INSTITUT FÜR
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THERMODYNAMIK
Institute for Energy Systems and Thermodynamics

DIPLOMARBEIT

Development and Simulation of an HVAC System for the St. Francis D'Assisi Hospital in Marial Lou, South Sudan

ausgeführt zum Zwecke der Erlangung des akademischen Grades
eines Diplom-Ingenieurs unter der Leitung von

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eingereicht an der

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Wien, 25. Oktober 2012 Michael Mischkot

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Abstract

This thesis focuses on the modelling and simulation of an energy self-sufficient building, which is planned to be built at a hospital site in Marial Lou, Warrap, South Sudan in early 2013. The single-storey building consists of 17 rooms, including the operating room of the hospital as the most important one. The modelling and simulation is implemented in TRNSYS©, a software tool used to simulate the performance of transient systems. First, variations of certain properties of the building structure, different target temperatures and load scenarios are simulated in a preliminary draft. After determining these parameters, a refined model based on the calculated electricity generation of the planned on-site photovoltaic power plant combined with a backup power source is simulated in-depth. Variations regarding e.g. the size of the photovoltaic power plant and the number of heat pumps used to cool water are included. In the end, the amount of energy that has to be provided by the backup system to ensure satisfying conditions in the building throughout the year is calculated.

Kurzfassung

Diese Diplomarbeit beschäftigt sich mit der Modellierung und Simulation eines energieautarken Gebäudes, dessen Errichtung für Anfang 2013 auf dem Areal des Krankenhauses in Marial Lou, Warrap, Südsudan geplant ist. Das eingeschossige Gebäude besteht aus 17 Räumen, deren Kern der Operationssaal bildet. Die Modellbildung und Simulation wird in TRNSYS©, einem Softwarepaket, das zur Simulation des Verhaltens instationärer Systeme dient, umgesetzt. Zuerst werden Variationen gewisser Parameter der Gebäudestruktur, verschiedene Zieltemperaturen und Lastszenarien in einem Vorentwurf simuliert. Nach der Festlegung dieser Parameter wird ein detailliertes Modell ausführlich simuliert, wobei die Stromproduktion des am Areal geplanten Photovoltaik-Kraftwerks in Kombination mit einer Backup-Stromversorgung berücksichtigt wird. In dieser Simulation wird außerdem die Größe des Photovoltaik-Kraftwerks und die Anzahl der Wärmepumpen zur Kaltwassererzeugung variiert. Zuletzt wird die Energiemenge berechnet, die durch das Backup-System bereitgestellt werden muss, um das ganze Jahr lang zufriedenstellende Verhältnisse im Gebäude zu gewährleisten.

Contents

1 Introduction

One essential commonality among all hospitals around the world is their indefatigable commitment to saving lives. Best standards are realised, most modern technology is used wherever possible and doctors urge the use of state of the art medicine and treatment methods. However, due to limitations of financial resources and infrastructure this noble mind cannot be put into practice in all areas of the world.
A new operating room is planned to be built at the hospital site in Marial Lou, Warrap, South Sudan in early 2013. Certain conditions of this project differ essentially from what the average engineer might expect when start planning an HVAC concept (heating, ventilation and air conditioning) for a hospital facility.

- Supply of clean water, electricity and fuel is not adequate or often even non-existent.
- The location is very outlying and the operating room in Marial Lou is the only one within 300 km. Furthermore, due to the wet seasons transportation of people and goods by both, air or road is practically impossible during several months per year.
- Education in South Sudan is in general very low. The system must be low-maintenance since technicians are hard to find.

Nevertheless, a reliable concept for heating, ventilation and air conditioning shall be realised at the given site. A comfortable climate in an operating room facilitates the operation for all parties involved. The process is less exhausting and the risk of wound infections due to drops of sweat is reduced significantly.

A brief overview of the requirements on the HVAC system is given below.

- The target temperature in the operating room is around 25°C.
- The energy supply shall be solar powered (self-sufficient). A cold water tank acts as the primary energy storage to reduce excessive loads and store surplus solar power.
- The operating hours of the backup electricity supply consisting of batteries and a diesel generator have to be minimized.
- The installation of energy-saving measures is a primary goal, as optimized shading, intelligent illumination, and energy-saving equipment can lower energy consumption significantly.
- European standards, especially regulations concerning hygiene and safety, shall be implemented as far as possible.

This project includes unusual challenges for the European engineer. Cooling technology will be put into operation in a place where it was never used before. The investigations in this thesis focus on the modelling and simulation of the system behaviour in order to facilitate a successful implementation.

2 Conditions

2.1 Location

The St. Francis D'Assisi Hospital is located in Marial Lou, Warrap, South Sudan (a detailed map can be found on the following page). At the location, the surrounding infrastructure is still in a great need of improvement.
During the wet season from May to October, overland travel is extremely difficult, even with 4x4 vehicles. Also air transport is heavily affected, since runways are often closed due to damages caused by heavy rains and floods.

South Sudan

Warrap is one of the 10 states of South Sudan and part of the historical Bahr el Ghazal region. Its most "prominent" neighbour is the region of Abyei to the north, which is currently heavily disputed between Sudan and South Sudan for many different reasons, among which its resources of crude oil may be mentioned as the economically most important one.

Figure 2.1: South Sudan [8]

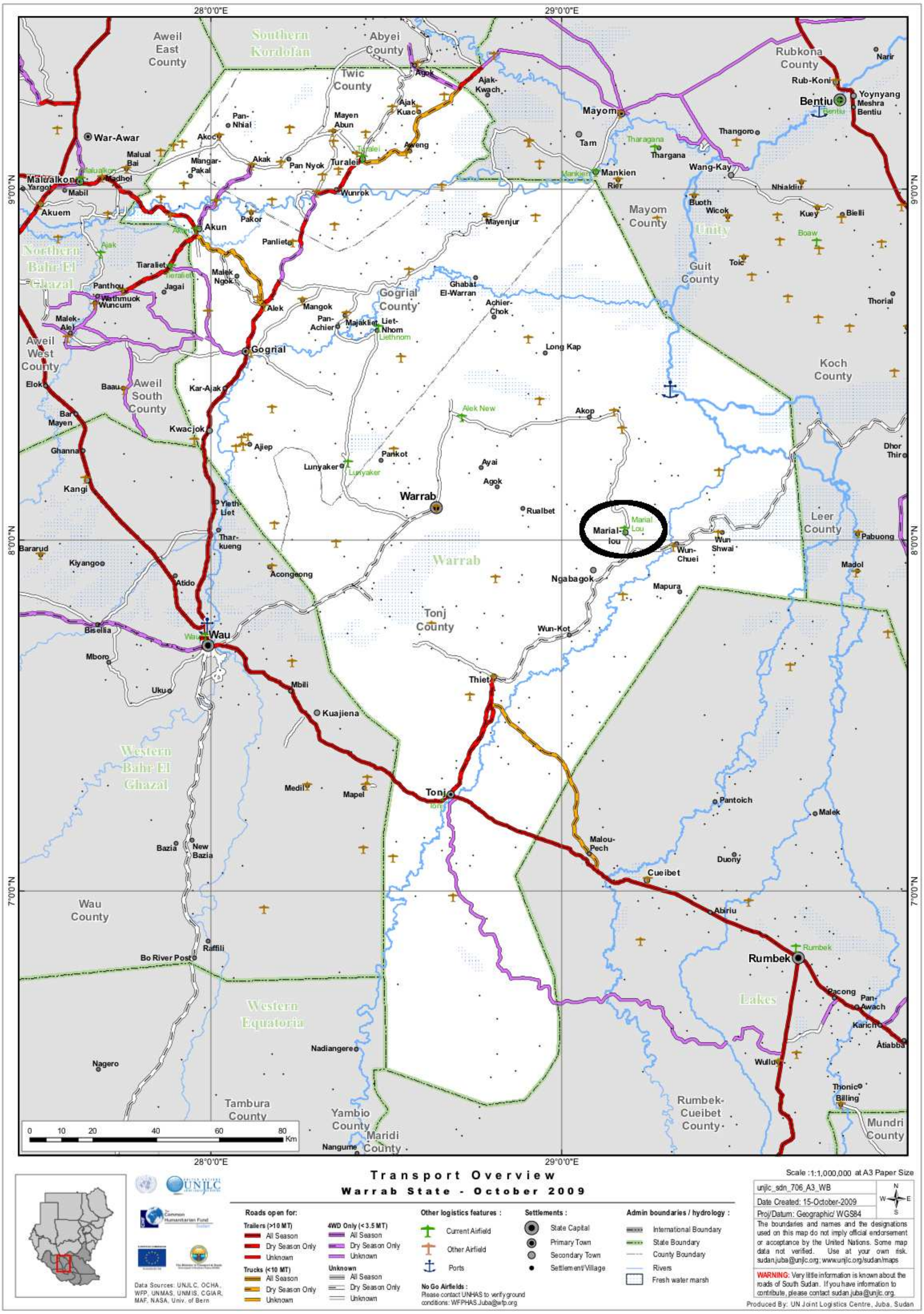

Figure 2.2: Warrap, South Sudan [12]

Referring to a map of the United Nations given in figure 2.2, the current state of the road to Marial Lou is unknown. Information about possible truck loads is not available either. Therefore, logistics have to be planned relying heavily on information from local residents.

2.2 Medical Conditions

In this subsection three operating rooms of different hospitals are analysed and compared.

Klinikum Karlsruhe, Karlsruhe, Germany

Figure 2.3: Hybrid Operating Room at Klinikum Karlsruhe, Germany [9]

The picture above shows a hybrid operating room at Klinikum Karlsruhe in Germany. In this operating room, surgeons can rely on newest technology and highest hygienic standards and are able to operate interdisciplinary. A comprehensive security system ensures among others a steady and reliable supply of electricity, clean air and medication. In comparison to standards at Marial Lou, the sterile environment in a modern hospital might even appear meticulously clean. Klinikum Karlsruhe includes 1 400 beds. 485 doctors and more than 4 000 people in total work at the hospital site. The annual budget is 270 million euros.[11]

St. Mary's Hospital Lacor, Gulu, Uganda

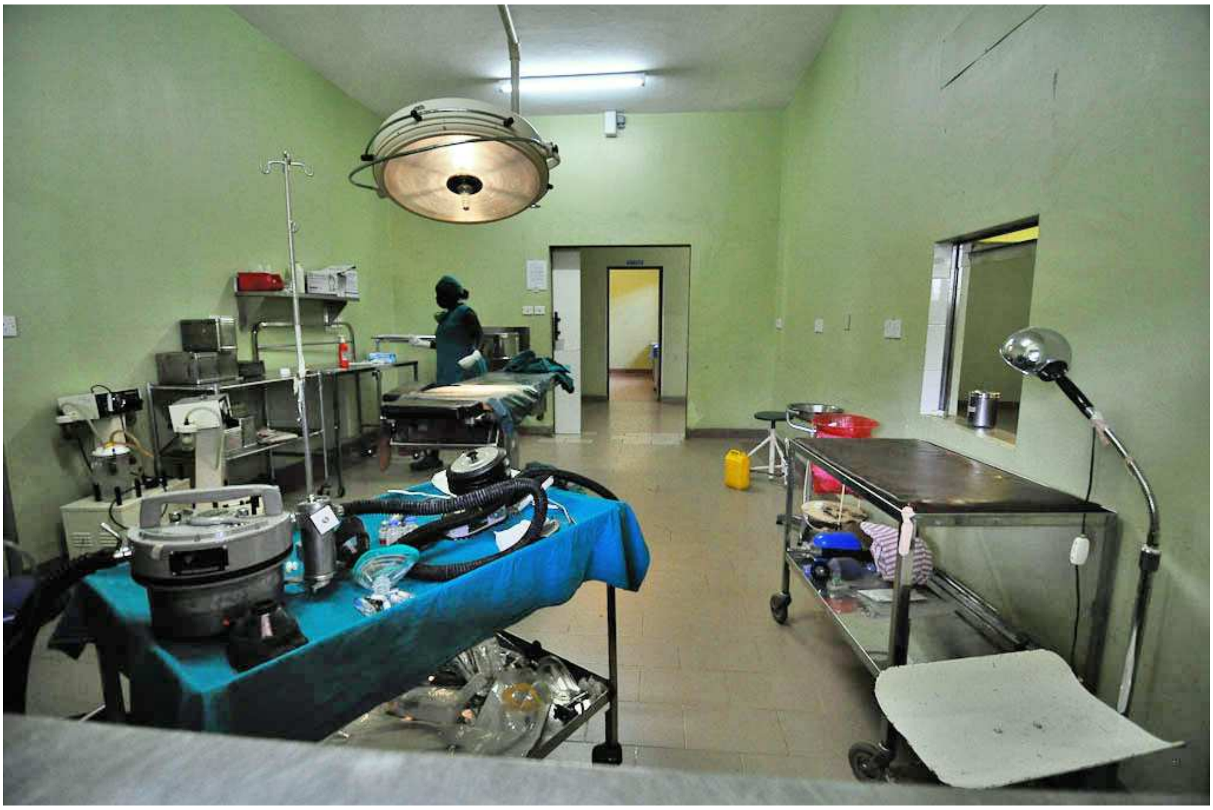

Figure 2.4: Operating Room at St. Mary's Hospital Lacor, Uganda ©Jano Rusnak

The St. Mary's Hospital Lacor in Gulu is among the best hospitals in northern Uganda. In this university clinic, the training of hospital staff and the implementation of new standards is part of the whole concept. One step includes e.g. the implementation of a controlled ventilation system above the operating area. St. Mary's Hospital Lacor has a capacity of 482 beds. Founded in 1959, more than 300 000 patients are treated every year, more than 50% of them children younger than six years old. Despite its size, the hospital has to rely on its own infrastructure, including a sewage treatment system and generators to provide electricity. The building structure consists of multi-storey buildings and includes concepts to ensure acceptable climatic conditions.[1]

St. Francis D'Assisi Hospital, Marial Lou, South Sudan

The field hospital close to Marial Lou was founded in 1997. The quality of the structure of existing buildings is mediocre to poor. The four different areas of the hospital include a total of 42 beds. Access to the hospital is difficult, especially during the wet season, since access roads are in very poor condition. The free space between the buildings is of high importance, since relatives of the patients live there while waiting for the patients to be dismissed.
The current operating room at the St. Francis D'Assisi Hospital has no air locks or controlled air conditioning. High temperatures due to the hot climate exacerbate the working conditions of the surgeons. Dropping sweat beads can cause severe infections of wounds and pose a risk for the patients' health. Also, the absence of a preperation room as well as a recovery room lead to difficulties before and after the actual operation.

Figure 2.5: Operating Room at St. Francis D'Assisi Hospital, South Sudan ©Jano Rusnak

2.3 Climate

Sudan is a tropical country with both a rainy and dry season. The average temperature in South Sudan is around 30°C throughout the year and varies with the rains. During the wet season from May to October, the rains can be extremely heavy.[4]
However, even then several hours of sunshine per day can be expected, which suggests the installation of photovoltaic power plants.

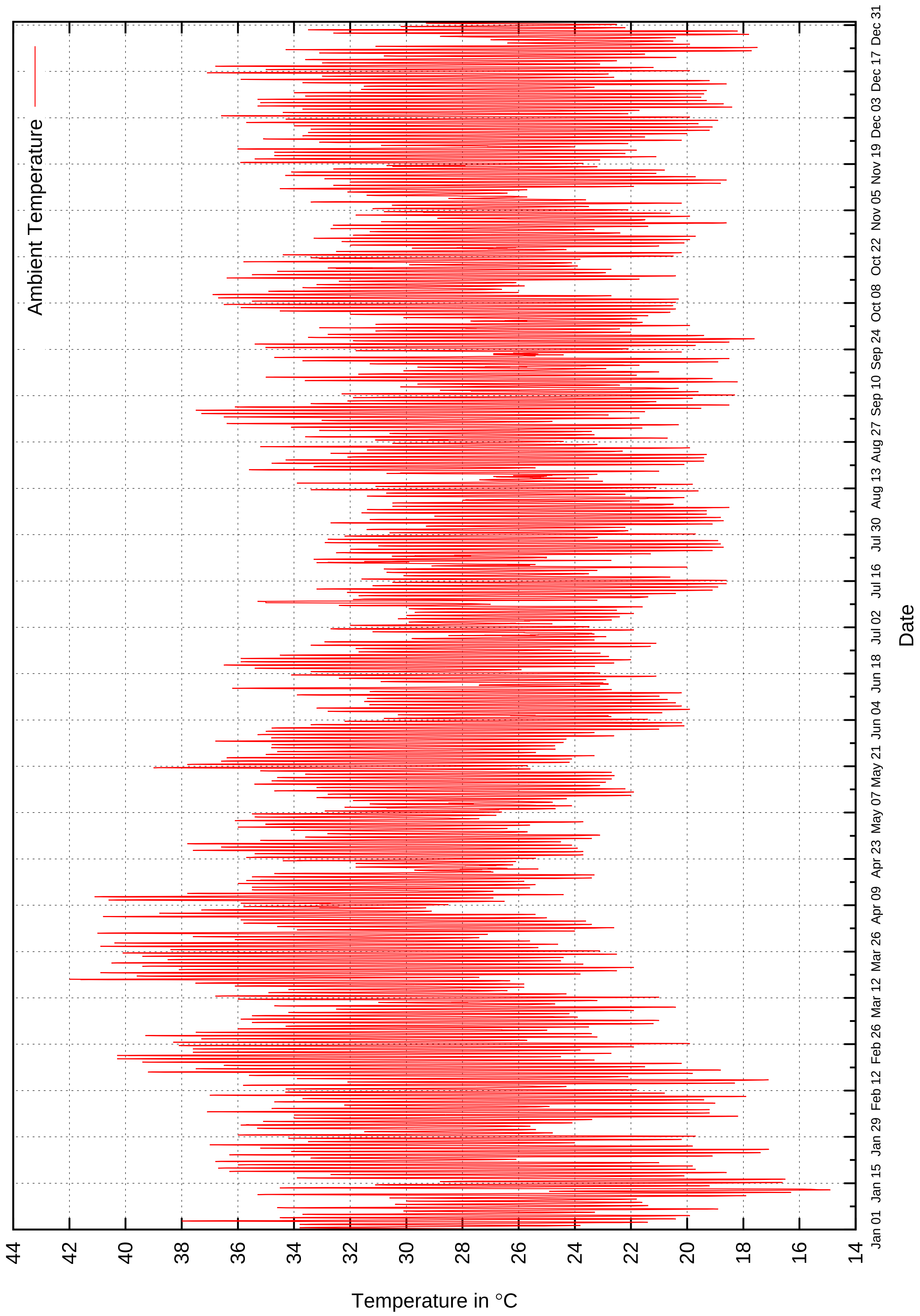

Figure 2.6: Ambient temperature in Wau, South Sudan, provided by ©Meteonorm, Bern

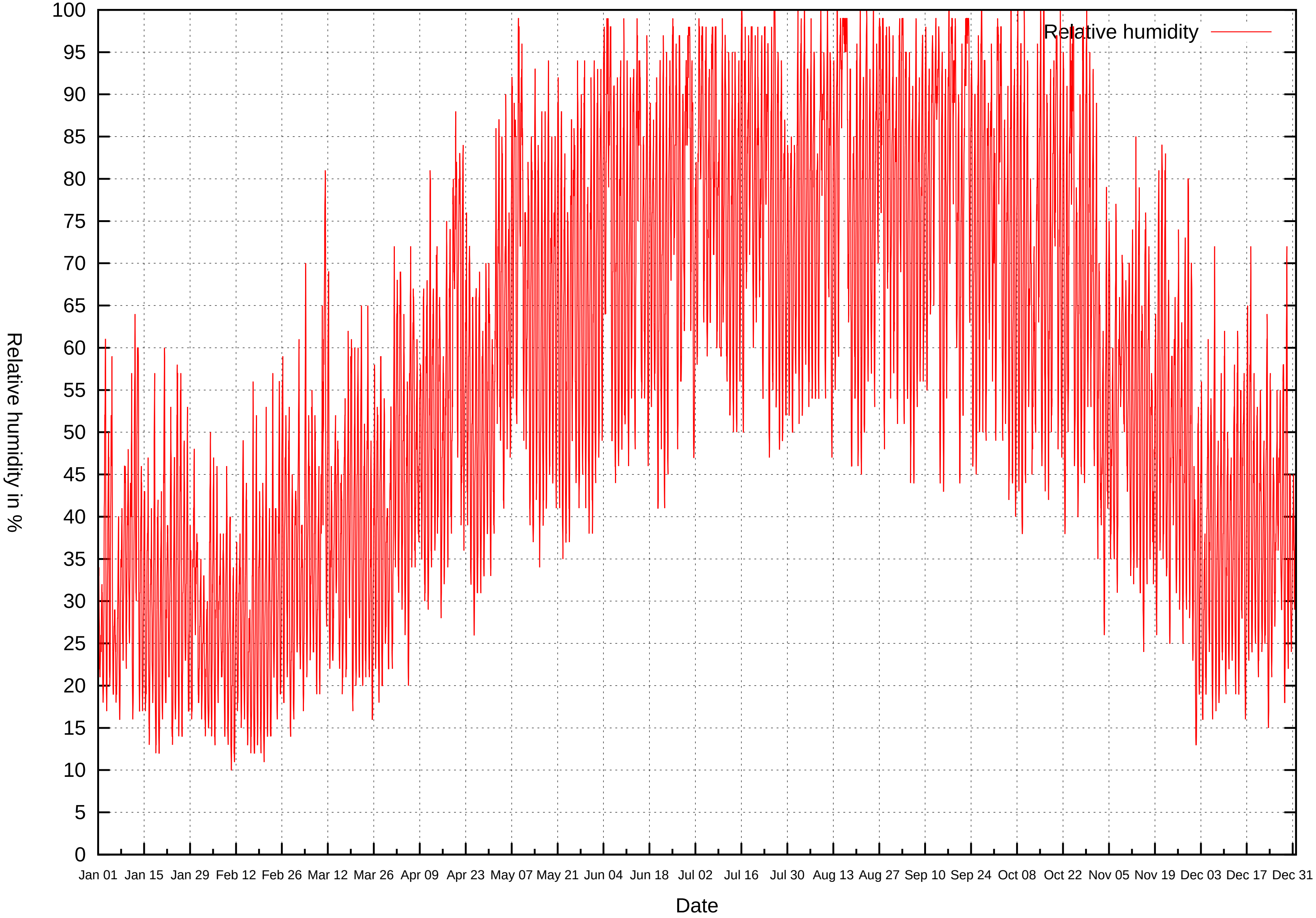

Figure 2.7: Relative humidity in Wau, South Sudan, provided by ©Meteonorm, Bern

2.4 Project Structure

The St. Francis D'Assisi Hospital in Marial Lou is operated by the non-government organisation "Arkangelo Ali Association" (AAA). The hospital was originally built by Médicins Sans Frontières (MSF). As a consequence of the peace agreement between North and South Sudan in 2005, MSF decided to hand it over to AAA. Today, the operating organisation AAA is supported by the Slovakian NGO "eRko" and the Austrian NGOs "Dreikönigsaktion" (DKA) and "Beschaffungsbetrieb der Missions-Verkehrs-Arbeitsgemeinschaft" (BBM). The project is financed by the German NGO "Misereor".

Figure 2.8: Involved Organisations

Figure 2.9: Houses in Marial Lou ©Jesko von Jeney

3 Requirements

3.1 Layout

Hospital Site

Two maps including the old and new buildings at the hospital site are given on pages 18 and 19. The building analysed in this thesis is highlighted in orange in figure 3.2.

Operating Room

Figure 3.3 on page 20 shows a detailed layout of the building containing the operating room. It consists of 17 rooms with a total area of 196.48m². In the operating room, two surgeries can be performed at the same time. The installation room in the center of the building will host the cold water tank as well as other technical equipment. The sterilization room is located at a corner of the building to avoid other areas of the building to be overly affected by the heat emitted by the autoclave.

A well planned layout of this building is essential for the usability of the whole system. Three separated circuits for patients, medical staff and surgical instruments have been developed by the architect Jesko von Jeney.

- **Patients:** Reception → Preparation Room → Operation Theatre → Recovery Room → Exit Room
- **Medical Staff:** Dressing Room → Staff Room → Transfer Room → Operation Theatre → Transfer Room → Staff Room → Dressing Room
- **Surgical Instruments:** Operation Theatre → Wash Up Room → Sterilization → Packing Room → Operation Theatre

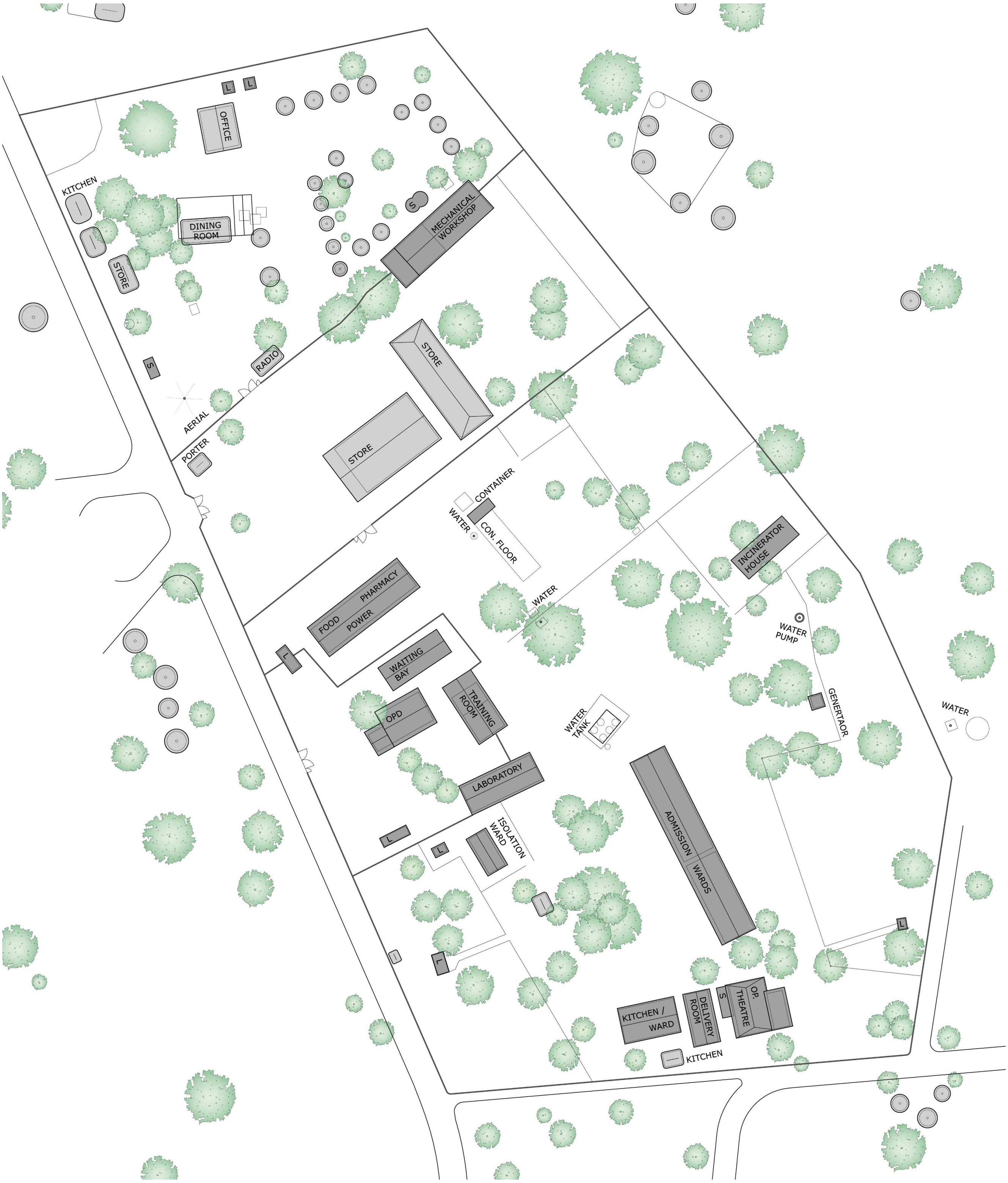

Figure 3.1: Map of the old hospital buildings ©Jesko von Jeney

Figure 3.2: Map of the new hospital buildings ©Jesko von Jeney

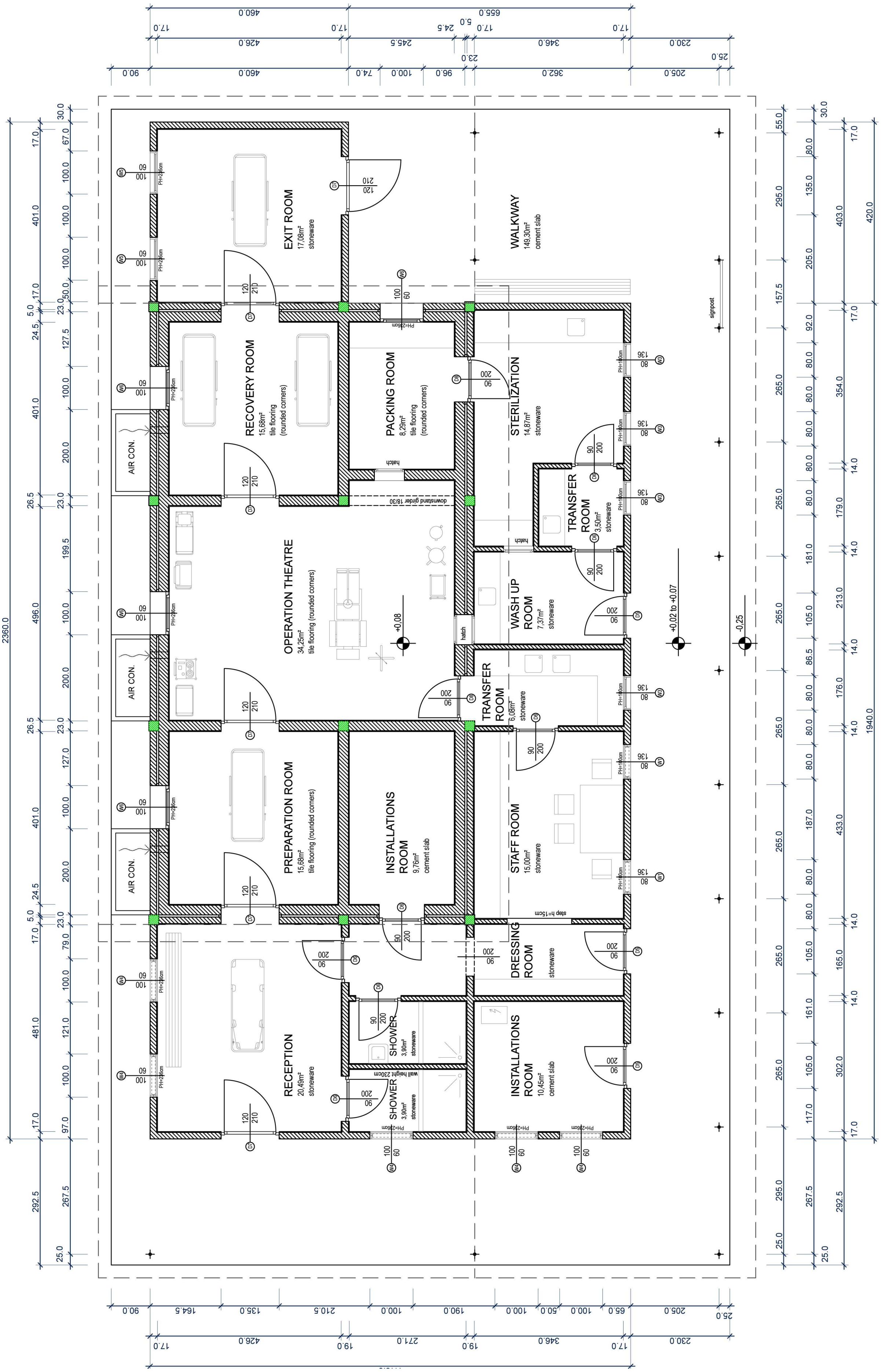

Figure 3.3: Floor plan

3.2 Walls

Three different types of bricks will be used in the construction of the building. All three of them are imported from a company in Uganda. For the implementation in TRNSYS, technical data from the brick manufacturer has been used to calculate the necessary parameters to ensure a high quality of the simulation.

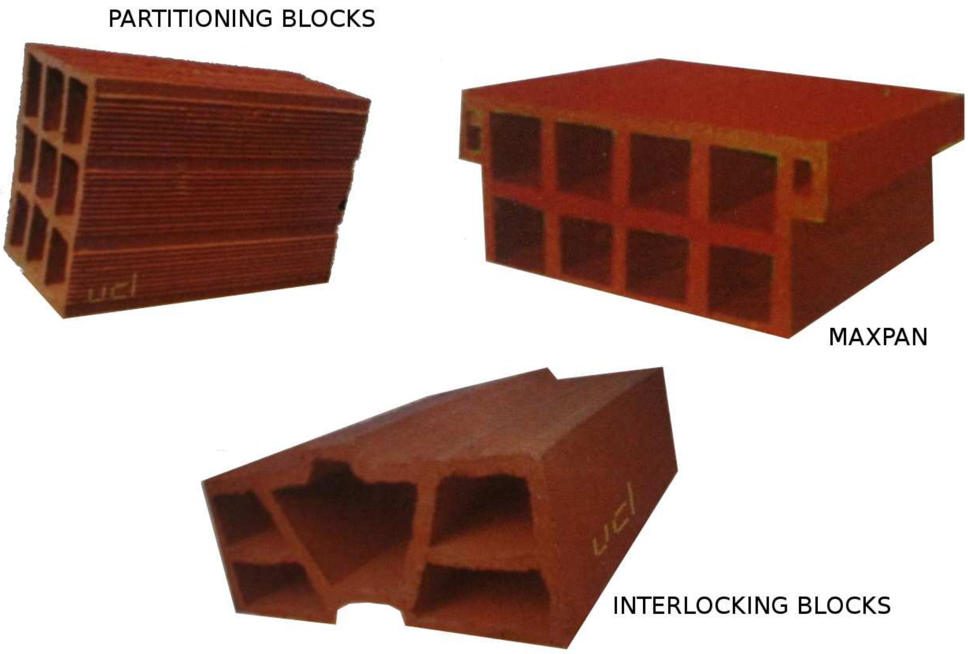

Figure 3.4: Types of bricks used to build the operating room ©Uganda Clays Ltd

Room height

The room height of the cooled area is set to 2.92 m. This is necessary to enable the use of medical equipment like surgical lights. Above the ceiling of the cooled area, another zone with 0.47 m height will be built to enable the installation of building services, MEP (mechanical, electrical and plumbing) and HVAC (heating, ventilation and air conditioning).
The room height of the unchilled area is set to 2.65 m.

3.3 Windows

Three different kinds of windows will be installed. First, an ordinary single layer window in two different sizes (80 cm / 136 cm and 100 cm / 60 cm). Second, a double layer isolation window. Third, a louver glass window is used to enable a high air change rate in the uncooled Zone A[1] without the use of electrically driven fans or ventilators. The isolation windows will be imported from Austria, as up till now double glazing is not standard technology in South Sudan.

[1]for details about zone segmentation, see figure 6.1 and figure 6.18

Figure 3.5: Louver glass window ©Jesko von Jeney

3.4 Roof

A sketch of the roof structure can be seen in figure 3.6. The roof structure is designed to facilitate the air flow underneath the roof. Great care is taken to ensure a high air change rate, since vent holes in ordinary brick buildings in South Sudan are often too small. During the day, the temperature of the air underneath the roof is rising very fast. The heat is transferred to the living area below which can lead to unbearable climatic conditions inside the building. Avoiding this scenario is a major priority in order to reduce energy consumption for cooling.

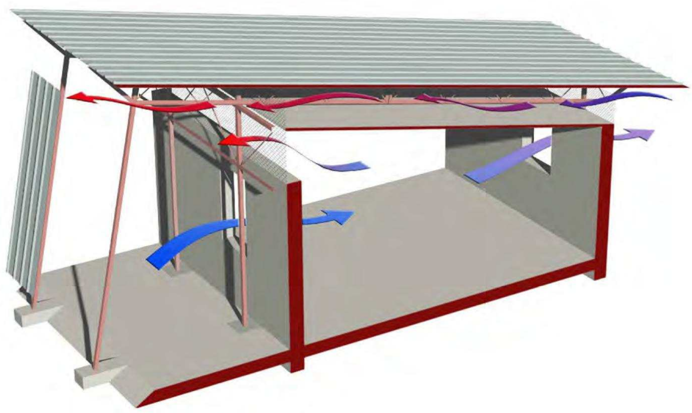

Figure 3.6: Possible air flow scenario in the building [14]

3.5 Medical Requirements

When designing a hospital in Europe, almost every little detail is predefined by regulations and standards. In the case of the Marial Lou Hospital, certain compromises must be made due to the extraordinary circumstances given in Chapter 2. For this operating room, the Austrian standard "ÖNORM H 6020" is considered as far as possible. Nevertheless, certain guidelines had to be adapted to obtain a high standard solution which is still feasible. This part was elaborated together with Dr. Marek Ďuriš, a Slovakian doctor who worked at the Marial Lou Hospital several months per year from 2002 to 2010.

The most critical deviations from the ÖNORM standard are listed below.

- Like in similar hospitals in South Sudan (e.g. Mapourdit), a **window** will be installed close to the ceiling of the operating room. Although this would certainly not be tolerated in any Austrian hospital due to hygiene requirements, it is truly necessary at the Marial Lou site since electricity and consequently illumination cannot be guaranteed all the time. For hygienic reasons, this window must be opened in emergencies only.
- The **target temperature** during operation of the air conditioning system will be set to **24-25°C**. This rather high temperature level will not only reduce energy consumption but also ensures that patients will not experience thermal shocks when being transferred to the ward soon after the surgery. In Europe, patients usually stay in the recovery room for up to 2 hours. Due to shortage of space, patients in Marial Lou can stay in the recovery room only for about 5 minutes. The actual recovery takes place afterwards in the ward, which is located in a different building so that, during transfer, patients are fully exposed to the environment soon after the surgery.
- **Air filtration** is of particular importance for the effective operation of a hospital. State of the art are High-Efficiency Particulate Air filters (HEPA, H13 and finer)[2]. In Marial Lou, coarser filters will be used for economic reasons.

Operating Room - Particular Requirements

Certain circumstances and regulations make air conditioning of an operating room more difficult than climitisation of usual buildings. Among them are:

- Only fresh air must enter the operating room (OR) and must not be used afterwards due to hygienic reasons.
- The temperature-humidity environment has to be controlled and kept within strict boundaries.
- All surfaces have to be easy to clean.
- The air has to be especially filtered.
- The OR has to be kept slightly pressurized to prevent air from entering from adjacent rooms.

[2]ÖNORM EN 779 and ÖNORM EN 1822-1

- The air must flow practically without turbulences from the ceiling to the floor (see figure 3.7).
- etc. (see e.g. ÖNORM H6020)

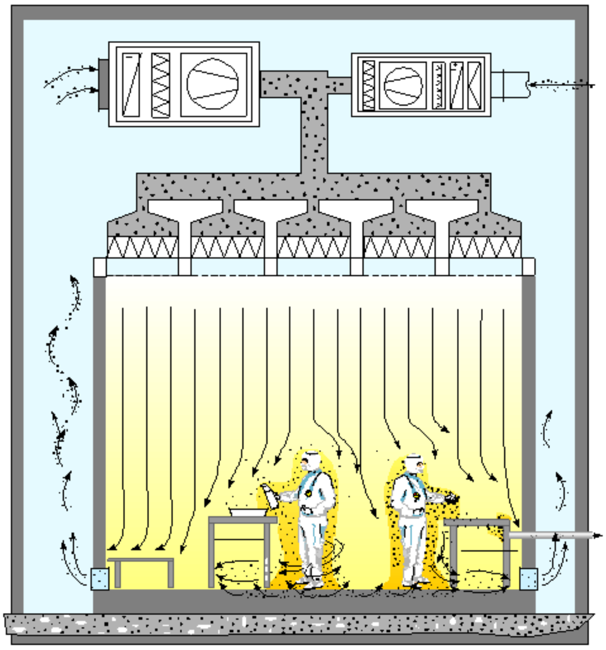

Figure 3.7: Laminar flow in a cleanroom [10]

However, due to cost restrictions and lack of infrastructure and equipment at the hospital site, it will not be possible to meet all European standards.

4 Energy Supply

Energy supply for a hospital site at such an outlying location is a particular challenge for the hospital operator. Usually, this is done by installing an appropriate diesel generator. However, although crude oil is extracted from the ground relatively close to Marial Lou, diesel supply is very difficult to accomplish, expensive and not reliable during most of the time. As a consequence, possible alternatives are discussed in this chapter, including the feasibility of different energy saving measures and the analysis of several energy storage systems.

4.1 Energy Production

4.1.1 Diesel Generator

Due to a lack of infrastructure, military conflicts in the area and a diesel price even higher than in Europe no reliable fuel supply is existing at Marial Lou at the moment. Therefore, the diesel generator at the hospital site should not be used more often than necessary. The diesel generator acts as a backup when no solar power is available and all other energy storages are depleted. The minimization of the operating hours of the diesel generator is among the primary goals of this diploma thesis and is treated in chapters 7 and 9.

4.1.2 Solar Energy

The probably most obvious way to produce energy in Africa is solar energy. Figure 4.1 shows that in Marial Lou an average irradiation of around 2 200 kWh/m^2 per year can be expected.

Solar Cooling

There are many ways to use the power of the sun. Especially for solar air conditioning the range of possibilities is very large, as can be seen in figure 4.2.

The most common solar cooling techniques have been analysed with focus on their ability to meet the needs of a well-adapted air conditioning unit for the operating room. However, certain circumstances like the remoteness of the site from any infrastructure make it difficult to suggest the installation of a solar thermal refrigeration system. The use of relatively new technology like solar thermal refrigeration contains the risk of long standstills due to unforeseen problems, which could eventually not be solved even within weeks or months due to bad road conditions and the absence of maintenance staff and/or spare parts. This might even lead to significant harm for patients as an adequate temperature in the operating room is crucial for hygienic surgery and wound healing shortly after the intervention. As a consequence, solar thermal refrigeration will not be used in Marial Lou.

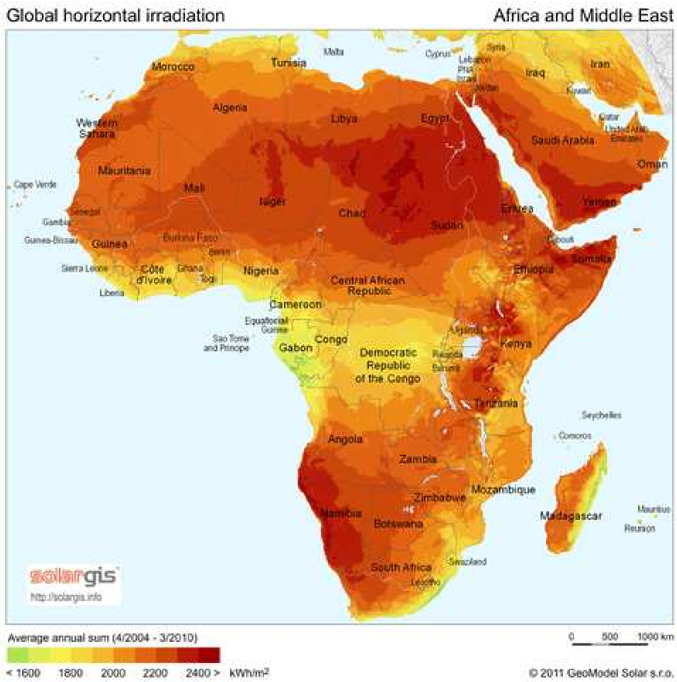

Figure 4.1: Global Horizontal Irradiation for Africha and Middle East, SolarGIS 2011 ©2011 GeoModel Solar s.r.o.

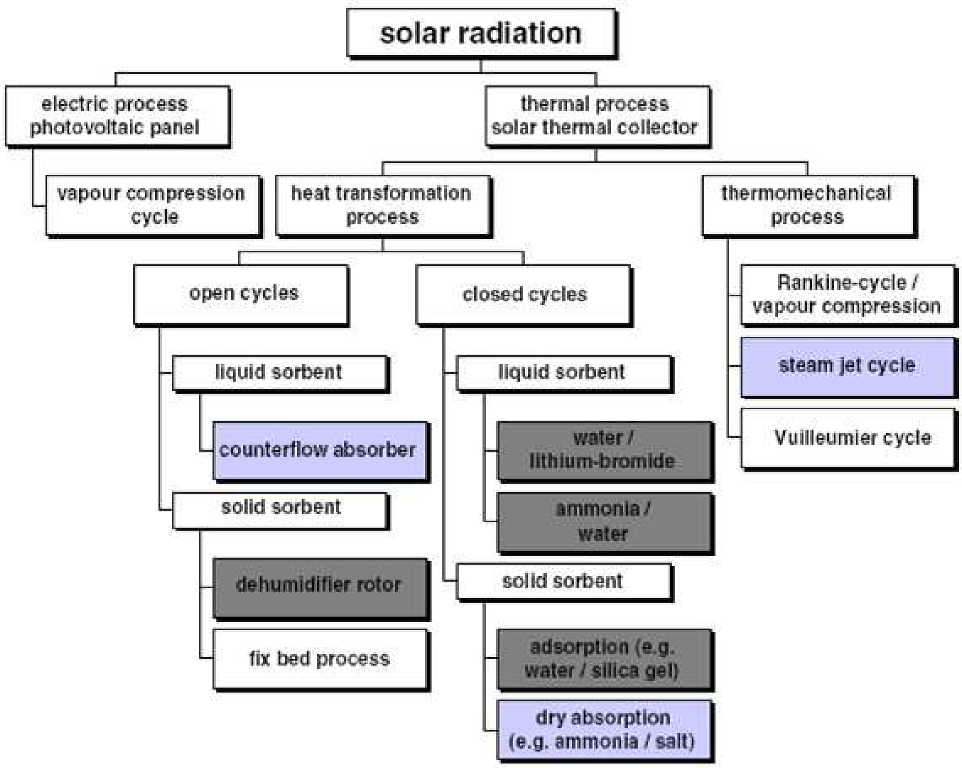

Figure 4.2: Different ways to use solar radiation for air conditioning [5]

Solar Electric Energy

Since prices for photovoltaic modules have been dropping very fast in the last years, a rather large photovoltaic power plant will be operated to generate electricity at the hospital site. The goal is to produce almost all electricity needed at the campus from solar power. The modules will be installed at the roofs of the hospital buildings as well as on the ground. Difficulties might arise from sand polluting and damaging the glass covering the modules.
The photovoltaic modules are chosen from a company with experience in remote areas. The specifications are depicted below.

All technical data at standard test conditions[1]:
Air mass $AM = 1.5$, solar radiation $E = 1\,000\,\mathrm{W/m^2}$, cell temperature: 25 °C

Peak power	*Pmax*	W	120
Tolerance		%	+3/-3
Max. power current	*Imp*	A	7.0
Max. power voltage	*Vmp*	V	17.1
Short circuit current	*Isc*	A	7.7
Open circuit voltage	*Voc*	V	21.8
Temperature coefficient for Pmax		%/°C	-0.50
Temperature coefficient for Voc		%/°C	-0.35
Temperature coefficient for Isc		%/°C	0.09
Max. system voltage		V	1 000

Table 4.1: Electrical data of the LC120-12P PV module ©Lorentz[3]

Solar Thermal Energy

The use of solar thermal energy to supply hot water at the hospital site is a very reasonable decision. Contrary to that, the use of solar thermal power for solar cooling is not recommendable, as can be seen further up in this section.

4.1.3 Others (Biomass, Hydro Power, Wind Energy)

Biomass

Biomass is among the primary energy sources used in South Sudan. Due to this fact, local biomass resources are depleted very fast. Still, the use of biomass remains at an unsustainable level, since almost no alternatives are available for local residents. As a consequence, the use of biomass for energy production for the hospital campus is not taken into consideration.

Hydro Power

The lack of mountains close to the hospital and the absence of any electrical grid inhibit the use of hydro power for electricity generation. The area is mainly flat and hydro power

[1] For example, in South Sudan the power generated by one module can easily exceed its peak power (120 W).

plants using the water of the Nile and its tributaries can only be found further down the river.

Wind Energy

Large scale wind power has not been installed in South Sudan until now. Again, a reliable electrical grid is essential for the installation of large wind power plants.
Small scale wind power does not seem to be a satisfying solution for electricity generation due to low wind speeds in the area. Also, in comparison to solar power wind power is rather a high-maintenance technology, which can make the operation difficult at the given site.

4.2 Energy Saving Measures

4.2.1 Shading

Trees represent the easiest and most obvious possibility to realise shadowing for surrounding buildings. In the design of the new hospital campus, the preservation of existing trees is a high priority. Nevertheless, trees are not considered in the TRNSYS simulation, since no reliable data about the trees and its leaves is available. Still, any positive effect on the indoor temperature and/or the energy consumption for cooling is welcome.
A large **fabric roof** over the building hosting the operating room or even the whole campus might be an interesting concept to develop. However, no such plan is pursued as a realistic solution.
Generously **extended roofs** will be implemented, leading to a reduced irradiation on the walls of the building. In addition to that, the sheltered ground beneath the walls can be used as additional storage area protected from the rain.

4.2.2 Ventilation

Owing to the louver glass windows installed in most parts of Zone A, a high air change rate can be achieved by natural ventilation. Also during the night, the louver glass will be tilted open to facilitate the influx of cooler air from outside. Still, air temperature does not fall significantly during the night due to climatic conditions.
However, no such ventilation is possible in Zone B (Zone B1, Zone OP and Zone B2) for hygienic reasons. Windows in this area must only be opened in case of emergency after a breakdown of the cooling system.

4.2.3 Illumination

Illumination will be based on energy saving technology like fluorescent tubes, energy saving lightbulbs or light emitting diodes. Especially for the operating light, the use of most modern LEDs is recommendable since the heat emitted by the lamp is directly affecting the heads of the medical staff at the operating table.
Windows will enable sunlight to enter the building, which facilitates illumination but leads to a higher cooling load. In Zone B (Zone B1, Zone OP and Zone B2), windows will be installed close to the roof to protect the patient's privacy.

4.2.4 Others (Ground Heat Pump, Evaporative Cooling)

Ground Heat Pump

Both soil and ground water are usually too hot for the use of ground source heat pumps. As a consequence, this option is not developed further in the project.

Evaporative Cooling

Like in many African regions, water is a scarce resource in South Sudan. Therefore, evaporative cooling is not an option at the given site.

4.3 Energy Storage

4.3.1 Storage Demand

Reasons for the installation of an energy storage system are the following:

- In general, one main advantage of the use of solar power for cooling is the coincidence of solar irradiation and cooling demand. Still, there remains a shift of about 1-2 hours between both peaks due to thermal inertia of the building.
- Shortages of solar radiation due to heavy clouds during some few days in the wet season
- Load patterns that do not follow the supply curve (e.g. constant internal loads if the operating room is used all day long)

Usually, a seasonal heat store or an additional energy supply must compensate for interseasonal variations in the supply of solar power. However, in South Sudan, even during the wet season several hours of sunshine a day provide enough energy for high yields of solar collectors.

The following different forms of energy will be stored at the hospital:

- **Electrical energy** for e.g. machines (heat pumps), illumination and building services
- **Thermal energy below ambient temperature** to supply the thermally activated building systems (TABS)
- **Thermal energy above ambient temperature** for reheating the air in the air handling unit (AHU) after dehumidification

The three options to store energy in Marial Lou are covered below.

4.3.2 Batteries

The batteries installed at the hospital campus store electrical energy generated in the photovoltaic power plant. If the state of charge of the batteries drops below a predefined level, a diesel generator is started to supply the consumers instead.
Unfortunately, disadvantages of batteries include high costs and short lifetime. As a

consequence, the use of batteries shall be reduced to a minimum.
In the TRNSYS simulation, the system behaviour of batteries and diesel generator is not analysed, since the electricity demand of the other buildings at the campus is unknown.

4.3.3 Hot Water Storage

The hot water tank is used to absorb thermal energy above ambient temperature generated by the heat pump described in section 5.5.1 and has a capacity of 1.5 m^3. The temperature of the hot water should be rather low, for a higher temperature in the hot water tank leads to a lower efficiency of the heat pump. As a consequence, the water in the hot water storage will be cooled in a dry cooling tower. It is expected that the tower can cool 1 500 kg/hr to 5 K above ambient temperature.

Hot Water for Hot Water Demands

Hot water demands include e.g. reheating the air in the AHU after dehumidification, doing the laundry or preheating water used for the sterilisation of surgical instruments. If the hot water supply by the heat pumps is not sufficient to cover these demands, separate solar thermal collectors can be installed easily. The calculation of these collectors is not part of this diploma thesis.

4.3.4 Cold Water / Ice Storage

Thermal energy below ambient temperature level can be stored in a cold water tank or in an ice storage. A brief overview of the advantages and disadvantages of a cold water storage is given below.

Cold Water Storage

Advantages	**Disadvantages**
The temperature gap "water - surrounding air" is smaller than in hot water storages, leading to lower heat losses for the same insulation.	As a result of the small temperature gap, the storage capacity is rather low.
Depending on the COP of the chiller, the amount of energy to be stored can be lower than for hot water storages.	Condensed water on tank walls or pipe connections has to be drained.

Table 4.2: Advantages and Disadvantages of Cold Water Storages [6]

In Marial Lou, a cold water tank with a volume of V_{cwt}=5m^3 will be installed. In this simple assessment, we expect the water temperature to fluctuate between 5°C and 15°C ($\Delta\theta$=10 K). Taking into account the heat capacity of water c_p and the density of water ρ leads to an energy storage capacity $Q_{thermal}$ of:

$$Q_{thermal} = V_{cwt}\rho c_p \Delta\theta = \frac{5\text{m}^3 \cdot 1000\,{}^{\text{kg}}\!/\!_{\text{m}^3} \cdot 4.18\,{}^{\text{kJ}}\!/\!_{\text{kgK}} \cdot 10\text{K}}{3600\,{}^{\text{s}}\!/\!_{\text{h}}} = 58.06\text{kWh} \tag{4.1}$$

In comparison to common battery capacities, the storage capacity is, although representing thermal instead of electrical energy, pretty large. Even if a heat pump COP of around 3 is taken into account, the cold water tank can theoretically replace nearly 20 kWh_{el}. It can therefore be recommendable to reduce the battery capacity in favour of a larger cold water tank.
The cold water tank will be planted close to the operating room in the center of the building. Thereby, "losses" (heat transferred from the surrounding to the cold water) result in further cooling of the building.

Ice Storage

For the use of ice storage the refrigeration equipment must be able to cool below 0°C, which is generally not the case. On the plus side, an additional cooling capacity of 335 kJ/kg is added due to the latent heat of fusion of water, thereby leading to a very compact storage size (10-20% in comparison to a comparable cold water tank [6]). Also, higher dehumidification can be achieved. However, for simplicity reasons this concept will not be pursued at the hospital site.

5 TRNSYS Simulation - Modelling

TRNSYS is a simulation environment for the simulation of transient systems, including multi-zone buildings. In the simulation studio, a project is set up by connecting components (types) graphically. Each type is described by a mathematical model in the TRNSYS simulation engine. Connections between types enable the transfer of information (physical quantities, signals, parameters - see figure 5.5). More detailed information can be found in [2].
An overview of the most important types (components) used in this simulation is given below.

5.1 Climate Data

The climate data is provided by ©Meteonorm, Bern, Switzerland. The data provides hourly values of a typical year and includes beam radiation, diffuse radiation, ambient temperature as well as wind speed and relative humidity at the station in Wau, WMO Nr. 628800, coordinates (longitude: 7.7°, latitude: 28.017°). The weather station in Wau is located about 140 km from Marial Lou and is the closest one to the hospital site.
In TRNSYS, the climate data is read by type 109, which processes the data to obtain tilted surface radiation and the angle of incidence for all surfaces used in the respective TRNSYS project.

5.2 Building Shell

The building shell is represented in the building component 56a and can be edited by using the software ©TRNBuild. The building can be divided into up to 25 thermal zones. In addition to that, the impact of shading is calculated in type 34.

5.2.1 Walls

Walls are a compound of different layers of different materials and thickness. For calculating the overall heat transfer coefficient U (U-value), at least heat capacity, heat conductivity and density of each material are needed. For the bricks, these parameters are provided by the manufacturer ©Uganda Clays Ltd.
Walls representing borders between TRNSYS zones are considered as adjacent walls. Further walls inside the TRNSYS zone can be added as internal walls. However, in this simulation walls inside the different TRNSYS zones are taken into account in the cooled area only, since the heat capacity of the thin walls of the unchilled zones can be neglected. Additionally, the data of external walls can be entered.

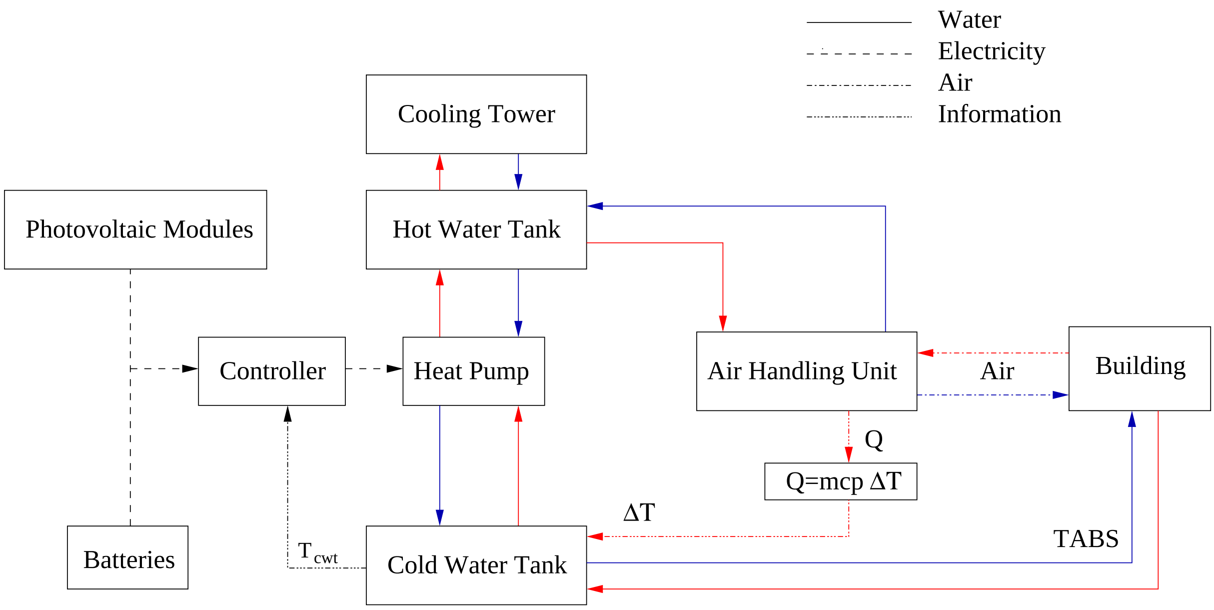

Figure 5.1: Block diagram of the TRNSYS modelling

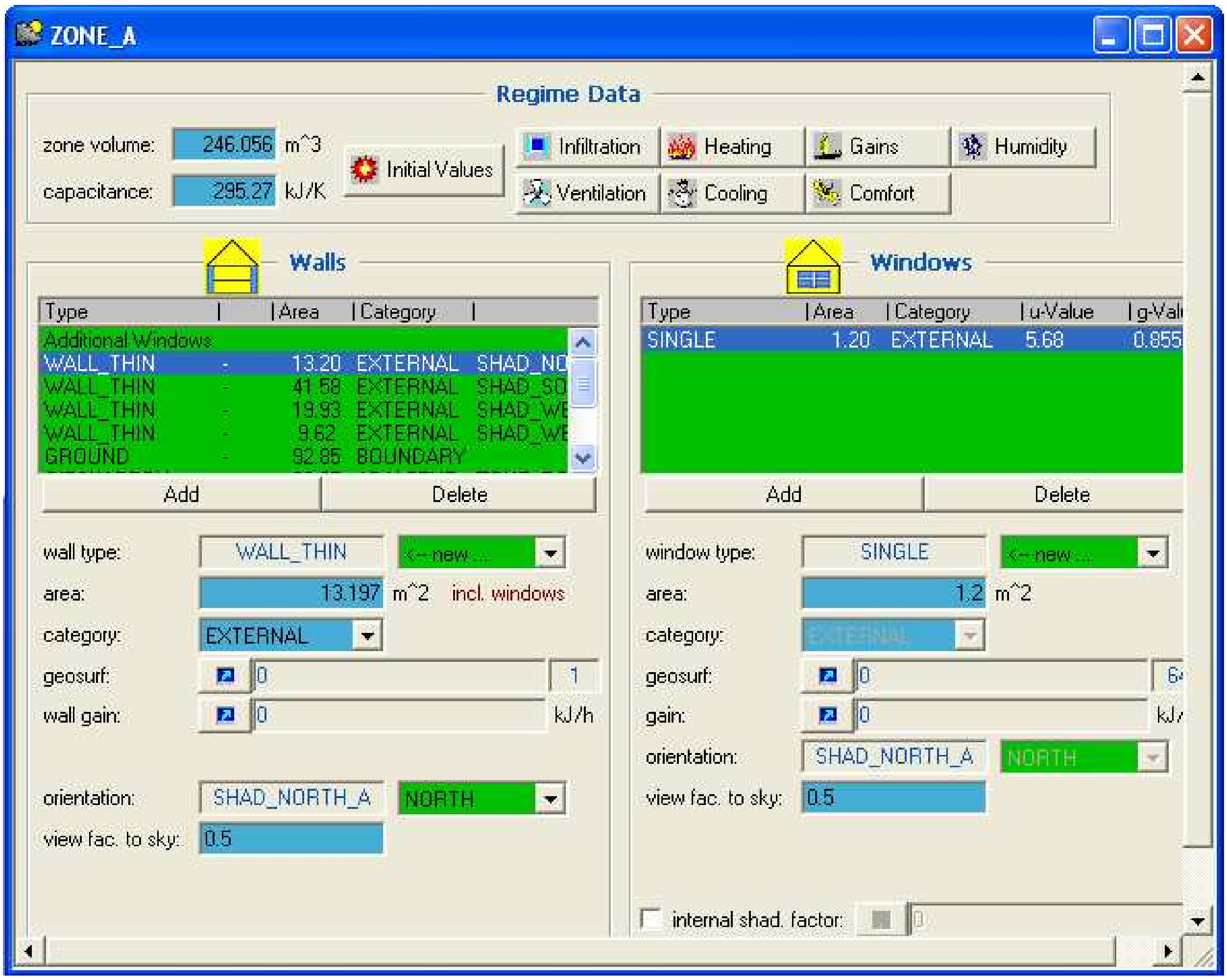

Figure 5.2: Modelling of the building in ©TRNBuild

5.2.2 Windows

Since the actual windows are not yet chosen, standard windows from the TRNSYS library are used in the simulation.

- Single layer window: $U = 5.68\,\mathrm{W/m^2K}$, area frame/window = 0.15
- Double layer isolation window: $U = 1.4\,\mathrm{W/m^2K}$, area frame/window = 0.2
- Louver glass window: represented by a single layer window combined with an air change rate[1] of $8\,\mathrm{1/h}$

5.2.3 Roof and Ground

The **roof** made of corrugated iron is represented as two different parts above the cooled and the uncooled zone, respectively, in agreement with the actual realisation.
As no reliable data about the **ground** is available, the default ground properties are taken. Among others, they include a floor, stone as well as concrete and a final insulation.

5.2.4 Shading

Type 34 takes into account the extended roof and calculates the resulting incident diffuse radiation on the walls assuming an isotropic sky model. The average total solar radiation (beam + sky diffuse + ground reflected diffuse) and the average beam radiation for all affected surfaces are passed on to type 56.

5.3 Infiltration and Ventilation

In type 56 (building), "Infiltration" and "Ventilation" represent two ways to model air flowing in and out of the building.

Infiltration

The following phenomena are modelled as infiltration (air change rate):

- Air changes in the cooled area due to a slight overpressure for hygienic reasons and air transfer when doors are opened
- Natural ventilation in the uncooled area due to louver glass windows tilted to open position

Ventilation

"Ventilation" represents the cooled air blown into the operating room. Type 334 (air handling unit - AHU) is passing the necessary data to type 56 (building). A detailed overview is given in chapter 5.5.3.

[1] Air change rate: how many times the air within the defined zone is replaced

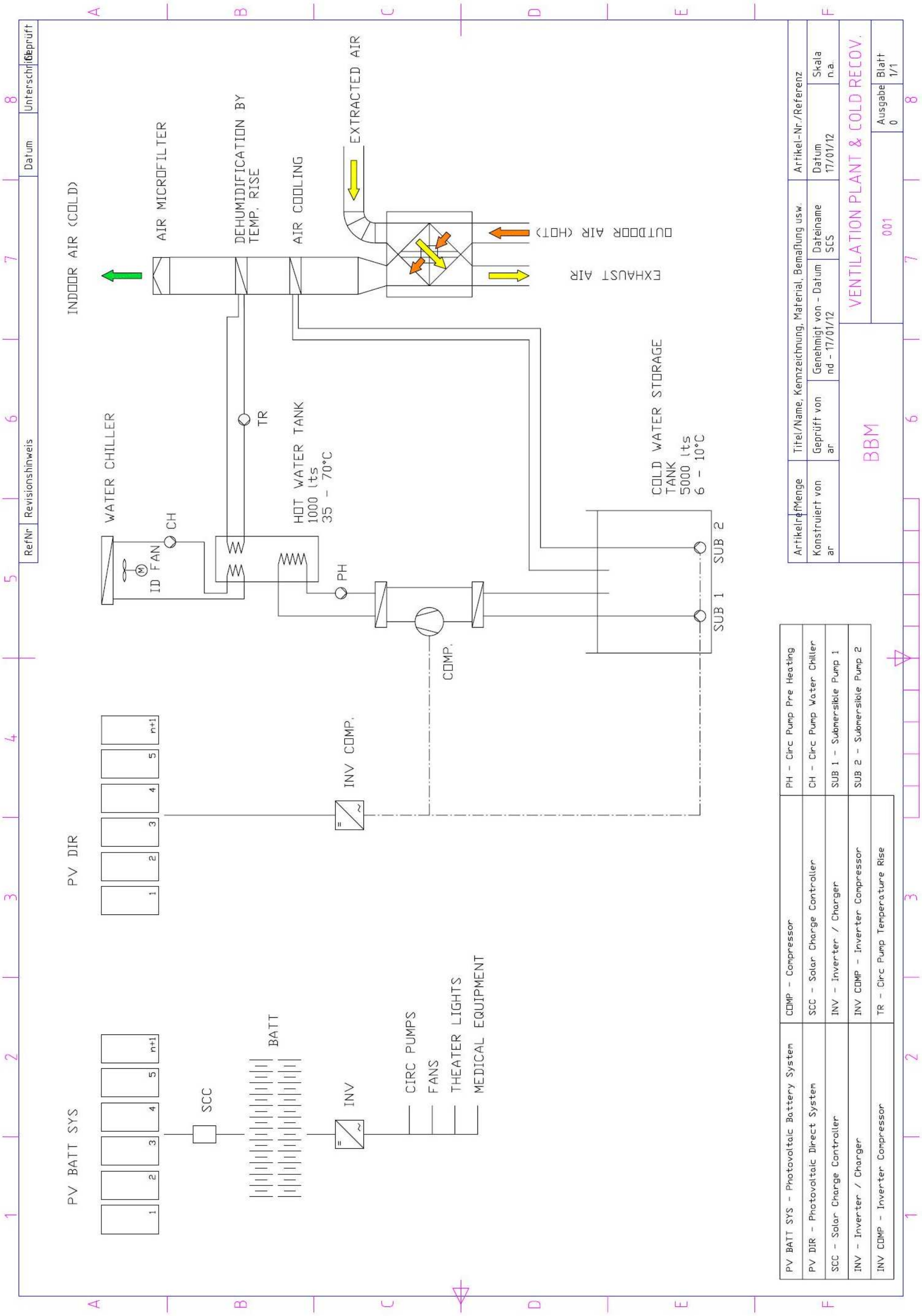

Figure 5.3: Simplified overview of ventilation

5.4 Internal Gains

Internal gains of the building include heat emitted by humans, illumination and machines as well as humidity emitted by humans. The emitted heat consists of a convective and a radiative part. Heat transfer due to heat conduction is neglected.

Humans

Data about heat emission of humans and illumination can be found in VDI 2078[13]. It is found that for a room temperature of 25°C a single person emits 115 W in total, consisting of 75 W sensible heat and 40 W latent heat. For calculating the influence of human water evaporation on the humidity level of the building, TRNSYS demands the total amount of water emitted, which is about 60 grams of water per hour per person.

Illumination

Regarding illumination, the use of energy saving lightbulbs like fluorescent lamps is highly recommended. In Zone A (see figure 6.1), heat emission from illumination is expected to be around $10\,\mathrm{W/m^2}$, since many windows enable a relatively high penetration of daylight. In Zone B, windows are highly restricted and only installed close to the ceiling to enable a minimum amount of daylight to illuminate the operating room when no electricity can be provided. As a consequence, the installed illumination power is set to $20\,\mathrm{W/m^2}$. For illumination in general, the radiative part of the emitted heat is expected to be around $1/10$, whereas the convective part represents $9/10$.

Machinery

The necessary power to provide all different kinds of machines in the building can only be guessed up to a certain point. Although most of the machines to be installed are already chosen, the actual use of the installations depends heavily on the patients' needs, which can hardly be predicted at all. To be on the safe side, the heat emitted by machines in Zone A as well as in Zone B is set to 300 W each. According to VDI 2078, heat emitted by machines has to be regarded as convective only, since no reliable data about the radiative heat emission of the machines in use can be found.

Final Model

In the final model, the building is separated further into different zones. For internal gains, the heat emitted in Zone B (old model) is split by a ratio of 1:3:1 (Zone B1 / Zone OP / Zone B2).

Sterilisation

Once a day, sterilisation of surgical instruments takes place in Zone Sterilis. One sterilisation cycle takes around 35 minutes and consumes $2.94 \cdot 10^7\,\mathrm{J}$ of which $1 \cdot 10^6\,\mathrm{J}$ is latent heat. In TRNSYS, the energy emission by sterilisation is spread over one hour for simplicity reasons. However, due to a high air change rate of $8\,1/\mathrm{h}$ and the active cooling of the nearby Zone OP and Zone B2 the temperature rise in Zone Sterilis is acceptable.

5.5 Cooling

5.5.1 Heat Pump

Two or three heat pumps are used in this simulation, respectively. They are represented in type 668 and connected to the cold water and the hot water tank. A detailed screenshot can be seen in figure 5.4. Type 668 uses a file containing data about the heat transfer rate P_{cool} and electrical power demand P_{el} based on the temperature of the water entering on the source/hot side T_{hwt} and on the load/cold side T_{cwt}, respectively. This data is provided by the heat pump manufacturer HKT Huber-Kälte-Technik GmbH, Halfing, Germany. Unfortunately, type 668 does not support part load operation. As a consequence, the heat pumps will be switched on and off by a modified control signal which is explained in chapter 7.3.

T_{cwt}	T_{hwt}	P_{el}	P_{cool}
4°C	40°C	2.2 kW	6.7 kW
4°C	50°C	2.6 kW	6.0 kW
4°C	60°C	2.7 kW	4.4 kW
7°C	40°C	2.1 kW	6.7 kW
7°C	50°C	2.6 kW	6.3 kW
7°C	60°C	2.8 kW	5.1 kW
10°C	40°C	2.2 kW	8.1 kW
10°C	50°C	2.6 kW	7.2 kW
10°C	60°C	2.9 kW	5.9 kW
20°C	40°C	2.3 kW	12.4 kW
20°C	50°C	2.8 kW	10.7 kW
20°C	60°C	3.3 kW	8.9 kW

Table 5.1: Heat pump performance at different operating points ©HKT Huber-Kälte-Technik

5.5.2 Thermally Activated Building System - TABS

A thermally activated building system (TABS) will be installed in the ceiling of the operating room as well as in the walls adjacent to Zone B1 and Zone B2, respectively. In TRNSYS, it is modelled as an active wall in type 56 (building). For an accurate simulation, basic information like pipe diameter, wall thickness, pipe wall conductivity and also the distance between the pipes are supplied from the manufacturer Variotherm Heizsysteme GmbH, Leobersdorf, Austria. Usually, 1100 $\frac{\mathrm{kg}}{\mathrm{h}}$ water are pumped through the pipes permanently. However, if T_{cwt} exceeds 15°C the water flow is stopped to keep the temperature in the tank at an acceptable level. The water flow is distributed evenly according to the dimensions of the TABS. 500 $\frac{\mathrm{kg}}{\mathrm{h}}$ water flow through the ceiling (25m^2), 300 $\frac{\mathrm{kg}}{\mathrm{h}}$ through every wall (15m^2 each).

5.5.3 Air Handling Unit - AHU

A simplified overview of the ventilation system is given in figure 5.3. As can be seen, water from the cold water tank flows through the air handling unit (AHU) to cool the air before entering the operating room. However, this system behaviour is not represented in any of the TRNSYS types available at the moment. The type used in this simulation (type 334) calculates the energy consumption to cool and dehumidify air to a certain setpoint. In addition to that, "cold" recovery from air streaming back from the operating room to the AHU is taken into account.
In general, the AHU is operated during office hours only (Mo-Sa, 9-16 h). 1 800 $\frac{\mathrm{kg}}{\mathrm{h}}$ cooled air are transferred to Zone OP resulting in an air change rate of ~18 $\frac{1}{\mathrm{h}}$. In TRNSYS, the AHU is stopped if T_{cwt} exceeds 20°C to ensure physically correct behaviour of the system. The temperature of the supply air T_{AHU}(from AHU to building) is set by the formula

$$T_{AHU} = \max(22, \min(T_{cwt} + 10, T_{op})) \tag{5.1}$$

with T_{op} as the temperature in Zone OP.

Table 7.3 gives an overview of the system behaviour depending on the temperature in the cold water tank T_{cwt}.

Calculation of the temperature rise in the cold water tank due to AHU

To ensure a simulation as realistic as possible, the following approach is implemented. The output "total cooling capacity for latent and sensible demands" (regarded in this simulation as the heat Q_{AHU} transferred from the hot air to the cold water) is divided by the heat capacity of the water c_p and the water mass in the cold water tank m. The calculated temperature increase ΔT is finally added to the temperature of the cold water tank.

$$\Delta T = \frac{Q_{AHU}}{c_p \cdot m} \tag{5.2}$$

Humidity control

In order to achieve a relative humidity ϕ of 40-60% in the cooled area of the building, the relevant parameter in type 334 (absolute water content of the air entering the building x) is controlled using a proportional controller.

$$x = 0.0075\,\frac{\mathrm{g}}{\mathrm{kg}} - \frac{\phi - 40}{60 - 40} \cdot 0.004\,\frac{\mathrm{g}}{\mathrm{kg}} \tag{5.3}$$

Reducing relative humidity after cooling

After being cooled down, the air volume has to be slightly heated up again to reduce its relative humidity. In figure 5.3, this is done by using water from the hot water tank. However, it is unclear whether the temperature level in the tank is high enough to meet the demand of the AHU. As a consequence, it is recommendable that heat will be provided from a solar thermal collector.

5.6 Energy Storage

The water tanks are modelled using TRNSYS type 60c, representing a stratified vertical cylinder tank with two inlets and two outlets.

5.6.1 Hot Water Tank

The hot water tank (source tank) has a capacity of 1 500 litres and serves as an energy sink for the heat pump (type 668). In reality, a dry cooling tower will pass the heat on to the environment. It is expected that this measure will cool down the tank temperature to a level of 5 K above ambient temperature. In TRNSYS, this is realised as a water change of 1 500 litres per hour at the respective temperature level. The pump capacity between heat pump and tank amounts to 1 900 litres per hour.

5.6.2 Cold Water Tank

The cold water tank (load tank) has a capacity of 5 000 litres and provides a "cold storage" for the heat pump (type 668). The tank supplies the air handling unit (AHU) as well as the thermally activated building system (TABS). The pump capacity between heat pump and tank amounts to 1 935 litres per hour.

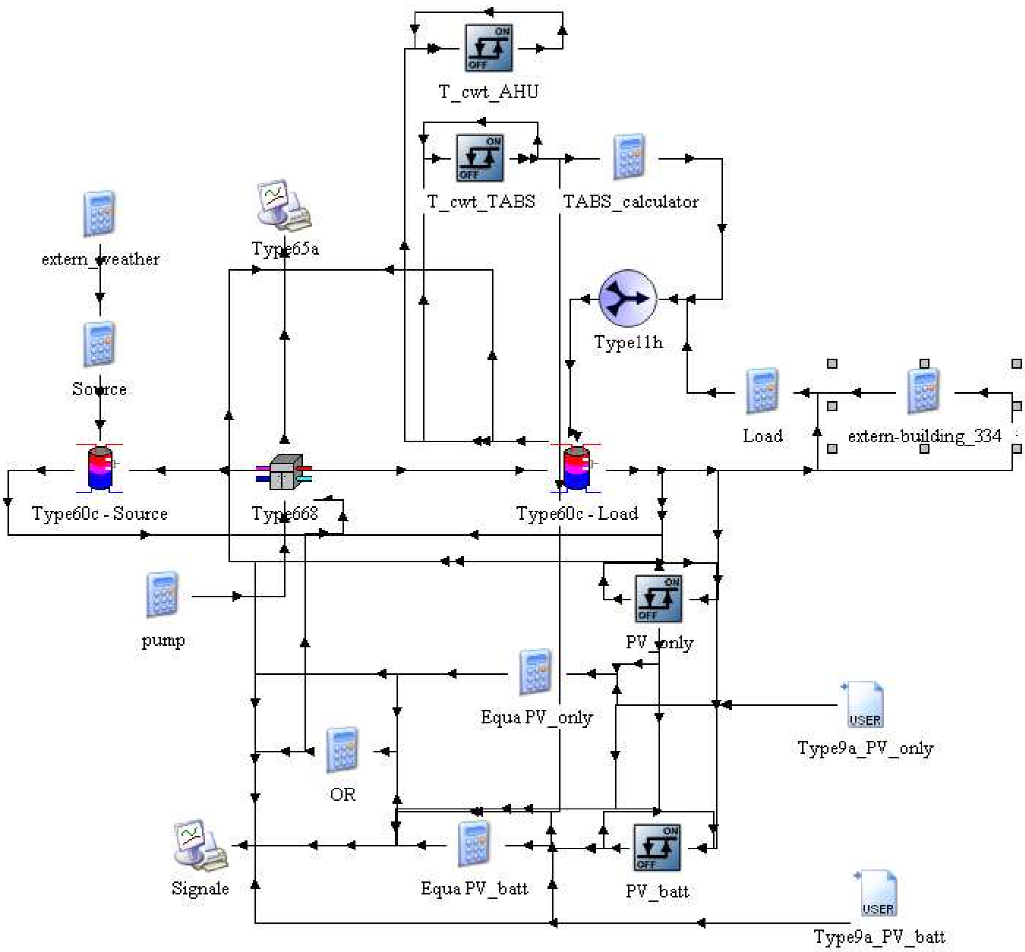

Figure 5.4: TRNSYS-macro simulating the heat pump and two water tanks

5.7 Photovoltaic Power Plant

The yield of the photovoltaic power plant is calculated in a separate TRNSYS project using type 94a. The necessary parameters are provided by the manufacturer of the photovoltaic modules and described in detail in chapter 4.1.2.

5.8 Start Time and Stop Time

The goal of this diploma thesis is the simulation of the system behaviour during one year (8 760 hours). When the simulation is started, it uses given initial values which lead to "wrong" results in the first few days. As a consequence, 9 504 hours are simulated instead of 8 760 hours. As for the results, the initial January (hours 0-744) is replaced by the January of the following year (hours 8 760-9 504). The difference between the first and the second January simulation at hour 744 is already negligible.

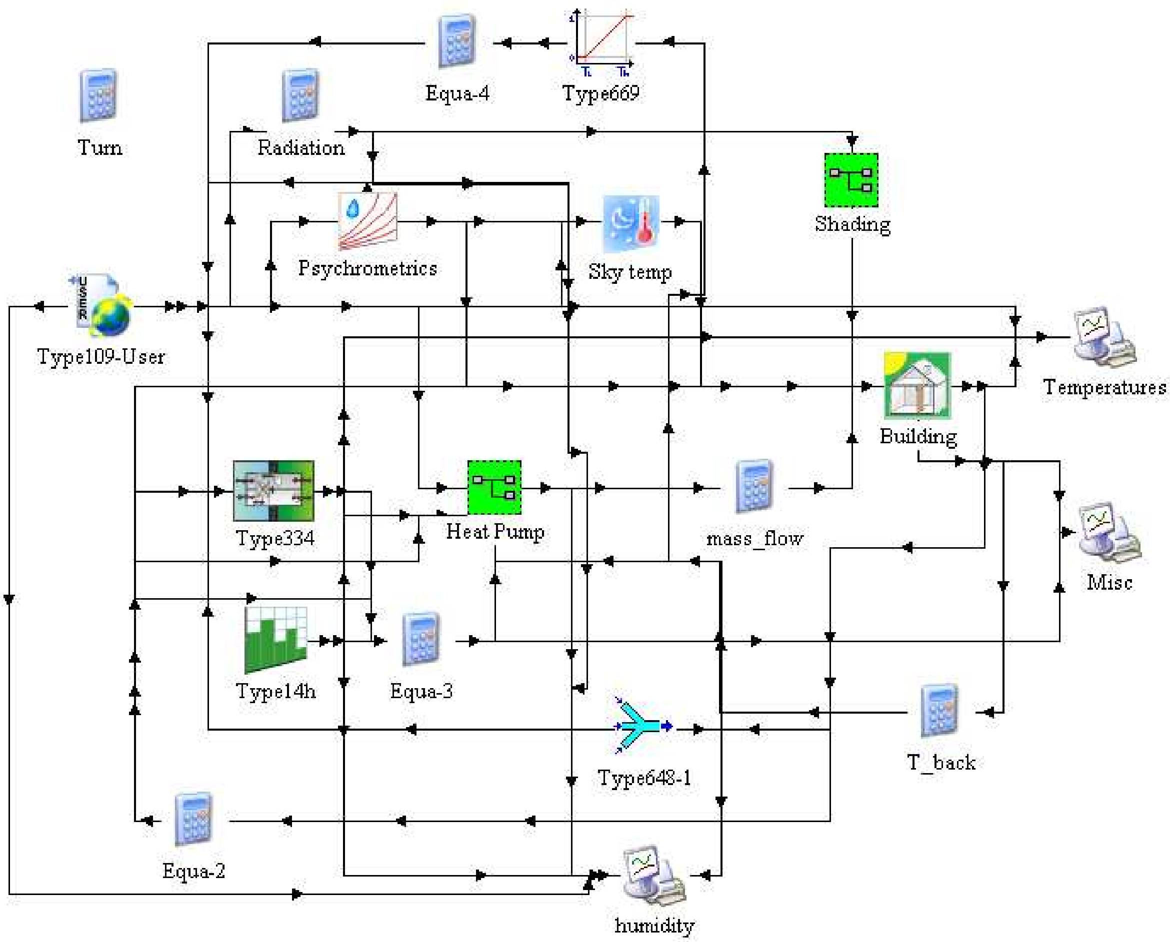

Figure 5.5: Main block diagram of the final version

6 TRNSYS Simulation - Preliminary Draft

In this first part, several parameters are varied to optimize the design of the operating room. The time step is chosen to be one hour. The behaviour of the building is analysed assuming ideal cooling in Zone B and the available cooling power is set unlimited. Active cooling is not implemented in Zone A. Depending on the variation, the most significant outputs are analysed in detail.

- Dissipated heat due to ideal cooling - thermal energy in kWh that is removed from the cooled Zone B
- Maximum cooling load (maximum thermal power removed from Zone B)
- Temperature time curve

The following variations are analysed in this chapter:

Building Orientation

The original orientation of the building is rotated by 90 degrees clockwise.

Exit Room

To reduce thermal shocks for patients leaving the operating room, it is tried to reduce the temperature gradient as far as possible, e.g. by installing a separate exit room. However, since the construction of an additional room leads to higher costs, the influence of the exit room on the cooling demand is analysed to facilitate the decision making process. The addional exit room is removed in this variation.

Target Temperature

The target temperature in the cooled area is varied to calculate possible energy savings through a slight increase in the desired temperature.

Glazing

The glazing in the cooled area is changed. Highly insulated windows of European standard are expensive and have not yet been installed in buildings in South Sudan. The goal of this variation is to find out whether possible energy savings are worth the effort of installing completely new technology in such an outlying area.

Ventilation

This variation analyses the influence of ventilation during the night on the temperature in the uncooled Zone A.

Load Scenario

Worsening conflicts in the borderland between Sudan and South Sudan, epidemics or mass starvation can lead to an increased number of patients. Therefore, an intensive load scenario is developed and analysed in detail.

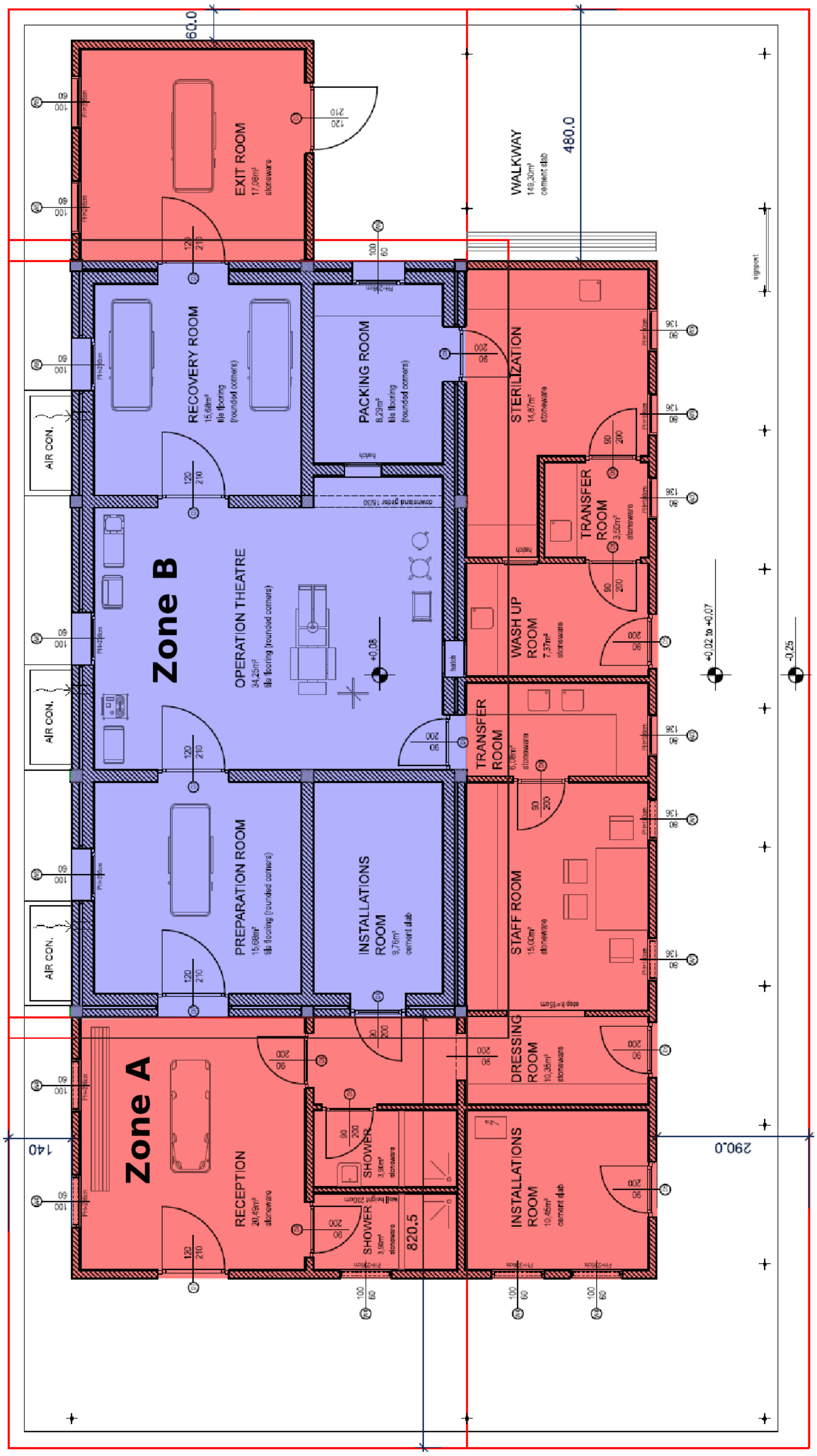

Figure 6.1: Zone segmentation of the building in the preliminary draft

6.1 Building Orientation

A clockwise rotation of the building by 90 degrees leads to a reduced energy demand for cooling from May to August and an increased energy demand during all other months. Altogether, the dissipated heat increases by 3.94 %.
The variation of the cooling load during the day of the year when the maximum cooling load is reached is most pronounced in the morning (figure 6.4). During sunrise, the sun is shining on the long side of the cooled area, as can be seen in figure 6.2. During the day, no significant changes can be observed, since the location of the hospital is already pretty close to the equator.
Shadows from existing trees that can be seen on the map might change the results of the simulation. However, they are not taken into account in the TRNSYS model, as it is not yet clear whether some of the trees might be removed. Also, no reliable data about the presence of leaves is available.
Equally, the influence of adjacent buildings is not considered in the modelling.

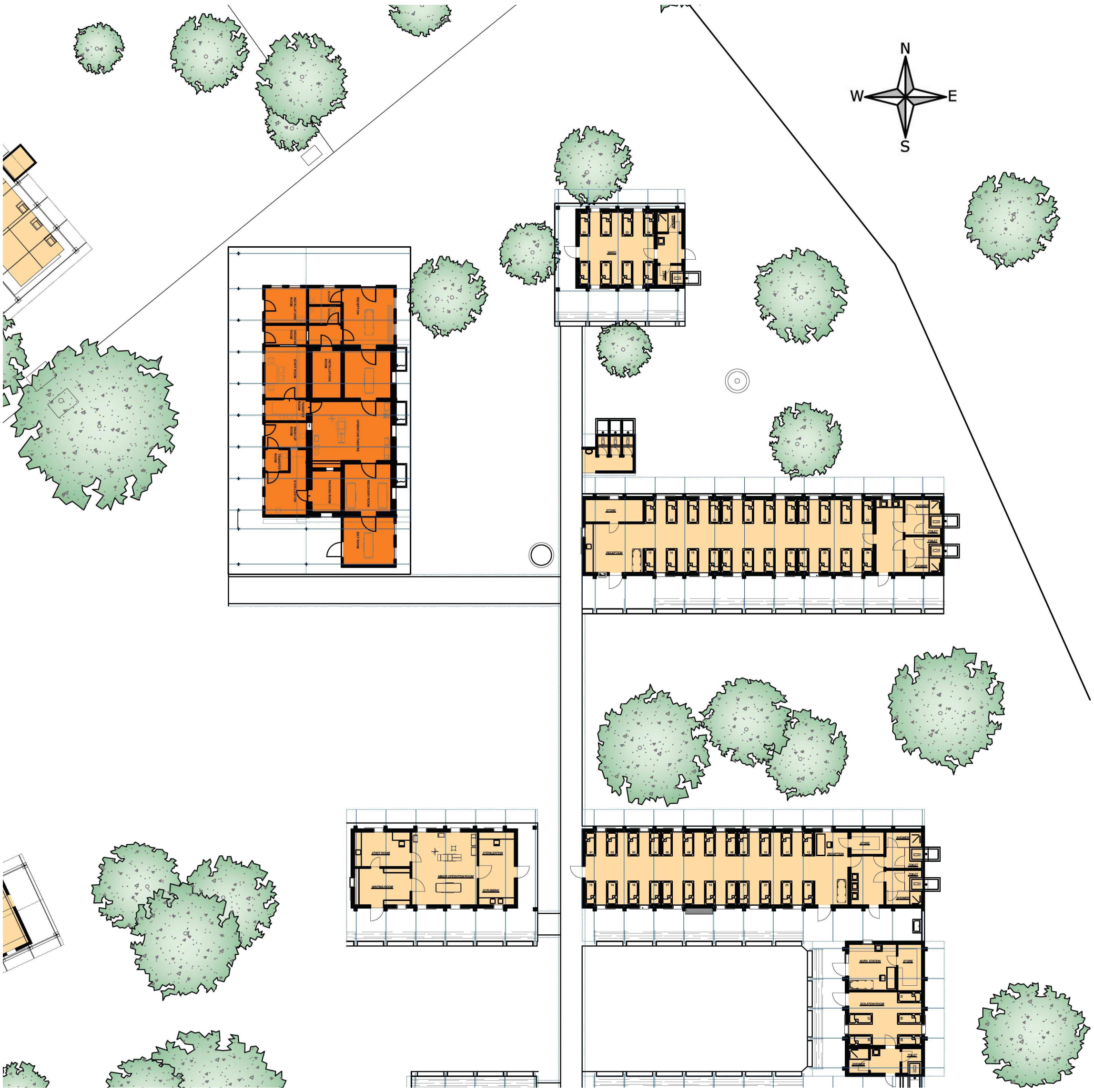

Figure 6.2: Rotated layout (with exit room) [14]

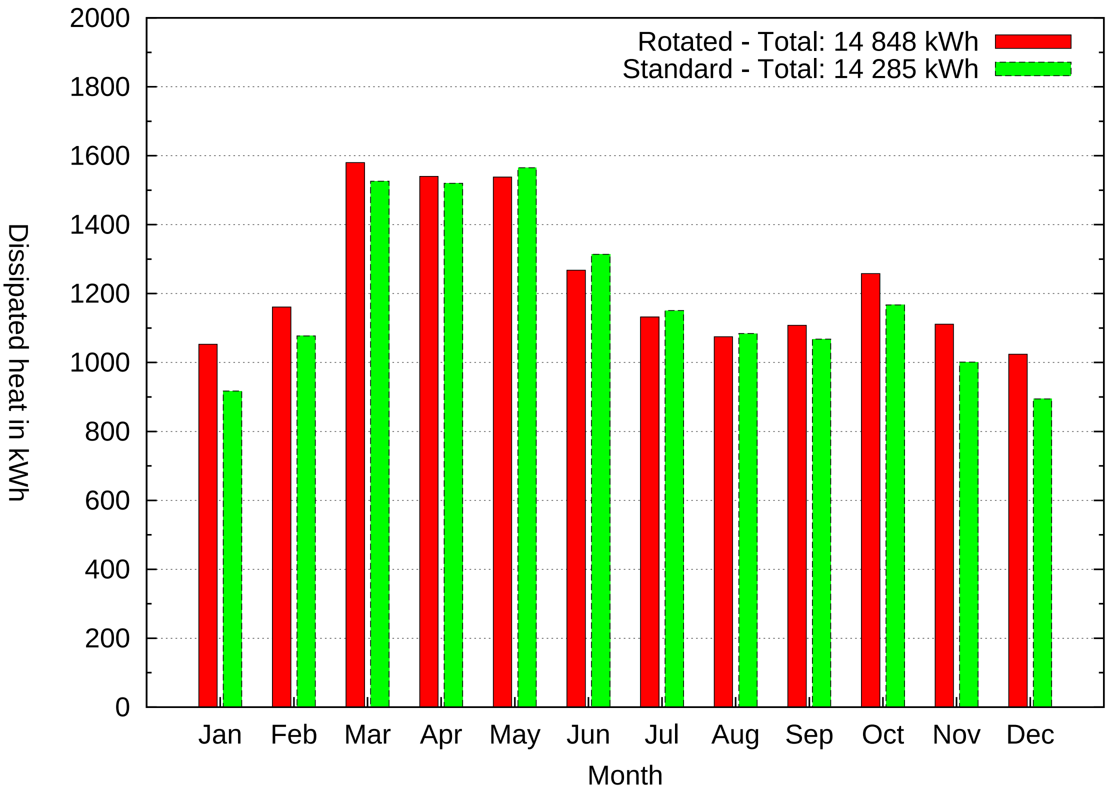

Figure 6.3: Rotated layout - Energy transfer during ideal cooling of the cooled area

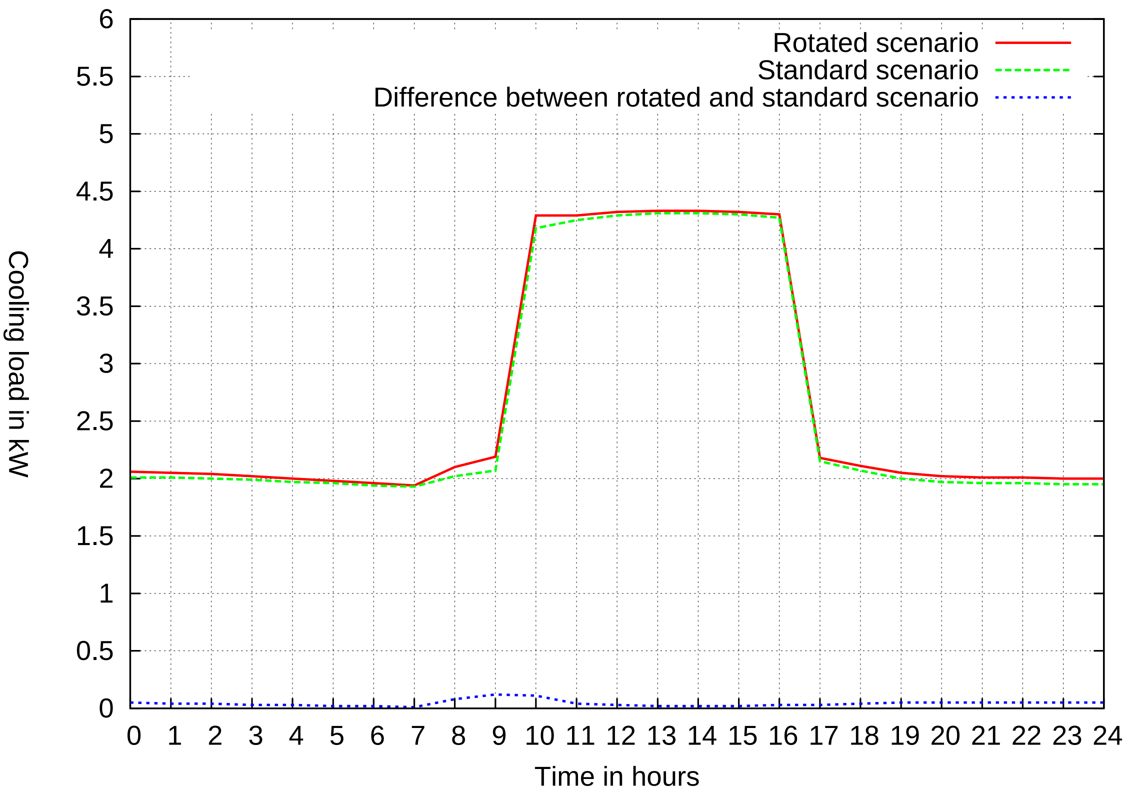

Figure 6.4: Rotated layout - Cooling load during the day of the year when the maximum cooling load is reached

6.2 Exit Room

Since the exit room is located in the uncooled area of the building, the influence of its absence on the total cooling demand is rather low. The difference amounts to merely +0.97%.

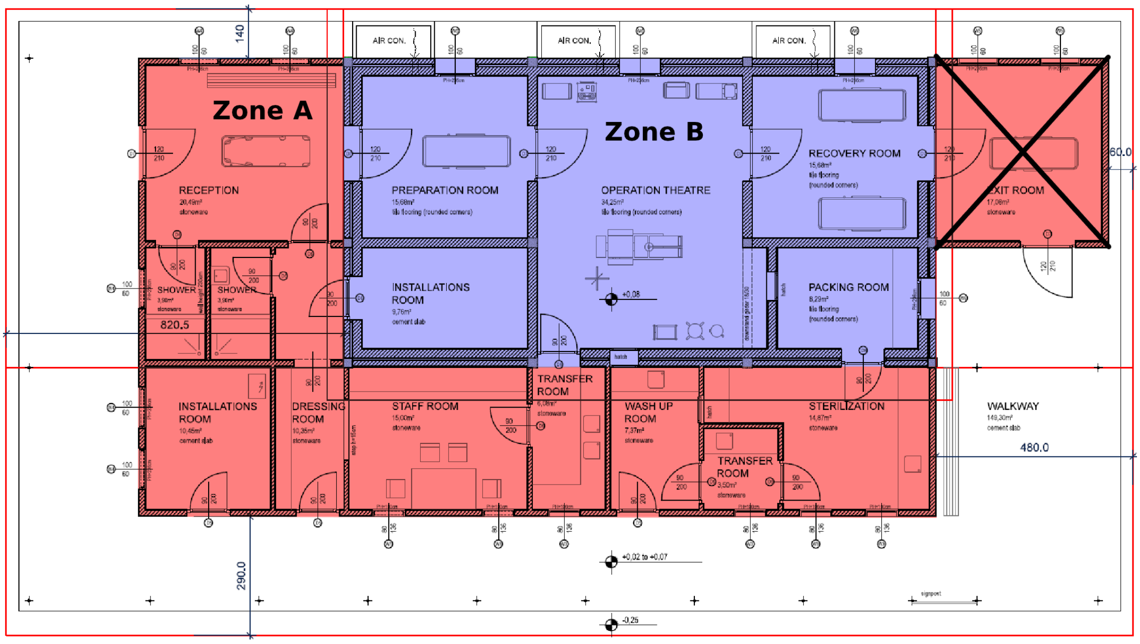

Figure 6.5: No exit room - Map

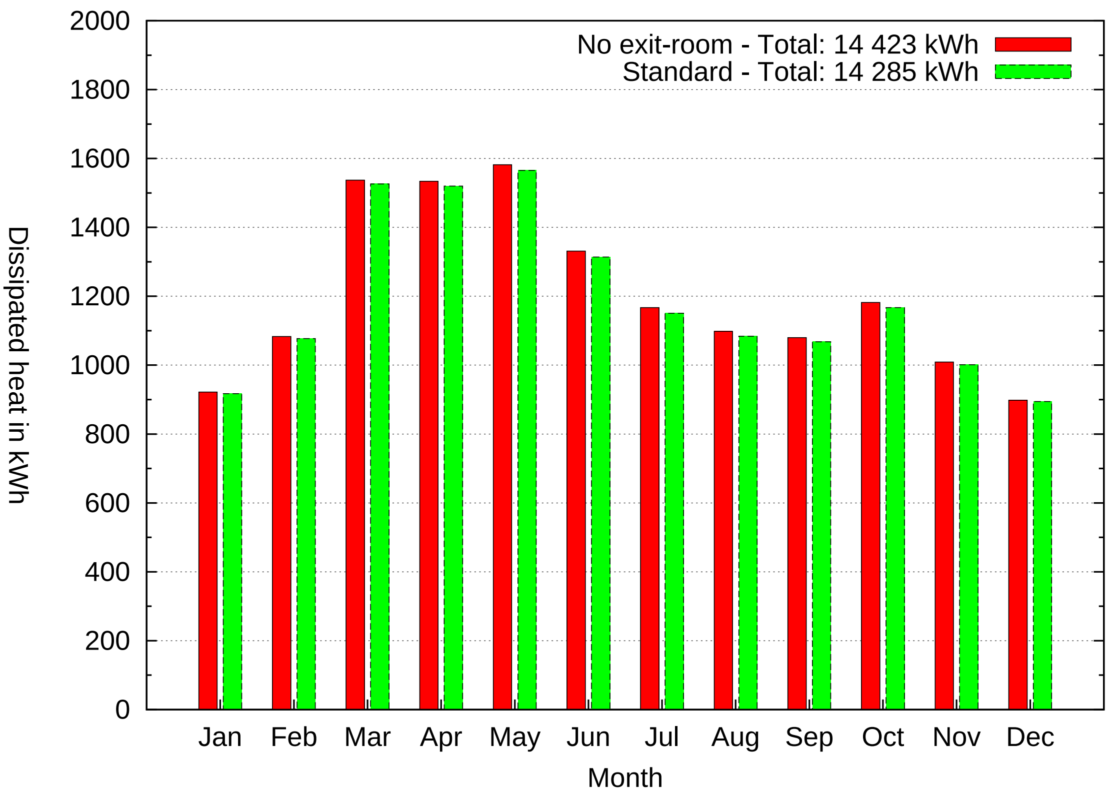

Figure 6.6: No exit room - Energy transfer during ideal cooling of the cooled area

6.3 Target Temperature

As expected, a rise in the target temperature from 25°C to 26.5°C leads to a significant reduction (-13.67%) in the total cooling demand. In addition, it shall be noted that the resulting temperature change in the uncooled area is negligible as can be seen in figure 6.8. As a consequence, one temperature curve is practically overlapping the other.

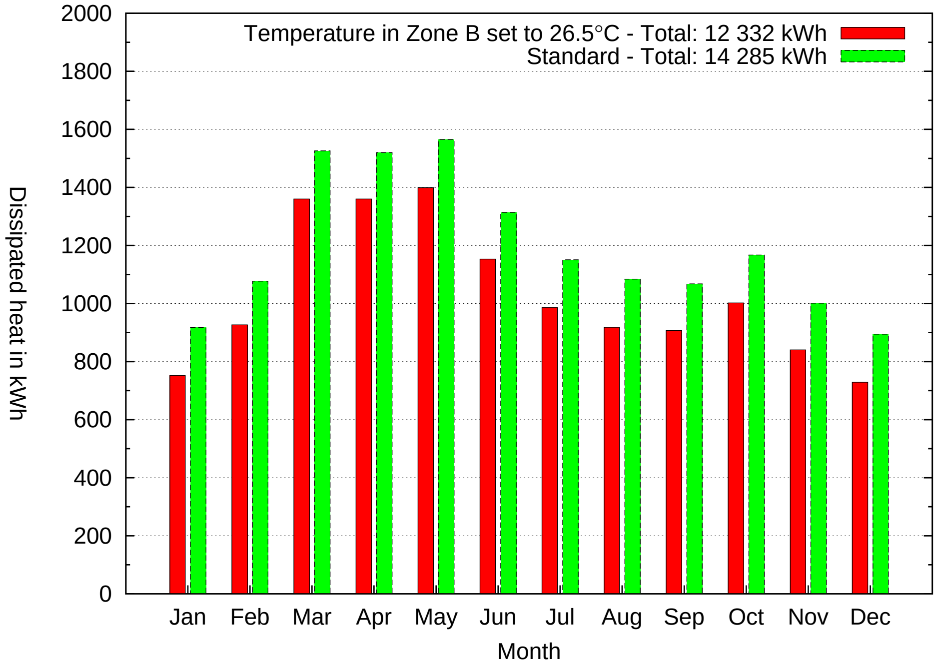

Figure 6.7: Target Temperature - Energy transfer during ideal cooling of the cooled area

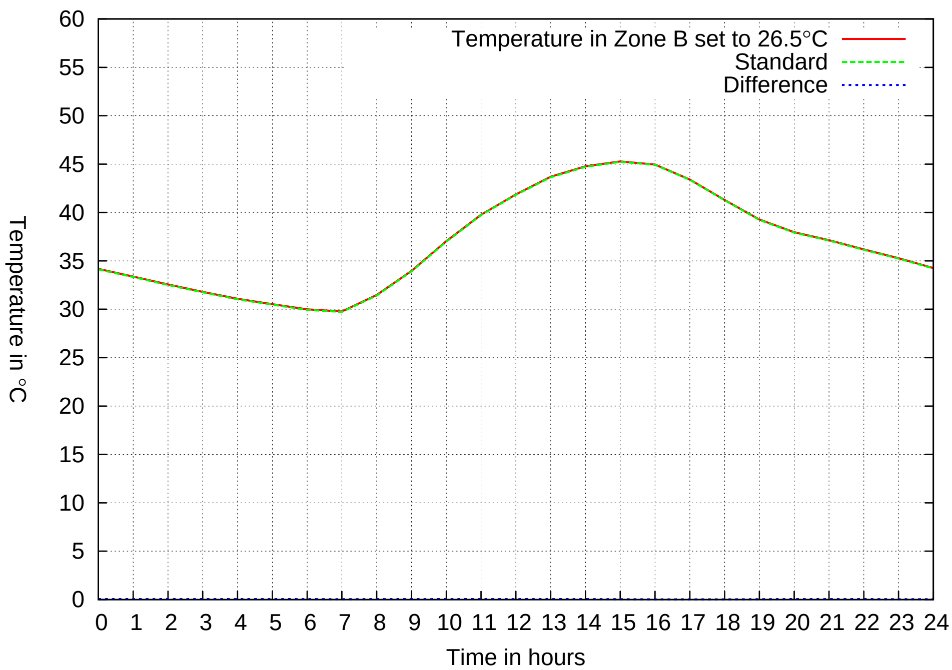

Figure 6.8: Target Temperature - Temperature in the uncooled area during the day of the year when the maximum cooling load is reached

6.4 Glazing

The data for the two different glazings is taken from the TRNSYS library. The differences between single and double glazings are depicted below.

	single glazing	double glazing
U-value	5.68 W/m^2K	1.4 W/m^2K
ratio frame/window	0.15	0.2
reflection coefficient[1]	0.1	0.5

Table 6.1: Glazing data from TRNSYS library

Single glazing leads to a higher energy demand for cooling (+3.01%). Again, the parameter change in Zone B does not significantly influence the temperature in Zone A (figure 6.11). Again, one temperature curve is hardly visible in figure 6.9 due to overlapping.

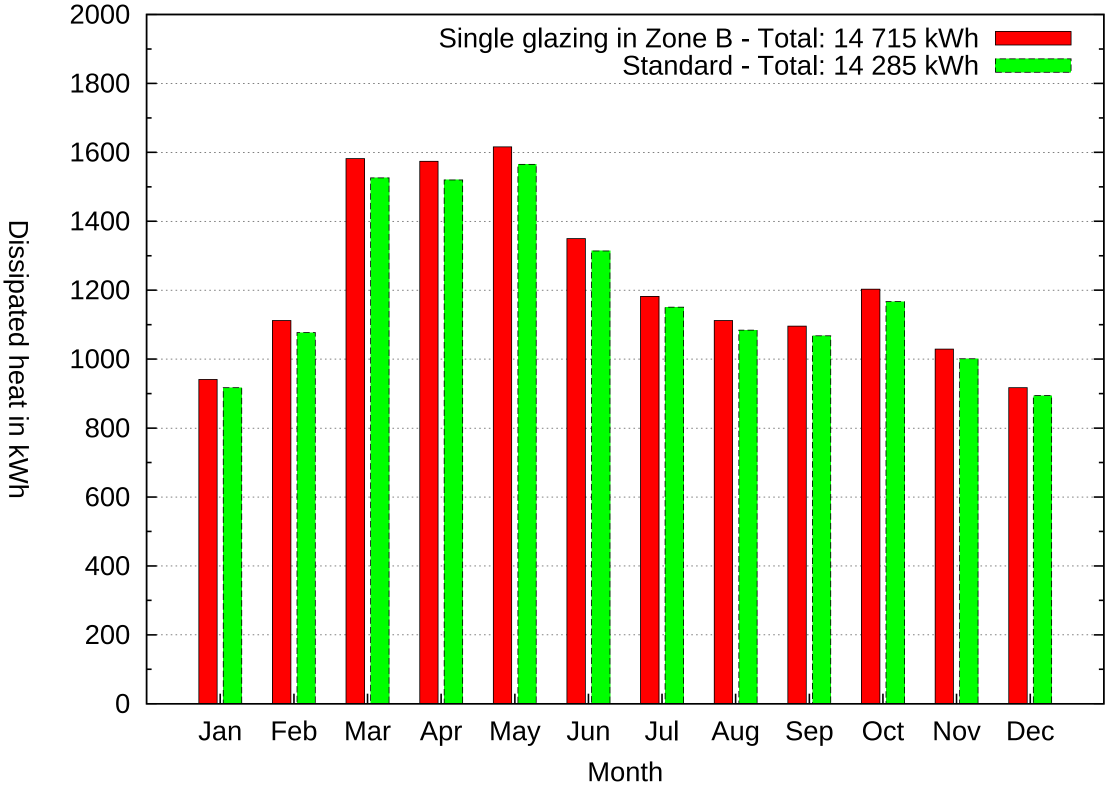

Figure 6.9: Glazing - Energy transfer during ideal cooling of the cooled area

[1]reflection coefficient of internal devices towards zone

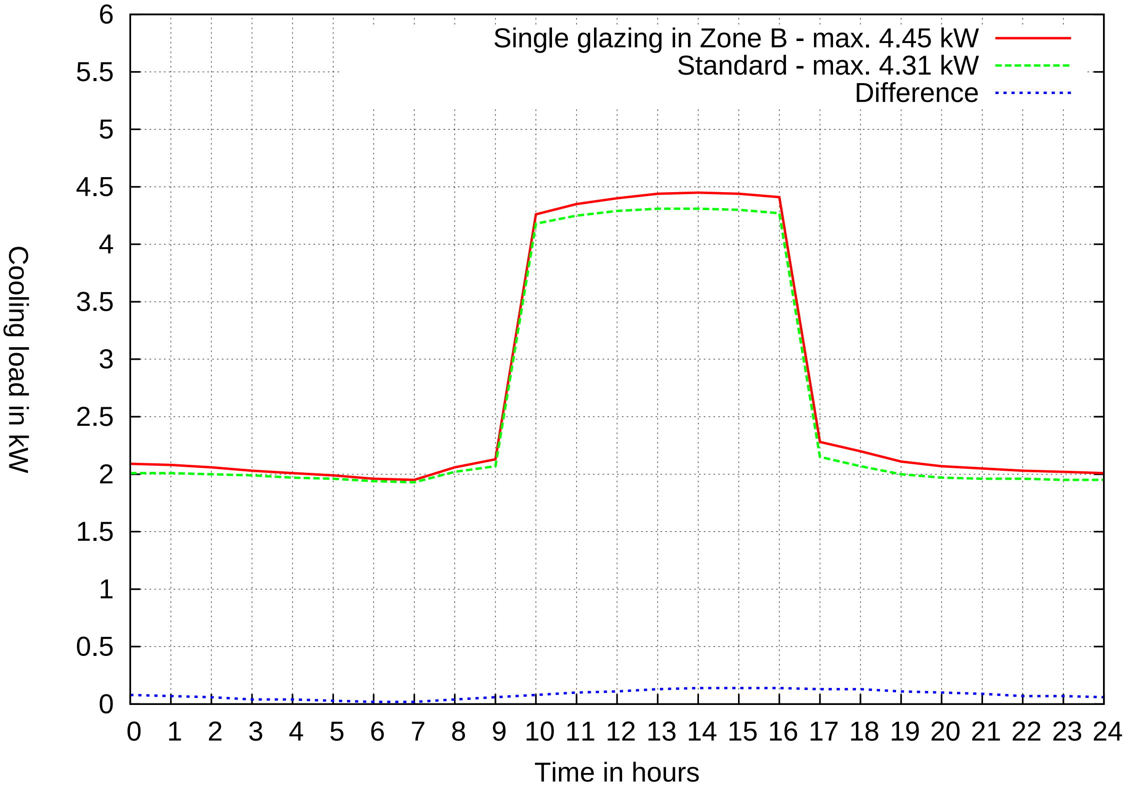

Figure 6.10: Glazing - Cooling load during the day of the year when the maximum cooling load is reached

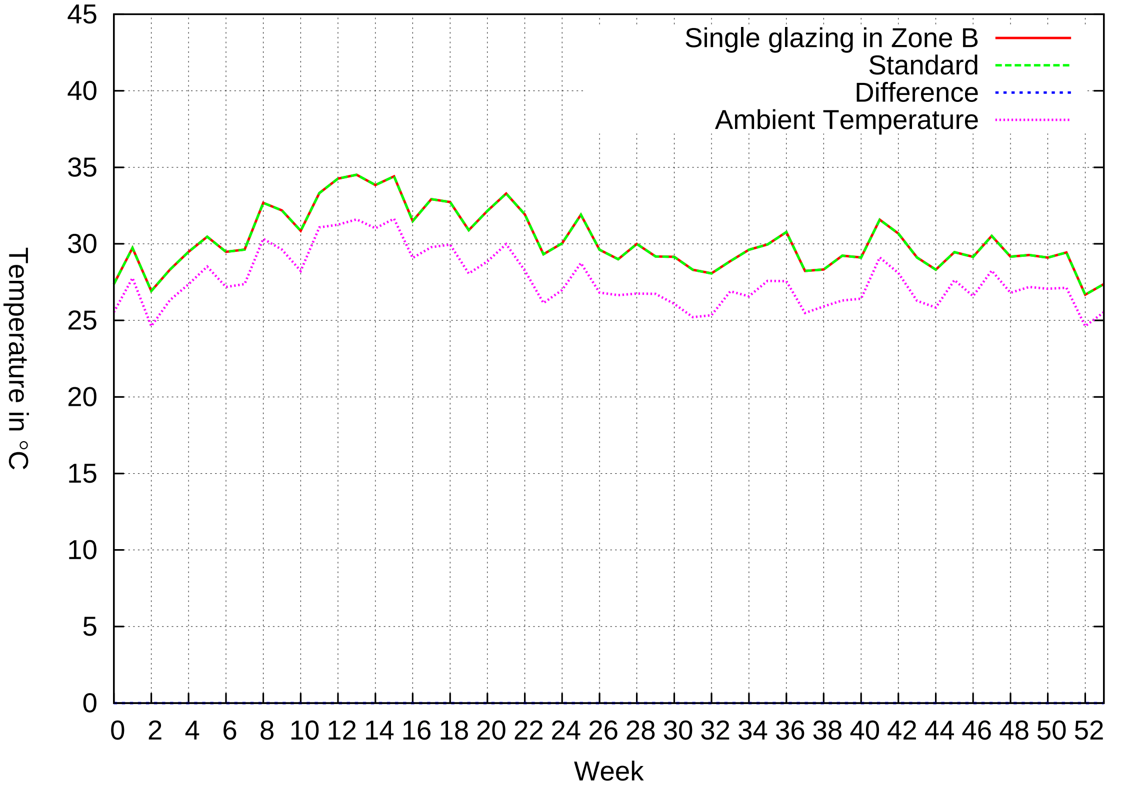

Figure 6.11: Glazing - Average temperature in the uncooled area

6.5 Ventilation

Definition

In TRNSYS, the ventilation of Zone A is implemented as an air change rate of 8 $^1/_h$.
As expected, the ventilation of Zone A during day and night leads to significant energy savings (figure 6.12). Also, the actual difference in temperature is pretty remarkable, as can be seen in figures 6.13 and 6.14.

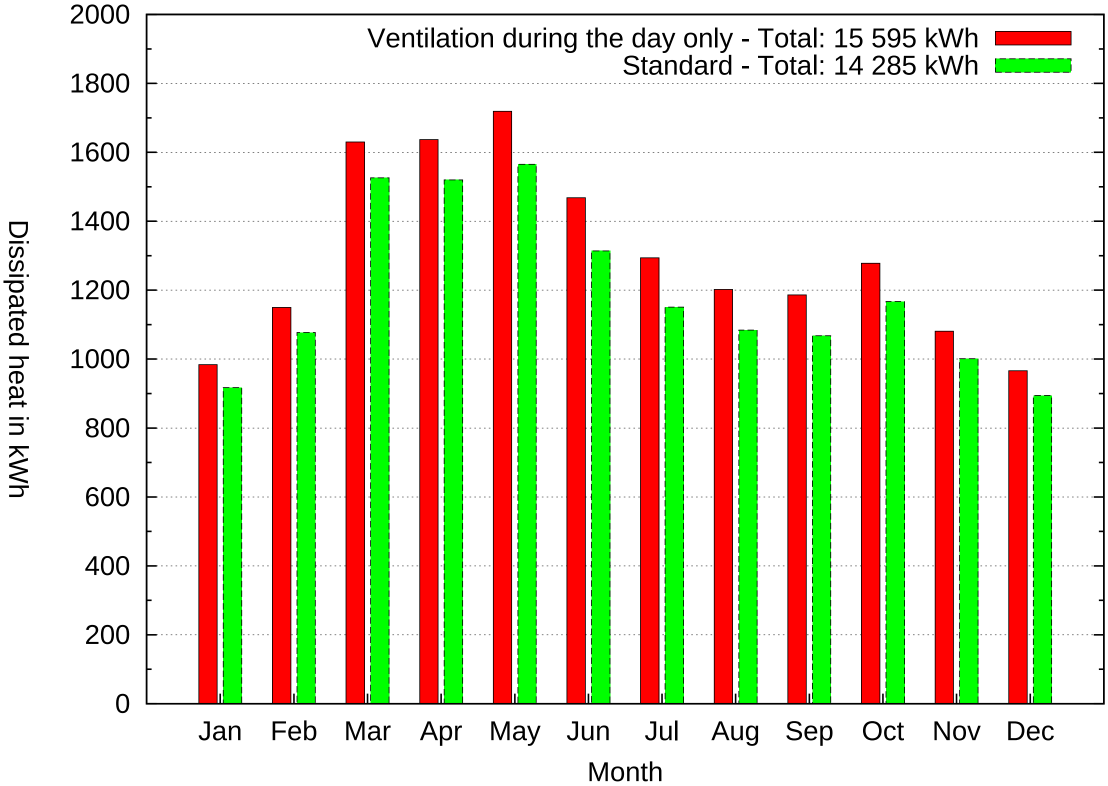

Figure 6.12: Ventilation - Energy transfer during ideal cooling of the cooled area

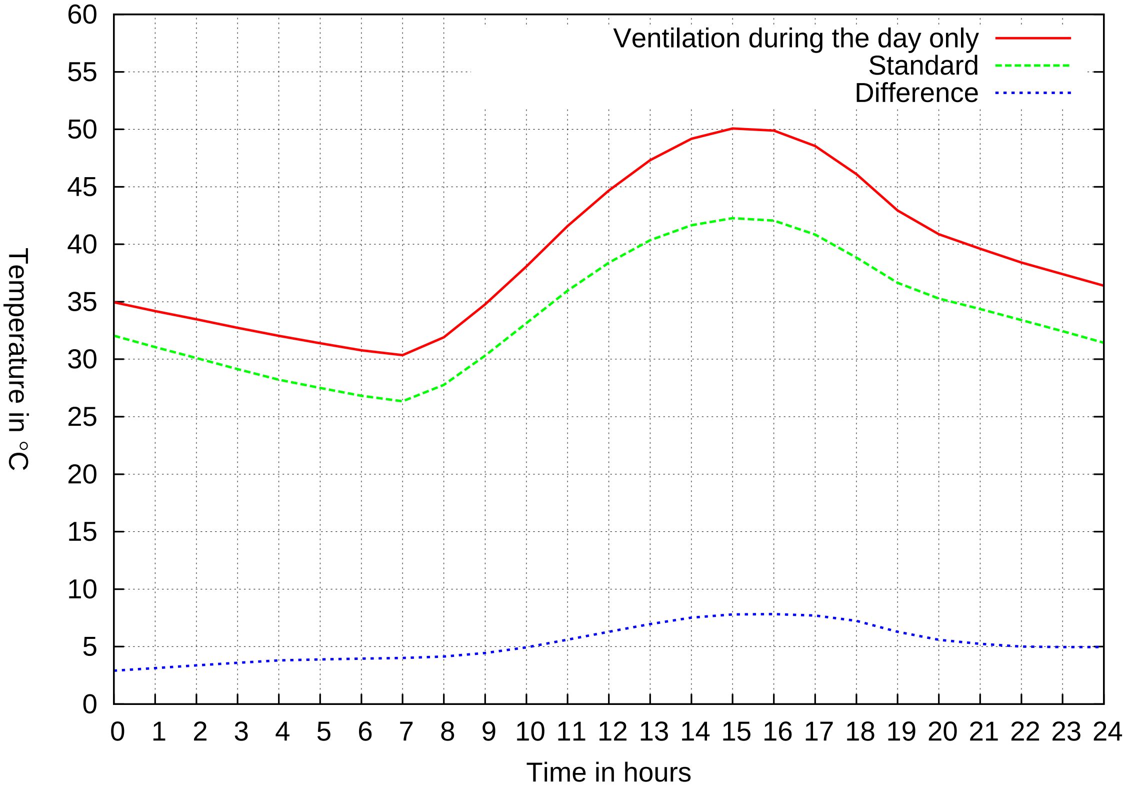

Figure 6.13: Ventilation - Temperature in the uncooled area during the day of the year when the maximum cooling load is reached

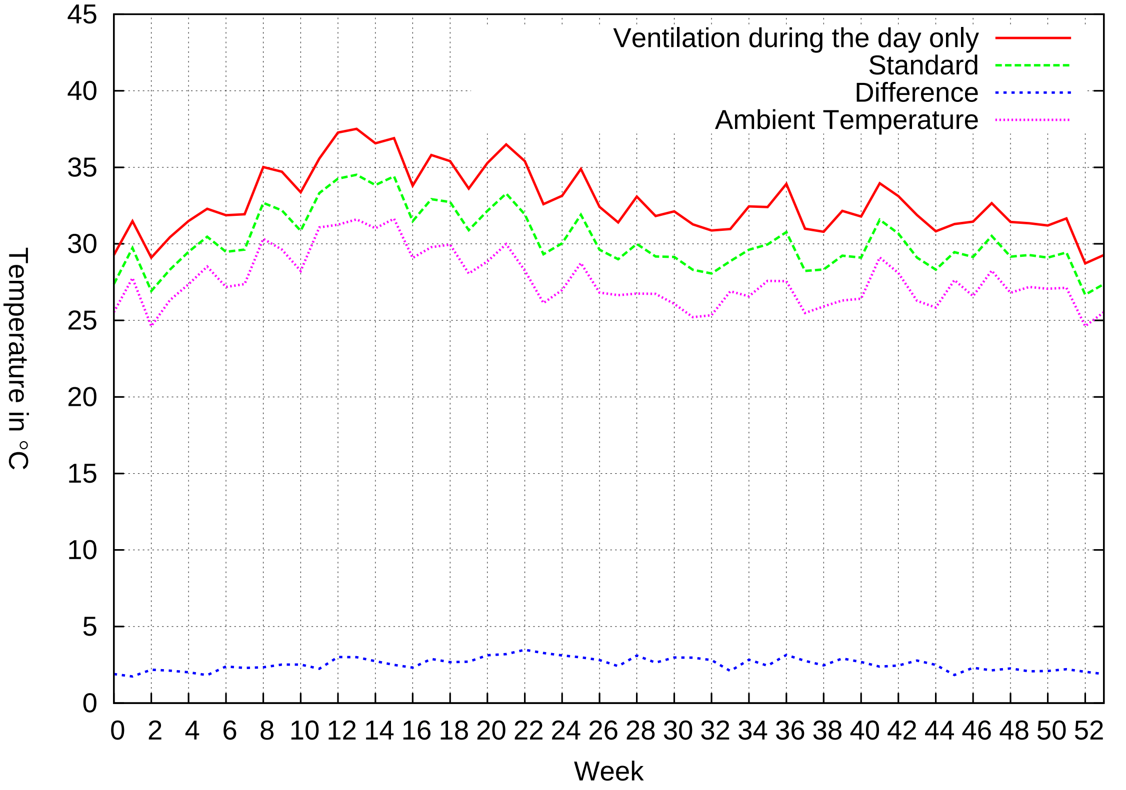

Figure 6.14: Ventilation - Average temperature in the uncooled area

6.6 Load Scenario

The differences between the "normal" and "intensive" load scenario are depicted in table 6.2.

	normal	intensive
Zone A - persons	4	6
Zone A - power of machines	300 W	400 W
Zone B - persons	5	8
Zone B - power of machines	300 W	600 W
Working hours	Mo-Sa, 9-16h	Mo-So, 0-24h

Table 6.2: Intensive load scenario - differences

In the intensive scenario, the dissipated heat more than doubles in comparison to the normal scenario.
Normally, the operating room is used during the day (Mo-Sa, 9-16h) only. Since it is working 24/7 in the intensive scenario, the cooling load is changing massively during the night.

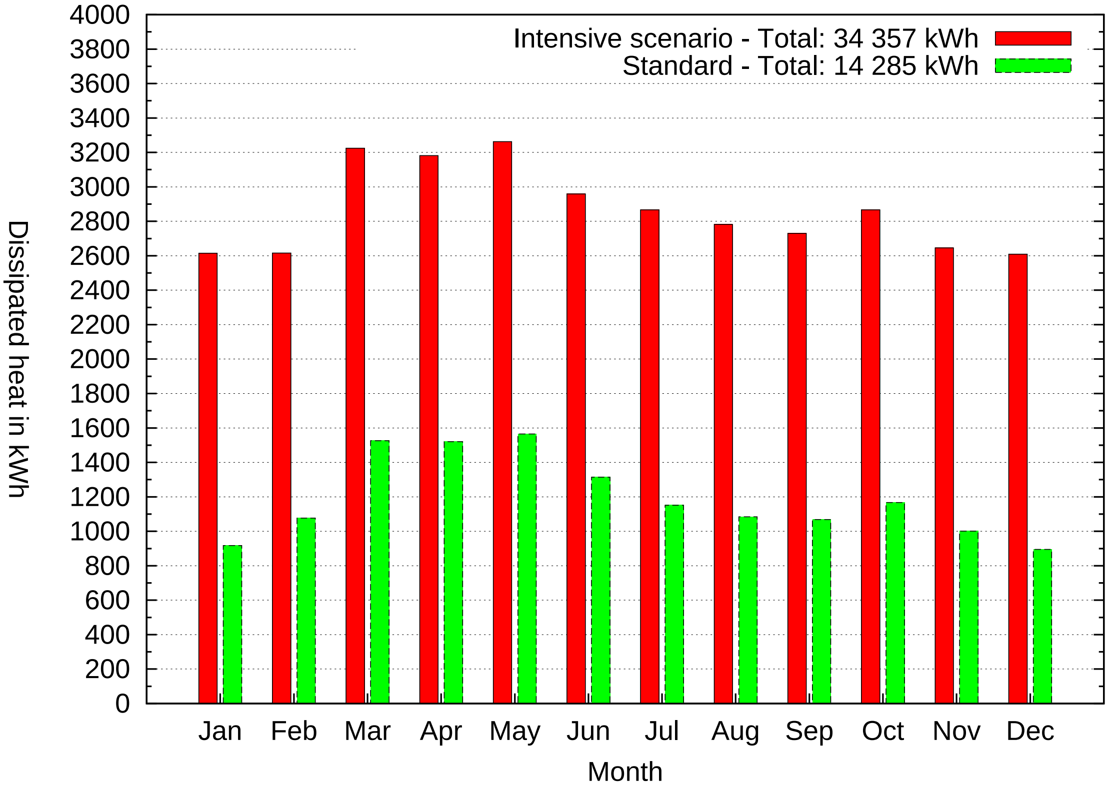

Figure 6.15: Load Scenario - Energy transfer during ideal cooling of the cooled area

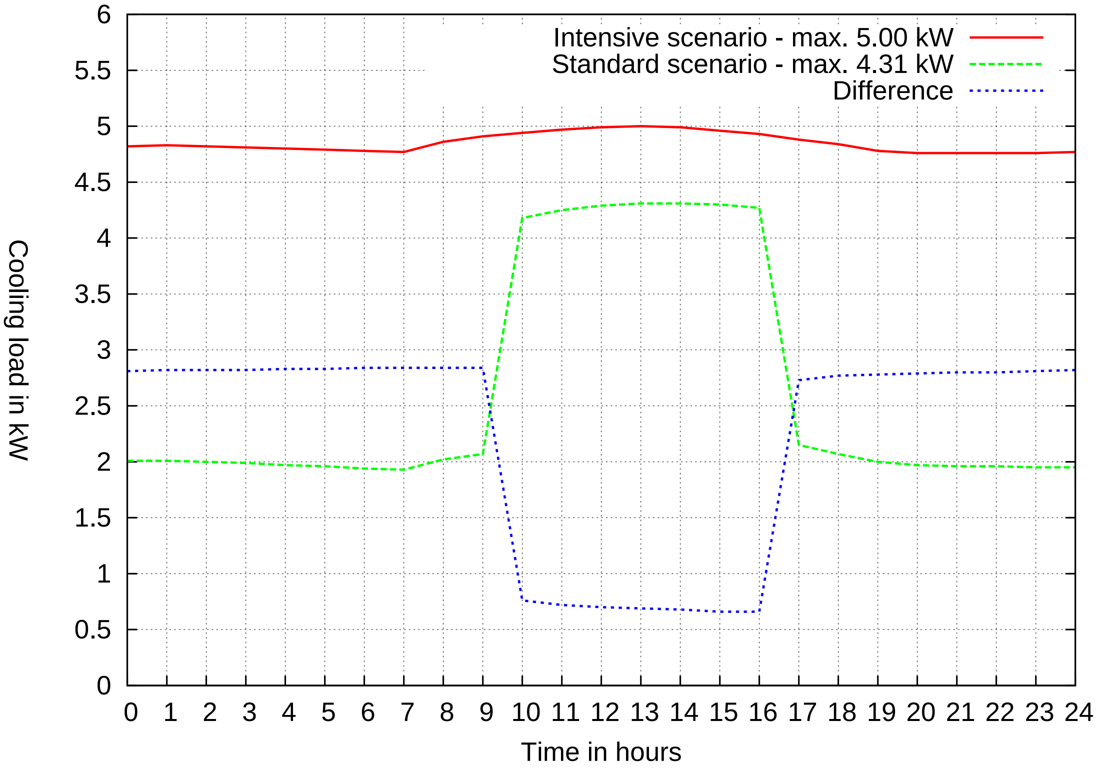

Figure 6.16: Load Scenario - Cooling load during the day of the year when the maximum cooling load is reached

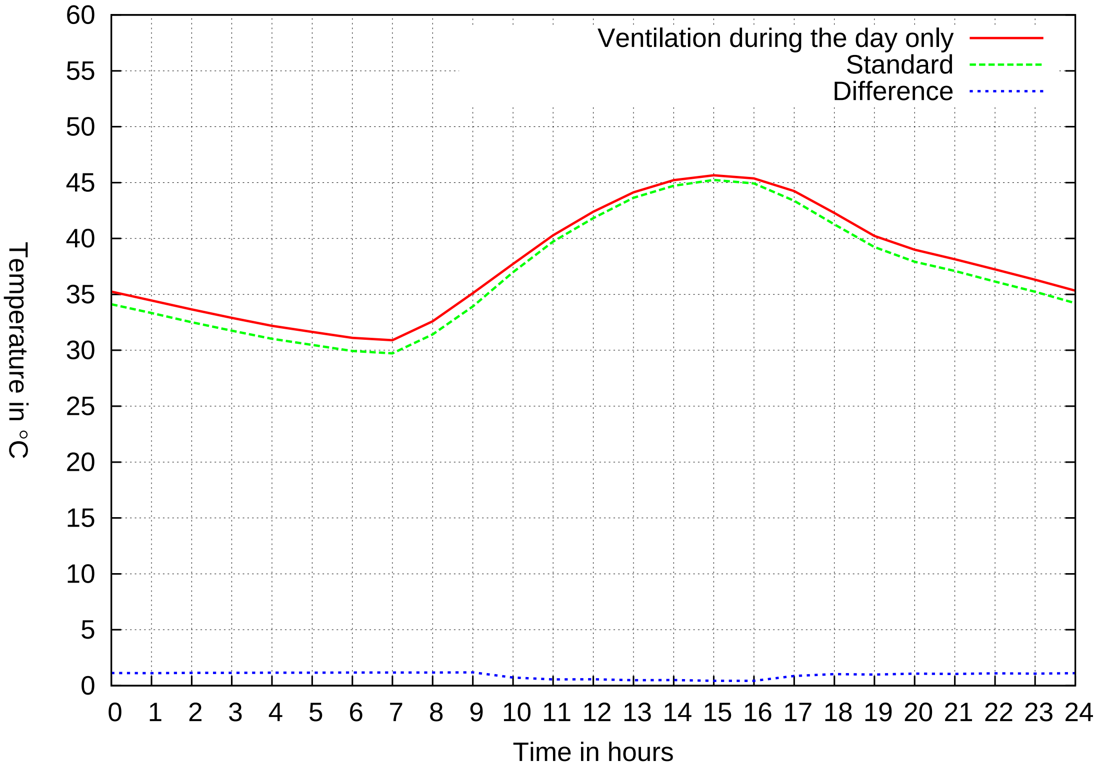

Figure 6.17: Load Scenario - Temperature in the uncooled area during the day of the year when the maximum cooling load is reached

6.7 Consequences

After a careful evaluation of all results, the following variation is chosen to be developed further:

- Building Orientation: The original orientation is retained unchanged.
- Exit Room: The exit room is implemented for the benefit of the patients.
- Target Temperature: The target temperature remains at 25°C.
- Glazing: To ensure an optimal weather tightness for hygienic reasons, double glazing is implemented in the cooled area of the building.
- Ventilation: Louver glass windows in Zone A will stay open during the night to ensure an enhanced ventilation. If necessary, the installation of e.g. ceiling fans is possible.
- Load Scenario: The normal load scenario is developed further.

6.8 Final Zone Segmentation

The final zone segmentation is more detailed for several reasons:

- to obtain more exact and therefore more realistic simulation results
- to enable the consideration of the impact of heat emitted during the sterilisation process
- to enable an adequate implementation of TABS in the TRNSYS model

Changes to the initial layout

The initial Zone A is separated into three different zones. Zone Sterilis is added since it comprises the autoclave used for sterilisation. The heat emitted by the sterilisation process is taken into account in TRNSYS as an "internal gain" distributed over the respective zone. Therefore, the room comprising the autoclave is modeled as a separate zone. In addition to that, Zone Exit is defined for its distance to the other rooms of initial Zone A.
The initial Zone B is separated into three different zones as well to obtain adjacent walls[2] necessary for the implementation of TABS in TRNSYS. Further, "internal gains" like persons and machines can be distributed more precisely.

[2]walls shared with neighbouring zones

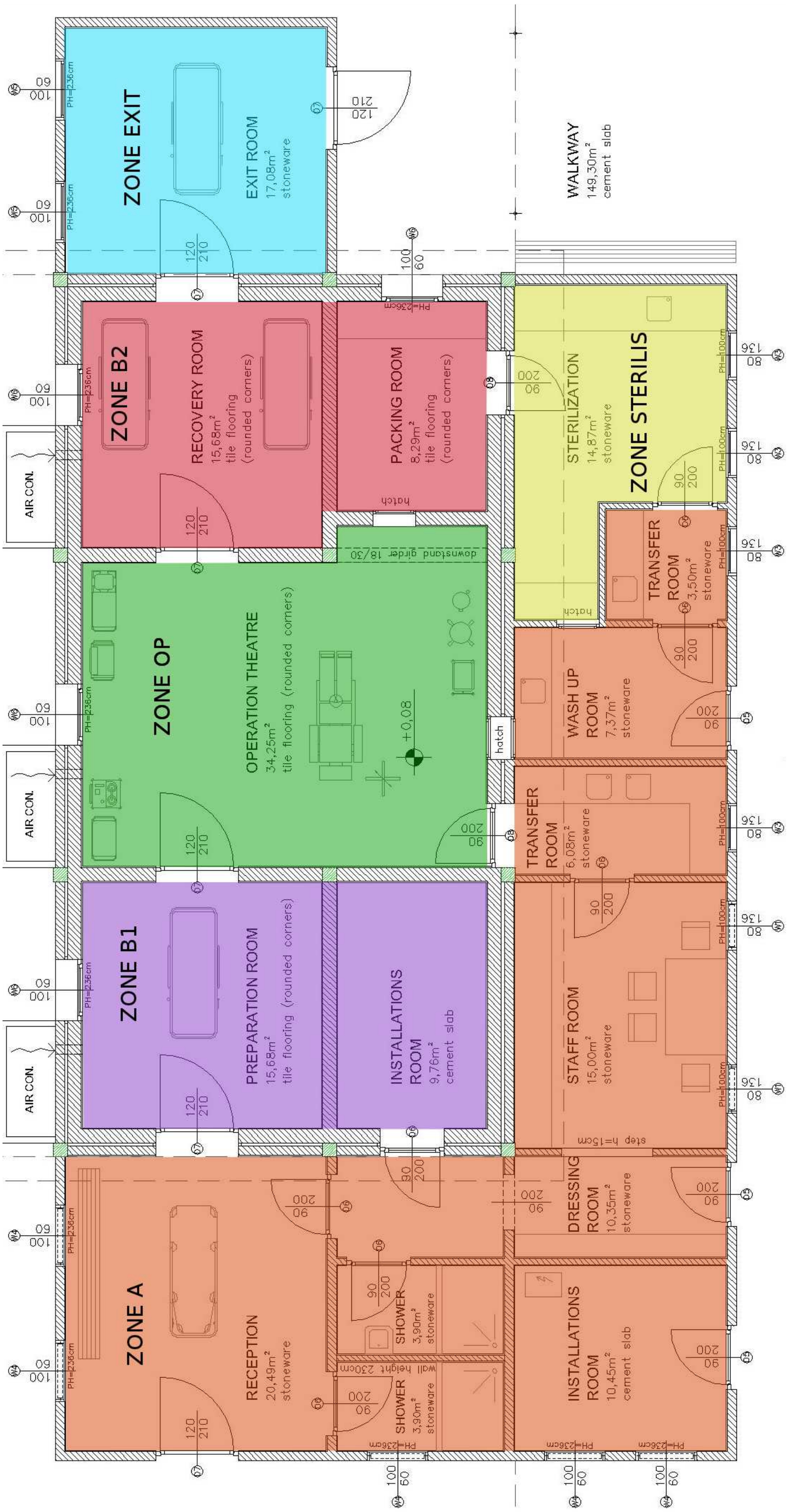

Figure 6.18: Final zone segmentation

7 TRNSYS Simulation - Photovoltaic Power Plant

7.1 Energy Yield

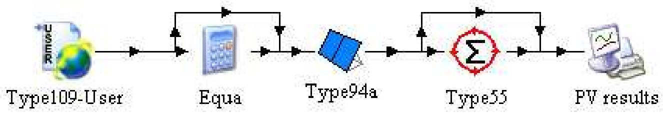

Figure 7.1: TRNSYS model of the photovoltaic power plant

In TRNSYS, the photovoltaic power plant is simulated independently in a different model. Since the number of photovoltaic modules is an essential parameter for the electricity production of the power plant, a small and a large plant are compared. In reality, the number of modules given below will be multiplied with a factor of 1.25 to account for yield losses due to dirty modules or scratched glass on the front of the module (caused by sand).

- The **small photovoltaic power plant** consists of 56 modules in total - 14 units in series, each consisting of 4 modules connected in parallel.
- The **large photovoltaic power plant** consists of 84 modules in total - 14 units in series, each consisting of 6 modules connected in parallel.

Figure 7.2 shows the yield of the large power plant during a whole year. Thanks to a high solar irradiation, the maximum electric power of the plant exceeds by far the nominal power[1] of 10 080 W ($14 \cdot 6 \cdot 120$ W). The black line at 1 200 W represents the approximate electrical power necessary to operate one heat pump at partial load.

[1]under laboratory illumination conditions

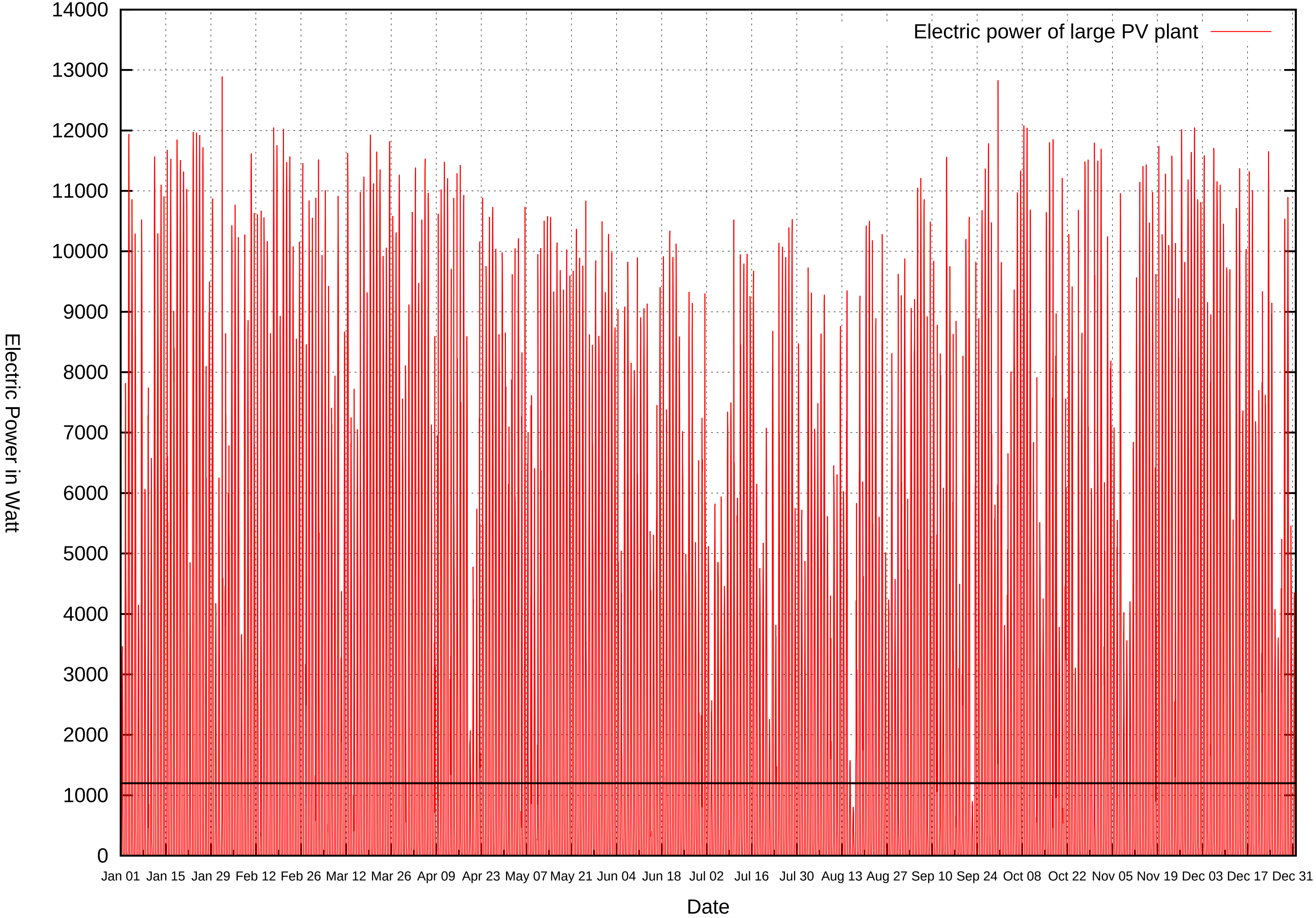

Figure 7.2: Power output of the large photovoltaic plant during one year

A detailed overview of the electricity production is given in table 7.1. The efficiency of the power plant does not depend on the number of modules. As a consequence, the energy yield for any plant size can be calculated by multiplying it with the appropriate size ratio.

	14x4 modules	**14x6 modules**
Jan	1 334 kWh	2 001 kWh
Feb	1 244 kWh	1 865 kWh
Mar	1 375 kWh	2 063 kWh
Apr	1 245 kWh	1 867 kWh
May	1 307 kWh	1 961 kWh
Jun	1 132 kWh	1 698 kWh
Jul	1 043 kWh	1 564 kWh
Aug	994 kWh	1 491 kWh
Sep	1 170 kWh	1 755 kWh
Oct	1 211 kWh	1 817 kWh
Nov	1 280 kWh	1 920 kWh
Dec	1 296 kWh	1 944 kWh
Total	**14 631 kWh**	**21 946 kWh**

Table 7.1: Energy yield of the two different photovoltaic power plants

The capacity factor[2] C can be calculated by dividing the actual electricity production w_{actual} by w_{theor}, i.e. the electricity production if the plant had operated at nominal power the entire time. C is very high for a photovoltaic plant and amounts to almost 25%.

$$C = \frac{w_{actual}}{w_{theor}} = \frac{14\,631\,\text{kWh}}{6\,720\,\text{W} \cdot 8\,760\,\text{h}} = 0.249 \tag{7.1}$$

Figure 7.3 depicts the power output of the small photovoltaic plant during two different weeks. The electricity production varies significantly due to weather conditions. It illustrates the importance of a large cold water tank, which acts as a short term energy storage. The shape of the curve is rather surprising since week 22 is part of the wet season while at the end of December sunny weather is expected.

Power duration curves for different sizes of the photovoltaic power plant are given in figure 7.4. Bold lines are drawn at 1 200 W, 3 000 W, 6 000 W and 9 000 W. At 1 200 W, the first heat pump can operate at part load. The importance of this level is explained in chapter 7.3. The other levels represent the maximum power demand at the worst operating point for 1, 2 and 3 heat pumps, respectively.

[2]Capacity factor: Ratio of the actual electricity output and the potential output if the power plant operates the entire time at nominal capacity

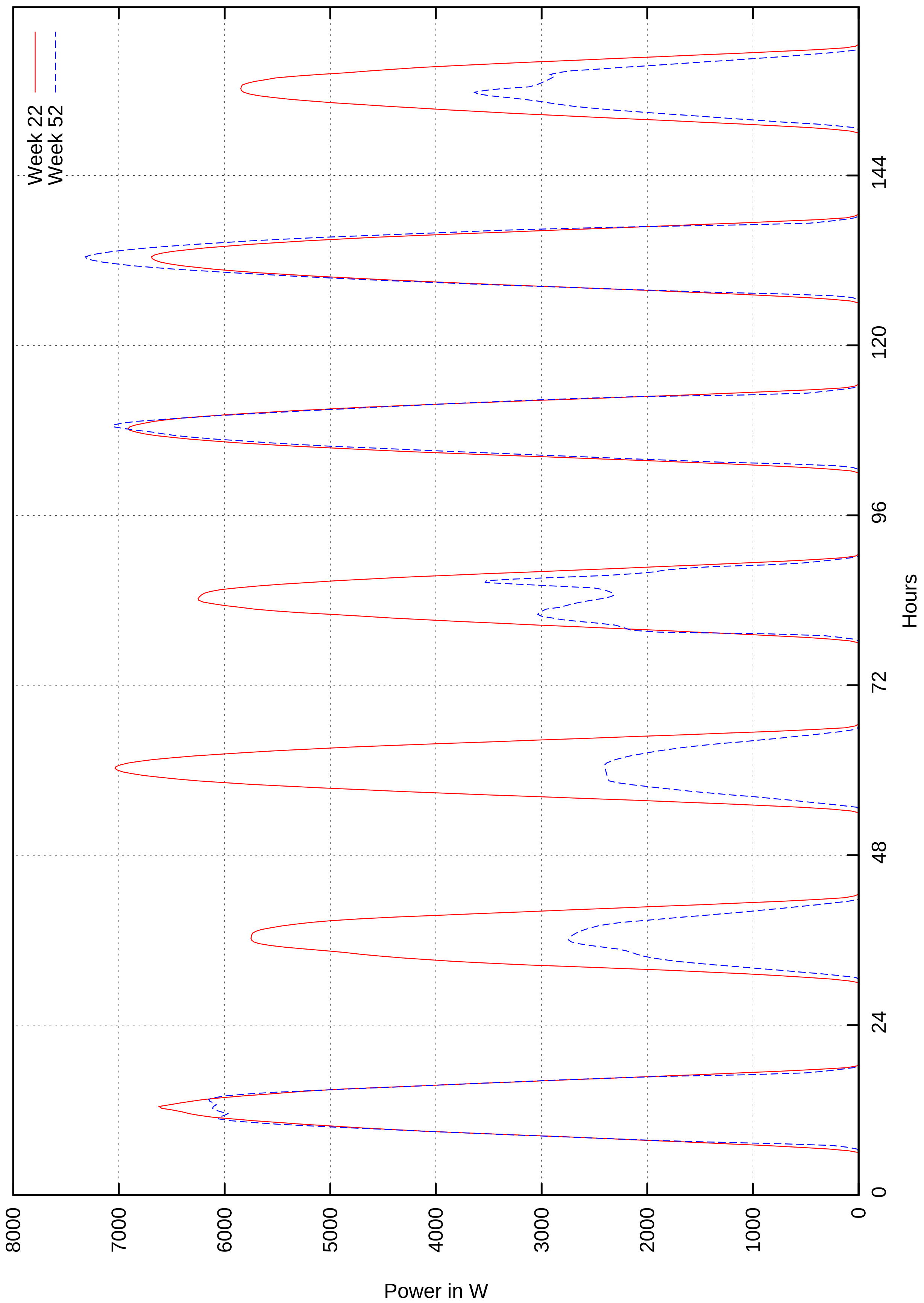

Figure 7.3: Power output of the small PV plant during one week in May/June and one week in December

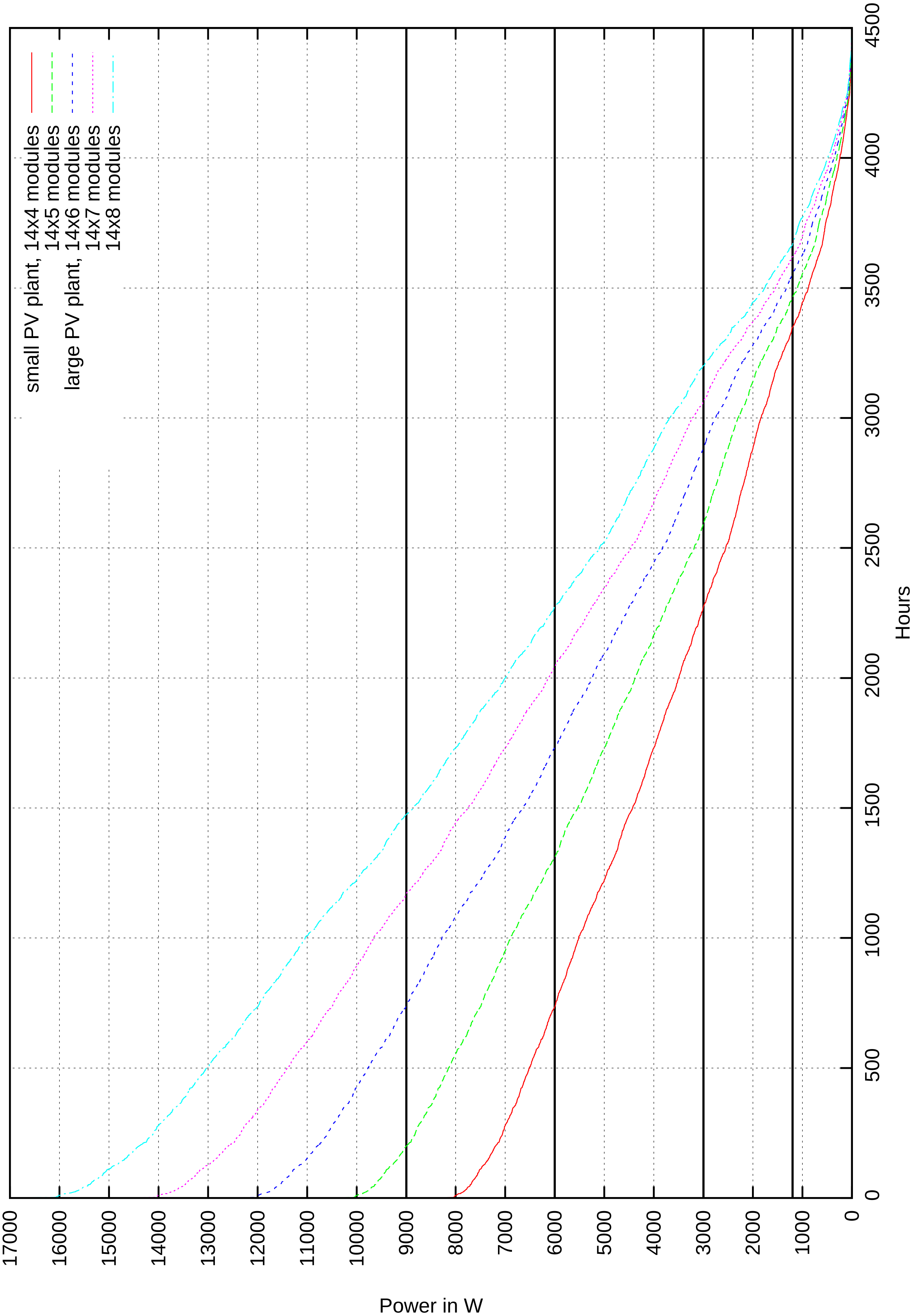

Figure 7.4: Power duration curves of different photovoltaic plants during one year

7.2 Inclination of the Modules

The yield of the photovoltaic power plant depends, among others, heavily on the orientation of the modules. At the hospital site, the inclination is set to an angle of around 15°, measured from the horizontal. Thus, modules are cleaned from sand and dust by rainwater. An auto tracking system to follow the sun during the day will not be installed. Still, the modules can be mounted facing north or south.

Month	**North**	**South**	**Optimised**
Jan	1 531 kWh	2 001 kWh	2 001 kWh
Feb	1 558 kWh	1 865 kWh	1 865 kWh
Mar	1 922 kWh	2 063 kWh	2 063 kWh
Apr	1 926 kWh	1 867 kWh	1 926 kWh
May	2 253 kWh	1 961 kWh	2 253 kWh
Jun	1 998 kWh	1 698 kWh	1 998 kWh
Jul	1 757 kWh	1 564 kWh	1 757 kWh
Aug	1 576 kWh	1 491 kWh	1 576 kWh
Sep	1 702 kWh	1 755 kWh	1 755 kWh
Oct	1 591 kWh	1 817 kWh	1 817 kWh
Nov	1 502 kWh	1 920 kWh	1 920 kWh
Dec	1 465 kWh	1 944 kWh	1 944 kWh
Total	**20 781 kWh**	**21 946 kWh**	**22 875 kWh**

Table 7.2: Yield of PV plant facing north or south, respectively (third column explained in the text)

Figure 7.5 shows the difference in the power output between modules facing north or south, respectively. Due to the sun path given in figure 7.6, the modules facing north produce more electricity from around April till September. It is therefore recommended to change the orientation of the modules twice a year. Since weather cannot be predicted exactly, it is not possible to calculate the optimum day for reorientation. Still, table 7.2 calculates the yield difference if the modules are reoriented on April 1st and September 1st, respectively. The electricity yield increases by more than 4.2 % in comparison to modules facing south all year long.

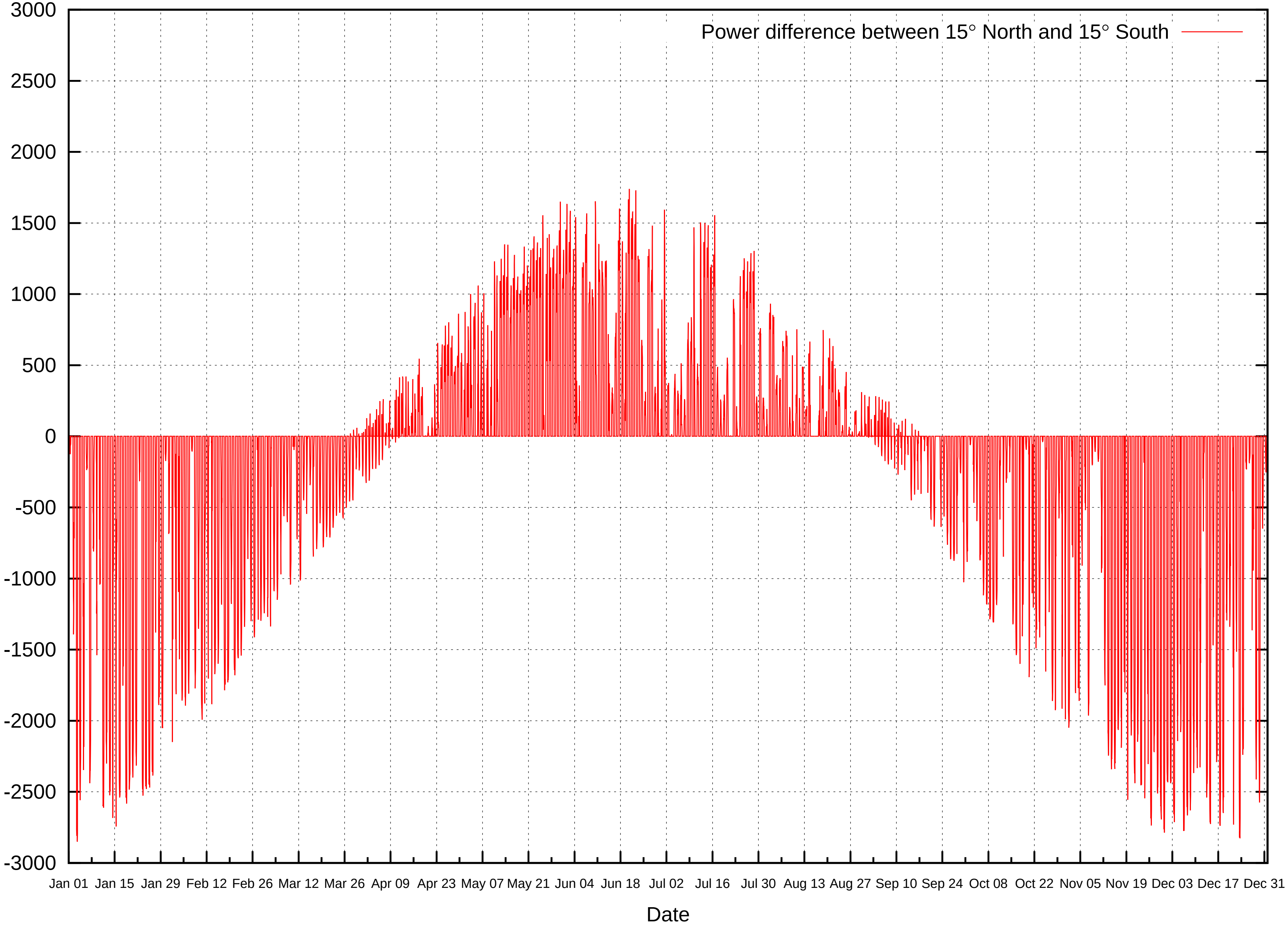

Figure 7.5: Large photovoltaic plant - power difference between modules facing north or south, respectively

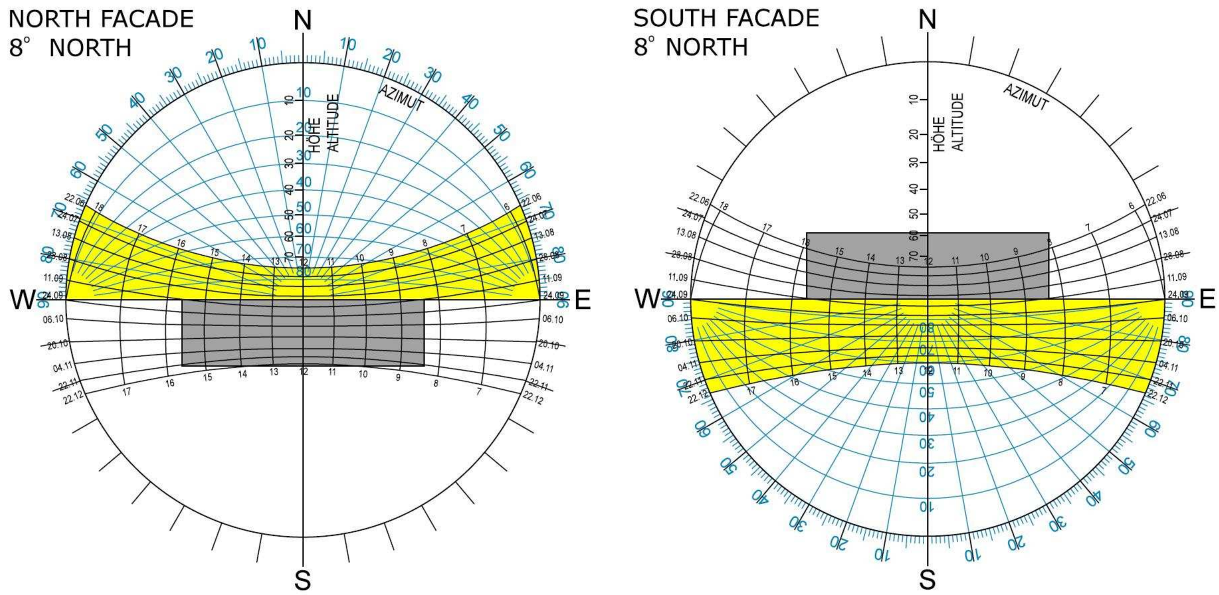

Figure 7.6: Approximate sun path at the hospital site [7]

7.3 Heat Pump Control Signal Generation

TRNSYS type 668 does not support part load operation. As a consequence, a specific strategy has to be implemented to ensure the simulation results to be as realistic as possible. The following procedure is implemented for two respective three heat pumps at the hospital site. First, the initial time step of one hour is reduced twentyfold to three minutes. Then, a heat pump control signal based on the current power output of the photovoltaic plant is generated. The power output of the photovoltaic power plant P_{PV}[3] is divided by 5 000 W or 7 500 W[4], multiplied by 20 and then rounded to the nearest integer. The resulting integer represents the number of time steps of this hour during which the heat pump control signal is set to one. The remaining time steps are set to zero.

For example: At the hospital site three heat pumps are installed. $P_{PV} = 2\,547.58\,\mathrm{W}$ according to the weather data.

$$\frac{2\,547.58\,\mathrm{W}}{7\,500\,\mathrm{W}} \cdot 20 = 6.7935 \tag{7.2}$$

For seven out of twenty time steps distributed equally during this hour, the control signal is set to one. Like this, TRNSYS simulates full load for all three heat pumps during these seven time steps (21 minutes). During the remaining 39 minutes, all heat pumps are switched off.

[3] which changes only at regular intervals of one hour due to the limited time resolution of the given climate data and remains constant inbetween

[4] At full load, the electric power demand of one heat pump ranges from around 2 kW to 3 kW depending on the water temperatures in the tanks (see table 5.5.1). An average power demand of around 2.5 kW is expected, which leads to 5 000 W (7 500 W) necessary to operate both (all three) heat pumps at the same time.

Power outputs higher than 5 000 W (7 500 W) are treated like 5 000 W (7 500 W).

If the power output of the photovoltaic power plant is lower than 1 200 W, the missing power to operate one heat pump in part load is expected to be supplied from the battery or the diesel generator.
The exact implementation is depicted in figure 7.7.

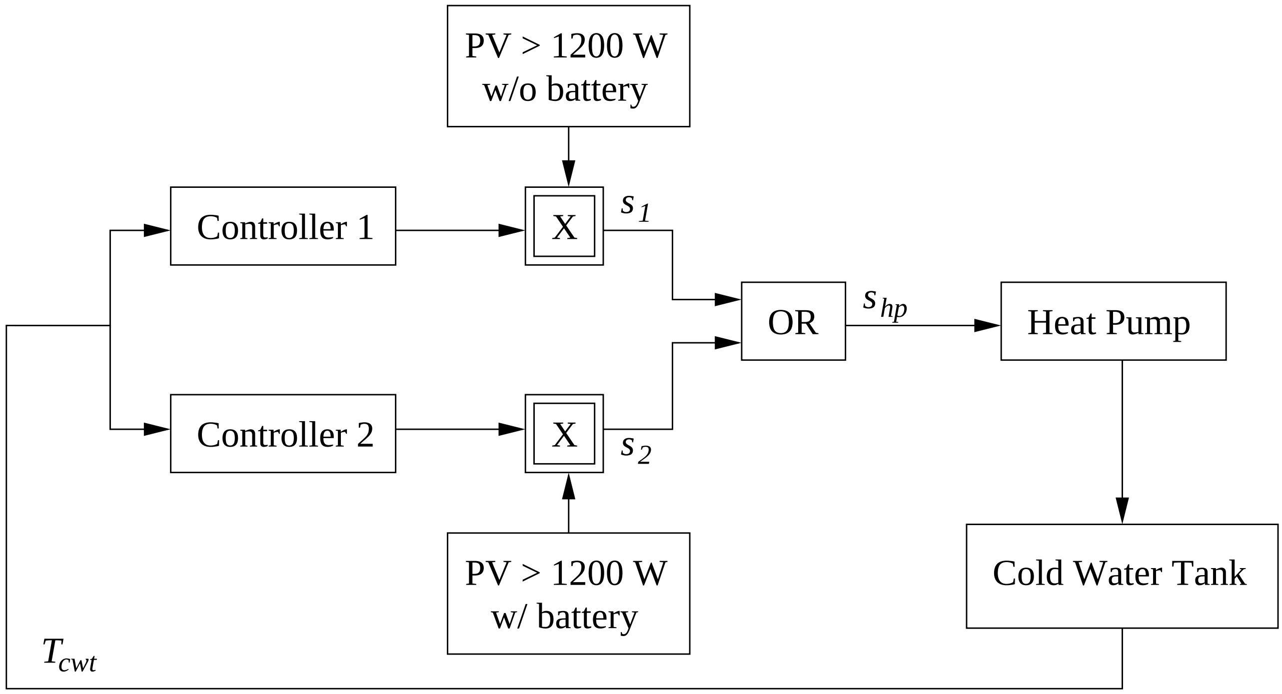

Figure 7.7: Heat pump - Feedback control loop

Controller 1 is set to 1 if T_{cwt}>5°C

Controller 2 is set to 1 if T_{cwt}>10°C

PV>1200 W, with battery provides a signal based on the approach described on page 62.

PV>1200 W, without battery provides a signal based on the approach described on page 62, but power outputs smaller than 1 200 W are treated like 0 W.

An overview about the different operating ranges depending on T_{cwt} are given in the table below.

T_{cwt}	T_{AHU}	Heat pump	AHU	TABS
<5°C	22°C	off	on Mo-Sa 9-16h	on 24/7
5-10°C	22°C	on if P_{PV}>1 200 W	on Mo-Sa 9-16h	on 24/7
10-12°C	22°C	on (backup power supply till 1 200 W)	on Mo-Sa 9-16h	on 24/7
12-15°C	eq.5.1	on (backup power supply till 1 200 W)	on Mo-Sa 9-16h	on 24/7
15-20°C	eq.5.1	on (backup power supply till 1 200 W)	on Mo-Sa 9-16h	off
>20°C	eq.5.1	on (backup power supply till 1 200 W)	off	off

Table 7.3: Overview of the system behaviour depending on T_{cwt}

The additional energy W_{add} required to operate at least one heat pump at partial load during the whole year whenever necessary (controller 2) is calculated using equations 7.3 and 7.4.

$$s(i,j) = s_{hp}(i,j) - s_1(i,j) \tag{7.3}$$

$$W_{add} = \sum_{\{i:\exists\, s_{ij}>0\}} (P \cdot (\frac{1}{20} \cdot \sum_j s(i,j))\mathrm{h} - P_{PV}(i) \cdot 1\mathrm{h}) \tag{7.4}$$

i Time variable - hour of the year from 1 to 8 760

j Three minute time step - 1 to 20 for every hour i

P Average power demand by two (three) heat pumps at full load - 5 000 W (7 500 W)

P_{PV} Average power output of the photovoltaic power plant during hour i

Equation 7.4 requires the availability of a short term electricity storage (battery) in order to be physically correct. In the most extreme case, controller 2 triggers the heat pump operation at the end of hour i. If two heat pumps are installed, they are then operated at full load at time step j=17 (thereby simulating part load operation for j=17 to 20). Since equation 7.4 subtracts the total electricity produced in the PV power plant during hour i (including j=1 to 16), the maximum additional total storage demand amounts to $\frac{16}{20}\mathrm{h} \cdot 1.2\,\mathrm{kW} = 0.96\,\mathrm{kWh}$.

8 TRNSYS Simulation - Refined Model

In this chapter, the heat pump signals created in section 7.3 are used to analyse the system behaviour in several variations. Two or three heat pumps and the small or large photovoltaic power plant are installed, respectively. For each variation, figures of the temperature in the cold water tank and the temperature in Zone OP are given.

8.1 Small PV Plant, 2 Heat Pumps

Figure 8.1, Temperature of cold water tank and T_{AHU}

April-November Apart from the weekends, the system is almost always dependent on additional electricity from the backup energy supply. Possible reasons include a low electricity yield of the photovoltaic power plant and a high energy demand of the AHU for dehumidification (figure 2.7).

December-March Most of the time the temperature in the cold water tank stays below 10°C. The small photovoltaic power plant and two heat pumps ensure a sufficient supply of cold water for the AHU and TABS.

Figure 8.2, Temperature in Zone OP

- In the wet season, the temperature in Zone OP is rather high, sometimes exceeding even 28°C. In this period the TABS cannot work effectively due to a high temperature in the cold water tank (figure 8.1).
- In December and January the temperature remains at a low level. Temperatures below 22°C might even be too cold. In this case, the mass flow in the TABS can be reduced significantly to save energy and to increase the temperature in Zone OP.

8.2 Small PV Plant, 3 Heat Pumps

Figure 8.3, Temperature of cold water tank and T_{AHU}

Figure 8.3 shows similar behaviour to figure 8.1.

Figure 8.4, Temperature in Zone OP

Again, only minor differences can be found when comparing figure 8.4 to figure 8.2.

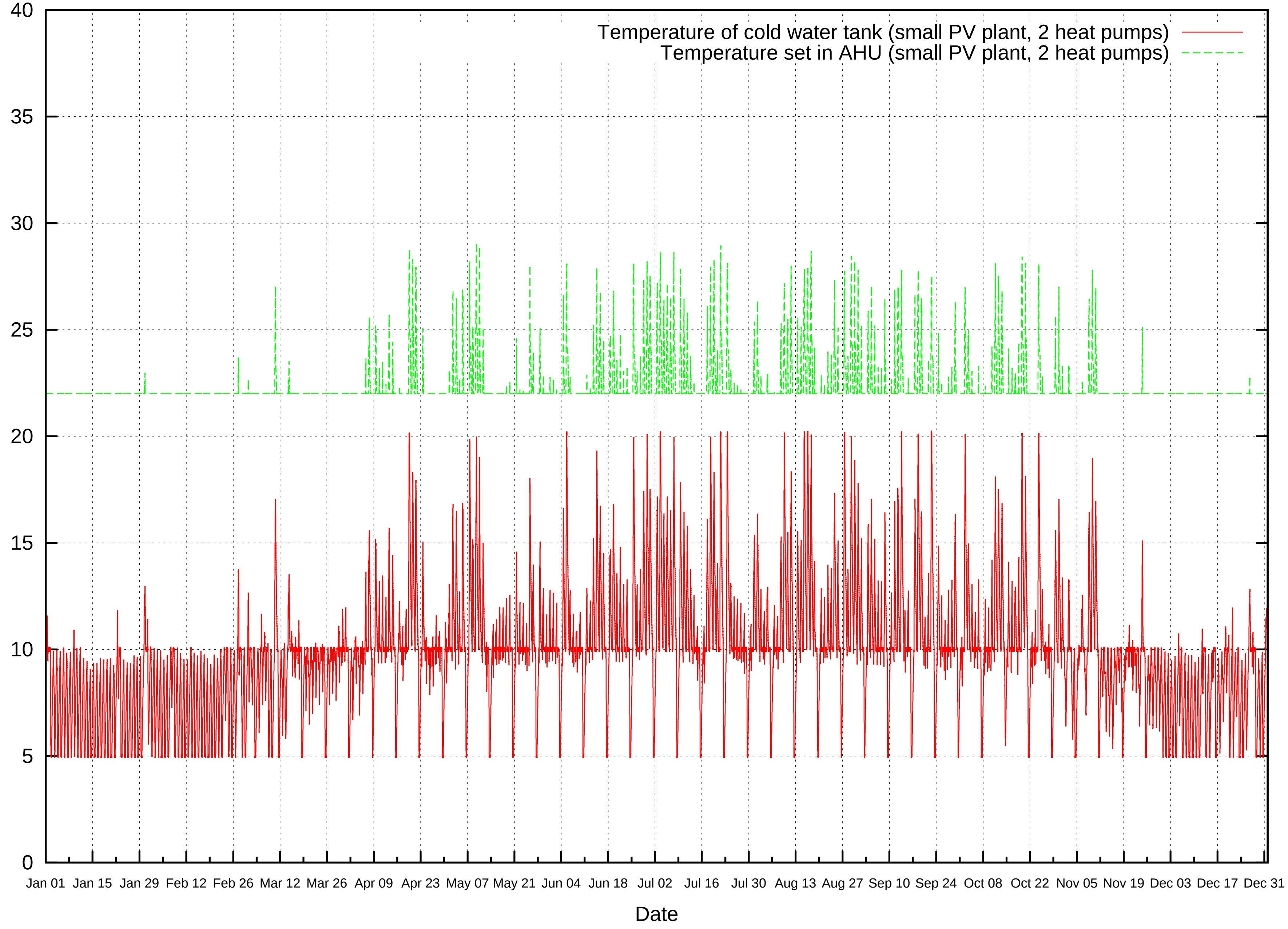

Figure 8.1: T_{cut} and T_{AHU} (small PV plant, 2 heat pumps)

Figure 8.2: Temperature in Zone OP (small PV plant, 2 heat pumps)

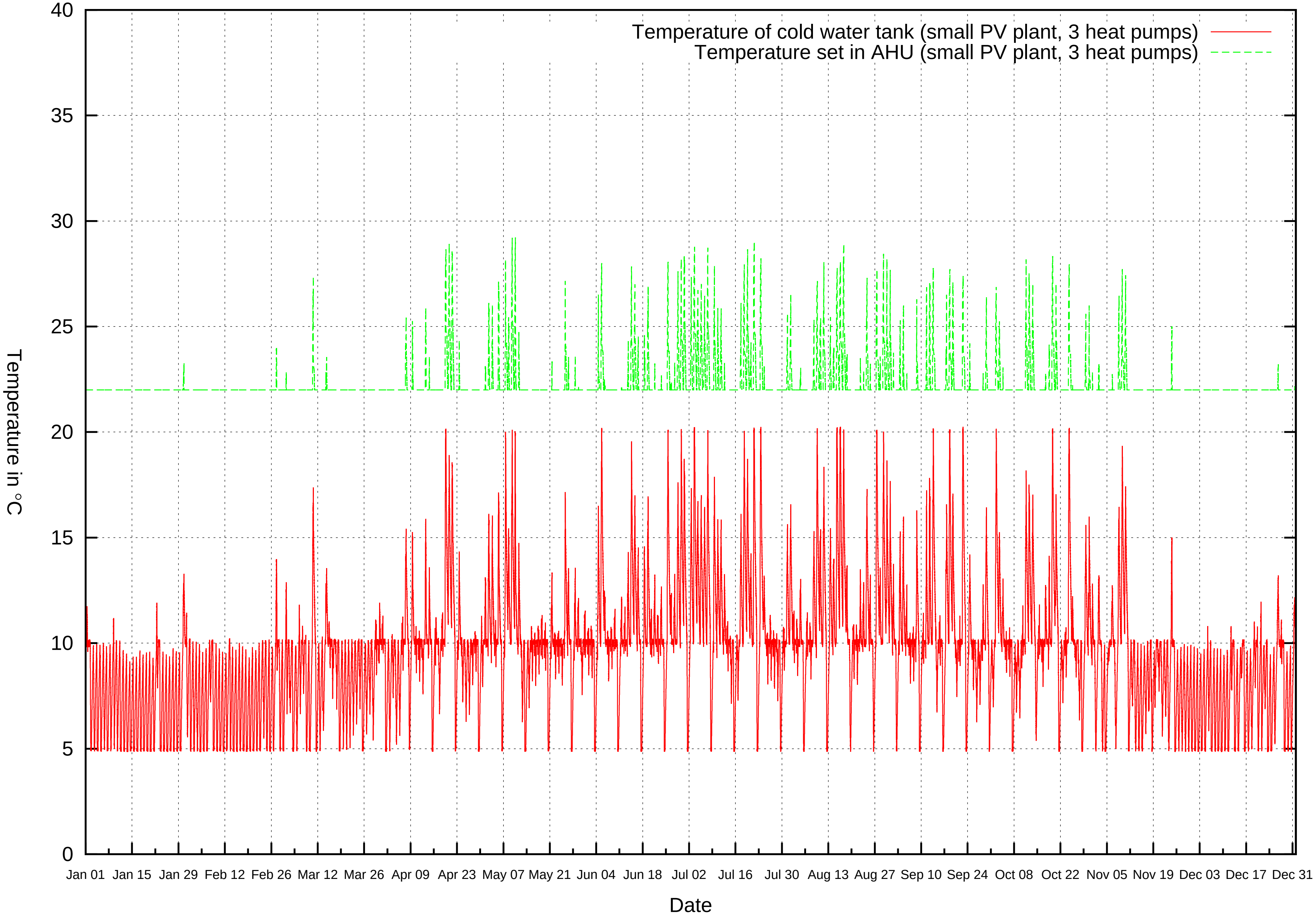

Figure 8.3: T_{cwt} and T_{AHU} (small PV plant, 3 heat pumps)

Figure 8.4: Temperature in Zone OP (small PV plant, 3 heat pumps)

8.3 Large PV Plant, 2 Heat Pumps

Figure 8.5, Temperature of cold water tank and T_{AHU}

The implementation of the large PV plant leads to a significant reduction of the peak temperature in the cold water tank during the wet season. In this period, also T_{AHU} (see equation 5.1) is significantly lower.

Figure 8.6, Temperature in Zone OP

The positive effect of the large PV plant can also be seen in figure 8.6. From April till October, the temperature level is lower than in figure 8.2. Sometimes, the temperatures in both figures are equal. During that time, the small PV plant is sufficient to ensure proper cooling of the operating room.

8.4 Large PV Plant, 3 Heat Pumps - Including In-depth Analysis

Figure 8.7, Temperature of cold water tank and T_{AHU}

This time, the third heat pump has a considerable impact on the temperature of the cold water tank. Since it is supplied with enough electricity from the large photovoltaic power plant, T_{cwt} stays between 5°C and 10°C most of the time even during the wet season, leading to a significant reduction of the operating hours of the backup energy supply.

Figure 8.8, Temperature in Zone OP

The positive effect of the third heat pump can also be seen in figure 8.8, leading to a lower temperature in Zone OP during several periods of the year. Again, too low temperatures in the operating room during December and January can be avoided by an appropriate regulation of the mass flow in TABS.

In-depth Analysis

The in-depth analysis can be found on page 75ff.

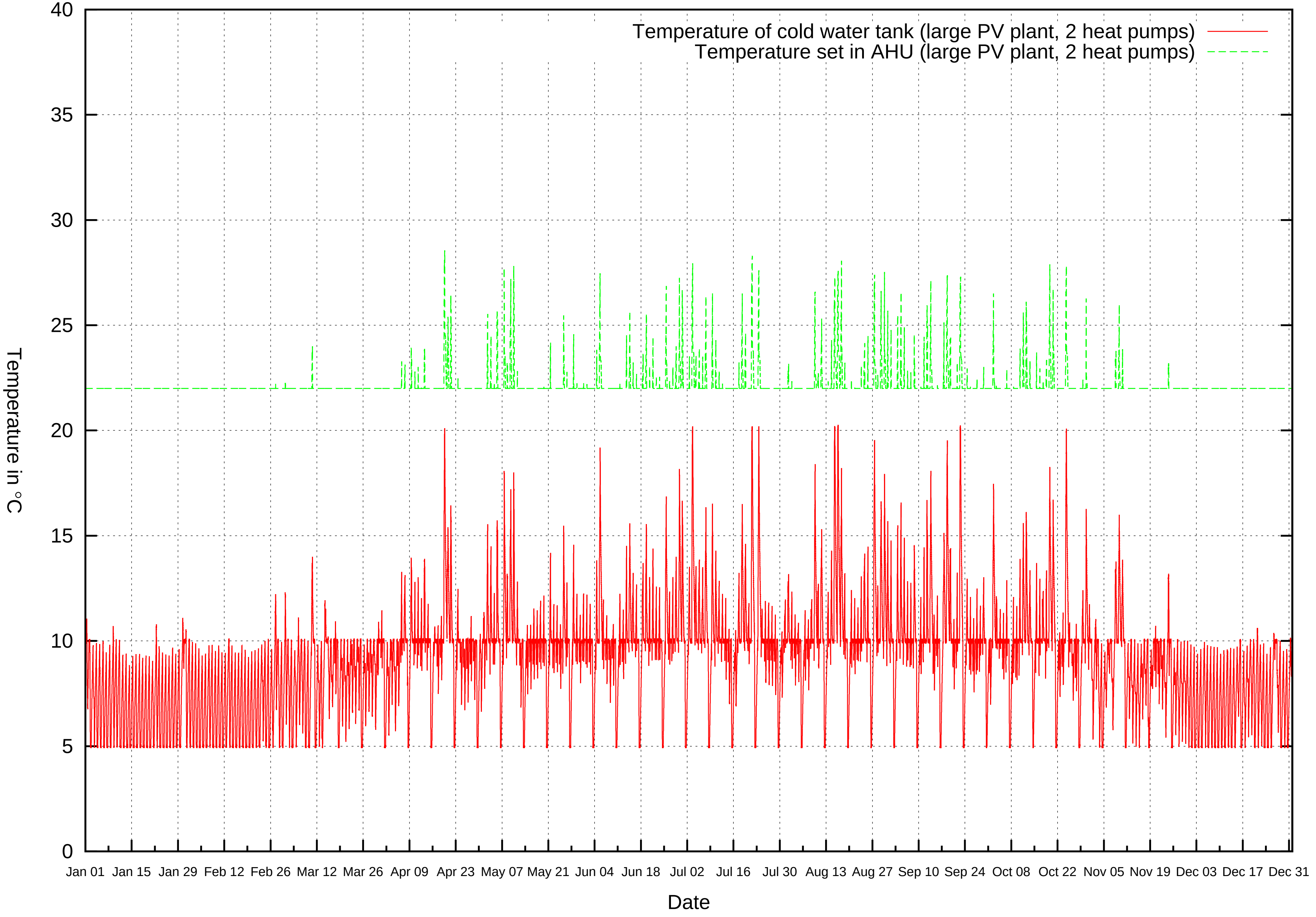

Figure 8.5: T_{cut} and T_{AHU} (large PV plant, 2 heat pumps)

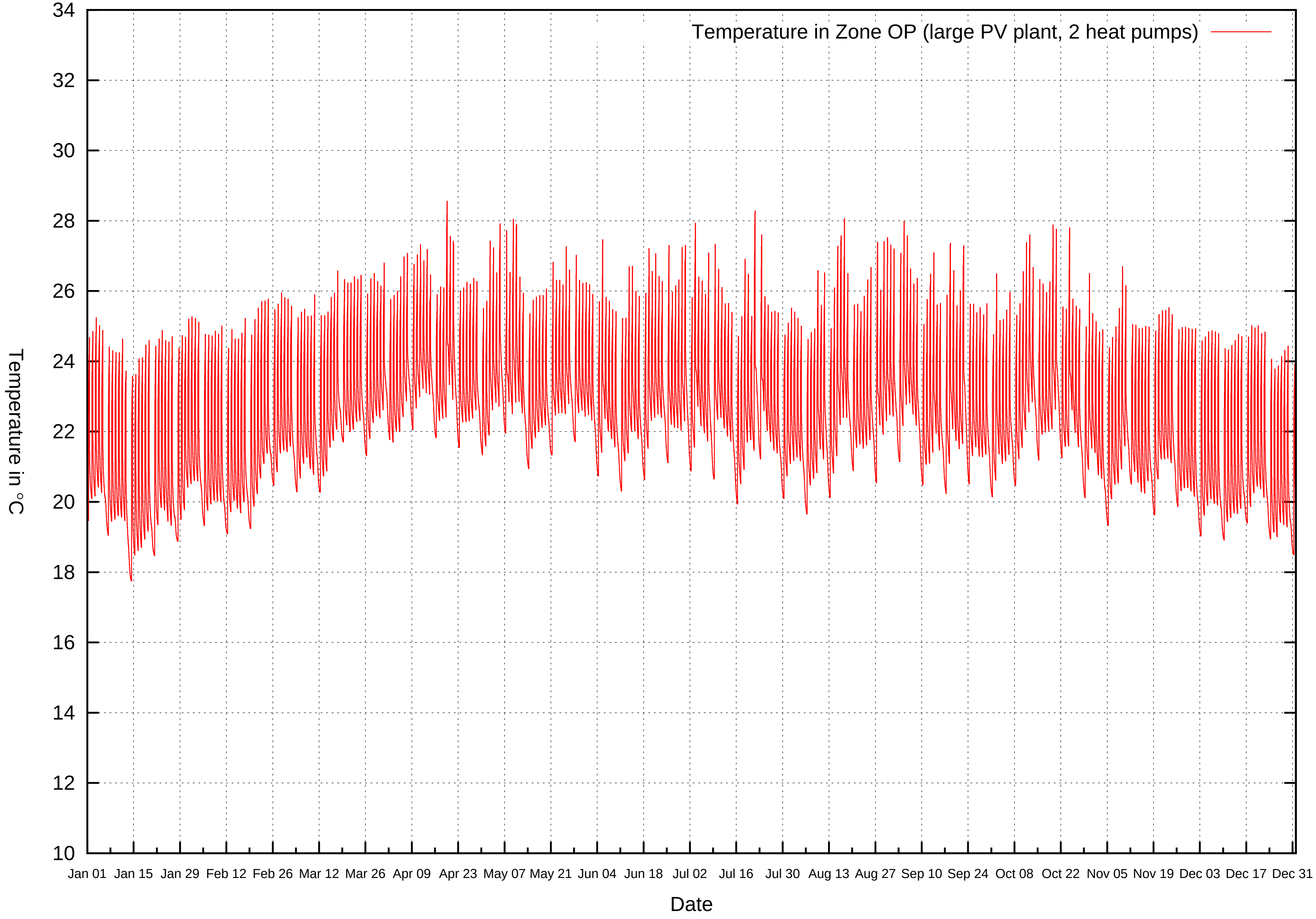

Figure 8.6: Temperature in Zone OP (large PV plant, 2 heat pumps)

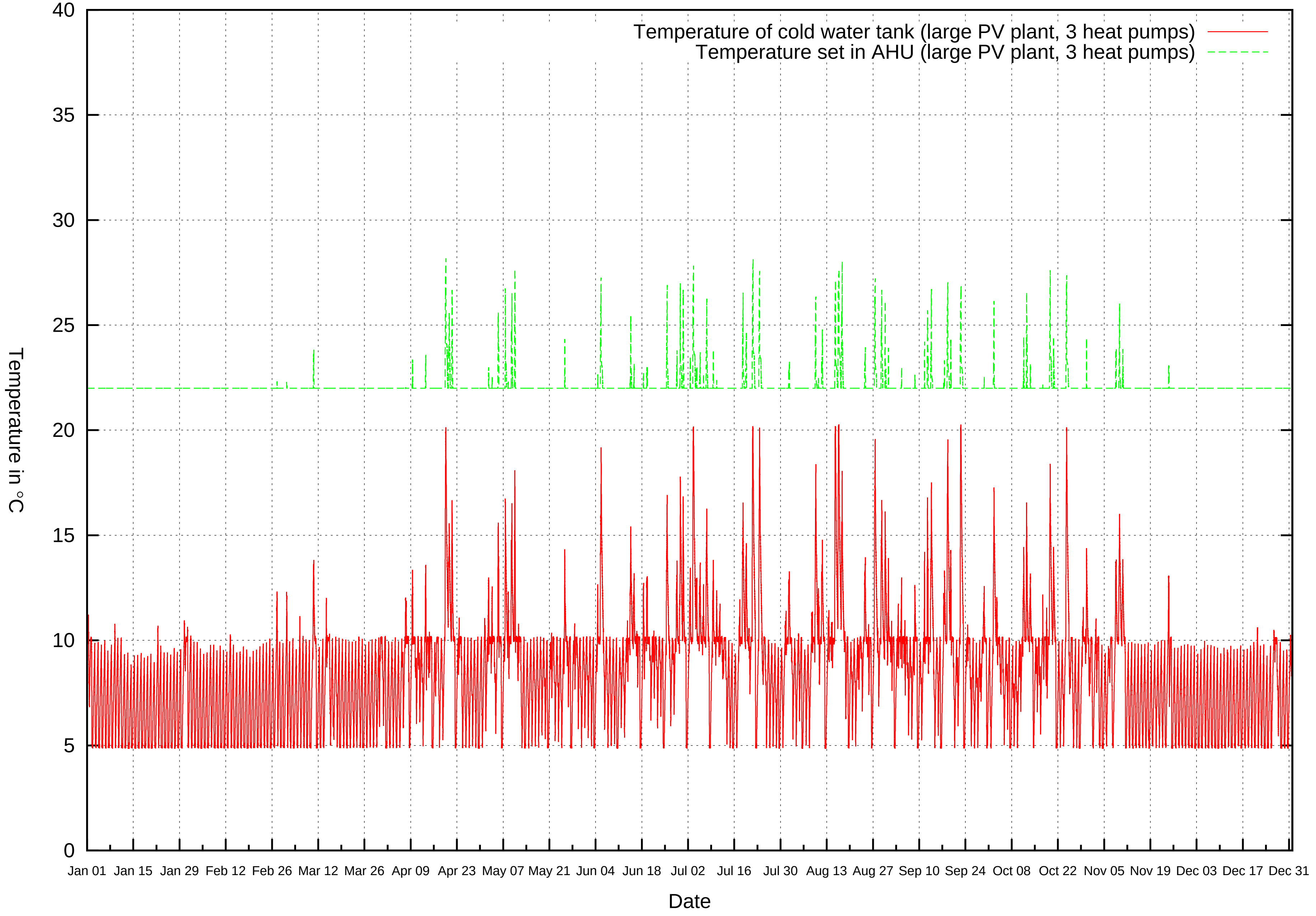

Figure 8.7: T_{cwt} and T_{AHU} (large PV plant, 3 heat pumps)

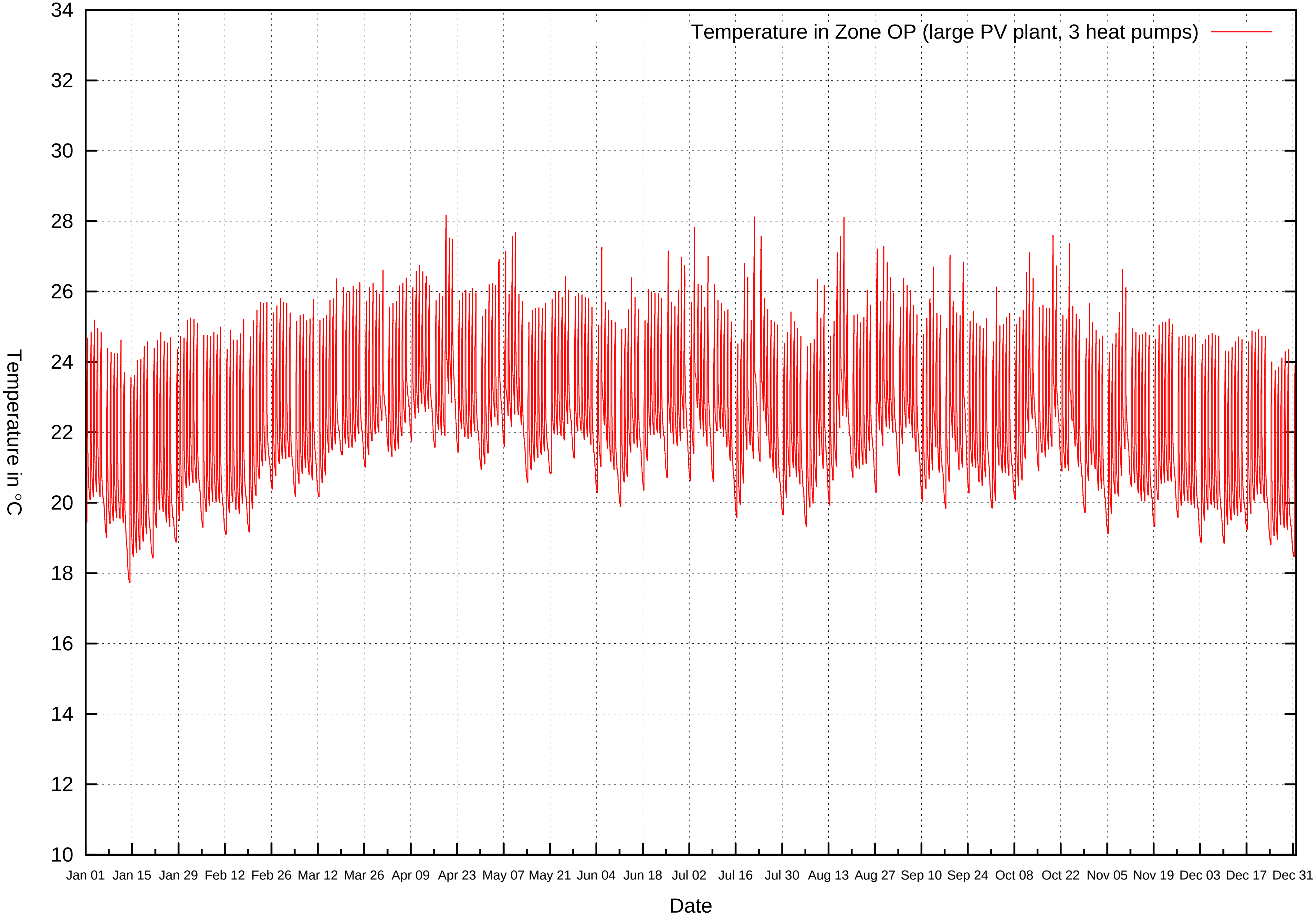

Figure 8.8: Temperature in Zone OP (large PV plant, 3 heat pumps)

In-depth Analysis

The figures above show that the implementation of the large PV plant combined with three heat pumps provides the most satisfying results. As a consequence, this version is investigated further.

Figure 8.9, Temperature in Zone A:[1]

The temperature of Zone A and the corresponding duration curve are given in figure 8.9. Since this area is not cooled by TABS or AHU, the air temperature is considerably higher than in Zone OP.

Figure 8.10, Duration curve of heat pump electricity consumption:

This duration curve represents the heat pump electricity consumption. As can be seen, the heat pump is operating 2 143 hours per year. The electricity consumption can be reduced by installing a more powerful cooling tower to lower the temperature in the hot water tank.

Figure 8.11, Energy transfers due to air conditioning:

Different energy transfers are depicted in figure 8.11.

- The energy transfer in the AHU is significantly higher from May till October which is not due to high temperatures (figure 2.6), but for the increased relative humidity (figure 2.7) leading to a high energy demand for dehumidification.
- In the TABS, the total energy transfer in kW seems to be rather small. However, the TABS is operating 24/7 whereas the AHU is restricted to "office hours" (9-16h).
- The energy transfers by TABS in Zone B1 and Zone B2 are almost identical. As a consequence, the first curve is hardly visible because it is covered by the second.

[1] Note: The air temperature in Zones B1 and B2 is almost identical to the temperature in Zone OP. Hence, it is not presented in this chapter.

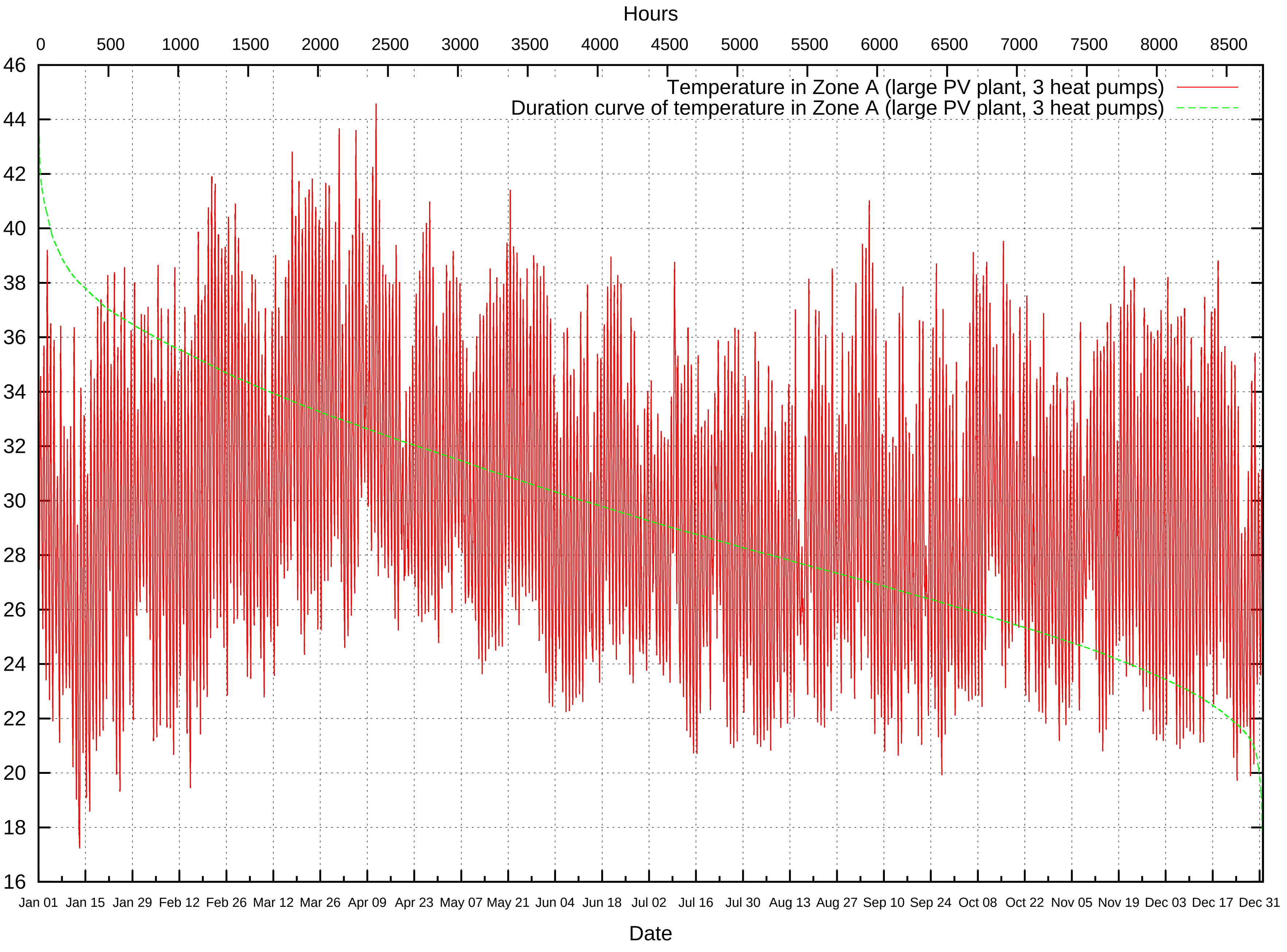

Figure 8.9: Temperature in Zone A

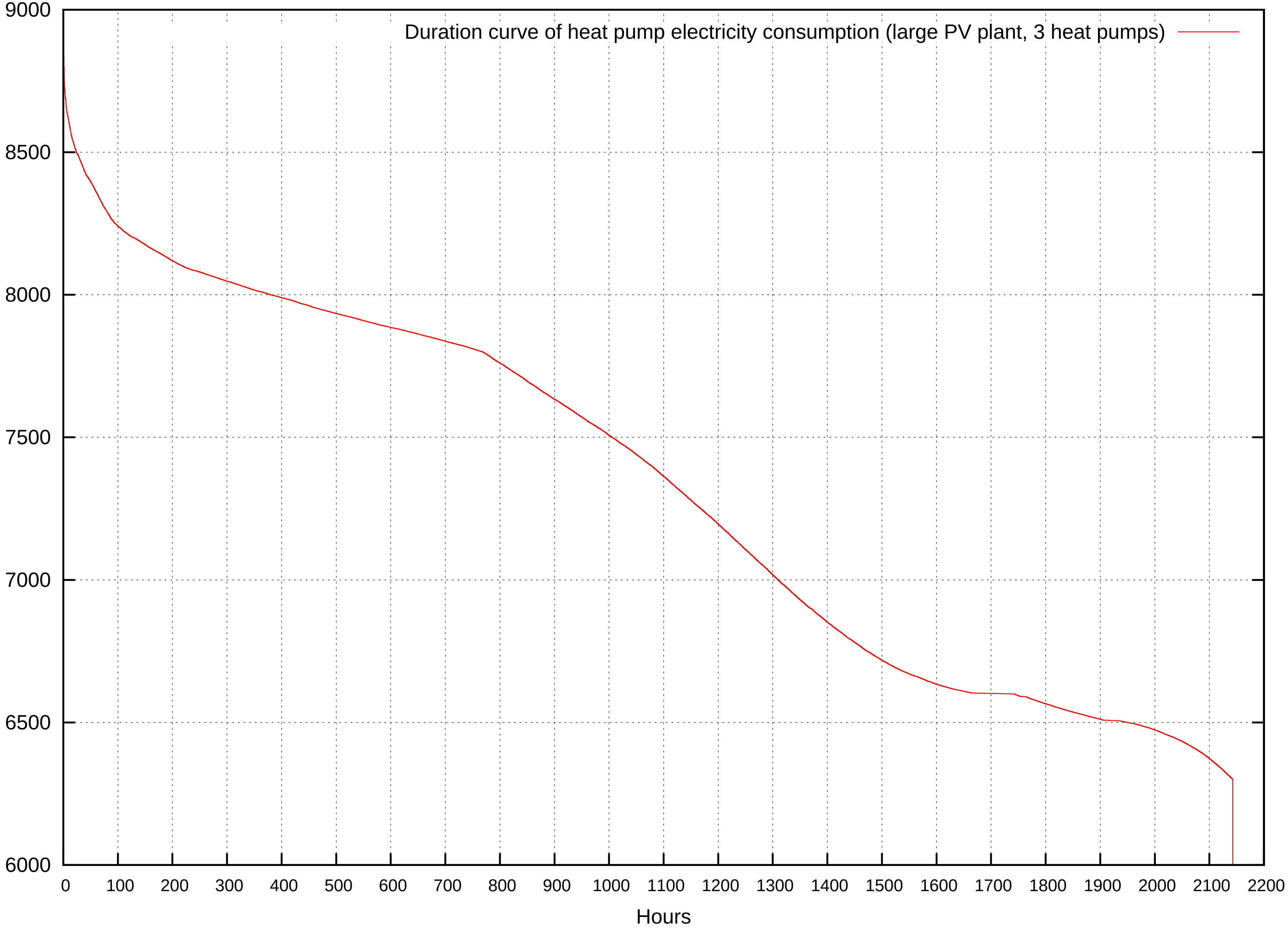

Figure 8.10: Duration curve of heat pump electricity demand

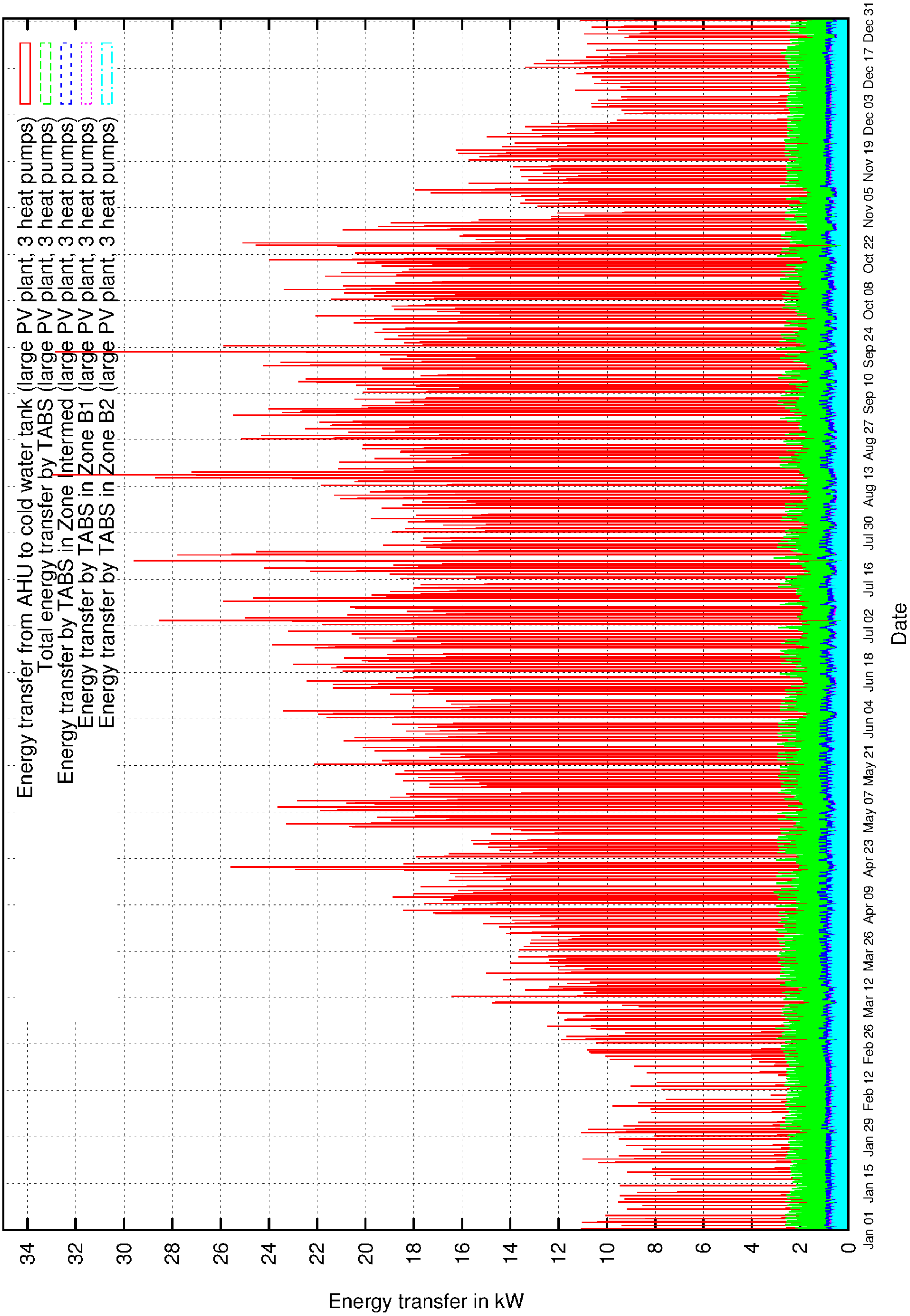

Figure 8.11: Energy transfers due to air conditioning

8.5 Comparison

Figure 8.12, Temperature duration curves of cold water tank:

Figure 8.12 clearly shows the influence of the size of the photovoltaic power plant. The duration curves based on the large PV plant meet all three temperature levels much earlier than the curves based on the small PV plant.
As expected, the large power plant in combination with three heat pumps gives the best results. When the available solar power exceeds 5 000 W (average consumption of two heat pumps), the third heat pump enables a better use of this free energy source. An additional electricity supply (T_{cwt}>10°C) is only necessary during 2 004 hours per year. The exact numbers are given in the table below.

	10°C	15°C	20°C
small PV, 2 heat pumps	4 171 h	444 h	31 h
small PV, 3 heat pumps	3 830 h	459 h	30 h
large PV, 2 heat pumps	3 100 h	214 h	15 h
large PV, 2 heat pumps	2 004 h	183 h	14 h

Table 8.1: Intersection of duration curves of T_{cwt} with 10°C, 15°C and 20°C

Figure 8.13, Duration curves of temperature set in AHU:

By installing the large PV plant in combination with three heat pumps, T_{AHU} stays at the desired level of 22°C for a much longer period of time, since T_{AHU} is heavily influenced by T_{cwt} (see equation 5.1).

Figure 8.14, Duration curves of temperature in Zone OP:

The duration curves of the temperature in Zone OP given in figure 8.14 are as expected. A larger photovoltaic power plant and more heat pumps lead to a lower temperature in Zone OP.

Figure 8.15, Edited temperature duration curves of cold water tank, 9-16h only:

Figure 8.15 is even more convincing. Only temperatures during office hours (Mo-Sa, 9-16h) are taken into account for the edited temperature curves. If the large plant and three heat pumps are installed, the temperature in Zone OP exceeds 25°C and 26°C during 558 hours and 109 hours, respectively.

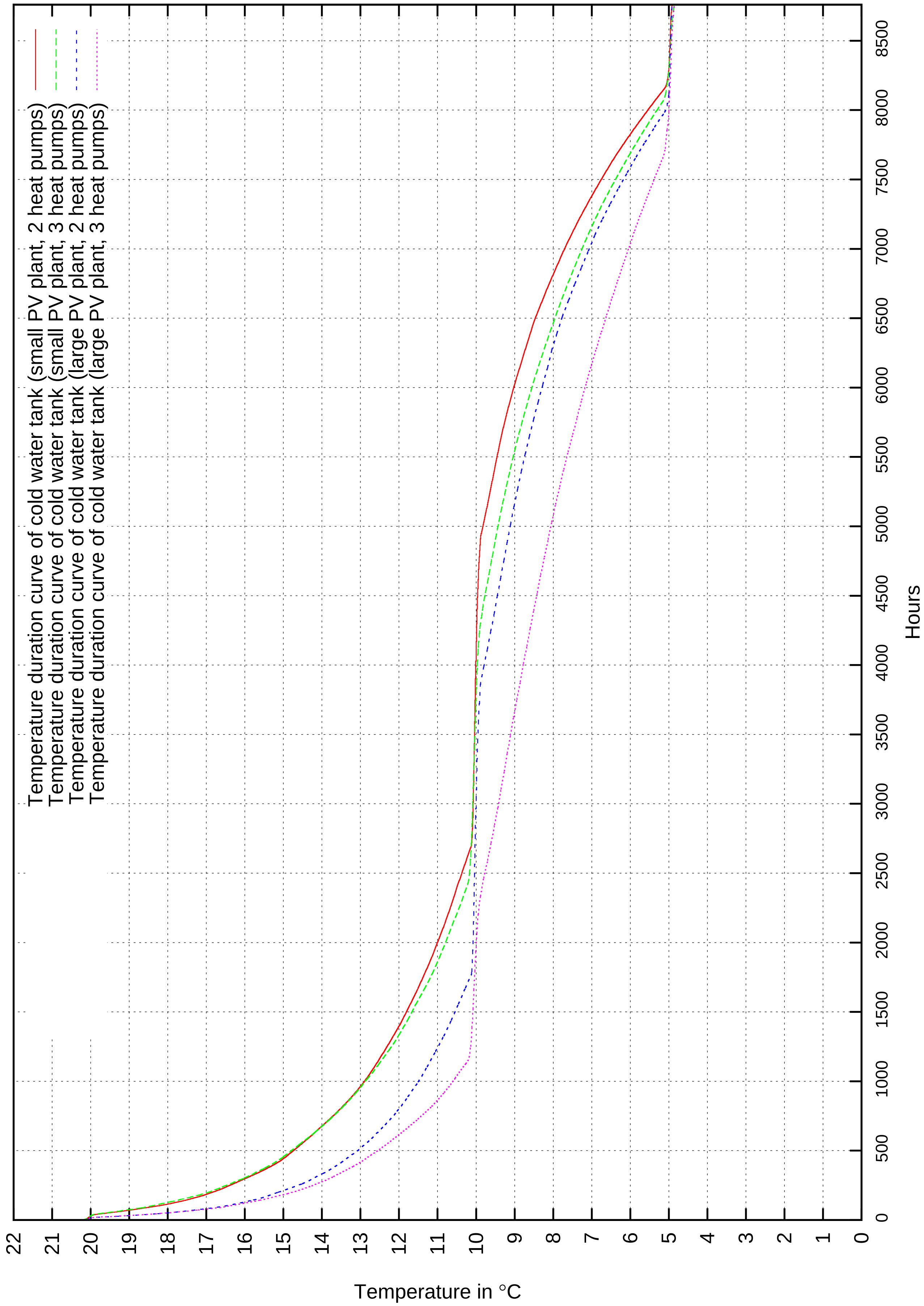

Figure 8.12: Temperature duration curves of T_{cwt}

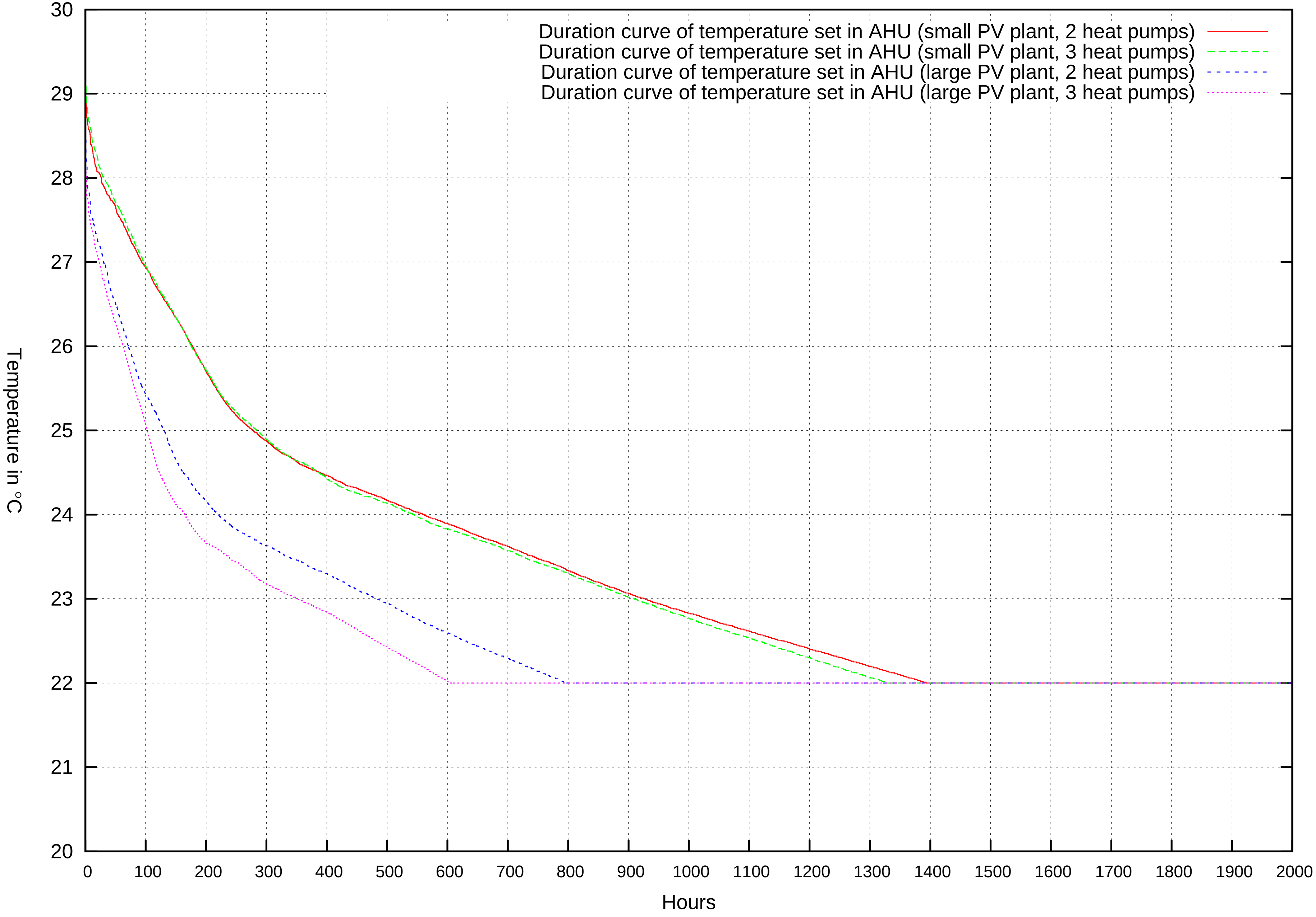

Figure 8.13: Duration curves of temperature set in AHU

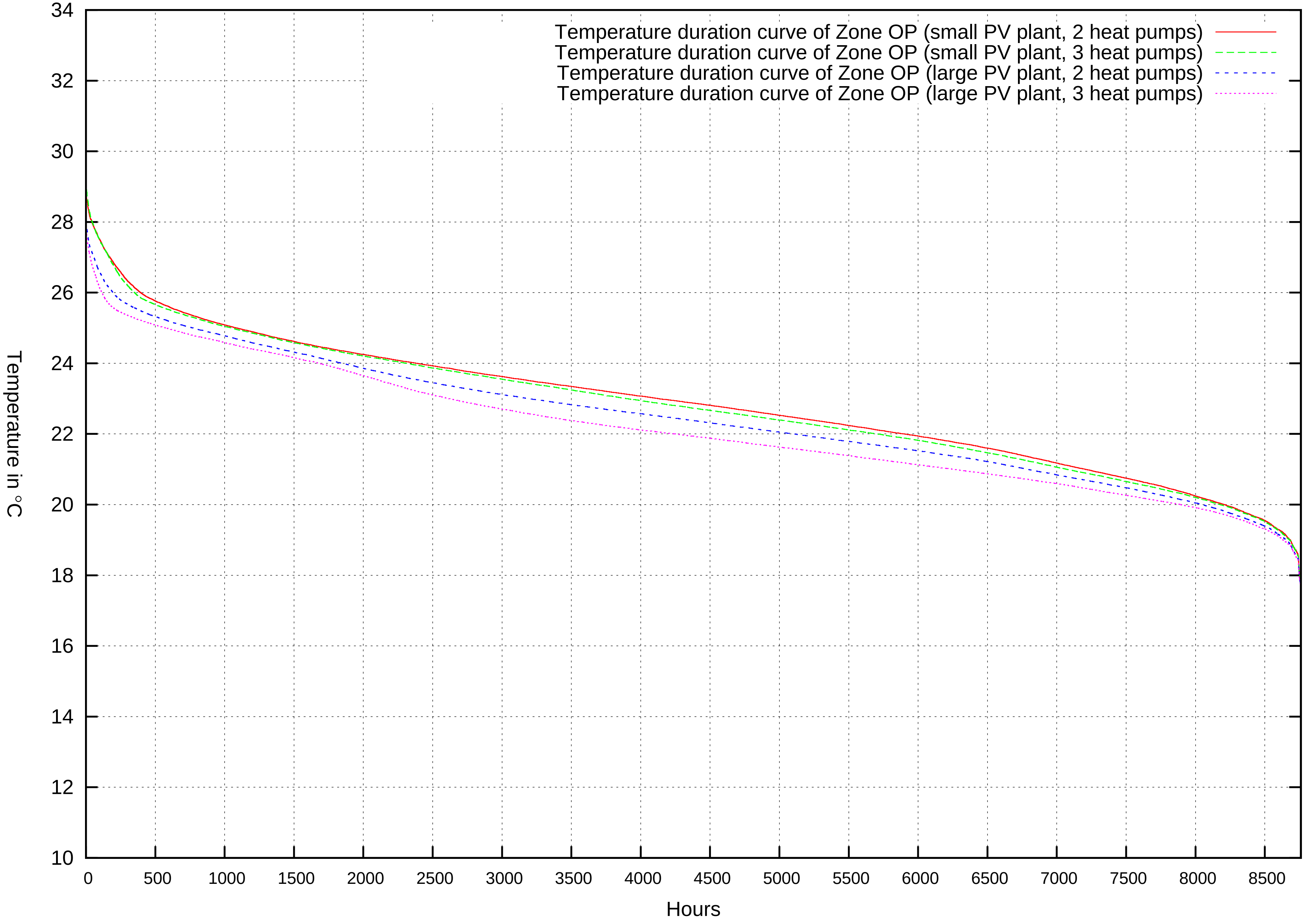

Figure 8.14: Duration curves of temperature in Zone OP

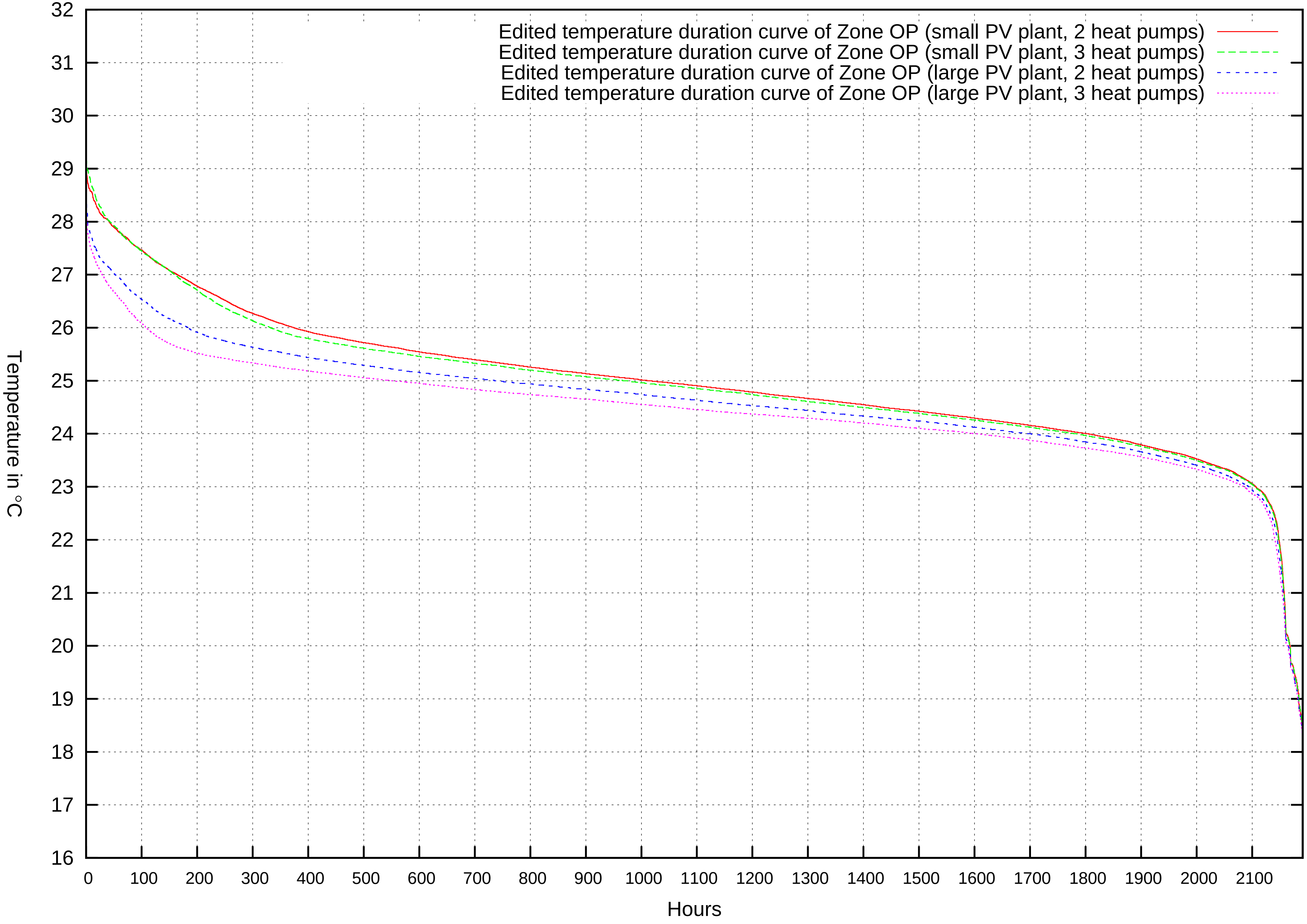

Figure 8.15: Edited duration curves of temperature in Zone OP (office hours only)

9 TRNSYS Simulation - Analysis and Discussion of Results

9.1 Results

The results of the different simulations suggest the following measures:

- Realisation of the large photovoltaic power plant (12.6 kW including yield loss factor[1])
- Installation of three identical heat pumps described in section 5.5.1
- Installation of TABS described in section 5.5.2
- Retaining of the original orientation of the building (figure 3.2)
- Implementation of the exit room
- Implementation of double glazing in the cooled area of the building
- Louver glass windows in Zone A stay open during the night

For the scenario based on the measures given above, an overview about the resulting operating ranges during one year (8 760 h) is given in the table below (based on table 7.3).

T_{cwt}	hrs/year	Heat pump	AHU	TABS
<5°C	730	off	on Mo-Sa, 9-16h	on 24/7
5-10°C	6 026	on if P_{PV}>1.2 kW	on Mo-Sa, 9-16h	on 24/7
10-15°C	1 821	on (backup power supply till 1.2 kW)	on Mo-Sa, 9-16h	on 24/7
15-20°C	169	on (backup power supply till 1.2 kW)	on Mo-Sa, 9-16h	off
>20°C	14	on (backup power supply till 1.2 kW)	off	off
	8 760			

Table 9.1: Overview of the system behaviour depending on T_{cwt} during a whole year

If the photovoltaic power plant provides less than 1.2 kW, the backup electricity supply based on a diesel generator and batteries have to provide up to 1.2 kW in order to supply additional electrical power for a permanent operation of one heat pump at partial load, if necessary (Controller 2 in figure 7.7). This required additional energy W_{add} is calculated using equation 7.4. The volume V_{diesel} of the respective diesel consumption is given below.

[1]for details, see page 55

$$V_{diesel} = \frac{W_{add}}{\rho_{diesel} \cdot LHV \cdot \eta} = \frac{1\,045\,\frac{\mathrm{kWh}}{\mathrm{year}} \cdot 3}{0.82\,\frac{\mathrm{kg}}{\mathrm{l}} \cdot 11.8\,\frac{\mathrm{kWh}}{\mathrm{kg}}} = 324\,\frac{\mathrm{l}}{\mathrm{year}} \tag{9.1}$$

in which ρ_{diesel}=0.82 $\frac{\mathrm{kg}}{\mathrm{l}}$ is the density of diesel, LHV=11.8$\frac{\mathrm{kWh}}{\mathrm{kg}}$ the lower heating value and η=$\frac{1}{3}$ the efficiency of the diesel generator.

- Due to W_{add}, this equation demands an available short term electricity storage (battery) of up to 0.96 kWh to be physically correct (explained on page 64). If this storage capacity is not installed, the diesel consumption will be slightly higher than calculated.
- As can be seen in table 9.1, the AHU is switched off for 14 hours per year to limit the temperature in the cold water tank. This is not acceptable for hygienic reasons. Additional backup power higher than 1 200 W has to be provided to keep T_{cwt} below 20°C all year long. Since the considered period is only 14 hours, the resulting total diesel consumption will only be a few percent higher than 324 $\frac{\mathrm{l}}{\mathrm{year}}$ (equation 9.1).

9.2 Backup Electricity Supply

Among others, the following measures present simple options to reduce the diesel consumption of the backup electricity supply significantly:

- Reduction of air change rate in Zone OP (After consultation with the medical staff only!)
- Increase of the storage capacity of the cold water tank by cooling the water to e.g. 4°C instead of 5°C (Attention to potential freezing in the heat pump!)
- Increase of T_{AHU} and thereby T_{OP}
- Increase of the desired humidity level (Attention to potential water condensation and formation of mold in Zone OP due to TABS!)

9.3 Potential Errors

This section gives an overview of different errors which might occur in the TRNSYS simulation described in this diploma thesis.

Modelling

The accuracy of the modelling is of great importance in any numerical simulation. In TRNSYS, many different systems have already been modelled in a large variety of TRNSYS types. Alas, some of the machines to be used at the hospital site are not that common yet. No corresponding types have been developed up till now. It is obvious that a more accurate modelling might lead to more accurate results, as can be seen in section 9.4.

External Data

- Weather Data: Reliable weather data either from satellites or recorded manually at the given site is extremely helpful. Still, weather is by far the largest random variable of the system. As a consequence, parameters like solar irradiance or humidity might vary significantly from year to year. In addition to that, it is difficult to guess the deviation of the "standard" year used in the simulation unless weather data is recorded permanently at the hospital campus.
- Heat Pump: Data about the heat pump is given for certain operating points. However, all of them supply data under full load since TRNSYS type 668 does not enable partial load operation. Also, interpolation between the operating points represents a potential source of error.

Computational Errors

- Rounding errors: Every simulation is limited by the available computing capacity. Since memory and calculation speed are restricted, rounding errors must occur in every model calculation. Unfortunately, the TRNSYS user can hardly keep track of the existence and magnitude of rounding errors.
- Time step: Choosing the right time step is of vital importance. The smaller the time step, the higher the accuracy of the solution. However, restrictions concerning computing capacity have to be taken into account as well. First, a time step of one hour is chosen to calculate the system behaviour, which is a good tradeoff for the parameters analysed in chapter 6. However, a time step of 60 minutes is too coarse to describe certain phenomena at a satisfying level. In chapter 7 and chapter 8, the time step is reduced to three minutes (for details, see section 7.3).

User Errors

User errors include e.g. incomplete or wrong parameter sets for a given TRNSYS type or false connections between types. To avoid errors and to facilitate fault finding in the development process the TRNSYS model is built up gradually. After each step the results of a test run are analysed and compared to previous results. Thereby, qualitative control is possible up to a certain level (e.g. the installation of a larger photovoltaic power plant increases the (possible) number of operating hours of the heat pump). However, quantitative control is difficult since no results of similar simulations or measurements of already existing buildings are available. Also, misinterpretation of the simulation results represents a possible source of errors caused by the user.

Propagation of Errors, Stability

A quantitative error estimation based on well established statistical methods is not feasible due to the lack of error bars associated with the various quantities calculated in this TRNSYS simulation. As a consequence, errors can compensate or - much worse - accumulate each other. Instead, the stability of the model was tested semi-quantitatively by varying the input parameters over a reasonable range.

9.4 Potential Improvements

There is always a way to make it better. Certain measures that have not been implemented for a lack of resources, might significantly enhance the accuracy and integrity of the simulation results. A brief overview is given below.

Air Handling Unit - AHU

The air handling unit is represented in type 334. This type calculates the energy consumption to cool and dehumidify air to a certain setpoint. However, the actual installation uses water from the cold water tank to cool down the supply air of the operating room, as can be seen in figure 5.3. Programming a new TRNSYS type exceeds the scope of this thesis. Still, as soon as a more suitable type is available the simulation could be rerun to compare results.

Heat Pump

A significant amount of time, the heat pump will be in partial-load operation since the electric power supplied by the solar panels is volatile and has to be used immediately. Unfortunately, TRNSYS type 668 is not able to simulate partial-load behaviour. Although basically implemented (section 7.3), a better modelling of partial-load operation can particularly improve the accuracy of the results, especially when focusing on short-term changes like temperature curves during a particular day. Apart from a refined TRNSYS type, additional corresponding data about the cooling performance of the heat pump has to be provided by the heat pump manufacturer.

Control Engineering

As soon as a refined TRNSYS type is provided to simulate the heat pump behaviour, an appropriate feedback control system must be included in the simulation. When the photovoltaic power plant provides enough power, the controller must run the heat pump in partial-load. In addition to that, the operating room could be cooled slightly below the desired level and thereby act as an additional "cold" storage.

Short Term Behaviour

Smaller time steps might enable a better analysis of short term behaviour like peak temperatures:

- Zone Sterilis: In this zone, a large amount of heat is emitted by the autoclave. On average, the sterilisation process takes place once a day and lasts for around 35 minutes. As a result, a time step of three minutes is too coarse for a reliable calculation of the temperature profile in this zone during and immediately after the process.
- Zone Roof A and Roof B: These zones are particularly exposed to solar irradiation. Peak temperatures that might occur during several minutes per day can only be assessed roughly. For the analysis of peak temperatures, a simulation of the hottest week of the year with a time step of e.g. one minute might be a recommendable option.

9.5 Outlook

The operating room is going to be built in the near future. When the hospital campus is put into operation, the parameters simulated in this thesis should be recorded in order to verify the accuracy and integrity of the simulation results. Also, permanent recording of weather data at the hospital site would enable a more thorough analysis of the quality of the simulation results.

Nomenclature

Abbreviations

AAA Arkangelo Ali Association

AHU Air Handling Unit

BBM BeschaffungsBetrieb der Missions-Verkehrs-Arbeitsgemeinschaft

COP Coefficient Of Performance

DKA DreiKönigsAktion

eRko Christian Children Communities Movement

HEPA High-Efficiency Particulate Air filter

HVAC Heating, Ventilation and Air Conditioning

LED Light Emitting Diode

MEP Mechanical, Electrical and Plumbing

MIVA MIssions-Verkehrs-Arbeitsgemeinschaft

MSF Médicins Sans Frontières

NGO Non-Governmental Organisation

OR Operating Room

TABS Thermally Activated Building System

TRNSYS TRaNsient SYstems Simulation

Variables

η Efficiency of the diesel generator

ϕ Relative humidity in %

ρ Density of water in $\frac{\mathrm{kg}}{\mathrm{m}^3}$

ρ_{diesel} Density of diesel in $\frac{\mathrm{kg}}{\mathrm{l}}$

C Capacity factor

c_p Specific heat capacity of water in $\frac{\mathrm{kJ}}{\mathrm{kgK}}$

LHV Lower Heating Value of diesel in $\frac{\mathrm{kWh}}{\mathrm{kg}}$

P Average electrical power demand by two or three heat pumps, respectively

Q_{AHU} Energy transferred to water in the air handling unit (AHU) in kJ

$Q_{thermal}$ Energy storage capacity in kWh

T_{AHU} Temperature of the air exiting the AHU and entering Zone OP in °C

V_{cwt} Volume of Cold Water Tank in m^3

V_{diesel} Diesel consumption in $\frac{\mathrm{l}}{\mathrm{year}}$

w_{actual} Electricity production of the photovoltaic power plant in one year in kWh

W_{add} Additional Energy that has to be provided by the backup power source to ensure part load operation of one heat pump throughout the year

w_{theor} Electricity production of the photovoltaic power plant in one year if it had operated at nominal power the entire time in kWh

x Absolute water content of the air exiting the AHU and entering the cooled zones in $\frac{\mathrm{g}}{\mathrm{kg}}$

ΔT Temperature increase in cold water tank due to air handling unit (AHU) in K

$\Delta\theta$ Temperature gap in K

P_{cool} Heat transfer rate of one heat pump in kW

P_{el} Electrical power demand of one heat pump in kW

T_{cwt} Temperature in the cold water tank in °C

T_{hwt} Temperature in the hot water tank in °C

AM Air mass

E Solar radiation in $\frac{\mathrm{W}}{\mathrm{m}^2}$

Imp Max. power current in A

Isc Short circuit current in A

m Water mass in the cold water tank in kg

$Pmax$ Peak power in W

U Overall heat transfer coefficient (U-value) in $\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$

Vmp Max. power voltage in V

Voc Open circuit voltage in V

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