IEA ECES ANNEX 20

SUSTAINABLE COOLING WITH THERMAL ENERGY STORAGE

FINAL REPORT

Summary

Annex 20 followed a project oriented approach for optimized integration of Thermal Energy Storage (TES) in cooling systems by demonstrating and evaluating the sustainability (energy saving and CO2 emission reduction) of cooling system with TES system.

The objectives of the Annex 20 were

- Subtask A "Demonstration projects & system performance evaluation for actual projects".
  - Technology development (short-term, long-term, alternative combinations of short-term with long-term TES utilizing renewable/natural energy).
  - Establishment of design method (evaluation of design tools)
  - Feasibility studies
  - Demonstration projects

- Subtask B "Design procedure and system performance evaluation tools."
  - Existing design manuals and tools for the short and long term thermal storage will be reviewed using inventory developed in Annex 14 or from other activities.
  - Evaluation of design tools with respect to possibility of their use in various stages of design procedure will be examined.
  - For a specific system, performance evaluation with two or more design tools will be performed, and the results will be compared.

- Subtask C "Information Dissemination and technology transfer"

For information Dissemination and Technology Transfer within participating countries and to other countries, the following meetings and workshops were organized.

- Kick-off Meeting and Workshop Sep. 14 – Sep. 16, 2005, Nagoya, Japan
- Meeting and Workshop Jun. 03.2006, Stockton USA
- Meeting and Workshop 28.-29.11.2006, Stockholm, Sweden
- Meeting and Workshop (only Subtask B) 30.11.2006, Stockholm, Sweden
- Meeting and Workshop 23.-25.04.2007, Beijing, China
- Meeting and Workshop 27.-28.11.2007, Ankara, Turkey
- Meeting and Workshop 26.-27.05.2008, Seville, Spain
- Meeting and Workshop 24-25.11.2008, Seoul, Korea
- Meeting 14.06.2009, Stockholm, Sweden

- Meeting 16.-17.11.2009, Nagoya, Japan

Especially at the meeting in Beijing, many researchers, who were interested in TES technologies participated from China.

The achievements of Annex 20 can be summarized as:

- Monitored data from 20 demonstration plants from eight countries using six different thermal energy storage techniques were evaluated in terms of sustainability.
- In these systems thermal energy storage was the central component that provided cooling for the built environment using different cold sources.
- Different sources are made available for cooling with thermal energy storage. In the demonstration projects, these were renewable energy (solar), natural sources (ambient outside air, ocean water, Underground, air inside greenhouse) and waste heat (from CHP plant).
- For seasonal purposes, UTES (ATES, BTES and energy plies) systems and ground coupled heat pumps give efficient solutions.
- With appropriate climate conditions seasonal free cooling systems have COPs in the range of 10 – 30.
- PCM is incorporated in building materials for passive cooling and decrease heating and/or cooling demand.
- For short term systems (ice and water), measured storage efficiencies were around 100%.
- Primary energy conversion COPs of the projects are greater than 1 indicating energy conservation and reduction of CO_2 emissions.
- Combined use of absorption chiller units and cold water storage is realized to increase efficiency of combined heat and power plant (CHP) and utilize waste heat as source for absorption chiller.
- Existing design manuals and tools for the short and long term thermal storage were reviewed and an inventory comparing different aspects was made.
- Monitoring of plants and climate data is very important for benchmark in Subtask A and the evaluation of design tools in Subtask B. The measured data show the real boundary conditions and the efficiency.
- For a specific system, performance evaluation with two or more design tools was performed, and the results were compared.

For future work the following recommendations can be given:

- Update and/or complete missing data in the project database
- R&D activities on cross-sectional between different thermal storage and hybrid systems
- Performing life cycle analysis of TES with cooling systems

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1.1. Introduction

Energy consumption is increasing every day, especially for cooling applications. This situation results in higher greenhouse gas emissions, global warming, increase of the pollution and short availability of fuels.

Annex 20 follows a project oriented approach for optimized integration of TES in cooling systems by demonstrating and evaluating the sustainability of cooling system with TES. Within this scope, cooling achieved through a system that

- reduces energy demand
- maximizes the use of renewables
- uses energy resources most efficiently

and as a result reduces CO_2 emissions is considered to be sustainable within the scope of this Annex.

Annex 20 aims to demonstrate the prospects of sustainable cooling using **short-term, long-term and alternative combinations of short-term with long-term** thermal energy storage**.**

In Subtask A, demonstration projects for implementation of thermal energy storage in energy systems has been carried out in participating countries. Table 1 gives the list of countries and representative bodies responsible for each project.

Table 1. Countries and representative bodies for the demonstration projects

Country	Representative Body	Project #	References
Canada	High Performance Energy Systems	D1	-
China	Hundred Group	D2, D3	-
Germany	Chemnitz University of Technology	D4	[1-7]
	Technical University of Braunschweig	D5 - D9	[8-12]
Japan	Harumi DHC, Gifu Building	D10, D11	-
Spain	University of Lleida	D12 – D14	[13-24]
	University of Zaragoza	D15	[25-28]
Sweden	SWECO	D16 – D17	[29-32]
Turkey	Cukurova University	D18	[33-34]
USA	Richard Stockton College	D19-D20	-
Total		**20**	

The systems were evaluated based on data from a monitoring program of the actual thermal energy storage.

This report gives the results of Subtask A based on the deliverables from the demonstration projects.

1.2. Thermal Energy Storage Technologies

Cooling with thermal energy storage technologies covered in the demonstration projects in Subtask A are classified as follows:

- Long term
  - Underground Thermal Energy Storage(UTES)
- Short term
  - Phase Change Materials (PCM)
    - PCM in building envelope
    - PCM in HVAC
  - Ice Storage
  - Chilled Water Storage

1.2.1. Underground Thermal Energy Storage

Underground soil and/or rock provide a large, invisible and isolated storage volume. UTES technologies use the heat capacity of this volume to store thermal energy from any natural or artificial source for seasonal or diurnal applications. These technologies, shown in Figure 1 are:

- Aquifer Thermal Energy Storage (ATES)
- Borehole Thermal Energy Storage (BTES)
- Thermal Energy Storage in Building Foundation Piles
- Cavity Thermal Energy Storage (CTES)
  - Caverns
  - Pits

1.2.1.1. Aquifer Thermal Energy Storage(ATES)

ATES involves the free cooling or heating from an aquifer - natural ground water basins – using groundwater as the medium of heat transfer between an external energy source and the aquifer. The groundwater has a constant temperature normally related to the mean annual temperature of the site. During the winter natural or artificial cold is stored at the cold side of the aquifer while pumping away heat from the warm side. During the cooling season the stored cold is pumped back and the waste heat from the cooling process is stored at the warm side. A heat exchanger transfers the heat or cold from the groundwater loop to the user. The aquifer is connected by conventional water wells, one or several at each side. In many cases the ATES systems combine heating and cooling, often by using a heat pump for an extended heat or cold production.

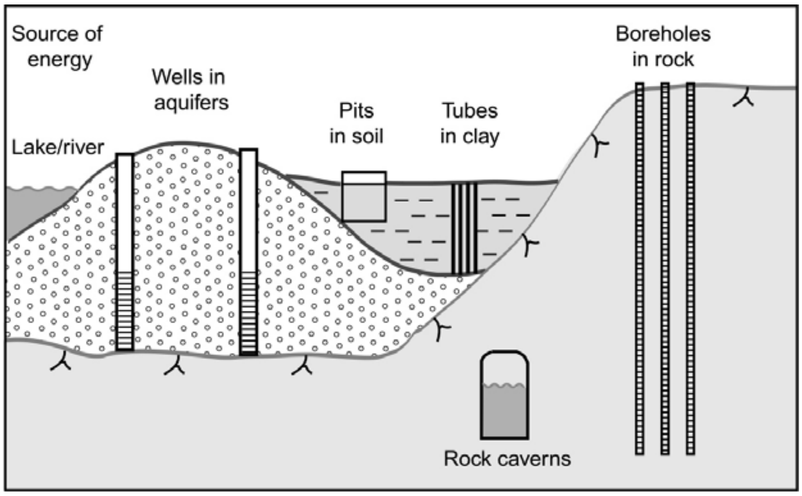


Figure 1. UTES technologies

1.2.1.2. Borehole Thermal Energy Storage (BTES)

In a BTES system thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes. The boreholes are equipped with different kinds of borehole heat exchangers (BHE), making the boreholes acting as large heat exchanger towards the ground. The most common BHE is a single U-tube made of plastic pipes. However, some times more effective BHE systems are used, e.g. a double U-tube. Heat or cold is delivered or extracted from the underground by circulating a fluid in a closed loop through the boreholes. The fluid has often an antifreeze to allow the system to work below the freezing point if so required.

Ground Source Heat Pumps (GSHPs) are systems combining heat pumps with BHEs. For these systems earth is used as a heat source during heating mode and as a heat sink during cooling mode.

1.2.1.3. Building Foundation Files

In this case, the foundation of the building serves as heat exchanger to store thermal energy for heating and cooling purposes in the ground. In the majority of cases this constellation is taking advantage of synergetic effects by using statically required massive foundation slabs („foundation absorber“) or pile foundations („energy piles“). The heat transmitting surface is defined by static aspect of the foundation.

<u>Energy piles</u>

There is no difference in the production of regular foundation piles or energy piles, except for placing the necessary circulation system within the body of the energy pile. The circulation pipes are usually fitted at different angles on the inside of the reinforcing cage of the pile (Figure 2). This procedure takes place directly on the construction site for cast-in-place piles or in the factory for prefabricated piles. Energy piles are cost effective as long as statically required foundation piles can be used.

Figure 2. Pile top and fitted outlets of an energy pile (on the left), circulation pipes inside of the reinforcing cage (on the right)

After driving the piles, outlets of the heat exchanger pipes surfacing on top of the pile are either being installed in the base course or in the foundation slab of the building. Hydraulic joints between energy pile and the entire supply system of heat and cold are fitted equivalent to the methods used for borehole heat exchanger.

<u>Foundation absorber</u>

Foundation absorbers and ground absorbers operate the same way as above described energy piles. In this manner, the ground slab of the building is used to enable combined storage of heating and cooling energy in the ground. Individually controllable pipe loops are placed in the body of the foundation. They activate storage capacities of the concrete and the surrounding ground just as they do when fitted inside energy piles. Depending on the massiveness of the ground slab this setting request a heat insulating layer on side of the building. Alternatively, pipes can be placed and laid out below the ground slab (Figure 3,4). In this case, the direct contact with the surrounding ground and a minimized thermal interaction of store and building climate are of advantage. In both cases, a discharge of the backflow temperature below 4°C should be avoided in winter to rule out a possible endangering of the adjoining concrete structure (formation of cracks).

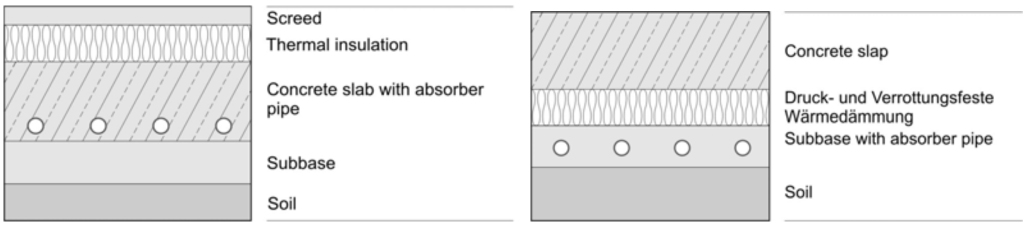


Figure 3. Schematic structure of foundation absorbers

Figure 4. Completion of the foundation absorber

1.2.2. Phase Change Materials (PCM)

Thermal energy storage systems provide several alternatives for efficient energy use and energy conservation [35]. Solid-liquid phase change materials (PCM) are used in latent heat thermal energy storage systems [36]. The use of phase change materials in building products has rendered it feasible to store significant amounts of thermal energy in the building envelope without the uncomfortable temperature swings and large structural mass associated with sensible heat storage. More detailed information can be found in Zalba et al. [37] and Khudair [38].

In thermal energy storage systems, cost is a very important factor of viability. Therefore, even though paraffin interactions with plastics are known by industry, plastics are commonly proposed as encapsulated materials for PCM in many applications. It is not possible to find in the literature experimental studies of organic PCM migration in plastics and its effects on plastic properties. Some behavior predictions can be found in Lane [39]. These interactions are a case study of environmental stress cracking (ESC), which is the simultaneous exposure to a chemical environment under a stress or strain, leading to a reduction of time of failure respect to air environment. ESC is considered one of the most common causes of plastics failure.

1.2.2.1 PCM in building envelope

Phase Change Materials (PCM) has been considered for thermal storage in buildings since before 1980. With the advent of PCM implemented in gypsum board, plaster, concrete or other wall covering materials, thermal storage can be part of the building structure even for light weight buildings. In the literature, development and testing were conducted for prototypes of PCM wallboard and PCM concrete systems to enhance the thermal energy storage (TES) capacity of standard gypsum wallboard and concrete blocks, with particular interest in peak load shifting and solar energy utilization. More detailed information can be found in [37, 40-42].

During the last 20 years, several forms of bulk encapsulated PCM were marketed for active and passive solar applications, including direct gain. However, the surface area of most encapsulated commercial products was inadequate to deliver heat to the building after the PCM was melted by direct solar radiation. In contrast, the walls and ceilings of a building offer large areas for passive heat transfer within every zone of the building. Several researchers have investigated methods for impregnating gypsum wallboard and other architectural materials with PCM. More detailed information can be found in [43-46]. Different types of PCMs and their characteristics are described. Manufacturing techniques, thermal performance and applications of gypsum wallboard and concrete block, which have been impregnated with PCMs, are discussed in several references like [13,38].

An option in building materials is the sandwich panel (Figure 5), which offers excellent characteristics in a modular system. The use of these panels means an advance in the construction area and insulation of buildings, sports, industrial buildings surfaces, etc. They integrate the functions of cladding, thermal insulation, water tightness, mechanical strength and aesthetic appeal. It is a product composed of a ribbed sandwich panel formed by two sheets metal and insulating polyurethane core injected. The partial replacement of insulation material with a heat storage material has been theoretically studied. More detailed information can be found in [47]. Different types of sandwich panel prototypes were studied, including air layer between the PCM (macroencapsulated in rigid containers) and the metal sheet. Results of the energetic behaviour were similar.

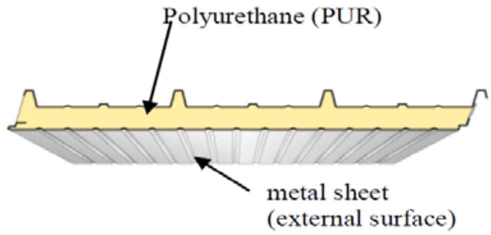


Figure 5. View of the sandwich panel

1.2.2.2 Phase Change Material (PCM) in HVAC

Demand for air-conditioning and refrigeration has been growing at a fast rate in recent years. More energy efficient solutions for cooling that can use local and renewable resources are becoming more important than ever. Thermal energy storage in Phase Change Materials (PCMs) is used in cooling applications like air-conditioning, transportation of temperature sensitive materials [37]. Ice is the oldest PCM used for cold storage. In ancient times people used ice and/or snow to store their foods. Some advanced cooling technologies of today originate from this basic ancient concept. Seasonal snow storage in Sweden stores tones of snow from winter to summer to meet the cooling demand of a hospital [48].

Mechanical ice storage systems that make use of multiple electricity tariffs are used for air conditioning in many countries. Ice with 0ºC melting point can only be used for applications that are around its melting point.

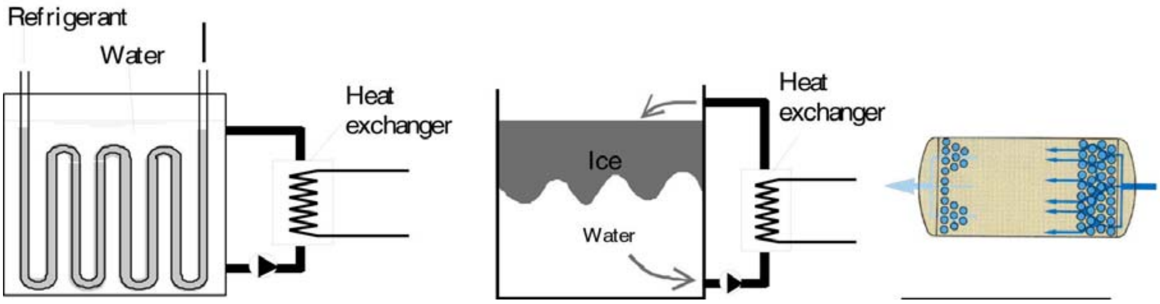
For cooling applications that require other temperatures than melting point of ice, new PCMs are needed. PCMs are usually classified into two groups as organics and inorganics. Inorganics have higher storage capacities and thermal conductivities, but can cause problems like corrosion and supercooling. Non-corrosive organics without any supercooling can be more reliable as PCMs. Main drawbacks for organics are their flammability and low thermal conductivity. PCMs for cooling applications investigated in previous studies are summarized in Table 2. In most of these studies n-alkanes and their mixtures are used as PCMs. Melting points of n-alkanes with carbon numbers 12-40 are between -10ºC to 80ºC [49]. Melting points increase with increasing molecular weight. PCMs with different melting points can be prepared by mixing n-alkanes of different carbon numbers.

Table 2. Studies on PCMs for cooling applications

PCM	Melting range (ºC)	References
Water/ice	(-20)-(-10)	Chen ,1992
C_{14}-C_{16}	0 - 18	Choi et al., 1992
Water/ice	-6	Bedecarrats et al.,1996
C_{14}-C_{16}	1.7 – 17.9	He and et al.,1999
C_{12}–C_{14} C_{13}–C_{14} C_{13}–C_{15} C_{14}–C_{15} C_{14}–C_{16}	-50 - 10	Mondieg et al., 2003
C_{15}-C_{16}	8	Zalba et al.,2003
Water/ice	(-8)–(-3.5)	Kousksou et al.,2005

1.2.3. Ice Storage

The annual load factor of electricity in Japan is improving due largely to the popularity of ice storage systems named “eco-ice system”. The government is giving subsidies to users who install air conditioning systems utilizing thermal energy storage. In addition to that night time electricity rates for buildings using ice storage was approximately one fifth of the daytime rate as of 2000 [50]. Ice making is an established technology in food industry. The concept of ice making has to be developed in order to adopt it to buildings. Figure 6 shows the types of ice storage that are commonly used in Japan [51].



(a) Ice on coil (b) Slurry (c) Encapsulated

Figure 6. Types of Ice storage tanks[51]

Figure 7 shows the history of energy storage development in Japan. Oldest actual thermal storage system was installed in a film studio in 1952. It already had the philosophies which of saving energy with high load factor operation and the reduction of facility capacity. In the 60's and 70's, there were many studies of the thermal response of water storage tank and mathematical and control models were adopted for actual building designs and operations. In 80's, many kind of thermal storage systems were developed for the reduction of the electricity demand in day-time during summer. Especially developments of the latent sensible heat materials or enlargement of storage quantity using post-and-beam were performed by many companies and universities. However, only water and ice storage systems survived to 2010's. Because there were so many problems on endurance capacity, stability, manageability, economic efficiency, safety, disposability, etc.

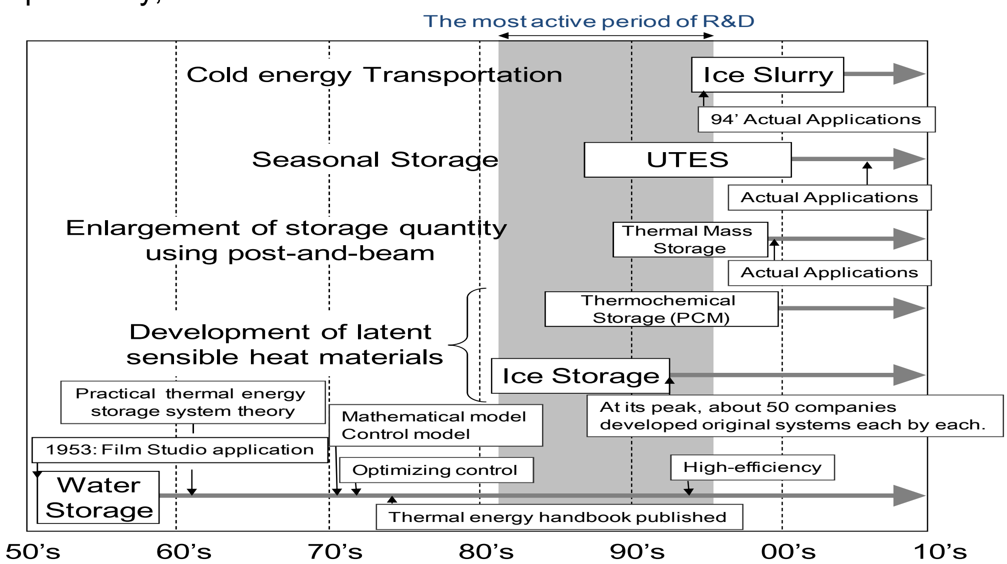


Figure 7. R&D history of the energy storage in Japan

1.2.4. Water Storage

Stratified chilled water storage is generally acknowledged as the simplest, most efficient, and cost-effective method (Figure 8). Stratification in the chilled water storage tanks is based on the density difference of water to form horizontal layers or temperature zones based on its density. As water gets colder, it becomes denser, until it reaches 4°C. As water is cooled below this point, it becomes less dense, until it freezes. Cold water near to 4°C and up to 6°C will collect and stabilize in the lowest regions of the tank, while warmer water between 10 to 18°C will collect in the upper regions of the tank. During the charging cycle, cold water from the chilling equipment enters the tank through diffusers at the bottom, and warm water exits the tank at the top. As the volume of chilled water increases and warm water is displaced, the thermo-cline rises. The total volume of water in the tank remains the same. The flow of water is reversed during discharging. The system draws chilled supply water from the low portion of the tank and sends warm return water into the top of the tank. The storage capacity of a stratified chilled water tank increases with the temperature difference between the stored chilled water and the warm water returning from the load, as in the other chilled water storage methods. In addition, a larger temperature differential increases the density difference between the warm and cold water through a chilled water tank, further enhancing stratification.

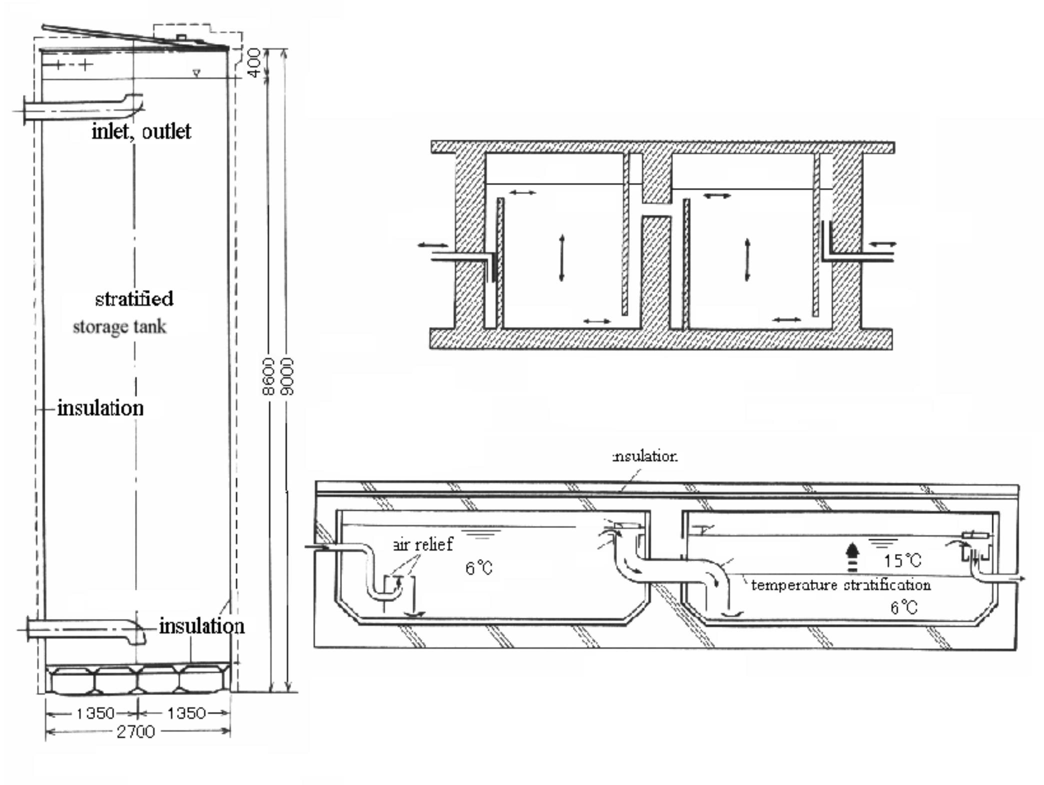


Figure 8. Stratified water tanks [52]

1.2.5. Alternative Combinations

Any alternative combinations of the TES technologies described above can be:

- Short term – short term
- Long term – long term
- Short term– long term

Thermal storage systems can be applied to several sectors commercial and institutional buildings, residential, district heating and cooling, agriculture, industry and transportation.

1.3. Demonstration Projects

Demonstration projects from eight different countries use different thermal energy storage technologies as shown in Table 3. Information on these projects can be found in the project templates given in Collected data 1.

Table 3. Demonstration project distribution in Subtask A

	ATES	BTES	Ice	Water	Energy Piles	BTES+Water	PCM	**Total**
Canada		1						1
China			1			1		2
Germany		2		1	3			6
Japan			1	1				2
Spain							4	4
Sweden	2							2
Turkey	1							1
USA	1	1						2
Total	4	4	2	2	3	1	4	20

The demonstration projects were done for the following applications:

- Buildings
  - Airport
  - Offices
  - Shopping mall
  - Residential
  - University
- Combined heat and power generation
- District heating and cooling
- Greenhouses
- Passive cooling

1.4. System Performance Evaluation of Demonstration Projects

1.4.1. Data Collection

A template prepared in Excel program is used to evaluate the system performance of the demonstration projects. These sheets for each of the projects are included in Collected data 2. The structure of the template is shown in Figure 9.

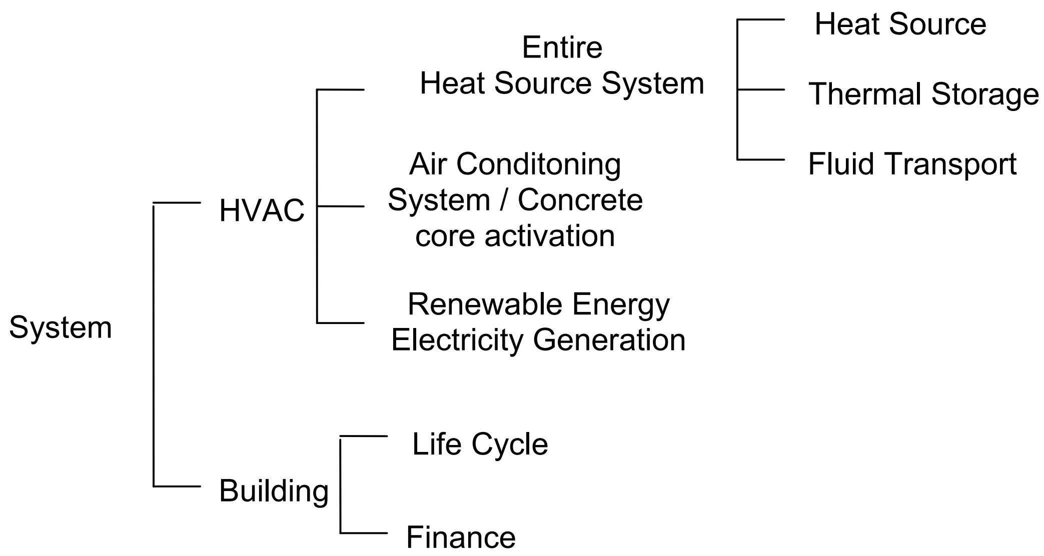


Figure 9. The structure of the template used in system performance evaluations.

1.4.2. Performance Evaluations

Monitored information on annual capacity, energy consumption, load ratio, COP, efficiency, etc. of the demonstration projects are entered in the corresponding cells on the terminal points of the structure given in Collected data 2. Performance data for the demonstration projects collected with this method are compared in Table 4. A schematic diagram showing COP calculation conditions for the demonstration project is also included in the templates given in Collected data 2.

Table 4. Comparison of performance data for demonstration projects

General						Heat Source Section								Renewable Energy	
Country	City	Project#	Term	TES Type	Notes	Heat Source Capacity		Heat Source Energy Consumption		Heat Source Load Ratio		Heat Source COP		Renewable Energy	note
						MWh/annual		MWh/annual		% (Annual)		– (Annual) (Annual)		MWh/annual	
						C	H	C	H	C	H	C	H		
Canada	Halifax	D1	Long	BTES	Ocean	2,275		455				5.0		520	Ocean
China	Nanjing	D2	Long	BTES+Water	GSHP	186		82				2.3			
China	Beijing	D3	Short	Ice	Cooling Only	425	181	143	75			3.0	2.4		
Germany	Chemnitz	D4	Short	Water	Waste Heat	9,763		15,588	–	67%		0.6			
Germany	Berlin	D5	Long	Energy piles	Free Cooling	57	141	2	28	30%	50%	30.6	5.1	48	PV
Germany	Hamburg	D6	Long	BTES	Free Cooling	64	214	3	55	26%	59%	21.6	3.9		
Germany	Lüneburg	D7	Long	Energy piles	Free Cooling	2680(kWh)	43	320(kWh)	13	6%	9%	8.4	3.4		
Germany	Berlin	D8	Long	Energy piles			189		57		67%		3.3		
Germany	Gelsenkirchen	D9	Long	BTES		552	588	66	251	44%	28%	3.6	3.6	15	PV
Japan	Tokyo	D10	Short	Water		27,830	10,464	4,973	3,096	98%	100%	5.6	3.4		
Japan	Gifu	D11	Short	Water & Ice		1,130	564	253	151			4.5	3.7		
Spain	Lleida	D12	Short	PCM	Concrete							2.0			
Spain	Lleida	D13	Short	PCM	Brick	145.8(kWh)		52.1(kWh)				2.8			
Spain	Lleida	D14	Short	PCM	Alveolar Brick	145.8(kWh)		52.1(kWh)							
Spain	Zaragoza	D15	Short	PCM	Free Cooling		13.5(kWh)		13.5(kWh)				1.0		
Sweden	Stockholm	D16	Long	ATES											
Sweden	Malmö	D17	Long	ATES											
Turkey	Adana	D18	Long	ATES	Green House	7	13	2	2			3.2	7.6		
USA	Stockton	D19	Long	ATES											
USA	Stockton	D20	Long	BTES											

Based on the data collected in the heat source section, COPs of the demonstration projects are compared in Figure 10. Heat Source COP is calculated according to Equation (1):

$$COP = \text{Generated Cooling} / \text{Input Energy} \quad (1)$$

Except for free cooling systems, COPs of most of systems are under 5 even though they have different capacities. This indicates that free cooling systems do not use much energy for generating chilled water. Energy is consumed only for pumps and fans. Performance of free cooling systems depends on the climate condition. Therefore, to compare different thermal energy storage systems, we need to take differences in climate into consideration. This issue of difference of climate conditions is discussed in Subtask B.

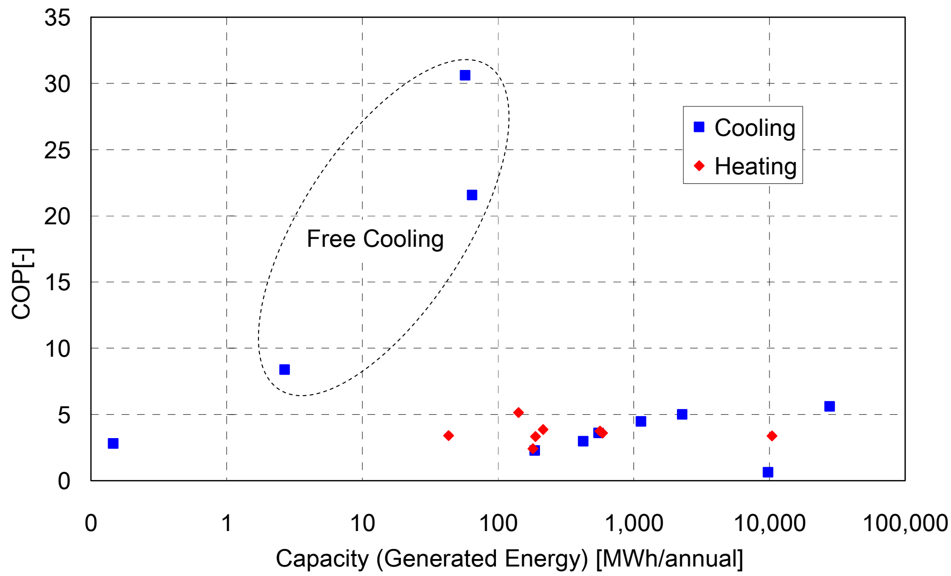


Figure 10. The heat source section COP comparison.

1.4.3. Sustainability Aspects of Demonstration Projects

Within the scope of this Annex three important aspects of a sustainable system are

- Reducing energy demand,
- Maximizing the use of renewables
- Using energy resources most efficiently

The ultimate aim is reducing CO_2 emissions and greenhouse effect. Therefore the degree of sustainability depends on the amount CO_2 emissions reductions. The reduction of energy demand of a system will result in less primary energy consumption, less energy from power plants and less fuel extraction. Thermal energy storage can contribute to this energy demand reduction in two ways: direct reduction of the heating/cooling load and increase of the performance of the system. Sustainability aspects of the demonstration projects are given in Table 5.

Table 5. Sustainability aspects of demonstration projects.

General			Thermal Storage Section				Water (Liquid) Transport Section		Entire Heat Source System				
Country	Project#	TES Type	Storage Capacity		Storage Efficiency Ratio		Temperature Difference		Energy Consumption (Inc Aux)	Primary Energy COP	Night Shift Ratio	CO2 Emitions	Peak Shaving
			MWh/annual		%/annual		Δt degree Annual average		MWh /annual	– (Annual)	% (Annual)	MJ/t-CO2 (Annual)	% (Annual Max)
			C	H	C	H	C	H	C + H	C + H	C + H	C + H	C or H
Canada	D1	BTES	5		86%		9.0						
China	D2	BTES+Water	9		80%		2.0						
China	D3	Ice	358	181	134%	58%	4.5	5.0				1,066	
Germany	D4	Water	33		99%		8.0		n. a.	n. a.	42.0%	n. a.	59%
Germany	D5	Energy piles	71	109	65%	153%	1.9	1.5	29	2.51		35,652	
Germany	D6	BTES	64	176	37%	273%			58	1.77		25,184	
Germany	D7	Energy piles	5	25	21%	487%	0.4	0.2	13	1.31		18,611	
Germany	D8	Energy piles		147		0%			57	1.24		17,588	
Germany	D9	BTES	403	193	208%	48%			317	1.33		18,935	
Japan	D10	Water	28,460	9,946	102%	95%	9.5	9.4	19,395	1.19	86.4%	82	27%
Japan	D11	Water & Ice	931	287	96%	70%			494	1.30	71.9%	232	
Spain	D12	PCM											
Spain	D13	PCM	4.9(kWh)						70.2(kWh)			1-1.5	
Spain	D14	PCM	6.1(kWh)						75.6(kWh)			1-1.5	
Spain	D15	PCM	7	7	73,5-94,1%	74-94%	8.0						
Sweden	D16	ATES	12(kWh)	10(kWh)									
Sweden	D17	ATES	10(kWh)										
Turkey	D18	ATES	7	13	21%	57%						12,670	
USA	D19	ATES	2,600,000		68%					approx 8			
USA	D20	BTES	15,200,003	64,000,000	96%	96%							

1.4.3.1. Storage efficiency

Annual storage efficiency ratio given in Table 5 is calculated according to Equation 2:

Storage Efficiency Ratio = Energy Input to TES / Energy Output from TES (2)

The storage efficiencies are compared in Figure 11. Most of the water or ice storage systems had storage efficiencies around 100%. Therefore, from the actual operation data, it was shown that short-term storage system has a stable performance.

UTES systems can be classified in two groups, which were marked on this graph. For the first group with storage efficiency more than 100%, the annual output energy was much higher than the input energy. Project D7 had the highest storage efficiency for heating, but the lowest storage efficiency for cooling. Therefore, for this project UTES is more suitable for heating.

Short-term storage systems are designed with the aim of 100% efficiency at the planning stage. Long-term storage system, especially UTES, should be evaluated based on the character of the load (climate) and thermal response of the ground.

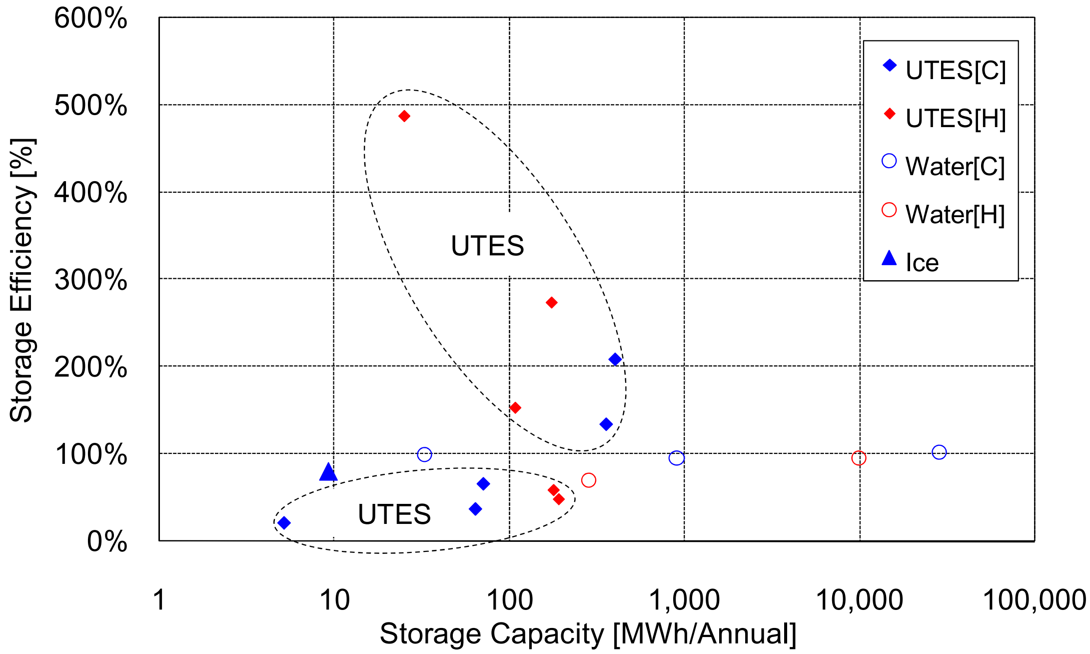


Figure 11. Storage efficiency comparison.

1.4.3.2. Reduction of heating/cooling load

The heating/cooling load is mainly dependent on the weather conditions and building envelope. For this reason the location of the system will determine its design and operation. A TES system also needs to take into account the weather conditions for its design.

Moreover the weather conditions will also determine the main parameter affecting the heating/cooling loads. Locations with extreme weather conditions and daily/seasonal temperature fluctuations will present a strong influence on the external conditions, while locations with mild temperatures all year long can be influenced by internal loads.

The use of some TES systems in the appropiate weather conditions can directly reduce the energy load of the building by storing excess energy and releasing it to the ambient in more favourable conditions passively. These system do not aim to affect the HVAC performance but protect the building from the external conditions. However, the performance of the HVAC system is expected to be improved.

The main TES technology used for this purpose is the applications of phase change materials in building envelopes to prevent excess heat entering the building. This would decrease the energy load of the building leading to energy savings. These systems have a restricted operation range which is the phase change temperature range. Therefore the weather conditions, the PCM used and its integration in the building envelope will determine the potential benefits of the system.

These systems can be evaluated by measuring and comparing the energy consumptions and savings achieved. Demonstration projects D13 and D14 show an example of such a system as well as the benefits achieved (Table 6).

Table 6. Reduction of energy consumption for passive PCM projects

Project No	Energy Consumption[1] (kWh/year/m^2)	Energy Savings (kWh/year/m^2)	Energy Savings (%)
D13	12.2	2.1	14.7
D14	13.1	2.7	17.1
[1]Set point of 24 ºC during 90 days per year (cooling demand)			

1.4.3.3. Improvement of the performance of the system

By using TES it is possible to improve the performance of the HVAC system. When more constant temperature and closer to the operational temperature is provided as a heat/cold source/sink, the performance of the system will improve, achieving a reduction of the primary energy consumption.

Nature provides cold sources that can be exploited by TES systems. These sources are renewable and do not cause adverse environmental effects like greenhouse effect or ozone depletion. Cold can be extracted from these sources for direct use (free cooling), but also can be transferred to another medium for storage for later usage by active or passive systems. The natural cold sources for TES are classified here as ambient air, water (rivers, lakes, deep ocean and sea water, snow, ice), ground, sky and solar.

Matching these available cold sources with demand for sustainable cooling requires consideration of several factors. Among these are:

- Availability of users
- Temperature
- Time and duration of demand
- Distance between supply and demand
- Power
- Capacity
- Comfort cooling requirements in urban environment
- Cooling (Heating) load
- Climate and Weather

Thermal energy storage technologies can close the mismatch resulting from the factors given above to utilize renewable cold sources. Depending on the conditions of the source the storage can be done for short term or seasonal purposes.

COP and storage efficiencies are two quantities that can indicate the level of renewable energy utilization in the system. In TES systems without heat pumps the energy consumption is due to auxiliary equipments like pumps and fans. For mechanical cooling systems in addition to the auxiliary equipments, the operation of the compressor increases energy consumption. For TES systems utilizing renewables for direct cooling, COPs can be higher than 10. However this will be possible under suitable climate and weather conditions. Therefore system should be chosen taking climate into account.

The primary energy conversion COP comparison for the demonstration projects is shown in Figure 12. Primary Energy COP is calculated according to Equation 3:

Primary Energy COP = Output to Heat Source System / Input from Heat Source System (3)

This value is directly related to CO_2 emission reduction. Free cooling systems have high efficiencies. UTES technology is the most appropiate for this application, providing both a better and constant temperature level and a high storage capacity. Moreover, when free cooling is used during summer period the performance of the system is dramatically improved.

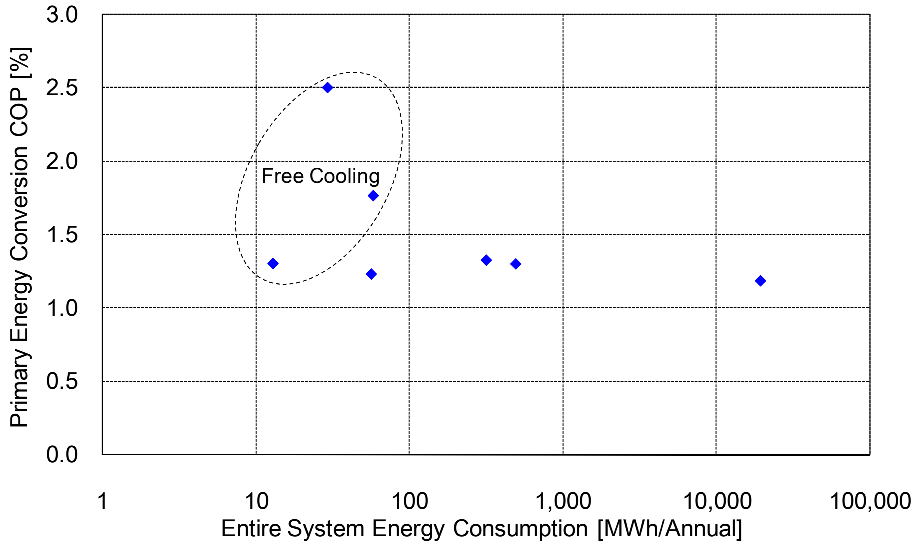


Figure 12. Primary energy conversion COP comparison.

1.5. Achievements of Subtask A

The achievements of Annex 20 Subtask A can be summarized as follows:

- Monitored data from 20 demonstration plants from eight countries using six different thermal energy storage techniques were evaluated in terms of sustainability.
- Thermal energy storage methods provide several alternatives to existing cooling technologies used for built environment.
- Different sources are made available for cooling with thermal energy storage. In the demonstration projects, these were renewable energy (solar), natural sources (ambient outside air, underground, ocean water, air inside greenhouse) and waste heat (from CHP plant).
- For seasonal purposes, UTES (ATES, BTES and energy plies) systems and ground coupled heat pumps give efficient solutions.
- With appropriate climate conditions seasonal free cooling systems have COPs in the range of 10 – 30.
- PCM is incorporated in building materials for passive cooling and decrease heating and/or cooling demand.
- For short term systems (ice and water), measured storage efficiencies were around 100% in accordance with design values.
- Primary energy conversion COPs of the projects are greater than 1 indicating energy conservation and reduction of CO_2 emissions.
- Combined use of absorption chiller units and cold water storage is realized to increase efficiency of combined heat and power plant (CHP) and utilize waste heat as source for absorption chiller.

1.6. Conclusions and Recommendations

As a result of the evaluation of the monitored data from 20 demonstration projects, sustainability of cooling with thermal energy storage requires consideration of several factors. The storage capacities of the demonstration projects were in a wide range between kWhs to GWhs.

It is difficult to compare the sustainability of such a range of projects with different storage concepts e.g. UTES with ice, UTES with PCM. Free cooling systems had very high COPs, but should be evaluated taking climate conditions into account.

The combination of underground thermal energy storage systems and slow reacting space heating like concrete core activation with faster reacting space heating systems (like radiators) have to be well combined.

Systems should be monitored in first period of operation. The controlling strategy has to be adapted to the real boundary conditions (e.g. earth temperature) and occupancy (profiles, internal head loads and so on).

The uneven energy balance of heat extraction and injection can cause a warming up of the underground. Therefore the free cooling mode could only be used for short time unless cold from winter air is injected to provide thermal balance.

Data collection templates developed in Subtask A can form the basis for a database of Annex 20 demonstration projects. Unfortunately, some of the data were not available for some demonstration projects. This was due to the fact that the monitoring plans for some of the projects were based on control of the system operation and were lacking data needed to evaluate energy conservation.

For future work the following recommendations can be given:

- Update and/or complete missing data in the project database
- Revise data measurement and storage method for evaluation
- Cross-sectional research between different thermal storage and hybrid systems
- Life cycle analysis of TES with cooling systems

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1.8 Collected data A. Project Templates for Demonstration Projects

Project D1

A Project Name Alderney 5 Cold Source Advanced Coaxial Energy Storage System Location: The Halifax Regional Municipality (HRM), Nova Scotia, Canada. Starting date-2008 Duration Indefinite

B Storage Technology Storage media Metamorphic Slate What is innovative and/or significant compared to state of the art knowledge? Use of Coaxial boreholes for "direct" cooling/no heat pumps

C Current progress Demonstration plant: Design stage & Demonstration plant

D System description Purpose: BTES DIRECT Cooling of 5 Municipal Buildings/Eliminate CFC refrigerants Capacity / dimensions: 450 KWe/2.2 MWth peak 2500MWh with 500 MWh Direct BTES & 2000 MWh Direct Harbour cooling Performance:

E Sustainability aspects i. Demonstration of the Advanced Coaxial Energy Storage (ACES™) technology & direct cooling with BTES. ii. Demonstration of simulation-based building energy integration & provision of enhanced design and optimization software for designers. iii. A 75% reduction in utility cost related to air conditioning resulting in a 2,000 tonne CO_2e reduction per annum. iv. Removal of all mechanical refrigeration for air conditioning (approximately 800 kg of CFC/HCFC).

F Operational experiences **NA**

G Finance: Preliminary project costs at this time are Class C engineering cost estimates based upon a pre-feasibility. Final Class A engineering cost estimates are currently under development.

H Contact Person / Project Partners **Frank Cruickshanks/High Performance Energy Systems/City of Halifax/Environment Canada** **References/ Web sites NA**

Project D2

A Project
Name: Nanjing Fengshang International Apartment Project
Location: Nanjing, China
Starting date: July, 2008
Duration:12 months

B Storage Technology
Storage media: Underground Thermal Storage
What is innovative and/or significant compared to state of the art knowledge? :
Cooling and heating sources of air-conditioning using a green energy saving and environmental protection of the ground source heat pump hybrid system, the ground source heat pump units making cooling combined with the conventional water chiller units in summer while it making heating in winter independently. In particular, it is worth mentioning that the project adopt the current international advanced green energy-saving comfort air-conditioning system forms -- the independent control system of the temperature and humidity, combined with the energy storage liquid desiccant and the capillary system so as to control the absolute humidity accurately of air supply and maintain the appropriate supply air temperature.

C Current progress / **Pilot plant** / **Demonstration plant** /
Current progress: The system started operation in July last year and are running well currently of the many favourable reviews by the owners.
Demonstration plant: the total construction area of 18133 m^2

D System description
Purpose: Cooling, Heating and providing domestic hot water
Capacity / dimensions: Cooling capacity of 386 kW (Maximum) and heating capacity of 141 kW (Maximum) of the total system
Performance: COP of 2.96 in cooling season and COP of 2.41 in heating season of the total amount system

E Sustainability aspects These may include: greenhouse gas avoidance, primary energy savings, peak load reduction, green energy, COP/SPF, sustainable materials, refrigerant displacement, energy life cycle:
Cooling and heating sources of air-conditioning using a green energy saving and environmental protection of the ground source heat pump hybrid system with the COP of 2.96 in cooling season and the COP of 2.41 in heating season, it can save 1093Mwh electric quantity and reduce 1066 ton carbon dioxide emission annually, in addition, it also can avoid the emission of the greenhouse gas completely and its energy life cycle of up to 100 years or even longer.

F Operational experiences:
None

G Finance:
Funding: Security
Financial support: Security

Life cycle cost analysis: Security

H Contact Person / Project Partners Contact Person: Fengtingting, HUNDRED GROUP Project Partners: Omission

References: **Boundary Conditions:** Energy costs: 665830 kWh annually Weather conditions: the average wet bulb temperature in cooling season of 28.5 C

Project D3

A Project
Name: Beinjing Huilongshen Industrial Park Ice Storage Air-conditioning System
Location: Beijing, China
Starting date: May, 2008
Duration:14 months

B Storage Technology
Storage media: Ice Storage
What is innovative and/or significant compared to state of the art knowledge? :
Cooling source of air-conditioning using a green energy saving and environmental protection of the ice storage system, the ice storage air conditioning system runs the double duty chiller units to build ice during the off-peak time of the electric power transmission-line system, and then melts the ice to meet the requirement of air conditioning load of the building in the on-peak periods, in addition, a base chiller is designed to fulfil the cooling load during the off-peak time and make cooling together with the double duty chiller units. In particular, it is worth mentioning that adopting the ice storage air conditioning system combined with the large temperature difference water supply and low temperature air supply is practicable in the project through an economical and technical analysis comprehensively, and that it can reduce initial investment and operation electric cost.

C Current progress / **Pilot plant** / **Demonstration plant** /
Current progress: The system started operation in May last year and are running well currently of the many favourable reviews by the owners.
Demonstration plant: the total construction area of 94224 m^2

D System description
Purpose: Cooling in summer
Capacity / dimensions: Cooling capacity of 8444 kW (Maximum) and ice storage of 2770 kW (Maximum) of the total cooling system
Performance: COP of 2.26 in cooling season of the total amount system

E Sustainability aspects:
Cooling source of air-conditioning using a green energy saving and environmental protection of the ice storage system with the COP of 2.26 in cooling season, through the transferring the run time of the chiller units, using the cheap power during the off-peak time and reducing the peak electric load, it can save the operation cost of the users and peak load shifting, in addition, it also can avoid the emission of the greenhouse gas completely and its energy life cycle of up to 15 years or even longer.

F Operational experiences:
None

G Finance:
Funding: Security
Financial support: Security
Life cycle cost analysis: Security

H Contact Person / Project Partners
Contact Person: Fengtingting, HUNDRED GROUP
Project Partners: Omission

References:
Boundary Conditions:
Weather conditions: the average wet bulb temperature in cooling season of 26.4 ℃

Project D4

A Project
Name: Pilot project for the optimization of large-scale systems on the base of combined heat and cool and power cycle by means of cool thermal energy storage
Location: Germany, Chemnitz
Starting date: 11/2005
Duration: 12/2009

B Storage Technology
Storage media: water
What is innovative and/or significant compared to state of the art knowledge?
- first large-scale cold storage in Germany
- better use of waste heat with absorptions chiller units (heat surplus during summertime)
- increase efficiency of power supply
- construction of the storage
- economical and ecological benefits of the combined use of absorption chiller units and cold water storage

C Current progress Design stage (2004 - 2006) / Simulation (2004 - 2007) / **Pilot plant** / **Demonstration plant** / setup phase 10/2006-06/2007 / operation since 06/2007

D System description
Purpose: extension of the large-scale district cooling system in Chemnitz
Capacity / dimensions: 3500 m³ water, tank with direct charging and discharging, height ca. 20 m (17 m water level), above the ground
Performance: ca. 5 MW (technical reserve ca. 8 MW)

E Sustainability performance

F Operational experiences: By the storage integration (2007) and by the new operational mode of the cold supply (district cooling) of Utility Company Chemnitz, the feasibility of the large-scale cold water storage concept could be verified for boundary conditions in Germany. The first operating results meet the expectations, so that the postulated advantages of this concept could be confirmed by monitoring. The system operation became more flexible due to storage utilization. The operator can choose between many different operating strategies.

G Finance:
Financial support: Federal Ministry of Economics and Technology (BMWi)
Represented by Project Management Organisation Jülich (PTJ)
Nr. 0327357B/C
Life cycle cost analysis: see [2], [3]

H Contact Person / Project Partners
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[3] Urbaneck, T.; Platzer, B.; Schirmer, U.; Barthel, U.; Uhlig, U.; Baumgart, G.: State of Cold TES Project in Chemnitz (Germany) – April 2007. International Energy Agency (IEA), Energy Conservation Through Energy Storage (ECES), Annex 20 Sustainable Cooling with Thermal Energy Storage, 4th Expert Meeting and Workshop, Beijing, China, 2007
[4] Urbaneck, T.; Uhlig, U.; Fiedler, G.; Göschel, T.; Baumgart, G.: First operational experiences at the Cold Thermal Energy Storage of the Utility Company Chemnitz. International Energy Agency (IEA), Energy Conservation through Energy Storage (ECES), Annex 20 Sustainable Cooling with Thermal Energy Storage, 5th Expert Meeting and Workshop, Ankara, Turkey, 2007
[5] Urbaneck, T.; Uhlig, U.; Göschel, T.; Baumgart, G.; Fiedler, G.: Operational Experiences with a Large-Scale Cold Storage Tank – District Cooling Network in Chemnitz. EuroHeat&Power, English Edition VWEW Energieverlag Vol. 5 (2008) Journal 1 p. 28-32 – ISSN 0949-166X
[6] Urbaneck, T.; Barthel, U.; Uhlig, U.; Göschel, T.: Only cold water?! - The success with the first large-scale cold water store in Germany. Effstock, 11th International Conference on Thermal Energy Storage, Stockholm (Sweden). – ISBN 978-91-976271-3-9

[7] Urbaneck, T.; Gehrmann, J.; Lottner, V.: First large-scale Chilled Water Stores in Germany. Effstock, 11th International Conference on Thermal Energy Storage, Stockholm (Sweden), 2009.– ISBN 978-91-976271-3-9

Web sites
http://www-user.tu-chemnitz.de/~tur/ks2/pilotpr_ks.htm (in German)

Boundary Conditions: Energy costs: see [2], [3]
Weather conditions – Cooling degree days average wet bulb temperature in cooling season: see [6], [7], Subtask B (in progress)
Dollars per stored kWh annual thermal: n.a.

Project D5

A Project	
Name	“EnergieForum Berlin” **(EFB)**
Location	Berlin, Germany
Starting date	commissioning date of the building early 2003
Duration	energy monitoring since spring 2003 and run on

B Storage Technology

Storage media: underground thermal energy storage (UTES), surrounding ground as storage media

What is innovative and/or significant compared to state of the art knowledge?
The underground is used for seasonal thermal energy storage. Heating combined with a heat pump in winter and free cooling in summertime.

C Current progress

Demonstration plant

D System description

Purpose: Low temperature space heating and high temperature cooling in combination with concrete core activation.

Capacity / dimensions

Concrete core activation: approx. 4250 m² in the wintertime and approx. 2000 m² in the summertime (since 2006),

198 **energy piles** with a length of 8,50 m each pile,

thermal power: 107 kW heat pump, 150 kW free cooling

Performance: objective: maximum of energy charge and discharge each 85 MWh per year

E Sustainability aspects

Apart from primary energy savings and green energy utilisation sustainable aspects of the foundation absorber at the “EnergieForum” is no need of compression chillers for space cooling. This is an advantage for the architecture and the climate in the city at summer time.

The seasonal performance factor (SPF) of the heat pump is about 5,4. The system including the circulation pumps reaches a SPF of 4,9 in heating mode at the moment (year 2008).

F Operational experiences:

The Combination of underground thermal energy storage systems and slow reacting space heating like concrete core activation with faster reacting space heating systems (like radiators) have to be well combined.

Systems should be monitored in first period of operation. The controlling strategy has to be adapted to the real boundary conditions (e.g. earth temperature) and occupancy (profiles, internal head loads and so on).

It seems that the underground is served with an external thermal source so that a higher energy discharge in the wintertime as a charge in the summertime is possible.

G Finance: -

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Boundary Conditions:

Energy costs 2008

electricity: 0,116 €/kWh
district heating: 0,033 €/kWh

Weather conditions Berlin 2008

Cooling degree days building
(estimation) approx. 160 Kd related to an outdoor temperature of 20°C,
$t_{cooling}$ = 56 days
heating degree days building
3044 Kd related to a room temperature of 20°C and an outdoor temperature of 12 °C,
$t_{heating}$ = 212 days

Radiators with district heating:

heating mode if average outdoor temperature of last 24 hours lower 20 °C
and present outdoor temperature lower 20 °C

Concrete core activation with underground thermal energy storage:

heating mode if average outdoor temperature of last 24 hours lower 14 °C
cooling mode if average outdoor temperature of last 24 hours higher 20 °C

Project D6

A Project	
Name	Gelsenwasser AG **(GEW)**
Location	Gelsenkirchen, Germany
Starting date	commissioning date of the building January 2004
Duration	energy monitoring 3 years (2007 - 2009), continuation is possible

B Storage Technology

Storage media underground thermal energy storage (UTES), surrounding ground as storage media

What is innovative and/or significant compared to state of the art knowledge?

The underground is used for seasonal thermal energy storage. Heating combined with a heat pump in winter and free cooling in summer time. To cover peak loads the heat pump could be used as a compression chillers in connection with the underground for recooling.

C Current progress

Demonstration plant

D System description

Purpose	low temperature space heating and high temperature cooling in combination with heating and cooling panels. Small part of thermal energy is used for air conditioning as well. Heating and cooling at the same time are possible. In this case the heat waste of server rooms for example is used as heat source for space heating. No additional heating and cooling system for space heating und cooling. Therefore the system has to cover peak loads as well.
Capacity / dimensions	
	Borehole heat exchanger with 38 probes each 150 m deep, thermal power: 326 kW heat pump, 200 kW free cooling, 320 kW compression chillers
Performance	-

E Sustainability performance

Apart from primary energy savings and green energy utilisation sustainable aspects of the borehole heat exchanger system at the Gelsenwasser AG are peak load reduction of

compression chillers or rather there is no need of compression chillers for space cooling. This is an advantage for the architecture and the climate in the city at summer time.
The combined seasonal performance factor heating and cooling is about 3,1. The factor includes the circulation pump of the borehole heat exchanger system.
To reach a much higher seasonal performance factor do not seem to be possible, due to the high percentage of operation time of the ground coupled compression chiller.

F Operational experiences:
The heat extraction of the underground is much smaller than estimated, due to the possibility using building zones with cooling demand as heat source for building zones with heat demand.

The uneven energy balance of heat extraction and injection causes a warming up of the underground. Therefore the free cooling mode only could be used for short time.

After using the ground coupled compression chiller it is generally difficult to switch back into free cooling mode due to the high temperature level of the condenser and the need of regeneration time to achieve the required temperature level for free cooling mode again.

G Finance:

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Boundary Conditions:
Energy cost 2008
No input data!
Weather conditions Gelsenkirchen 2008
Cooling degree days (estimation)
approx. 191 Kd related to an outdoor temperature of 20°C, $t_{cooling}$ = 74 days
heating degree days
2906 Kd related to a room temperature of 20°C and an outdoor temperature of 12 °C, $t_{heating}$ = 213 days
heating and cooling panels with underground thermal energy storage:
Different building zones with different heating and cooling requirements could by supplied by the underground thermal storage system parallel with heating and cooling energy all the time.

Project D7

A Project

Name	Rickmers Reederei **(RIC)**
Location	Hamburg, Germany
Starting date	commissioning date of the building September 2002
Duration	energy monitoring since autumn 2006 and run on

B Storage Technology

Storage media underground thermal energy storage (UTES), surrounding ground as storage media

What is innovative and/or significant compared to state of the art knowledge?

The underground is used for seasonal thermal energy storage.Heating combined with a heat pump in winter and free cooling in summertime.

C Current progress

Demonstration plant

D System description

Purpose: low temperature space heating and high temperature cooling in combination with concrete core activation and air conditioning, cooling in summertime only by underground, heating in wintertime additional by exhaust air and long-distance heat.

Capacity / dimensions

Concrete core activation: approx. 2657 m², air conditioning approx. 15820 m³/h

Borehole heat exchanger with 17 probes each 99 m deep, thermal power: 97 kW heat pump, 100 kW free cooling (thermal power of a new plate heat exchanger, changed in spring 2009, old one was dimensioned too small)

Performance: maximum of energy 2008: charge = 75 MWh and discharge = 155 MWh

E Sustainability performance

Apart from primary energy savings and green energy utilisation sustainable aspects of the foundation absorber is no need of compression chillers for space cooling. This is an advantage for the architecture and the climate in the city at summer time.

The seasonal performance factor (SPF) of the heat pump is about 4,2. The system including the circulation pumps reaches a SPF of 3,7 in heating mode at the moment (year 2008). In cooling mode (free cooling) the SPF is about 21,9.

F Operational experiences:
Systems should be monitored in first period of operation. The controlling strategy has to be adapted to the real boundary conditions (e.g. earth temperature) and occupancy (profiles, internal head loads and so on).
Because of a too small dimensioned plate heat exchanger, in summertime heat charge was smaller then discharge in winter in the last years, the temperature-level in the underground drop. Drawing the conclusion from the balance, in the last winter the BTES must turn off due to an output temperature under 0°C.

G Finance: -

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Boundary Conditions:
Energy costs 2008

electricity: 0,11 €/kWh
district heating: 0,05 €/kWh

Weather conditions Hamburg 2008
Cooling degree days building
(estimation) approx. 127 Kd related to an outdoor temperature of 20°C,
$t_{cooling}$ = 45 days
heating degree days building
3068 Kd related to a room temperature of 20°C and an outdoor temperature of 12 °C,
$t_{heating}$ = 218 days

underground thermal energy storage:
heating mode if average outdoor temperature of three times (6 o´clock, 10 o´clock and 15 o´clock) lower 16 °C
cooling mode if average outdoor temperature of three times (6 o´clock, 10 o´clock and 15 o´clock) higher 18 °C
district heating:
heating mode if heating demand is bigger than making available by energy storage

Project D8

A Project	
Name	Volkswagen Library of the Technical University of Berlin **(TUB)**
Location	Berlin, Germany
Starting date	commissioning date of the building October 2004
Duration	energy monitoring 4,5 years (2005 till 2009)

B Storage Technology

Storage media underground thermal energy storage (UTES), surrounding ground as storage media

What is innovative and/or significant compared to state of the art knowledge?

The underground is used for seasonal thermal energy storage. Heating combined with a heat pump in winter and free cooling in summertime.

C Current progress

Demonstration plant

D System description	
Purpose	low temperature space heating and high temperature cooling in combination with concrete core activation
Capacity / dimensions	
	Concrete core activation: approx. 7 700 m²
	Foundation absorber: approx. 8 000 m², 126 parallel circuits, 21.300 m complete tube length,
	thermal power: 100 kW heat pump, 70 kW free cooling
Performance	objective: maximum of energy charge and discharge each 142 MWh per year

E Sustainability aspects

Apart from primary energy savings and green energy utilisation sustainable aspects of the foundation absorber at the Volkswagen Library are peak load reduction of compression chillers or rather there is no need of compression chillers for space cooling. This is an advantage for the architecture and the climate in the city at summer time.
In heating mode the seasonal performance factor (SPF) is about 4,8. The factor includes the heat pump as well as the circulation pump of the foundation absorber.

F Operational experiences:

No cooling power for free cooling mode in consequence of a warm up underground as a result of a fault in operation. Temperature regeneration takes several seasons.

Beginning of operation has to be in winter time in need of creating a heat sink. Cooling power is only influenced by the level of earth temperature.

The Combination of underground thermal energy storage systems and slow reacting space heating like concrete core activation with faster reacting space heating systems have to be well combined.

Systems should be monitored in first period of operation. The controlling strategy has to be adapted to the real boundary conditions (e.g. earth temperature) and occupancy (profiles, internal head loads and so on).

G Finance:

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Boundary Conditions

Energy costs 2006:

electricity:	0,09	Euro/kWh
district heating:	0,0353	Euro/kWh

Weather conditions Berlin 2008
cooling degree days building (corresponding to EnergyForum):
(estimation) approx. 160 Kd related to an outdoor temperature of 20°C,
$t_{cooling}$ = 56 days
heating degree days building (corresponding to EnergyForum):

3044 Kd related to a room temperature of 20°C and an outdoor temperature of 12 °C,
$t_{heating}$ = 212 days
Radiators with district heating:
heating mode if average outdoor temperature of last 72 hours lower 14 °C
and present outdoor temperature lower 17 °C
Concrete core activation with underground thermal energy storage:
heating mode if average outdoor temperature of last 72 hours lower 9 °C
cooling mode if average outdoor temperature of last 72 hours higher 15 °C

Project D9

A Project	
Name	VGH Lueneburg **(VGH)**
Location	Lueneburg, Germany
Starting date	commissioning date of the building autumn 2002
Duration	energy monitoring 2 years (2007 - 2008), continuation is possible

B Storage Technology

Storage media — underground thermal energy storage (UTES), surrounding ground as storage media

What is innovative and/or significant compared to state of the art knowledge?
The underground is used for seasonal thermal energy storage.Heating combined with a heat pump in winter and free cooling in summer time. To cover peak loads and to supply the air conditioning system of two single rooms the heat pump could be used as a compression chillers in connection with the underground for recooling.

C Current progress

Demonstration plant

D System description

Purpose	low temperature space heating and high temperature cooling in combination with concrete core activation at night time. Air conditioning of two single rooms at day time
Capacity / dimensions	
	101 **Energy piles** with each 17,5 m up to 21,5 m deep, thermal power: 82 kW heat pump, 80 kW free cooling, 89 kW compression chillers
Performance	-

E Sustainability performance

Apart from primary energy savings and green energy utilisation sustainable aspects of the energy pile system at the VGH Lueneburg are peak load reduction of compression

chillers or rather there is no need of compression chillers for space cooling. This is an advantage for the architecture and the climate in the city at summer time.
In heating mode the seasonal performance factor (SPF) is about 3,9. In cooling mode (free cooling as well as operation time of compression chiller) the seasonal performance factor is about 2,6. The combined seasonal performance factor heating and cooling is about 3,5. All values include the circulation pump of the energy pile system. Due to several faults in cooling mode there is potential of optimisation and improvement of the seasonal performance factor in the following year.

F Operational experiences:
After using the ground coupled compression chiller it is difficult to switch back into free cooling mode due to the high temperature level of the condenser and the need of regeneration time to achieve the required temperature level for free cooling mode again.

G Finance:

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Boundary Conditions:
Energy costs 2008 (average value including energy, power and measurement)

electricity:	0,147 Euro/kWh
district heating:	0,102 Euro/kWh

Weather conditions Lueneburg 2008

Cooling degree days (estimation)	approx. 103 Kd related to a room temperature of 20°C, $t_{cooling}$ = 43 days
heating degree days	3154 Kd related to a room temperature of 20°C and an outdoor temperature of 12 °C, $t_{heating}$ = 223 days

Radiators with district heating:
heating mode at day time if present outdoor temperature lower 18 °C
heating mode at night time if present outdoor temperature lower 5 °C
Concrete core activation with underground thermal energy storage:
heating mode only at night time if average outdoor temperature measured between 6:00 am and 6.00 pm of the previous day had been lower 17,5 °C
cooling mode only at night time if average outdoor temperature measured between 6:00 am and 6.00 pm of the previous day higher 22 °Cand present room temperature higher 20 °C

Project D10

A Project
Name: Harumi District Heating and Cooling
Location: Tokyo, Japan
Starting date: 2001. April (final completion)
Duration: energy monitoring from final completion, continuation is possible

B Storage Technology
Storage media: Water
What is innovative and/or significant compared to state of the art knowledge? :
This DHC has the largest thermal storage tanks (19,060 m3) in Japan.

C Current progress / Pilot plant / Demonstration plant /
Current Progress

D System description

Purpose: 1) To install the main plant in the center of this area.
2) To use a temperature difference of 10 °C.
3) To adopt huge thermal storage tanks.
4) To run the system using only electric power.

Capacity / dimensions:
1) Only cooling use : 4700m3 *2
2) Cooling and Heating use (Seasonal switching): 4700m3 * 2
3) Only for heating use : 260m3
4) In total: 19060m3

Performance:
1) Storage Efficiency Ratio (Annual) : 102.3%
2) Storage Tank Efficiency (Annual) : 98.9%
3) Night Shift Ratio (Annual) : 86.4%

E Sustainability aspects These may include: greenhouse gas avoidance, primary energy savings, peak load reduction, green energy, COP/SPF, sustainable materials, refrigerant displacement, energy life cycle:
CO2 Emitions in 2003 was 82.2 MJ/t-CO2 in annual. This value is only 40% of DHC average value in Japan. Primary Energy COP in 2003 was 1.19 in annual. This value is second-best value in Japan.

F Operational experiences: Due to the efficient operation of large thermal storage tanks, most of the energy consumption was shifted to the night-time and chillers were operated with a high load factor.

Project D11

A Project
Name: Gifu Branch Office (Chubu Electric Company)
Location: Gifu, Japan
Starting date: March, 2001(Completion Month)
Duration: We have monitored energy usage status since completion. e.g. Electricity in different use, Heating and cooling load, Thermal storage status

B Storage Technology
Storage media: Water thermal energy storage and Ice thermal storage system
What is innovative and/or significant compared to state of the art knowledge? :
Heat source: Water cooled ultra high efficiency heat pump unit, its designed cop 7.59
Thermal storage: Water thermal storage tank (Shallow and multiple stratification type)

C Current progress / **Pilot plant** / **Demonstration plant** / Current progress

D System description
Purpose:
This system mentioned above is installed into our Gifu branch office building, (Total floor area 24,097m^2, 11stories above ground and 1 story underground) and mainly applied for air-conditioning use except 11th floor where is used for health and welfare space. From the point of environmental load reduction, we adopted high efficiency apparatus and system such as ultra highly efficiency heat pump unit, water thermal storage system and stuff during design phase. Commissioning process is also applied after completion ,with a view to optimize energy saving performance of hole air-conditioning system in every season.
Capacity / dimensions:
Heat source
1) Ultra high efficiency heat pump unit (water cooled screw chiller) : R-01
Cooling Capacity 272kW, Heating Capacity 248kW (Heat recovery Mode)
2)Air cooled heat pump unit : R-02
Cooling Capacity 103kW, Heating Capacity 129kW
3)Water thermal storage tank (Water depth 1.5m)
Cold and Warm water tank A : 259m^3,
Cold water tank B : 309m^3, tank C : 191m^3
Large temperature differential system (Defferntial temperature 10 degree)
System for office
1)Single duct with VAV
2) Low temperature air conditioning system (Supply temperature 11 degree)
3)Air flow window(Only west side of the building)
4)Another specification: auto lighting control system with daylight control sensor

Performance: 2008.1 - 2008.12 results
1) Annual utilization factor on thermal storage tank
Cooling period : 95.9% Heating period : 82.4%
2)Annual load shifting ratio : 81.4%

E Sustainability aspects

Annual COP in 2008 (January -December)
1)Heat source COP(Including only compressor's electrical consumption) : R-01 was 5.2 and R-02 was 2.5.
2)System COP 1 (Including primary pump and well water pump) : R-01 was 4.4.
2 (Including primary pump): R-02 was 2.3.
3)Total system COP, Including R-01, R-02 and its accessories such as pumps, was 4.0.
4)Another aspect is using well water which is categorized renewable energy, as heat source for R-01.

F Operational experiences:
We had already carried out initial commissioning through 2001 to 2003 after completion. Now re-commissioning has been underway since 2008, aiming to further improvement of energy saving performance during durable period.

G Finance:
Funding: Chubu Electric Power Company
Financial support: Nothing
Life cycle cost analysis: No data

H Contact Person / Project Partners

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Boundary Conditions: Energy costs: No data
Annex 8 and 14 boundary conditions : No data
Weather conditions : Only outside temperature is available.
Cooling degree days average: No data
Wet bulb temperature in cooling season: No data
Dollars per stored kWh annual thermal: No data

Project D12

 

A Project
Name – PCM in concrete building envelopes
Location – Puigverd de Lleida (Spain)
Starting date – 01-04-03
Duration – 5 years (still going on)

B Storage Technology
Storage media – Phase Change Materials (PCM)
- Micronal - T_{PCM}= 26 ºC / h_{PCM}= 100 kJ/kg (Manufacturer)
  - T_{PCM}= 25-27 ºC / h_{PCM}= 98 kJ/kg (DSC results – 24-27 ºC)

What is innovative and/or significant compared to state of the art knowledge?
The first demonstration site using PCM in concrete for construction is designed, built and monitored. Many test using different cooling strategies have been done.

C Current progress Demonstration plant

D System description
Purpose – Free cooling

Capacity /Dimensions - Internal dimensions of the cubicles: 2.4x2.4x2.4 m
Amount of Micronal (both PCM and encapsulation): 250 kg

E Sustainability performance (See attached sustainability performance template)

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G References
- Cabeza LF, Castellón C, Nogués M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. (2007) Energy Buildings, 39, 113-119.
- Castellón C., Castell A., Medrano M., Martorell I., Cabeza L.F. Experimental study of PCM inclusion in different building envelopes, Journal Solar Energy Engineering, in press. doi:10.1115/1.3197843.

- Solé C, Castellón C, Ibáñez M, Nogués M, Roca J, Cabeza LF. Modelización y análisis de dos cubículos construidos en la localidad de Puigverd de Lleida (Lleida) mediante TRNSYS. (2005) Editorial Ochoa, pg 82-82. ISBN: 84-7359-586-6.
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- Castellón C, Medrano M, Roca J, Fontanals G, Cabeza LF. Increase of thermal comfort in building due to the use of phase change material in its concrete walls. (2007) Energy Sustainability 2007, Long Beach, California, USA.
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- Castell A. Use of PCMs in building envelopes to improve thermal inertia. Presentació Oral. (2007). Energy Challenges. Material Challenges for future applications in energy and environment. XaRMAE, Barcelona, Espanya.
- Cabeza LF, Medrano M, Castellón C, Castell A, Martorell I, Pérez G, Vila A. Design and monitoring of cubicles built with traditional construction materials and including new materials (PCMs, green roofs and green façades. Presentació Oral. (2008). Challenges in Materials for Energy, workshop XaRMAE, Barcelona, Espanya.
- Cabeza L F, Medrano M, Castell A. Optimització energètica d'edificis i millora de la inèrcia tèrmica de l'envoltant amb materials de canvi de fase (PCM). Presentació Oral. (2009). Solucions tecnològiques a l'abast de les PIMES: Aïllaments i altres materials avançats, Barcelona, Espanya.

Web sites

www.grea.udl.cat

Project D13


A Project
Name – PCM in Mediterranean construction materials – brick
Location – Puigverd de Lleida (Spain)
Starting date – 01-10-06
Duration – 2 years (still going on)

B Storage Technology
Storage media – Phase Change Materials (PCM)
- Paraffin RT-27 - T_{PCM}= 26-28 ºC / h_{PCM}= 179 kJ/kg (Manufacturer – 19-34 ºC)
  - T_{PCM}= 26-28 ºC / h_{PCM}= 95 kJ/kg (DSC results – 19-35 ºC)
  - T_{PCM}= 26-28 ºC / h_{PCM}= 60 kJ/kg (DSC results – 23-29 ºC)

What is innovative and/or significant compared to state of the art knowledge?
The first demonstration site using PCM in typical Mediterranean construction (using brick) is designed, built and monitored.
Free floating and controlled temperature experiments are performed and the energy consumption is measured.

C Current progress Demonstration plant

D System description
Purpose – Free cooling/Energy savings

Capacity /Dimensions – Internal dimensions of the cubicles: 2.4x2.4x2.4 m
Amount of PCM: 100 kg

E Sustainability performance (See attached sustainability performance template)

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G References
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Web sites

www.grea.udl.cat

Project D14

A Project
Name – PCM in Mediterranean construction materials – alveolar brick
Location – Puigverd de Lleida (Spain)
Starting date – 01-10-06
Duration – 2 years (still going on)

B Storage Technology
Storage media – Phase Change Materials (PCM)
- Hydrated salt SP-25 A8 - T_{PCM}= 25-26 ºC / h_{PCM}= 180 kJ/kg (Manufacturer - 15-30 ºC)
  - T_{PCM}= 27-29 ºC / h_{PCM}= 180 kJ/kg (DSC results - 19-35 ºC)
  - T_{PCM}= 27-29 ºC / h_{PCM}= 94 kJ/kg (DSC results - 24-30 ºC)

What is innovative and/or significant compared to state of the art knowledge?
The first demonstration site using PCM in typical Mediterranean construction (using alveolar brick) is designed, built and monitored.
Free floating and controlled temperature experiments are performed and the energy consumption is measured.

C Current progress Demonstration plant

D System description
Purpose – Free cooling/Energy savings

Capacity /Dimensions – Internal dimensions of the cubicles: 2.4x2.4x2.4 m
Amount of PCM: 120 kg

E Sustainability performance (See attached sustainability performance template)

F Contact Person / Project Partners
lcabeza@diei.udl.cat
acastell@diei.udl.cat

G References
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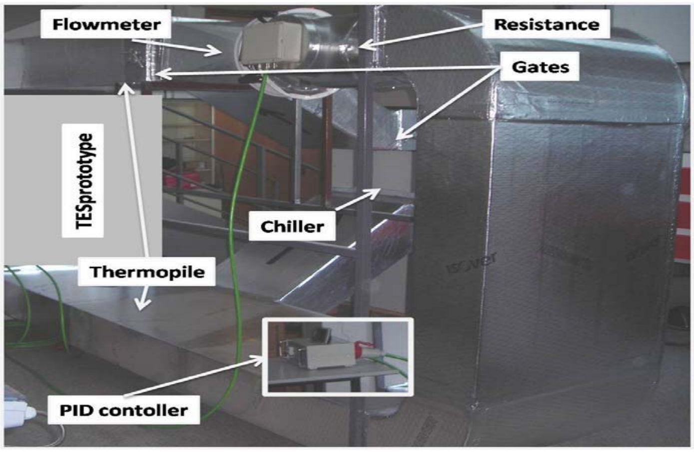
Web sites

www.grea.udl.cat

Project D15



A Project
Name – PCM-air Heat exchangers prototypes for building applications
Location – Zaragoza
Starting date – January 2005
Duration – 3 years.

B Storage Technology
Storage media – PCM
What is innovative and/or significant compared to state of the art knowledge?
The transitory characterization of real scale prototypes. The study of the influence of thermal properties of the PCM on the cooling power and on the temperature level maintenance.

C Current progress
Finished

D System description
Purpose – Daily storage for cooling applications
Capacity /Dimensions –
Prototype 1: 31584 kJ/27218 kJ/m^3
Prototype 2: 24395 kJ/19954 kJ/m^3

E Sustainability performance (See attached sustainability performance template)

F Contact Person / Project Partners
Belen Zalba/Ana Lazaro

G References
PCM-air heat exchangers for free-cooling applications in buildings: experimental results of two real-scale prototypes

Ana Lázaro, Pablo Dolado, José M. Marín, Belén Zalba 6th Workshop and Experts Meeting of IEA, ECES, Annex 20 "Sustainable Cooling with Thermal Energy Storage" Seville (Spain) May 26-27, 2008

"PCM-Air heat exchangers for Free-Cooling applications in buildings: Experimental results of two real-scale prototypes", Ana Lazaro, Pablo Dolado, Jose M. Marin, Belen Zalba, Energy Conversion and Management Volume 50, Issue 3, March 2009, Pages 439-443

"PCM-Air heat exchangers for Free-Cooling applications in buildings: Empirical model and application to design", Ana Lazaro, Pablo Dolado, Jose M. Marin, Belen Zalba, Energy Conversion and Management Volume 50, Issue 3, March 2009 Pages 444-449

"Technical viability and design of different cases of TES with PCM in air cooling applications" A. Lázaro, P. Dolado, J. M. Marín, B. Zalba, 11th International Conference on Thermal Energy Storage, Stockholm, Sweden (14-17 june 2009)

Web sites

Project D16

A Project
Name: The Arlanda ATES for heating and cooling
Location: Stockholm Arlanda Airport
Starting date: Operation June 2009
Duration: Seasonal

B Storage Technology
Storage media: An esker (shallow aquifer)
What is innovative and/or significant compared to state of the art knowledge? No heat pump is used. The heat is used for preheating of ventilation air and for ground coil heating systems at + 15-20 °C

C Current progress: Permit given. Environmental monitoring, as conditioned in the permit, started June 2009.

D System description
Purpose: Free cooling for air conditioning and for space heating and snow melting
Capacity / dimensions: Load capacity 10 MW; Stored thermal energy approx. 12 GWh/year
Performance: The performance factor expects to be in the order 50

E Sustainability aspects: The environmental assessment report suggests saving of 4-6 GWh electricity and some 10 GWh of district heat. This will reduce emissions of greenhouse gases with approx. 10 000 ton/years

F Operational experiences: First month of operation as expected

G Finance: Commercial funded. No LCC analyses performed

H Contact Person / Project Partners
Olof Andersson

References
Web sites: Some information may be found on: www.luftfartsverket.se
Paper: Andersson, O. 2009 The ATES Project at Stockholm Arlanda Airport- Technical Design and Environmental Assessment, *Effstock 2009.*
Boundary Conditions
Not analysed yet

Project D17

A Project
Name The Kranen ATES system
Location Malmö City, Sweden
Starting date late winter 2007
Duration Seasonal

B Storage Technology
Storage media: A limestone aquifer
What is innovative and/or significant compared to state of the art knowledge: Storage of cold only, using salt harbour water. Wells are constructed to be corrosion resistant.

C Current progress: Not in operation due to technical problems (iron precipitation)

D System description
Purpose: Free cooling for a district cooling system
Capacity / dimensions: 6 MW, with storage of some 10 GWh of cold annually
Performance: Expected to be operated with a PF of 30-40

E Sustainability aspects: Not analysed so far

F Operational experiences: Na

G Finance: Commercial funded

H Contact Person / Project Partners
Olof Andersson

References
Web sites:

Boundary Conditions
Not available

Project D18

A Project	
Name	Aquifer Thermal Energy Storage Application in Greenhouse Climatization
Location	Adana, Turkey
Starting date	2004
Duration	monitoring 2005-2006

B Storage Technology
Storage media Gravel aquifer
What is innovative and/or significant compared to state of the art knowledge?
The very first ATES application in greenhouses in Mediterranean climate, waste heat in the greenhouse is utilized as a renewable heat source for storage, winter air was used as the cold source for storage, a new heat distribution system in the greenhouse using fan coils and perforated polyethylene air ducts assembly

C Current progress Demonstration plant

D System description
Purpose
Heating the greenhouse growing tomatoes (Terminator-F1, hybrid) without using any fossil fuels and testing the potential of cooling the greenhouse with ATES
Capacity / dimensions

360 m^2 PE covered greenhouse, one warm and one cold well each at a depth of 80 m situated 108 m apart. The heating load of a greenhouse is about 150 W/m^2. Heating is needed for about 90 days at 8 hours/day during the year.

Performance: COP for the ATES system for heating and cooling for 2005-2006 period were 7.6 and 3.2, respectively.

E Sustainability aspects

With “zero” fossil fuel consumption- leading to 68% energy conservation, 20-40% increase in product yield depending on season and short payback time of less than 1 year, the ATES system shows a very high potential for greenhouse climatisation.

Longer harvest periods provided by the cooling process, increases product yield. Organic farming techniques to achieve in-greenhouse pollination by Bombus bees were also used. Calculated CO_2 emissions reduction is 5.6 tons/year compared to a conventional greenhouse using coal.

F Operational experiences:
Introduction of cooling in the greenhouse production elongated the harvest time. Another benefit of cooing, which could not be foreseen, was shifting of the harvest period to a period when market value of the product was at its peak. This peak in Mediterranean climate usually corresponds to the period between when greenhouse production is stopped due to high temperature in the greenhouse and production from open field agriculture is just starting. As a result of elongated and shifted harvest time economic value of the product was further increased in addition to the benefit of energy savings.Heat storage above +40 °C was avoided in order to avoid scaling problem that could be expected.

G Finance: Funded by Turkish Scientific Research Organisation - TUBITAK and Cukurova University Research Fund

H Contact Person / Project Partners
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References:
Turgut B., Paksoy H., Bozdag S., Evliya H., Abak K., Dasgan H.Y., (2008). Aquifer Thermal Energy Storage Application in Greenhouse Climatization, July 19-25, Glasgow.
Turgut B., Paksoy H.Ö., Bozdag S., Evliya H., Abak K., Dasgan Y. (2006), Aquifer Thermal Energy Storage Application in Greenhouse Climatization, 10th International Conference on Thermal Energy Storage, Ecostock , NJ, USA, 31 May – 2 June, 2006, 29-36.

Boundary Conditions:
<u>Growth requirements for tomatoes</u>
Temperature inside the greenhouse should be within 12 -30 °C
<u>Sources of energy for storage</u>
Temperatures in the greenhouse varied between 40-60ºC about 6 hours/day for 5 months in this climate. Winter air colder than 10ºC is the source for cooling.
<u>ATES operational conditions</u>
Heat storage in summer if indoor greenhouse temperature is lower than 40 °C
Heat recovery in winter if indoor greenhouse temperature is lower than 11 °C
Cold storage in winter if outdoor temperature is lower than 10 °C
Cooling in summer if indoor greenhouse temperature is greater than 30 °C

Project D19

A Project
Richard Stockton College of New Jersey ATES system
Pomona, New Jersey USA
Starting date (full operation November 2008)
Permanent installation life expectancy over 30 years

B Storage Technology
Cold Aquifer (sand and gravel)Store
First application on commercial scale in the US. Designed by IF Technology (Netherlands) based on their substantial experience

C Current progress Demonstration plant/full commercial application

D System description
This system ties into a chilled water loop between five campus buildings not currently on the BTES geothermal heat pump system. In addition a new campus student center (currently starting construction) will utilize half the capacity for cooling in two years time. The chilled water loop is utilizing traditional chillers and is designed as a back up system for individual buildings. The ATES system will provide base load cooling for these buildings.
The cooling capacity is 600-800 tons (2 – 2.6 MW) depending on future use patterns. It will store 86million gallons (320k m^3) of chilled water. Two clusters of three wells are situated approximately 300 m apart. The three wells in a cluster are 30 m from each other forming a cold store and a warm store. A 750 ton (2.4 MW) cooling tower is used to charge the cold store at a temperature of 6 ^oC and discharged over the summer to a maximum of 12 ^oC .

E Sustainability performance (See attached sustainability performance template)

F Contact Person / Project Partners
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Aart Snijders
IF Tech International

G References/ Web sites

Project D20

A Project
First Ave Elementary School
Newark, New Jersey USA
Starting date (full operation September 2007)
Permanent installation life expectancy over 30 years

B Storage Technology
BTES geothermal heat pump (cold store)
Unusual (perhaps first) application on commercial scale in the US of a BTES system fully designed to store cold in the winter to achieve a thermal balance. Designed by IF Technology (Netherlands) based on their substantial experience

C Current progress Demonstration plant/full commercial application

D System description
This system will serve to heat and cool the classrooms. The thermal energy required for heating is substantially less than for cooling (a factor of 1 to 10) due to a very well designed building envelope. A dry cooler of 100 tons (350 kW) capacity is used in the winter to store the additional cold required for cooling. The loop temperature will vary from a low of -3^{o}C to a high of 35 ^{o}C over the year.

The cooling capacity is 230 tons (800 kW). The borehole field consists of seventy 450 ft (135m) deep single u-tube high density polyethylene pipes located in the playing field courtyard of this one city block school.

E Sustainability performance (See attached sustainability performance template)

F Contact Person / Project Partners
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Aart Snijders
IF Tech International

1.9 Collected data B. Performance Evaluation Tables for Demonstration Projects

Performance Evaluation Tables Structure

1. Heat Source Section

Heat Source Section	Chiller (Total amount of system)		Capacity	kWh	Annual	
			Energy Consumption	kWh	Annual	
			Load Ratio	%	Annual	
			COP	-	Annual	
			*	*	*	
	Heat Source (Total amount of system)		Capacity	kWh	Annual	
			Energy Consumption	kWh	Annual	
			Load Ratio	%	Annual	
			COP	-	Annual	
			*	*	*	
	Auxiliary Machine	Cooling Tower	Energy Consumption	kWh	Annual	
		Primary Pump	Energy Consumption	kWh	Annual	

2. Thermal Storage Section

Thermal Storage Section	Underground Thermal Storage	Cooling	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			*	*	*	
		Heating	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			*	*	*	
		Pumps	Energy Consumption	kWh	Annual	
		Cooling Tower	Energy Consumption	kWh	Annual	
	Phase Change Material	Cooling	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			*	*	*	
		Heating	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			*	*	*	
		Fans (Pumps)	Energy Consumption	kWh	Annual	
		Cooling Tower	Energy Consumption	kWh	Annual	
	Water Storage	Cooling	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			Storage Tank Efficiency	%	Annual	
			*	*	*	
		Heating	Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			Storage Tank Efficiency	%	Annual	
			*	*	*	
		Pumps	Energy Consumption	kWh	Annual	
	Ice Storage Tank		Capacity	kWh	Annual	
			Storage Efficiency Ratio	%	Annual	
			Storage Tank Efficiency	%	Annual	
			Pump Energy Consumption	kWh	Annual	
			*	*	*	

3. Water(Liquid) Transport Section

Water(Liquid) Transport Section	Cooling	WTF (Water Transport Factor)	-	Season or Annual	
		Temperature difference(Δt)	degree	Annual	
		*	*	*	
	Heating	WTF (Water Transport Factor)	-	Season or Annual	
		Temperature difference(Δt)	degree	Annual	
		*	*	*	
	Pumps	Energy Consumption	kWh	Annual	

4. Entire Heat Source System

Entire Heat Source System	Heat Source System Energy Consumption	kWh	Annual	
	Primary Energy COP	-	Annual	
	Night Shift Ratio	%	Annual	
	CO2 Emitions	MJ/t-CO2	Annual	
	Peak Shaving	%	Annual	
	*	*	*	

5. Air Conditioning System

Air Conditioning System	Cooling	AHU / FCU Energy Consumption	kWh	Annual	
		ATF (Air Transport Factor)	-	Season	
		*	*	*	
	Heating	AHU / FCU Energy Consumption	kWh	Annual	
		ATF (Air Transport Factor)	-	Season	
		*	*	*	

6. Renewable Energy

Renewable Energy ex. photovoltaic cell, wind generation,,,,	Capacity	kWh	Annual	
	Capacity	kWh	Annual	
	Capacity	kWh	Annual	

7. Energy Consumption

Energy Consumption	Primary Energy Consumption per Area	GJ / m^2	Annual	

8. Building

Building	LCA	LCCO2	t-CO2 / m^2	Lifetime	
		*	*	*	
	Finance	LCC	euro	Lifetime	
		Operation Cost	euro	Lifetime or Annual	
		Initial Cost	euro	-	
		Capital	euro	-	
		Insurance cost	euro	Lifetime or Annual	
		Depletion	euro	Lifetime or Annual	
		TAX	euro	Lifetime or Annual	
		Building lifetime	Year	-	
		Facility lifetime	Year	-	
		*	*	*	

Performance Evaluation Tables

Heat Source Section

General						Heat Source Section											
						Chiller (Total amount of system)					Heat Source (Total amount of system)					Auxiliary Machine	
																Cooling Tower	Primary Pump
Project#	Country	City	Term	TES Type	Notes	Capacity	Energy Consumption	Load Ratio	COP	*	Capacity	Energy Consumption	Load Ratio	COP	*	Energy Consumption	Energy Consumption
						MWh	MWh	%	-	*	MWh	MWh	%	-	*	MWh	MWh
						Annual	Annual	Annual	Annual	*	Annual	Annual	Annual	Annual	*	Annual	Annual
D1	Canada	Halifax	Long	BTES	Ocean	2,275	455		5.00							27	1
D2	China	Nanjing	Long	BTES+Water	GSHP	186	82		2.26								
D3	China	Beijing	Short	Ice	Cooling Only	425	143		2.96		181	75		2.41		5	386
D4	Germany	Chemnitz	Short	Water	Waste Heat	9,763	15,588	67%	0.63							1,307	
D5	Germany	Berlin	Long	Energy piles	Free Cooling	57	2	2985%	30.62		141	28	5038%	5.14			#VALUE!
D6	Germany	Hamburg	Long	BTES	Free Cooling	64	3	2624%	21.56		214	55	5932%	3.87			#VALUE!
D7	Germany	Lüneburg	Long	Energy piles	Free Cooling	3	0	600%	8.38		43	13	900%	3.41			
D8	Germany	Berlin	Long	Energy piles		0	0	0%			189	57	6728%	3.34			
D9	Germany	Gelsenkirchen	Long	BTES		552	66	4400%	3.59	*	588	251	2768%	3.59	*		
D10	Japan	Tokyo	Short	Water		27,830	4,973	98%	5.60		10,464	3,096	100%	3.38		0	1
D11	Japan	Gifu	Short	Water & Ice		1,130	253		4.46		564	151		3.74			58
D12	Spain	Lleida	Short	PCM	Concrete				2.00								
D13	Spain	Lleida	Short	PCM	Brick	0	0		2.80								
D14	Spain	Lleida	Short	PCM	Alveolar Brick	0	0		2.80								
D15	Spain	Zaragoza	Short	PCM	Free Cooling						0	0		1.00			
D16	Sweden	Stockholm	Long	ATES													
D17	Sweden	Malmö	Long	ATES													
D18	Turkey	Adana	Long	ATES	Green House												
D19	USA	Stockton	Long	ATES													
D20	USA	Stockton	Long	BTES													

Storage Section (UTES, PCM)

General				Underground Thermal Storage								Phase Change Material							
				Cooling			Heating			Pumps	Cooling	Cooling			Heating			Fans	Cooling
Project#	Country	Term	TES Type	Capacity	Storage Efficiency Ratio	Temperature difference (Δt)	Capacity	Storage Efficiency Ratio	Temperature difference (Δt)	Energy Consumption	Energy Consumption	Capacity	Storage Efficiency Ratio	*	Capacity	Storage Efficiency Ratio	*	Energy Consumption	Energy Consumption
				MWh	%	degree	MWh	%	degree	MWh	MWh	kWh	%	*	kWh	%	*	kWh	kWh
				Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	Annual	*	Annual	Annual	*	Annual	Annual
D1	Canada	Long	BTES	5	86%					2	26,900								
D2	China	Long	BTES+Water																
D3	China	Short	Ice	358	134%		181	58%		374									
D4	Germany	Short	Water																
D5	Germany	Long	Energy piles	71	65.4%	1.6	109	152.9%	1.2	4									
D6	Germany	Long	BTES	64	36.6%	1.2	176	273.4%	2.1	9									
D7	Germany	Long	Energy piles	5	20.5%	0.3	25	487.2%	1.7										
D8	Germany	Long	Energy piles	0			147		1.8										
D9	Germany	Long	BTES	403	208.2%		193	48.0%											
D10	Japan	Short	Water																
D11	Japan	Short	Water & Ice																
D12	Spain	Short	PCM																
D13	Spain	Short	PCM									5							
D14	Spain	Short	PCM									6							
D15	Spain	Short	PCM									7	73,5−94,1%		7	74−94%		1	
D16	Sweden	Long	ATES	0.012			0.010			0.00024									
D17	Sweden	Long	ATES	0.010						0.00025									
D18	Turkey	Long	ATES	7	21%		13	57%		4									
D19	USA	Stockton	Long	2,600	68%					300									
D20	USA	Stockton	Long	15,200	96%		64,000	96%		6,372		3							

Storage Section (Water, Ice)

General				Water Storage									Ice Storage Tank				
				Cooling				Heating				Pumps					
Project#	Country	Term	TES Type	Capacity	Storage Efficiency Ratio	Storage Tank Efficiency	*	Capacity	Storage Efficiency Ratio	Storage Tank Efficiency	*	Energy Consumption	Capacity	Storage Efficiency Ratio	Storage Tank Efficiency	Pump Energy Consumption	*
				MWh	%	%	*	MWh	%	%	*	MWh	MWh	%	%	MWh	*
				Annual	Annual	Annual	*	Annual	Annual	Annual	*	Annual	Annual	Annual	Annual	Annual	*
D1	Canada	Long	BTES														
D2	China	Long	BTES+Water										9	80%	99%		
D3	China	Short	Ice														
D4	Germany	Short	Water	33	99%												
D5	Germany	Long	Energy piles														
D6	Germany	Long	BTES														
D7	Germany	Long	Energy piles														
D8	Germany	Long	Energy piles														
D9	Germany	Long	BTES														
D10	Japan	Short	Water	28,460	102%	99%		9,946	95%			102					
D11	Japan	Short	Water & Ice	908	96%			287	70%			7	24			4	3,667
D12	Spain	Short	PCM														
D13	Spain	Short	PCM														
D14	Spain	Short	PCM														
D15	Spain	Short	PCM														
D16	Sweden	Long	ATES														
D17	Sweden	Long	ATES														
D18	Turkey	Long	ATES														
D19	USA	Stockton	Long														
D20	USA	Stockton	Long														

Entire Heat Source System & Air Conditioning System

General				Entire Heat Source System						Air Conditioning System					
										Cooling			Heating		
Project#	Country	Term	TES Type	Heat	Primary	Night Shift	CO2	Peak	*	AHU /	ATF (Air	*	AHU /	ATF (Air	*
				MWh	-	%	MJ/t-CO2	%	*	kWh	-	*	kWh	-	*
				Annual	Annual	Annual	Annual	Annual	*	Annual	Season	*	Annual	Season	*
D1	Canada	Long	BTES												
D2	China	Long	BTES+Water												
D3	China	Short	Ice				1,066								
D4	Germany	Short	Water	n. a.	n. a.	42%	n. a.	59%							
D5	Germany	Long	Energy piles	29	2.5		35,652								
D6	Germany	Long	BTES	58	1.8		25,184								
D7	Germany	Long	Energy piles	13	1.3		18,611								
D8	Germany	Long	Energy piles	57	1.2		17,588								
D9	Germany	Long	BTES	317	1.3		18,935								
D10	Japan	Short	Water	19,395	1.2	86%	82	27%							
D11	Japan	Short	Water & Ice	494	1.3	72%	232								
D12	Spain	Short	PCM	0.07											
D13	Spain	Short	PCM	0.07			1−1.5			70					
D14	Spain	Short	PCM	0			1−1.5			76					
D15	Spain	Short	PCM												
D16	Sweden	Long	ATES												
D17	Sweden	Long	ATES												
D18	Turkey	Long	ATES				12,670			–					
D19	USA	Stockton	Long		approx 8										
D20	USA	Stockton	Long												

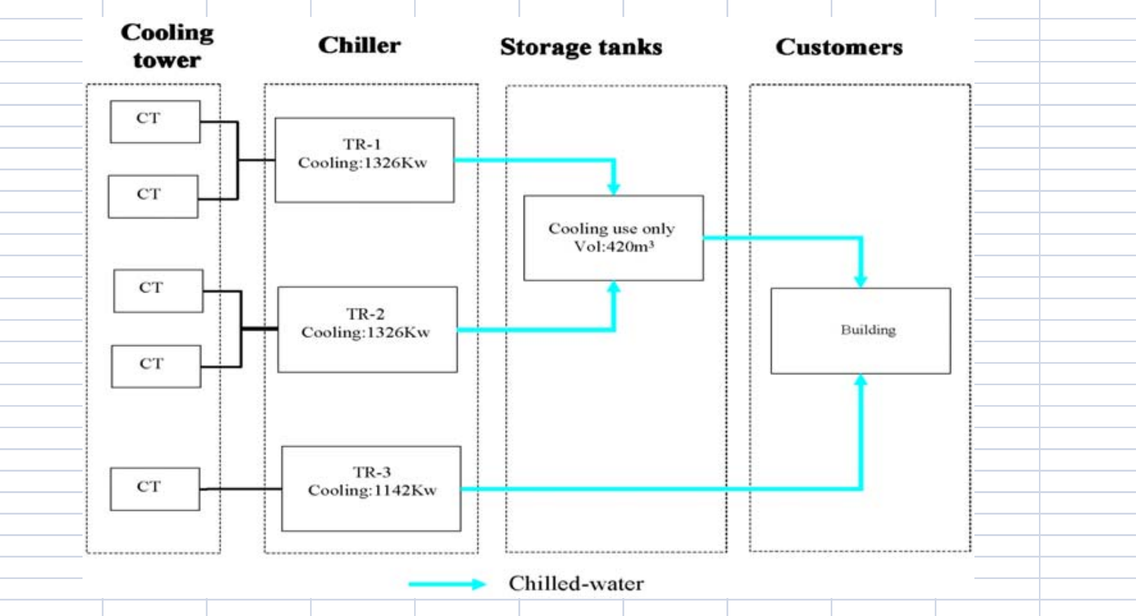
Renewable Energy & Building

General				Renewable Energy			Energy Consumpti	Building											
								LCA		Finance									
Project#	Country	Term	TES Type	Capacity	Capacity	Capacity	Primary	LCCO2	*	LCC	Operation	Initial Cost	Capital	Insurance	Depletion	TAX	Building	Facility	*
				MWh	kWh	kWh	GJ / m^2	t-CO2 / m^2	*	euro/US$	euro/US$	euro/US$	euro/US$	euro/US$	euro/US$	euro/US$	Year	Year	*
				Annual	Annual	Annual	Annual	Lifetime	*	Lifetime	Lifetime or Annual	-	-	Lifetime or Annual	Lifetime or Annual	Lifetime or Annual	-	-	*
D1	Canada	Long	BTES	520						517,912	257,616	$ 1.6 M CDN		NA				25	
D2	China	Long	BTES+Water																
D3	China	Short	Ice																
D4	Germany	Short	Water																
D5	Germany	Long	Energy piles	48															
D6	Germany	Long	BTES																
D7	Germany	Long	Energy piles																
D8	Germany	Long	Energy piles																
D9	Germany	Long	BTES	15															
D10	Japan	Short	Water																
D11	Japan	Short	Water & Ice				0.276												
D12	Spain	Short	PCM																
D13	Spain	Short	PCM				0.114												
D14	Spain	Short	PCM				0												
D15	Spain	Short	PCM																
D16	Sweden	Long	ATES																
D17	Sweden	Long	ATES																
D18	Turkey	Long	ATES																

Schematic Diagram & COP calculation conditions

Project D2

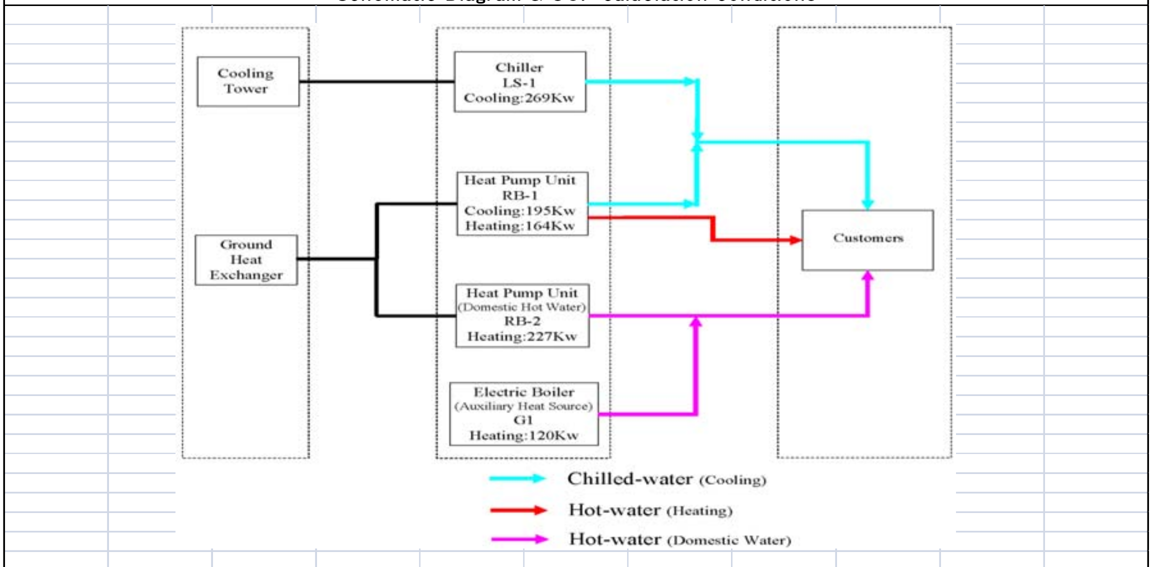
Location
Nanjing, China
Project Properties (use / short or long term / kind of storage / others)
Short term Storage / Underground Thermal Storage / completion in 2008
Schematic Diagram & COP caluclation conditions



Written by
Hundred Group

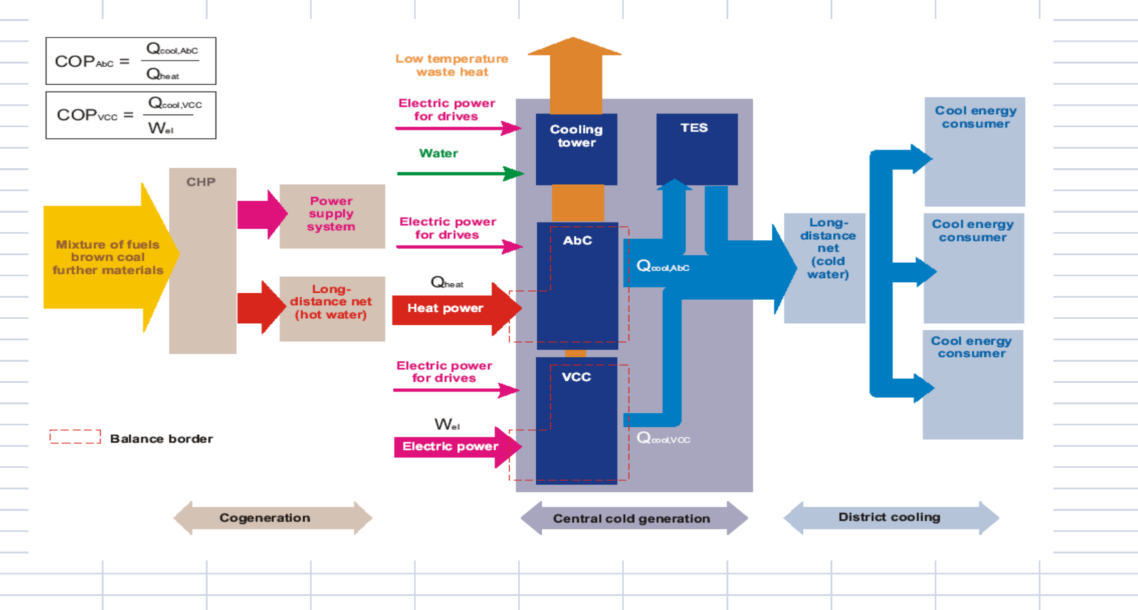
Project D3

Location
Beijing, China
Project Properties (use / short or long term / kind of storage / others)
Short term Storage / Ice storage / completion in 2008
Schematic Diagram & COP caluclation conditions

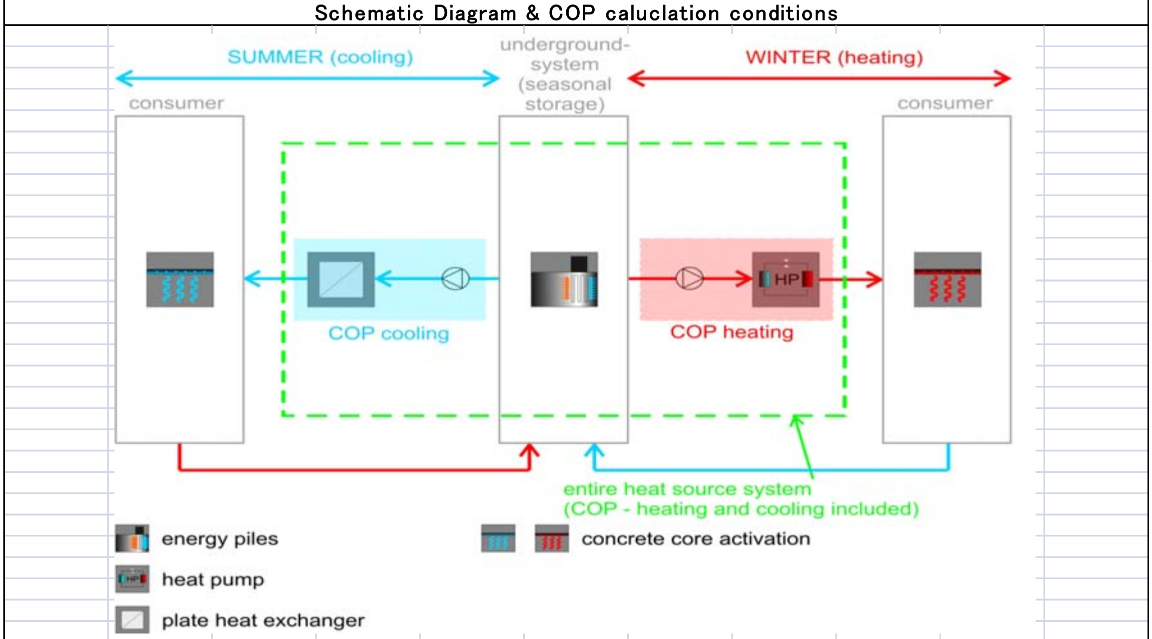


Written by
Hundred Group

Project D4

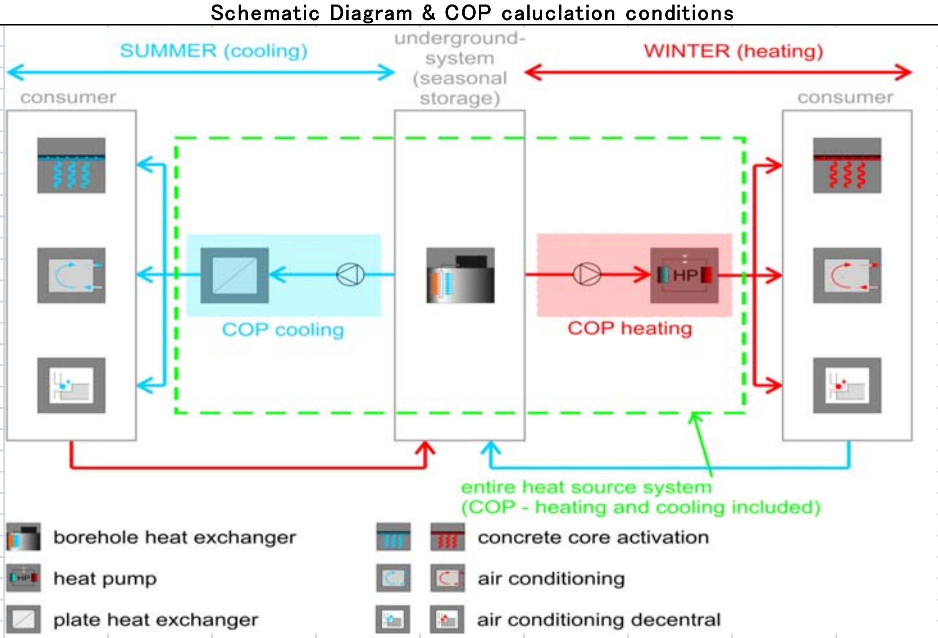
Chemnitz (Germany)
Project Properties (waste heat / short term / cold water storage)
Schematic Diagram & COP calculation conditions

Written by Thorsten Urbaneck

Project D5

Location
EFB – Berlin, Germany
Project Properties (use / short or long term / kind of storage /others)
heating and cooling / long term storage / UTES (foundation) / completion 2003
Schematic Diagram & COP caluclation conditions

Written by
Franziska Bockelmann

Project D6

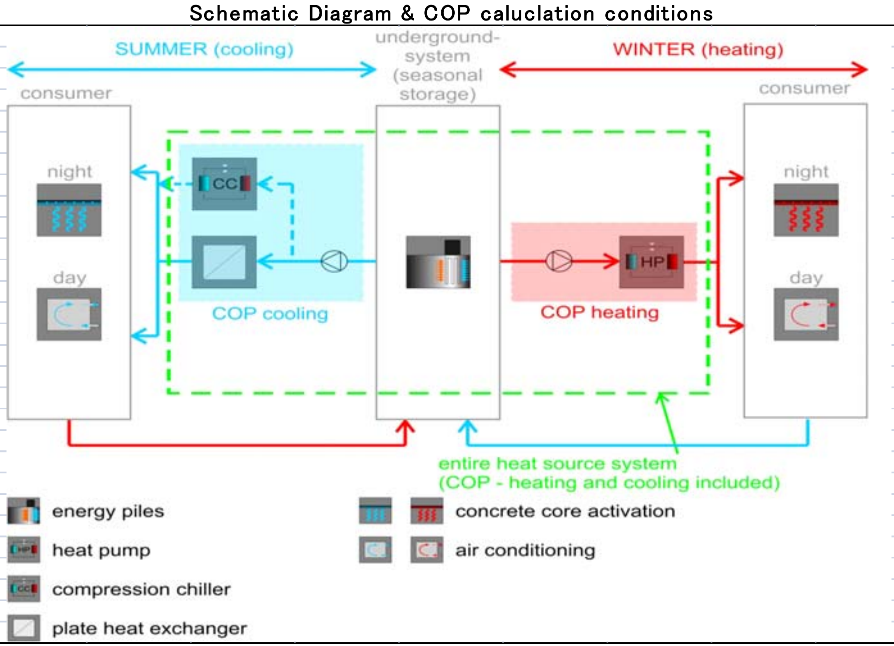
Location
RIC – Hamburg, Germany
Project Properties (use / short or long term / kind of storage /others)
heating and cooling / long term storage / BTES (foundation) / completion 2002
Schematic Diagram & COP caluclation conditions



Written by
Franziska Bockelmann

Project D7

Location
VGH – Lüneburg, Germany
Project Properties (use / short or long term / kind of storage /others)
heating and cooling / long term storage / UTES (foundation) / completion 2002
Schematic Diagram & COP caluclation conditions



Written by
Franziska Bockelmann

Project D8

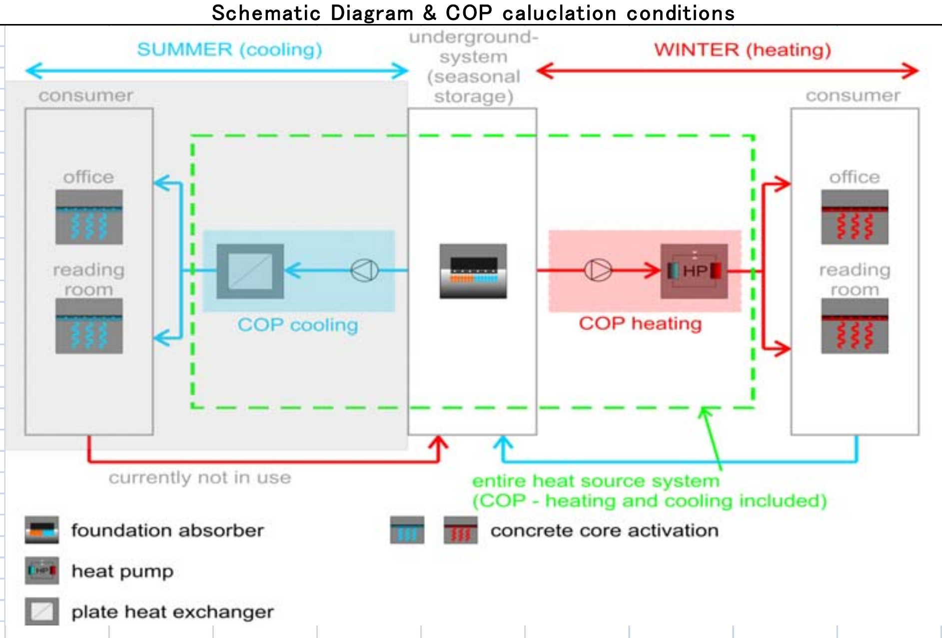
Location

TUB – Berlin, Germany

Project Properties (use / short or long term / kind of storage /others)

heating and cooling / long term storage / UTES (foundation) / completion 2004

Schematic Diagram & COP caluclation conditions



Written by

Franziska Bockelmann

Project D9

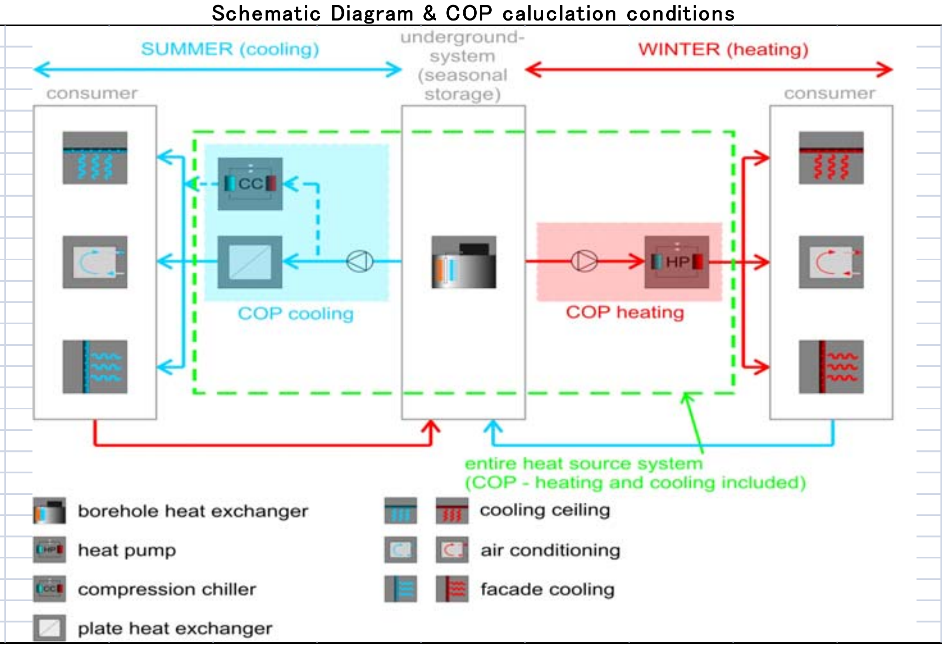
Location

GEW – Gelsenkirchen, Germany

Project Properties (use / short or long term / kind of storage /others)

heating and cooling / long term storage / BTES (foundation) / completion 2004

Schematic Diagram & COP caluclation conditions

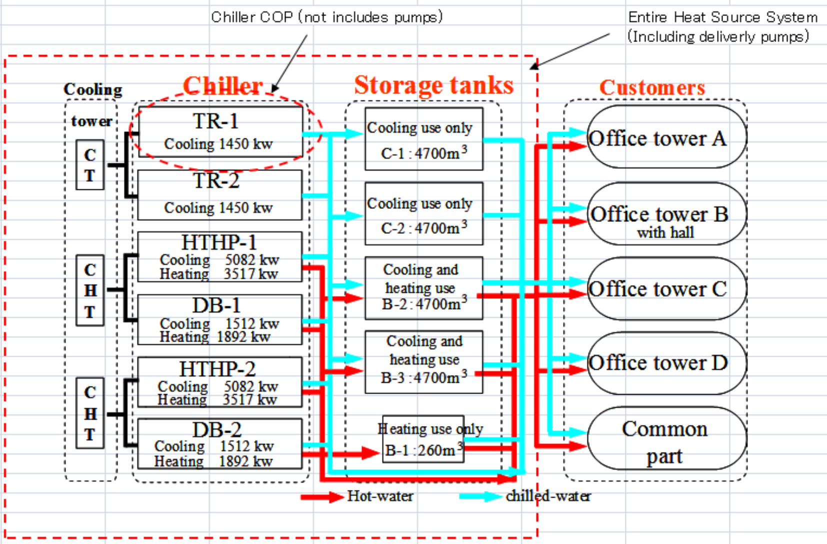


Written by

Franziska Bockelmann

Project D10

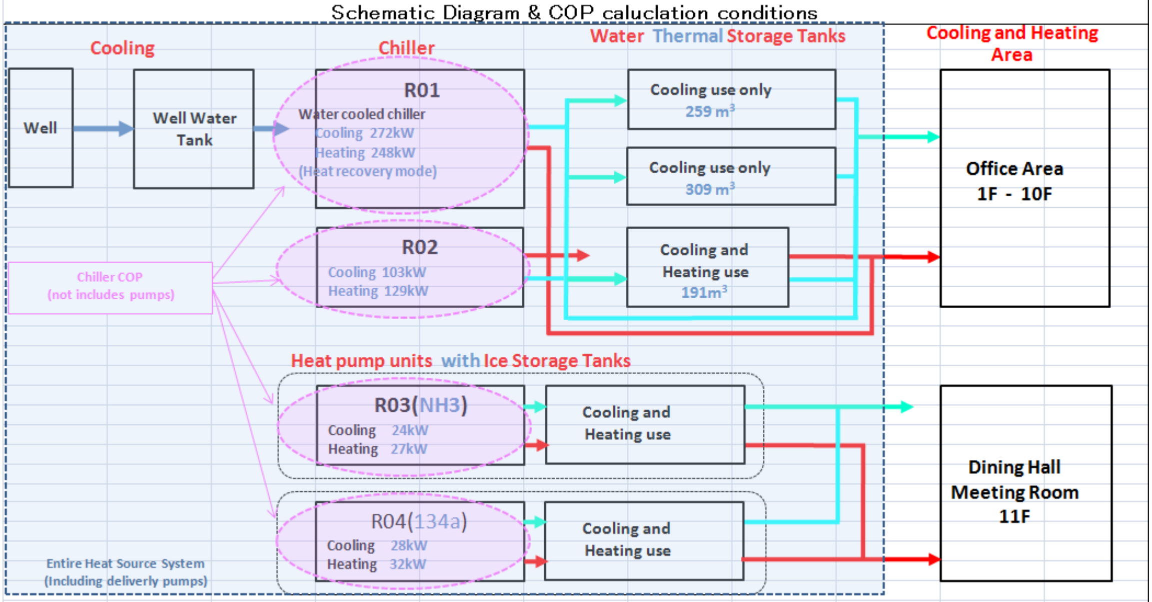
Location
Japan, Tokyo
Project Properties (use / short or long term / kind of storage / others)
DHC / Short term Storage / water storage / completion in 2001
Schematic Diagram & COP caluclation conditions



Written by
Masashi Momota

Project D11

Location
Japan, Gifu
Project Properties (use / short or long term / kind of storage / others)
This Office / Short term Storage / water storage, ice storage / completion in 2001
Schematic Diagram & COP caluclation conditions



Written by
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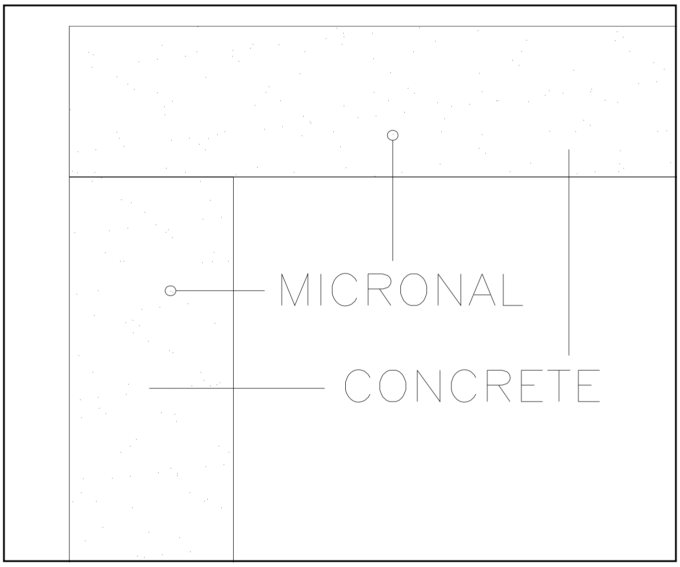
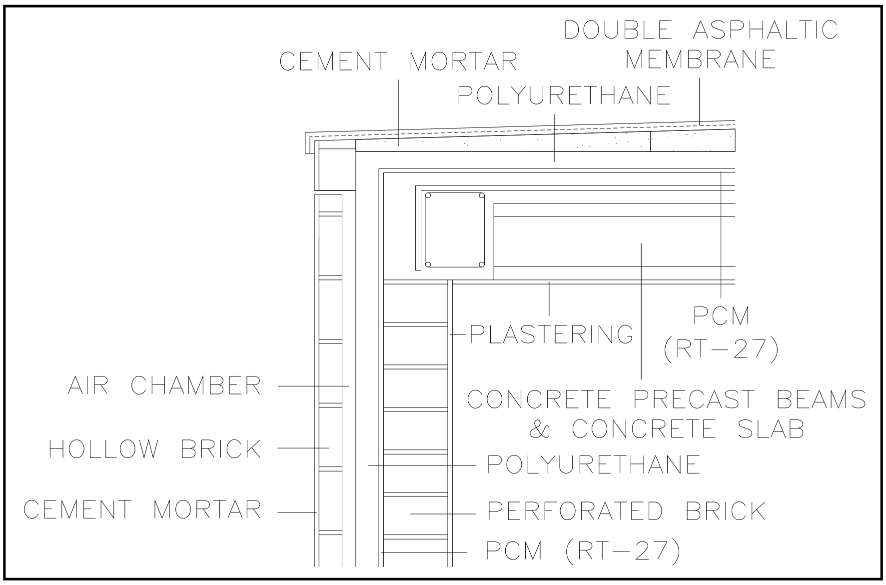
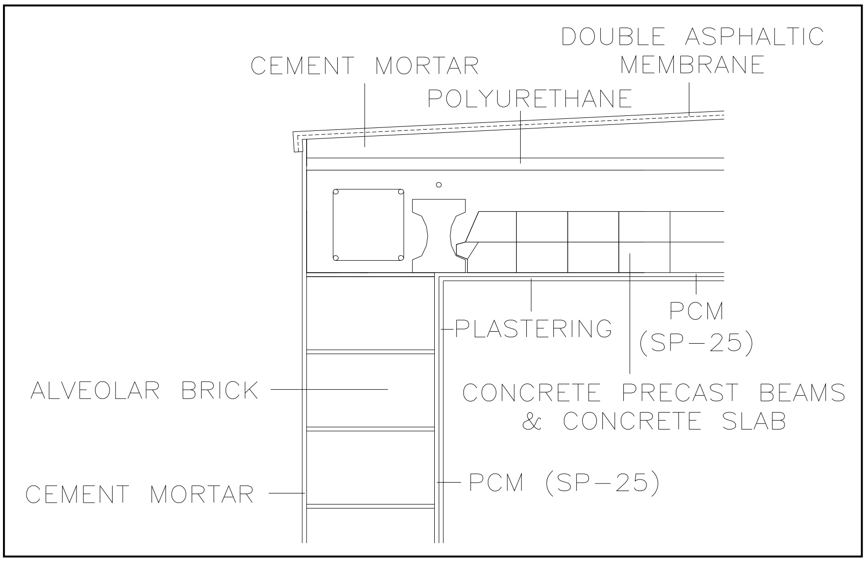
Project D12



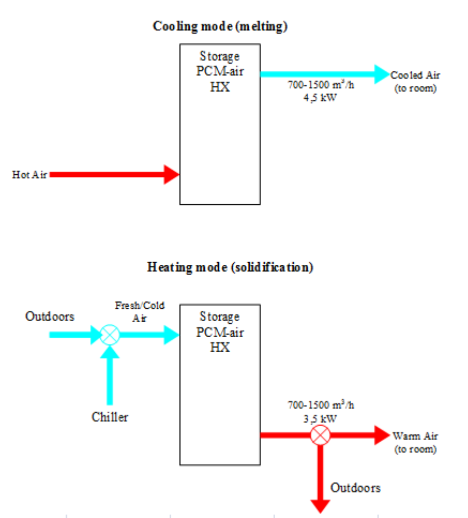
Project D13



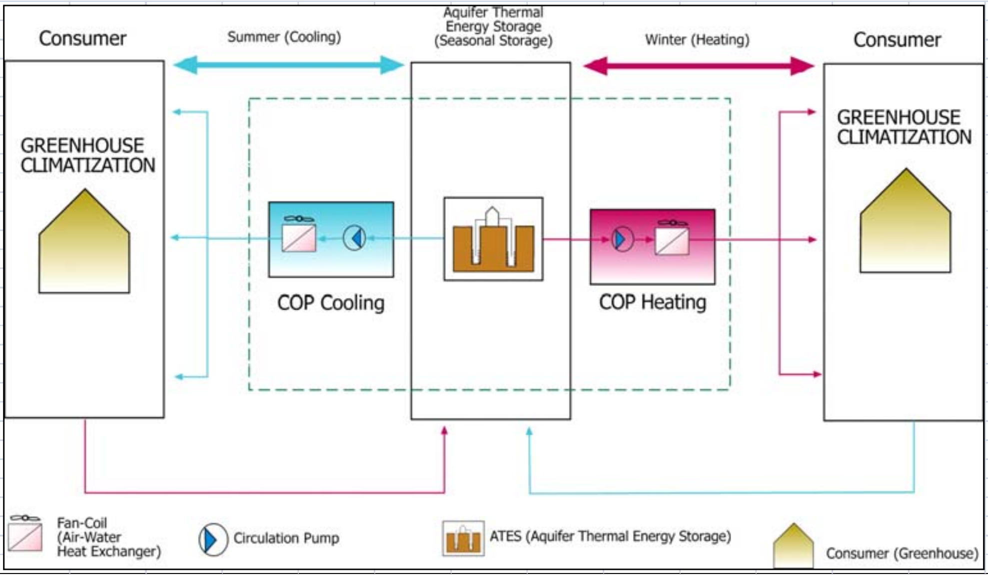
Project D14



Project D15

Location
Zaragoza, Spain
Project Properties (use / short or long term / kind of storage /others)
Freecooling, Room temperature control / short term / PCM (air as HTF)
Schematic Diagram & COP caluclation conditions

Written by
Ana Lázaro, Pablo Dolado

Project D18

Location
Çukurova Üniversity Adana-Turkey
Project Properties (long term (seasonal) storage)
direct heating and cooling / long term storage / ATES application/ completion 2006
Schematic Diagram & COP calculation conditions

Written by
Bekir Turgut

2. Subtask B "Design procedure and system performance evaluation tools"

Subtask B List of Contributors

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2.1. Introduction

Many advantages can be achieved by the employment of Cool TES, for example the reduction of peak load in the electric power supply, the reduction of energy consumption, the substitution of environmental harmful refrigerants, the improvement of system operation etc. This problem concerns not only the countries with a warm climate. World-wide measures must be taken for the improvement of the cooling supply and air conditioning. It is to be noted that the energy consumption for cooling rises in the world. The challenge in Annex 20 consists of the fact that in individual member countries different boundary conditions apply at present, which affect the respective technical solution and/or the procedure significantly. The different boundary conditions are the following:

- Climate with different load curves and consumption,
- Basic approach relating to the energy industry (e.g. employment of waste heat),
- Standards, guidelines, planning tools, systems, modes of operation.

2.2. Objective

A good design is necessary to demonstrate energy-saving performance of a thermal storage system. For a good design, the manuals and design tools that were developed with the correct understanding of performance of a system are required. Another important issue is the proper operation of thermal storage system. For the optimal operation of thermal storage system, the appropriate operation tools and manuals are needed. So, in this subtask:

- Existing design manuals and tools for the short and long term thermal storage will be reviewed using inventory developed in Annex 14 or from other activities.

- Evaluation of design tools with respect to possibility of their use in various stages of design procedure will be examined.

- For a specific system, performance evaluation with two or more design tools will be performed, and the results will be compared.

Finally the comprehensive design/evaluation tool which leads to realization of the optimized integration of TES in cooling system is established. Source: [1]

2.3. Proceeding

During the meetings different questions were clarified. A challenge was that many different storage types and systems were examined. It was necessary to analyze various points:

- Evaluation concerning design tools (Calculation, Simulation, Design)
  - Overview concerning Software, Software Modules, Guidelines and Manuals (see Collected data A)
  - Outline for several Software, Software Modules, Guidelines and Manuals (see Collected data B)
- Detailed analysis of on measurement of boundary conditions – Monitoring and norms (see Collected data C)
- Further analysis of weather and load data (see Collected data C)
- Application of design tools – Examples (see Collected data D)
- Compensation of design and operation (see Collected data D)

2.4. Subtask B Conclusions

2.4.1 Collected data A and B

Many Software, Manuals and Guidelines are available. We have a development in the last 4 years (from Annex 14). The report shows tendencies of software and design tools for cooling with TES. But every expert work with different programs. The activities in Subtask B close the gap between the specialists. The complex problems desire the application of program (e. g. simulation of storage behaviour and life cycle analysis).

2.4.2 Collected data C

Monitoring of plants, of building and weather is very important for benchmark in Subtask A and the evaluation of design tools in Subtask B. The measured data show the real boundary conditions and the efficiency of solution with Cool TES. We must distinguish between normal and extreme years in central Europe. The ambient temperature (and humidity) has a big influence on cooling capacity and cooling demand. The higher ambient temperatures in the last years cause more capacity and higher demand.

2.4.3 Collected data D

Various examples in Collected data D give a short overview concerning application of design tools. It is necessary to grasp of the aim for Individual Software, Models and Manuals by understanding of what kind of input data did tool need, and what kind of results gave.
Information of this survey would help suitable application of tools for cooling TES system, the spread of cool TES and energy conservation.
The future challenge is to gather application example of tools and detailed information of mathematical and/or analytical TES model, and then to classify tools depending on characteristics, to organize application phase and case for tools.

2.5 References

[1] INTERNATIONAL ENERGY AGENCY (IEA) ENERGY CONSERVATION THROUGH ENERGY STORAGE (ECES) ECES Annex20: Sustainable Cooling with Thermal Energy Storage. Prepared by Prof. Halime Paksoy Çukurova University, Turkey, Prof. Masaya Okumiya, Nagoya University, Japan

2.6 Collected data A. Design and Analysis Tools (Computer Software, Models and Manuals) - Overview

Based on this annex, new information of existing design manuals and tools for the short and long term thermal storage are added to the tool inventory of Annex 14.

A.1 Design and Analysis Tool List for Cooling TES

A.1.1 Computer Software

Table 1: Short-term Storage (C…Commercial tool, F…Freeware)

No	Name	Nationality	Source	Manual	OS	Availability
1	DOE21	US	Fortran	EN	Win&Dos	C
2	BLAST1	US	Fortran	EN	Win&Dos	C
3	TRNSYS17	US	Fortran	EN	Win	C
4	ESP-r	UK	Fortran	EN	Win	F
5	TRACE 700	US	Fortran	EN	Win	C
6	HAP V4.0	US	-	EN	Win	C
7	System Analyzer	US	CA-Realizer	EN	Win	C
8	WINTST	JP	C/C++	JP	Win	F
9	TESEP-W	JP	Visual Basic	JP	Win	C
10	ICE-Club	JP	Visual Basic	JP	Win	F
11	HVACSIM+(J)	JP	Fortran	JP (EN)	Win&Dos	F
12	HASP/ACSS/8502	JP	Fortran	JP	Win&Dos	C
13	BECS/CEC/AC	JP	Visual Basic	JP	Win	C
14	Gemis2	DE		EN, DE	Win	F
15	ecoinvent2	CH		En, DE	Win	C
16	LCEM Tool	JP	Excel	JP	Win	F
17	PCM-express	DE		DE	Win	C
18	ANSYS CFX2	US	Fortran	EN	Multi-Platform	C

[1] Environment

[2] Analysis tool, also useable for Long-Term Storages

Table 2: Long-term Storage (C…Commercial tool, F…Freeware, R…Only for study use)

No	Name	Nationality	Source	Manual	OS	Availability
1	AST	SE	Fortran	EN	Dos	C
2	CONFLOW	SE	Fortran	EN	Dos	C
3	EED	DE/SE	Delphi	EN	Win	C
4	GHS	SE	-	EN	Dos	C
5	GLHEPRO	US	Pascal	EN	Win	C
6	HST3D	US	Fortran	EN	Dos	F
7	HST2D/3D IF 3.0	NL	Fortran	EN	Dos / Win	C
8	MODFLOW	US	-	EN	Win	C
9	PIA12	NL	-	EN	Dos	C
10	SHEMAT	GE	Fortran	EN	Win	C
11	SnowSt-WCI3	SE	Excel	EN	Win / Mac	R
12	THETA	FI	Fortran	EN	Dos / Unix	R
13	THOUGT Ver.20	US	Fortran	EN	Multi-Platform	F
14	Tradikon	DE	Fortran	EN	Dos	R
15	TWOW	SE	Fortran	EN	Dos	C
16	FEFLOW	DE		EN, DE	Win / Unix	C
17	Ground Club	JP		JP	Win	C
18	TRNSYS17	US	Fortran	EN	Win	C
19	MATLAB/Simulink1,4	US	Fortran	EN	Multi-Platform	C
20	ANSYS CFX	US	Fortran	EN	Multi-Platform	C

3 SnowSt-WCI: Snow Storage with Wood Chips Insulation
4 Analysis tool, also useable for Short-Term Storages

A.1.2 Software module

Table 3: Short-term Storage (C…Commercial tool)

No	Name	Nationality	Source	Manual	OS	Availability
1	TRNSYS / MULTIPORT	DE	Fortran	EN	Win / Linux	C
2	TRNSYS / Cold Storage Tank (CST)	DE	Fortran	EN	Win / Linux	
3	TRNSYS / TYPE204	FI	Fortran	EN	Win / Linux	
4	TRNSYS / TYPE232	ES	Fortran	EN	Win / Linux	
5	TRNSYS / TYPE241	AT	Fortran	EN	Win / Linux	

Table 4: Long-term Storage

No	Name	Nationality	Source	Manual	OS	Availability
1	TRNSYS / Duct Ground Heat Storage Model (DST / TYPE141)	SE	Fortran	EN	Win / Unix	C
2	TRNSYS / Superposition Borehole Model (SBM / TYPE346)	CH	Fortran	EN	Win / Unix	R
3	TRNSYS / Stratified Storage Temperature Model (SST)	IT	Fortran	EN	Win / Unix	R
4	TRNSYS / Multi-Flow Stratified Thermal Storage Model (XST / TYPE142)	SE, IT	Fortran	EN	Win / Unix	C
5	TRNSYS / EWS (TYPE251)	CH	Fortran	EN	Win / Unix	C
6	TRNSYS / Aquifer Thermal Energy Storage (AST)	SE	Fortran	EN	Win / Linux	C
7	TRNSYS / ICEPIT (TYPE143)	DE	Fortran	EN	Win / Linux	C

A.1.3 Guide & Manuals

Table 3: Short-term Storage

No	Name	Nationality	Publisher	Document
1	Cold Storage Guide, 3rd Edition	US	ASHRAE	EN
2	Design Guide for Cool Thermal Storage	US	ASHRAE	EN
3	Successful Cool Storage Projects from Planning to Operation	US	ASHRAE	EN
4	Cold Air Distribution Guide	US	EPRI	EN
5	Commercial Cool Storage Design Guide	US	EPRI	EN
6	Cool Storage Technology Guide	US	EPRI	EN
7	Guide to Successful Implementation of Cool Storage Projects	US	EPRI	EN
8	Cool Storage Open Hydronic System Design Guide	US	EPRI	EN
9	Basics and Applications of Thermal Storage System	JP	SHASE	JP
10	Design and Control Manual of Thermal Storage System	JP	HPTCJ	JP
11	Manual for Ice Thermal Storage Air Conditioning Systems	JP	HPTCJ	JP
12	Design Guide for Ice Storage Air-Conditioning System	JP	JRAIA	JP

Table 4: Long-term Storage

No	Name	Nationality	Publisher	Document
1	Numerical Simulation of Reactive Flow in Hot Aquifers	GE	Springer	EN

A.2 Scope of Tools

A.2.1 Computer Software

Table 5: Short-term Storage

No	Name	Feasibility	Pre-Design	Detailed Design	TES Characteristics	System Evaluation	Dynamic Simulation
1	DOE2			○		○	
2	BLAST			○		○	
3	TRNSYS			○	○	○	○
4	ESP-r			○	○	○	○
5	TRACE 700		○	○		○	
6	HAP V4.0		○	○		○	○
7	System Analyzer	○	○			○	
8	WINTST				○		
9	TESEP-W	○	○		○	○	
10	ICE-Club	○	○		○	○	
11	HVACSIM+(J)			○	○		○
12	HASP/ACSS/8502		○	○			○
13	BECS/CEC/AC		○	○		○	
14	Gemis	○				○	
15	ecoinvent	○				○	
16	LCEM Tool		○	○	○	○	
17	PCM-express	○	○	○	○	○	○
18	ANSYS CFX			○	○		○

Table 6: Long-term Storage

No	Name	Feasibility	Pre-Design	Detailed Design	TES Characteristics	System Evaluation	Dynamic Simulation
1	AST	○	○	○	○		
2	CONFLOW	○	○		○		
3	EED	○	○	○			
4	GHS	○					
5	GLHEPRO	○	○	○	○		
6	HST3D			○			
7	HST2D/3D IF 3.0			○			
8	MODFLOW			○			
9	PIA12	○	○		○		
10	SHEMAT			○			
11	SnowSt-WCI *				○		
12	THETA		○	○	○		
13	THOUGT Ver.20		○	○			
14	Tradikon	○	○	○			
15	TWOW		○	○	○		
16	FEFLOW	○	○	○	○		○
17	Ground Club		○	○	○	○	
18	MATLAB/Simulink		○	○	○	○	

A.2.2 Software module

Table 7: Short-term Storage

No	Name	Feasibility	Pre-Design	Detailed Design	TES Characteristics	System Evaluation	Dynamic Simulation
1	TRNSYS / MULTIPORT			○	○	○	○
2	TRNSYS / CST			○	○	○	○
3	TRNSYS / TYPE204			○	○	○	○
4	TRNSYS / TYPE232			○	○	○	○
5	TRNSYS / TYPE241			○	○	○	○

Table 8: Long-term Storage

No	Name	Feasibility	Pre-Design	Detailed Design	TES Characteristics	System Evaluation	Dynamic Simulation
1	TRNSYS / DST (TYPE141)			○	○	○	○
2	TRNSYS / SBM			○	○	○	
3	TRNSYS / SST			○	○	○	
4	TRNSYS / XST (TYPE142)			○	○	○	○
5	TRNSYS / EWS (TYPE251)			○	○	○	
6	TRNSYS / AST			○	○	○	○
7	TRNSYS / DST			○	○	○	○
8	TRNSYS / SBM			○	○	○	○
9	TRNSYS / ICEPIT			○	○	○	○

A.2.3 Guide & Manuals

Table 9: Short-term Storage

No	Name	Planning	Design	Characteristics	Construction	Operation	Maintenance	Economics
1	Cold Storage Guide, 3rd Edition	○	○	○	○	○	○	○
2	Design Guide for Cool Thermal Storage	○	○	○	○	○	○	○
3	Successful Cool Storage Projects	○						
4	Cold Air Distribution Guide	○						
5	Commercial Cool Storage Design Guide	○	○	○	○	○	○	○
6	Cool Storage Technology Guide	○	○	○	○	○	○	○
7	Guide to Successful Implementation of Cool Storage Projects	○	○		○	○		
8	Cool Storage Open Hydronic System Design Guide		○		○	○		
9	Basics and Applications of Thermal Storage System	○	○	○	○	○	○	○

10	Design and Control Manual of Thermal Storage System	○	○	○	○	○	○	○
11	Manual for Ice Thermal Storage Air Conditioning Systems	○	○	○	○	○	○	○
12	Design Guide for Ice Storage Air-Conditioning System	○	○	○	○	○	○	

Table 10: Long-term Storage

No	Name	Planning	Design	Characteristics	Construction	Operation	Maintenance	Economics
1	Numerical Simulation of Reactive Flow in Hot Aquifers			○				

A.3 Types of TES

A.3.1 Computer Software

Table 11: Short-term Storage

No	Name	Water Storage			ICE Storage	
		Full-Mixed	Multi connected	Stratified	Static Type	Dynamic Type
1	DOE2	○			○	○
2	BLAST			○		
3	TRNSYS	○		○	○	○
4	TRACE 700			○	○	
5	HAP V4.0		○	○	○	
6	System Analyzer			○	○	
7	WINTST			○		
8	TESEP-W		○	○		
9	ICE-Club		○	○	○	○
10	HVACSIM+(J)	○		○	○	
11	HASP/ACSS/8502		○			
12	BECS/CEC/AC		○		○	
13	LCEM Tool		○	○	○	

Table 12: Long-term Storage

No	Name	Aquifer	Boreholes	Ducts	Cavern	Tank	Pit	Snow
1	AST	○						
2	CONFLOW	○						
3	EED		○					
4	GHS		○	○				
5	GLHEPRO		○					
6	HST3D	○	○					
7	HST2D/3D IF 3.0	○	○					
8	MODFLOW	○						
9	PIA12	○						
10	SHEMAT	○	○					
11	SnowSt-WCI							○
12	THETA	○						
13	THOUGT Ver.20	○						
14	Tradikon	○	○	○				
15	TWOW	○						
16	FEFLOW	○						
17	Grand Club		○					

A.3.2 Software module

Table 13: Short-term Storage

No	Name	Water Storage			Ice Storage		PCM
		Full-Mixed	Multi connected	Stratified	Static Type	Dynamic Type	
1	MULTIPORT	○	○	○			
2	CST-Model			○			
3	TYPE204						○
4	TYPE232						○
5	TYPE241						○

Table 14: Long-term Storage

No	Name	Aquifer	Boreholes	Cavern	Tank	Pit	Snow
1	TRNSYS /DST		○				
2	TRNSYS / SBM		○				
3	TRNSYS / SST			○	○	○	
4	TRNSYS / XST			○	○	○	
5	TRNSYS / EWS		○				
6	TRNSYS / AST	○					
7	TRNSYS / ICEPIT4			○	○	○	

[4] also Gravel-Water, Sand-Water

A.3.3 Guide & Manuals

Table 15: Short-term Storage

No	Name	Water Storage		ICE Storage		PCM Storage
		Multi connected	Stratified	Static Type	Dynamic Type	
1	Cold Storage Guide, 3rd Edition	○	○			
2	Design Guide for Cool Thermal Storage	○	○	○	○	○
3	Successful Cool Storage Projects			○		
4	Cold Air Distribution Guide			○		
5	Commercial Cool Storage Design Guide	○	○	○		
6	Cool Storage Technology Guide	○	○	○	○	○
7	Guide to Successful Implementation of Cool Storage Projects	○	○	○	○	○
8	Cool Storage Open Hydronic System Design Guide		○	○	○	○
9	Basics and Applications of Thermal Storage System	○	○			
10	Design and Control Manual of Thermal Storage System	○	○			
11	Manual for Ice Thermal Storage Air Conditioning Systems			○	○	
12	Design Guide for Ice Storage Air-Conditioning System			○	○	

Table 16: Long-term Storage

No	Name	Aquifer	Boreholes	Cavern	Tank	Pit	Snow
1	Numerical Simulation of Reactive Flow in Hot Aquifers	○					
2	High Temperature Underground Thermal Energy Storage, State-of-the-art and Prospects.	○	○	○			

A.4 Evaluation Index

A.4.1 Computer Software

Table 17: Programs

No	Name	Energy Cons.	Economics	Environment	Other
1	DOE2	○			
2	BLAST	○			
3	TRNSYS	○			
4	ESP-r	○			
5	TRACE 700	○	○		
6	HAP V4.0	○	○		
7	System Analyzer	○	○		
8	WINTST				Tank efficiency, temp. profile
9	TESEP-W	○			Tank volume, tank efficiency
10	ICE-Club	○	○		
11	HVACSIM+(J)				Dynamic characteristics of components
12	HASP/ACSS/8502	○			
13	BECS/CEC/AC	○			
14	Gemis			○	Life-cycle analysis program and database for energy, material, and transport systems
15	ecoinvent			○	Life cycle inventory (LCI), database, life cycle management (LCM) data and services
16	LCEM Tool	○	○		

Table 18: Long-term Storage

No	Name	Energy Cons.	Economics	Environment	Other
1	AST				Extraction temp., heat balance, temperature field in the aquifer
2	CONFLOW				Streamlines, isobars, thermal fronts.
3	EED				Minimum depth of borehole, thermal resistance values, average temp. of the medium
4	GHS				Storage heat losses and heat transfer capacity of ground heat exchanger.
5	GLHEPRO	○			Fluid temp., minimum depth of borehole
6	HST3D				Fluid temp., groundwater flow, pressure
7	HST2D/3D IF 3.0				Fluid temp., groundwater flow, pressure
8	MODFLOW				Ground-water flow, areal recharge, evapotranspiration, flow to drains, flow through riverbeds
9	PIA12	○	○		Size of the store, the cooling units, temperature levels,
10	SHEMAT				Groundwater flow, conductive heat transport, diffusive species transport, chemical reactions
11	SnowSt-WCI				Heat characteristics
12	THETA				Recovery temp., pressure, potential, flow field, energy recovery ratio.
13	THOUGT Ver.20				Bottom hole pressures, flow rate
14	Tradikon				Temp. field, hydraulic head field
15	TWOW				Extraction temp., heat balance, temp. field in the aquifer and surrounding layers.
16	FEFLOW	○			Groundwater flow, conductive heat transport, diffusive species transport, chemical reactions
17	Ground Club	○		○	

A.4.2 Software module

Table 19: Short-term Storage

No	Name	Energy Cons.	Economics	Environment	Other
1	MULTIPORT	○			Heat balance, outlet temp., heat transfer rates, and temp. field in water
2	CST-Model	○			Heat balance, outlet temp., heat transfer rates, and temp. field in foundation, water, gas filled zone
3	TYPE204	○			PCM temperature
4	TYPE232	○			PCM temperature
5	TYPE241	○			PCM temperature

Table 20: Long-term Storage

No	Name	Energy Cons.	Economics	Environment	Other
1	TRNSYS / DST (TYPE141)	○			Heat balance, outlet temp., heat transfer rates, and temp. field in the ground.
2	TRNSYS / SBM	○			Heat balance, outlet temp., heat transfer rates, and temp. field in the ground.
3	TRNSYS / SST	○			Outlets fluid temp., injected-extracted energy, and heat losses.
4	TRNSYS / XST (TYPE142)	○			Outlets fluid temp., injected-extracted energy, and heat losses.
5	TRNSYS / EWS (TYPE251)	○			Total mass flow rate, source temp. of the brine, heat transfer rate, monitor temperatures
6	TRNSYS / AST	○			Extraction temp., heat balance, temperature field in the aquifer
7	TRNSYS / ICEPIT	○			Heat balance, outlet temp., heat transfer rates, and temp. field in water/gravel and ground

2.7 Collected data B. Outline of the Computer Software, Models and Manual

B.1 Tanks, Pits

B.1.1 LCEM TOOL

- Ministry of Land, Infrastructure, Transport and Tourism
- HVAC System Simulation Tool for Life Cycle Energy Management (LCEM)
- Simulation of component/system behaviour
- Excel
- Source: [1]
- URL: http://www.mlit.go.jp/gobuild/sesaku_lcem_lcem.html

LCEM TOOL which is a HVAC System Simulation Tool for Life Cycle Energy Management has been developed by Ministry of Land, Infrastructure, Transport and Tourism in Japan [32]. A overall system or sub system simulation model is constructed by connecting a lot of modularized components, respectively. The plat form of this tool is MS-Excel. System energy balance convergence calculation is run using by a repetition function in the MS-Excel. Instantaneous or one hour discrete states of system energy balance can calculation in this tool. Characteristics equations of heat source equipments such as chillers, heat pumps and boiler, pump, fan and AHU heat exchanger coil are adopted an experimental regression equation provided by manufactures. This tool includes thermal water storage (connected fully-mixed and stratified water tank) and ice thermal storage (static type) model that are adopted mathematical models based on experimental results.

B.1.2 TESEP-W

- Heat Pump & Thermal Storage Technology Center of Japan
- Storage tank efficiency evaluation tool for water thermal storage
- Simulation of thermal behaviour
- Stand-alone program
- Source: [2]
- URL: http://www.hptcj.or.jp/technology/program/index.html#1

TESEP-W which is a short-term water storage tank efficiency evaluation tool is distributed by Heat Pump & Thermal Storage Technology Center of Japan.[2] The software was developed for the purpose which is to make the most of the system's operating cost merit, and to avoid design faults and/or mistakes in a designing phase. Besides this purpose, the software can be used to grasp of system fault, and to detect and diagnose system problems, and/or to improve operating conditions, to train operators or young engineers.

B.1.3 ICE CLUB

- Heat Pump & Thermal Storage Technology Center of Japan
- Storage tank efficiency evaluation tool for water thermal storage
- Energy consumption, Operational costs of Ice Storage
- Stand-alone program
- Source: [3]
- URL: http://www.hptcj.or.jp/technology/program/index.html#1

ICE Club which is planning and designing tool of a short-term ice storage tank is distributed by Heat Pump & Thermal Storage Technology Center of Japan [3]. Short term ice storage system has many kinds (types) of system variation. Special feature of this software, many kinds of ice storage system can be evaluated by system energy performance and comics at the planning and designing phase.

B.1.4 MULTIPORT-Storage-Model

- Institut für Thermodynamik und Wärmetechnik, Universität Stuttgart, Pfaffenwaldring 6, D - 70550 Stuttgart, Germany, email: drueck@itw.uni-stuttgart.de [34]
- Stratified fluid storage tank with four internal heat exchangers, ten connections for direct charge and discharge and an internal electrical heater
- Simulation of storage behaviour (Water tanks, solar heating or cold water)
- TRNSYS Type 340 Distribution: [35]

B.1.5 CST-Model

- Chemnitz University of Technology, Faculty of Mechanical Engineering, Department of Technical Thermodynamics, 09107 Chemnitz, Germany, Thorsten Urbaneck, email: thorsten.urbaneck@mb.tu-chemnitz.de
- Stratified large-scale cold water storage tank with for direct charge and discharge
- Simulation of storage behaviour (Cold water tanks)
- TRNSYS Type, Non-standard
- Reference: [36]

Overground water storages consist of insulated wall, insulated roof, insulated foundation, water filling, charge and discharge device at the bottom and on the top and gas room above the water surface. The tank storage is loaded and unloaded with water. Losses occur on the surface. The storage operation with stratification of water is significant for cooling systems.
Heat transfer (internal, external) is calculated by an one dimensional model (horizontal layers, discretised by time with the Crank-Nicolson-Method). A mixture model regards a possible inversion of density. Monitoring data are used for the boundary conditions (load, weather and ground). Special sensors are

used for the surface temperatures on roof and wall. An internal Thomas-Algorithm solves the equations of energy balances. The CST-Model (Cold Storage Tank) was implemented in TRNSYS 15. A validation of the model with monitoring data shows a good agreement.

B.1.6 ICEPIT

- Author: Martin Hornberger
- Stratified fluid storage tanks and pit with water or gravel-water for direct an indirect charge and discharge, glaciations
- Simulation of storage behaviour
- TRNSYS Type 343
- Distribution: [35]

The most efficient model for gravel-water-storages (ICEPIT) in the range of system-simulation-programs so far was created by Hornberger [37] in 1994. This model is marked by following capability characteristics:

- direct loading and unloading across the top layer,
- indirect loading and unloading across a coil in each storage layer,
- optional glaciations of the storage water,
- storage construction as subterranean cylinder and frustrum
- given spatial discretization,
- two-dimensional heat transmission in the ground,
- convective heat transfer and
- absorption of the global radiation on the earth's surface.

If a temperature inversion between two layers appears, this layers will be mixed completely, because it isn't possible to calculate the buoyant flow with TRNSYS, the superior simulation program of ICEPIT. By loading and unloading, a vertical plug flow is arising between the top layer and the lowest layer. A thermal stratification can be mapped well by this.
The source code is open like in all models of TRNSYS. This model was validated by experimentally determined material data and by the thermal behaviour of the gravel-water-storage in Stuttgart (Germany).

B.1.7 Continuum model for Gravel-Water-Storages

- Chemnitz University of Technology, Faculty of Mechanical Engineering, Department of Technical Thermodynamics, 09107 Chemnitz, Germany, Thorsten Urbaneck, email: thorsten.urbaneck@mb.tu-chemnitz.de
- Stratified large-scale hot and cold water storage pit with for direct charge and discharge
- Simulation of storage behaviour (Gravel-water pits)
- CFX [40]
- Reference: [38], [39]

Detailed information can be obtained only by use of ″complex″ models in which all relevant physical effects are included. ″Simple″ models (e.g. TRNSYS [34], [36], [37]: no computation of the flow due to layer models for hot water and gravel water heat storage) are only regarded as partly suited. The effects of flow are strongly simplified (e.g. by complete mixture or ideal stratification). Thus, no interactions between flow and temperature field can be examined.
The numerical solution of the extensive model is obtained by CFX-4.4 [40] extended with subroutines (commercial program package for Computational Fluid Dynamics (CFD) with special programs: Meshbuild, Solver CFX-4.4, View, User Fortran).
With CFX-4.4 computation of the flow in systems of porous material is only isothermally possible according to standard proposal. A routine from HOYAL (AEA Technology, Otterfing) for implementation of heat transfer was additionally available. This routine had to be changed substantially and adapted. The model was developed basing on a continuum approach.

B.1.8 Ground Club

- Hokkaido University & Zeneral Heatpump Industry CO., Ltd.
- Design and evaluation software for Ground Source Heat pump system by BTES
- Decision of the number of Borehole and Simulation of storage behaviour
- Visual Basic
- Reference: [38]

Ground Club which is a Design and evaluation software for Ground Source Heat pump system by BTES is developed by Prof. Nagano Laboratory (Hokkaido University) & Zeneral Heatpump Industry CO., Ltd.of Japan.[44] The number of Borehole can be decided and storage thermal behaviour and energy performance, CO_2 emission and economic efficiency can be estimate by this software. Exchanger types of Bore hole are single/double U cube.

B.2 Storages with PCM

B.2.1 TRNSYS Type 840

- Schranzhofer, Puschnig, Heinz, Streicher
- Simulation of storage behaviour
- TRNSYS, Type 840
- Reference: [6], [29]

W. Streicher et al. [6] developed a TRNSYS model (Type 840) to simulate microencapsulated PCM-slurries as storage medium as well as storage integrated modules of PCM materials of various shapes (cylinders, spheres, plates). The model was validated with real data obtained in previous experiments [29].

The first experiments with a water and a PCM slurry storage showed already very good results [30]. For further validations of the model concerning the use of PCM modules in the water tank, experiments with cylindrical modules were carried out. The correlation between experiment and simulation was very satisfactory.

B.2.2 TRNSYS Type 860

- Bony, Citherlet
- Simulation of storage behaviour
- TRNSYS, Type 860
- Reference: [31]

Bony and Citherlet [31] developed a TRNSYS model to simulate heat transfer in phase change materials (PCM) plunged in water tank storage. This model, based on the enthalpy approach, takes into account the conduction and the convection into PCM as well as at the interface between PCM and water of the storage. Hysteresis, subcooling and convection are also taken into account. This model was implemented in an existing TRNSYS type of water tank storage (type 60). It allows the simulation of a water storage tank filled with PCM modules made of different materials and different shapes such as cylinders, plates or spheres bed. Comparisons between measurements and simulations has been undertake to evaluate the potential of this model.

B.2.3 Schultz – TRNSYS Type 185

- Schultz
- Simulation of storage behaviour
- TRNSYS, Type 185

Two different designs of the PCM storage can be modeled: a cylindrical storage with the subsections stacked on top of each other or a distributed storage, where the sub-volumes are placed side by side e.g. for the purpose of integrating the storage in a “slab on ground” floor construction.

Each sub-volume includes a heat exchanger for the solar collector loop and for the load loop. The heat transfer coefficient is assumed identical in all sub-volumes, but can be different between the solar collector loop and the load loop. The energy content in each sub-volume is determined from the temperature, Ti, and the “degree of melting”, Si. The storage is uniformly insulated and heat losses to the environment takes place through all free surfaces. For the cylindrical stacked storage solution this corresponds to the surface of the cylinder. The storage model is “an ideal model”, i.e. the boundaries between the sub-volumes are adiabatic. Furthermore, each sub-volume is treated as a lumped model with a uniform temperature and degree of melting.

B.3 Ground

B.3.1 FEFLOW

- DHI-WASY GmbH, Waltersdorfer Straße 105, 12526 Berlin-Bohnsdorf, Germany [41] (Source of outline)
- Application for aquifer storages
- Thermal storage behaviour and ground water flow
- Stand-alone program
- Distribution: [41]

Spatial discretization of the study area is a prerequisite for any numerical modeling. Classic groundwater simulation codes use finite difference discretization. In contrast, FEFLOW is based on the finite-element technique. Major advantages of finite-element modeling include:

- Unstructured meshing, thus much better representation of features like rivers, fractures, well locations by adaptation of the mesh,
- Better representation of sloping layers and anisotropy,
- Local mesh refinement without having to refine the whole column/row,
- Moving meshes for free-surface calculations,
- Automatic mesh refinement and coarsening,
- Less computational effort due to reduced element numbers for large regional models,
- Broad range of small-scale and large-scale applications.

B.4 Buildings

B.4.1 TRNSYS Type 185

- Ghoneim, Klein, Duffie
- Simulation of component behaviour
- TRNSYS, Type 185
- Reference: [1]

Ghoneim et al. [1] developed a simple numerical model (assuming one-dimensional thermal circuit) to simulate a collector-storage wall using PCM. The model was validated for the conventional non-PCM wall, comparing the results with numerical studies previously done at Los Alamos, and incorporated to TRNSYS.

B.4.2 TRNSYS Type 232

- Ibáñez, Lázaro, Zalba, Cabeza
- Simulation of component/system behaviour
- TRNSYS, Type 232
- Reference: [5]

An innovative approach to evaluate the influence of walls with PCM in the whole energy balance of a building was developed by Ibáñez et al. [5] using TRNSYS software. The model is based on active layers, which consist on controled active systems integrated in the walls. The behaviour of the PCM in its melting/solidifying process is simulated as a water flow rate at phase change temperature, controled by a new developed Type 232. An equivalent heat transfer ratio is introduced to the model as an additional key parameter. This parameter, that can be defined by the user and introduced in each step of the simulation, is the one that really characterizes the operative way of the thermal behaviour of the wall with PCM, because it allows to give to the simulation the rate at which the thermal energy transfer processes due to the storage material occur.

The new model was validated with real experimental data from an energy storage test rig built in the University of Zaragoza. This test rig is an air closed loop that goes inside a chamber where the material to be tested is located. The experimental data provide an empirical equivalent heat transfer ratio for the model, ensuring its accuracy. For other PCM-composites a different heat transfer ratio must be determined.

In the framework of european project MOPCON, two experimental cubicles were build and tested. The obtained data showed good agreement with the simulation results.

B.4.3 TRNSYS Type 241

- Schranzhofer, Puschnig, Heinz, Streicher
- Simulation of component behaviour
- TRNSYS, Type 241

- Reference: [6]

W. Streicher et al. [6] also developed a TRNSYS model (Type 241) to simulate PCM in walls using finite difference approach. The obtained results were the expected, although they were not validated.

B.4.4 TRNSYS Type 204

- Lammberg
- Simulation of component behaviour
- TRNSYS, Type 204
- Reference: [7]

P. Lamberg developed a TRNSYS model (Type 204) to simulate PCM in walls [7]. The model was not experimentaly validated and there is no available documentation in English on how the model works.

B.4.5 TRNSYS Type 58 Subprogram

- Stritih and Novak
- Simulation of component behaviour
- TRNSYS, Type 58 Subprogram
- Reference: [8]

In 1996 a new TRNSYS numerical method for PCM simulation in walls was developed [8], based on finite difference and enthalpy method. The model is written in FORTRAN language as a TYPE58 subprogram which is a module for the program package TRNSYS for the simulation of solar systems.

B.4.6 ESP-r – PCM Model Heim and Clarke

- Heim and Clarke
- Simulation of component behaviour
- ESP-r
- Reference: [9], [10], [11]

In 2004 Heim and Clarke ([9] and [10]) developed a modified ESP-r program to simulate PCM-impregnated gypsum plasterboard. Using control volumes, the effective heat capacity method and assuming equivalent homogeneous properties of PCM-gypsum composite. Unfortunately, the numerical model was not validated with real data and further macro-scale experiments are necessary. Moreover, Heim [11] compared both Effective Heat Capacity method and Additional Heat Source method on PCM walls simulation. The results were very similar, but they need more refinement and experimental validation.

B.4.7 ESP-r – PCM Model Schossig

- Schossig, Henning, Gschwander, Haussmann

- Simulation of component behaviour
- ESP-r
- Reference: [12]

Schossig et al. developed an ESP-r model to simulate micro-encapsulated PCM in gypsum wallboard [12].

B.4.8 EnergyPlus – PCM Model Barbour and Hittle

- Barbour and Hittle
- Simulation of component behaviour
- EnergyPlus
- Reference: [13], [14]

A new approach to PCM simulation in walls was studied by Barbour and Hittle in 2006 [13]. Conduction transfer funcions (CTF) were used to implement a numerical model for annual simulations in EnergyPlus, requiring less calculation capacity. The model was one dimension and was based on an ASHRAE Toolkid. The model was validated with real data from previous experiments done by Kedl [14], finding good agreement in the temperature prediction, but some problems in the energy balance when simulating high heat flux or temperature increase/decrease rates. When implemented in EnergyPlus, the simulations showed unacceptable errors when using PCM, probably due to the switching between different CTF depending on the temperature during the phase change. Further development and improvemt must be done in the model to reach acceptable accuracy.

B.4.9 EnergyPlus – PCM Model Pedersen

- Pedersen
- Simulation of component behaviour
- EnergyPlus
- Reference: [15]

A new improved version of EnergyPlus was presented in April 2007 which incorporates the capability to simulate PCM in building envelopes [15]. The simulation of building surface constructions has relied on Conduction Transfer Functions (CTF) simplifying the mathematical problem. This approach is restricted to use constant properties.
A new implicit finite difference thermal model of building surfaces has been incorporated into EnergyPlus, making it possible to use temperature dependent thermal properties. The model simulates the performance of PCMs using an enthalpy or heat content formulation so energy accounting is accurate, and the phase change enthalpy is included fully. Simulations with PCM in any location within the surface structure can now be done.

B.4.10 Fortran – PCM Model

- Stritih and Butala
- Simulation of component behaviour
- Stand alone program
- Fortran
- Reference: [16]

Stritih and Butala [16] developed a model in fortran to simulate PCM. They perfomed real experiments with a free-cooling system and validated the model, achieving a good agreement.

B.4.11 PCM Model for Gypsum Wall

- Athenienitis, Liu, Hawes, Banu, Feldman
- Simulation of component behaviour
- Stand-alone program
- Reference: [17]

In 1997 Athenienitis et al. [17] developed and validated a numerical model for PCM-gypsum wallboard simulation. The model was based on explicite non-linear finite difference and the enthalpy method, and assumed one dimensional homogeneous material, determining the transient heat diffusion of the composite. DSC analysis provided important data of the released or absorved latent heat rate. The validation of the model with real data obtained from a test-room determined a rms difference of 0.25ºC, occurring the maximum error during the freezing process (around 0.6ºC out of 1.5ºC of improvement of using PCM) due to non-uniform phase change of the PCM in the drywall.
The mathematical model may be used in conjunction with other building thermal analysis software to evaluate the design parameters and the operational characteristics of buildings with PCM gypsum board or other phase change materials as inside wall lining.

B.4.12 Ismail and Castro

- Ismail and Castro
- Simulation of component behaviour
- Stand-alone program
- Reference: [18]

A numerical model to simulate PCM filled walls and roofs was developed by Ismail and Castro [18]. The model was based on a one-dimensional assumption for the phase change problem controlled by pure conduction. The numerical treatment was based upon using finite difference approximations and the ADI scheme. Other considerations were: neglected convection and end effects; constant initial temperatures, physical properties and heat transfer coefficients.

The results obtained were compared with experimental measurements showing a poor accuracy of the model.

B.4.13 Neeper

- Neeper
- Simulation of component behaviour
- Stand-alone program
- Reference: [19]

Neeper [19] used a one-dimensional model and experiments to provide guidelines for the optimal use of PCM wallboard installed throughout a building, and for estimating the benefits of PCM architectural products for heating and cooling systems.

B.4.14 Darkwa and O'Callaghan

- Dawkwa and O'Callaghan
- Simulation of component behaviour
- Stand-alone program
- Reference: [20], [21], [22]

Another simulation model was developed by Darkwa and O'Callaghan [20], [21], [22] using the implice finite difference method and the implicit enthalpy method. In the model, no convective heat transfer in the liquid phase of PCM is considered.

B.4.15 Huan and Eames

- Huang, Eames, Hewitt, Norton
- Simulation of component behaviour
- Stand-alone program
- Reference: [23], [24]

Huang et al. [23] studied the effect of using various quantities of different PCM materials with phase change temperatures of 28 and 43 ºC incorporated into a selection of wall constructions for selected ambient conditions of temperature and insolation.
A two-dimensional temperature-based finite volume numerical model used to moderate the temperature rise of building integrated photovoltaic (PV) in a PV/PCM system was developed and experimentally validated [24]. This model is now used to simulate the effect of including PCM in buildings.

B.4.16 Pasupathy and Velraj

- Pasupathy and Velraj
- Simulation of component behaviour
- Stand-alone program
- Reference: [25], [26]

Pasupathy and Velraj [25], [26]) studied a double layer PCM concept to achieve year round PCM effect (heating and cooling) and passive thermal management. The model assumptions are: one-dimensional heat conduction in the composite wall; constant thermal conductivity of concrete; homogeneous and isotropic PCM; neglected end effects in the wall, convection effect in the molten PCM and interfacial resistances.
The latent heat value of the PCM is modeled as uniform high sensible heat value during the phase change process. The governing equations along with the boundary conditions are discretized using semi-implicit control volume formulation. The system of equations is solved using tridiagonal matrix algorithm (TDMA).

B.4.17 Halford and Boehm

- Halford and Boehm
- Simulation of component behaviour
- Stand-alone program
- Reference: [27]

Halford and Boehm studied the potential peak air conditioning load shifting by using encapsulated PCM within the ceiling or wall insulation (RCR – resistive, capacitive, resistive) [27].
They developed a simplified numerical model based on explicit numerical solution and finite difference method. When the PCM was in one-phase the system was governed by the one-dimensional diffusion equation, and when it was in two-phase by the Stefan condition.
The authors remark that the simulation is a merely first approach at modelling an extremely complex problem. Many simplifications were done and must be validated (such as the variation of temperatures is steady-periodic). An experimental set-up is being built and the results will be used to validate and improve the model.

B.4.18 Esam M. Alawadhi

- Alawadhi
- Simulation of component behaviour
- Stand-alone program
- Reference: [28]

Alawadhi studied numerically the behaviour of a PCM-brick composite for hot climates (Kuwait city) [28]. The PCM was introduced in the cylindrical holes of the bricks, and different amounts, PCM materials and locations were studied. The model was two-dimensional and used the finite elements method and the effective heat capacity to simulate the PCM. The improvement of using PCM is determined by comparison of the heat flux at the indoor surface of the wall with and without PCM. A significant reduction of the heat gains was achieved.

B.4.19 PCM express

- Dr. Valentin EnergieSoftware GmbH, Stralauer Platz 34, 10243 Berlin, Germany
- Planning and Simulation Program for the Use of Phase Change Materials (PCM)
- Stand-alone program
- Cooperation: see below
- Source: [42], [43]

Background
PCM express was created in connection with the research project "Development of a user-friendly planning and simulation program in the combined project 'Active PCM storage systems for Building PCM Active' ", which we ran in collaboration with the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg and partners from industry. We would like to thank the BMWi (German Ministry for Business and Technology), which made it possible for us to carry out the work and supported it under FKZ 0327370S and 0327370F-K and the project sponsor Jülich for its support.

Concept
PCM express is a planning and simulation program for buildings using phase change materials (PCM). It aims to support architects and planners in planning by facilitating reliable decision-making in dimensioning the system and by speeding up the market launch of PCMs.
In this respect, PCM express provides users with a simple method of defining a PCM system. This includes the use of PCMs in wall structures and changes in the associated mains services. In particular, the low-energy approach is to be supported in the form of activated building components (panel heating, cooling areas) and energy-saving cooling techniques. Depending on the situation, the use of PCMs may be justified by the increased level of comfort provided (private houses with wellness requirements) or by economic considerations (office buildings). Both strategies are supported by the program, through the use of menus, predefined usage profiles and adapted presentation of the results.

Use of PCMs
The use of PCMs can reduce or prevent a room overheating for a day. The cooling load is deflected from the high daytime temperatures into the night times with a reduction in the peak capacity of the cold generators. This means that cooling systems based on natural heat reduction (night air, earth) can be used. Various options are available for the regeneration of the PCMs. Manual window opening by users, automatic summer night ventilation if there is a ventilation system or cooling of the PCM layers by mats supplied with cooling water that are integrated into the layers (panel activation).

Calculation core and algorithms

PCM express has a component-oriented calculation core with time stages less than six minutes. The program includes Europe-wide meteodata sets for radiation and temperature, broken down by hours, which are evaluated for heating, cooling and the room models. Cold can be incorporated via cooled incoming air and cooling panels. Possible generators: compression cold, earth probes, earth collectors and heat exchangers. Radiators and panel heaters can be used for heating.

Room parameters

Up to three rooms can be grouped into a room combination. Heat is exchanged between these rooms through the walls. For the rooms, the room geometry and the inner gains and air change rate are requested. For the walls, a wall structure is selected and the windows defined. For the PCM system, the wall structures can be defined independently, i.e. the materials and surface activation of the wall structures can be different. The rooms and layers of the wall structures are mapped in a node model. For the PCM layers, temperature-related characteristic curves are used for the capacity (according to the RAL Quality Requirements for PCM).

Calculation of economic efficiency

The algorithms of the comparative economic efficiency calculation are based on the provisions of VDI 2067. The aim of the economic efficiency analysis is to justify the additional costs of investing in a PCM system compared with the reference system by the lower operating and consumption costs.

Results

The results are presented in project reports for the customer and planner and clear illustrations showing a comparison of the systems:

- Operative room temperatures applied across a varying outside temperature according to EN 15251
- Frequency distribution of the room temperatures
- Daily progress charts with the highest PCM effects
- Heating and cooling energies
- Illustrated evaluations for calculating economic efficiency
- Report for presentation to customers with central inputs and results
- Report for expert documentation of all requirements and results

B.5 Environmental Aspects

B.5.1 GEMIS

- Öko-Institut and Gesamthochschule Kassel (GhK), Germany [33] (Source of outline)
- Life-cycle analysis program, database for energy, material, and transport systems
- Stand-alone program
- Source: [33]

GEMIS is a life-cycle analysis program and database for energy, material, and transport systems - it is available freely at no cost (public domain).
The basic version 1.0 of the computer program GEMIS was developed in 1987-1989 as a tool for the comparative assessment of environmental effects of energy by Öko-Institut and Gesamthochschule Kassel (GhK). Since then, the model was continuously upgraded and updated. This work is sponsored by several donors, especially the Ministry for Environment in Hesse, Germany, and was done in close cooperation with partners . Since version 3.0 (1996), GEMIS is freely available as public domain software which can be copied and distributed without restriction. The GEMIS database offers information on:

- fossil fuels (hard coal, lignite, natural gas, oil), renewables, nuclear, biomass (residuals, and wood from short-rotation forestry, miscanthus, rape oil etc) and hydrogen (including fuel composition, and upstream data)
- processes for electricity and heat (various powerplants, cogenerators, fuel cells, etc.)
- materials: raw and base materials, and especially those for construction, and auxiliaries (including upstream processes)
- transports: airplanes, bicycles, buses, cars, pipelines, ships, trains, trucks (for diesel, gasoline, electricity, and biofuels).

GEMIS includes the total life-cycle in its calculation of impacts - i.e. fuel delivery, materials used for construction, waste treatment, and transports/auxiliaries.

- The GEMIS database covers for each process:
- efficiency, power, capacity factor, lifetime
- direct air pollutants (SO2, NOx, halogens, particulates, CO, NMVOC)
- greenhouse-gas emissions (CO2, CH4, N2O, SF6, all other Kioto gases)
- solid wastes (ashes, overburden, FGD residuals, process wastes)
- liquid pollutants (AOX, BOD5, COD, N, P, inorganic salts)
- land use.

GEMIS can also analyze costs - the respective data are implemented for fuels and energy systems. Furthermore, GEMIS allows also to value results by aggregated indicators: resources into CER and CMR, greenhouse gases into CO2 equivalents, air pollutants into SO2 equivalents and ozone-precursor equivalents, as well as external costs.

B.6 References

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2.8 Collected data C. Boundary Condition – Weather, Loads and Monitoring

Subtask A deals with demonstration projects and system performance evaluation. Balances (energy, costs and materials) are set up and analyzed in Subtask A. Different climates are to be found however in the countries (projects in Subtask A). The climate affects particularly the cooling loads (and the chiller units). The analysis of the climatic and load data is therefore necessary. The climatic data and load data flow into simulation and the evaluation (e.g. Monitoring).
Many simulation programs (see IEA ECES Annex 14, Subtask 3) work with data records, in order to read in the boundary conditions (weather and the cooling loads). The goal of this chapter is the description of boundary conditions: Weather and cooling loads.

C.1 Global climatic data source

Examples of climatic data and analysis software are shown in Table1.

Table 1: Global climatic data and analysis software (C…Commercial tool, F…Freeware)

No	Name	Nationality	Publisher	meas. station	Availability	Weather data item
1	CLIMATE 1	CH	eclim	1,200	C	7 monthly mean data.
2	METEONORM 6	DE	Meteotest	8,055	C	8 monthly mean data
3	Weather Data Viewer	US	ASHRAE	1,444	C	6 monthly mean data
4	RETScreen 4	CA	NRCan	4,700	F	6 monthly data & degree day

C.2 Projects/Study

C.2.1 Germany, Chemnitz District Cooling

<u>State of system from 1993 until 2006:</u> Many consumers in the city centre of Chemnitz (department stores, office buildings, opera, computer cluster of Chemnitz University of Technology etc.) are supplied with chilled water via the district cooling net. The air conditioning needs approx. 93 % of the annual distribution of cooling energy and the technological cooling approx. 7 %. The annual cooling distribution has doubled itself in the last 10 years. The connections of the customers constantly rose.
The central plant (Figure 1) supplies the consumer with the chilled water. This plant is in proximity to the consumers at the edge of the city centre. The absorption chiller units (AbC 1 and AbC 2 since 1993, AbC 3 since 1998) are base load chillers and the vapour compression chillers (VVC 4 since 2002 and VVC 5 since 2004) are peak load chillers. Table 2 combines all important information concerning the system.

Storage refitting (2007): The ambient air conditions in summer 2003 and the increasing consumer connections caused extremely high loads in the net. Utility Company Chemnitz had to increase the cooling capacity of the central plant. This question of the retrofit was examined in the context of a feasibility study (Feasibility evaluation for empowerment of CHCP by means of cool thermal energy storages in large supplying systems [1]). This investigation shows that significant economic, energetic and ecological advantages can be achieved by the retrofit of a large-scale cold water store (conversion by a pilot project [2], community project of Utility Company Chemnitz and Chemnitz University of Technology) [3], [4], [5], [6], [7], [8], [9], [10]. The exploitation of waste heat with the existing absorption chiller units is intensified by the storage exertion. The electric power consumption is reducing at the same time.

Table 2: Description and parameters of district cooling system in Chemnitz

Chiller unit	Type, Description	Nominal cooling capacity [kW]
AbC 1	Absorption chiller, LiBr-H2O, single-effect, hot water (120 °C) driven generatora, water-cooled absorber and condenserb (Carrier, 16JH065-28)	1,800
AbC 2	Absorption chiller, LiBr-H2O, single-effect, hot water (120 °C) driven generatora, water-cooled absorber and condenserb (Carrier, 16JH065-28)	1,800
AbC 3	Absorption chiller, LiBr-H2O, single-effect, hot water (120 °C) driven generatora, water-cooled absorber and condenserb (York, YIA HW-2B1-50-A)	500
VCC 4	Vapour compression chiller, turbo compressor, R134a, water-cooled condenserb (York, YK GB FB HF 5CTE)	3,000
VVC 5	Vapour compression chiller, screw compressor, R134a, air-cooled condenserb (York, YCAS 1215FB50YF)	1,242
a Use of waste heat of combined heat and power plant in Chemnitz over district heating net, admixture on the hot water side b Recooling system with 10 open evaporative cooling towers, 18.360 kW, 28/37 °C, constant flow rate on the side of chilled and recooled water		
Store	Cold water storage, 5/13 °C, 3500 m³, 33,2 MWh/cycle, aboveground tank, thermally insulated, direct water exchange for charging and discharging (on top and at the bottom)	
	Charging	4,000
	Discharging	5,000
Net	2 pipes, 5/13 °C, 4,2 km length of marked-out route (Figure 2)	
	Maximum of capacity	ca. 20,000
	17 substations, total capacity on the base of contracts (Figure 3)	ca. 13,000

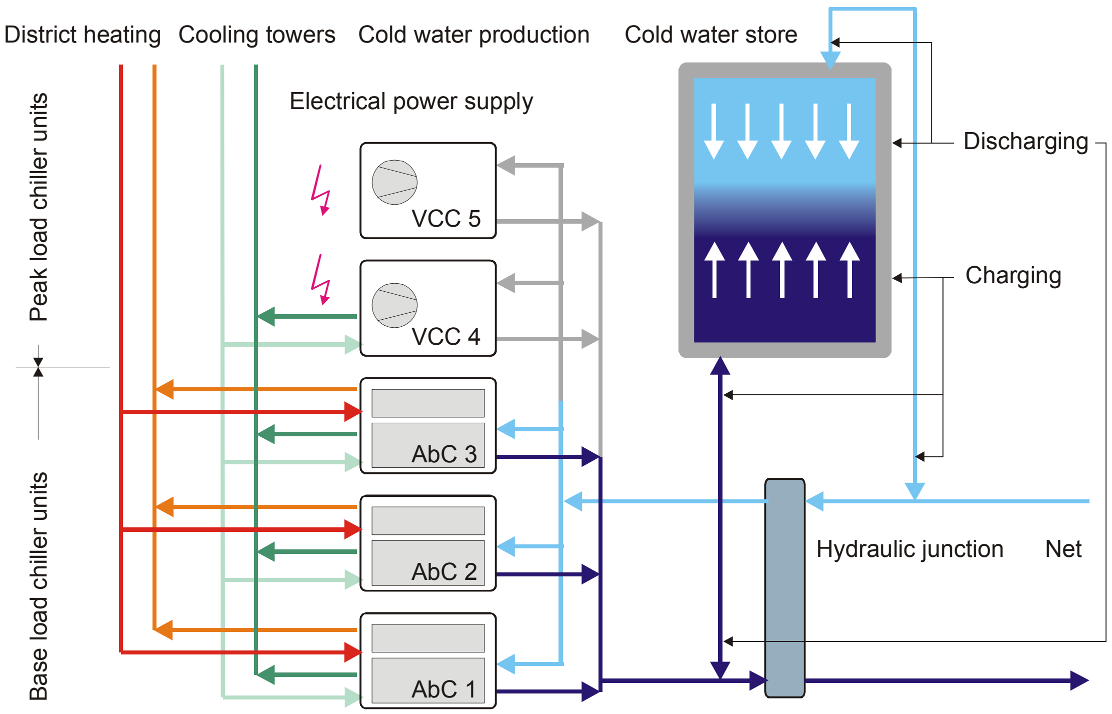

Figure 1: Division of the chillers (AbC … absorption chiller, VCC … vapour compression chiller), the hydraulic storage connection and the operational modes charging and discharging

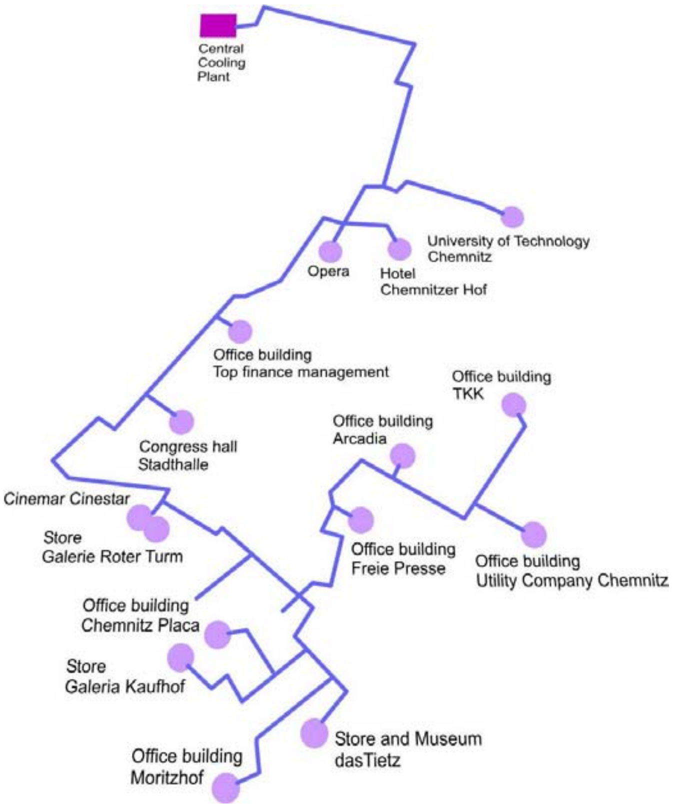

Figure 2: Topology of District cooling in Chemnitz

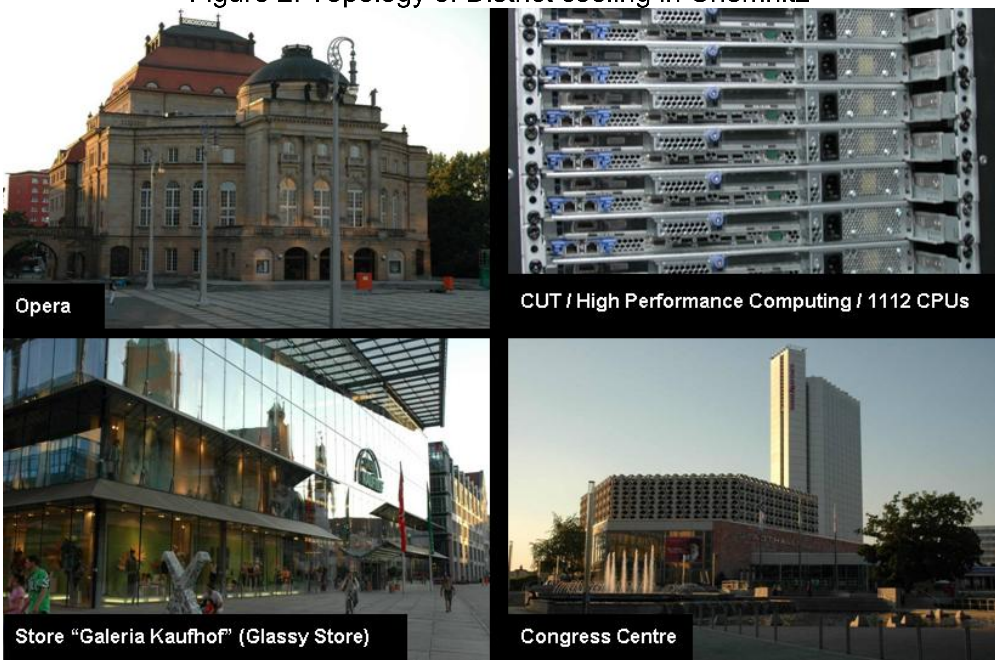

Figure 3: District cooling in Chemnitz, Consumer

C.2.2 Germany, Berlin, Office building, EnergieForum

The EnergieForum Berlin (finished in early 2003) offers office space under one roof for production and service-oriented companies, company representatives, institutions and scientific facilities which take active part in energy and environmental engineering.
The brick building (warehouse/stock) at Stralauerplatz was complemented by two side wings that span space for a glassed-in atrium (in total approx. 21,700 m² net floor area).
Thematic goal of this building was an energy concept for a low-energy building (heating < 40 kWh/ m²a; electricity < 20 kWh/m²a) with particular attention paid to regenerative and rational energy conversion techniques. The innovative approach of this project was emphasised by the variety of components which have just left the laboratory and achieved maturity or pre-maturity phase.
The targeted value for heat energy consumption will be achieved by comprehensive heat insulation, a ventilation concept using a heat recovery system and collecting passive solar heat energy. The electrical requirements for building automation and artificial lighting can be reduced to the required value by using energy efficient automation technologies, highly transparent glazing and sunscreens which redirect sunlight.
Consistent reduction of energy requirements allow for the use of regenerative and rational techniques. Energy piles, which use the building's foundation as seasonal thermal storage, play a central role in providing energy. In winter, heat is drawn from the ground using an electrical heat pump, and is conveyed to thermally activated building system. The ground, which cools off during winter months, is used as a cooling source for concrete core activation during the summer. Lower building levels are cooled by nightly ventilation. A classical climate control system with compression-based air conditioning units becomes unnecessary.
The early integration of energy engineers into the design and planning process allowed for the optimal coordination of the building's construction and its systems engineering tasks. In terms of quality control, the planning team received support while implementing the building's concept. Requests for changes and deviations to the original plan could be responded to at an early stage. Conformance to fixed energy goals and systems operation is being observed over a monitoring by the Institute of Building Services and Energy Design [11] at the University of Braunschweig.

- Content: Developing a sustainable energy concept for an energy efficient office building
- Funding: Bundesministerium für Wirtschaft und Arbeit (BMWA)
- (German Federal Ministry of Economics and Labour)
- Building type: Existing building with two new wings, glazed atrium
- Usage: Office building
- Classification: New building and renovation of an existing building
- Location: Stralauer Platz, Berlin
- Completion: 2003

- Architect: Design new building: Bothe, Richter, Teherani (BRT Architects), Hamburg
- Design existing building: Jentsch Architects, Berlin
- Construction management: Jahn Architects, Berlin
- Builder: Hanseatica HPE Property GmbH, Berlin
- Investor: R+V Insurance, Wiesbaden
- Net floor area: Approx. 21700 m²
- Heating requirements: Low energy standard approx. 40,0 kWh/m^3a
- Average U-value
  - External wall: 0,21 W/m²K
  - Roof: 0,22 W/m²K
  - Foundation: 0,32 W/m²K
  - Windows: 1,30 W/m²K
- Energy source heating
  - District heating
  - Heat pump energy piles
  - Heat pump exhaust air
  - Energy source hot water: Electrical

Figure 4: EnergieForum Berlin [12]

C.2.3 Japan, Tokyo, Office building

The analysis in this chapter based on a simulation study with following parameters:

- Building Location: Tokyo
- Structure: R.C. 10 story office building (floor height: 4.0m, ceiling height: 2.7m ratio of window area to floor area: 0.3)
- Floor area: 14,400m², typical floor: 1,440m²
- Overall heat transfer coefficient
- Exterior wall: 1.0 W/m²/K
- Window glass: 3.0 W/m²K
- Inner wall: 1.7 W/m²/K
- Floor&Ceiling: 3.0 W/m²/K
- Roof: 0.7 W/m²K
- Typical floor plan (Figure 5)
- Floor area
- South interior: 369 m²
- North interior: 369 m²
- South perimeter: 133 m
- North perimeter: 133 m
- West perimeter: 72 m
- East perimeter: 72 m
- Operational condition
- HVAC mode cooling: 1 June to 30 Sep.
- Heating: 1 Dec. to 31 Mar.
- Mid season: No Heating & Cooling
- Operational hour: Mon. to Fri. 8:00-18:00 (1 hour Pre Heating & Cooling)
- Fresh air volume: 30m³/h Person
- Internal heat gain
- Human: 0.1 W/m2
- Lighting: 20 W/m2
- Machine: 20W/m2
- Room set Temp.
- Cooling term: DB: 28 °C RH: 50%
- Heating term: DB: 19 °C RH: 40%
- Schedule (Figure 6, Figure 7)

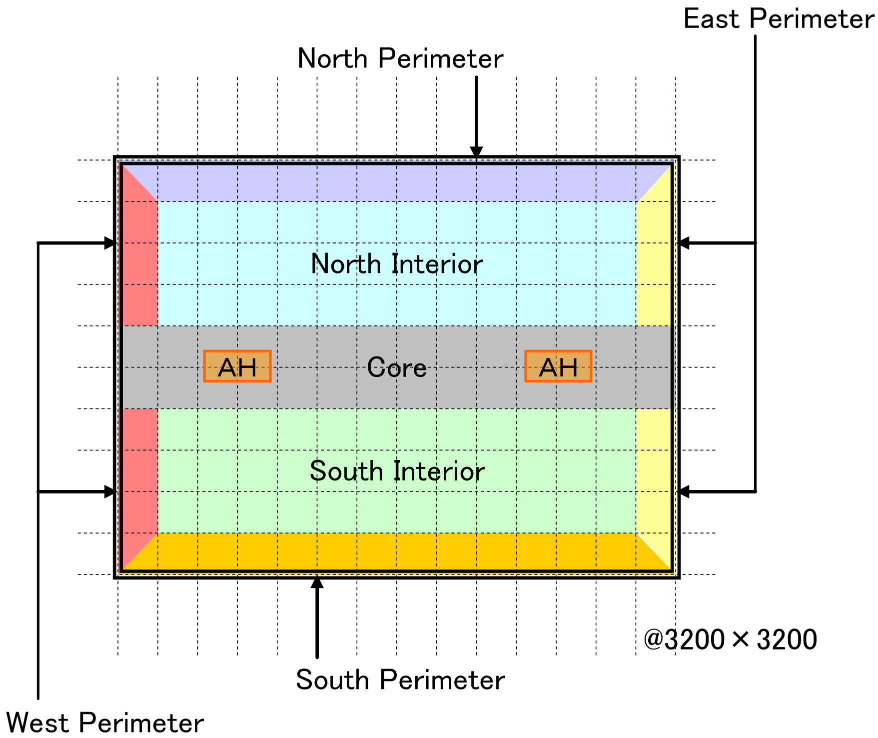

Figure 5: Typical floor plan

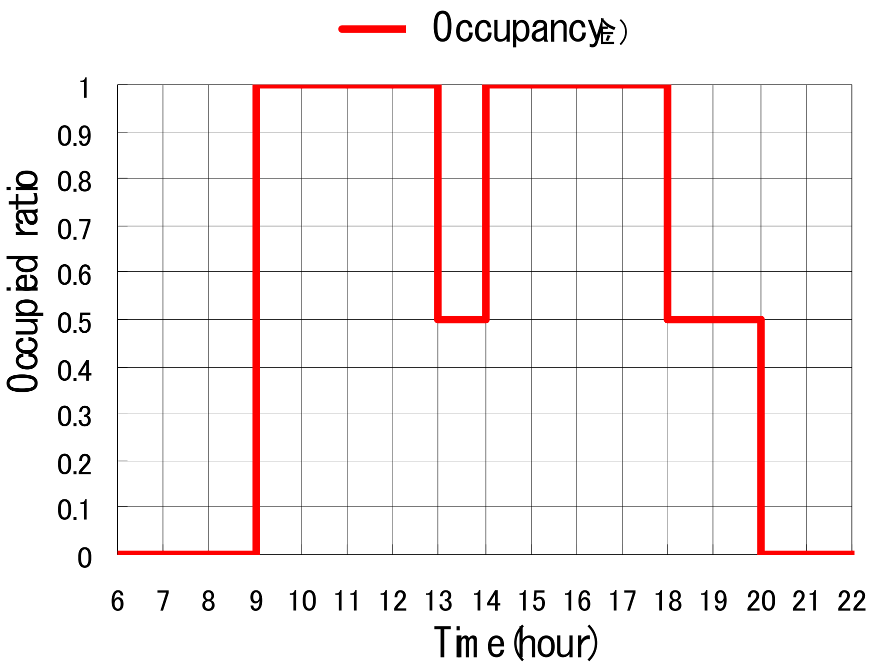

Figure 6: Occupancy of building, weekdays

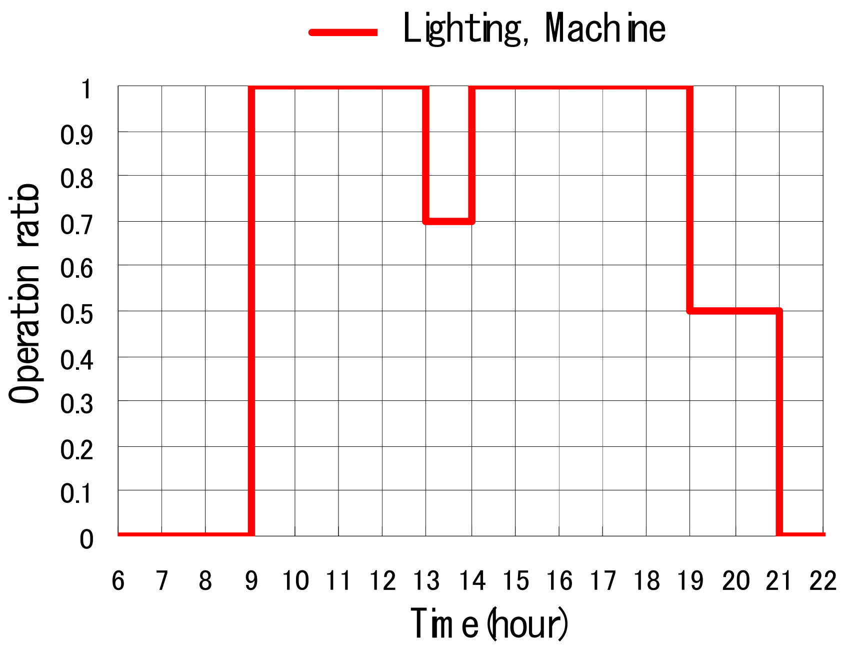

Figure 7: Operation of lightning and machines, weekdays

C.3 Example for detailed analysis of boundary conditions measurement – Monitoring and norms

Example: Project in Subtask A D4: Pilot project for the optimization of large-scale systems on the base of combined heat and cool and power cycle by means of cool thermal energy storage (Sec. 0)

- **Weather**
  - measured sizes/measuring instruments (Figure 8)
    - solar radiation: global, beam (difference between global and diffuse), diffuse; Kipp & Zonen CMP6; CMP121B [13]
    - ambient temperature: ASF/E-20 [14]
    - ambient humidity: ASF/E-20 [14]
    - wind speed: WG2/O-10 [14]
    - wind direction: WRG2/O-10 [14]
    - precipitation: NW/O-20 [14]
    - air pressure: AD/A [14]
  - technology/software further processing
    - own monitoring technique: mainly, product: TopMessage [15] (Figure 9)
    - control technique: partially, takeover of values of control technique
  - data processing (Figure 10)
    - samples: 3 min values, without averaging
    - mean value: hourly mean values of temperature, humidity, wind speed and direction
    - integral value (hour, day): solar radiation, precipitation (time of precipitation)
  - data formats: ASCII/EXCEL
  - relevant standards
    - VDI 3789-2: Environmental meteorology - Interactions between atmosphere and surfaces - Calculation of short-wave and long-wave radiation [16]
    - VDI 3789-3: Environmental meteorology - Interactions between atmosphere and surfaces - Calculation of spectral irradiances in the solar wavelength range [19]
    - Miscellaneous norms (e. g. measuring technique) [19]
- **Cooling loads**
  - measured sizes/measuring instruments
    - heat flux
    - flow rate
    - temperature
  - technology/software further processing
    - own monitoring technique mainly, product: TopMessage [15] (Figure 9)

    - control technique: net load (e. g. heat flux and flow meter from owner, (doubling) signal processing)
    - external meter: no
- data processing
    - samples: 3 min values, without averaging
    - mean value: 3 min, only several values (e.g. temperature of net supply and return)
    - integral value (hour, day): hourly values
- data formats: ASCII/EXCEL
- relevant standards
    - DIN 4710: Statistics on German meteorological data for calculating the energy requirement for heating and air conditioning equipment (in German) [16]
    - VDI 2078-Part 1: Cooling load calculation of air-conditioned buildings with room-conditioning from cooled walls and ceilings (in English and German)[5] [16]
    - DIN EN ISO 15927 Part 4: Hygrothermal performance of buildings - Calculation and presentation of climatic data - Part 4: Hourly data for assessing the annual energy use for heating and cooling (German version) [16]
    - DIN EN ISO 15243: Ventilation for buildings - Calculation of room temperatures and of load and energy for buildings with room conditioning systems [16]
    - DIN EN15255: Energy performance of buildings - Sensible room cooling load calculation - General criteria and validation procedures [16]
    - DIN EN15265: Energy performance of buildings - Calculation of energy needs for space heating and cooling using dynamic methods - General criteria and validation procedures [16]
    - DIN V 18599-7: Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 7: Final energy demand of air-handling and air-conditioning systems for non-residential buildings [16]
    - VDI 6007 Part 1: Calculation of transient thermal response of rooms and buildings - Modelling of rooms [16]
    - VDI 2067 Part 1: Economic efficiency of building installations [16]

[5] The calculation procedure is applicable to rooms for which temperature requirements must be complied with in the case of thermal loads, and humidity requirements in the case of humidity loads.

Figure 8: Weather station on top of cold water TES

Figure 9: TopMessage, Source: [15]

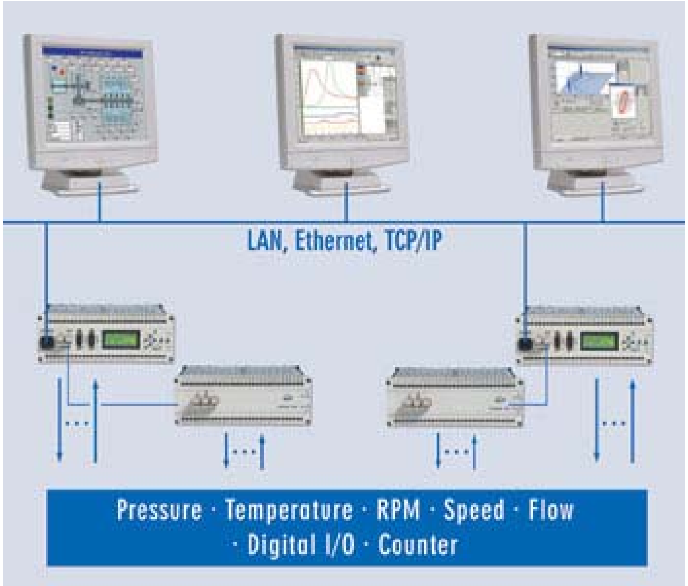

Figure 10: Data interface of TopMessage, Source: [16]

C.4 Boundary conditions

C.4.1 Germany, Chemnitz

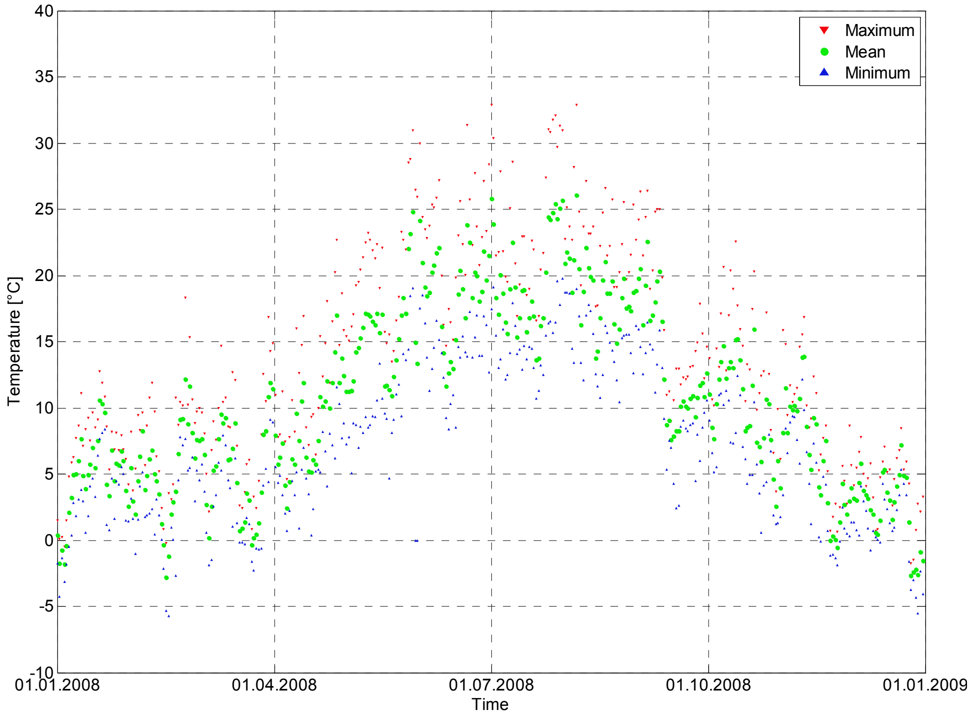

Figure 11: Ambient air temperature, maximum (red), mean (green), minimum (blue), Chemnitz (Germany), Year 2008, hour values

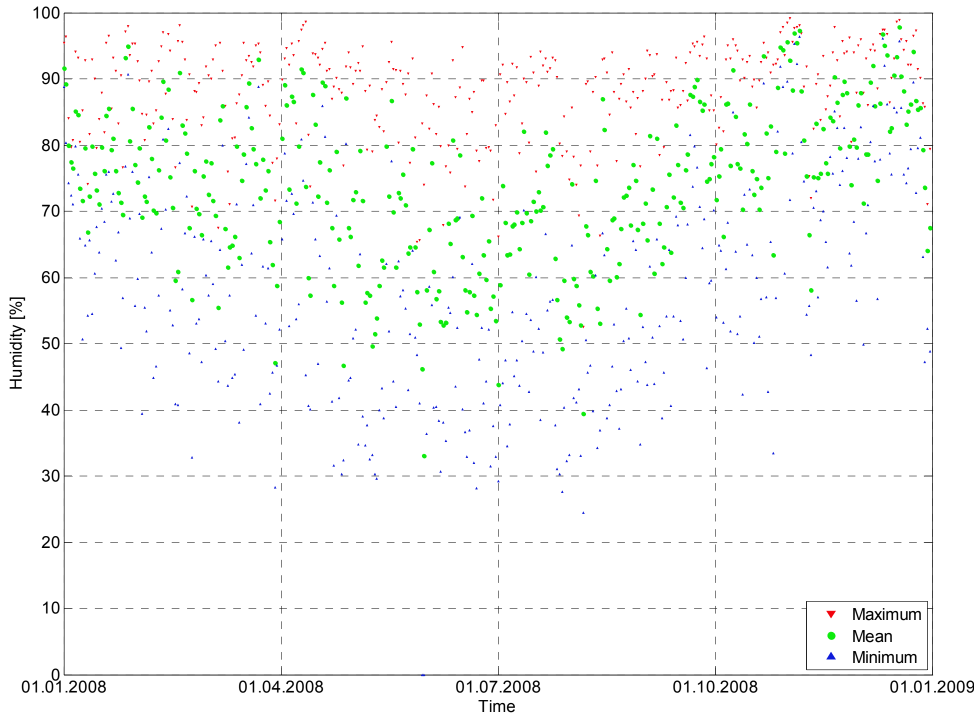

Figure 12: Relative humidity of ambient air, maximum (red), mean (green), minimum (blue), Chemnitz (Germany), Year 2008, hour values

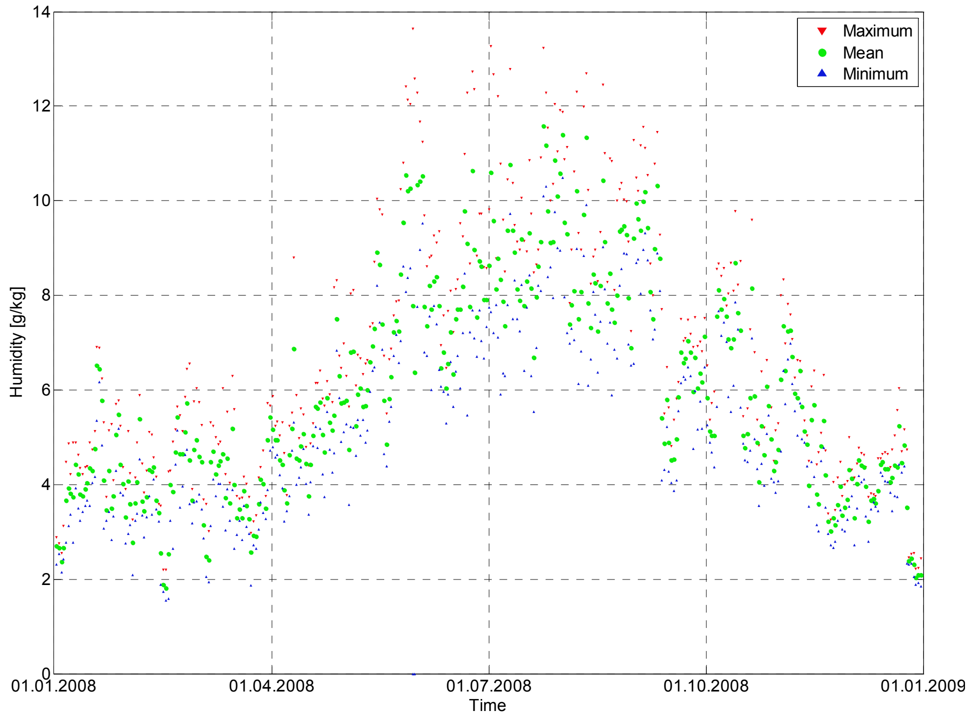

Figure 13: Absolute humidity of ambient air, maximum (red), mean (green), minimum (blue), Chemnitz (Germany), Year 2008, hour values

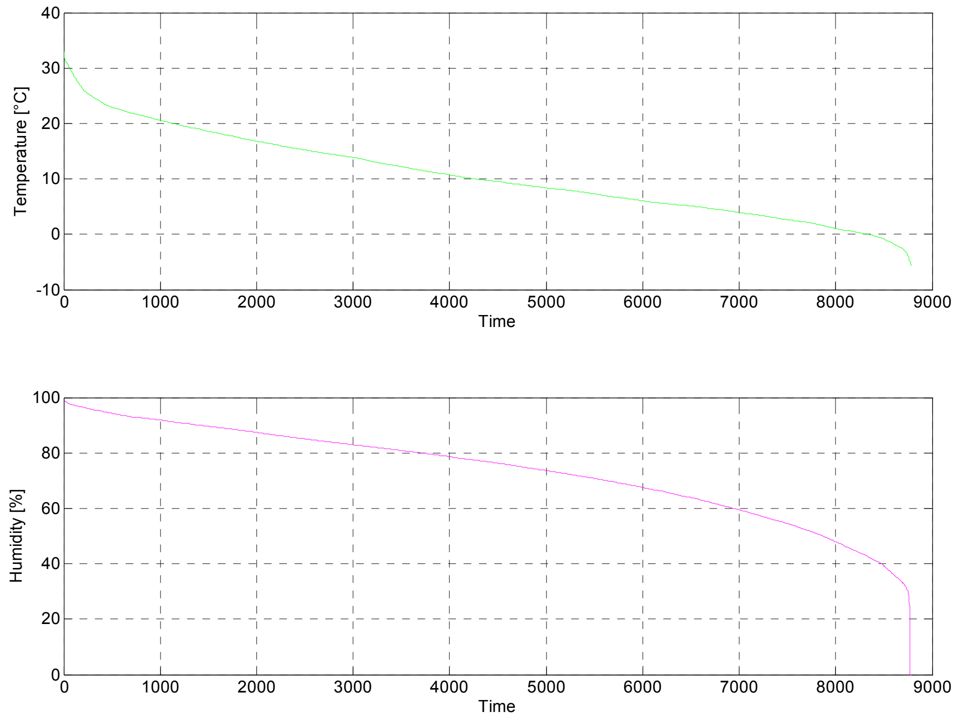

Figure 14: Temperature and humidity of ambient air, Chemnitz (Germany), Year 2008, sorted hour values

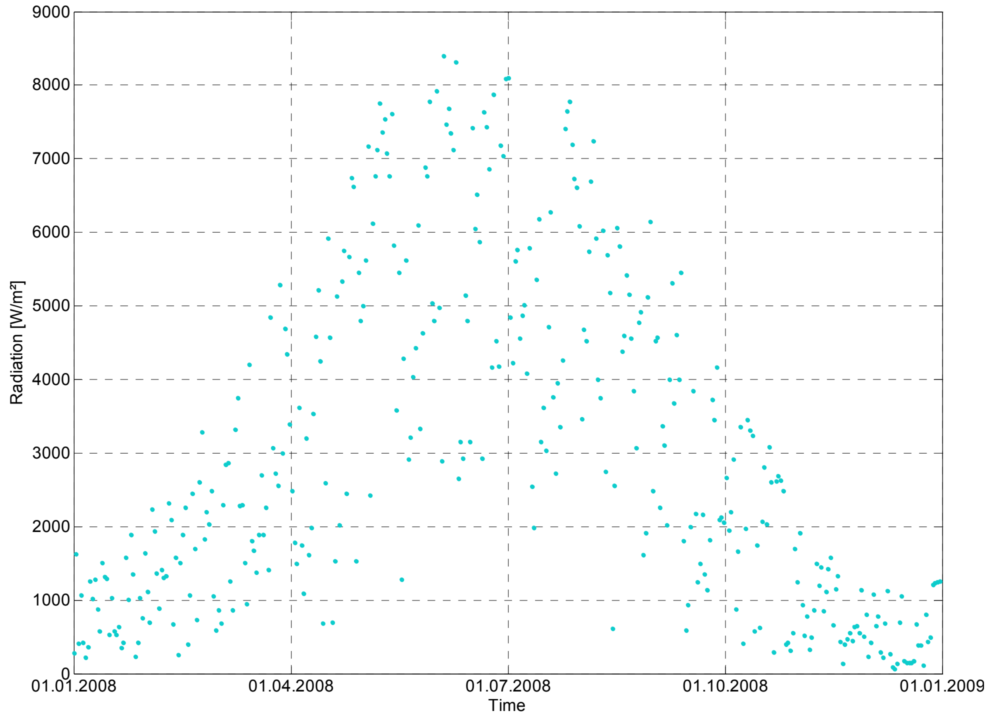

Figure 15: Solar radiation density, global, horizontal, Chemnitz (Germany), Year 2008, day values

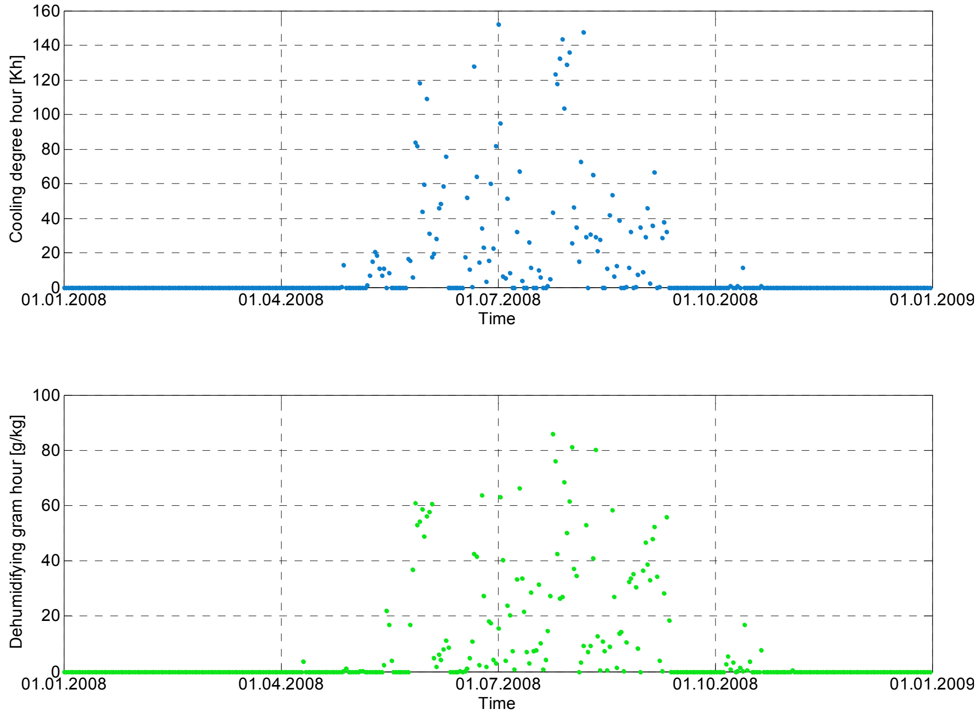

Figure 16: Degree hour for cooling and heating, gram hour for dehumidifying and dehumidifying, Chemnitz (Germany), Year 2008, day values

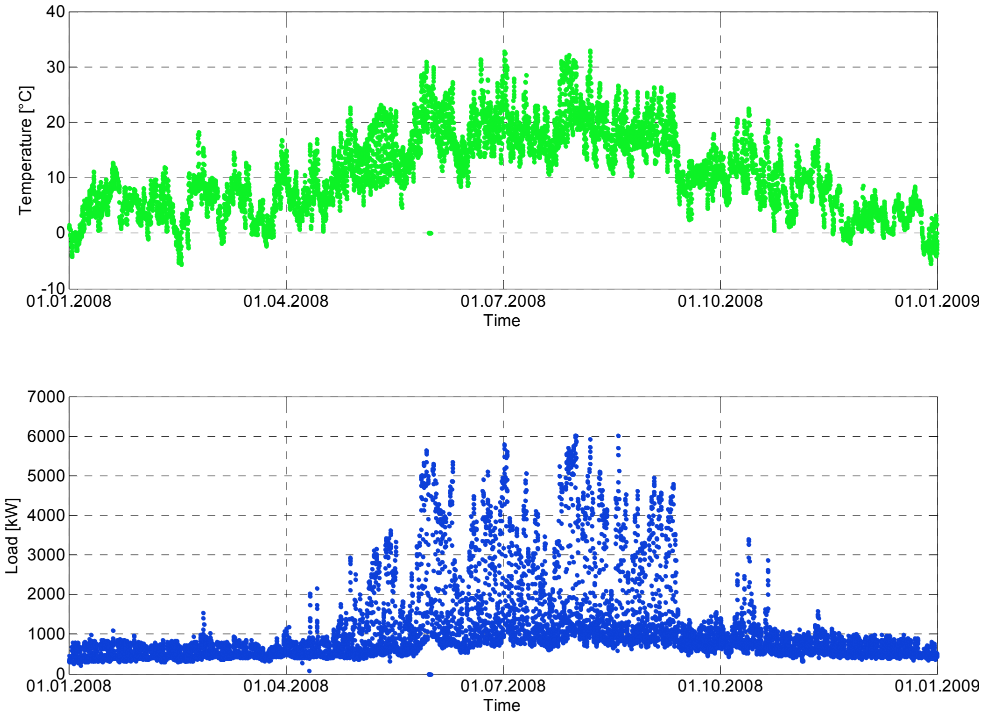

Figure 17: Ambient air temperature and net load of district cooling, Chemnitz (Germany), Year 2008, hour values

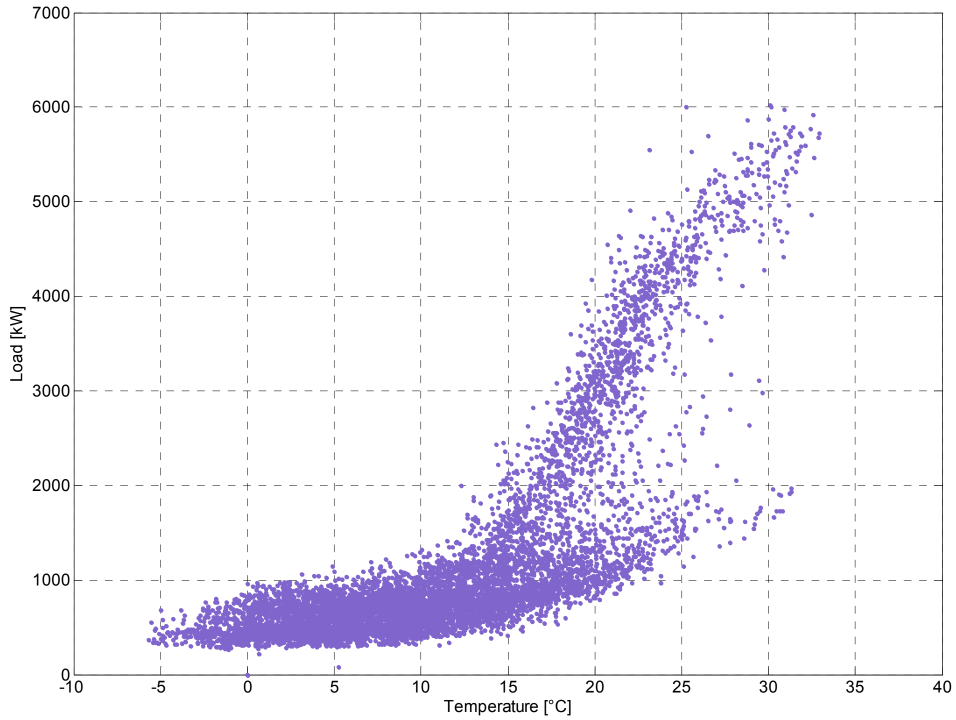

Figure 18: Net load of district cooling in dependence of ambient air temperature, Chemnitz (Germany), Year 2008, hour values

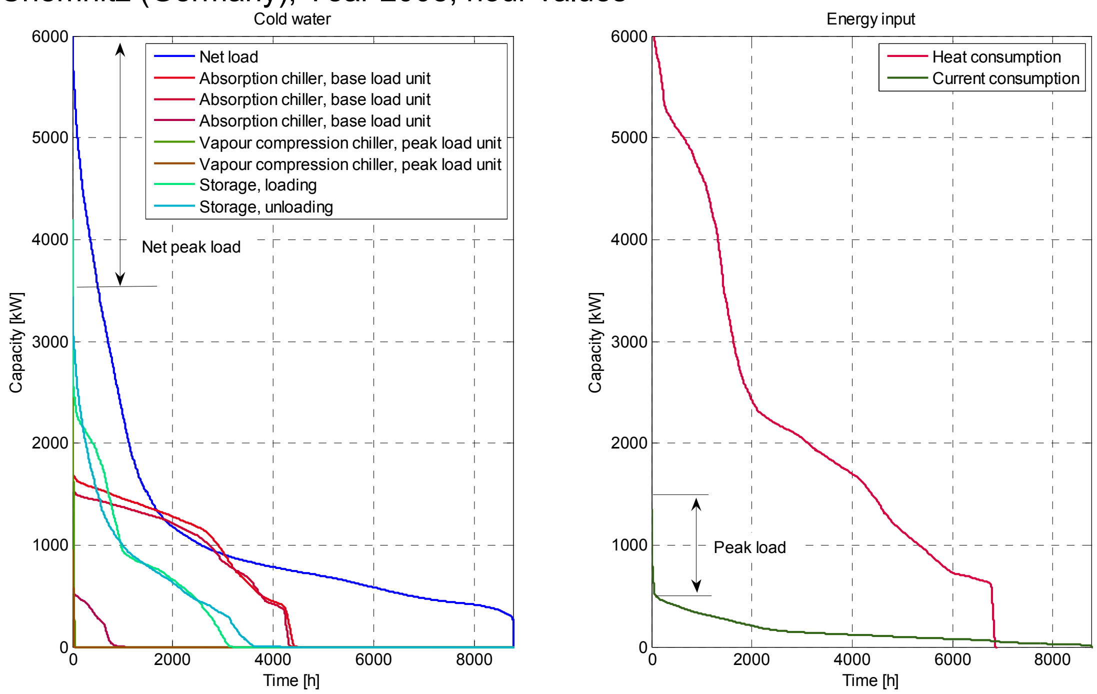

Figure 19: Sorted courses of loads and capacities, Chemnitz (Germany), Year 2008, hour values [10]

C4.2 Germany, Berlin

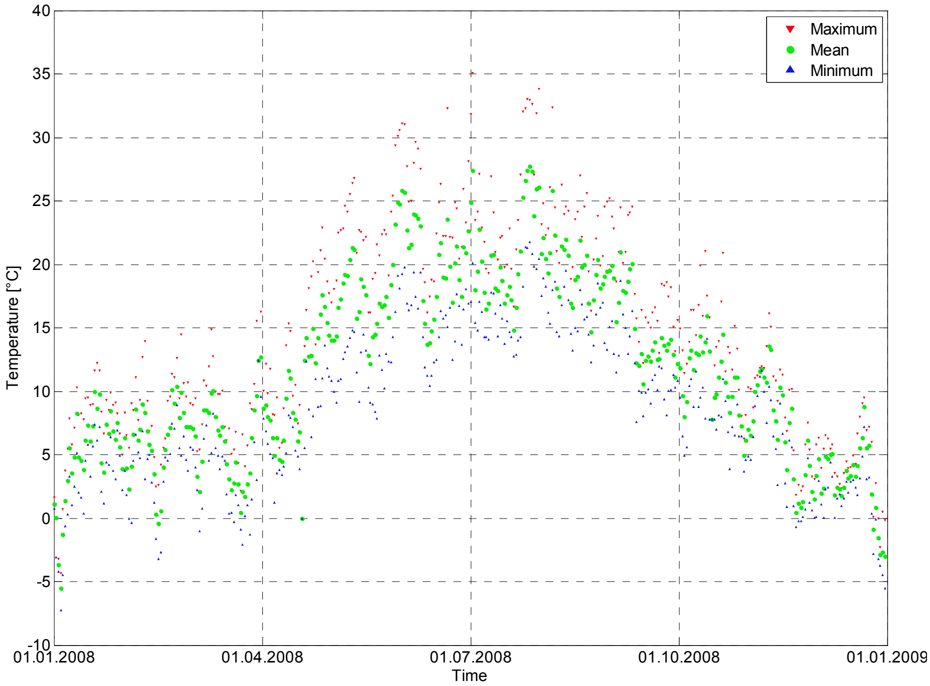

Figure 20: Ambient air temperature, maximum (red), mean (green), minimum (blue), Berlin (Germany), Year 2008, hour values

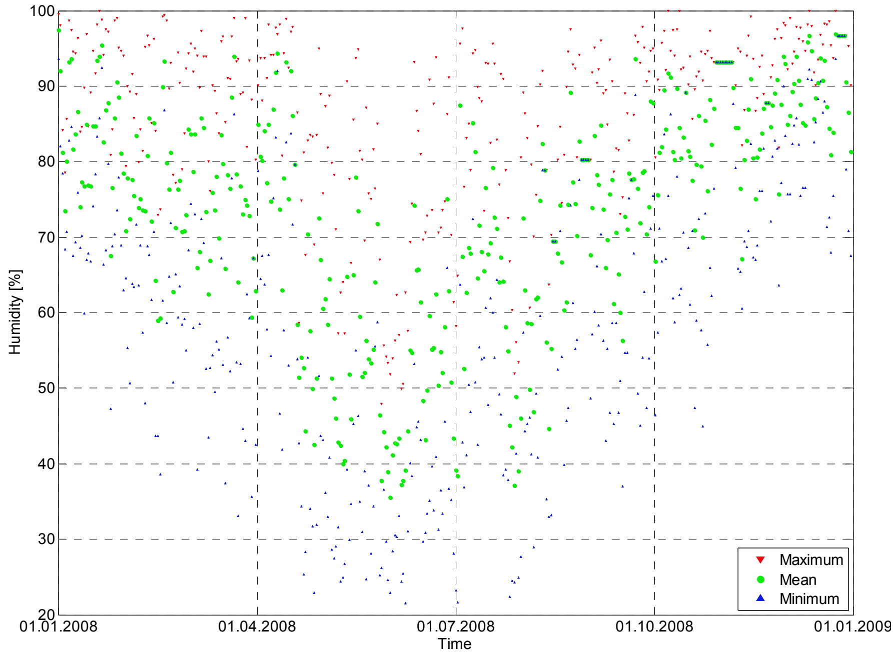

Figure 21: Relative humidity of ambient air, maximum (red), mean (green), minimum (blue), Berlin (Germany), Year 2008, hour values

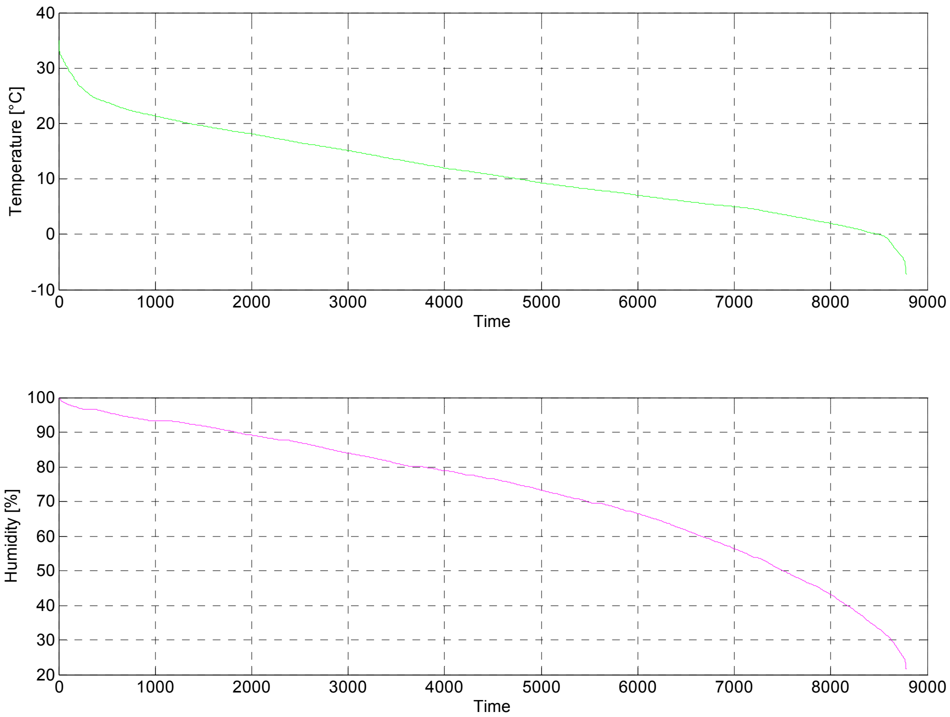

Figure 22: Temperature and humidity of ambient air, Berlin (Germany), Year 2008, sorted hour values

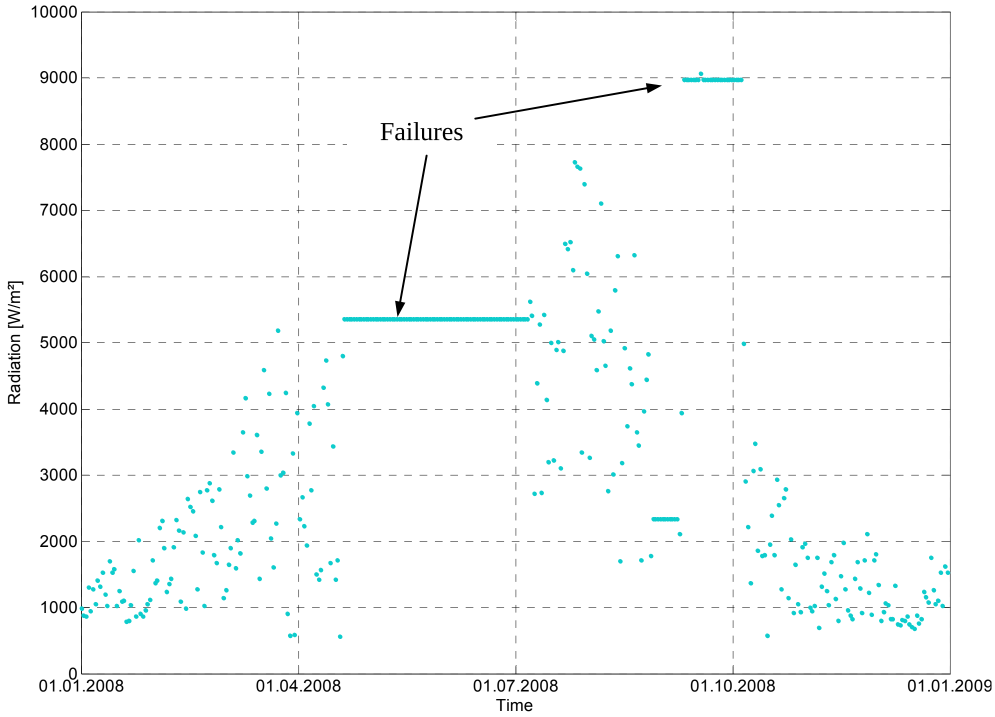

Figure 23: Solar radiation density, global, horizontal, Berlin (Germany), Year 2008, day values

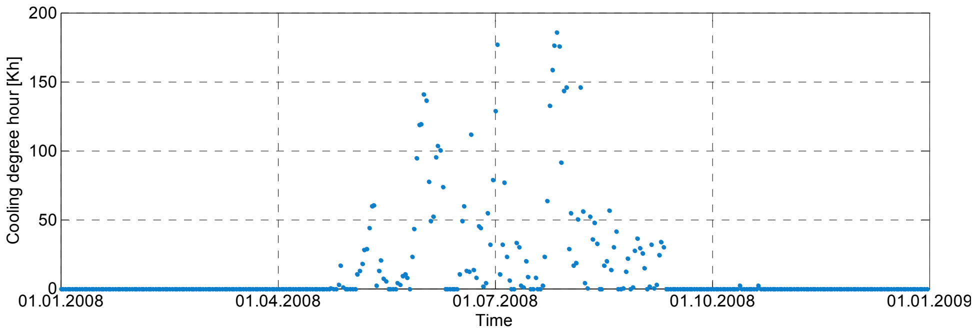

Figure 24: Degree hour for cooling (CDH), Berlin (Germany), Year 2008, day values

Figure 25: Ambient air temperature and cooling load of building, Berlin (Germany), Year 2008, hour values

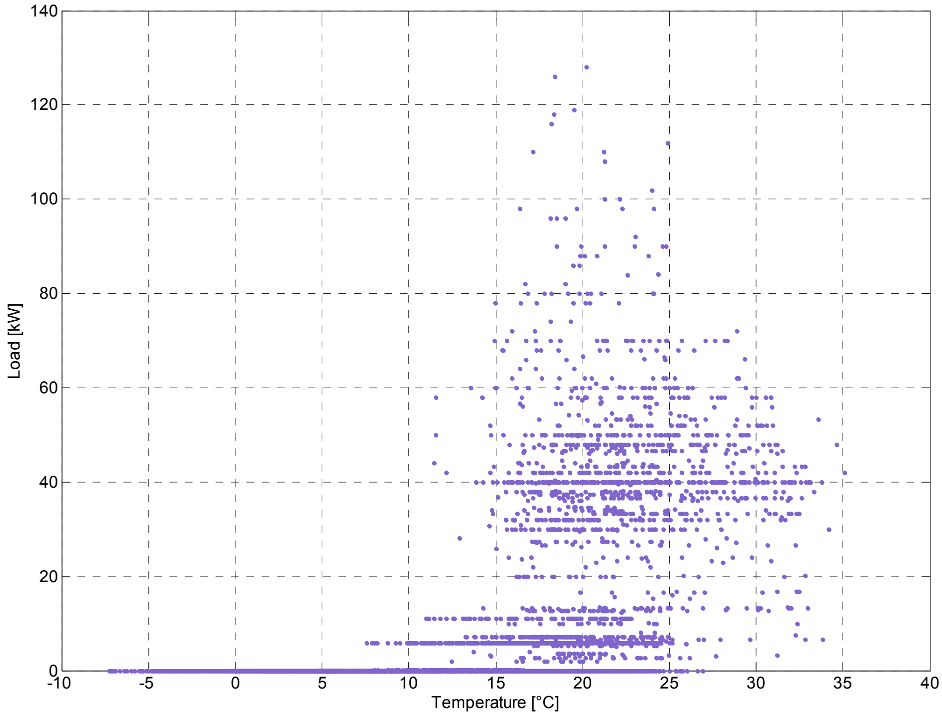

Figure 26: Cooling load of building in dependence of ambient air temperature, Berlin (Germany), Year 2008, hour values

C4.3 Japan, Tokyo

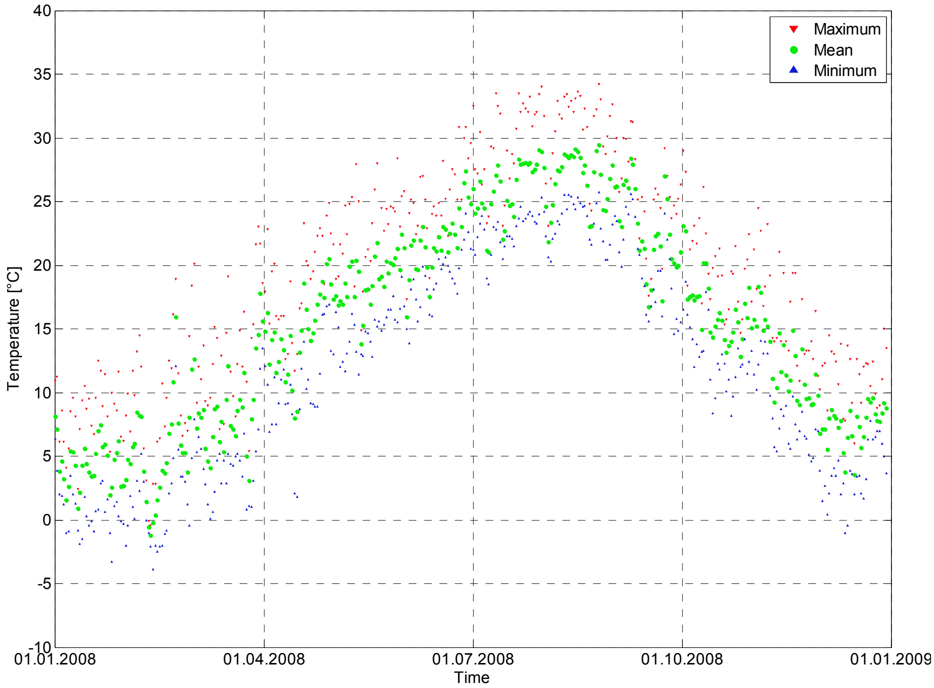

Figure 27: Ambient air temperature, maximum (red), mean (green), minimum (blue), Tokyo (Japan), hour values

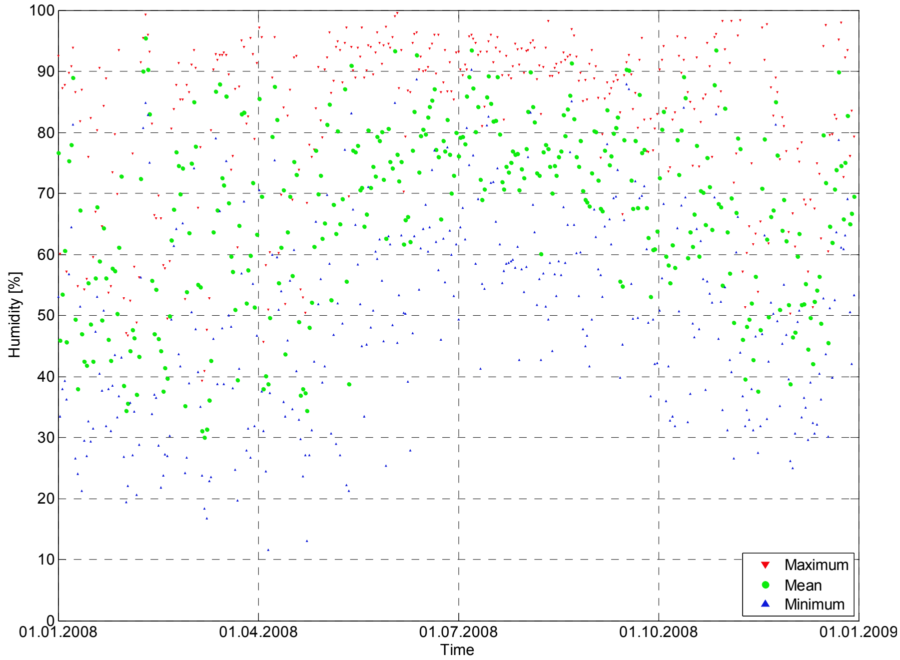

Figure 28: Relative humidity of ambient air, maximum (red), mean (green), minimum (blue), Tokyo (Japan), hour values

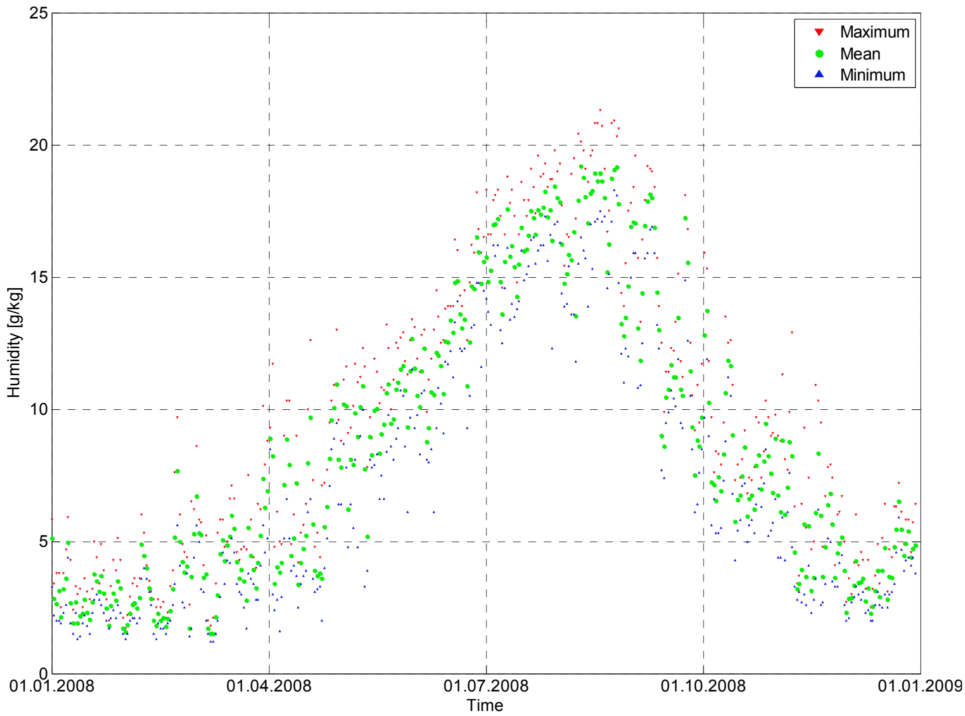

Figure 29: Absolute humidity of ambient air, maximum (red), mean (green), minimum (blue), Tokyo (Japan), hour values

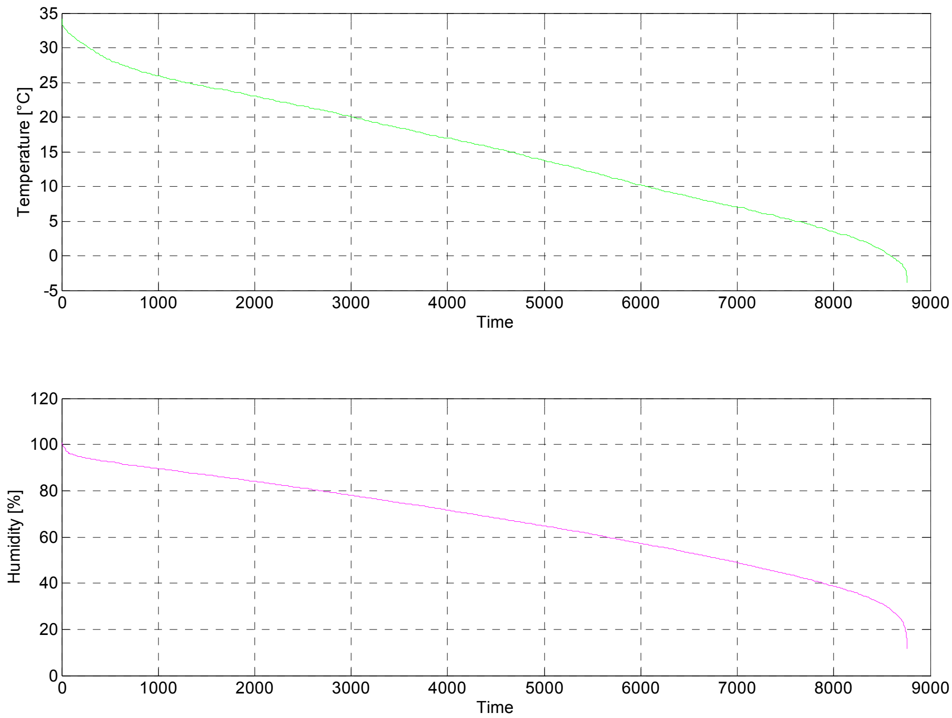

Figure 30: Temperature and humidity of ambient air, Tokyo (Japan), sorted hour values

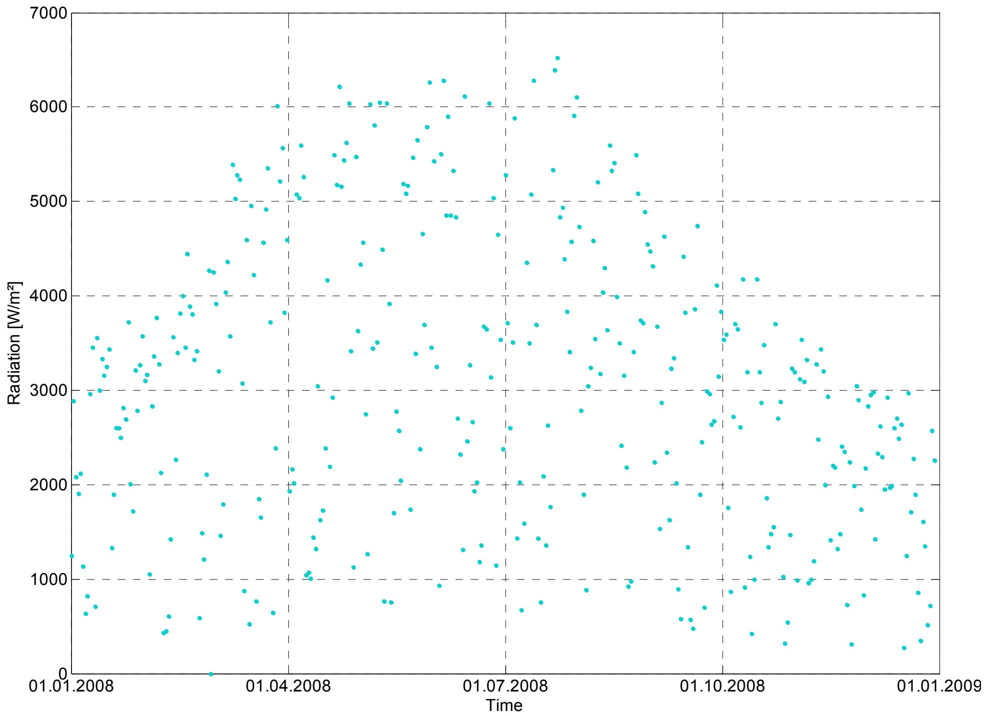

Figure 31: Solar radiation density, global, horizontal, Tokyo (Japan), day values

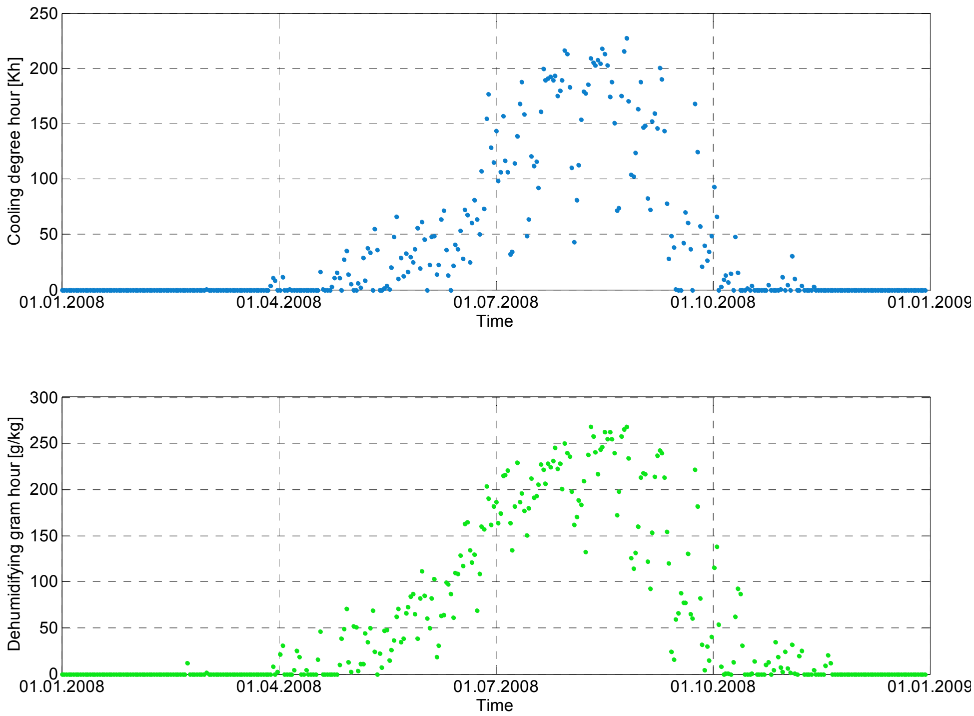

Figure 32: Degree hour for cooling (CDH), gram hour for dehumidifying (DGH), Tokyo (Japan), day values

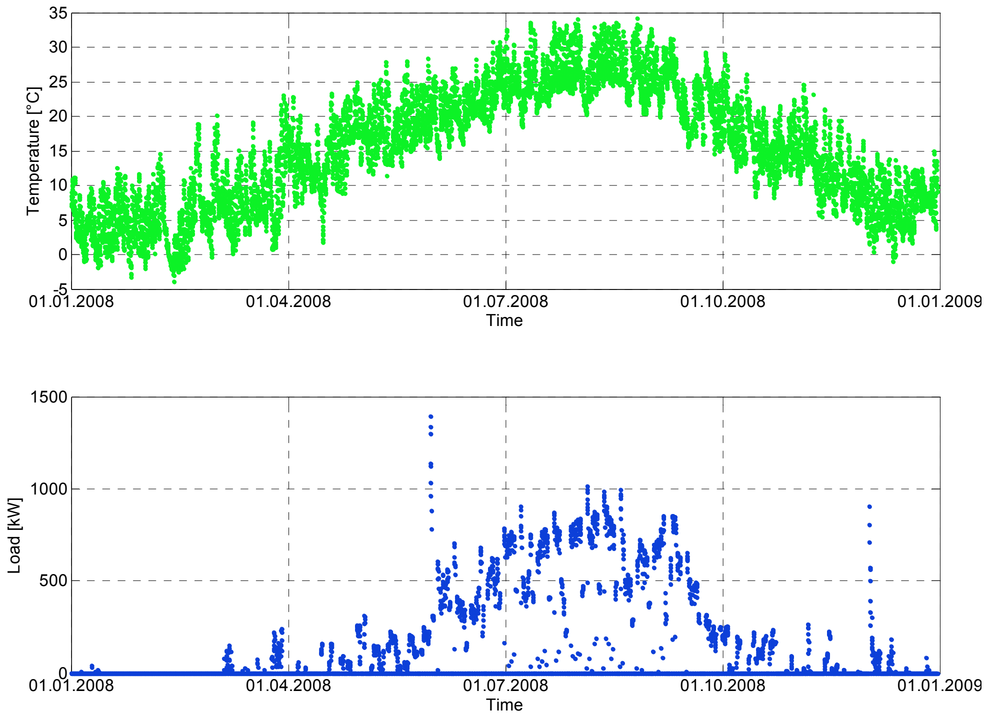

Figure 33: Ambient air temperature and cooling load of building, Tokyo (Japan), hour values

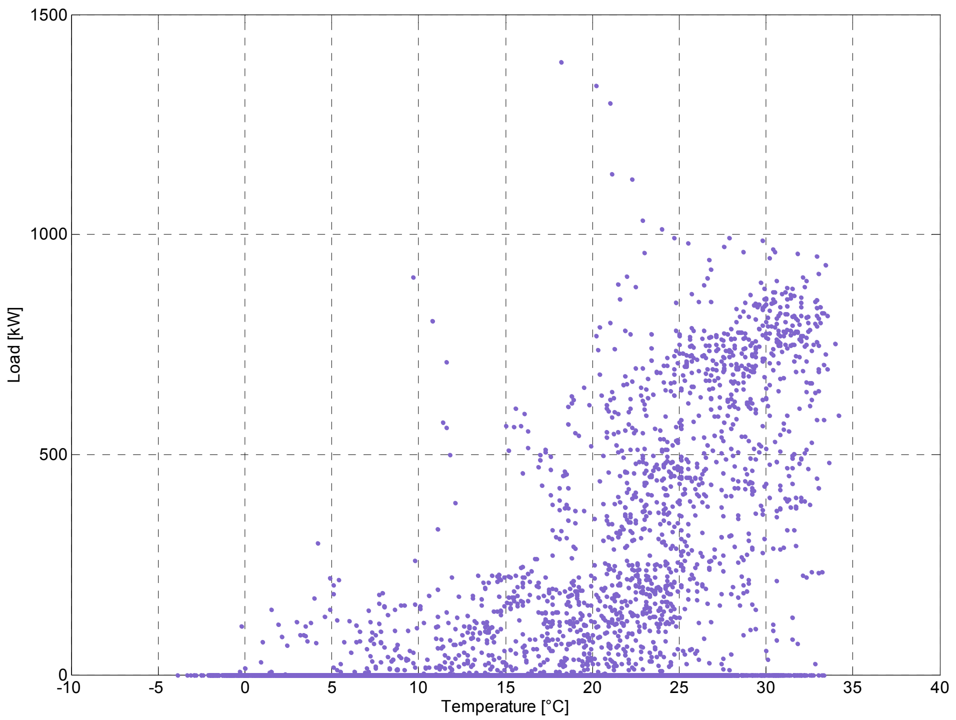

Figure 34: Cooling load of building in dependence of ambient air temperature, Tokyo (Japan), hour values

C.5 Comparison

Table 21: Annual data of projects, Year 2008

	Germany, Chemnitz	Germany, Berlin	Japan, Tokyo
Project in Subtask A	D4	D5	
	Monitoring	Monitoring	Simulation
Load [MWh/a]	8.798	54	545
Ambient air temperature [°C]	11	12	15
Relative humidity of ambient air [%]	74	73	67
Absolute humidity of ambient air [g/kg]	6	-	9
Global radiation [kWh/m²a]	1087	-	1106
Cooling degree hour [Kh/a]	4003	5006	14721
Dehumidifying gram hour [gh/a]	2854	-	22320

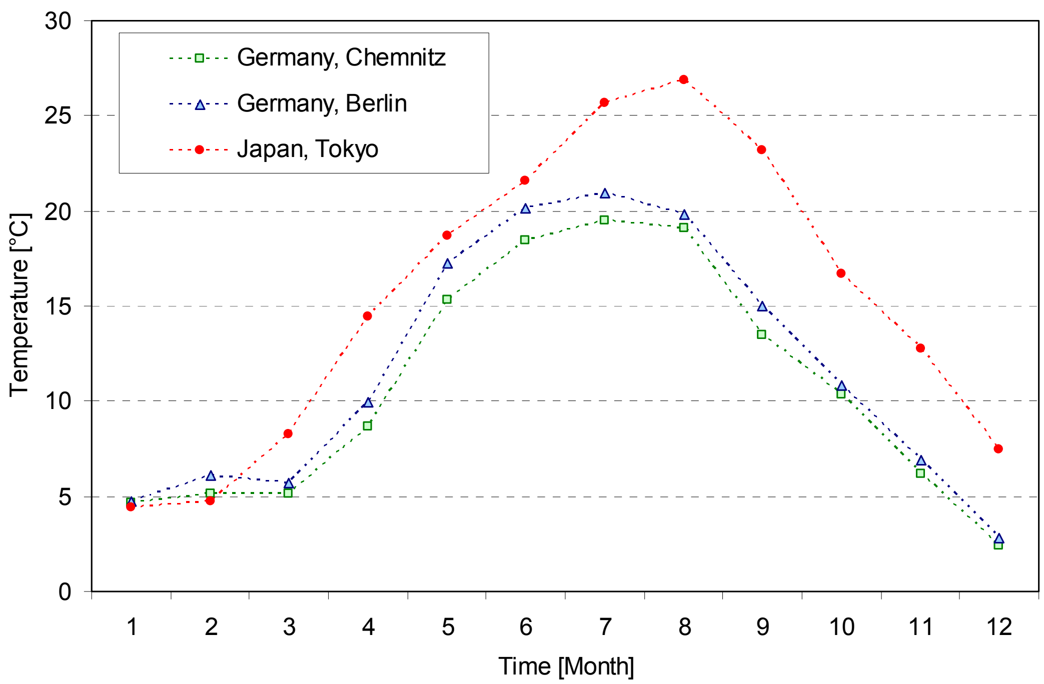

Figure 35: Ambient air temperature, Year 2008

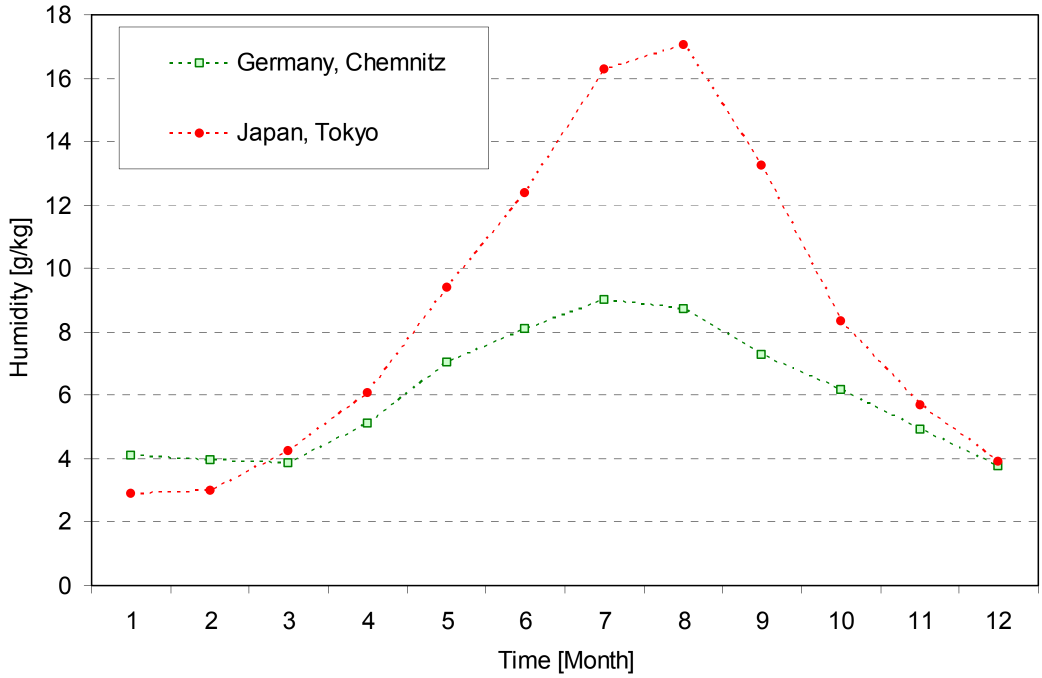

Figure 36: Absolute humidity of ambient air, Year 2008

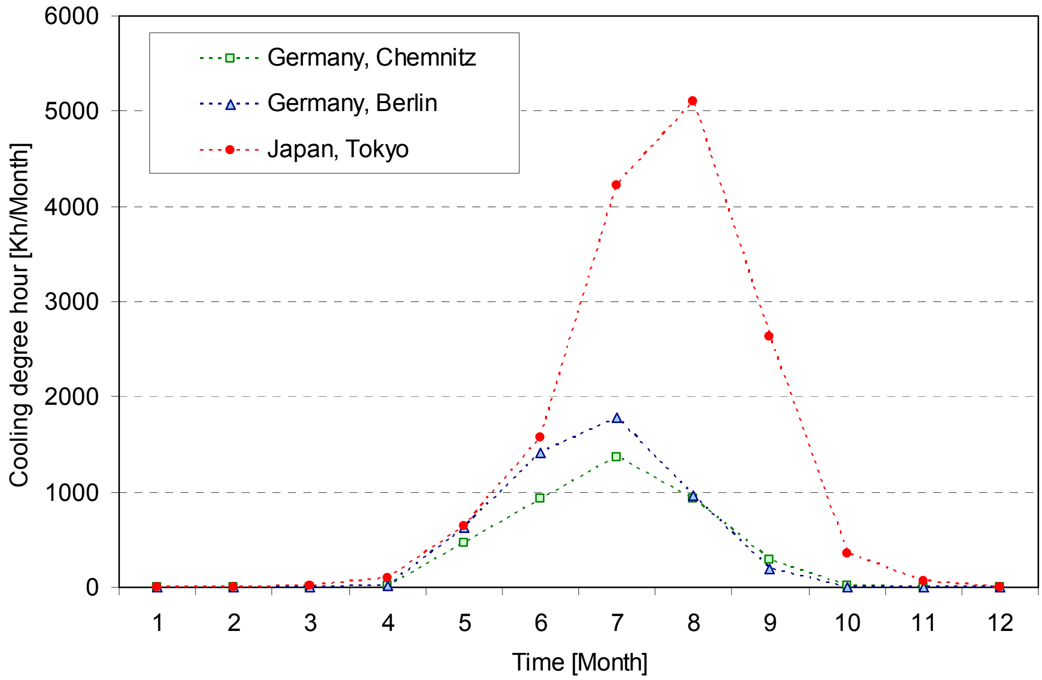

Figure 37: Cooling degree hour

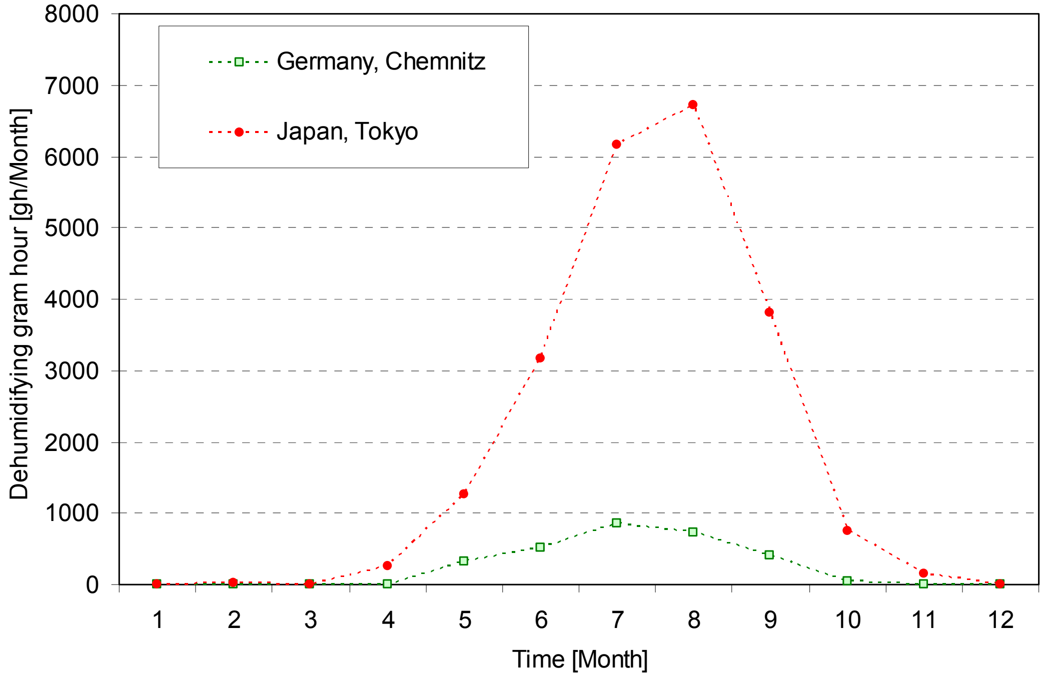

Figure 38: Dehumidifying gram hour, Year 2008

C.6 References

[1] Urbaneck, T.; Uhlig, U.; Platzer, B.; Schirmer, U.; Göschel T.; Zimmermann, D.: Machbarkeitsuntersuchung zur Stärkung der Kraft-Wärme-Kälte-Kopplung durch den Einsatz von Kältespeichern in großen Versorgungssystemen. Final report, Project of Federal Ministry of Economics and Labour, Identification 0327357A, Chemnitz: Utility Company Chemnitz, Chemnitz University of Technology, 2006. - ISBN 3-00-015770-0

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[6] Urbaneck, T.; Schirmer, U.; Platzer, B.; Barthel, U.; Uhlig, U.; Zimmermann, D.; Göschel, T.: Kurzzeitige Kältespeicherung – Optimierung der Energieversorgung

durch den Einsatz großer Kaltwasserspeicher. BWK - Das Energie-Fachmagazin, Verein Deutscher Ingenieure (Hrsg.), Düsseldorf, Springer-VDI-Verlag, 59. Jg., 06-2007, S. 55-59. - ISSN 1618-193X

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[10] Urbaneck, T.; Gehrmann, J.; Lottner, V.: First large-scale Chilled Water Stores in Germany. Effstock, 11th International Conference on Thermal Energy Storage, Stockholm (Schweden), 2009. – ISBN 978-91-976271-3-9

[11] Institute for Building Services and Energy Design, Technical University of Braunschweig: www.igs.bau.tu-bs.de. 2009

[12] Energieforum Berlin: http://www.energieforum-berlin.de. 2009

[13] http://www.kippzonen.com/?productgroup/111/Solar+Instruments.aspx

[14] http://www.fuehlersysteme.de/index.php?l=_en

[15] http://www.delphin.com/

[16] http://www.beuth.de/cmd;jsessionid=C54E43A54DAD31110EB34078CF98 56EA.2?level=tpl-home&languageid=en

2.9 Collected data D. Application of Software

D.1 An example of the LCEM tool application [1]

Subtask A: Project D11

Outline of the Building:

- Completion: 1999/4 – 2003/3
- Structure: SRC (B1F – 11 Stories)
- Total floor Area: 24,000 m²
- Typical floor Area: 2,000 m²
- Building height GL + 47m
- Building height GL + 47m

]

Figure 39: Appearance of Gifu Building

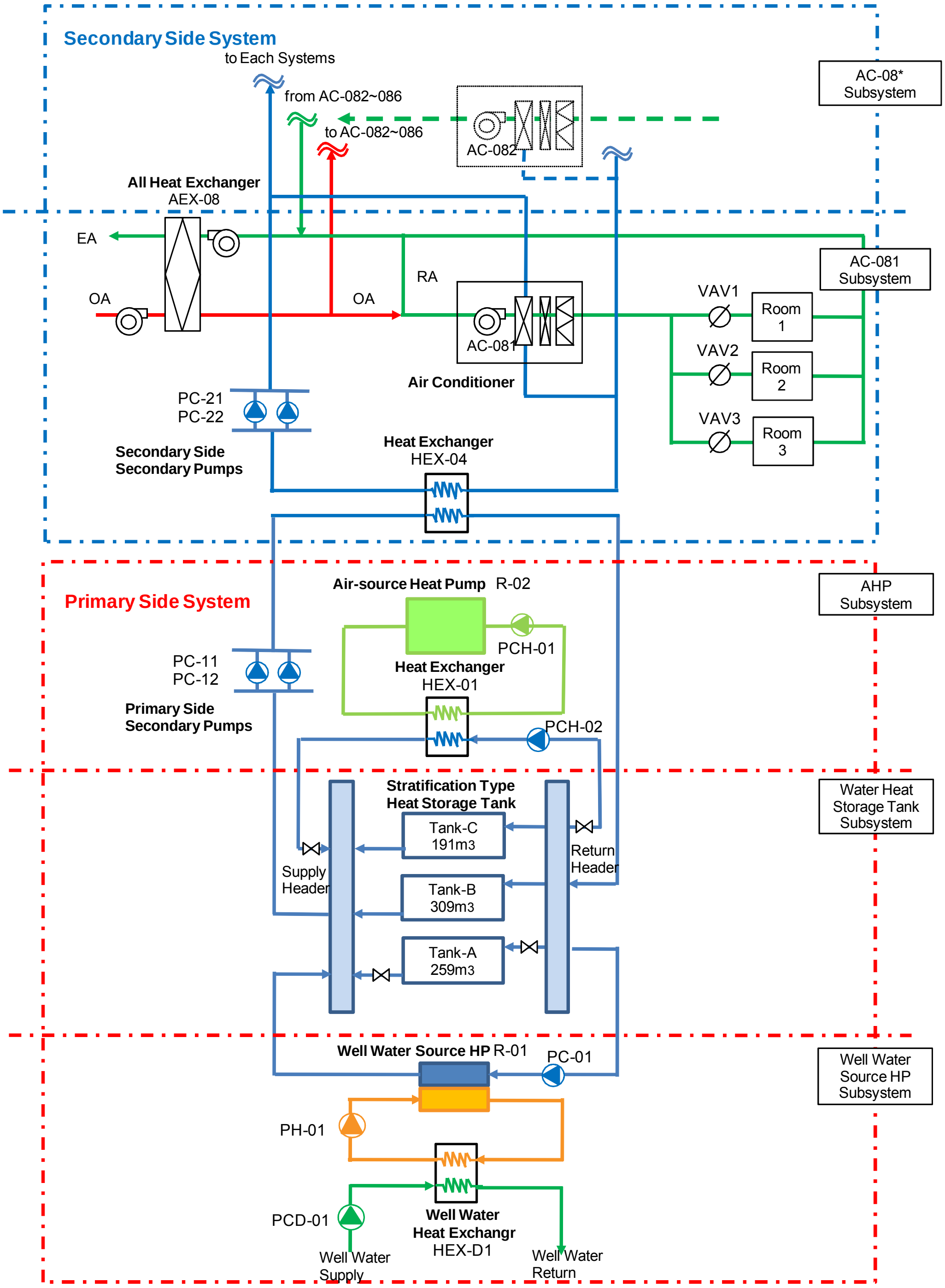

Figure 40: Overall HVAC System-diagram of Gifu Building

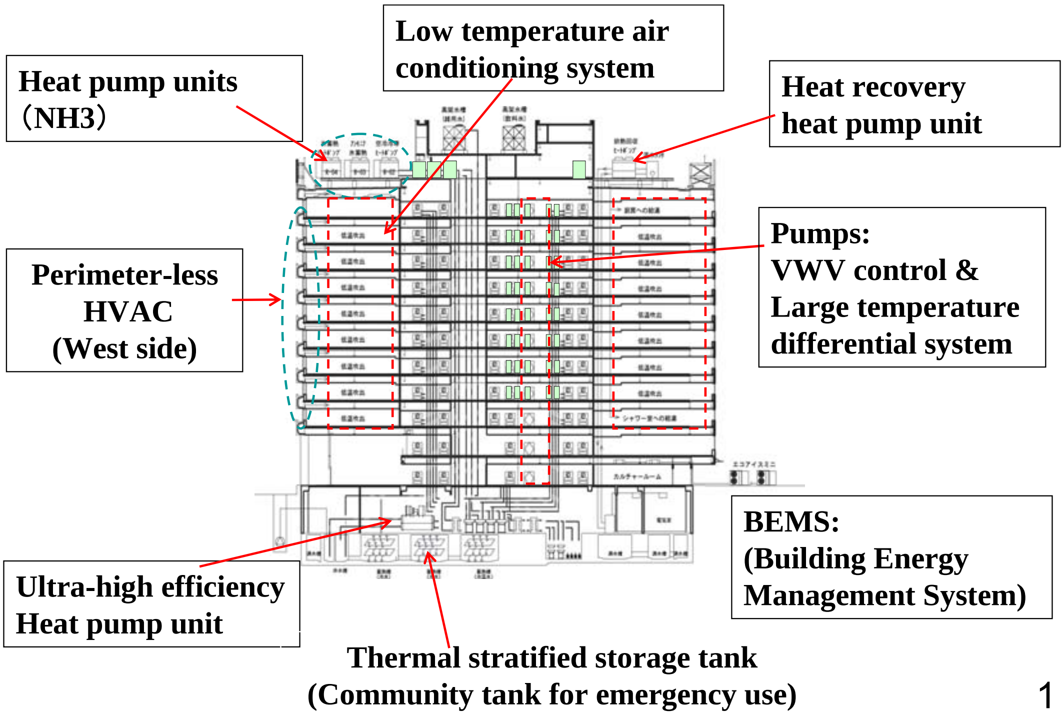

Figure 41: Cross section layout plan of the water TES system

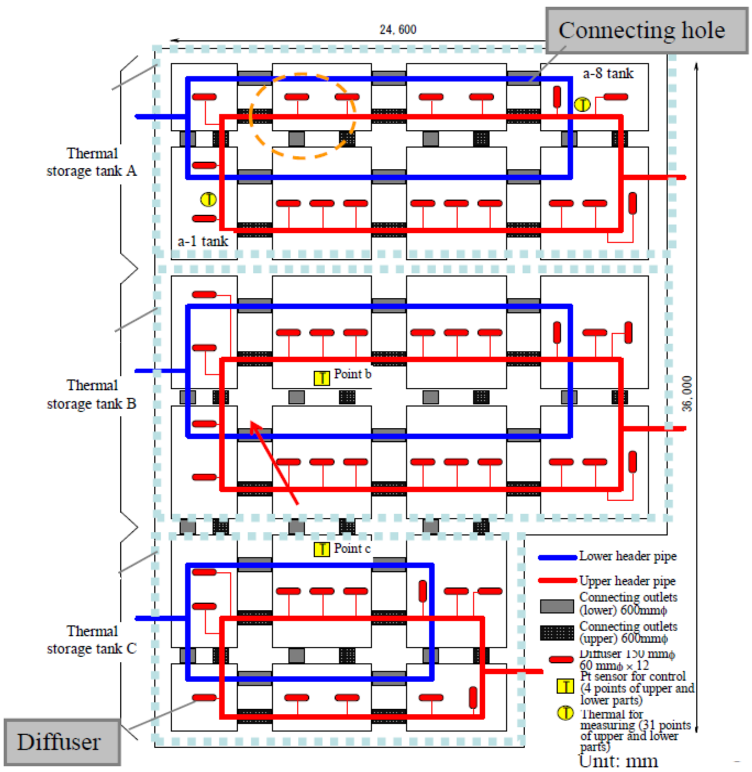

Figure 42: Configuration of the water TES tank (Distributer layout plan)

Outline of the Cooling TES

Total tank volume (759m^3)

- Storage medium : water
- Temperature Stratification tank
- Consist of 3 tanks (259m^3, 309m3, 191m^3)
- TES tank efficiency above 90%
- Depth of tanks is 1.5m
- Use the building foundation
- Cold water 5-15°C (Δt=10°C)
- Hot water 47-37d°C

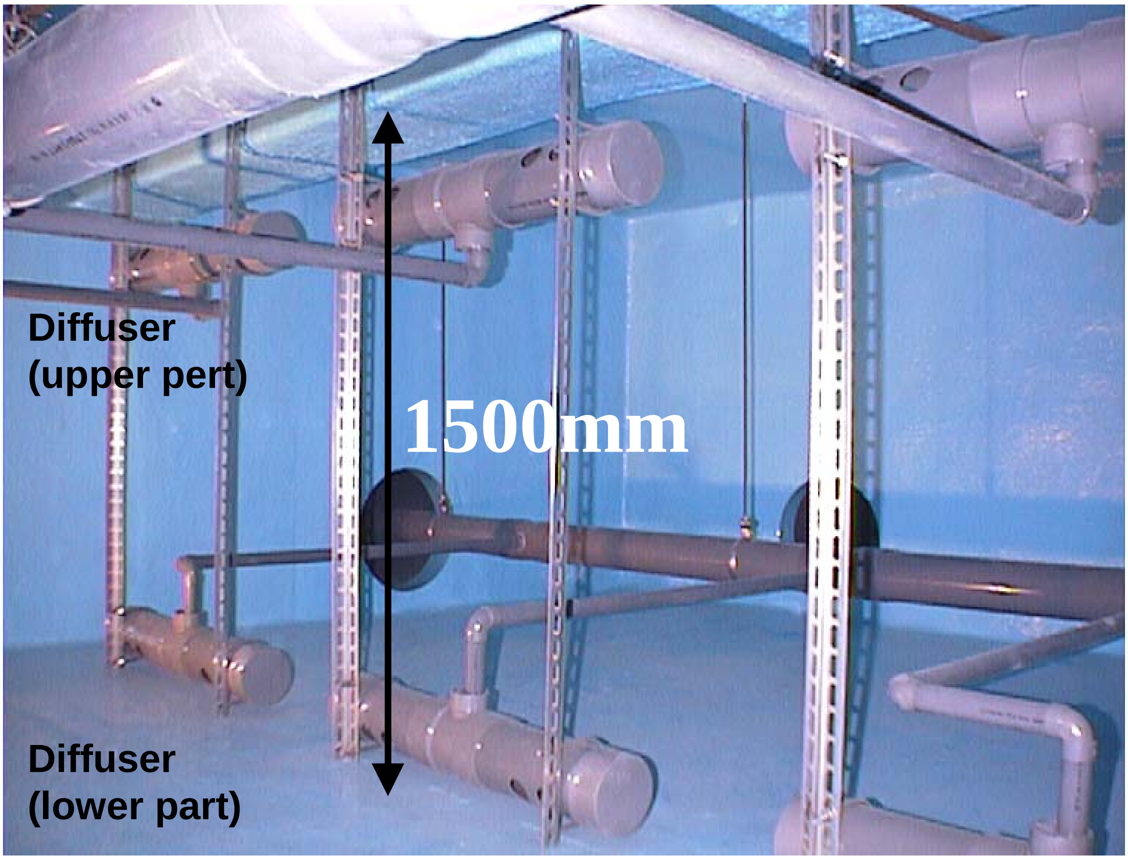

Figure 43: Distributer in the water tank

Simulation model of the Cooling TES

Simulation model of the cooling TES using a model of multi-connected fully mixed Tank. Depth of complete mixing zone (D) is determined by the condition of flow velocity at inlet- temperature difference between inlet water and tank water

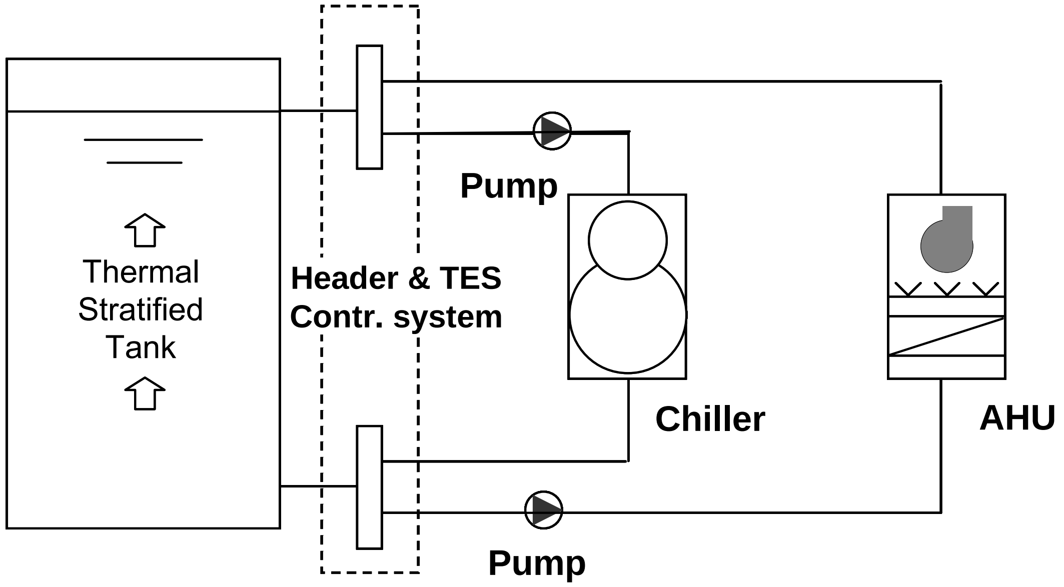

Figure 6: System diagram of the water TES system

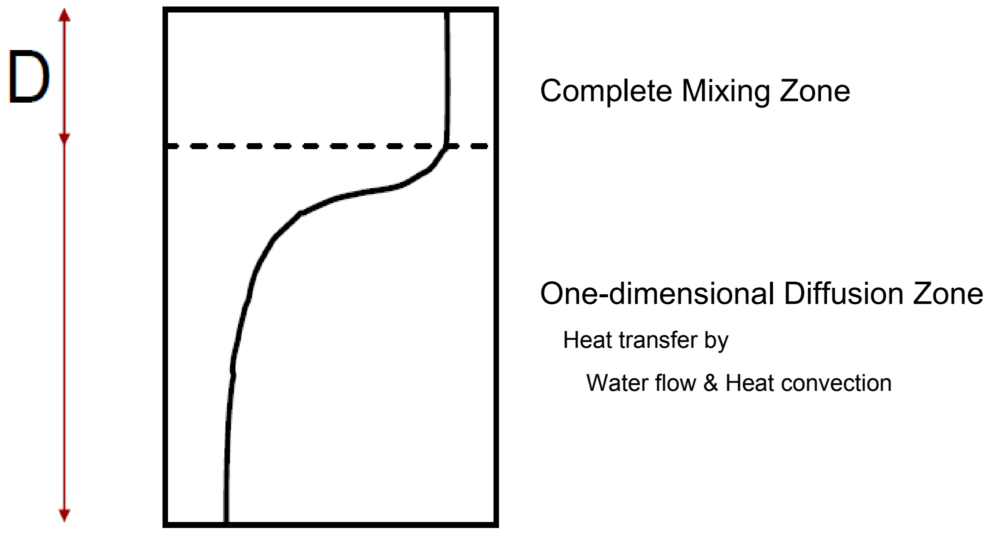

Figure 7: R value Model of the water tank

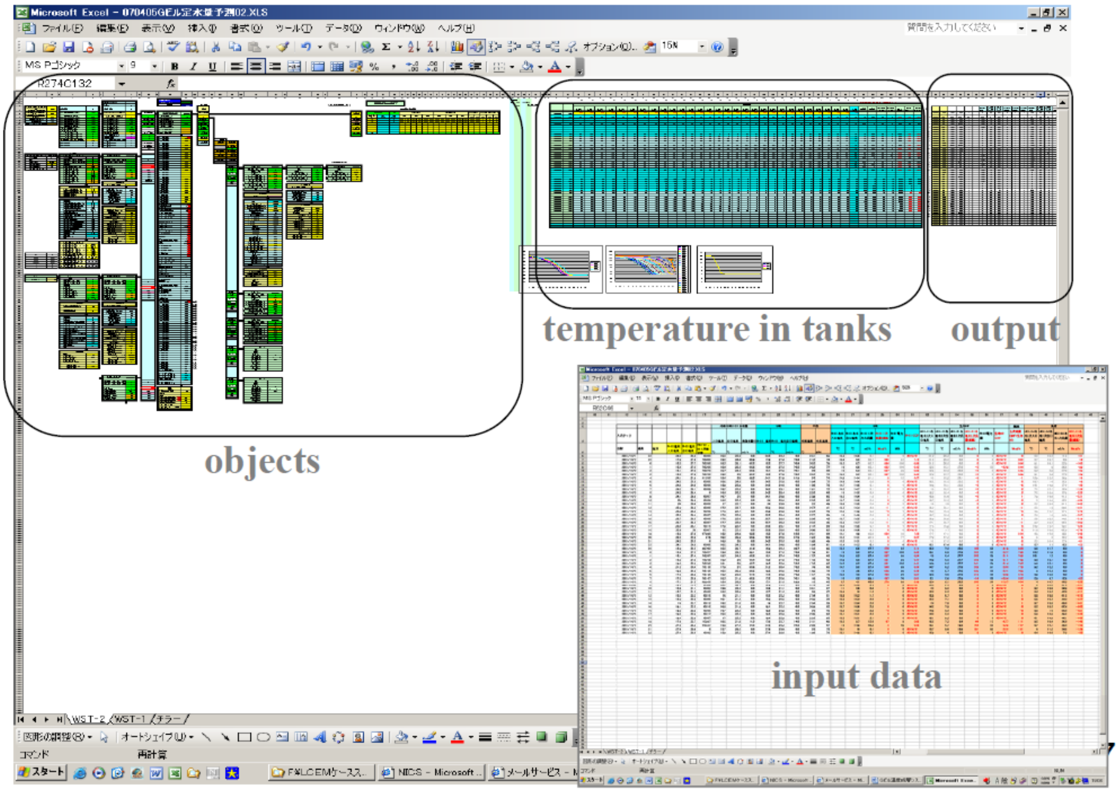

Figure 8: Whole aspect of modeling of the LCEM Tool [2]

Table 1: Input and Output data for the system simulation by LCEM Tool

INPUT DATA	OUTPUT DATA
Dry bulb temperature, °C	Chilled water volume, lit/min
Wet bulb temperature, °C	Chilled water temperature °C
Cooling water temperature, °C	Electric consumption for Well source HP (R-01), kWh
Chilled water volume, lit/min	Electric consumption for Air source HP (R-02), kWh
Return chilled water temperature °C	Elec. consumption for Pump, kWh
	Cooling water Pump
	Chilled water Pump
	Secondary water Pump
	Chilled water Temp. from TES, °C
	Stored heat amount in TES, MJ
	Heat amount of stored / released, kW

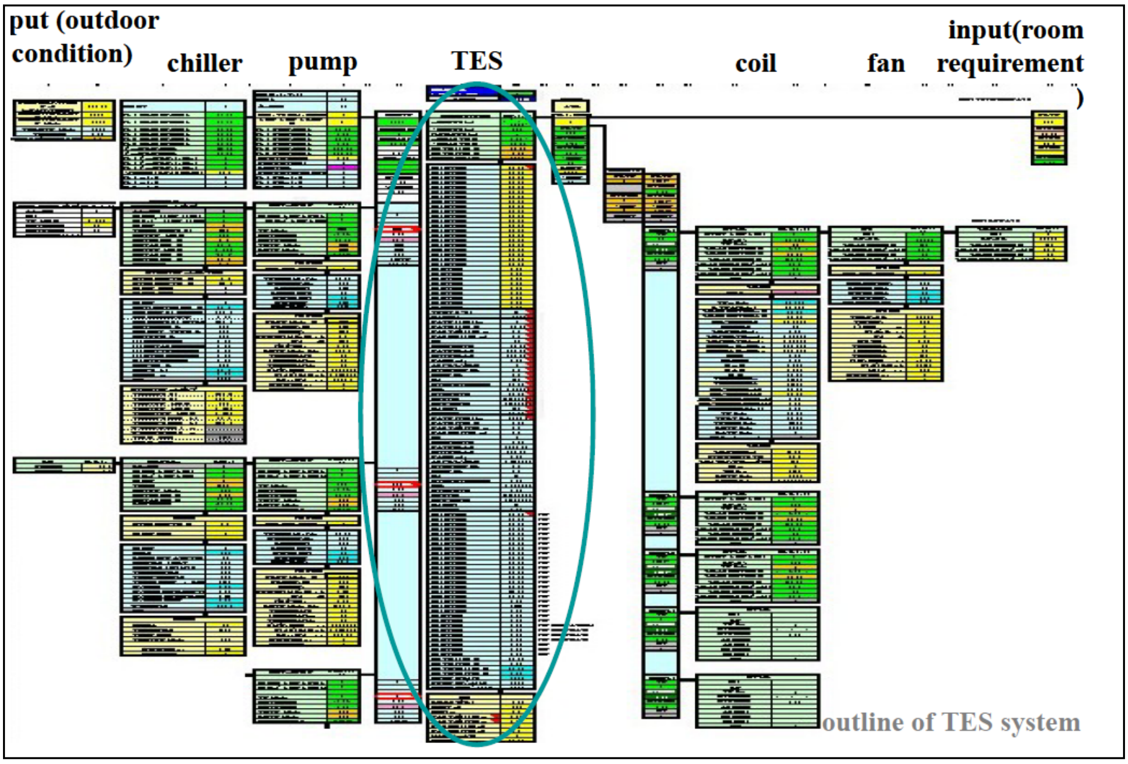

Figure 44: Overall TES system description using by LCEM Tool

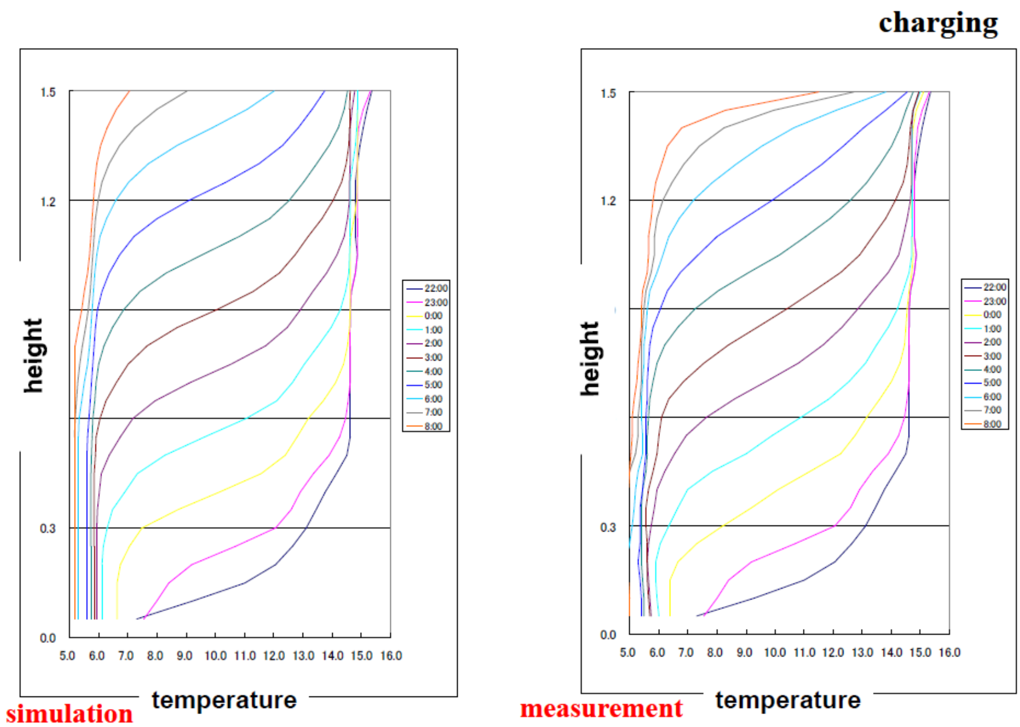

Figure 45: Estimation Results of temperature profile of the water tank (Charging)

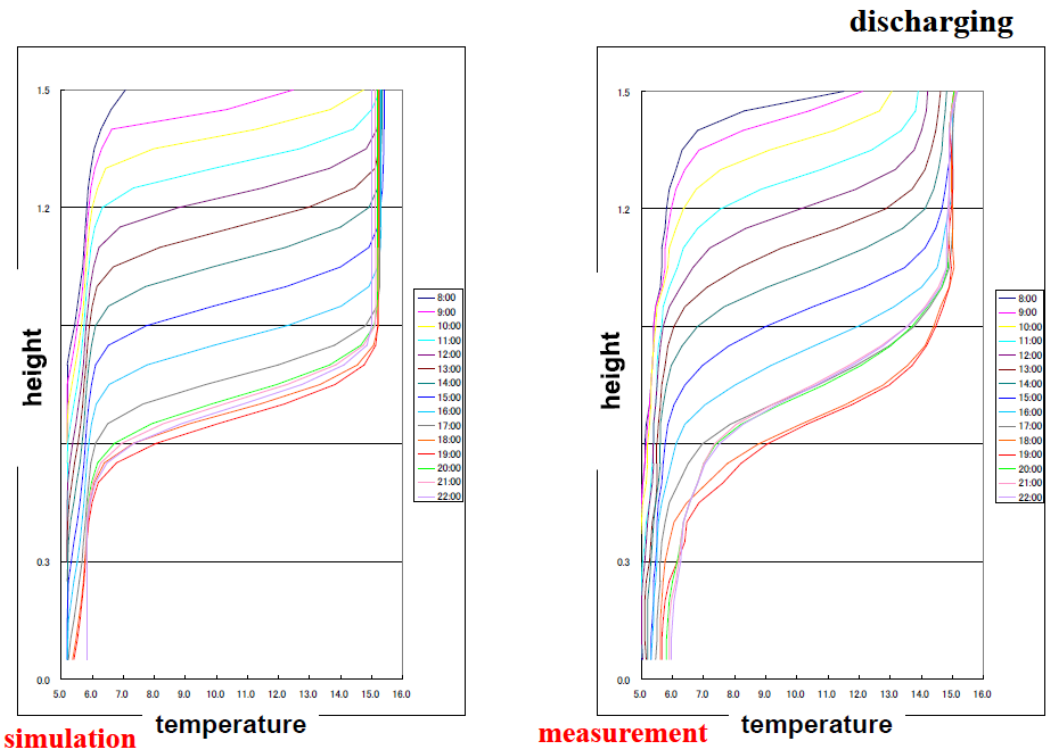

Figure 11: Estimation Results of temperature profile of the water tank (Discharging)

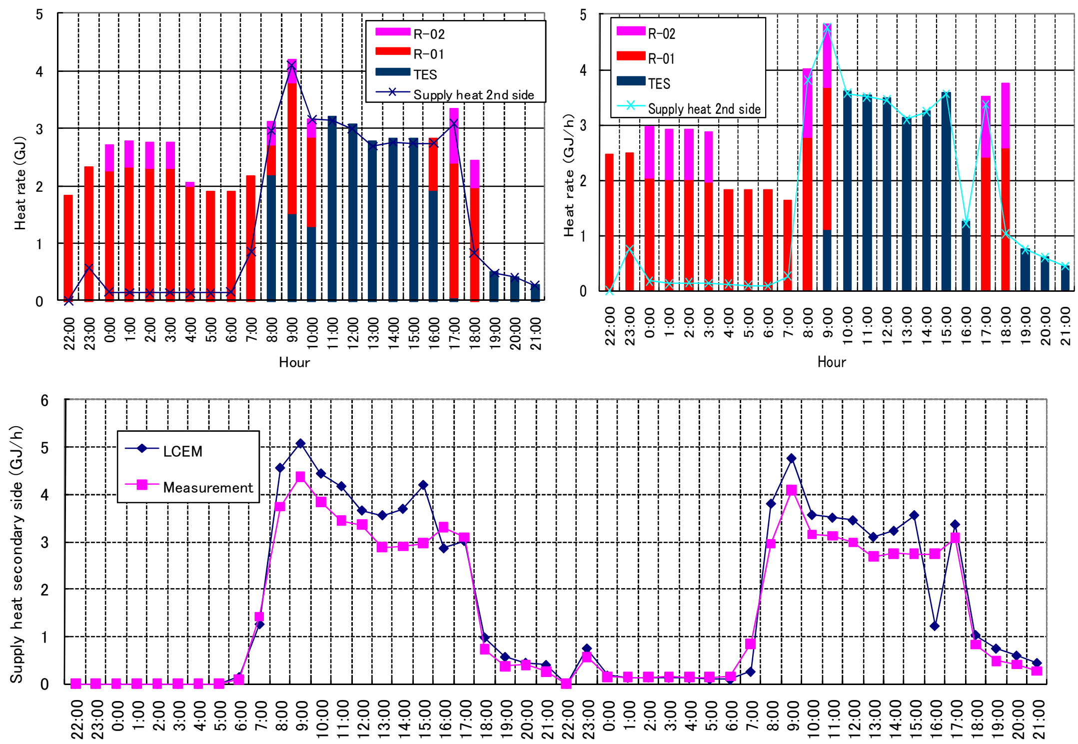

Figure 46: Supply heat from heat-source equipments to secondary HVAC side

D.2 Subtask A: An example of EnergyPlus

Subtask A: Project D13
Outline of the Building (Figure 47)

- Completion: 2007/2 – 2007/5
- Total floor Area : 5.76 m²
- Building height GL + 3m

Outline of the Cooling TES

- Storage medium: PCM (RT-27)
- PCM amount (100 kg)
- Phase Change Temperature: T_{PCM}= 26-28 ºC
- Phase Change Enthalpy:
  - h_{PCM}= 179 kJ/kg (Manufacturer – 19-34 ºC)
  - h_{PCM}= 95 kJ/kg (DSC results – 19-35 ºC)
  - h_{PCM}= 60 kJ/kg (DSC results – 23-29 ºC)

Figure 47: RT27+PU cubicle

Figure 48, Figure 49 and Figure 50 show configuration of simulation model with Cooling TES using EnergyPlus. Obtained results from the EnergyPlus simulations are presented in Figure 51.

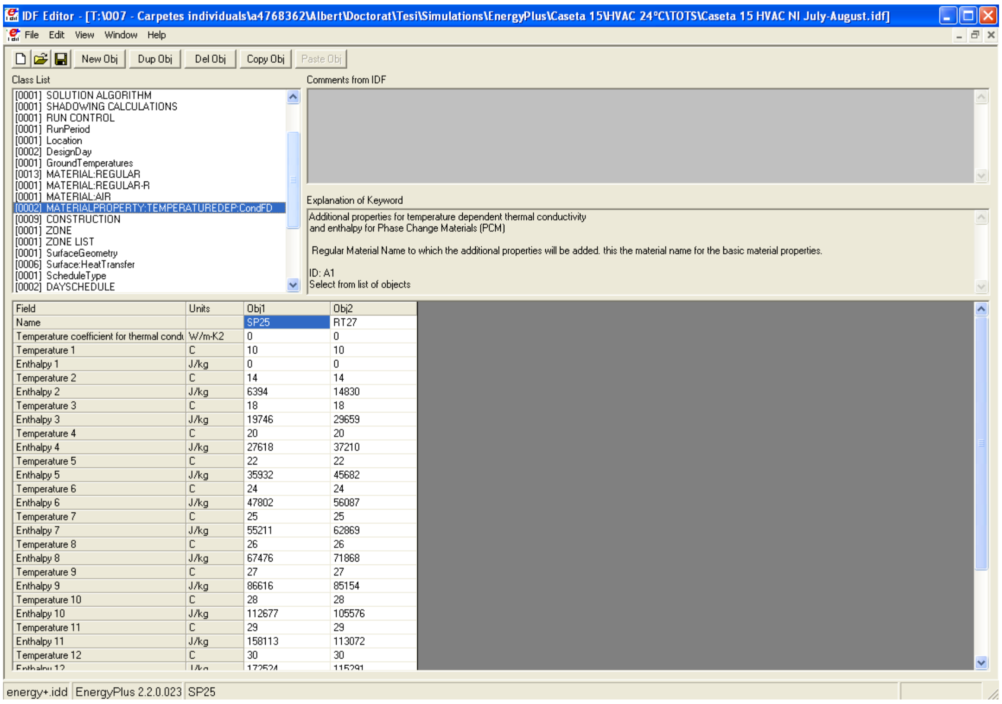

Figure 48: Introduction of the PCM data (enthalpy as a function of temperature)

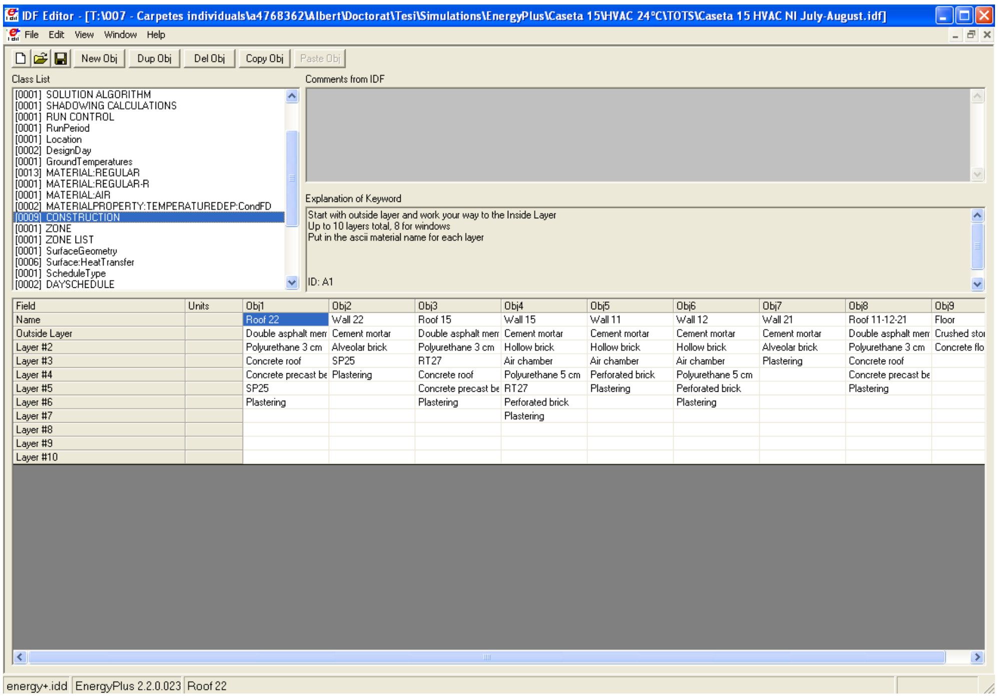

Figure 49: Constructive system definition (walls and roofs)

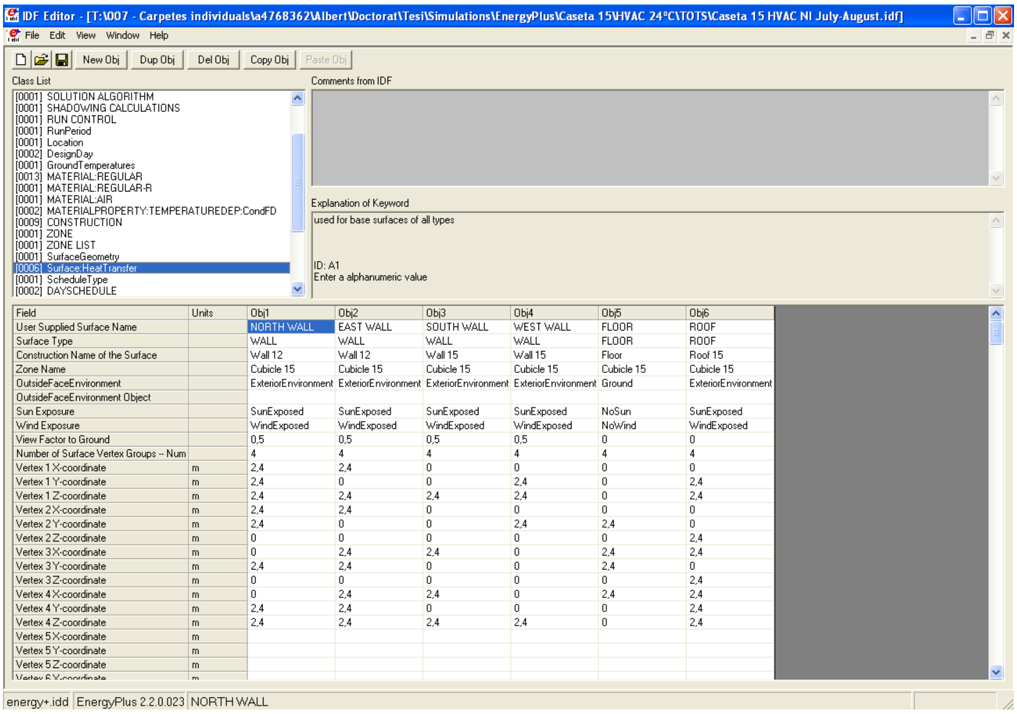

Figure 50: Definition of the cubicle (dimensions and selection of constructive solutions)

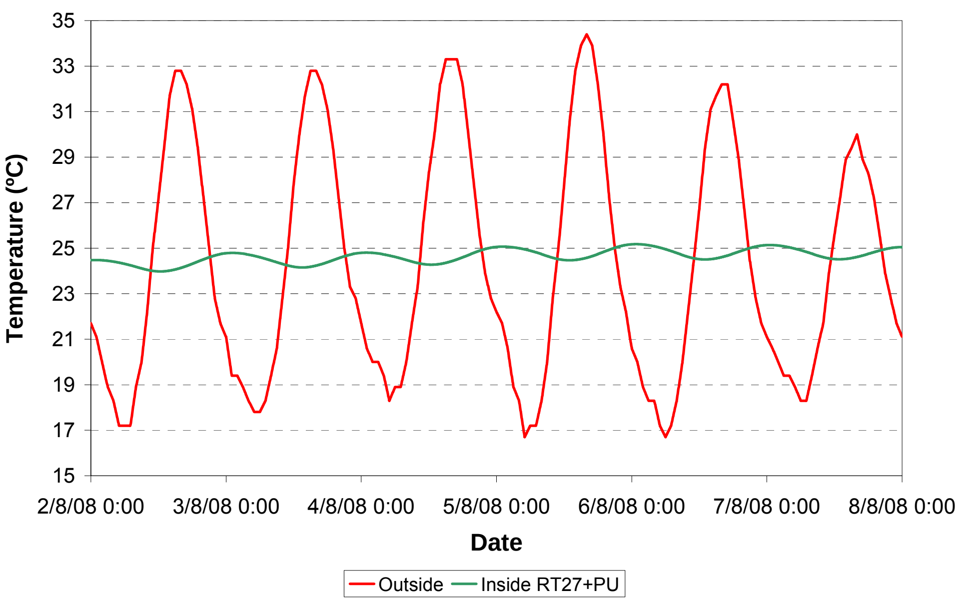

Figure 51: Outside and inside temperature of the RT27+PU cubicle

D.3 Subtask A: An example of the CONFLOW Model

The model is used for the heating and cooling of the greenhouse (Figure 52) with ATES system in Adana, Turkey. Description of the greenhouse:

- Subtask A: Project D 23
- 360 m^2 floor area
- Growing tomatoes and eggplants
- Plastic covered

Figure 52: ATES for greenhouse heating and cooling in Adana, Turkey

Input data for CONFLOW Model

CONFLOW is a Thermal Front Tracking Model. It simulates a two dimensional horizontal groundwater flow. The input data is entered using the spreadsheet shown in Figure 53. The spreadsheet has two sections.

```
 GROUND WATER FLOW PATTERN      F6-Options   F7-Help   LOCATIONS OF WELLS/FLOW RATES
Aquifer: Thickness             4.0_______   m          x (m)  y (m)  Q (m3/s) Colour
Aquifer: Vol. heat capacity    2.00e6       J/m3K      100.0  200.0  -0.001    10
Aquifer: Hydr. conductivity    1.0e-4       m/s        200.0  300.0  0.001     5
Fluid: Vol. heat capacity      4.18e6       J/m3K      0.0    0.0    0.0       0
                                                       0.0    0.0    0.0       0
Boundary: (Closed/No/Open)<->  No                      0.0    0.0    0.0       0
   Point 1: x-value                         m          0.0    0.0    0.0       0
   Point 1: y-value                         m          0.0    0.0    0.0       0
   Point 2: x-value                         m          0.0    0.0    0.0       0
   Point 2: y-value                         m          0.0    0.0    0.0       0
                                                       0.0    0.0    0.0       0
Regional flow: x-direction     0.0          m/s        0.0    0.0    0.0       0
Regional flow: y-direction     0.0          m/s        0.0    0.0    0.0       0
                                                       0.0    0.0    0.0       0
Viewport: Minimum x-value      -200.0       m          0.0    0.0    0.0       0
Viewport: Maximum x-value      600.0        m          0.0    0.0    0.0       0
Viewport: Minimum y-value      -100.0       m          0.0    0.0    0.0       0
                                                       0.0    0.0    0.0       0
Streamline angular resolution  20                      0.0    0.0    0.0       0
Erase streamlines (Y/N)        N                       0.0    0.0    0.0       0
                                                       0.0    0.0    0.0       0
Duration of simulation         3m                      0.0    0.0    0.0       0
Erase frontpoints (Y/N)        Y                       0.0    0.0    0.0       0
 F1-Run   F2-Save   F3-Load   F4-Reset   F5-Print                        ESC-Quit
```

Figure 53: CONFLOW data input spreadsheet

In the first section (on the left-hand side of Figure 53) the following data is entered.

- The thickness of the aquifer layer (m)
- The hydraulic conductivity of the aquifer layer (m/s)
- The volumetric heat capacity of the aquifer layer (J/m^3 K)
- The volumetric heat capacity of the groundwater (J/m^3 K)
- Whether there is a boundary, and if it is open or closed
- Two different points on the hydraulic boundary if a boundary is present (x_1,y_1), (x_2,y_2)
- The regional groundwater flow in the aquifer layer (m^3/m^2s)

The above data are based on the results from a test well. In the second section, the following information on the wells is entered.

- The coordinates of each well
- The flow rate of each well (m^3/s)
- Color of the thermal front

The flow rate is positive when groundwater is injected into the well and negative when groundwater is extracted.

Output

As a result of the simulation, the model gives the motion of the thermal fronts in an aquifer layer. The flow pattern along with the thermal fronts can be displayed graphically as an output. Figure 54 shows the result of the CONFLOW simulation for the ATES system for greenhouse after warm injection. The streamlines represent the flow pattern in the aquifer layer. The groundwater is extracted from the cold well and injected to the warm well. The pink thermal front in the case of warm injection is seen around the warm well. It is essential to avoid overlap of cold and warm thermal fronts – that is thermal breakthrough - in an ATES system. The minimum distance between the wells that avoids thermal breakthrough in the CONFLOW simulation should be used in the final design of the system.

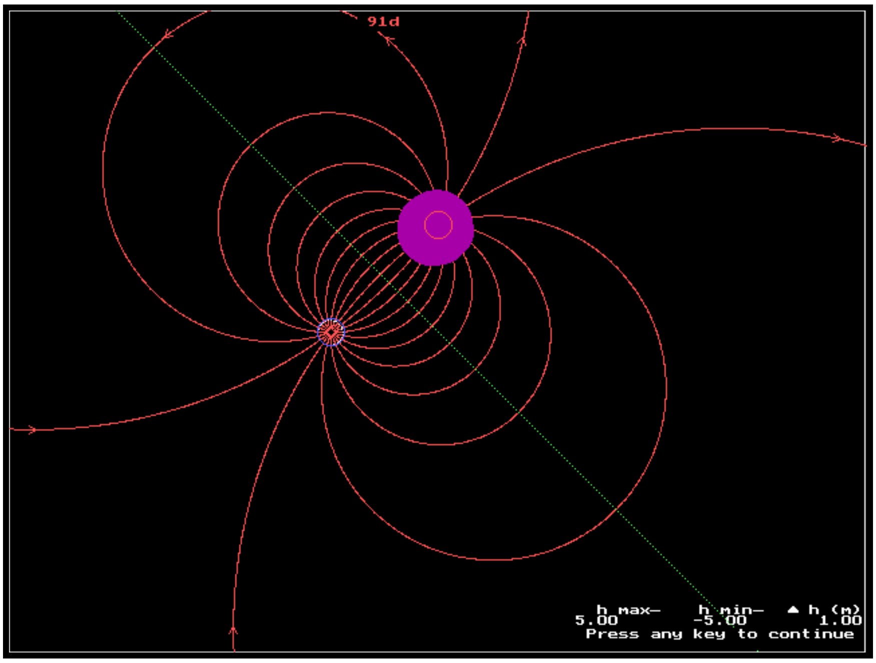

Figure 54: CONFLOW simulation result after warm injection

References

[45] Prediction for Performance of Short-Term TES Using Simulation Tool “LCEM”, IEA/ ECES Annex20 6th Workshop, Seville, Spain, R.Muranishi, H.Tanaka and M.Okumiya (2008)

[46] Development of HVAC System Simulation Tool for Life Cycle Energy Management, Part1: Outline of the developed simulation tool for Life Cycle Energy Management and Part2: Development of component models for HVAC equioment, M Ito et a.l, Proc.of Building Simulation 2007, pp.1610-1622 (2007)

3. Conclusions

In Subtask A, demonstration projects for implementation of thermal energy storage in energy systems has been carried out in participating countries. In total 20 projects were examined. The systems were evaluated based on data from a monitoring program of the actual thermal energy storage.

The thermal energy storage technologies for cooling covered in the demonstration projects in Subtask A are classified as follows:

- Long term
  - Underground Thermal Energy Storage(UTES)
  - Aquifer Thermal Energy Storage (ATES)
  - Borehole Thermal Energy Storage (BTES)
  - Thermal Energy Storage in Building Foundation Piles
  - Cavity Thermal Energy Storage (CTES)
    - Caverns
    - Pits

- Short term
  - Phase Change Materials (PCM)
    - PCM in building envelope
    - PCM in HVAC
  - Ice Storage
  - Chilled Water Storage

Demonstration projects from eight different countries use different thermal energy storage technologies. Information on these projects can be found in the project templates given in Collected data 1 of Chapter 1.

The demonstration projects were done for the following applications:

- Buildings
  - Airport
  - Offices
  - Shopping mall
  - Residential
  - University
- Combined heat and power generation
- District heating and cooling
- Greenhouses
- Passive cooling

System Performance Evaluation of Demonstration Projects consisted of data collection, performance evaluation including sustainability aspects of demonstration projects.

For data collection, a template prepared in Excel program is used to evaluate the system performance of the demonstration projects. These sheets for each of the projects are included in Collected data 2.

Monitored information on annual capacity, energy consumption, load ratio, COP, efficiency, etc. of the demonstration projects are entered in the corresponding cells on the terminal points of the structure given in Collected data 2. Performance data for the demonstration projects collected with this method were compared. This template also includes a schematic diagram showing COP calculation conditions for the demonstration project in Collected data 2 of Chapter 1.

The reduction of the energy demand of a system results in less primary energy consumption and also to a global reduction of the energy power plants and fuel extraction. Therefore, a reduction of the energy demand leads to sustainability by compensating the highly increase of energy consumption due to cooling applications. In the monitored Annex 20 projects, thermal energy storage is shown to contribute to this energy demand reduction by two main different ways: direct reduction of the heating/cooling load, and increase of the performance of the system.

As a result of the evaluation of the monitored data from 20 demonstration projects, sustainability of cooling with thermal energy storage requires consideration of several factors. Among these are:

- Availability of users
- Temperature
- Time and duration of demand
- Distance between supply and demand
- Power
- Capacity
- Comfort cooling requirements in urban environment
- Cooling (Heating) load
- Climate

The storage capacities of the demonstration projects were in a wide range between kWhs to GWhs. It is difficult to compare the sustainability of such a range of projects with different storage concepts e.g. UTES with ice, UTES with PCM. Free cooling systems had very high COPs, but should be evaluated taking climate conditions into account.

The combination of underground thermal energy storage systems and slow reacting space heating like concrete core activation with faster reacting space heating systems (like radiators) have to be well combined.

Systems should be monitored in first period of operation. The controlling strategy has to be adapted to the real boundary conditions (e.g. earth temperature) and occupancy (profiles, internal head loads and so on).

The uneven energy balance of heat extraction and injection can cause a warming up of the underground. Therefore the free cooling mode could only be used for short time unless cold from winter air is injected to provide thermal balance.

Data collection templates developed in Subtask A can form the basis for a database of Annex 20 demonstration projects. Unfortunately, some of the data were not available for some demonstration projects. This was due to the fact that the monitoring plans for some of the projects were based on control of the system operation and were lacking data needed to evaluate energy conservation.

An accurate design is necessary to demonstrate energy-saving performance of a thermal storage system. For this purpose, the manuals and design tools that were developed with the correct understanding of performance of a system are required. Another important issue is the proper operation of thermal storage system. For the optimal operation of thermal storage system, the appropriate operation tools and manuals are needed. So, **in Subtask B** these issues were discussed.

Existing design manuals and tools for the short and long term thermal storage were reviewed using inventory developed in Annex 14 and from other activities. The liability of software and design tools for cooling with TES were examined.
Also, evaluation of design tools with respect to possibility of their use in various stages of design procedure was conducted.

Monitoring of plants and weather is very important for benchmark in Subtask A and the evaluation of design tools in Subtask B. The measured data show the real boundary conditions and the efficiency of solution with Cool TES.

Various examples in Collected data D of Chapter 2 give a short overview concerning application of design tools. It is necessary to grasp the aim of the Individual Softwares, Models and Manuals by analyzing the required input data and the output. For a specific system, performance evaluation with two or more design tools is performed, and the results are compared.