real needs. Many rooms might be used differently as foreseen originally, and it must be assured that the ventilation has also been adapted to these new needs. In many laboratories, where many fume hoods have been installed, it is possible to reduce or switch off the regular ventilation flow, as the minimum air flow is already provided by the fume hoods. In many cases, where the ventilations system has not been changed for a long period, energy savings through volume flow reduction can be immense. [97, 98] According to detailed studies, energy savings of 75 % can be realized through adjustment of ventilation to the needs.[99]

3.3.8.4 Two innovative systems for reduced volume flow

In the labs where different fume hoods are installed, a so called *single room controller* makes sense. A single room controller registers the position of the fume hoods front slider (open: maximum flow; closed: min. flow), and regulates the air flows of the fume hoods and the room ventilation accordingly. Furthermore the single room controller takes into account

- Time and day
- Presence of people
- Min. and max. flows for the different hoods and fans
- Minimum required air flow for the lab

Example calculations show that this configuration can easily reduce the overall air flows by 59 % in comparison to conventional systems (where each fan is controlled independently), still respecting minimum air flow regulations and without degrading working conditions.[100]

For lecture halls, the following ideal system should be considered: A central ventilation unit provides an air flow with constant pressure and is equipped with adjustable motors and frequency converters. Each lecture hall connected to the system is equipped with a damper and motor valves. As lecture halls are used very irregularly (they are either empty or not used, or they are intensively used), the air flow should be controlled by a CO_2- sensor and temperature sensors.

[95] *EPFL- Pl- DII_E* (2006), p. 33, p. 49- 52
[96] according to *EPFL- Pl- DII_E*
[97] Birnbaum et al.(2007), p. 60
[98] *http://www.igb.fraunhofer.de/www/service/buws/dt/Laborlueftung.dt.html,* 31.7.2009
[99] Birnbaum et al. (2007), p. 27
[100] Birnbaum et al. (2007), p. 96

3.3.9 Results and conclusions

For a retrofit of the ventilation system, the following savings were determined:

Actual consumption ventilation EPFl [kWh_{el}]	Consumption If SIA limit values were met [kWh_{el}]	Consumption If SIA target values were met [kWh_{el}]	*Realizable* savings for lim/tar scenario in [kWh_{el}]	New consumption after retrofit [kWh_{el}]
12.188.895	7.476.220	2.328.644	8.173.827 + 562.117 = **8.735.944**	4.899.702

Financial implications:

Investment of considered measures in [SFR]	Annual capital costs (20 years amort.) in [SFR]	Annual monetary savings in [SFR]	Annual costs per kWh_{el} saved (20 years amortization time) in $[\frac{SFR}{kWh}]$	Annual costs per kWh_{el} saved (25 years amortization time) in $[\frac{SFR}{kWh}]$
62.473.619	5.013.045	2.171.710	$\frac{5.013.045}{8.735.944}$ = **0,57**	**0,51**

- By comparison with the SIA benchmark values it must be assumed that there exist substantial potentials for energy savings especially in buildings used as laboratories, like the *PH* and *CH* building.
- In this work it could not be determined, whether the extreme high consumptions are caused mainly due to high air flow rates, or through inefficient fans. One can assume that the reason is a combination of both. It was shown, that a reduction of air flows, still respecting required ventilation rates according to SIA or DIN norms, would in many buildings also significantly reduce the heat demand.
- The economic calculation showed that an assumed complete retrofit of all buildings, where saving potential was detected, is from an economic point of view not profitable. The annual capital costs are more than twice as high as annual savings through energy consumption reduction. Anyway, the resulting costs might be overestimated to the following facts:
  - A specific cost for a total retrofit off the ventilation system was considered and applied to all the building where elevated ventilation consumption was detected. In many new buildings, a total retrofit of the ventilation system will not be necessary. Adapted air flows, adapted control and operation modes are effect measures and might be sufficient to significantly reduce ventilation consumptions in building with relatively modern ventilation systems.
  - Reduced maintenance costs, which were not considered in the calculation (as they are not known), will possibly have a big impact on the result of the calculation.
- The share of *energy relevant additional costs* of the total costs needs to be further analyzed
- It is strongly recommended to start a “task force” or similar, to examine the ventilation systems of the buildings, starting with the older buildings like *PH* and *CH*. Such a task force

could consist mainly of students guided by an expert, which would also have a strong educational effect. The first goal should be to compare provided air flows and air exchange rates throughout the day and on weekends with real needs and norm values. This would not only be the first step to detect inefficiencies in the ventilation systems, but it would also allow one to derive pretty exact information about:
  - Quantity of heat lost through ventilation and transmission
  - Efficiency of the heat recovery installations
  - Effects of refurbishment measures of the ventilation system and the building envelope on the energy consumptions of the buildings
- The non-existent measures about the *real* air flows of the mechanical ventilation systems in the buildings were the biggest barrier for a more exact analysis of the reasons for the elevated ventilation consumptions.

Annotations

- *Every building is different. As one can see in the previous figures, the buildings differ strongly from each other in their consumption balance. Furthermore every building has a different installation, which might have changed over the years; the exact actual state is unknown. It was shown that there are significant efficiency potentials for different buildings, and general propositions were made how to improve the efficiency of ventilation systems. But without a technical study of the buildings' ventilations systems on- site, the reasons for the deficiencies cannot be identified, which would be necessary to determine more adapted measures and exact related costs. Such a study on the different buildings' installations was not realizable within this project.*
- *To execute a detailed analysis on one building and to extrapolate this analysis on the other buildings is also not a suitable way to determine overall efficiency potentials; this would lead to big estimations errors, due to the very specific characteristic of each building.*
- *A building- by building analysis is therefore inevitable. This work can serve as a first indication where to start. The literature also used for this chapter gives an introduction on how to conduct such an analysis.*

3.4 Lighting

In this chapter, the consumption of the lighting system at EPFL shall be analysed, and a first estimation of saving potentials shall be derived. Lighting is supposed to be the biggest consumer on the grid *Lighting+ Measuring*, and one of the main energy consumers at EPFL.

3.4.1 Approach to determine lighting consumption and reference values at EPFL

To obtain a first impression of the performance of the lighting system at EPFL, an approach similar to the one explicitly explained in the chapter 3.3 is used: The SIA- standards specify for each room category specific limit and target value for the installed specific lighting power and for the related annual operational hours. For a building *b* with the *n* different room categories, the annual limit and target energy consumption is then derived as followed:

- $C_{light,limit,b} = \sum_{i=1}^{n} p_{limit,i,b} \times t_{limit,i,b} \times a_{i,b} \quad [kWh_{el}]$
  - $With\ i\ =\ room\ category\ according\ to\ Norm\ Din\ 277/2$
  - $p_i\ = specific\ lighting\ power\ in\ [\frac{W}{m^2}]\ for\ room\ category\ i$
  - $a_{i,b} = surface\ of\ room\ category\ i\ in\ building\ b\ in\ [m^2]$
  - $t_i\ =\ annual\ operational\ hours\ of\ lighting\ for\ room\ category\ i$
- $The\ equation\ for\ target\ values\ is\ defined\ accordingly$

The according limit and target values are published in the SIA bulletin 2024.

The limit and target consumptions for lighting are calculated for all buildings at EPFL. They can then be compared with the real consumptions for lighting. These are recorded on the counters on the grids *Lighting + Measuring* in the different buildings. Unfortunately, not only lighting is recorded on these grids, but also measuring instruments in the laboratories, switch cabinets and batteries for the auxiliary power supply, which assures a stable frequency and power supply in case of failure of the grid. To make the consumptions on the grid comparable, they must be corrected with an adequate factor. In buildings with a high share of laboratories, around 50 % of the consumption on the grid *L + M* seems to be caused by measuring instruments, switch cabinets, auxiliary power supply etc. This assumption is derived from the following figures, which represent measurements executed for the DIAGELEC- study about electricity consumption at EPFL in 1999.[101] One can observe that the base load energy consumption makes up a substantial fraction of the total consumption on the grid *L + M* in laboratory buildings. This base load is not directly related to lighting, as lights are consequently switched off at night.

[101] *EPFL- Pl- DII_E (2006)*

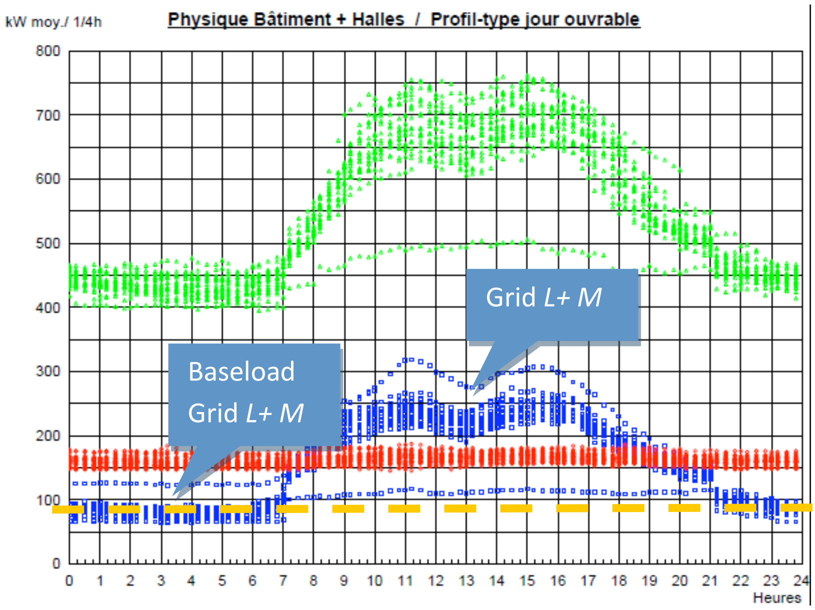

Figure 26: Load curves in the building PH, blue graph for grid L +M (source: Diagelec (1999))

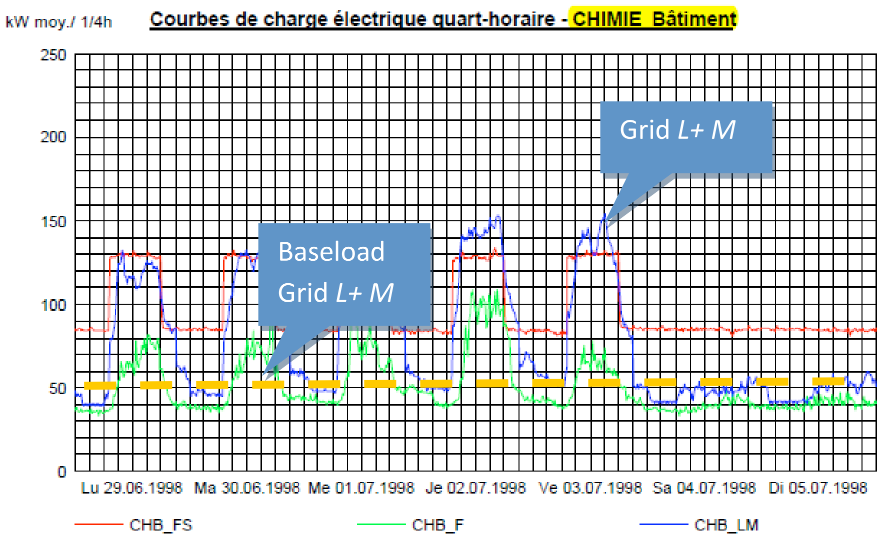

Figure 27: Load curves in the building CH, blue graph for grid L +M (source: EPFL- Pl- DII_E (Ed.) (2006))

For buildings where a small share of rooms is used as laboratories, a reduction factor of 40 % is applied. For buildings, which are not used as laboratories, a reduction factor of 30 % is applied.[102] This factor seems to be appropriate when regarding the following figure. The measures were also taken in the course the DIAGELEC- study at EPFL in the *BS* building, which is used exclusively as administrative building:[103]

[102] please see *Ligting_calc_EPFL.xls/comparison* for the applied factor in each building
[103] *EPFL- Pl- DII_E (2006)*

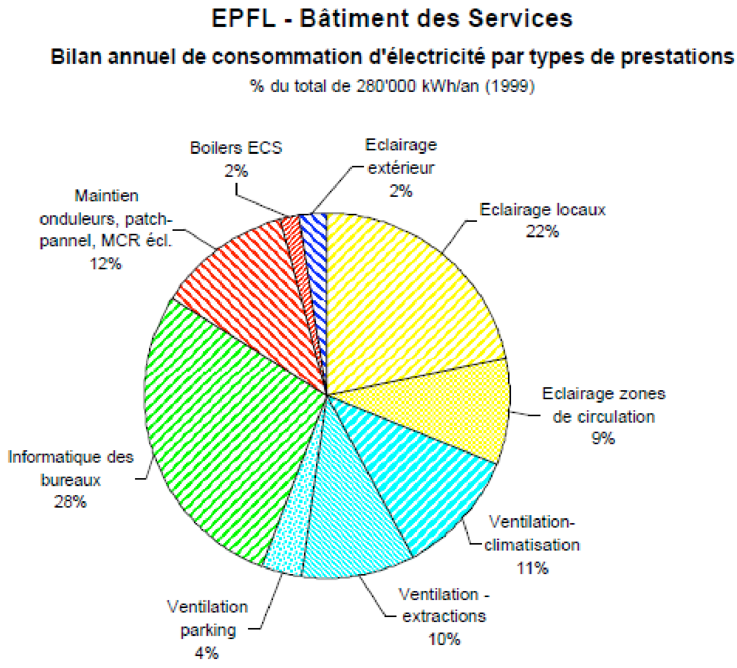

Figure 28: electricity consumption in the BS- buildings (source: EPFL- PI- DII_E (Ed.) (2006))

Around 12 % of the total electric consumption was allocated to measuring instruments, switch cabinets, auxiliary power supply etc., and 29 % for indoor lighting. All these categories were recorded on grid *L + M*. Therefore it is assumed that around 30 % of the electric- consumption on grid *L + M* in administrative buildings is not directly caused by lighting.

One could now state, that auxiliary power supply is also part of consumptions for lighting. Anyway it must be subtracted in this case to make the lighting consumption of EPFL comparable to standards and other benchmarks.

3.4.2 Comparison between consumptions and reference values

The recorded consumptions on the grid *L+ M* for each building are reduced by the above derived reduction factors, and the limit and target values for lighting consumption for each building are calculated according to the described approach:

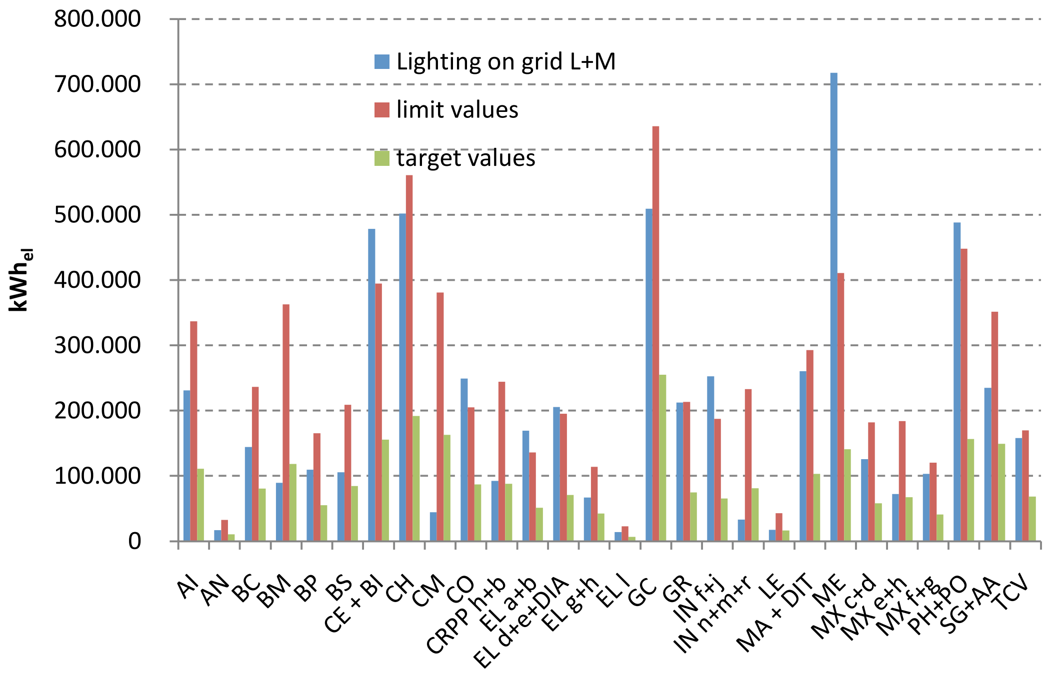

Figure 29: Actual lighting consumptions and target and limit values for EPFL buildings

On can observe, that in most of the cases, the lighting consumption can be found within the SIA limit and target values, sometimes even below the target values. Exceptions are basically the buildings *CE+ Bi*, *ME*, *CH* and *PH + PO*.

For the buildings *CE* and *BI*, where no laboratories exist, the values must be further analyzed.

The *BI* building (the library) consumes 189.504 kWh$_{el}$ on the grid *L + M*, its calculated limit value is 80.776 kWh$_{el}$. There is no real justification for the elevated consumptions; therefore it must be assumed that the lighting installations are pretty inefficient. The library is about to move in the *LC* building, and the *BI* building will be refurbished, which will possibly solve the problem of lighting inefficiency. The *CE* building has a calculated limit value of 314.081 kWh$_{el}$. The corrected lighting consumption is 345.547 kWh$_{el}$. So there might be a potential for electric savings in lighting.[104]

The biggest difference between real consumptions and limit values can be found in the *ME* building. The high consumptions might be caused through numerous measuring installations in the experimental installations and the workshops. A more detailed analysis to quantify the real fraction of lighting consumption on the grid *L+ M* would be necessary to make further statements.

In the building *PH*, the detailed analysis in the DIAGELEC study from 1999 can help to further analyze the results. A lighting consumption of 475.540 kWh was determined there. The calculated SIA limit value is 433.282 kWh. Also in the *PH* building might therefore still be bigger potentials for savings in lighting.

[104] Values from *Lighting_calc_EPFL.xls* and *Elec_EPFL_V4.xls*

It shall be furthermore calculated, what savings could be achieved, if the lighting consumptions were reduced to SIA target values. A reduction to limit values makes not really sense, as most buildings' lighting consumptions are already below the calculated limit values.

The total consumption determined for lighting is 5.704.213 kWh_{el}.[105] If in every building ,where lighting consumption exceeds the calculated target values, the consumptions were reduced to target values, the total consumptions for lighting at EPFL would drop to 2.397.460 kWh, which would represent savings of 60 %.[106]

3.4.3 The different aspects of electrical lighting consumption

At first it shall be shown what determines the consumptions for lighting. This is best demonstrated with the equation from the SIA for the expected lighting consumption in a building. The specific electric consumption for a certain room amounts to:[107]

- $c_{Li} = \frac{p_{Li} \times t_{Li}}{1000} \quad [\frac{kWh_{el}}{m^2}]$
    - $p_{Li} = specific\ power\ lighting\ in\ [\frac{W}{m^2}]$
    - $t_{Li} = annual\ full\ load\ hours$

So the lighting consumptions is basically determined by the installed power and the full load hours, and these are the two determinants to reduce the consumption.

The installed power is further determined as:[108]

- $p_{Li} = \frac{E_{VM} \times p_V}{ή_V \times ή_{Lo} \times ή_R} \quad [\frac{W}{m^2}]$
    - $E_{VM} = light\ intensity\ according\ to\ norms\ in\ [lx]$
    - $p_V = planning\ factor\ lighting \quad [-]$
    - $ή_V = lighting\ efficiency\ in\ [\frac{lm}{W}]$
    - $ή_{Lo} = lighting\ fixture\ efficiency \quad [-]$
    - $ή_R = room\ efficiency\ factor \quad [-]$

The *lighting intensity* E_{VM} is the first variable aspect. In offices at EPFL, the typical 500 lux are applied.[109] In the *Phytosphäre* - report, the standard office lighting intensity was reduced from 500 to 300 lux, which should be generally enough for "screen"- workplaces. This will already lead to reductions in the annual lighting consumptions. The lighting can then be supplemented by small workplace lamps if required, so higher intensity is only applied directly in the working area.

[105] results calculated in table *Lighting_calc_EPFL.xls*
[106] Values from *Lighting_calc_EPFL.xls* and *Elec_EPFL_V4.xls*
[107] SIA 380/4, p. 36
[108] SIA 380/4 (2006), p. 36
[109] *EPFL- PI- DII_E* (Ed.)(2006)(2), p. 30 + SIA 380/4 (2006), p. 37

The *planning factor lighting* accounts for the reduction of efficiency through deterioration, placement of the lamps and the distribution of light in the room, and shall not be further treated here.

The *lighting efficiency* accounts for the performance of the bulb or tube itself. Classical bulbs emit around 12 lm/W, whereas modern efficient fluorescent tubes achieve values around 95 $\frac{lm}{W}$. Fluorescent tubes always require a so called *ballast converter,* which can be operated conventionally (magnetic) or electronically. Electronic ballasts can significantly reduce the lamp's energy consumption. A 26 mm fluorescent tube with a conventional ballast emits 73 $\frac{lm}{W}$, whereas a recent 16 mm tube with electronic ballast achieves 94 $\frac{lm}{W}$.[110] An electronic ballast is also precondition for a dimming system.

The *lighting fixture efficiency* quantifies the diminution of the light flow through the lighting fixture. Older conventional fixtures with an opaque covering achieve an efficiency of only 30- 50 %, whereas for high- reflecting reflector grids, 70- 75% are common.[111]

The *room efficiency factor* accounts for the following aspects:

- geometry of the room
- degree of reflection of the walls, ceiling etc.,
- distribution characteristics in the room

Also these issues can be expressed over equations. As these values are pretty much fixed in the existing building, it is not further treated here. It shall only be added, that in general, bright paintings and suspended ceilings improve the capacity of reflection of the room and therefore reduce the need for artificial lighting.[112]

The *full load operation hours* $t_{Li,\ 11}$ are evaluated, assuming a 11 h daily working period, and are dependent from the window surface factor, which represents the relation between window surface and floor surface. Furthermore, *reduction factors* are integrated in the calculation for:[113]

- Daylight controlling: a factor 1, when artificial light is constantly adapted to daylight appearance, a factor 2 for manual on/off.
- Reflection factor of room: a factor 1 for bright interior, factor 1,5 for dark interior
- A correction factor accounting for the transmission capacity of windows
- A correction factor for sun blinds: a factor 1, if the sun blind is intended for daylight optimization (see picture below), a factor 1,4 for a simple conventional sunblind
- Further correction factors considering the window lintel (height of window over ground), existence of a balcony and possible shadows through buildings in front of the building

When $t_{Li,\ 11}$ is known, the *effective full load hours* are evaluated as follows:

[110] Birnbaum et al.(2007), p. 72
[111] Birnbaum et al.(2007), p. 72 + SIA 380/4 (2006)p. 37
[112] SIA380/4, p. 37
[113] SIA380/4, p. 37 ff.

- $t_{Li} = k_{Pr} \times \frac{t_{Li,11} \times t_{ud}}{11h} + t_{un} \quad [h]$
    - With $k_{Pr} = correction\ factor\ presence\ sensor \quad [-]$
    - $t_{ud} = using\ hours\ day \quad [h]$
    - $t_{un}\ using\ hours\ night \quad [h]$

The presence factor can vary from 1,0 for a room with continuous presence over 0,8 for normal presence to 0,7 for a room with sporadic presence.

The whole equation for t_{Li} in the SIA norms is not presented here in its full extent, as this would go beyond the required level of detail for this work. The explication above shall rather show, which factors influence finally the lighting consumption of a room.

For the rest of this analysis, the following lighting efficiency measures , which seem to be applicable at EPFL, shall be considered:

- Replacement of older lightig systems through high efficient systems
- Installation of presence and daylight sensors

The more extensive use of daylight is another option of reducing the lighting consumption. As shown in the picture below, daylight optimizing sun blinds allow daylight to enter into the room in summer, when they are closed to protect the offices from direct sunlight. Therefore, the upper blades are in a fixed 38° position, also when they are closed. For the retrofit of *Phytosphäre* (*FZ Jülich)*, simulations showed that 12-15 % of artificial lighting could be saved compared to conventional sun blinds.[114] This option could be interesting for EPFL, but because of the uncertainty about the effects, it was not further examined in this work.

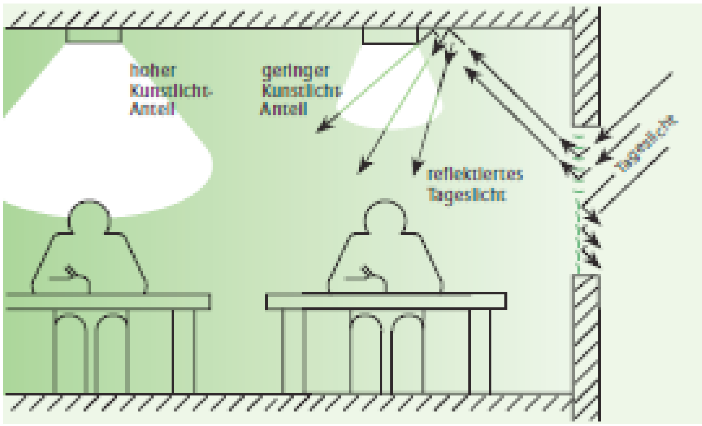

Figure 30: Daylight optimizing solar blind (source: dena[115])

[114] Birnbaum et al.(2007), p. 160
[115] *https://www.energieeffizienz-im-service.de/uploads/tx_zrwshop/DL_Beleuchtung.pdf, 5.11.2009*

3.4.4 The lighting system at EPFL

The lighting installations at EPFL are heterogeneous, as in older buildings, the original lighting installations have already partly been replaced by more modern systems, so it took several visits in place and several discussions to identify the predominant lighting system for each building. Finally the following predominant systems for tubes, lighting fixture and ballast were identified:

- *Modern system*: the newest buildings, the buildings *SV* and *BC* one can find the newest generation of light systems: 16 mm fluorescent tubes (*T5- Technology*) with electronic ballasts. These systems achieve, according to different sources, a lighting efficiency of 95 lm/ W. Furthermore the fixtures are highly reflecting grid casings, which achieve a *lamp efficiency factor* of 75 %. The total luminous efficiency then amounts to:
    - $\acute{\eta}_{V,LO} = 95\ \frac{lm}{W} \times 75\ \% = 71{,}25\ \frac{lm}{W}\ \approx 0{,}014\frac{W}{lm}$
        - $\acute{\eta}_{V,LO} = total\ luminous\ efficiency\ \ [-]$

  These combinations can be found in the new buildings *SV, BC*, and represent 20 %of lighting installed in the buildings of the 1st construction period, namely *CE, BI, CH, CM, GC, GR, LE, CM, MA, ME* and *PH*. In the buildings *SG, AA, BM and AI*, a walkabout showed that the buildings are also mainly equipped with 16 mm or 26 mm tubes, in many cases in combination with highly reflecting casings, so for the calculation it is assumed that their efficiency is identical to the system described above.[116]

- *Medium system*: the predominant system in the buildings in the second construction phase consists of 26 mm tubes, which achieve together with the electronic ballast an efficiency of 95 lm/ W. They are covered with transverse louvers or opaque coverings, for which one can assume a *lamp efficiency factor* of around 55 %.[117]
    - $\acute{\eta}_{V,LO} = 95\ \frac{lm}{W} \times 55\% = 52{,}25\ \frac{lm}{W}\ \approx 0{,}019\frac{W}{lm}$
    - Saving potential to *modern system:* $1 - \frac{0{,}014\frac{W}{lm}}{0{,}019\frac{W}{lm}} = 27{,}7\%$

  This is the typical system in the buildings from the 2n construction phase, namely *BS, CO, CRPP, EL, IN, MX, ODY* and *TCV*.[118]

- *Old system*: In the building of the first building phase, the predominant lighting system is a combination of 38 mm fluorescent tubes (T12- Technology), with a magnetic ballast and simple lighting fixture or casings, with opaque covering or transverse louvers. The tubes are not very common anymore on the market, 26 mm and 16 mm systems have mostly replaced them. Magnetic ballasts further reduce the efficiency of the system. Since 2005, they may not be sold anymore within the EU due to their bad efficiency.[119] On *www.licht.de* a calculation example is given: a typical 58 W tube with magnetic ballast has a total power

[116] According to *EPFL- Pl- DII_E*
[117] SIA 380/4 (2006), p. 40
[118] According to *EPFL- Pl- DII_E*
[119] http://www.licht.de/de/.../energie-effizienz-index/ , 30.9.09

input of 71 W, so the magnetic ballast increases the consumption by 22 %.[120] Similar values can also be found in other sources. According to different sellers and producers, the 38mm tubes emit 4000-4650 lumen at a nominal power of 65 W.[121] As shown before, one can assume an additional consumption of 22 % for the magnetic ballast. This amounts to a total consumption of 79W.With an assumed lumen output of 4650 lm, one derives a lighting efficiency of:

- $ή_V = \frac{4650\ lm}{79\ W} = 59\ \frac{lm}{W}$

Furthermore, these lighting systems have older fixtures with opaque coverings or transverse louvers, which achieve according to different sources a *lamp efficiency factor* of only 55 %.[122]

- $ή_{V,LO} = 59\ \frac{lm}{W} \times 55\ \% = 32{,}37\ \frac{lm}{W}\ \approx 0{,}031\frac{W}{lm}$
- Saving potential to *modern system:* $1 - \frac{0{,}014\frac{W}{lm}}{0{,}031\frac{W}{lm}} = 55\ \%$

These lighting systems represent more than 80 % of lighting installed in the buildings of the 1st construction period, namely *CE, BI, CH, CM, GC, GR, LE, CM, MA, ME* and *PH*.[123] In the following it shall be considered that 80 % of the electrical consumptions are caused by the old systems.

Presence sensors are only installed in single cases, e.g. in toilets. Daylight sensors with dimming units are not common at EPFL.

3.4.5 Effects of a refurbishment of the lighting system

3.4.5.1 Exchange of lamps

The effect of an exchange of the older system to the modern system shall now be calculated. For the buildings of 1st construction phase, the electrical consumption after an exchange of old systems amounts to:

- $C_{li,new\ ,1st} = C_{li,old} \times \frac{0{,}014\frac{W}{lm}}{0{,}031\frac{W}{lm}} \times 80\ \% + C_{li,old} \times 20\ \%\ \ [kWh_{el}]$

120 http://www.licht.de/.../magnetische-vorschaltgeraete/ am 30.9.09
121 Appendix D and *www.leuchtmittel-direct.de* am 30.9.09
122 Birnbaum et al.(2007), p. 72 + SIA 380/4 (2006), p. 40
123 Estimation according to *EPFL- Pl- DII_E*

For the buildings of 2nd construction phase, the electrical consumption after an exchange of old systems amounts to:

- $C_{li,new,2nd} = C_{li,old} \times \frac{0{,}014\frac{W}{lm}}{0{,}019\frac{W}{lm}} \quad [kWh_{el}]$

For the buildings where new systems are used, the consumptions are equal as before. The following table shows calculated lighting consumptions before and after exchange of the systems:[124]

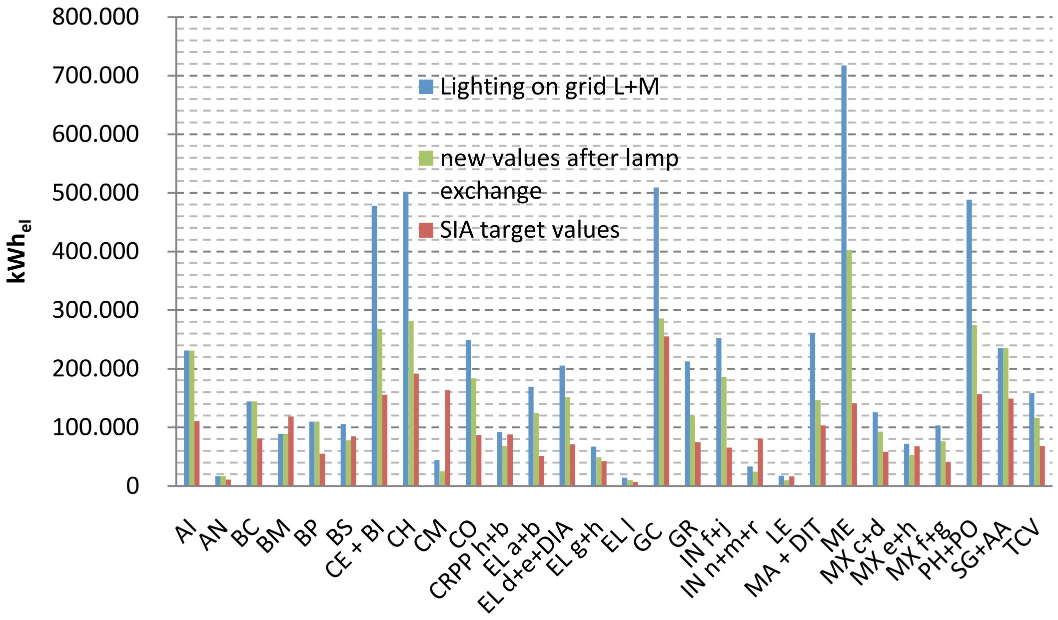

Figure 31: consumptions before and after lamp exchange

The total lighting consumption for the considered buildings would drop from 5.704.213 kWh$_{el}$ to 3.853.418 kWh$_{el}$ (in the following called $C_{li,new,}$). As mentioned before: the total consumption, if all buildings would comply with SIA target limits (or lower, some buildings are already below SIA limits), the consumption would amount to 2.397.460 kWh$_{el}$.

3.4.5.2 Presence and daylight sensors

An option to further reduce consumptions for lighting at EPFL is doubtlessly the application of presence sensors and daylight sensors with dimming devices. Several studies examined the effects of the appliance of such sensors:

A study of Li (2006) measured and calculated the possible energy savings by a lighting dimming system, which was operated by illumination sensors, in an office building at *City University of Hongkong*. Therefore a field study in an open plan office on the northwest side of the building was

[124] Results calculated in *lighting_Calc_EPFL.xls*

conducted. A photo sensor with a dimming system was installed. The goal was to consequently use natural daylight, if possible. The internal luminance level was set at 500 Lux, and the electricity use of the lighting system was continuously monitored. Through the installation of the dimming system, a reduction of 33 % of energy use for lighting was measured, not including savings for cooling (see also appendix F).

Related to EPFL, the results show the significant potential for energy saving through daylight sensors, also for bigger offices with several workplaces. Offices on the southside would of course even more profit from such a dimming appliance

The study of Bourgeois (2006) shows the effects of lighting on the total energy consumption for different control options:

- Constant overhead- lighting, which is constantly switched on during occupied hours
- Manual: on/off lighting switching and manual blind control of person actively seeking daylight (this is assumed to be the case at EPFL)
- Automated control: additionally to the manual control of lighting and blinds, a photocell sensor with dimming control to match the required 500 Lux at desk level, and occupancy-sensors switching the system off after 5 min of non presence.

The energy consumption of a fictive single person's south facade office is then simulated over a whole year. Heating is provided by a hot water baseboard system, cooling provided by a local AC unit. Two different locations or climate zones were then simulated. These are Rome, where the need for cooling is dominant, and Quebec, where the need for heating is dominant. The results were the following: an active manual control of lighting results in reduction of electric consumption of about 79 % for Rome and 79 %for Quebec, with an automated control even 98 % and 95 % respectively. The reduction in lighting loads affects also the cooling needs. The total reduction of cooling loads with automated control was for Rome and Quebec 49 % and 62 % respectively. However, there is an increase in annual heating loads, around 90 % for Rome and around 40 % for Quebec. The overall reduction in primary energy use for the different controls is also calculated, respecting transportation and distribution losses, conversion efficiencies etc. Manual control already reduces total primary energy needs for Rome by 60 % and Quebec by 43 %. By the introduction of an automated control in Rome, the reduction of lighting load is amplified by a reduction of the sum of heating and cooling needs, whereas in Quebec, the automated lighting reduces lighting loads, but increases the total primary energy needs for heating and cooling.

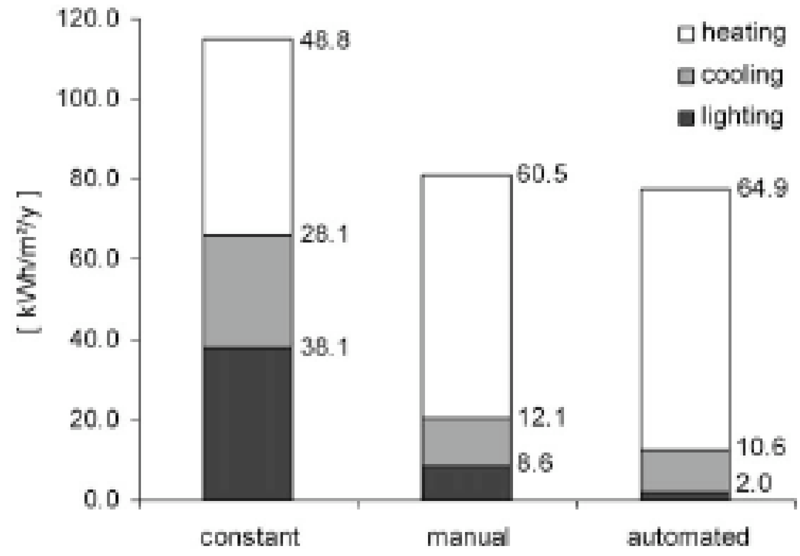

Figure 32: Annual energy consumptions for lighting, cooling, and heating (kWh/m2/year), for various lighting control options in Quebec (source: Bourgeois (2006))

The important message for this work about EPFL is, that in Quebec, the automated control could lower the energy consumption for lighting by almost 77 % compared to manual control. This result is of course only limited to the simulated office environment. The study shows, that an integrated view is necessary to verify the overall energetic impact of such efficiency measures, as a more efficient lighting systems reduce required cooling loads, but increase required heating loads. The parallel increase of heat demand needs to be considered, but will be of lower importance at EPFL due to the high efficiency of heating (total COP of 3.6).

As the studies above showed, there is a significant potential for daylight and presence sensors. But it is also very difficult to estimate the effects of these systems on a whole building complex. Whereas one can find simulations and studies about the savings of theses sensors and dimming for offices, the effects on other room categories stay unclear and little information is available. Therefore the reduction factor for presence sensors on the electric lighting consumption given in the SIA standards shall be applied here for a first approximate calculation. It is for all the relevant room categories 0, 8 (representing savings of 20 %).[125]

- $k_{pres} = 0,8$

For the daylight sensors, the SIA does not give a specific value. The values are dependent on numerous factors, e.g. the relation between window surface and ground surface of a room etc. As these values cannot be evaluated in this work, a reduction factor of 0, 7 (representing a saving of 30%) is assumed, which is in line with the above presented studies.

- $k_{illu} = 0,7$

[125] see *Lighting_Calc_EPFL.xls*

Especially regarding the study from Bourgeois (2006), the chosen values are very conservative, and represent rather the lower limit of savings.

These sensors would possibly not be installed in all locations on campus. Therefore, the effect of these sensors is only considered for the most appropriate room categories at EPFL, which are namely: [126]

- Offices (62.390 m^2, representing 13,75 % of total surface of EPFL)
- Laboratories (96.199 m^2, representing 21,20 % of total surface of EPFL)
- Traffic areas (corridors, halls, stairways): 62.024m^2, representing 13,67 % of total surface of EPFL)

In the retrofit of the *FZ Jülich*, the following measures were applied in the above mentioned room categories:

- *Offices:* only presence detectors were installed, as researchers were considered to change frequently between labs and offices. The general illumination level was lowered from 500 to 300 Lux and, if required, supplemented by additional desktop lamps. This seems to be very attractive solution for a higher efficiency. But as the effects of these measures are not known, it is for EPFL assumed, that the illumination level at office area is kept constant, and also equipped with daylight and presence sensors, which leads to a saving potential of:
  - $e_{li,office} = 1 - k_{illu} \times k_{pres} = 1 - 0{,}7 \times 0{,}8 = 44\ \%$
    - $e_{li,office} =$ $saving\ potential\ for\ room\ category\ office\ through\ sensors$ $[\%]$
    - $k_{illu}, k_{pres} =$ $reduction\ factors\ for\ daylight\ and\ presence\ sensors\ with\ dimming\ control$ $[-]$

- *Labs:* installation of presence and illumination sensors with dimming control.
  - $e_{li,labs} = 1 - k_{illu} \times k_{pres} = 1 - 0{,}7 \times 0{,}8 = 44\ \%$

- *Traffic areas:* basic illumination level of 33 %, controlled by presence and illumination sensors with dimming control. Can be manually augmented to 100 % if required (e.g. for cleaning). As also here the results of this measure is not clear, it is assumed the savings through the sensors and dimming amount to:
  - $e_{li,traffic} = 1 - k_{illu} \times k_{pres} = 1 - 0{,}7 \times 0{,}8 = 44\ \%$

The total reduction factor for lighting consumption at EPFL through sensor and dimming installation in the three room categories at EPFL amounts to:

- $e_{li,EPFL} = a_{office} \times e_{li,office} + a_{labs} \times e_{li,labs} + a_{office} \times e_{li,labs} =$ $(13{,}75\ \% + 21{,}20\ \% + 13{,}67\ \%) \times 44\ \% = 21{,}39\ \%$
  - $e_{EPFL} = resulting\ savings\ for\ EPFL\ through\ sensor\ application\ in$ $[\%]$
  - $a_{office}, a_{labs}, a_{office} =$ $share\ of\ room\ category\ in\ total\ surface\ at\ EPFL\ in$ $[\%]$

[126] calculation executed in *Lighting_calc_EPFL.xls/Surf_and_cons*

The new consumption for lighting at EPFL is then:

- $C_{li,final} = (1 - e_{li,EPFL}) \times C_{li,new\,,EPFL} = (1 - 21{,}39\%) \times 3.853.418\; kWh_{el} = 3.028.998\; kWh_{el}$

The savings in energy amount to:

- $E_{li} = C_{li,actual\,,EPFL} - C_{li,final\,,EPFL} = 5.704.213\; kWh_{el} - 3.028.998\; kWh_{el} = 2.675.216\;\; kWh_{el}$

3.4.5.3 Thermal effects

The reduction of the electric consumption reduces the internal heat gains. These have to be partly compensated by the heating system. In 4 months of the year the heating system is completely shut down. In the 2 months before and after this period it is partly heated. One can with sufficient exactness assume that on 7 months in the year the heating system must compensate for the reduced lighting heat emission. As described before, the COP of the heating system is 3, 6. Therefore, the *energy fine* for the heating system amounts to:

- $C_{fine\,,li} = 2.675.216\;\; kWh_{el} \times \frac{7}{12 \times 3{,}6} = 433.484\; kWh_{el}$

The effects through lower cooling loads are not quantified: for most rooms no active cooling is provided. The electrical savings for reduced cooling load are low, but the reduction of lighting will increase the room climate in the summer months.

Considering the thermal effect, the energy savings of the examined lighting retrofit amount to:

- $E_{li,total} = E_{li} - C_{fine\,,li} = 2.675.216\;\; kWh_{el} - 433.484\; kWh_{el} = 2.241.732\; kWh_{el}$

3.4.7 Economic analysis

In the documentation for the *Phytosphäre* refurbishment, which again serves as a reference, costs for lighting refurbishment were to 100 % considered as *energy relevant additional costs*, as a split into basic costs and energy relevant additional costs was not possible.

T5- fluorescent tubes, the most efficient fluorescent tubes, are only slightly more expensive as the vastly used T12- Technology (4, 70 Euro vs. 3, 70 Euro). The tubes anyway need to be exchanged constantly. The longer life time from T5- technology vs. T12- technology (25000 h vs. 10000 h) compensates for the slightly higher prices. Therefore the price differences for the tubes are not considered in the investment calculation.[127]

[127] *www.leuchtmittel-direkt.de,* 3.10.2009

When replacing an older lighting system, generally the whole system is exchanged, including casing and ballast.[128] For highly reflecting casings, including an electronic ballast with integrated dimming functionality, one can consider a price of 150 Euro (= 225 SFR).[129] The price of the system is mostly not dependent on its power output.

Furthermore, an installation cost of 50 SFR is considered. The cost for the exchange of the lamp is then:

- $225\,SF + 50\,SFR = 275\,SFR$

To determine the number of casings, ballasts and fixtures to be exchanged, an approximative calculation needs to be executed. In a first step, the installed lighting power per building needs to be determined. This is done by the now well known approach: The SIA target values for the installed specific lighting power in $[\frac{W}{m^2}]$ are given for every room category and the surface of each room category in each building is known, which lets one derive the SIA target values for installed lighting power per building:

- $P_{light,target\ ,b} = \sum_{i=1}^{n} p_{target\ ,i,b} \times a_{i,b} \quad [W]$
    - $With\ P_{light,target\ ,b} =\ installed\ lighting\ power\ in\ building\ b\ in\ [W]$
    - $i\ =\ room\ category\ according\ to\ Norm\ Din\ 277/2$
    - $p_{target\ ,i,b}\ = specific\ target\ lighting\ power\ in\ [\frac{W}{m^2}]\ for\ room\ category\ i$
    - $a_{i,b} = surface\ of\ room\ category\ i\ in\ building\ b\ in\ [m^2]$

It is appropriate to use the specific SIA target values here, as the new systems will cope with the requested efficiency of the SIA *target* norms. The according values are published in the SIA bulletin 2024.

The calculated installed lighting power according to SIA target norms is achieved by summing up the power of the according buildings, and amounts to:[130]

- 1st building phase: 1.326.993 W
- 2nd building phase: 902.780 W

A standard medium sized system with 65 W, which is also the most common size for the older installed systems, is assumed to derive the number of the lamps to be installed:

- 1st building phase: $\frac{1.326.993\ \mathrm{W}}{\frac{65\ \mathrm{w}}{\mathrm{lamp}}} = 20.415\ \mathrm{lamps}$
- 2nd building phase: $\frac{902.780\ \mathrm{W}}{\frac{65\ \mathrm{w}}{\mathrm{lamp}}} = 13.889\ \mathrm{lamps}$

The costs for the exchange of old lamps in the old building amount to:

- $80\ \% \times 20.415\ lamps \times 275 \frac{SFR}{lamp} = 4.491.362\ SFR$

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[128] according to *EPFL- Pl- DII_E*
[129] *www.leuchtmittel-direkt.de*, 3.10.2009
[130] see *Lighting_calc_comparison.xls/comparison*

The cost in the building of the 2nd construction phase amount to:

- $13.889\ lamps \times 275 \frac{SFR}{lamp} = 3.819.475\ SFR$

Different sources name costs for combined presence and daylight sensors around 160 Euro, plus an additional 40 Euros for the installation, which results in costs of around 200 Euro (= 300 SFR).[131] The total considered surface for sensor installation is:

- $62.390\ \mathrm{m}^2\ (offices) + 96.199\ \mathrm{m}^2\ (traffic\ areas) + 62.024\ \mathrm{m}^2\ (labs) = 220.613\ \mathrm{m}^2$

To account for the typical size of labs and offices, it is assumed that one sensor is necessary per 40m². The number of required sensors then amounts to:

- $\frac{220.613\ \mathrm{m}^2}{\frac{40}{\mathrm{m}^2}} = 5.515\ sensors$

This results in a cost for the installation of sensors of:

- $5.515 \times 300\ SFR = 1.654.594\ \mathrm{SFR}$

The investment costs for the lighting retrofit then amount to:

- $I_{li} = 4.491.362\ SFR + 3.819.475\ SFR + \ 1.654.594\ \mathrm{SFR} = 9.965.431\ \mathrm{SFR}$

It shall again be mentioned, that these cost calculations only represent a first approximation. The installation of presence and daylight sensors would possibly require further changes in the electric system at EPFL, which cannot be considered for the moment.

The investment is annualized, and amortization and interest rate are considered to be 15 or 20 years, and 5 %. For 15 years the annual capital costs amount to:[132]

- $A_{li} = I_{li} \times \frac{i \times (1+i)^n}{(1+i)^n - 1} = 9.965.431\ \mathrm{SFR} \times \frac{0{,}05 \times (1+0{,}05)^{15}}{(1+0{,}05)^{15} - 1} = 960.092\ SFR$

For a 20 year amortization period one derives annual capital costs of 799.652 SFR.

The monetary savings are calculated assuming an electricity price of 0, 20 SFR, increasing 2 % annually over the next 15 (20 years). The average electricity price is:

- $P_{elec,aver} = 0{,}5 \times P_{elec,act} \times (1+(1+i)^n)$

For 15 years one derives the following annual monetary savings:

- $G_{li} = P_{elec,aver} \times E_{li} = 0{,}23 \frac{SFR}{kWh} \times 2.241.732\ \mathrm{kWh} = 525.881\ \mathrm{SFR}$

For a 20 year amortization period one derives average annual savings of 557.283 SFR (due to the higher average electricity price).

[131] Example: *http://www.merten.de/download/DL_broschueren/DE_Praesenzmelder_492010.pdf,* 30.9.2009
[132] The calculations are executed in *Financial_calculations.xls*

3.4.8 Results and conclusions

The results are displayed in the following table:

Actual consumption for lighting at EPFl in [kWh_{el}]	Consumption if all buildings meet SIA target values (or better) in [kWh_{el}]	Proposed measures result in savings of: in [kWh_{el}]	New consumption after retrofit in [kWh_{el}]
5.704.213	2.397.460	2.675.216- 433.484= **2.241.732**	3.028.998 (+ 433.484 for heating)

Financial implications:

Investment of proposed measures in [SFR]	Annual capital Costs of proposed measures (20 years amort.) in [SFR]	Monetary annual savings (20 years) through proposed measures in [SFR]	Annual costs per kWh_{el} saved (15 years amortization time) in [SFR]	Annual cost per kWh_{el} saved (20 years amortization time) in [SFR]
9.965.431	799.652	557.283	799.652/2.241.732 = **0,43**	**0,36**

- It was shown, that the extensive retrofit of lighting at EPFL can lead to significant savings in the electrical consumption.
- For a considered 20 years amortization period, costs per saved kWh are with 0,36 SFR above the average electricity price of 0,249 SFR. When only 70 % of the refurbishment costs would be considered as *energy relevant additional costs* (and not 100 %), the *energetic* refurbishment would be *profitable.*
- The share *of energy relevant additional costs* in total refurbishment costs needs to be further examined.
- It can be assumed that also other operational costs would be reduced with a refurbishment. If these additional savings were considered, it would again lower the specific costs per saved kWh.
- It is strongly recommended to conduct a study at EPFL about the effects of the extensive appliance of presence and daylight sensors. Therefore representative rooms from the three above considered room categories should be equipped, and the effects measured, to draw more exact conclusions for the effect of an extensive appliance. Such a study could be executed by students and would also represent an attractive master or semester project. It is not absolutely clear to which extent the values found in literature can be extrapolated to EPFL.
- The reduction of the illumination level in offices from 500 to 300 lux and additional appliance of desktop lamps will further increase the saving potential.

3.5 Personal IT- consumption at EPFL

13.407.651 kWh_{el} are consumed on the grid *Force* at EPFL. The consumptions for the server centers are already subtracted and treated separately. It is assumed that an important share of consumptions in the category *Force* is caused by IT equipment, especially desktop PCs. Other consumers on the grid like printer, telephones, experimental installations etc. are difficult to categorize and analyze. Therefore it shall be estimated, how much electricity is consumed by PCs, and what measures can be taken to reduce these consumptions.

3.5.1 Thin Clients as desktop-PC replacement

Thin Client systems represent an innovative option to reduce energy consumption and operational costs for personal IT. In today's common server/client- networks data processing is working with the principle of *distributed resources*, which means, that processes are executed locally on the different workstations. Every user has its own calculation capacities on its proper workstation. The network serves to distribute and exchange data between the different workstations.[133] In this case the workstations are also called *Fat Clients*. [134]

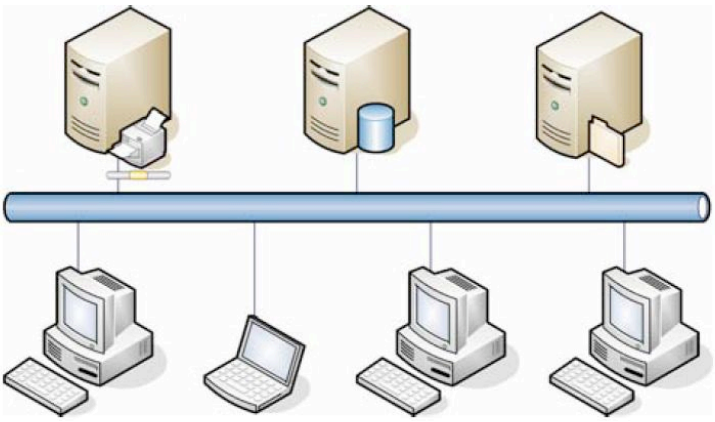


Figure 33: *Fat Client* infrastructure (source: Knermann (2008))

By contrast, *Thin Clients* represent a reduced workstation. They are significantly smaller than PCs, and do normally not include hard disks or fans. The whole data processing takes place on the central servers. All necessary capacities for data processing and applications are transferred to the servers. The network does *not* transfer user data, but only the input- and output- video and audio data between user and server.[135]

[133] Knermann(2008), p. 8
[134] Knermann(2008)[2], p. 11
[135] Knermann(2008), p.10- 11

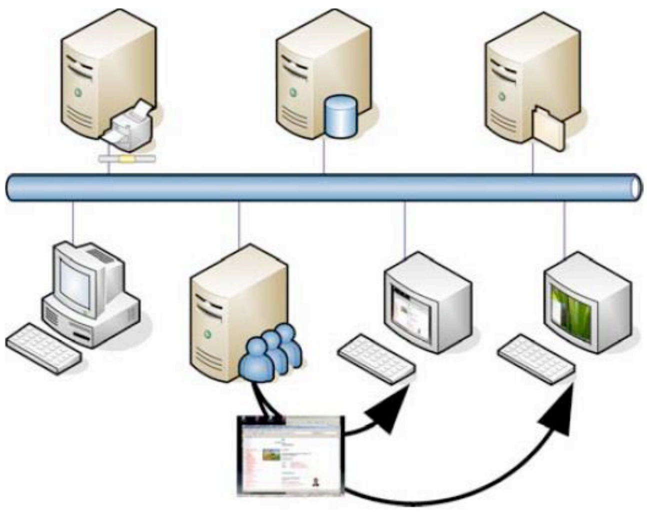


Figure 34: *Thin Client* Infrastructure (source: Knermann (2008))

No further technical explanations shall be made here, as the focus is on the energetic and economical differences between the two systems, at a comparable performance level for the user. For further explanations, the studies from *Fraunhofer Institute* and *BITKOM* are recommended.[136]

Figure 35: *Thin Client* vs. Desktop- PC (source: Knermann (2008))

3.4.2 The *Fraunhofer* Thin Client study

The *Fraunhofer- Institute IUSE* compared PC desktop systems with laptops and so called Thin Client systems in terms of their ecological impact. The analysis included not only the operation phase of the systems, but their whole lifecycle. The lifecycle can be separated into production-, distribution-,

[136] Knermann (2008), Knermann (2008)[2],

operation- and disposal phase.[137] All effects were summed up, and the *Global Warming Potential* was determined, which is expressed in CO_2- equivalents (CO_2eq). Thin Clients may not be regarded alone, as a terminal server is always necessary to execute the main calculation work. One terminal server can serve several Thin Clients, and the server's ecological impact must then be passed on the users. For these reasons different standard user categories were created:

- The light user, using generally only one application at a time
- Medium user, using two or three standard applications at a time
- Power using, always using several application at a time, working with applications with high computing time.[138]

A standard terminal server was defined (HP Pro Liant DL360 G4p), and its ecological impact and energy consumptions were passed on the connected clients with the following factors. These depend on the number of users or Thin Clients, which can be served by one server at a time:

- Light user: 1/50
- Medium user: 1/35
- Power user: 1/20

For the determination of energy consumptions, standard PC Desktop configurations were assumed, and their energy consumption was measured.[139] For the comparison calculation, a standard Thin Client system was chosen (IGEL 3219 LX Compact, most sold system from market leader in Germany). [140]

For the **production** and the **distribution** phase of the different systems parameters like primary energy need, water consumptions, waste amount and emissions were calculated.[141]

For the **operation** phase (which is the most relevant part for this work), electric consumptions for the different systems were determined, and the emissions derived through assumed CO_2- emissions of the German electricity mix (0, 61 kg CO_2eq/kWh_{el}, 0,58 kg $CO_2/kWh_{el,}$).[142] To obtain the annual electric consumptions, assumptions and examinations were made about the different operation modes ("idle","soft- off") and operation times of the desktop PC. Thin Clients were assumed to be used 9 hours a day. By contrast to desktops PCs, they were considered to be all switched off at night, as there is no reason for the user to *not* switch off. The actual session keeps on running on the terminal server, and one can directly continue to work on it the next morning. The energy consumption of the servers was also measured during day and night, and then passed on to the consumption of the *Thin Clients.*[143] A factor of 1/35 was finally chosen to represent the average user, which means that around 35 Thin Clients can be served by one terminal server.[144]

[137] Knermann (2008), p.22
[138] Knermann (2008) p.23
[139] Knermann (2008) p.24
[140] Knermann (2008) p.25
[141] Knermann (2008) p.32
[142] Knermann (2008) p.34
[143] Knermann (2008) p.37
[144] Knermann (2008) p.54

The following values were measured or taken from actual studies about electric consumptions of IT systems. The average was calculated by assuming that a computer is switched on 9 h per day and in "soft off" at night. The average daily consumption of the terminal, which is also running at night, was passed on the 35 connected Thin Clients:

	Desktop PC	**Laptop**	**Thin Client**	**Server**	**Thin client + server fraction**	**LCD monitor**	**CRT monitor**
Consumption switched on in [W]	78,2	22	18,3	214, 9 - 246,6		31,4	69,5
Consumption Soft-off in [W]	2,7	1,2	1,4		-	0,8	1,5
Consumption average 24h in[W]	31	9	7,5		7, 5 + 246,6/ 35 =**14,5**	12,3	27

The servers have a slightly reduced consumption on weekends and in non- working hours (214, 9 W).

Monitors did not enter in the comparison of PCs and Desktops. For laptops it as assumed that an additional external monitor is necessary, as it is required according to German working environment standards.

For the different systems the annual electric consumptions were then calculated, assuming 220 working days per year. On non- working hours, week- ends etc., the units are in *soft- off*. For PCs, it was additionally considered in the study that they were not switched off in- non working hours in 1/3 of the cases. [145] This is in the following called "1/3 Scenario". After discussions with responsible persons from the *EPFL- PI- DII_E,* it became clear that at EPFL, rather 2/3 of all the computers are *not* switched off at night or on weekends. Many PCs are also found in laboratories, and researchers might not want to switch of their PCs due to running applications and calculations during the night or on the weekend. Therefore an additional calculation is made here assuming a PC is not switched off in non- working hours in 2/3 of the cases, in the following called "2/3 Scenario". Thin Clients were assumed to be switched off in non- working hours. For the servers, an additional amount of energy equal to the servers' consumption itself was added to account for the cooling needs in the required data center.

A calculation example shall be demonstrated here:[146]

- PC "Idle": $365\ days \times 24h \times 78{,}2\ W = 685{,}03\ kWh$
- PC "soft off": $220\ days \times 24\ h \times 31{,}0\ W + 145\ days \times 24h \times 2{,}7\ W = 173{,}08\ kWh$
- Annual consumption "1/3 Scenario PC": $\frac{1}{3} \times 685{,}03\ kWh + \frac{2}{3} \times 173{,}08\ kWh = 343{,}73\ kWh$

[145] Knermann (2008), p. 37
[146] Knermann (2008), p. 69

	Desktop PC	**Laptop**	**Thin Client**	**Server**	**Thin client + server share**	**LCD monitors**	**CRT monitors**
"1/3 Scenario": Annual consumption in [kWh_{el}]	343,73	51,70	44,47	2049,90 (+2049,90 for cooling)	2049,90*2/35 + 44,47= **161,61**	67,73	147, 78
"2/3 Scenario": Annual consumption in [kWh_{el}]	514,38	-	-	-	-	-	-

Finally the systems were compared in terms of the impact through **recycling** or **disposal**.

The following values were determined in the *Fraunhofer* study: The electricity related emissions were derived, considering an emission intensity of 0,61 kg $\frac{CO2eq}{kWh_{el}}$ for the German electricity mix, and assuming an operational time of 5 years. The following table shows the CO_2eq emitted over a five-year- lifecycle. The values for servers were not explicitly given in the study, but were directly passed on the Thin Clients:[147]

		Desk-top PC	**Laptop**	**Thin Client**	**Server**	**Thin client + server fraction**	**LCD monitor**	**CRT monitor**
Production	Primary energy in [GJ]	1,9	1,1	0,7		0,78	0,8	0,8
Production	CO_2eq in [kg]	117	71	37	1,5 x PC	42	46	42
Assembly	CO_2eq in [kg]	…	…	…	1,5 x PC	…	…	…
Distributio n	CO_2eq in [kg]	…	…	…	1,5 x PC	…	…	…
operation	CO_2eq in [kg]	1048,38	157,69	135,63	-	492,9	206,58	450,73
Recycling	CO_2eq in [kg]	…	…	…	1,5 x PC	…	…	…
sum	**CO_2eq in [kg]**	**1210,74**	**250,2**	**185,00**	**-**	**554,36**	**276,95**	**542,47**

The main results are:

- The replacement of PCs by a *Thin Client* Infrastructure can cut lifecycle CO_2eq emissions by 54 % and electricity consumption by more than 50 %.
- Including the monitors (LCD), the emission reduction is still 44 % and the electricity consumption reduction almost 50 %.

147 All the values in the shown tables were taken from Knermann (2008), p. 39- 70.

- Notebooks save around 79 % CO_2eq emissions over the lifecycle compared to a desktop PC, and 55% compared to a Thin Client infrastructure. These results should be regarded with caution, as the notebooks in this study were only used stationary. The comprehensive stationary application of laptops is not advisable due to security reasons. Furthermore it must be considered that a laptop will be more expensive in purchase. [148]
- LCD monitors cause half as much CO_2eq emissions as CRT monitors during their lifecycle.

3.5.3 Implications for EPFL

Unfortunately there are no statistics about the number of existing or used computers at EPFL. After discussions with responsible persons from *EPFL- DIT (Domain IT)- Help Desk* , the numbers of PCs at EPFL is roughly estimated at 4000, which is also the number of employees at EPFL. With the above calculated values, annual consumptions for PCs and electricity saving potential, when desktop PCs are replaced by Thin Clients, can be estimated. The values are also calculated considering a more realistic scenario, where just 75 % of PCs are replaced by Thin Clients. By applying the well known approach of the average electricity price for the next 5 years one obtains 0, 21 $\frac{SFR}{kWh_{el}}$. The tables below shows the results for the “1/3 Scenario” and “2/3 Scenario”:

“1/3 Scenario”	**Desktop PC + LCD disp.**	**Thin Client incl. Server + LCD disp.**
Annual consumption per user in [kWh_{el}]	411, 46	229, 34
Consumption EPFL (4000 user) in [kWh_{el}]	4000 x 411,46 = **1.645.840**	4000 x 229,34 = **917.360**
Annual savings EPFL when Thin Clients replace PCs in [kWh_{el}]	1.645.840 - 917.360 = **728.480**	
Monetary savings, in [SFR]	728.480 x 0, 21 = **152.981**	
75 % replacement: Annual savings EPFL when Thin clients replace PCs, in [kWh_{el}]	75% x 728.480 **= 546.360**	
75 % replacement: Monetary savings in [SFR]	**152.981**x 75% = **114.736**	

“2/3 Scenario”	**Desktop PC+ LCD disp.**	**Thin Client incl. Server + LCD disp.**
Annual consumption per user [kWh_{el}]	582, 11	229, 34
Consumption for EPFL (4000 user) in [kWh_{el}]	4000 x 582, 11 **=** **2.328.440**	4000 x 229,34 = **917.360**
Annual savings EPFL when Thin clients replace PCs in [kWh_{el}]	2.328.440– 917.360 = **1.411.080**	
Monetary savings, in [SFR]	1.411.080 x 0, 21 = **296.327**	
75% replacement: Annual savings EPFL when Thin clients replace PCs, in [kWh_{el}]	75% x 1.411.080= **1.058.310**	
75% replacement: Monetary savings in [SFR]	75% x 296.327 = **222.245**	

148 Knermann (2008),p. 72- 75

Concerning the savings of CO_2eq over the full life cycle for Thin Clients, an interesting calculation in the *Fraunhofer*- study shows the effect of such a replacement: considering a company with 10.000 employees, where 75 % of PCs are replaced by Thin Clients, 4923 tons of CO_2eq can be saved over the full 5 year lifecycle. If one extrapolates this result on EPFL, the CO_2eq emissions saved amount to 1969 tons. With this amount of CO_2 emitted, a fleet of 146 VW Golf TDI could be moved 20.000 km per year for the next 5 years![149]

3.5.4 Economic analysis

Another study of the *Fraunhofer UMSICHT*[150] *Institute* compares the *TCO (Total Cost of Ownership)* for desktop PCs and Thin clients. TCO are the summed up costs over the full lifecycle of the system.[151] Also included in these total costs are for example productivity losses due to non- availability of the system, and other related costs.

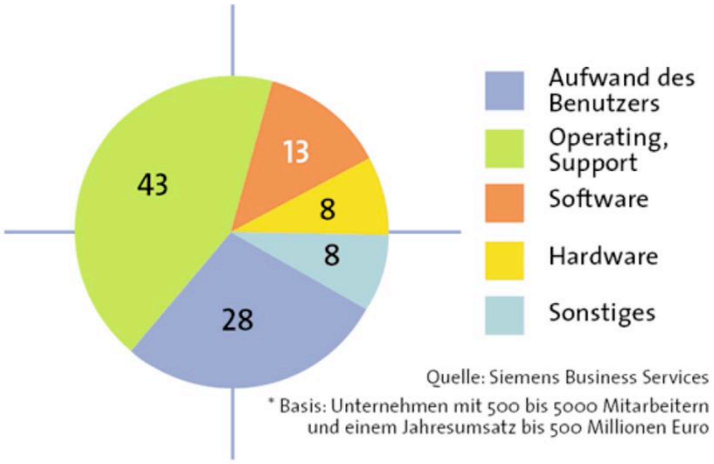


Figure 36: IT- Cost structure in a medium sized company (Source: Knermann (2008)[2])

The use of desktop PCs can be related with many undesirable effects:

- support is required as local hardware components fail
- local installation of software might be necessary
- failures through user intervention
- Local installation of non- authorized software.[152]

Thin Clients can lead to significant cost reductions mainly due to the reduction of support expenses.

[149] Knermann (2008), p. 75, assumed was a VW Golf TDI 1.9 emitting 135 g CO_2/km
[150] *Fraunhofer Institut Umwelt, Sicherheit, Energietechnik*
[151] Knermann (2008)[2]
[152] Knermann (2008)[2], p. 12

To make the two systems comparable, many parameters need to be evaluated including the working environment. Therefore a very detailed model was set up in the study, taking into account all related costs of the two systems. To give a short overview, some parameters shall be mentioned here:

- Working environment: number of employees, salaries, monthly work time etc.
- Processes in terms of purchase: costs for purchase? Who purchases? How much time does it take? Expenses for software? Etc…
- Processes during operation phase: software maintenance: who is doing it, how much time does it take? [153]

The following table shows the costs per workplace, dependent on the number of workplaces comparing a centrally administrated desktop PC and a Thin Client workplace. These costs represent the whole lifecycle costs over 5 years, incl. purchase, operation, support, administration etc. It is again considered that 35 Thin Clients require one server. Additionally the costs are calculated, when a further reserve server is used for compensation in case of failure or maintenance of another server:[154]

Number of users	TCO for centrally administrated desktop PC in [Euro]	TCO for Thin Client in [Euro]	TCO for Thin Client incl. reserve server in [Euro]	Monetary savings in [Euro]	Savings in %
35	2729	1587	2090	639	23
…					
175	2339	1587	1688	651	28
…					
350	2291	1587	1638	653	29

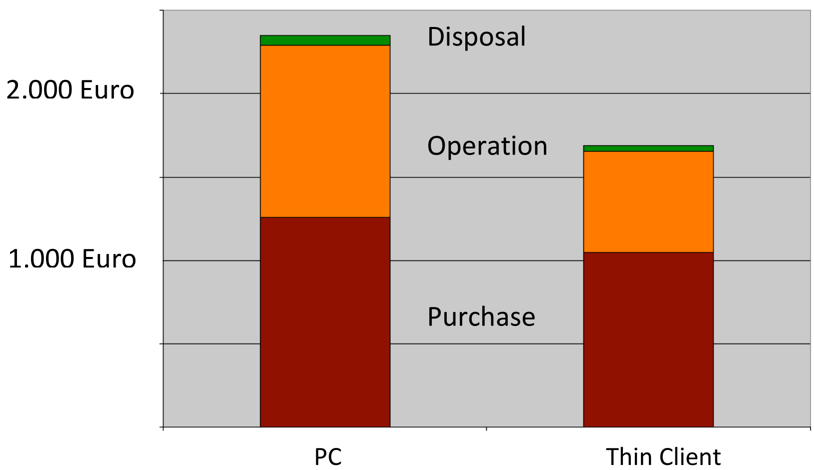


Figure 37: *total costs of ownership* for PC and Thin Clients (source: Knermann (2008) [2])

These costs can now be extrapolated to EPFL considering that 3000 desktop PCs (75 % of the estimated 4000 at EPFL) are replaced by Thin Clients. The costs and savings are transformed from

[153] Knermann (2008)[2], p. 17- 18
[154] Knermann (2008)[2], p. 21

Euro in *SFR*, assuming an exchange factor $\frac{SFR}{Euro} = 1,5$ and another factor of 1, 2 to account for higher equipment and salary costs in Switzerland. Salary costs represent in the *Fraunhofer* study an important fraction within the operation and also within the purchase costs.

desktop PCs replaced		Lifecycle costs for PCs	Lifecycle for Thin Clients incl. reserve server	Savings
3000	**in [Euro]**	3000 x 2291 = **6.873.000**	3000 x 1638 = **4.914.000**	1.959.000
	in [SFR]	12.371.400	8.845.200	3.526.200

Also for this efficiency measure, a *cost* per saved electricity unit shall be derived. Therefore, the monetary savings for electricity consumption reduction still need to be deducted from the above obtained monetary savings. In the *Fraunhofer* study, the “1/3- Scenario” was considered for the energy savings, and an electricity price of 0,15 $\frac{Euro}{kWh_{el}}$. The monetary savings due to energy cost reduction for 5 years are then:

- $5 \times 546.360\, kWh_{el} \times\ 0{,}15\ \frac{Euro}{kWh_{el}} = 409.770\, Euro$

The monetary savings over the full lifecycle, not considering electricity savings, are then:

- $1.959.000\, Euro - 409.770\, Euro = 1.549.230\, Euro = 2.788.614\, SFR$

It is now obvious, that even when energy savings are not considered, Thin Clients are still the cheaper alternative compared to desktop PCs. This leads to the conclusion, that energy savings due to the replacement of desktop PCs by Thin Clients are related with *negative costs* or *profits*. The costs for additional heat requirement still need to be included.

3.5.5 Thermal effects of the replacement

The reduction of electric consumption will have an effect on the internal heat loads of the buildings. In the colder months, these missing heat loads will have to be compensated by the heating system. As shown above the annual electric al consumption for the “1/3- Scenario” is 343,73 kWh_{el} per PC, the value for the “2/3- Scenario” is equally determined at 514,38 kWh_{el}. For the *Thin Clients*, a value of 44,47 kWh_{el} annually was determined. The following table shows the annual internal heat load reduction. The EPFL is only heated 8 months per year, and in the months before and after the summer period heating will be partly provided. Therefore the heat energy to be compensated is approximated by multiplying the annual electricity savings with the factor 7/12. To derive the additional electricity consumption for the heat production, the heat energy is transformed into electricity savings with the total COP- factor 3,6. The costs are derived by assuming an average electricity price for the next 5 years of 0,21 SFR per kWh_{el}.

	Annual consumption PC in [kWh_{el}]	Annual consumption Thin Clients in [kWh_{el}]	Annual reduction of internal heat gains through replacement in [kWh]	Annual reduction of internal heat gains at EPFL with 3000 PCs replaced in [kWh]	Amount of heat to be compensated in [kWh]	Annual additional electricity in [kWh_{el}]	Costs in [SFR)
"1/3-Scenario"	343,73	44,47	299,26	897.780	523.705	145.474	30.549
"2/3-Scenario"	514,38		469,91	1.409.730	822.343	228.428	47.970

In short words: the replacement is also related with an energetic fine of 897.780- 1.409.730 kWh of heat per year, which need to be compensated by the heating system and will result in an additional electricity consumption of 166.256- 261.061 kWh_{el}.

Furthermore, the reduction of internal heat load brings advantages in the hot summer months, as it will improve the indoor climate. The changes in cooling loads are- as always- not quantified.

3.5.6 Results

The results for the replacement of 75 % of the PCs through Thin Clients and the scenario "2/3", in which it is considered that 2/3 of all desktop pcs are not switched off at night, are:

Total annual electrical savings in [kWh]	TCO savings over 5 years according to *Fraunhofer* in [SFR]	TCO savings excluding energy savings in [SFR]	Annual monetary savings excluding energy savings in [SFR]	Additional monetary savings per saved kWh_{el} in [$\frac{SFR}{kWh_{el}}$]
1.058.310 - 228.428 = **829.882**	3.526.200	2.788.614	2.788.614/5 = **557.723**	557.723/829.882 = **0, 67**

- Personal PCs and monitors stand for around 1.645.840 kWh_{el} - 2.328.440 kWh_{el} of EPFL's electricity consumption. The values represent a smaller share on the grid *Force*, as it was originally expected from the author.
- The replacement by Thin Clients makes ecologically and economically sense. It was shown that between 546.360 kWh_{el} and 1.058.310 kWh_{el} of electricity could be saved, reducing the annual electricity costs between 114.736 SFR and 222.245 SFR by replacing 75 % of the desktop PCs with Thin Clients. The required additional heating amounts to 598.520- 939.820 kWh of heat, or 166.256- 261.061 kWh_{el} of electricity, and costs of 33.251- 52.212 SFR. The values were determined for two scenarios, where 1/3 (or 2/3 respectively) of the used PCs was not switched off in non- working hours.
- According to the *Fraunhofer* studies, the *total cost of ownership* over the full 5 year lifecycle could be substantially reduced, and around 3.294.000 SFR could be saved at EPFL, which results in 658.800 SFR per year. Furthermore 1969 tons of CO_2eq could be saved regarding the full 5 year lifecycle emissions for PCs and Thin Clients *(annotation: These values consider*

the German electricity mix, which emits more CO_2eq per kWh_{el} as the Swiss mix, so the emission savings calculated for Switzerland would be lower).

- In contrast to the other examined efficiency measures, *negative costs* or monetary gains per saved electricity unit are derived here. This means, that even when the energy consumption reductions are not considered the measure is profitable. This is a result of all the other efficiencies related with the application of Thin Clients. Once more: for other efficiency measures and the related costs per saved electricity unit, only the annual capital costs were considered.

4. Integration of thermal flows

4.1 Introduction

In this chapter it shall be examined whether there exist significant potentials of between the different thermal streams at EPFL, which could be utilized e.g. through heat recovery.

The goal of energetic process integration is generally to identify eventual synergies between *hot* and *cold streams*. In process integration *cold streams* are streams which need to be heated up, for example the water for the heat supply of the buildings. *Hot streams* need to be cooled down, for example the exhaust air from acclimatization units, or from server rooms. Each stream is defined by its thermal load and by the temperature level where heat is absorbed (cold stream) or emitted (hot stream).[155]

The most obvious option for heat recovery, namely heat recovery in ventilation systems, is not further emphasized here, as heat is already recovered from exhaust air whenever technically feasible, according to *EPFL- Pl- DII_E.*

4.2 Cooling loads at EPFL

The *cold streams* at EPFL are basically represented by the heating system, or more exactly by the water which distributes heat to the buildings over the heat distribution network. The heating system was already partly introduced in chapter 2.1 and will also be further treated in chapter 5.3.

The *hot streams* at EPFL are finally all “bundled” in the ejected industrial water. In other words: basically all exhaust heat at EPFL is lead away over the industrial water system, including heat from the room cooling units, from the server rooms and from other installations which require cooling. The industrial water is extracted from Lake Geneva at around 7 °C and injected again at around 12 °C. The temperatures are slightly varying (6- 7 °C and 12- 14 °C), but are here considered as being constant. Measures for the monthly industrial water streams exist; these can be transformed into monthly waste heat streams with the following equation:

- $Q_{IW,m} = \frac{V_{IWm} \times c_p \times \Delta T \times d_W}{3600} = \frac{V_{IWm} \times 4{,}18 \frac{kJ}{kg \times K} \times 5K \times 1000 \frac{kg}{m^3}}{3600} \quad [kWh]$
  - $V_{IW,m} = measured\ industrial\ water\ stream\ in\ month\ m\ in\ [m^3]$
  - $c_p = specific\ heat\ capacity\ of\ water = 4{,}18\ \frac{kJ}{K \times kg}$

[155] Kemp (2007), p. 15 ff.

- $d_W = density\ of\ water = 1000\ \frac{kg}{m^3}$
- $Q_{IW,m} = monthly\ waste\ heat\ led\ away\ with\ indutrial\ water\ in\ [kWh]$

For the year 2008 the following values were measured for EPFL, the values for 2007 are included for comparison:[156]

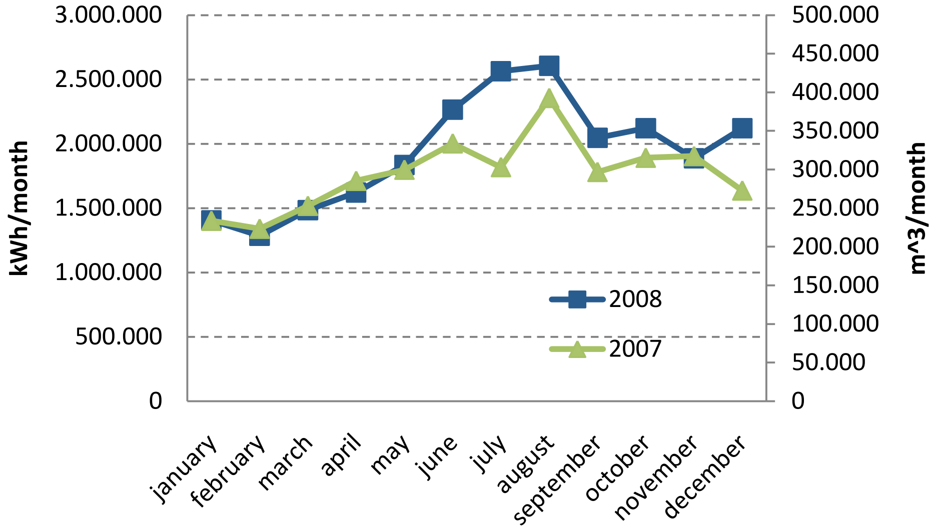


Figure 38: Monthly industrial water streams and waste heat streams for EPFL

One can observe that the cooling load consist to a substantial part of a base load, and also in cold winter months the cooling load does not drop under 1.285.774 kWh/month. The cooling load is only partly dependent on exterior temperatures. The total annual flow of industrial water amounts to 4.003.711 m^3 or 23.243.767 kWh. This is almost as much as the total annual heat consumption for the EPFL. One could therefore come to the conclusion, that the whole annual heat demand could be covered, if waste heat was consequently reused for heating. This would be indeed possible, if waste heat could be stored over the seasons without significant losses, and if the temperature level was high enough. As explained before, the heat network is designed for temperatures of up to 65°C.

Variations between the different years can also be observed. However, he following analysis will be based on measures for 2008.

The next figure shows the monthly cooling loads, expressed as a constant power in kW, by dividing the cooling energy in kWh/month through the according hours per month.[157]

[156] values from *calcs_hot_cold_flows.xls*
[157] values from *calcs_hot_cold_flows.xls*

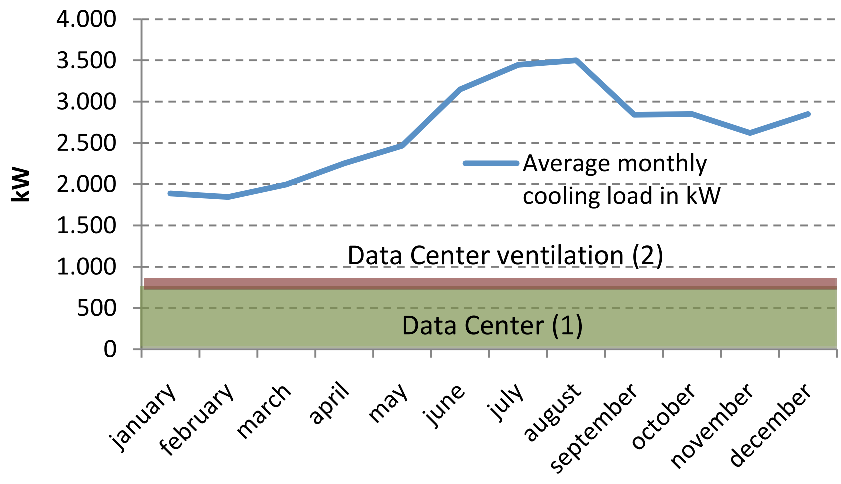


Figure 39: monthly cooling loads for EPFL

Even in February an average cooling load of 1.757 kW can be observed, which represents the cooling base load. To evaluate the possibilities for heat recovery, it is now necessary to identify the different origins of these cooling loads, and to determine the according energy loads and the temperature levels at which heat is emitted.

According to *EPFL- Pl- DII_E,* the above shown curves might be strongly influenced by problems with the regulation of the industrial water flows. So changes in the cooling loads cannot only be explained through variation of outside temperatures or real cooling needs. Furthermore, the *SV-* building *(Science de la Vie)* with its extensive steam production went into operation in the beginning of 2008, which also might have strongly influenced the total cooling needs. Exact values were not available for this building.

The following origins of cooling demand can be identified, which represent the *hot streams* at EPFL:

- As mentioned before, 820 kW of constant cooling load can already be attributed to **data centers** (see surface 1 in figure above). The data centers are primarily cooled with air; the heat is finally led away over heat exchangers with industrial water. The electricity from the fans is transformed into heat, so another significant amount of heat energy will be emitted by the fans. It is here assumed to be 10 % of the server loads of the data centers. The air temperature for the racks in the MA data center is not known, but the first cooling cycle is operating at 15/18 °C. In the other data centers, air is cooled at 24/15 °C, but as further explained in chapter 4.4 these temperatures could possibly be raised. [158]
- The rest of the cooling base load is caused by all the other **technical equipment** at EPFL, for example experimental installations or electricity supply equipment. The systems are very heterogeneous, so it is neither possible to specify the exact cooling load nor the temperature levels. Most of the technical installations are not directly cooled over the industrial water

[158] according to *EPFL- Pl- DII_E*

cooling cycle, but with a second cooling cycle at round 8/15 °C, and the heat is then lead away over a heat exchanger to the industrial water cooling cycle.[159]

- The **room cooling** need: there are basically two different systems for room cooling at EPFL: in the buildings of the first building phase air is directly cooled in the mono- blocks, with industrial water at 7/12 °C. The air condenses at this temperature level, and the condensate needs to be lead away. In the newer buildings, air is directly cooled with cooling batteries. To avoid condensation, air is directly cooled with a water cycle at 20/15°C, the heat is then evacuated over a heat exchanger with the primary industrial water cycle at 7/12C°
- The **steam production** in the SV- building could be a possible “hot” source, but up to this point of time it was not possible to get any information about the steam cycle there. According to the *EPFL- Pl- DII_E,* heat is partly recovered in the condensing process, and reused for hot water production and pre- heating.

On can draw from this information the following conclusions:

- Simple heat recovery is not possible, as all the cooling processes (“hot flows”) which could be categorized here, have a lower temperature level as the only heating process (“ cold flow”), namely the heating process for the building.
- Heat recovery for room heating could be realized in data centers, if the cooling medium temperature was raised. This option is further evaluated in the chapter 4.4.
- In all the other cases, heat pumps would be necessary to raise the temperature level of the cooling medium. This could be realized be local heat pumps. On the other hand, there are already two heat pumps existent, which are fed with lake water at 7 °C. So the most obvious solution would be to supply these heat pumps with the industrial water at 12 °C instead (or perhaps even a higher temperature). As it was shown above, the industrial water transports an enormous amount of heat, but needed to be “pumped” to a higher temperature level. This option will therefore be the second emphases of the chapter 4.

[159] according to *EPFL- Pl- DII_E*

4.3 Recirculation of industrial water in heat pumps

4.3.1 Heat pump efficiency at EPFL

Before analyzing the reuse of industrial, the actual COP needs to be determined. The total amount of heat emitted is annually 29.451.000 kWh. The heat pumps consume 6.462.900 kWh_{el} per year. This leads to the COP of the heat pumps of at EPFL: [160]

- $COP_{HP,EPFL} = \frac{29.451.000 \text{ kWh}}{6.462.900 \text{ kWh}_{\text{el}}} = 4{,}56 \quad [-]$

To derive the total COP, the consumptions of the auxiliary units need to be taken into account. The booster pumps to distribute the hot water in the heat distribution network consume 615.104 kWh_{el} annually. The engines to pump the water from the lake to EPFL consume 1.772.060 kWh_{el} per year. Not the whole consumption can be taken into account here: From the 11.325.907 m^3 of water pumped, only 7.322.196 m^3 are used in the heat pumps, the rest is used as industrial water for cooling. Therefore the consumptions of the lake water pumps are considered with a factor of $\frac{7.322.196}{11.325.907}$. The total COP, including consumption of auxiliary units, is then derived as follows:

- $COP_{total\ ,EPFL} = \frac{29.451.000}{6.462.900 + \frac{7.322.196}{11.325.907} \times 1.772.060 + 615.104} = 3{,}58 \quad [-]$

From the values above one can derive the specific consumption for the lake water pumps:

	Total amount of lake water	Lake water for heat pumps	Lake water for cooling
Annual volume flow in $[m^3]$	11.325.907	7.322.196	4.003.711
Pump consumption in $[kWh_{el}]$	1.772.060	1.145.636	626.424
Specific consumptions in $[\frac{kWh_{el}}{m^3}]$	0,156		

4.3.2 Effect of recirculation of industrial water for COP

As explained in the chapter 4.2, 4.003.711 m^3 of water are extracted from the lake at around 7 °C and used for cooling, and thereby warmed up to 12 °C. To visualize this amount of water: it represents a cube of 100m x 100m x 400m! A total of 23.243.767 kWh of heat is annually lead way.

The question is now, if a part of this heat could not be re- used in the existing heat pumps, instead of using colder lake water as heat source.

[160] values from *Diagr_flux_2008.xls* and *Elec_EPFL_v4.xls*

For the heat pump process, a theoretical COP value can be derived. The theoretical COP of a heat pump is the bigger, the smaller the temperature differences between the heat source and the heat sink are. The theoretical COP can be defined as: [161, 162]

- $COP_{theor} = \frac{\Delta T_{lm}^{hot}}{\Delta T_{lm}^{hot} - \Delta T_{lm}^{cold}}$ [-]
- $\Delta T_{lm}^{hot} = \frac{T_{out}^{hot} - T_{in}^{hot}}{\ln \frac{T_{out}^{hot}}{T_{in}^{hot}}} \quad [K]$
- $\Delta T_{lm}^{cold} = \frac{T_{in}^{cold} - T_{out}^{cold}}{\ln \frac{T_{in}^{cold}}{T_{out}^{cold}}} \quad [K]$
    - $\Delta T_{lm}^{hot} =$ $logarithmical\ average\ of\ heat\ sink\ temperature\ in\ heat\ exchanger\ in\ [K]$
    - $\Delta T_{lm}^{cold} =$ $logarithmical\ average\ of\ heat\ source\ temperature\ in\ heat\ exchanger\ in\ [K]$

The following illustration shows the different water flows from the Lake Geneva to the heat pumps at EPFL, and from the heat pumps to the distribution network in the actual situation:

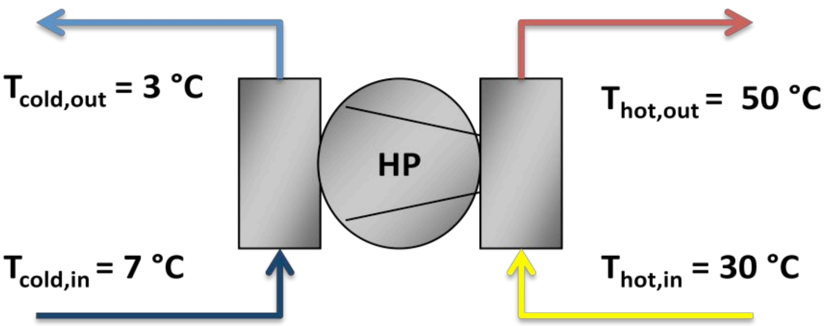


Figure 40: Temperature levels at heat pumps at EPFL (own illustration)

According to the *EPFL- PI- DII_E,* the heat pumps are either working under full load conditions, and fill up a thermal storage tanks with the excessive heat, or are switched off. Therefore, condensation and vaporization temperatures can assumed as constant.[163] The vaporization point is around 2 °C, the condensation point is around 50 °C.

T_{in}^{hot} is in reality variable, the return temperature of the HDN varies between 25 °C and 35 °C. It is here assumed to be constantly 30°C.[164]

This leads to the following theoretical COP for the EPFL:[165]

[161] Beranger (2008), p. 18
[162] Girardin (2009), p. 8
[163] Schmid (2005), p. 3
[164] Schmid (2005), p. 7
[165] See *calc_hot_cold_flows.xls*

- $COP_{theor,EPFL} = \frac{\Delta T_{lm}^{hot}}{\Delta T_{lm}^{hot} - \Delta T_{lm}^{cold}} = \frac{\frac{323K-303K}{ln\frac{323K}{303K}}}{\frac{323K-303K}{ln\frac{323K}{303K}} - \frac{280K-276K}{ln\frac{280K}{276K}}} = 8,965$

The real COP is - as shown before - lower as the theoretical COP, and needs to be adapted with a technical efficiency factor:

- $COP_{HP,real,EPFL} = COP_{theor} \times ή_{tech} \quad [-]$
    - $ή_{tech} = technical\ efficiency\ of\ heat\ pump$

- $ή_{tech,EPFL} = \frac{COP_{HP,real,EPFL}}{COP_{theor,EPFL}} = \frac{4,56}{8,965} = 0,51$

It is now assumed that the temperature of the *heat source* in the evaporator is raised by 5 K to 12 °C, by using industrial water instead of colder lake water. Also the vaporization point can be raised by 5 K, up to 7 °C. It is considered here that the heat exchanger is still the same. Raising the vaporization point is equivalent to raising the pressure in the heat pump cycle between depressurization valve and compressor. Or differently expressed: the compressor needs to produce less under- pressure on the vaporization side.[166] Its electrical consumption decreases, which is then reflected in a higher COP. The new theoretical COP is then:

- $COP_{theor,new,EPFL} = \frac{\frac{323K-303K}{ln\frac{323K}{303K}}}{\frac{323K-303K}{ln\frac{323K}{303K}} - \frac{285K-281K}{ln\frac{285K}{281K}}} = 10,47 \quad [-]$

This represents an elevation of the theoretical COP of 17 % compared the actual theoretical COP.

It can be assumed that the technical efficiency of the heat pumps does not change. The new COP is then:

- $COP_{HP,new,EPFL} = COP_{theor,new,EPFL} \times ή_{tech,EPFL} = 10,47 \times 0,51 = 5,32 \quad [-]$

The same amount of heat could then be produced consuming 18 % less of electricity, as the real COP would increase from 4,56 to 5,32. Furthermore, less water needed to be pumped up from the lake, as the water would be used *twice* (first for cooling, then for heating) on campus.

166 Issue was discussed with researchers in the field of heat pumps at the LENI- Institute

4.3.3 Energy savings through recirculation of industrial water

As the heat curve (heat load dependent on exterior temperature) for EPFL is known (Ch. 3.2), as well as the hourly temperatures for 2008, it is now possible to re- simulate the monthly heat consumptions for EPFL, by summing up the hourly heat consumptions for each month.

The next step is to calculate, how much heat per month can be produced in the heat pumps with available Industrial water at 12 °C. It can be assumed, that the heat exchanger in the heat pump is still the same, and the difference between T_{in}^{cold} and T_{out}^{cold} is still 4 K, as it was before:

- $T_{in}^{cold} = 12°C, \ T_{out}^{cold} = 8°C$

Then available heat from the industrial water for each month *m* amounts to:

- $Q_{IW,m} = \frac{V_{IWm} \times c_p \times \Delta T \times d_W}{3600} = \frac{V_{IWm} \times 4{,}18 \frac{kJ}{kg \times K} \times 4\ K \times 1000\ \frac{kg}{m^3}}{3600} \quad [kWh]$
  - $V_{IW,m} = available\ industrial\ water\ flow\ in\ month\ m\ in\ [m^3]$
  - $c_p = specific\ heat\ capacity\ of\ water = 4{,}18\ \frac{kJ}{K \times kg}$
  - $d_W = density\ of\ water = 1000\ \frac{kg}{m^3}$
  - $Q_{IW,m} = monthly\ waste\ heat\ led\ away\ with\ indutrial\ water\ in\ [kWh]$

The required additional electricity for the heat pumps, using industrial water as heat source, is:

- $C_{HP,IW,m} = \frac{Q_{IW,m}}{(COP_{HP,new,EPFL} - 1)} \quad [kWh_{el}]$

The amount of heat, which the heat pumps can provide on the required temperature level in month *m*, by extracting heat from the industrial water, is then:

- $Q_{total,IW,m} = Q_{IW,m} + C_{HP,new} \quad [kWh]$

The following figure shows the simulated monthly heat consumptions at EPFL, and the amount of heat which can be produced using industrial water as heat source. The monthly heat requirement for EPFL is calculated with ENERGIS, considering the heat curve and the hourly exterior temperatures for the according month:[167]

[167] Calculated in *calc_hot_cold_flows.xls*

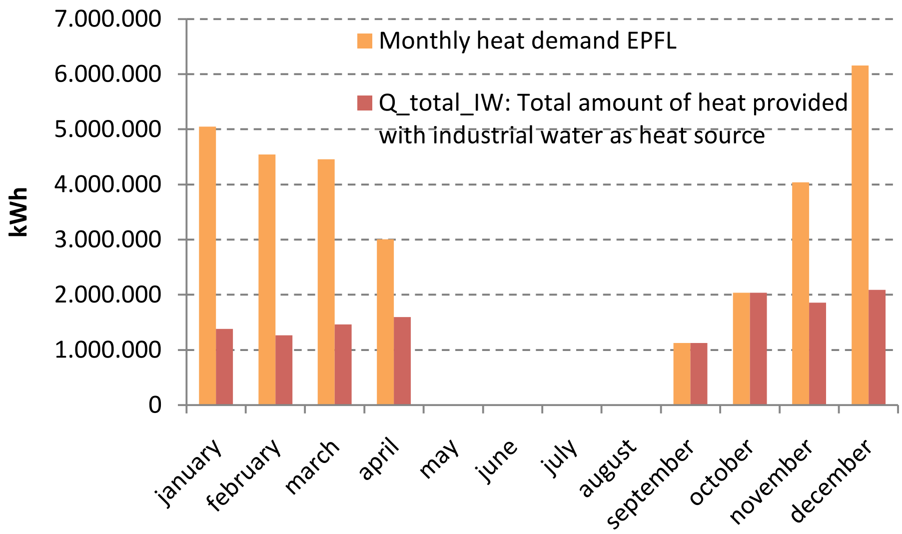


Figure 41: monthly heat demand and available heat from industrial water

The monthly heat demand exceeding $Q_{total,IW,m}$ needs to be covered - as before - with lake water as heat source:

- $Q_{total,LW,m} = Q_{h,m} - Q_{total,IW,m} \quad [kWh] \quad if\ Q_{h,m} > Q_{total,IW,m}$
    - $else\ Q_{total,LW,m} = 0$
    - $Q_{h,m} = heat\ demand\ EPFL\ in\ month\ m\ in\ [kWh]$

The monthly electric consumption of the heat pumps to provide this heat:

- $C_{HP,LW,m} = \frac{Q_{total,LW,m}}{COP_{HP,EPFL}} \quad [kWh_{el}]$

So the monthly electrical consumptions, when industrial water and lake water are used as heat source amount to:

- $C_{HP,new,m} = C_{HP,IW,m} + C_{HP,LW,m} \quad [kWh_{el}]$

This value can now be compared with the traditional electrical consumption, when only lake water is used as heat source:

- $C_{HP,actual,m} = \frac{Q_{h,m}}{COP_{HP,EPFL}}$

The results shall be displayed in the following table and figure:[168]

[168] Calculated in *calc_hot_cold_flows.xls*

	January	**February**	**March**	**April**
Monthly heat demand EPFL $Q_{h,m}$ in $[kWh]$	**5.049.857**	**4.542.762**	**4.456.490**	**3.002.102**
Heat from IW $Q_{IW,m}$ in $[kWh]$	1.123.194	1.028.619	1.188.026	1.296.868
Additional electricity IW $C_{HP,IW,m}$ in $[kWh_{el}]$	259.842	237.963	274.840	300.020
Total amount of heat available with IW as heat source $Q_{total\ ,IW,m}$ in $[kWh]$	1.383.036	1.266.582	1.462.866	1.596.889
Resting heat to be produced with lake water $Q_{total\ ,LW,m}$ in $[kWh]$	3.666.821	3.276.180	2.993.624	1.405.213
Heat from LW $Q_{LW,m}$ in $[kWh]$	2.862.694	2.557.719	2.337.128	1.097.052
Electricity cons. LW $C_{HP,LW,m}$ in $[kWh_{el}]$	804.127	718.460	656.497	308.161
Electric cons. in actual state in $C_{HP,actual\ ,m}$ in $[kWh_{el}]$	1.107.425	996.220	977.301	658.356

	September	**October**	**November**	**December**	**Sum**
Monthly heat demand EPFL $Q_{h,m}$ in $[kWh]$	**1.124.935**	**2.036.712**	**4.036.085**	**6.156.921**	**30.405.864**
Heat from IW $Q_{IW,m}$ in $[kWh]$	913.584	1.654.059	1.509.082	1.697.150	**10.410.582**
Additional electricity IW $C_{HP,IW,m}$ in $[kWh_{el}]$	211.351	382.654	349.114	392.622	**2.408.407**
Total amount of heat available with IW as heat source $Q_{total\ ,IW,m}$ in $[kWh]$	1.124.935	2.036.712	1.858.197	2.089.772	**12.818.988**
Resting heat to be produced with lake water $Q_{total\ ,LW,m}$ in $[kWh]$	0	0	2.177.888	4.067.149	**17.586.876**
Heat from LW $Q_{LW,m}$ in $[kWh]$	0	0	1.700.281	3.175.230	**13.730.105**
Electricity cons. LW $C_{HP,LW,m}$ in $[kWh_{el}]$	0	0	477.607	891.919	**3.856.771**
Electric cons. in actual state in $C_{HP,actual\ ,m}$ in $[kWh_{el}]$	246.696	446.647	885.106	1.350.202	**6.667.953**

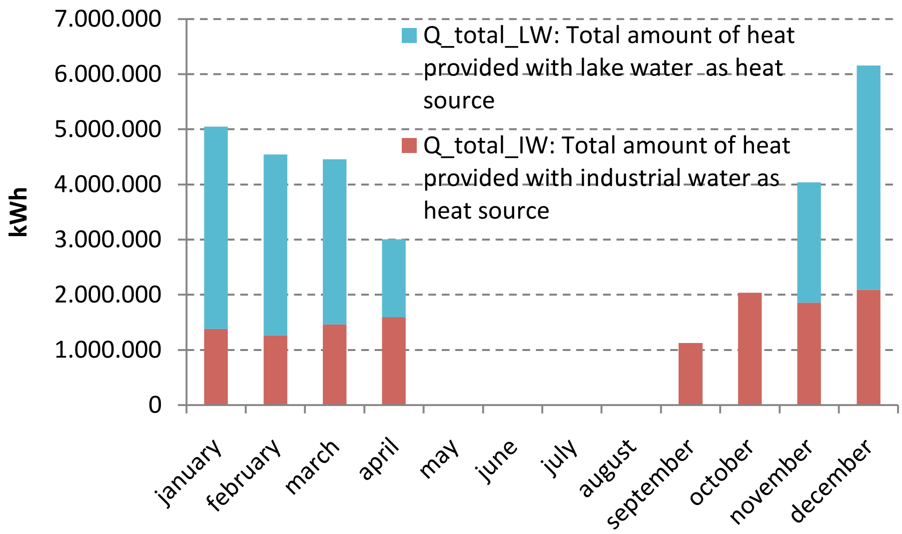


Figure 42: possible provision of heat pumps with industrial water

The electricity savings in the heat pump can now be derived through comparison of both options:

- $E_{HP} = C_{HP,actual,m} - \left(C_{HP,IW,m} + C_{HP,LW,m}\right) = 402.775\ kWh_{el}$

Further savings are achieved on the lake water pump: industrial water only needs to be pumped up once from the lake to the campus and is used *twice*. So the difference between the pumped lake water in the actual situation and pumped lake water, when additionally industrial water is used in the heat pumps, needs to be evaluated. The volumes of pumped lake water now, and when industrial water serves as additional heat source, amount for the whole year to:

- $V_{LW,actual} = \sum \frac{Q_{h,m} \times 3600}{c_p \times \Delta T \times d_W} = 5.111.034\ \mathrm{m}^3$
- $V_{LW,new} = \sum \frac{Q_{LW,m} \times 3600}{c_p \times \Delta T \times d_W} = 2.956.243\ m^3$

In Ch. 4.2.1 the specific consumption of the lake water pump was calculated. The additional savings trough the re- use of industrial water, are:

- $E_{pump} = (5.111.034\ m^3 - 2.956.243\ m^3) \times 0{,}156\ \frac{kWh_{el}}{m^3} = 336.147\ kWh_{el}$

4.3.4 Results

The total annual energy savings for the industrial water re- use in the heat pumps are:

- $E_{IW} = 336.147\ kWh_{el} + 402.775\ kWh_{el} = 738.922\ kWh_{el}$

To realize the proposed measure, a modification of the canalization system would be required, as industrial water is for the moment directly led back to the lake. It is for the moment not possible to derive a price for this measure, therefore the financeable maximum investment shall be determined. The investment can be seen as long-term investment, an amortization period of 25 years seems to be adequate, which leads to an average electricity price of 0,264 $\frac{\text{SFR}}{\text{kWh}_{\text{el}}}$. The annual energy cost savings then amount to:

- $G_{IW} = P_{elec,aver} \times E_{IW} = 0,264 \ \frac{\text{SFR}}{\text{kWh}_{\text{el}}} \times 738.922 \ \text{kWh}_{\text{el}} = 195.075 \ SFR$

The max .investment that could be financed over 25 years with this annual monetary savings can again be derived with the following equations:

- $a = \frac{i \times (1+i)^n}{(1+i)^n - 1}$
- $I_{IW,max} = \frac{G_{IW}}{a} = \frac{195.075 \ SFR}{0,071} = 2.750.013 \ \text{SFR}$

Industrial water re- use	**Annual Electricity savings in $[\mathbf{kWh_{el}}]$**	**Annual monetary savings in [SFR]**	**Max. investment for 25 years amortization period in [SFR]**
	738.922	195.075 SFR	2.750.013

A few more explications:

- This calculation can approximate the effects of an industrial water reuse. It was executed on a monthly basis, assuming that the considered flows are constantly available throughout the month, which will partly not be the case in reality.
- The question, how the proposed solution is technically realized, needs still to be answered. One could imagine that one of the two existing heat pumps is operated only with industrial water, the other one with lake water. Another option would of course be the continuous mix of industrial water with lake water. When the amount of industrial water does not suffice to cover the heat demand, additional lake water is added. Then one obtains a variable temperature level of the heat source, varying between 7 °C and 12 °C. Theoretically it should be no problem to permanently adapt the heat pumps, specifically the compressor, to the variable heat source temperatures. It was discussed with responsible persons for the heating central, whether such a strategy would be realizable for the existing heat pumps, but the issue could not be conclusively clarified. However, the reuse of industrial water should be definitely considered for heat pumps, which will be installed in the future.

4.4 Recovery of data center waste heat

4.4.1 Energy efficiency at data centers

An important fraction of cooling demand is caused by the server rooms in the buildings *MA, MA ext., BC, IN j, ME* and *AI*. They have a constant power (and therewith a heat output) of 820 kW (see Ch. 2.2) throughout the year. Around a third of the total cooling base load at EPFL is caused by the servers, and the electrical consumption of more than 6 million kWh per year represents of course a substantial fraction of overall electrical consumption at EPFL; the electrical consumption for cooling purposes is here not yet included.

A paper from the *German ministry of Environment* specifies in his paper *"Energy efficiency in data centers"* 6 different dimensions for energy efficiency in date centers:

1. ***Applications and data…*** often a substantial part of unnecessary data occupies the hardware resources. This data should be minimized and eventually deleted. Future Hardware occupancy can already be considered when new software is bought and installed.
2. ***Virtualization*** … utilization can be decreased from 5-15 % to 60-80 %, and electricity consumption halved. More and more common.

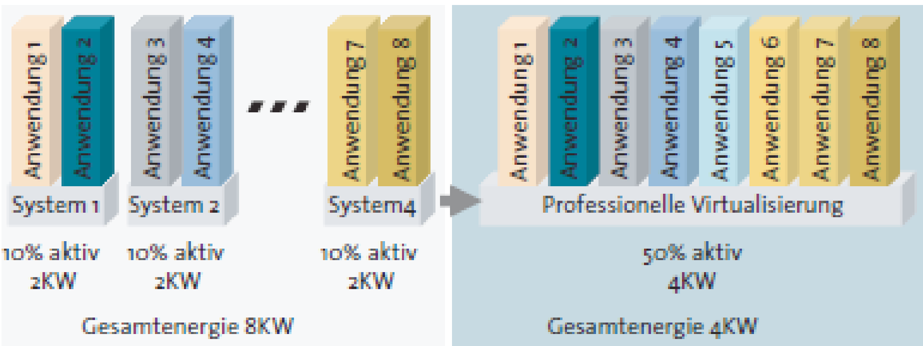


Figure 43: Energy savings through virtualization (Source: BITKOM(Ed.) (2008))

3. ***IT- Hardware*** … energy efficiency should be considered when purchasing new servers. Since 2007 an efficiency benchmark exists, measured in *[ssj_ops/Watt]*, which makes servers comparable in terms of energy efficiency.
4. ***Uninterrupted power supply (UPS)*** …the necessity of backup- systems or transformation systems, like batteries, causes higher consumption. The UPS- system needs therefore work with high efficiency and should be correctly dimensioned. Detailed information can be found in the paper "Energy efficiency in data centers" from bitkom.org.[169]

These 4 dimensions represent the *optimization of processes,* so their improvement and adaptation would be located in the innermost layer of the *onion diagram* approach. Before thinking about how to reuse waste heat from data centers, one should try to minimize electric consumption and waste heat. However, these very specific and technically complex topics cannot be further treated within

[169] BITKOM (Ed.) (2008), p. 10 ff.

this work. It is considered that the electric consumption of data centers at EPFL is fixed. The next dimensions are:

5. ***Acclimatization*** *…*The *DCIE (Data Center Infrastructure efficiency) - index* is defined as $CIE = \frac{Energy\ \ consumptions\ \ \ IT}{Total\ \ energy\ \ consumption\ \ \ of\ data\ \ center}$, and displays the efficiency of a data center. The consumption of the cooling system can be as high as the consumption of the IT-Installations itself. Older data centers will in most cases not reach a *DCIE- index* of higher than 50 %, not even by applying efficiency measures. Modern centers reach values of 70 %, best-practice examples achieve around 85 % by applying innovative technologies like geothermal cooling.
6. ***Heat recovery****…* waste heat can be reused to supply offices or other buildings.
7. ***Electricity purchase****…*purchase of renewable energy…not further treated here.

Acclimatization and heat recovery will be further treated for EPFL. Although energy efficiency of data centers is improving and more attention is given to "Green IT", it is pretty unlikely that the energy consumption of the data centers will decrease, as at the same time the need for calculation capacity is constantly rising. Therefore it makes sense to think about the reuse of waste heat.[170]

4.4.2 Improvements for the existing system

The racks itself in the smaller data centers are cooled with air at around 15/24 °C.[171] Generally it is possible to raise the ΔT of the cooling air up to 15K, for modern *Blade* servers up to 28K, which minimizes the necessary air volume streams.[172] Directly at the exit of the racks a temperature of 35°C and more can be accepted. A higher temperature level of the air would make the air more valuable for an eventual reuse; also the cooling process becomes more efficient. Practice shows that just a better separation of hot and cold flows, and the resulting higher temperature differences can lead to significant energy savings in the cooling process, as volume flows can be reduced.[173,174]

The most common measures to improve energy efficiency on the cooling level can be summed up as followed:[175]

- Increasing of the temperature level of the cooling medium (air).
    - One can make the observation for example in the *ME* data center, that the exhaust air could be captured at a much higher temperature level: At the moment it exits from the rack, and then streams to the ceiling of the room where it is sucked of trough opening in the ceilings. On its way from the rack to the ceiling the cooling air is mixed with the ambient air and therefore loses some degrees.
- Strict separation of the cold and heat streams through intelligent alignment of the servers.

[170] BITKOM (Ed.) (2008), p. 10 ff.
[171] according to *EPFL- Pl- DII_E* + Forrer SA (Ed.)(2007)
[172] BITKOM (Ed.) (2008), p. 18
[173] Fichter (2008), p.23 + p. 27
[174] BITKOM (Ed.) (2008), p. 17
[175] BITKOM (Ed.) (2008), p. 13-17

    - See above for *ME* center
- A load adapted ventilation with variable air streams.
- Generally improve operating temperatures of data centers.[176]
    - In the *MA* data center, one can notice an extremely low indoor temperature. This is a clear sign, that heat is not directly captured at the heat source, and the cooling is not provided in an efficient way. The mix up of hot and cold streams lowers the ΔT and requires therefore increased air volume flows with high energy consumption. There are numerous examples, where the indoor temperature in data centers has been risen up to 33- 35 °C, without derogation of the server performance. For longer maintenance measures, the temperature can be lowered temporarily.[177]

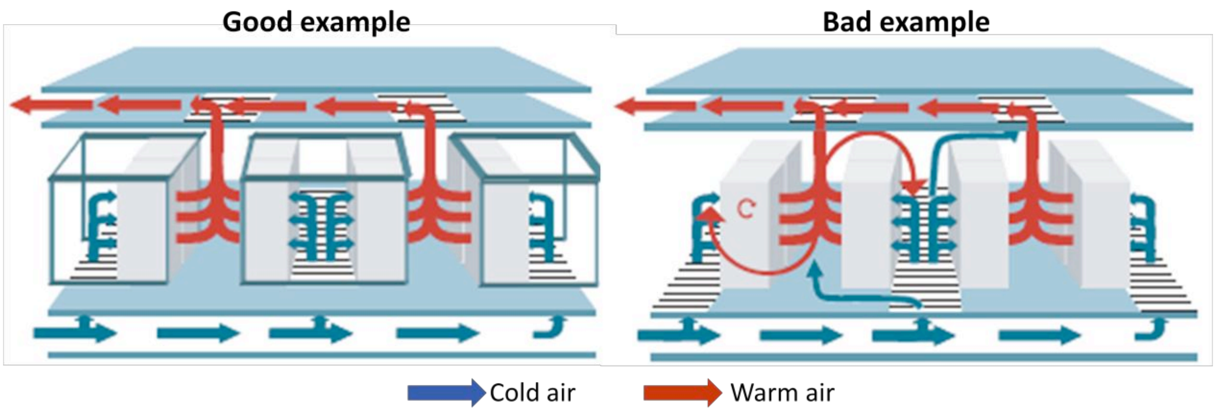


Figure 44: examples of well separated and mixed- up cold and warm flows in data centers (source: BITKOM (Ed.) (2008))

It can be assumed that, there are still significant potentials in the EPFL data centers, which can be realized with relatively marginal measures, as the examples above show. Anyway, to quantify exactly the effects of such changes, a detailed technical analysis is necessary. Many advises and case studies, which could be applied at EPFL, can be found in the brochures *BITKOM (2008) „Energieeffizienz in RZ"* and Fichter (2008) *"Energieeffiziente Rechenzentren".*

4.4.3 Energy savings through liquid cooling

In a joint project between ETH Zürich, EPF Lausanne and IBM, a water cooled server is in development. The heat is directly captured at the point of origin, namely on the chip itself. Little channels on the backside of the chips assure the heat transfer. The cooling water will enter at a temperature of about 60 °C and exit at about 65 °C which keeps the temperature of chips below the critical point of 85 °C. The high temperature level of the cooling liquid makes the heat energetically very "valuable", the heat could be directly transferred into the campus' heat distribution network,

[176] Fichter (2008), p.13
[177] Fichter (2008), p.26

which is operating at a maximum temperature of 65 °C.[178] This way, the biggest part of the steady heat emissions of about 820 kW of the data centers could be used for room heating, without any further complex installations. The second advantage is that no more energy is needed for cooling units and ventilators as it is necessary for air cooled systems, which can cause a substantial fraction of the data centers' total energy consumption. A small fraction of the heat still needed to be lead away through ventilation, as not all the heat will be recoverable with liquid cooling. This could then be realized with energy efficient *free cooling*.

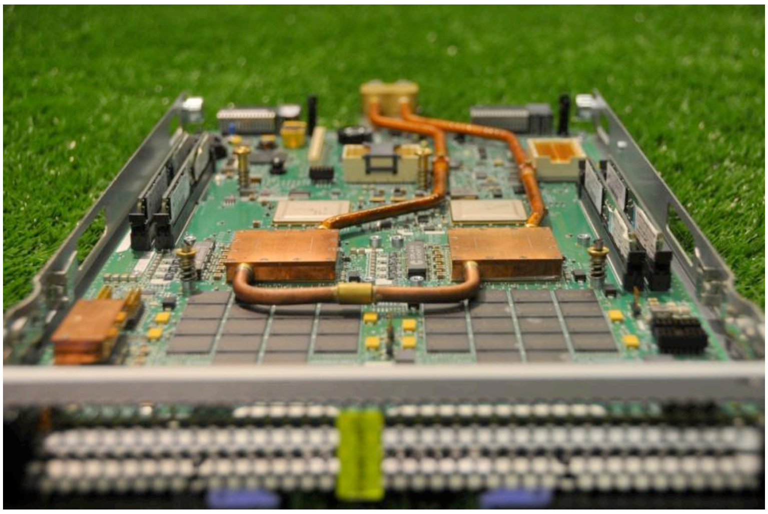


Figure 45: water cooled processor for AQUASAR (source: IBM)

A similar system is developed also at EPFL at the *Laboratory of Heat and Mass Transfer (LTCM)*. The heat is directly captured on the chip in small evaporators, and then evacuated over a condenser to a second cycle, where the hot water can then be distributed to satisfy heat demands. According to the *LTCM,* the goal of the project is a temperature level of the second cycle of more than 50 °C, which would be sufficient for heating for all the newer buildings at EPFL. Furthermore, it is aimed for a heat recovery rate of more than 70 %. The electricity demand for water pumping in the first cycle, will be- according to *LTCM*- in every case lower than 5 % of the heat transferred. This energy for the water pump is due to its little significance not considered in the following calculations.

These values shall now be considered as basis for a short calculation to show the eventual energy and monetary savings through such a system. The calculation is executed for the case that the direct-liquid- cooling is applied to

- the big data center in the MA- buildings (400 kW)
- all the mentioned data centers at EPFL (820 kW)

It is assumed that the electrical consumption of the servers itself remains constant in the near future. As mentioned, two advantages need to be taken into account for the calculation:

- reduction of energy consumption for air cooling
- reuse of hot water for building heating

[178] *http://www.zurich.ibm.com/news/09/zed.html* am 15.9.2009

The calculation of energy and monetary savings on the cooling and ventilation system shall be based on an analysis about different cooling systems for the data centers, executed in cooperation with an external expert for EPFL in 2007.[179] Running costs were calculated for different systems. The two different applied cooling systems at EPFL shall be shortly presented (see appendices H and I):

1. In the data centers *MA ext*. and *Pleiades* in the *ME*- Building, air is circulating in the racks. It enters the racks from below from a "false" floor at 14 °C, streams through the racks and is then extracted by suction through openings in the ceiling. The heat from the cooling air is then led away through a heat exchanger, where industrial water enters at 7 °C and exits at 12 °C. It is not exactly known which cooling system is used in the other data centers, but it is assumed that they are quiet similar to this one (in the following called system 1).
2. The system for the main data center in the MA building consists mainly of a double water cycle. A casing seals the racks, and air is circulating within these casings. The heat is evacuated from the casings through cooling batteries, where water enters and exits at 15 /18 °C, keeping the air within the casings on the required temperature. The heat from the first water cycle is then evacuated from the second cycle, namely the industrial water cycle in a heat exchanger at the common 7/12 °C (in the following called system 2).[180]

In the mentioned analysis, the following approximations were made (among others) for an assumed thermal output of 50 kW: The pressure loses of the different systems, the workings efficiencies of the ventilators and the necessary volumetric air flows were evaluated. This allows calculating the energy consumptions for the ventilators. The electricity price was calculated, assuming an actual price of 0,15 $\frac{SFR}{kWh_{el}}$. It is for this analysis replaced by a price of 0,20 $\frac{SFR}{kWh_{el}}$, increasing by 2 % annually. As amortization period 5 years are chosen, due to the short lifecycles of IT- equipment. The average price for the next five years is taken for the investment calculation:[181]

System	**Assumed thermal output in [kW]**	**Operation time**	**Price cooling water (with ΔT= 5K) in $[\frac{SFR}{m^3}]$**	**Average electricity Price in $[\frac{SFR}{kWh}]$**
1	50	24hours/day, 365days/year	0,305	0,21
2	50			

System	**Annual requirement for cooling in [kWh]**	**Cooling water consumption (with ΔT= 5K) in [m^3]**	**Electric consumption ventilators in [kWh_{el}]**	**Electricity for water pumps [kWh_{el}]**
1	438.000	75.445	14.892	1.100
2	438.000	75.445	8.760	1.900

This results in the following annual costs for cooling. The result for the exemplary 50 kW unit is then extrapolated to the size of EPFL data centers: system 1, which is supposed to be used for all the

[179] Forrer SA (Ed.)(2007)
[180] Forrer SA (Ed.)(2007)
[181] Values from Forrer SA (Ed.)(2007)

smaller data centers at EPFL (summed up 420 kW) and system 2, which is used for the central data center in the MA building (400 kW):[182]

System	Costs for cooling water in [SFR]	Costs for electricity for ventilation in [SFR]	Costs for electricity for water pumps in [SFR]	Total annual energy costs (for a fictional 50 kW unit) in [SFR]	Real power of data centers in [kW]	Total annual energy costs cooling [SFR]
1	23.011	3.133	231	26.376	420	221.555
2	23.011	1.843	400	25.254	400	212.131
1+2	-	-	-	-	820	433.686

The second aspect is the savings of heat energy for EPFL, when waste heat from server rooms is directly transferred to the heat distribution network at 65°C.

To evaluate the potential for heat recovery, it needs to be determined how much of the 400 kW or 820 kW of heat load be can be reused throughout the year. These numbers can be determined with the help of ENERGIS. The heat curve of EPFL can be calculated, and therewith the required heat loads for each hour of the year, when the exterior temperatures are known (see for details chapter 3.2 and 5.3). The hours where a certain heat load is excelled, are then summed up. Again, the weather data time series for 2008 is applied. The following figure shows number of hours per year, in which a certain heat load is reached or excelled, excluding the months May, June, July and August where no heating is provided:

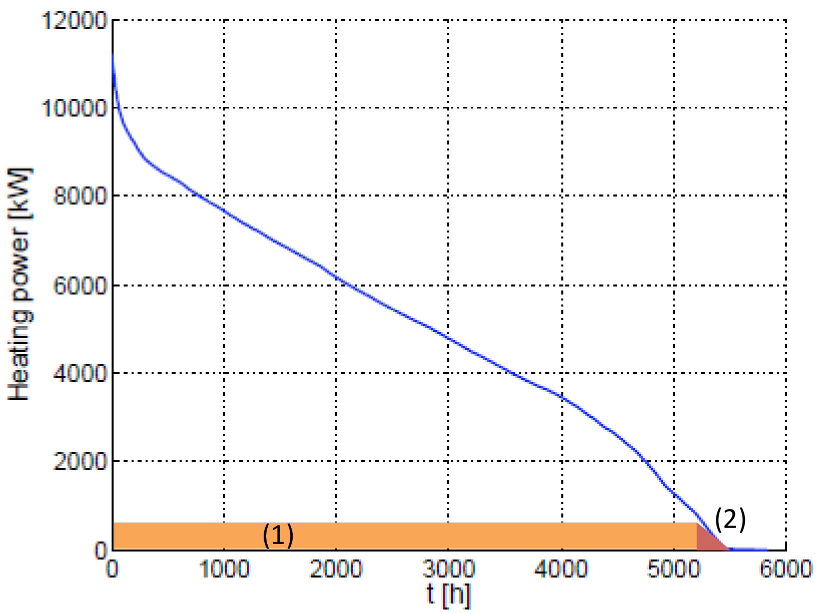


Figure 46: number of hours per year, at which a certain heat load is reached or excelled at EPFL

[182] Calculated in *Financial_calculations.xls*

For example, at around 4700h/year, a total heat load of equal or superior to 2000 kW is required for EPFL.

As mentioned, around 70 % percent of the waste heat from the servers should be recoverable with the liquid cooling system.[183] For the considered servers with a total of 400 kW or 820 kW of heat emissions, this results in 280 kW or 574 kW respectively of recoverable heat load.

Two cases are now possible:

- The required heat load at EPFL is at a certain time bigger than 280 kW (574 kW). In this case, the whole 280 kW (574 kW) can be reused. This energy is represented by the **surface (1)** in the figure above:
    - $Q_{1,X} = X \times h_{P \geq X} \quad [kWh]$
        - $With\ P\ =\ required\ heat\ load\ for\ EPFL\ in\ [kW]$
        - $X =\ heat\ load\ provided\ by\ data\ center\ [kW]$
        - $h_{P \geq X} =\ related\ annual\ hours\ where\ P > X\ in\ [h]$

- The required heat load is smaller than 280 kW (574 kW). In this case the waste heat supplies the full amount of heat at that time. This energy is represented in the figure above by **surface (2)**:
    - $Q_{2,X} = \sum_{P<X} P \times h_P \sim 0{,}5 \times X \times h_{0<P<X} \quad [kWh]$
        - $h_P =\ related\ annual\ hours\ with\ heat\ demand\ P\ in\ [h]$

The total amount of reusable waste heat is then:

- $Q_X = Q_{1,X} + Q_{2,X} \quad [kWh]$

The results for 280 kW and 574 kW available heat load are:

- $Q_{400\,kW} = 280\ kW \times 5440\ h + 0{,}5 \times 280\ kW \times 60\ h = 1.531.600\ kWh$
- $Q_{820\,kW} = 574\ kW \times 5370\ h + 0{,}5 \times 574\ kW \times 140\ h = 3.122.560\ kWh$

These numbers represent the heating energy that could be saved per year, if the waste heat from data centers was directly reused in the heat distribution network. This would lower the required heat to be produced by the heat pumps, and thereby its electrical consumption. The total COP was calculated to be 3,6. The average electricity price is again calculated, starting at 0,20 $\frac{SFR}{\mathrm{kWh}_{\mathrm{el}}}$, with a price increase of 2 % over the next 5 years, and the interest rate is 5 %. The effects are displayed in the following table:[184]

System	**Recoverable waste heat load in [kW]**	**Annual recoverable heat in [kWh]**	**Annual electricity savings in [kWh]**	**Annual monetary savings [SFR]**
2.	280	1.531.600	425.444	89.517
1. +2.	574	3.122.560	867.378	182.503

[183] According to *LTCM- EPFL*
[184] see *Financial_calculations.xls*

The total savings of electricity and monetary savings, due to abolishment of air cooling, and heat recovery directly into the HDN, are represented in the following table. The *maximum investment* is the additional investment still justified and re- financeable through the annual energy cost savings. The amortization period is set to 5 years and alternatively to 10 years, due to short lifecycle of servers. The equation was already introduced in chapter 4.3:

- $I_{DC} = \frac{G_{DC}}{\frac{i \times (1+i)^n}{(1+i)^n - 1}}$
  - $G_{DC} = monetary\ savings\ through\ liquid\ cooling\ in\ [SFR]$
  - $I_{DC} = maximum\ additional\ investment\ for\ liquid\ cooling\ in\ \ in\ [SFR]$

System	**Annual Electricity savings in [kWh]**	**Annual monetary savings in [SFR]**	**Max. Investment 5 years amortization in [SFR]**	**Max. Investment 10 years amortization in [SFR]**
2	510.724	212.131 + 89.517 = **301.648**	1.305.977	2.374.941
1 + 2	1.086.991	433.686 +182.503 = **616.189**	2.667.776	4.854.878

The maximum investment numbers represent the limit of additional costs, which are economically justified through energy savings, when either only the *MA* servers (system 2) or all the existing servers (1 + 2) are exchanged and replaced by the presented liquid cooled system .An additional room cooling might be necessary due to the high temperature level of the cooling liquid, but these relatively small heat loads could be lead away with energy efficient free cooling. The presented server cooling should be commercially available within the next five years.

4.4.4 Direct air distribution from data centres to buildings

Another option to reuse the emitted heat from the data centers would theoretically be the direct distribution of the warm air in the building. Generally heat distribution with air is critical, as the specific heat capacity of air per volume is 3500 times lower as for water, so for the same amount of energy transported, very high volumetric air flows need to be moved compared to water. [185] This results then in very high electrical consumptions for the fans. However, in some cases a heat distribution by air can be considered. According to different sources this is the case for houses with a very little heating demand at *passive house standard*. In these cases the costs for auxiliary units for a water distribution network can be saved. For bigger buildings with higher consumptions, it is not recommended to distribute heat by air: either the volumes streams for air and therewith the electrical consumption for their transport becomes very high, or the temperature needs to be elevated. In the second case, the humidity of the supply air decreases quickly, which then results in unacceptable, uncomfortable air conditions.[186, 187, 188]

[185] Oughton et al. (2008), p. 157
[186] *http://www.zukunft-haus.info/fileadmin/zukunft-haus/documents/waermeversorgung/waermeverteilung.pdf,* 5.9.2009

As the buildings with the data centers are generally ventilated naturally, no ventilation installations (ducts, etc.) exist, and needed to be integrated in the existing buildings.

In general, very little information can be found about heat distribution with air in bigger buildings. So due to the mentioned difficulties, a direct reuse of cooling air for building heating is not considered anymore within this work.

[187] *http://effiziento.de/luftheizung_lueftung.html,* 5.9.2009
[188] Oughton et al. (2008), p. 157

5. The conversion system

5.1 Efficiency and emissions of heat and electricity supply at EPFL

In the previous chapters, many options to improve the efficiency on the *demand side* were shown. Nevertheless, heat and electricity are already provided in a very clean way at EPFL, concerning the CO_2- emissions. As shown in chapter 4.3.1 one can consider a total COP of 3,6 for the heat supply, including the consumption of the lake water pumps. To compare this system in terms of emissions with a common heating system, the electricity mix and related emissions need to be evaluated.

Electricity is in Switzerland mostly produced in hydropower plants and nuclear power plants. The Swiss electricity production can be regarded as almost CO_2 free. At the same time significant import and export streams need to be considered, which burden the emission balance, as clean energy is exported and more CO_2- intensive electricity is imported. This is illustrated in the following figure, which shows electricity related CO_2 streams in [million tons]:

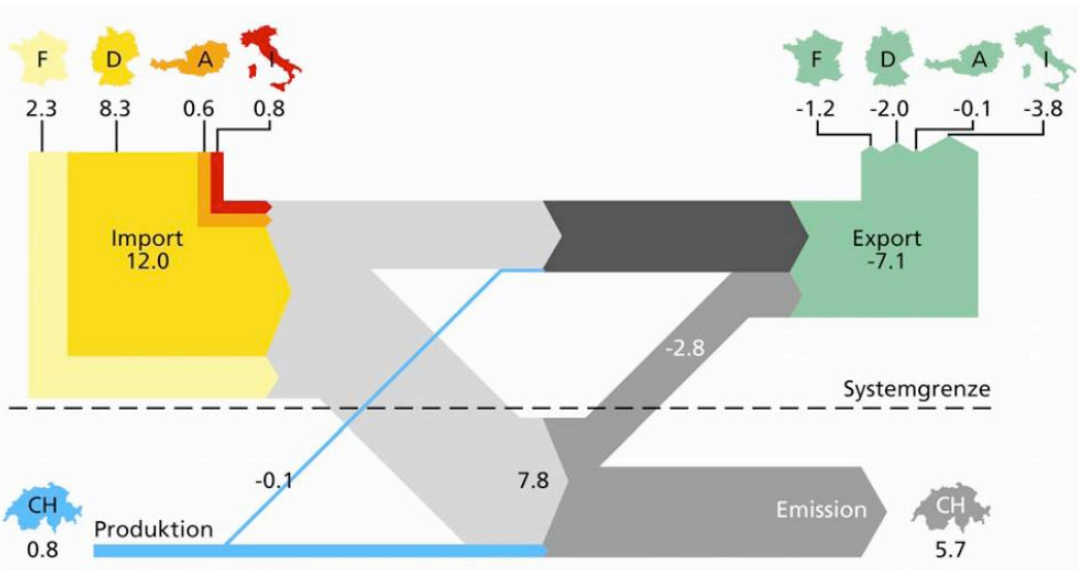


Figure 47: electricity related CO_2- streams for Switzerland, in million tons CO_2 (source: Jakob (2009))

The study from Jakob (2009) evaluated a CO_2- intensity for the Swiss electricity mix of 110 $\frac{g\ CO_2}{kWh_{el}}$.[189] Other sources come to similar conclusions. This represents a very low value compared to other

189 Jakob (2009), p. 7

European countries. For Germany one can assume a value of 590 $\frac{g\ CO_2}{kWh_{el}}$ for 2008, according to the German *Federal Environmental Agency*.[190]

When the total COP of 3,6 for EPFL is now applied, the emissions for a supplied heat unit amount to:

- $Emissions_{heat} = \frac{Emissions_{\ elec}}{3{,}6} = \frac{110\ \frac{g\ CO_2}{kWh_{el}}}{3{,}6} = 30{,}56\ \frac{g\ CO_2}{kWh}$

This value can now be compared with reference values for other technologies. The SIA specifies in the *bulletin 2031* specific emissions for district heating (including transmission losses) for different heat sources: For a gas fired plant, a value of 307 $\frac{g\ CO_2}{kWh}$ is derived, for oil fired plants even a value of 403 $\frac{g\ CO_2}{kWh}$.[191]

As it was shown, heat and electricity are provided at EPFL with very low related CO_2 emissions. For this reason, other general options for the conversion system, like the extension of the co- generation plant, were not further emphasized in this study. The question, whether nuclear power can be regarded as a clean source of energy is also not further discussed here. The CO_2- intensity of the Swiss electricity mix might rise drastically in the next years and decades up to 400 $\frac{g\ CO_2}{kWh_{el}}$, due to the planned shutdown of nuclear power plants and replacement with fossil fuel plants.[192] This will then of course change the emission balance for a heat pump based heat distribution system, and other conversion technologies would become interesting, when emission reduction is the main goal.

5.2 Photovoltaic plant

At EPFL recently the decision has been taken to install a big large photovoltaic plant on most of the roof surfaces. The plant will cover 20.000m^2 of surface, with a peak power of 2 MW and an annual estimated electricity production of 2 million kWh_{el}. The required investment amounts to 20 million SFR. According to the *BFE,* there are actually 30 MW of photovoltaic plants installed in Switzerland, so the additional 2 MW will substantially contribute to the Swiss solar power capacity.[193] The plant will progressively start operation in the years 2009, 2010 and 2011.[194]

The PV plant shall be compared with the efficiency measures with respect to costs and energy savings As for the efficiency measures, no “grey energy” consumed in the manufacturing process is considered, it is assumed that the solar energy is CO_2- free Then one can compare saved energy through efficiency measures with 100 % renewably produced energy. Or in other words: Energy efficiency is considered as an energy source.

[190] *http://www.umweltbundesamt.de/energie/archiv/co2-strommix.pdf*, 9.11.2009
[191] SIA 2031 (2009), p. 43
[192] Jakob (2009), p. 7
[193] *http://www.bfe.admin.ch/themen/00490/00497/index.html?lang=de* am 27.10.2009
[194] *http://actualites.epfl.ch/presseinfo-com?id=696*, 14.10.2009

Contractual issues shall not be considered here for the analysis, but it shall be mentioned however, that the investments are basically conducted by the energy distributor *Romande Energie*, and only a quarter of the produced electricity will *contractually* be consumed at EPFL. Anyway, one can assume that *physically* the EPFL can consume the whole amount of electricity produced, as electricity consumption is always above 2 MW, so the electricity will not have to be distributed over a high voltage grid and no distribution costs have to be considered.

Many sources name 30 years as an appropriate expected lifespan for solar modules. Possible subventions are not considered.

If one annualizes the 20 million SFR over 30 years, considering a 5 % interest rate one obtains the following annual capital cost:

- $A_{solar} = I \times \frac{i \times (1+i)^n}{(1+i)^n - 1} = 20.000.000 \text{ SFR} \times \frac{0{,}05 \times (1+0{,}05)^{30}}{(1+0{,}05)^{30} - 1} = 1.301.029\, SFR$

Maintenance costs can be estimated at 0,5 % of the investment, which makes in this case 100.000 SFR.[195] For an assumed annual production of 2 million kWh_{el}, the costs for one produced kWh_{el} of electricity amount to:

- $\frac{100.000\, SFR + 1.301.029\, SFR}{2.000.000\, kWh} = 0{,}70\, \frac{SFR}{kWh_{el}}$

This price is of course pretty elevated, not only compared to grid electricity prices, but also compared to the specific costs for efficiency measures. It must be added, that a certain budget for research might be included in the total investment, the pure electricity production cost might be slightly lower.

[195] *http://de.wikipedia.org/wiki/Photovoltaik*, 14.10.2009

5.3 The heating system of EPFL

5.3.1 Actual status of the heating system

In this chapter the remaining capacity of the heating system shall be determined with a simulation involving the ENERGIS tool and the related model. The simulation results shall be compared and validated with real measurement of the heat loads.

The heat curve of a building displays the required heat load as a function of the exterior temperature. When the heat load is modeled as a linear function of the exterior temperature, the following values are required to derive the heating signature:[196]

- the annual heat consumption of a building $Q_{hot,\,Y}$ in [kWh]
- the indoor comfort temperature T_{in} in [°C] (at EPFL: 21,5 °C)
- the cut- off non heating temperature $T_{cut,}$ in [°C]. Below of T_{cut} , no heating is provided (at EPFL: 16°C)
- the outdoor temperatures T_{ext} in [°C] for the period in which the heat consumptions were measured

The actual heat load requirement is then given by the following equation:

- $\dot{q}_t = \begin{cases} S \times T_{ext} + b & if\ T_{ext} < T_{cut} \quad [\frac{W}{m^2}] \\ & 0\ otherwise \end{cases}$
    - $\dot{q}_t = specific\ heat\ load\ in\ [\frac{W}{m^2}]$

The annual heat energy requirement for a certain building is given by:

- $q_Y = \int_Y \dot{q}_t \times dt \quad \frac{kWh}{m^2}$
    - $q_Y = specific\ annual\ heat\ consumption\ in\ \frac{kWh}{m^2}$

The cut off temperature and the slope define the heating curve. The slope of the heating curve is calculated as followed:

- $S = \frac{q_Y}{\int_{Y:T_{ext} < T_{cut}} T_{ext,t}\, dt - \int_{Y:T_{ext} < T_{cut}} T_{cut}\, dt} \quad [\frac{W}{°C \times m^2}]$
    - $S\ in\ [\frac{W}{°C \times m^2}]$

Furthermore:

- $b = S \times T_{cut}$
    - $b\ in\ [\frac{W}{m^2}]$

[196] Girardin (2009), p. 3 ff.

Additionally, at EPFL (and also in other buildings), an exterior dimensioning temperature $T_{ext,0}$ is defined where the maximum heat power is provided. At EPFL this is -10°C.[197] The *ENERGIS* tool calculates the heat curve for buildings executing the above mentioned calculation steps. The specific heat consumptions for 2008, for each building at the EPFL, connected to the heat distribution network, are known (see chapter 2.2), as well as the cut off temperatures (16 °C). As weather data, the hourly temperatures for 2008 from the weather station *Pully*, close to EPFL, are used. The period between 1st of may and 31st of August is explicitly excluded for the calculation of the signatures, as the heating system is shut down in this period, and is not producing heat even when exterior temperatures temporarily drop below 16 °C. With the given weather data, ENERGIS calculates the following heating curves for each building of EPFL:

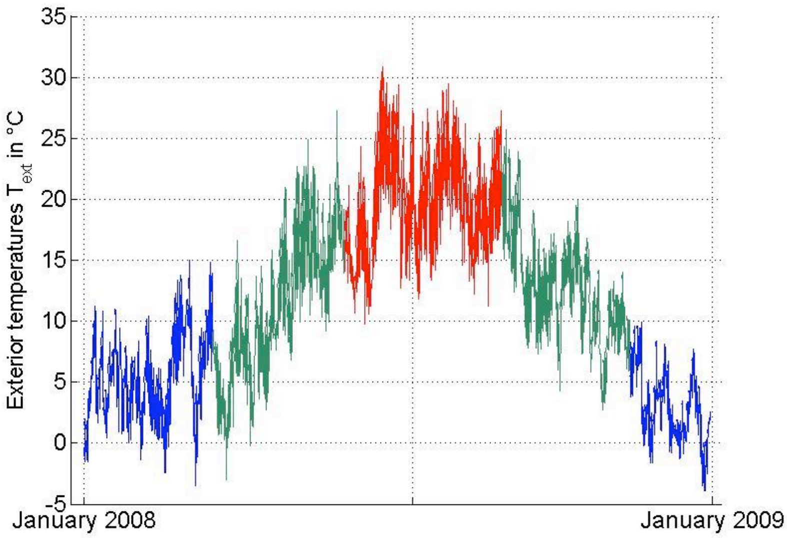


Figure 48: Exterior temperatures from weather station Pully (close to EPFL) for 2008

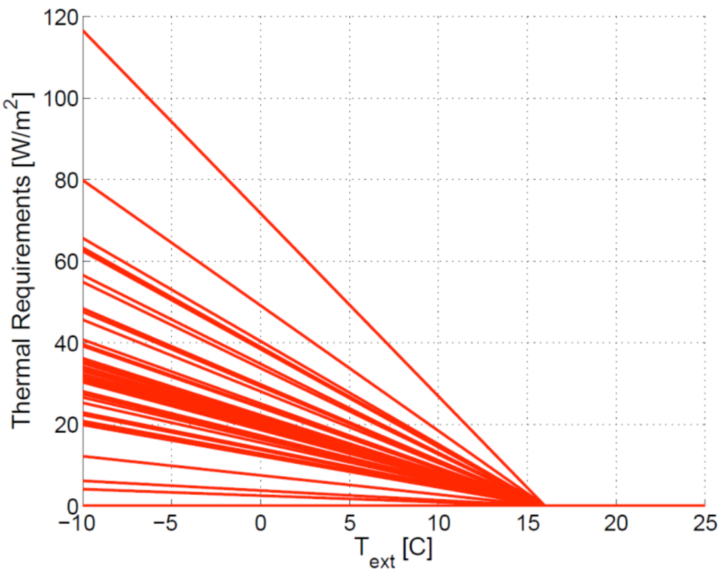


Figure 49: heating curves for EPFL buildings

197 Girardin (2009), p. 8- 9

As all buildings at EPFL have the same cut- off temperature and same exterior dimensioning temperature, the slopes *S* of the heat curves of the different buildings just need to be added up to obtain the heat curve for EPFL, which leads to the following result. Additionally to the simulated curve, a graph determined from the *EPFL- Pl- DII- E,* is added, which represents the linear regression of effectively measured values of heat produced in the heating central at different outdoor temperatures. These measures were taken between 10/2007 and 1/2008:[198]

Another important fact needs to be added: In the beginning of 2008, the building *SV* (Life Sciences) went into operation. Unfortunately there are no measures available about the heat consumption so far.[199] Therefore the consumption of this building could not yet be included in the simulations. It is only known, that the heating system installed has a maximum load of around 3, 4 MW. This is obviously a very big value, and one can assume that the SV will increase the total heat consumption of EPFL significantly. The resulting estimated graph is added in the figure below

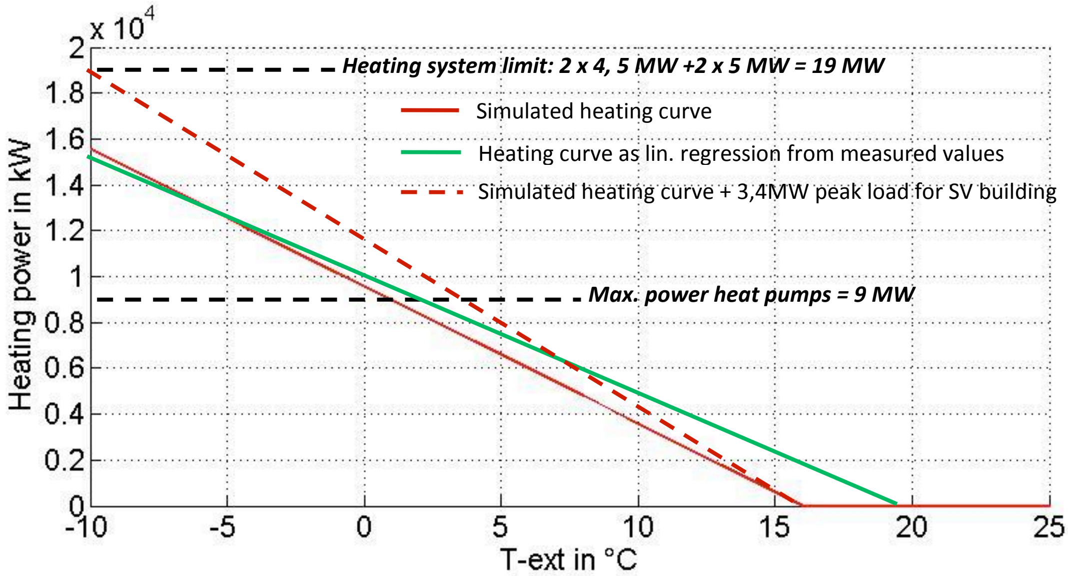


Figure 50: Heating signature for EPFL

The figure shows, that the results from the simulation agree pretty well with the measured values.

The simulated peak load at -10 °C exterior temperature is 15.539 kW. Together with the assumed 3,4 MW for the SV building, one must assume, that the heating system is at the limit of capacity (19 MW). This is *not* the case when a lower exterior dimensioning temperature is chosen, e.g. -5 °C. -10 °C was never reached in 2008

The graph of the linear regression derived from real measured values is slightly above the simulated values. This might be explained through the heat losses of the heat network, so the heating system will have to produce slightly more energy as demanded by the buildings. Furthermore, according to the *EPFL- Pl- DII_E,* the heating system is partly shut down at night and on weekends. This reduction of supplied heating energy must then be compensated in the morning or in the night to Monday

[198] information according to *EPFL- Pl- DII_E*
[199] information according to *EPFL- Pl- DII_E*

respectively, so the heating power will be higher compared to the power which the exterior temperature would implicate. Measures were only taken when the system produced heat, this might then lead to the differences between simulated and measured values.

5.3.2 The composite curve

It is now possible to determine the composite curve for heating of EPFL. Every thermal stream can be characterized by its enthalpy H or heat content, and the temperature T where heat is emitted or absorbed. So every stream can be displayed by a graph in a *T/H*- Diagram, where the extension on the x- axis represents the amount of heat emitted or absorbed. In process integration, very often multiple streams have to be handled. In this case, the so called *composite curve* is applied. The composite curve can display the total amount of heat or cooling required for multiple *cold* and *hot* streams. Every interval on a *hot* or *cold* composite curve represents the amount of heat or cooling required between two temperatures for the total of multiple thermal streams. The composite curve is an important instrument, for example in process integration, to evaluate for various hot and cold streams the potential for heat recovery, or to determine the optimal utility to provide cooling or heat. In particular the composite curve does not only account for the energy of a stream, but also for the *exergetic* aspect.[200]

The goal is now to model the composite curve, which represents the heat demand at EPFL. As the heat demand for steam production in the building SV is not considered her due to the lack of information, the heat demand consists only of the demand for building heating, which is provided by the heat distribution network. The buildings can be regarded as big heat exchangers. If one assumes a constant water flow $\dot{m}_0$ in the hat distribution network, than the delivered heat depends only on the ΔT between the supply and the return temperature. This assumption is not absolutely correct, as also the water flows at EPFL are slightly varying; for the model this assumption will be nevertheless made.

The design exterior temperature $T_{ext,0}$ represents the temperature, where the heating system reaches its maximum power output. When furthermore the indoor comfort temperature T_{in}- at EPFL 21, 5°C- and the sizing temperatures $T^{hot}_{supply\ ,0}$ and $T^{hot}_{return\ ,0}$ for the distribution network at the design exterior temperature$T_{ext,0}$ are known, then the heat distribution temperatures of the network can be modeled as a function of the required heat. The supply and return heat distribution temperatures are then derived as follows:[201]

[200] Kemp (2007), p.15-20
[201] Girardin (2009), p. 5

- $\dot{m}_0 \times c_p = \frac{\dot{Q}_0}{T^{hot}_{supply\ ,0} - T^{hot}_{return\ ,0}} \quad [\frac{kW}{K}]$
  - $\dot{m}_0 = water\ flow\ in\ [\frac{kg}{s}]$
  - $\dot{Q}_0 = maximum\ heat\ load\ at\ dimensioning\ exterior\ temperature\ in\ [kW]$
  - $T^{hot}_{supply\ ,0}, T^{hot}_{return\ ,0} =$ $sizing\ water\ supply\ and\ return\ temperatures\ for\ the\ HDN\ in\ [°C]$
- $T^{hot}_{supp\ ly} = T_{in} - \frac{\dot{Q}}{\dot{Q}_0} \times \left(T^{hot}_{supply\ ,0} - T^{hot}_{return\ ,0}\right) \times \frac{\alpha}{1-\alpha} \quad [°C]$
  - $\alpha\ charatcterizes\ the\ heat\ exchanger$
  - $T^{hot}_{supply}\ T^{hot}_{return} =$ $water\ supply\ and\ return\ temperatures\ for\ the\ HDN\ in\ [°C]$
  - $\alpha = \frac{T^{hot}_{supply,0} - T_{in}}{T^{hot}_{return,0} - T_{in}} = exp(\frac{U_0 \times A_0}{\dot{m}_0 \times c_p})$
    - $A_0 = heat\ transfer\ surface\ area\ [m^2]$
    - $U_0 = heat\ transfer\ coefficient\ [\frac{W}{m^2 \times K}]$
- $T^{hot}_{return} = T^{hot}_{supply} - \frac{\dot{Q}}{\dot{m}_0 \times c_p} \quad [°C]$

$T^{hot}_{supply\ ,0}$ and $T^{hot}_{return\ ,0}$ are at EPFL 65 °C and 45 °C for the medium temperature network (MT), connecting the older buildings from the 1st construction period, and 50 °C and 35 °C for the low temperature network (LT), connecting the newer buildings from the 2nd and 3rd construction phase. The design exterior temperature $T_{ext,0}$ at *EPFL* is -10 °C. The following figure shows the EPFL distribution heat curve:

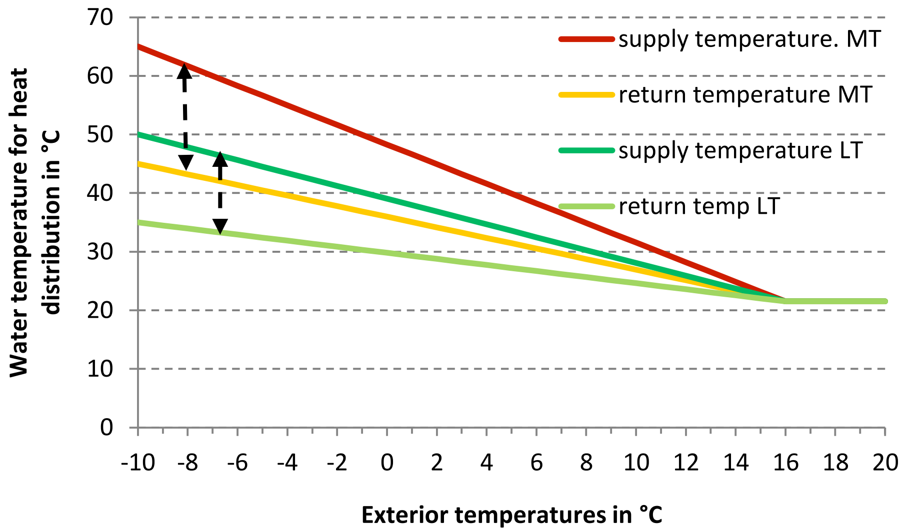


Figure 51: Heat distribution curve for EPFL

The following figure displays the resulting composite curve for EPFL, for different periods of the year. The composite curves shows the average heat load and the related temperature level on an hourly basis for the corresponding period, when the system is supposed to produce heat, which is the case when the outside temperature drops below 16°C. The periods are defined as follows:

- *Mid- season*:16/03/2008- 31/05/2008 and 01/09/2008- 14/11/2008
- *Winter- season*: 01/02/2008-15/03/2008 and 15/11/2008- 01/01/2009
- *"-10 °C- Scenario"*: composite curve for a considered exterior temperature of -10 °C
- The summer season is excluded, as the system is shut down during the summer months, and the very limited demand for heat for sanitary hot water is produced locally, so the heat demand for the distribution network is zero.

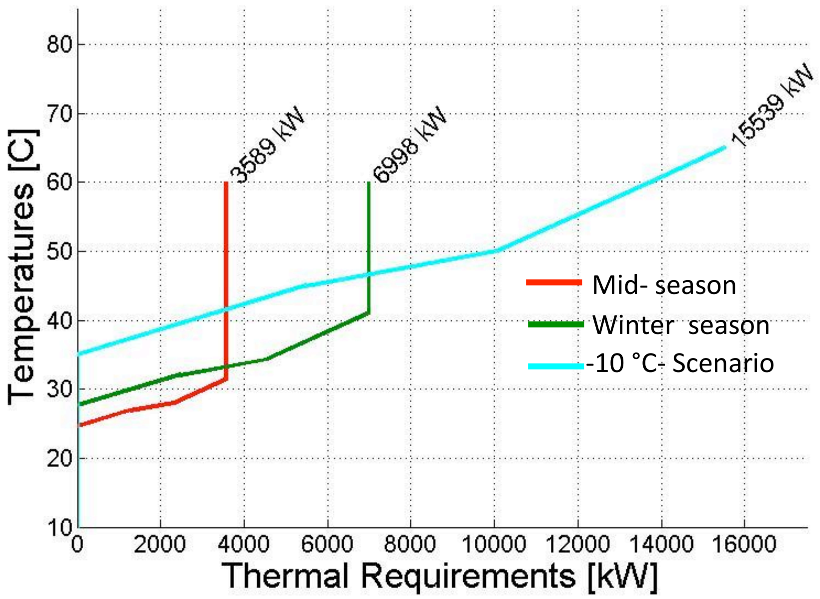


Figure 52: actual composite curve for EPFL

5.3.3 Impact of campus expansion on the heating system

For the next years, the following buildings will be added to the campus:

- The ROLEX learning center (*LC*), which will be finished at the end of 2009, adding a heated surface A_h of 25.600 m^2.
- The buildings *PSE D* (5325 m^2 A_h), *E* (5.325m^2), *F* (5.325 m^2), *G* (5.639m^2) and *K* (5.325 m^2), which will be finished in 2010
- The buildings *PSE H* (6057 m^2 A_h), *I* (5.325 m^2) and *J* (5.325 m^2), which will be finished in 2012.
- A congress center is planned to be erected until 2014. A size between 25.000- 35.000 m^2 is foreseen. For this calculation, a size of 30.000 m^2 A_h is assumed.[202]

[202] All information according to *EPFL- PI- DII_E*

The expected consumption for these buildings shall now be calculated. It is assumed that these buildings will meet *Minergie*- standards according to the SIA norms. A building must meet the following requirement to meet *Minergie* standard:[203]

- $q_h \leq 90\,\% \times q_{h,li} \quad [\frac{kWh}{m^2}]$
  - $q_h = heat\ demand\ building$
  - $q_{h,li} = limit\ value\ for\ heat\ demand\ according\ to\ SIA\ 380/1$

$q_{h,li}$ is defined as follows:[204]

- $q_{h,li} = q_{h,li0} + \Delta q_{h,li} \times \left(\frac{A_{th}}{A_E}\right) \ [\frac{kWh}{m^2}]$
  - $q_{h,li0} = basic\ value$
  - $\Delta q_{h,li} = adjustment\ factor$
  - $\left(\frac{A_{th}}{\mathrm{Ah}}\right) = ratio\ between\ thermally\ weighetd\ building\ envelope\ and\ heated\ surface$

$(\frac{A_{th}}{Ah})$ is not known for the considered buildings, but a factor of 1 shall be assumed here, which is an appropriate value for bigger buildings (the value can generally vary between 0,8 and 2,5, and is smaller for bigger buildings).

In SIA 380/1 the limit values $q_{h,li0}$ and $\Delta q_{h,li}$ for different building categories are given. The values for school buildings shall be applied here, as no category "university buildings" exists. The values for administrative buildings only slightly differ from the "school buildings", and also other building categories do not have significantly different limit values, so the choice has no big impact on the results. The specific limit values for "schools" are:[205]

- $q_{h,li0} = 70\frac{Mj}{m^2} = 20{,}28\frac{kWh}{m^2}$
- $\Delta q_{h,li} = 70\frac{Mj}{m^2} = 20{,}28\frac{kWh}{m^2}$

So if it is assumed that *Minergie* standards are just met, the specific heat consumptions for the new buildings are:

- $q_h = (q_{h,li0} + \Delta q_{h,li} \times (\frac{A_{th}}{A_E})) \times 90\% = (20{,}28\frac{kWh}{m^2} + 1 \times 20{,}28\frac{kWh}{m^2}) \times 90\% = 36{,}50\ \frac{kWh}{m^2}$

The annual heat consumptions for the new buildings then amount to:

- *LC* (25.600 m^2): $Q_h = 36{,}50\ \frac{kWh}{m^2} \times 25.600m^2 = 934.400\ \frac{kWh}{year}$

---

[203] *http://www.minergie.ch/standard_minergie.html#die-anforderungen,* 13.10.2009
[204] SIA 380/1 (2009), p. 25
[205] SIA 380/1 (2009), p. 25

The consumptions for the other building are calculated equivalently:

	LC	*PSE D*	*PSE E*	*PSE F*	*PSE G*
Surface in [m^2]	25.600	5.325	5.325	5.325	5.639
Erected in year	2009	2010	2010	2010	2010
Est. annual heat demand in [kWh]	934.400	194.363	194.363	194.363	205.824

	PSE K	*PSE H*	*PSE I*	*PSE J*	*Congress center*
Surface in [m^2]	5.325	6.057	5.325	5.325	30.000
Erected in year	2010	2012	2012	2012	2014
Est. annual heat demand in [kWh]	194.363	221.081	194.363	194.363	1.095.000

This means, that in the end of 2009, the heat system has to provide additional 934.400 kWh, until 2012 1.917.674 kWh and until 2014 3.622.479 kWh of heat. According to *EPFL- Pl- DII_E,* only the *LC* building will still be connected to the heat distribution network, whereas the other buildings will be equipped with own heat pumps.

For the new buildings dimensioning supply and return temperatures of 50 °C and 35°C - so equal to the temperatures from 2nd and 3rd construction phase - are assumed. The next figure shows the actual heating curve (as determined before), the new estimated signature with building *LC* in operation at the end of this year, and furthermore the signature for 2014, when the buildings *PSE (E, D, F, G, H, I, J, K)* and the *Congress Center* will be in operation. The values for the *SV* building are not known, so an additional peak load of 3,4 MW is assumed again:

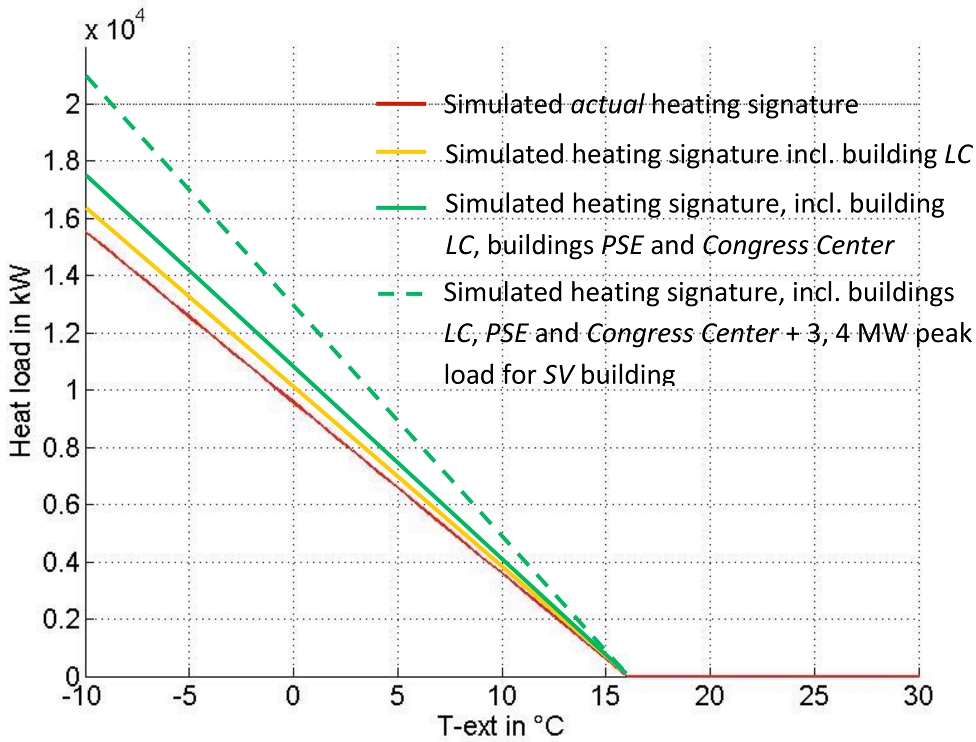


Figure 53: heating signatures EPFL including future buildings

When the *LC* building is connected to the grid, a peak power at -10°C of 16.015 kW (+ 3, 4 MW) of heat will be obtained. If also the buildings *PSE* and the *Congress Center* were connected, the peak load would rise to 17.385 kW (+ 3, 4 MW).

The following observations can be made:

- When the high *SIA- Minergie-* standards are applied for the new buildings, then the impact on the total heat load of EPFL is pretty limited, although the added surfaces are significant.
- The values determined are the real *needs* for the buildings. So heat losses during the transport in the network are not yet included. But the differences between produced heat in the heating central and supplied heat to the buildings amounts to not more than 2 %, so the losses are negligible.[206] Nevertheless, for all the new buildings going into operation after the *LC* building, new heat pump systems are planned; it is generally assumed at EPFL, that with the new building *LC*, the heating system would reach its capacity limit. This is in fact true, when an additional peak load of 3, 4 MW for the SV building is assumed, and the dimensioning exterior temperature of the conversion system is kept at -10 °C. This is shown with executed simulations. But it must be considered, that an exterior temperature of -10 °C was never reached in 2008. The minimal temperature reached in 2008 was -4 °C (see figure 48 with weather data). If a new sizing temperature of -5 °C was defined, the peak load of 19 MW of the heating system would be sufficient to provide all the new building *SV*, *LC*, *PSE* and *Congress Center*, including a reserve of around 10 % (see figure 53).

[206] *Chaleur_batiments_v1.xls* and *Diagr_flux_2008.pdf*

- What is not considered in this analysis is the fact, that heating is reduced on week- ends and at night, which has to be compensated with higher heat loads afterwards. But then the limitation of the system is rather caused by the heating strategy than by the dimension of the system.
- The additional heat demand of the buildings *LC, PSE* and *Congress Center* could also provided by measures reducing the heat demand of other buildings, e.g. ventilation refurbishment of the buildings *PH* and *CH* (see chapter 3.3.6). Furthermore the heat consumption of the *SV* building seems to be inappropriately high (although no exact numbers are known): Besides the heating system with 3, 4 MW peak load, a steam production with a size of 4, 5 MW exists, constantly producing steam for the *Life Science* research.[207] According to the *EPFL- Pl- DII_E,* only a very small fraction of the energy for the steam production is recovered for pre-warming of sanitary water, heat recovery installations for heating purposes do not exist. In principle, a consequent heat recovery within the steam cycle should allow to cover a substantial share of the heat demand of the building, as the heat can be recovered on a very high temperature level. Unfortunately no further information is available till now about the installations and the energy consumptions in this building, which is obviously a key factor for the total energy consumption and future efficiency measures at EPFL.

[207]according to *EPFL- Pl- DII_E*

5.4 *Outlook:* Extension of the heat distribution network to the community of Ecublens

In the context of this work, the basis for the analysis of a possible extension of the heat distribution network to the nearby community of Ecublens was established. This option of a HDN for Ecublens was also already discussed with responsible persons of the community, who showed much interest for this issue.

Some preliminary results shall be presented here without going into the details.

For the analysis of the heat demand of the community, a data set from the building data base of the Swiss OFS (***O****ffice* ***F****ederal* ***S****tatistique*) serves as primary data source. All existing buildings in Switzerland are listed in the OFS data base. Among others, it contains information about size, year of construction and building type for each building, and furthermore a geographical reference. This reference allows it to visualize every building in a GIS (**G**eographic **I**nformation **S**ystem) environment.

This information for each building can then be related with statistical data about thermal requirements for heating and sanitary water for different building categories (please see appendix J for the building categories and specific consumptions). The statistical data was collected during the development of ENERGIS. It contains a total of 80 building categories with different building types and construction periods. Each building in the OFS data set is then related with the according building category in ENERGIS. As the specific consumptions and building sizes are known, it is possible to calculate the thermal requirements for each building. By integration of the thermal requirements for all relevant buildings, it is finally possible to determine the thermal requirements for a district or a city, when no exact information about consumptions is available.

As the annual heat consumptions and the exterior temperatures over the year are known now, also the heat curve for each building and the district can be derived (see chapter 5.3.1).

The following figure shows the EPFL buildings (as polygons) and the buildings of Ecublens (as points), with different colors for their heat consumptions. The heat consumptions for Ecublens are calculated, the consumptions for EPFL are the real measured consumptions (figure is extracted from ARCGIS):

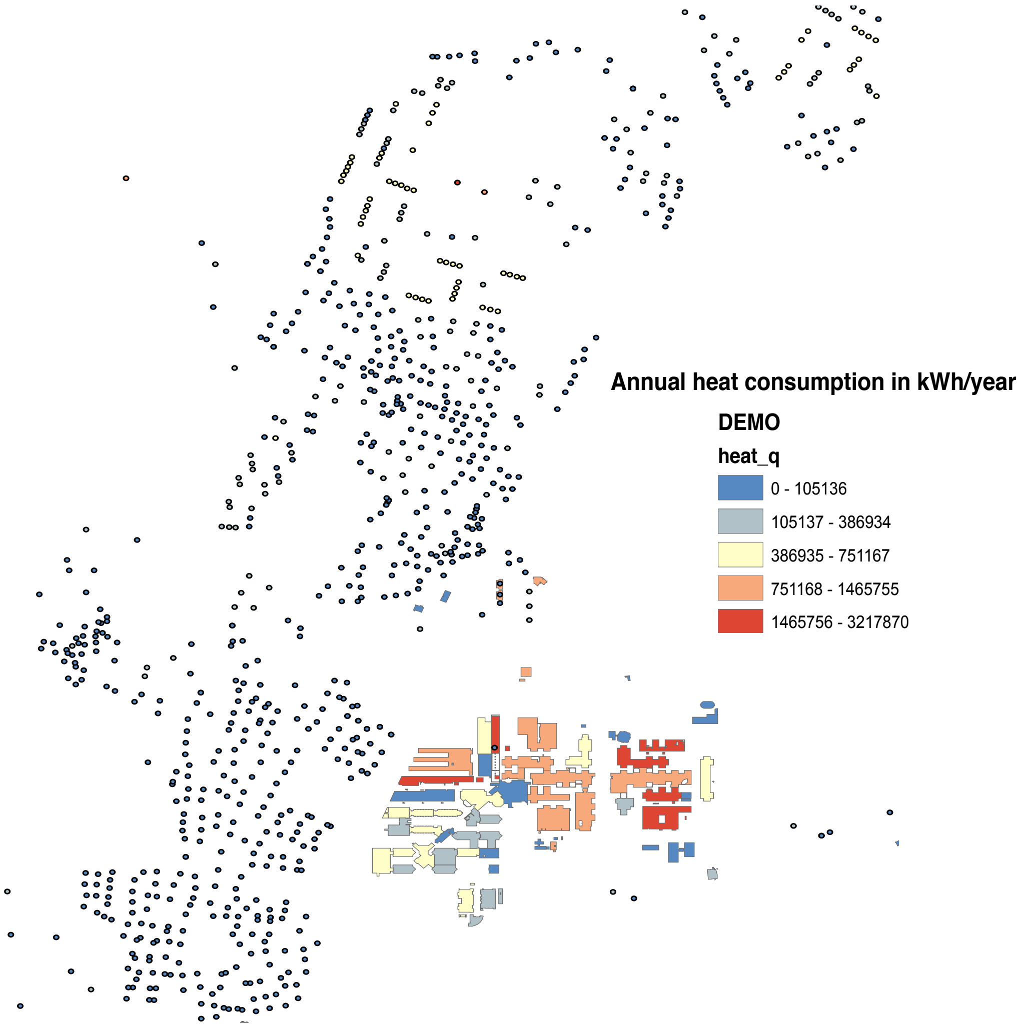


Figure 54: buildings of Ecublens and EPFL, with annual heat consumptions (extracted from ARCGIS; own illustration)

Additionally to the specific consumptions, sizing supply and return temperatures for the domestic heating system are defined for each building category ($T^{hot}_{supply,0}T^{hot}_{return,0}$) in ENERGIS, as well as the sizing temperatures for the sanitary water ($T^{HW}_{supply,0}T^{HW}_{return,0}$). As it was shown in chapter 5.3.2, it is then possible to derive the supply and return temperatures for every possible exterior temperature and for each building. By integration of all relevant buildings, and when the temperatures for a certain period are known, the average composite curve for the district can be calculated for the according period. In this case, the weather data for 2008 from *Pully* is integrated. The next figure shows the calculated composite curves for Ecublens for the seasons "winter" (light blue), "mid-season" (black), "summer"(red) and for -10 °C exterior temperature (dark blue) (the seasons are defined in chapter 5.3.2):

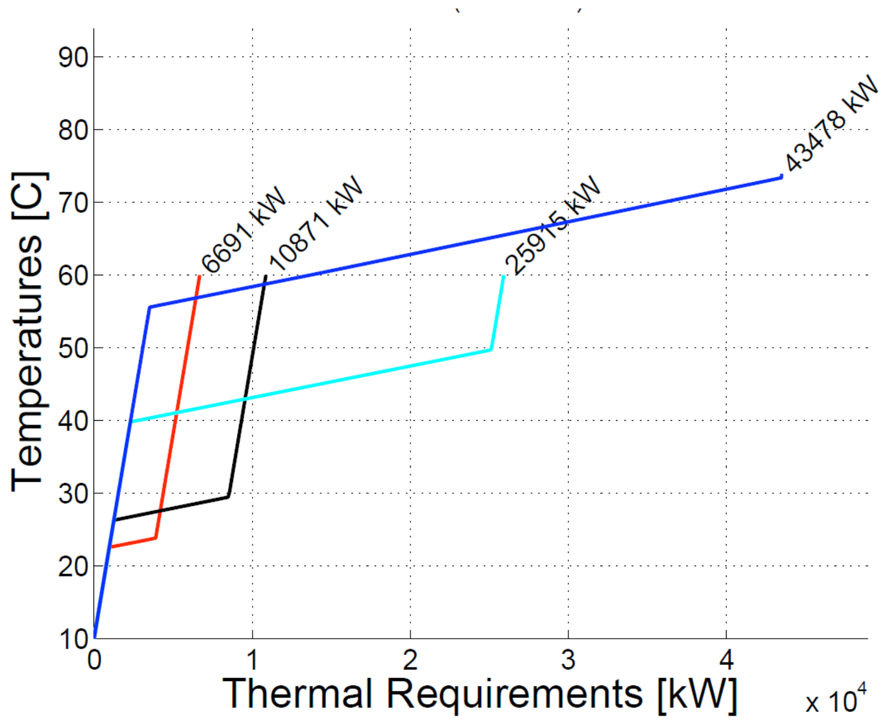


Figure 55: composite curves for Ecublens

As one can see the maximum heat load achieved at -10 °C for Ecublens is 43.478 kW.

The next figure shows the number of hours per year at which a certain heat load is excelled:

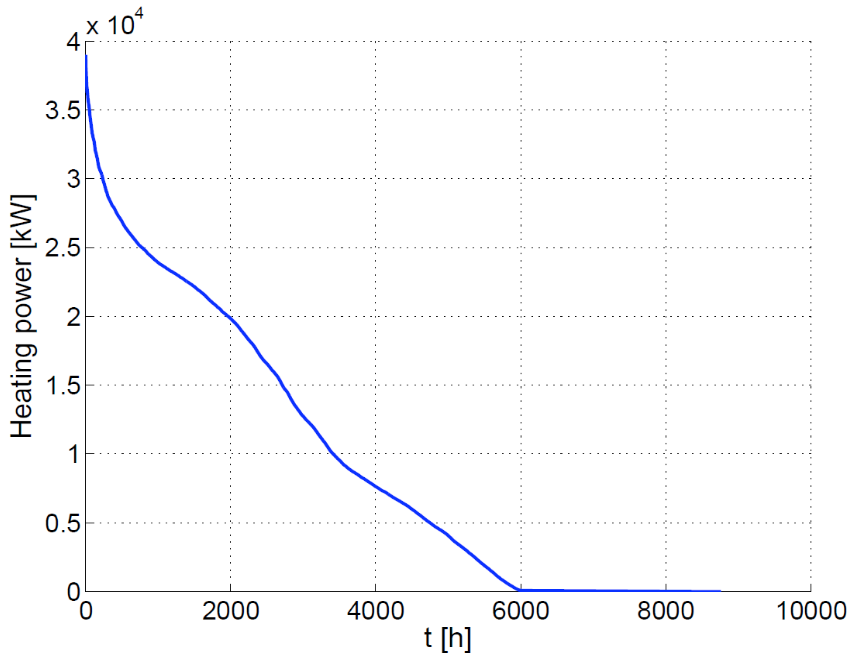


Figure 56: annual heat requirements for Ecublens

6. Results and recommendations

6.1 Summary

The following figure illustrates the results for the specific costs per saved kWh_{el}.:

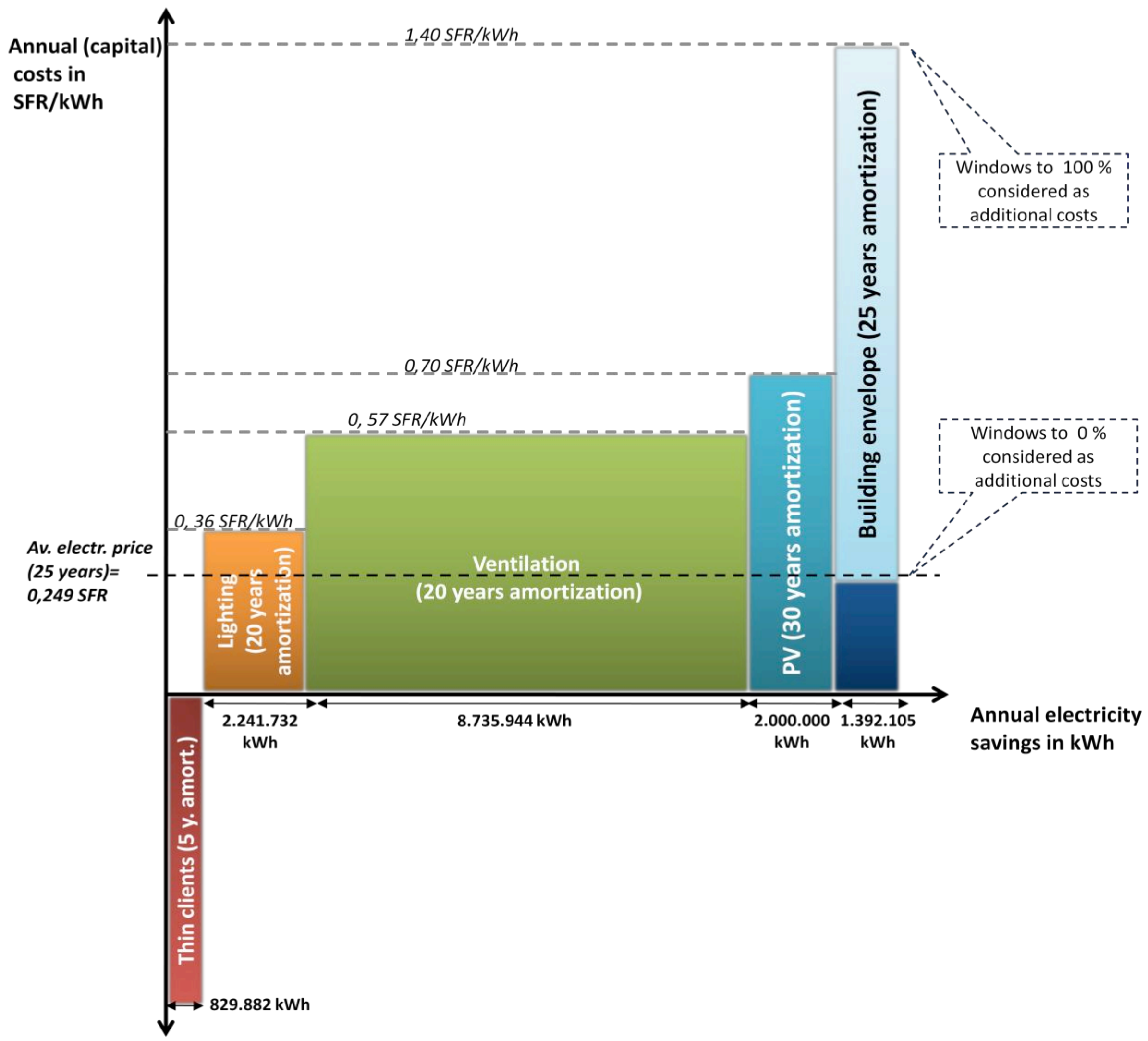


Figure 57: annual specific costs and energy savings for different efficiency measures at EPFL (own illustration)

The width of each box represents the electrical energy savings while the height shows the annual capital cost per saved electricity unit. The heat savings are included, as they are also transformed into electricity savings. For the Thin Clients, money is earned with every saved electricity unit, as *negative* specific costs were evaluated. It must be added that here the differences of annual TCO (total costs of ownership) for desktop PCs and Thin Clients were considered (including all operational costs). For the photovoltaic plant a relatively small fraction of annual maintenance costs entered additionally in the calculation. For the other measures only the energy relevant additional capital costs entered in the calculation, but in case of ventilation and lighting they make up 100 % of the total refurbishment costs (as explained extensively in chapter 3.1.2). The surface of each box represents then the annual (capital) costs for each efficiency measure. When more exact price information is available, the boxes can be adapted accordingly:

It can be observed that no measure except for Thin Clients can be exclusively re- financed by the monetary savings through a reduction in energy consumption as all the specific costs are above the average electricity price for the considered period. [208]

By far the largest energy saving potential for EPFL would result from a consequent energetic refurbishment of the **ventilation** system. Savings could not only be achieved on the electric consumption, but also on the heat consumption of the buildings. Just the refurbishment of the ventilation of one of the buildings *PH* o*r CH* would save enough heat (> 1.000.000 kWh), to satisfy the full calculated heat demand for the new *LC* building. It can be assumed that significant savings can be achieved with less expensive measures as assumed in the total refurbishment calculation.

For both the **lighting** system and the **ventilation** system refurbishment, it needs to be further analyzed to which extent both measures need to enter as *energy relevant additional costs* in the investment calculation, to make a more precise statement about the profitability of these measures.

The consequent replacement of desktop PCs with **Thin Clients** turned out to be a very profitable measure, but also savings in other operational costs entered here in the calculation. The replacement of PCs with laptops instead of Thin Clients would save even more energy, although at a higher price.

The most expensive measure to increase energy efficiency is the renovation of the **building envelopes**. The decisive factor for the costs here is to which extent the costs for the windows exchange enter in the calculation as *energy relevant additional costs.*

When energy efficiency measures are considered as an energy source, then **photovoltaic** electricity represents a very expensive way to produce energy compared to the other measures even though the highest amortization period (30 years) was applied.

The next figure is derived from the previous figure: it shows the annual savings that can be obtained with a certain annual capital cost (for *Thin Clients* total cost of ownership, excluding energy cost savings; For PV, maintenance costs are included; see according chapters). The slopes of the different sections of the graphs are the shown costs per saved electricity unit for the different measures. The red graph shows the costs when the lighting, ventilation, and windows refurbishment are fully considered as energy relevant additional costs. The blue graph shows the costs when only 50 % of these refurbishment costs are considered as energy relevant additional costs (…and the rest as *basic costs*) (please see chapter 3.1.2.2 for exact cost definition). The annual costs and energy savings for the photovoltaic plant are also illustrated for comparison. Additionally to the energy savings, the annually saved CO_2- emissions are added to the figure (in red). The upper value represents the CO_2-

[208] Average electricity prices for 25 and 30 years are for reasons of clarity not included in the figure, but are derived to 0,264 SFR/kWh and 0,281 SFR/kWh

savings, considering a CO_2- intensity of 110 $\frac{g\ CO_2}{kWh_{el}}$ for Switzerland. The value in brackets below is obtained when an emission intensity of 400 $\frac{g\ CO_2}{kWh_{el}}$ is considered, which might be a possible scenario when Swiss nuclear plants are shut down and replaced by fossil fuel plants (see chapter 5.1):[209]

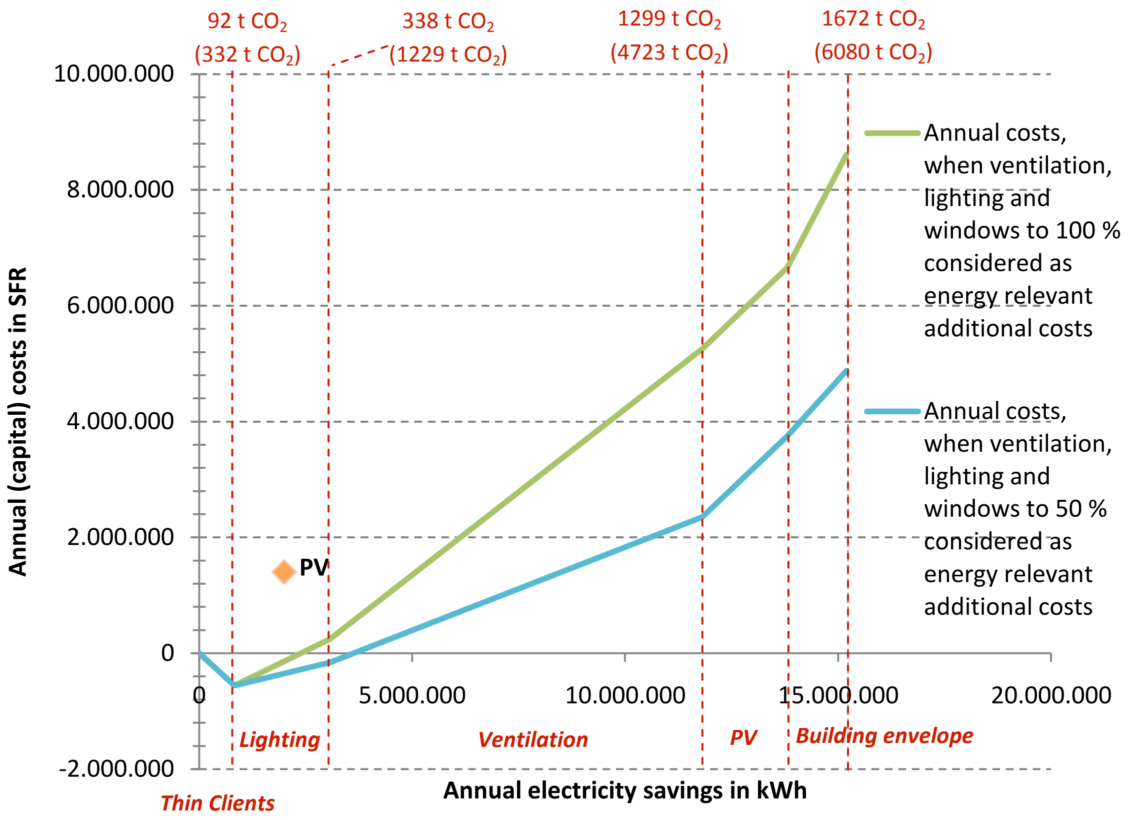


Figure 58: cost curve for electricity savings

One can observe that with the annual costs of the photovoltaic plant, significantly higher energy savings could be achieved if the money was invested in efficiency measures instead.

Further significant economies could be achieved by the reduction of energy consumptions in the data centers. The direct water cooling of servers (which will be a technical option in the near future), and thereby the possible use of heat for the heat distribution network, would save an estimated 3.122.560 kWh of heat per year or 867.378 kWh_{el} of electricity.

738.922 kWh_{el} of electricity could be saved annually by using industrial water in the heat pumps, instead of lake water.

It was shown, that the new buildings *LC, PSE* and *Congress Center* will have little influence on the new total heat loads at EPFL, when MINERGIE standard are considered for these buildings. It was shown that the heating system will reach ist limit capacity after the connection of building *LC*, mainly due to the additional consumptions of the building *SV,* which were not yet exactly verifiable.

[209] calculated in *results.xls*

When a sizing temperature of -5 °C is chosen, the system still has reserves, also after campus extension until 2014. Further significant capacities could be provided by measures such as ventilation refurbishment. New heat pumps for the new buildings would not be required anymore.

6.2 Recommendations

The goal of this work was to reveal the biggest potentials for energy savings and provide recommendations to realize them. Due to the results, one conclusion must be to focus on the adaptation and refurbishment of the ventilation system. Work groups could conduct more detailed analyses in the most important buildings (*PH, CH*, etc.) to get more information about possible measures on the ventilation system. These working groups could be guided by experts; measurements, e.g. about the real actual air streams, could be executed by students in related fields. Furthermore, innovative systems should be installed in selected buildings or zones, to gather practical experience with the performance of innovative systems. Costs could also be more precisely estimated and extrapolated to the rest of the university. This applies also to the lighting system, where especially the effect of the application of presence and daylight sensors at EPFL should be further examined.

The extensive replacement of desktops PCs with **Thin Clients** is also strongly suggested, as it does not only reduce the energy consumptions, but also operational costs. Alternatively, PCs can be replaced by laptops for scientific applications.

Possible heat recovery options for the steam cycle in the building *SV* should be definitely further examined.

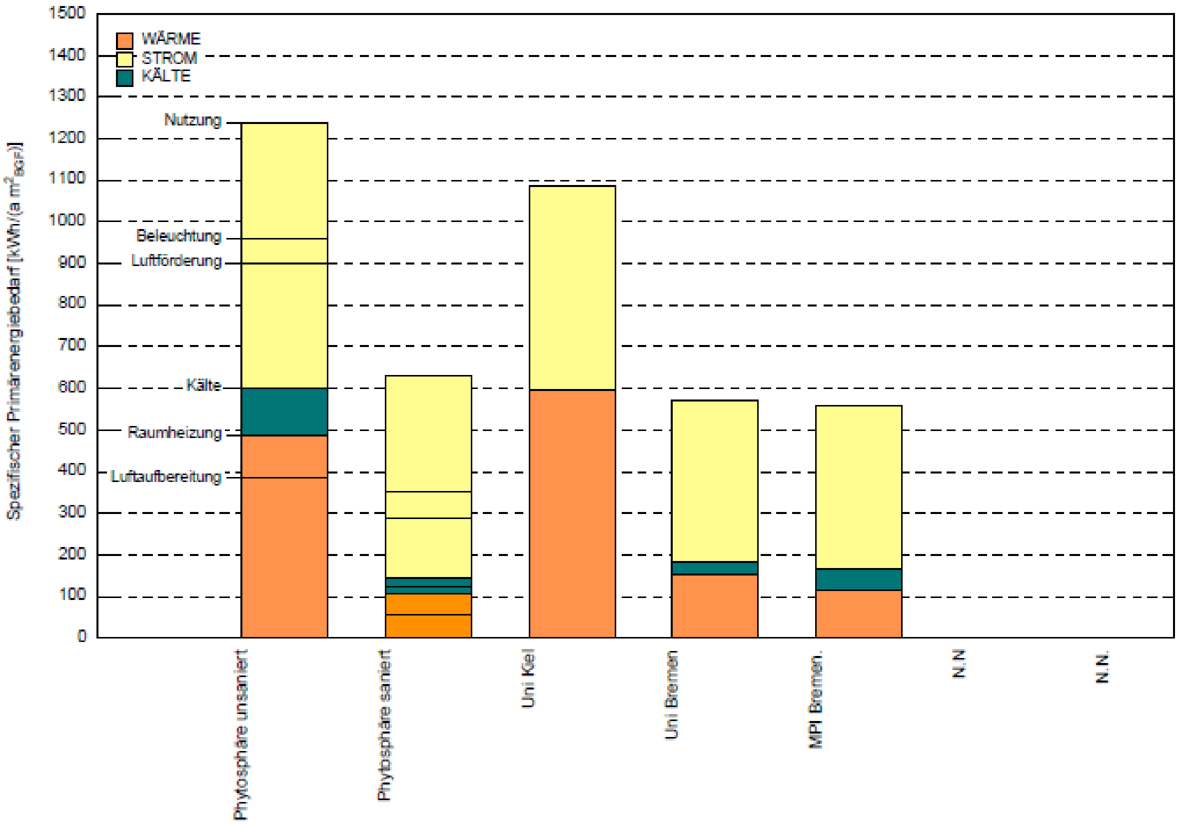
In the medium term, the direct heat recovery through liquid cooling in data centers represents a very attractive option to discharge the heating system.

"I often say that when you can measure what you are speaking about and express it in numbers you know something about it;
but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind:
it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be."
Lord Kelvin, 1883

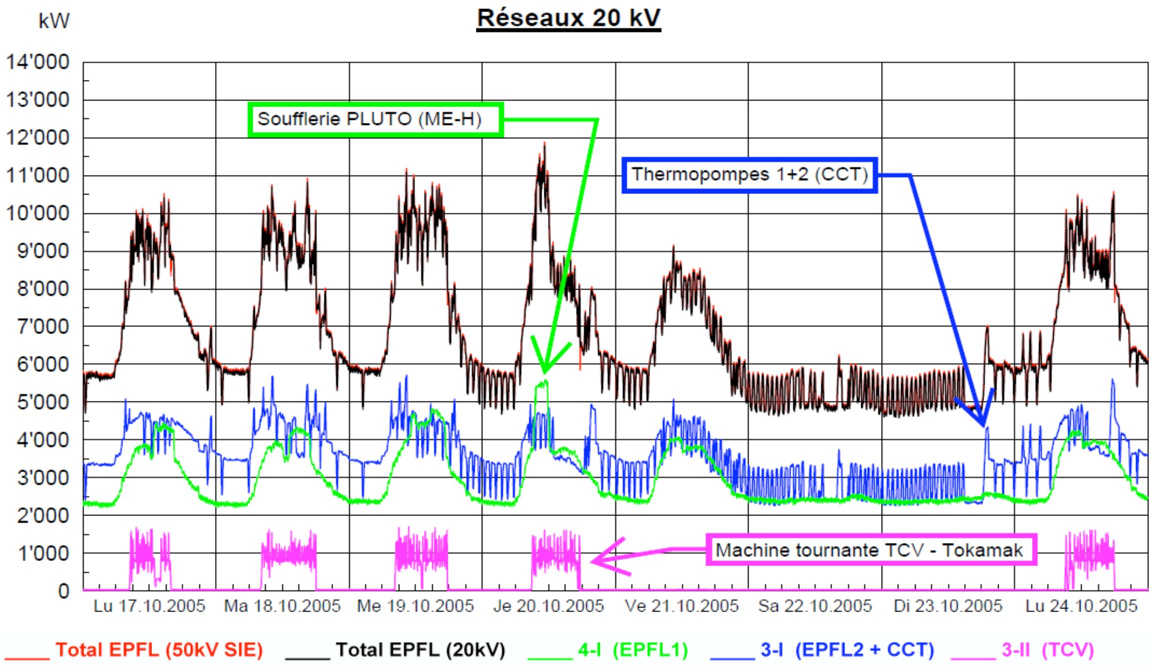
In the course of this study it became evident that the installation of **smart meters** would simplify similar future studies and analysis about energy consumptions at EPFL significantly. One could imagine smart metering for each building and each grid, the real- time load measurements could directly be broadcasted and published on a web page and would be accessible for everybody. This would not only have a strong educational effect, but would also enable the application of another important instrument towards increased energy efficiency: the introduction of **incentive systems** for energy consumption reduction. All examined measures in this study were *Top- down* measures, where the energy consumption can be influenced directly by the central administration. *Bottom- up* approaches are the natural counterparts, where the energy consumption can be influenced by behavior incentives. It was shown that a significant part of the energy consumption cannot be categorized and controlled “from above”. This is for example the case for the biggest fraction on the grid *Force,* which is caused by printers, telephones, experimental installations etc. These consumptions represent around 10 million kWh_{el} per year. They can only be influenced directly by the institutes through the purchase of the adequate and energy efficient equipment and by the employees through their *behavior*. It is no question that a behavior incentive system can only work effectively when the feedback on behavior changes is given quickly. The smart meters and the online broadcasting could then perform this task. One could then install an incentive system for each building, institute, or department. For the moment, there is no incentive for the different administrative units to save energy and to buy efficient equipment, as the energy consumptions cannot be directly allocated and the energy bill is not paid by the originator. In the future, an option would be to directly measure the energy consumption of the administrative units. Possible monetary savings through energy consumption reduction could then be added as incentive to the budget of the according unit. The master thesis from Paterek (2008) analyzes application options for smart meters in universities, and demonstrates examples of different European universities, where smart metering already contributes to an integrated energy management system.

A last personal observation and remark of the author: The establishment of an integrated *energy management system*, considering the preceding points, should also be aimed for at EPFL. The *energy system manager* should always be able to provide an overview over the system as a whole, and should then be able to develop specific efficiency measures and solutions in collaboration with the technically responsible persons for the different systems and installations. By contrast the energy system manager should *not* be involved in the maintenance, surveillance, etc. of the technical installations, as this might lead to conflicts of interests. The goal of the energy system manager should always be to assure that all services required for the functioning and operation of the campus and related with energy consumption, are delivered according to the principle: *as much as necessary, but as little as possible*.

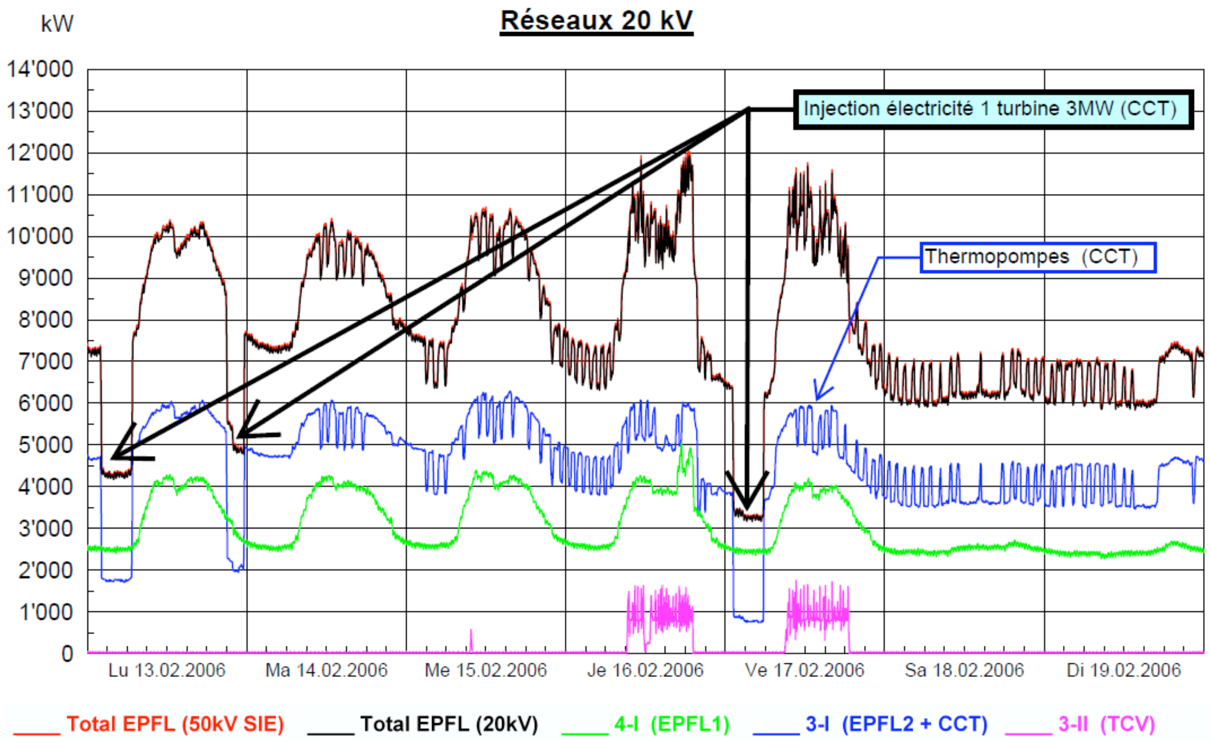
Appendices



Appendix A: specific primary energy consumptions for different universities in Germany (source: Birnbaum (2007))



Appendix B: Load curve for typical winter week at EPFL (source: EPFL- PI- DII_E)

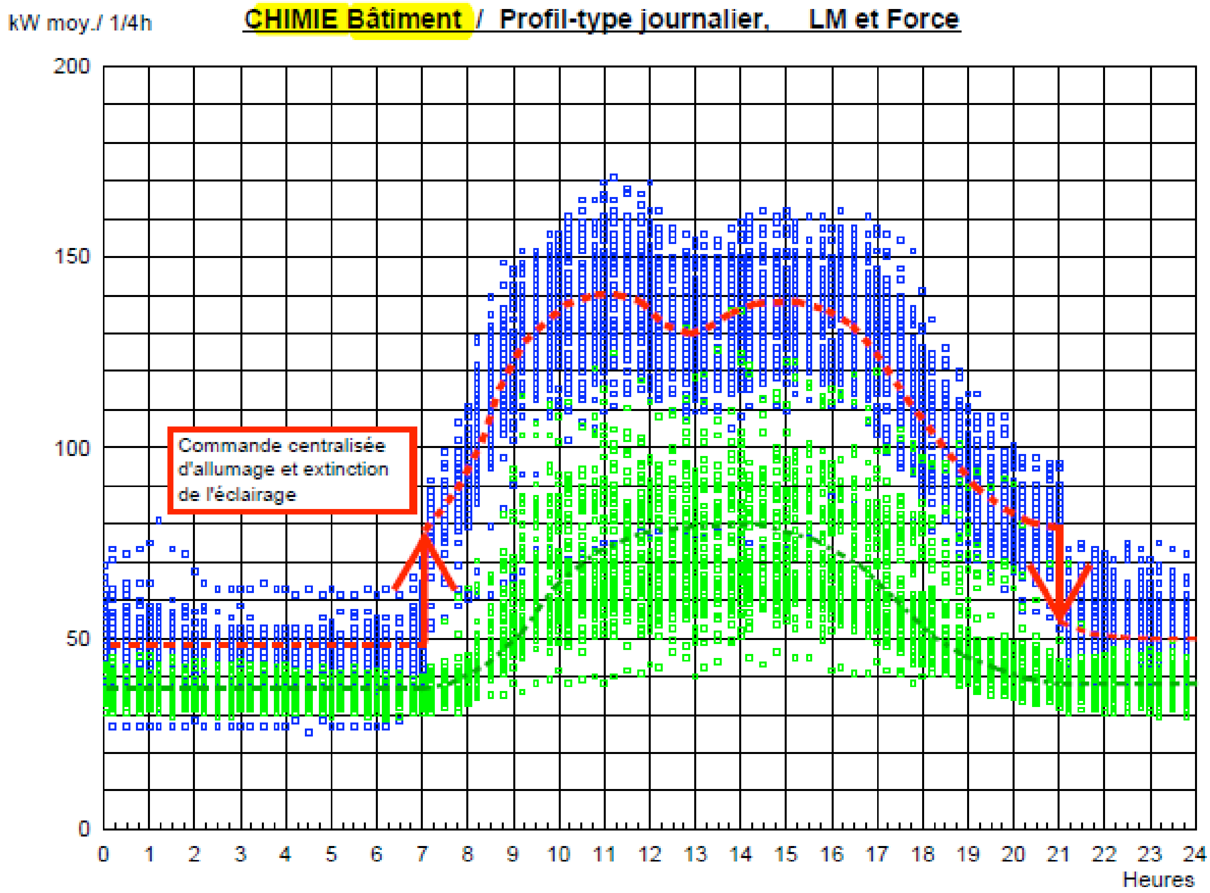


Appendix C: Load curve for typical winter week at EPFL, including electricity production from gas turbines (source: EPFL-PI- DII_E)

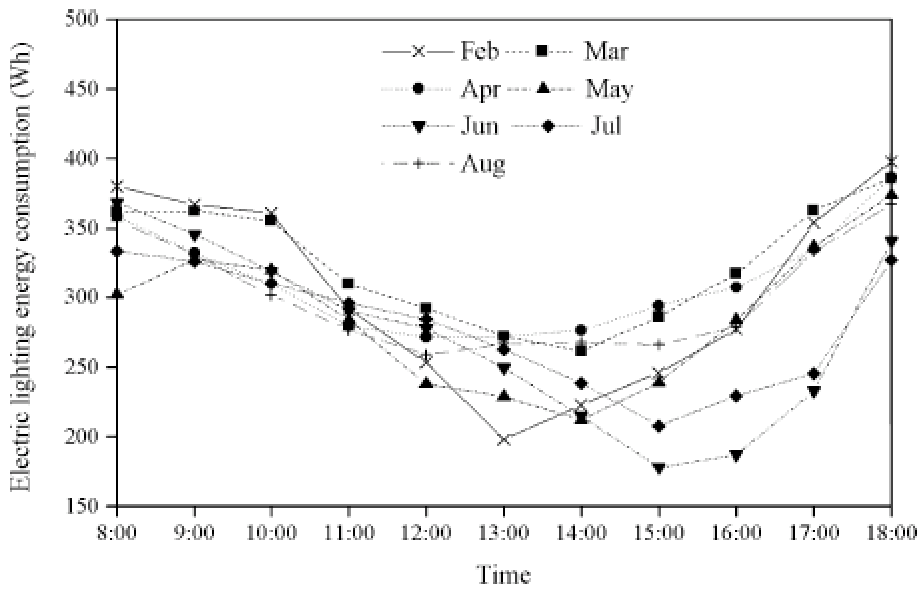
Commercial name	Type	Cap/ base	Lamp voltage V	Lamp current A	Colour designation temperature	Correlated colour K	Lumen output lm	Average luminance cd/cm²	Nett weight g	EOC
/25										
TL-RS	TL 20W /25 RS	G13	57	0.37	COOL WHITE	4000	1050	0.56	156	719416
TL-RS	TL 40W /25 RS	G13	101	0.43	COOL WHITE	4000	2650	0.67	292	719942
TL-RS	TL 65W /25 RS	G13	110	0.67	COOL WHITE	4000	4350	0.88	292	720481
/29										
TL-RS	TL 20W /29 RS	G13	57	0.37	WARM WHITE	2900	1150	0.61	156	719478
TL-RS	TL 40W /29 RS	G13	101	0.43	WARM WHITE	2900	3000	0.76	292	720009
TL-RS	TL 65W /29 RS	G13	110	0.67	WARM WHITE	2900	4750	0.96	360	720542
/33										
TL-RS	TL 20W /33 RS	G13	57	0.37	COOL WHITE	4100	1100	0.59	156	719560
TL-RS	TL 40W /33 RS	G13	101	0.43	COOL WHITE	4100	2850	0.73	292	720092
TL-RS	TL 65W /33 RS	G13	110	0.67	COOL WHITE	4100	4650	0.94	360	720634
/54										
TL-RS	TL 20W /54 RS	G13	57	0.37	COOL DAYLIGHT	6200	1000	0.53	156	719645
TL-RS	TL 40W /54 RS	G13	101	0.43	COOL DAYLIGHT	6200	2500	0.64	292	720276
TL-RS	TL 65W /54 RS	G13	110	0.67	COOL DAYLIGHT	6200	4100	0.83	360	720696

1

Appendix D: technical data for typical fluorescent tubes, used at EPFL (TL 65W/29 RS) (source: PHILIPS)



Appendix E: the blue line represents the load distribution on the grid L- M for the building CH (source: EPFL- PI- DII_E)



Appendix F: electric lighting load profile between February and August for university office in Hongkong (source: Li (2006))

1. Introduction

Le but de ce rapport est de comparer différentes solutions pour refroidir les locaux serveurs. Les aspects concernant les coûts d'investissement et ceux d'exploitation on été abordés dans ce document.

Les paramètres concernant la maintenance et les durées d'amortissement des installations n'ont pas été considérées dans les calculs.

Les 3 systèmes étudiés sont :
- refroidissement au moyen d'armoires de climatisation
- refroidissement au moyen d'éléments raccordés au réseau d'eau de refroidissement et montés à l'arrière des racks
- refroidissement par un monobloc à double-flux travaillant avec une part d'air extérieure variable (free-cooling).

2. Bases de calcul

dissipations thermiques d'équipement informatique	50 kW
durée d'exploitation	24h/24h et 365j/an
températures extérieures	6'180 h/a <+15°C
	2180 h/a >+15°C <+24°C
	400 h/a >+24°C
température ambiante local serveurs	24°C
température de pulsion	15°C
température de l'eau industrielle	7/12°C
température de l'eau froide monobloc et armoires de climatisation	10/15°C
température de l'eau froide racks réfrigérés	15/18°C
consommation d'énergie de froid armoire et racks réfrigérés	438'000 kWh/a
consommation d'énergie de froid monobloc	86'445 kWh/a
débit d'air pulsé (monobloc ou armoire)	17'000 m^3/h
débit d'air d'un rack qui dissipe 17 kW	3'100 m^3/h
pression totale ventilateur monobloc de pulsion	450 Pa
pression totale ventilateurs monobloc d'extraction	200 Pa
pression totale ventilateur armoire de climatisation	200 Pa
pression totale ventilateurs rack	150 Pa
rendement des ventilateurs du monobloc pulsion et extraction	75%
rendement du ventilateur de l'armoire de climatisation	65%
rendement des moteurs des ventilateurs	90%
rendement global des ventilateurs et moteurs des racks	40%
prix de l'énergie de froid basée sur les m^3 consommés et $\Delta T = 5K$	Fr. 0,305/m^3
prix de l'énergie électrique	Fr. 0,15/kWh

Appendix G: cost assumptions for data center cooling (source: Forrer (2007))

4. Coûts d'investissement et d'exploitation

Les prix sont en SFr HT

	désignation	variante 1 (armoire)	variante 2 (racks)	variante 3 (monobloc)
coûts d'investissement	raccordements eau glacée sur armoire, échangeur ou monobloc	5'000.-	5'000.-	5'000.-
	1 armoire de climatisation avec 50 kW de puissance frigorifique	40'000.-		
	3 racks réfrigérés à SFr. 19'400.- (info M. Glaus)		58'200.-	
	1 échangeur à plaques, 1 pompe, 80 m de conduites DN80, isolation	15'000.-	18'000.-	15'000.-
	monobloc double-flux de 17'000 m^3/h, raccordement sanitaire avec humidification			38'000.-
	60 m de gaines avec une surface de passage de 1m^2 pour les flux d'air neuf, pulsé aspiré et évacué, y compris montage			22'000.-
	isolation extérieure de 50% des gaines			7'000.-
	2 clapets coupe-feu, 2 amortisseurs de bruit sur les réseaux d'air neuf et d'air évacué			7'000.-
	TOTAL coût d'investissement SFr.	**60'000.-**	**81'200.-**	**94'000.-**
coûts d'exploitation	consommation de froid en kWh/an (sans assèchement)	438'000	438'000	86'445
	Consommation de froid en m^3/an (ΔT = 5K)	75'445	75'445	14'890
	consommation de froid en SFr./an	23'010.-	23'010.-	4'542.-
	consommation électrique des ventilateurs en kWh/an	14'892	8'760	39'832
	consommation électrique des ventilateurs en SFr./an	2'234.-	1'314.-	5'975.-
	consommation électrique de la pompe en kWh/an	1'100	1'900	1'100
	consommation électrique de la pompe en SFr./an	165.-	285.-	165.-
	consommation électrique de l'humidificateur en kWh/an (calcul SICC 83/2)			73'300
	consommation électrique de l'humidificateur en SFr./an			10'995.-
	consommation électrique totale en kWh/an	15'100	10'420	114'985
	consommation électrique totale en SFr./an	2'399.-	1'599.-	17'135.-
	TOTAL coût d'exploitation par an SFr.	**25'409.-**	**24'609.-**	**21'677.-**
	retour sur investissement sans tenir compte de l'intérêt en année		**26,5 ans**	**9,1 ans**

Appendix H: cost comparison for data center cooling (source: Forrer (2007))

Aufteilung in Sowieso- und Zusatzkosten				
	Gesamte Sanierungskosten	Sowieso-kosten	energierelevante Zusatzkosten	Anmerkungen
	EUR	EUR	EUR	
Kragarme				
Demontage Betonrippen	62.540		62.540	
Korrosionsschutz Schnittflächen	12.424		12.424	
Demontage Geländer	5.336		5.336	
Demontage, Entsorgung Betonplatten	22.966		22.966	
Fugenabdichtung	7.397		7.397	
Gerüstkosten	24.377	24.377		Gerüst wird sowieso benötigt
Planung, Ausführung zu Brandschutz	74.992		74.992	
Zwischensumme Kragarme	210.032	24.377	185.655	Alles außer Gerüst relevant
Außenwandbekleidung				
Demontage der alten Vorhangfassade	25.100	25.100		
Wärmedämmung	36.741		36.741	Wärmedämmung relevant
Aluminium-Verkleidung	45.938	45.938		
Armierung und Putz	74.264	74.264		
Zwischensumme Außenwand	182.043	145.302	36.741	
Dachsanierung				
Demontagearbeiten	3.323	3.323		
Dach mit RWA, Lichtkuppel etc	87.362	87.362		
Wärmedämmung PS 30 SE	22.155		22.155	Wärmedämmung relevant
Zwischensumme Dach	112.840	90.685	22.155	
Fenstersanierung				
Erneuerungskosten	216.418		216.418	Anteil der Sowiesokosten unklar
Zwischensumme Fenster	216.418		216.418	als energierelevant eingestuft
Sonnenschutz, Lichtlenkung				
Beleuchtung, Lichtlenkung	69.066		69.066	
Montagearbeiten für Lichtlenkung	10.918		10.918	Anteil der Sowiesokosten unklar
Zwischensumme Beleuchtung	79.984		79.984	alle Kosten energetisch
Raumlufttechnische Anlage (RLT)				
Pauschalpreis	1.592.037		1.592.037	Anteil der Sowiesokosten unklar
Zwischensumme RLT	1.592.037		1.592.037	alle Kosten energetisch
Fernwärmeversorgung				
Fernwärmeübergabestation PN 26	190.085		190.085	Anteil der Sowiesokosten unklar
Zwischensumme Fernwärmeanschluss	190.085		190.085	als energierelevant eingestuft
Gesamtsumme	2.583.439	260.364	2.323.075	

Tabelle 3–18: Übersicht der energetisch bedingten Sanierungskosten (ohne finanzielle Förderung)

Appendix I: refurbishment costs for the Phytosphäre laboratory (source: Birnbaum et al. (2007))

Category	Construction/renovation	n_b	$\overline{q}^{boil} \pm \sigma_{\overline{q^{boil}}}$	$\sigma_{q^{boil}}$	$q^{heat}_{2005,c}$	$q^{hw}_{2005,c}$	$q^{cool}_{2005,c}$	Electricity
		[-]	[kWh/(m^2 year)]			[kWh/(m^2 year)]		
Resid1	<1920	494	166.17 ± 3.11	69.14	115.27	34.28	0.00	27.78
Resid2	1920–1970	2533	181.39 ± 0.82	41.51	128.97	34.28	0.00	27.78
Resid3	1970–1980	938	174.84 ± 1.20	36.80	123.07	34.28	0.00	27.78
Resid4	1980–2005	1582	135.28 ± 1.06	42.24	87.47	34.28	0.00	27.78
Resid5	2005–2020	0	–	–	38.77	34.28	0.00	27.78
Resid6	2020–2030	0	–	–	26.60	34.28	0.00	27.78
Resid7	<1920 Renovated	0	–	–	35.12	34.28	0.00	27.78
Resid8	1920–1970 Renovated	0	–	–	52.17	34.28	0.00	27.78
Resid9	1970–1980 Renovated	0	–	–	47.30	34.28	0.00	27.78
Resid10	1980–2005 Renovated	0	–	–	54.60	34.28	0.00	27.78
Admin1	<1920	29	137.05 ± 12.04	64.86	111.92	11.43	0.00	22.22
Admin2	1920–1970	32	136.88 ± 6.15	34.80	111.76	11.43	0.00	22.22
Admin3	1970–1980	18	141.64 ± 8.11	34.41	116.05	11.43	13.15	22.22
Admin4	1980–2005	27	124.18 ± 9.59	49.81	100.33	11.43	19.11	22.22
Admin5	2005–2020	0	–	–	55.63	11.43	25.37	22.22
Admin6	2020–2030	0	–	–	44.45	11.43	27.99	22.22
Admin7	<1920 Renovated	0	–	–	52.28	11.43	25.98	22.22
Admin8	1920–1970 Renovated	0	–	–	67.92	11.43	26.03	22.22
Admin9	1970–1980 Renovated	0	–	–	63.45	11.43	27.55	22.22
Admin10	1980–2005 Renovated	0	–	–	70.16	11.43	25.49	22.22
Comm1	<1920	1	56.11 ± 0.00	0.00	27.65	22.85	0.00	33.33
Comm2	1920–1970	1	111.67 ± 0.00	0.00	77.65	22.85	0.00	33.33
Comm3	1970–1980	1	97.22 ± 0.00	0.00	64.65	22.85	34.33	33.33
Comm4	1980–2005	5	84.67 ± 14.14	31.63	53.35	22.85	44.12	33.33
Comm5	2005–2020	0	–	–	22.87	22.85	52.94	33.33
Comm6	2020–2030	0	–	–	15.25	22.85	56.45	33.33
Comm7	<1920 Renovated	0	–	–	20.58	22.85	53.32	33.33
Comm8	1920–1970 Renovated	0	–	–	31.25	22.85	53.39	33.33
Comm9	1970–1980 Renovated	0	–	–	28.20	22.85	56.46	33.33
Comm10	1980–2005 Renovated	0	–	–	32.77	22.85	53.00	33.33
Indus1	<1920	4	181.11 ± 18.21	36.43	151.57	11.43	0.00	16.67
Indus2	1920–1970	6	183.75 ± 19.80	48.51	153.95	11.43	0.00	16.67
Indus3	1970–1980	1	146.67 ± 0.00	0.00	120.57	11.43	0.00	16.67
Indus4	1980–2005	5	101.89 ± 16.92	37.84	80.27	11.43	0.00	16.67
Indus5	2005–2020	0	–	–	43.59	11.43	0.00	16.67
Indus6	2020–2030	0	–	–	34.42	11.43	0.00	16.67
Indus7	<1920 Renovated	0	–	–	40.84	11.43	0.00	16.67
Indus8	1920–1970 Renovated	0	–	–	53.68	11.43	0.00	16.67
Indus9	1970–1980 Renovated	0	–	–	50.01	11.43	0.00	16.67
Indus10	1980–2005 Renovated	3	144.26 ± 1.80	3.12	55.51	11.43	0.00	16.67
Educ1	<1920	1	100.83 ± 0.00	0.00	67.90	22.85	0.00	11.11
Educ2	1920–1970	1	192.50 ± 0.00	0.00	150.40	22.85	0.00	11.11
Educ3	1970–1980	2	196.11 ± 55.00	77.78	153.65	22.85	1.37	11.11
Educ4	1980–2005	0	–	–	153.65	22.85	3.04	11.11
Educ5	2005–2020	0	–	–	83.05	22.85	4.83	11.11
Educ6	2020–2030	0	–	–	65.40	22.85	5.65	11.11
Educ7	<1920 Renovated	0	–	–	77.75	22.85	5.21	11.11
Educ8	1920–1970 Renovated	0	–	–	102.46	22.85	5.23	11.11
Educ9	1970–1980 Renovated	0	–	–	95.40	22.85	5.52	11.11
Educ10	1980–2005 Renovated	0	–	–	105.99	22.85	4.95	11.11
Health1	<1920	0	–	–	96.51	45.71	0.00	27.78
Health2	1920–1970	0	–	–	86.41	45.71	0.00	27.78
Health3	1970–1980	5	159.56 ± 13.52	30.24	97.89	45.71	6.14	27.78
Health4	1980–2005	5	148.22 ± 28.42	63.55	87.69	45.71	8.01	27.78
Health5	2005–2020	0	–	–	34.33	45.71	9.98	27.78
Health6	2020–2030	0	–	–	20.99	45.71	10.77	27.78
Health7	<1920 Renovated	0	–	–	30.33	45.71	10.06	27.78
Health8	1920–1970 Renovated	0	–	–	49.01	45.71	10.07	27.78
Health9	1970–1980 Renovated	0	–	–	43.67	45.71	10.67	27.78
Health10	1980–2005 Renovated	0	–	–	51.67	45.71	10.00	27.78
Hotel1	<1920	5	159.00 ± 10.21	22.82	97.39	45.71	0.00	33.33
Hotel2	1920–1970	2	203.33 ± 12.22	17.28	137.29	45.71	0.00	33.33
Hotel3	1970–1980	2	223.33 ± 31.11	44.00	155.29	45.71	4.61	33.33
Hotel4	1980–2005	2	128.47 ± 2.64	3.73	69.92	45.71	7.56	33.33
Hotel5	2005–2020	0	–	–	23.67	45.71	10.83	33.33
Hotel6	2020–2030	0	–	–	12.11	45.71	12.49	33.33
Hotel7	<1920 Renovated	0	–	–	20.20	45.71	11.11	33.33
Hotel8	1920–1970 Renovated	0	–	–	36.39	45.71	11.13	33.33
Hotel9	1970–1980 Renovated	0	–	–	31.76	45.71	11.77	33.33
Hotel10	1980–2005 Renovated	0	–	–	38.70	45.71	10.78	33.33
Other1	<1920	903	150.49 ± 1.33	39.85	107.69	27.75	0.00	27.78
Other2	1920–1970	1421	173.59 ± 1.62	60.90	128.48	27.75	0.00	27.78

(*continued on next page*)

Appendix J: building categories and specific consumptions in ENERGIS (source: Girardin (2009))

Bibliography

ASHRAE (Ed.) (2004): *HVAC systems and equipment*; American Society of Heating, Refrigerating and Air-Conditioning Engineers; Atlanta, GA: ASHRAE.

BERANGER, Bruno (2008): *Les pompes à chaleur*; 2e éd. revue et augmentée; 3e tirage; Paris: Eyrolles.

BFE (*Bundesamt für Energie*)(Ed.)(2006): *Prozessintegration mit der Pinch- Methode- Handbuch zum BFE- Einführungskurs;* Bern: BFE (2006); web: *http://www.bfe.admin.ch/energie/00572/00870/index.html?lang=de&dossier_id=01259*.

BIRNBAUM , ULF ET AL.(2007): *Leitfaden für die energetische Sanierung von Laboratorien;* Forschungszentrum Jülich; Ed.: Forschungszentrum Jülich GmbH; web: *http://www.enob.info/fileadmin/media/Publikationen/EnSan/Leitfaden_LABSAN.pdf.*

BITKOM (Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V.)(Ed.) (2008): *Energieeffizienz im Rechenzentrum - Ein Leitfaden zur Planung, zur Modernisierung und zum Betrieb von Rechenzentren*; Berlin: BITKOM; web: *http://www.bitkom.org/files/documents/Leitfaden_Energieeffizienz_in_RZ_final_31072008.pdf*.

BOURGEOIS, Denis; Reinhart, Christoph; Macdonald, Iain(2006) ; *Adding advanced behavioral models in whole building energy simulation: A study on the total energy impact of manual and automated lighting control*; in: Energy and Buildings; Volume 38, Issue 7, Special Issue on Daylighting Buildings; July 2006; Pages 814-823; ISSN 0378-7788, DOI: 10.1016/j.enbuild.2006.03.002.

DAVID, Ruth et al.(2009*): Heizen, Kühlen, Belüften & Beleuchten: Bilanzierungsgrundlagen nach DIN V 18599;* 2. unveränderte Aufl.; Stuttgart: Fraunhofer IRB Verlag.

Standard DIN V 18599 (2007)*: Energy efficiency of buildings: calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting: prestandard*; Berlin: Beuth.

EICHLER, Martin et al.(2003*): Preisunterschiede Schweiz–EU: Eine branchenspezifische Bestandsaufnahme;* in: Die Volkswirtschaft; 2003; Edition 7- 2003; p. 11- 15.

ENERGHO (Ed.)(2000): *Energiesanierung der Monoblöcke von RLT- Anlagen;* Lausanne: ENERGHO (*Verein für Energie- Grossverbraucher öffentlicher Institutionen*).

FICHTER, Klaus; Clausen, Jensen; Eimertenbrink, Maik (2008): *Energieeffiziente Rechenzentren- Best-Practice-Beispiele aus Europa, USA und Asien;* Berlin: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU); web: *http://www.bmu.de/files/pdfs/allgemein/application/pdf/energieeffiziente_rechenzentren_de.pdf*

GIRARDIN, Luc et al. (2009): *EnerGis: A geographical information based system for the evaluation of integrated energy conversion systems in urban areas*; in: Energy, In Press, Corrected Proof, Available online 12 October 2009; ISSN 0360-5442; DOI: 10.1016/j.energy.2009.08.018.

HARRJE, David T.; Piggins, James M. (1991): *Reporting guidelines for the measurement of airflows and related factors in buildings*; Coventry: Air Infiltration and Ventilation Centre, 1991. (Technical note AIVC; 32).

INFORMATIONSZENTRUM ENERGIE (Ed.) (2002): *Energieeffiziente Lüftungsanalagen in Betrieben;* Stuttgart: Landesgewerbeamt Baden- Württemberg- Informationszentrum Energie; Web: *http://www.bubw.de/PDF_Dateien/Wichtig_fuer_alle_Branchen/BaWue_Lueftungsanlagen.pdf.*

JAKOB, Martin; Volkart, Kathrin; Widmer, Daniela (2009): *CO2-Intensität des Stromabsatzes an Schweizer Endkunden;* Zürich: TEP Energy GmbH; web: *http://www.tepenergy.ethz.ch/docs/CO2IntensitaetStromabsatz_TEP_Energy_Zusammenfassung.pdf*

JOOS, Lajos (Ed.)(2004): *Energieeinsparung in Gebäuden : Stand der Technik, Entwicklungstendenzen;* 2. Aufl. ; gemäß EnEV 2002; Essen: Vulkan-Verlag.

KEMP, Ian C. (2007): *Pinch analysis and process integration: a user guide on process integration for the efficient use of energy*; 2nd ed.; Amsterdam: Elsevier Butterworth-Heinemann.

KLUTTIG, Heike; Dirscherl, Andreas; Erhorn, Hans (2001): *Energieverbräuche von Bildungsgebäuden in Deutschland* ; Stuttgart: Fraunhofer Institut für Bauphysik; web: *http://www.enob.info/de/publikationen/publikation/details/energieverbraeuche-von-bildungsgebaeuden-in-deutschland/.*

KNERMANN, Christian et al. (2008): *Studie- Ökologischer Vergleich der Klimarelevanz von PC und Thin Client Arbeitsplatzgeräten 2008;* Oberhausen: Fraunhofer Institut für Umwelt,- Sicherheits-, Energietechnik UMSICHT; Web: *http://it.umsicht.fraunhofer.de/TCecology/docs/TCecology2008_de.pdf.*

KNERMANN, Christian (2008)[2]: *PC- vs. Thin Client- Wirtschaftlichkeitsbetrachtung- Version1.2008;* Oberhausen: Fraunhofer Institut für Umwelt,- Sicherheits-, Energietechnik UMSICHT; Web: *http://cc-asp.fraunhofer.de/docs/PCvsTC-de.pdf.*

LECHNER, Norbert (2009): *Heating, cooling, lighting: sustainable design methods for architects*; 3rd ed.; Hoboken, N.J.: Wiley.

LI, Danny H.W.; Lam, Tony N.T.; Wong, S.L.(2006): *Lighting and energy performance for an office using high frequency dimming controls*; in: Energy Conversion and Management; Volume 47, Issues 9-10; June 2006; Pages 1133-1145; ISSN 0196-8904; DOI: 10.1016/j.enconman.2005.06.016.

MROZ , Tomasz (2003): *Subtask A report: Overview of Retrofitting Measures;* Ed.: IEA (International Energy Agency) Energy Conservation in Buildings and Community Systems (ECBCS); web: http://www.annex36.de/eca/de/06util/pdf/A36SubtaskA_Report_RetrofitMeasures.pdf.

OUGHTON, D.R. et al. (2008): *Faber and Kell's heating and air conditioning of buildings*; 10th ed.; Oxford: Butterworth- Heinemann.

PARKER, Dave (2009): *Microgeneration: low energy strategies for larger buildings*; Amsterdam: Elsevier.

Paterek, Lukas (2008): *Electricity metering and savings at universities - the case of RWTH Aachen University;* Master Thesis*;* Aachen: E.ON Energy Research Center- RWTH Aachen.

PELET, X., Favrat, D., Voegeli, A.(1997): *Performance of a 3.9 MW Ammonia Heat Pump in a District Heating Cogeneration Plant: Status after eleven years of operation*; in: Compression Systems with Natural Working Fluids, IEA Annex 22 Workshop, Gatlinburg, TN, USA, 1997.

RAGER, Jakob (2009): *Urban Energy Integration and Resource Management- Applied in Geneva*; Master Thesis; Lausanne: LENI- EPFL.

RICHARZ, Clemens; Schulz, Christina; Zeitler, Friedemann (2007): *Energy efficiency upgrades: principles, details, examples*; Basel: Birkhäuser.

RISHEL, James B.; Durkin, Thomas H.; Kincaid, Benny L. (2006): *HVAC pump handbook*; 2nd ed.; New York: McGraw-Hill.

ROULET, Claude-Alain (2008): *Ventilation and airflow in buildings: methods for diagnosis and evaluation*; London: Earthscan; (Buildings, energy, solar technology).

Standard SIA (Ed.) 180 (1999): *Wärme- und Feuchteschutz im Hochbau*; Ed. 1999; Zürich: SIA.

Standard SIA (Ed.) 380/1 (2009): *Thermische Energie im Hochbau= L'énergie thermique dans le bâtiment= L'energia termica nell'edilizia*; Ed.: Schweizerischer Ingenieur- und Architektenverein; Zürich: SIA.

Standard SIA (Ed.) 380/4 (2006): *Elektrische Energie im Hochbau= L'énergie électrique dans le bâtiment= L'energia elettrica nell'edilizia*; Ed.: Schweizerischer Ingenieur- und Architektenverein; Zürich: SIA.

Standard SIA (Ed.) 382/1 (2007): *Lüftungs- und Klimaanlagen - Allgemeine Grundlagen und Anforderungen* = Installations de ventilation et climatisation - Basses générales et performances requises ; Ed.: Schweizerischer Ingenieur- und Architektenverein; Zürich : SIA.

Standard SIA (Ed.) 384.201 (2005): *Heizungsanlagen in Gebäuden - Verfahren zur Berechnung der Norm-Heizlast= Systèmes de chauffage dans les bâtiments - méthode de calcul des déperditions calorifiques de base= Heating systems in buildings - method for calculation of the design heat load*; Ed.: Schweizerischer Ingenieur- und Architektenverein. Zürich: SIA.

Bulletin SIA (Ed.) 2024 (2006): *Standard-Nutzungsbedingungen für die Energie- und Gebäudetechnik*; Ed.: Schweizerischer Ingenieur- und Architektenverein. Zürich: SIA, 2006.

Bulletin SIA (Ed.) 2031 (2009): *Energieausweis für Gebäude gemäss SN EN 15217 und SN EN 15603*; Ed.: Schweizerischer Ingenieur- und Architektenverein; Ausgabe 2009; Zürich: SIA.

SORRELL, Steve et al. (2004): *The economics of energy efficiency: barriers to cost-effective investment*; Cheltenham: Edward Elgar.

VAILLENCOURT, Richard (2008): *Simple solutions to energy calculations*; 4th ed.; Lilburn, GA: The Fairmont Press.

EPFL documents

EPFL- Pl- DII_E (Ed.)(2006): *Projet «DIAGELEC»- Méthode d'analyse et Bilan détaillé de la consommation d'électricité des bâtiments de l'EPFL*; Lausanne: *EPFL- Pl- DII_E.*

EPFL- Pl- DII_E (Ed.)(2006)(2): cahier de normalisation relatif aux installations électriques intérieures des bâtiments de l'EPFL raccordes au réseau du domaine immobilier et infrastructures- unité exploitations*;* Lausanne*:* EPFL- Pl- DII_E.

EPFL- Pl- DII_E (Ed.)(2007): *Bilan des Energies du site de EPFL a Ecublens*; Lausanne: *EPFL- Pl- DII_E.*

EPFL- Pl- DII_E (Ed.)(2008): *Cahier de normalisation des installations- chauffage, ventilation, sanitaire ;* Lausanne: *EPFL- Pl- DII_E.*

FORRER, Jacob (2007): Comparaison des systèmes de refroidissement des locaux servers; Lausanne: Jacob Forrer SA.

SCHMID, J.(2005): *Centrale de Chauffe par Thermopompes;* Lausanne: *EPFL- Pl- DII_E .*

Erklärung

Ich versichere hiermit wahrheitsgemäß, die Arbeit selbständig angefertigt, alle benutzten Hilfsmittel vollständig und genau angegeben und alles kenntlich gemacht zu haben, was aus Arbeiten anderer unverändert oder mit Abänderung entnommen wurde.

Thorsten Helms