A 3-field earth-heat-exchange system for a school building in Imola, Italy: Monitoring results

Elsevier Editorial System(tm) for Renewable Energy
Manuscript Draft

Manuscript Number: RENE-D-12-01303

Title: A 3-field Earth-Heat-Exchange System for a School Building in Imola, Italy: monitoring results

Article Type: Research Paper

Keywords: earth-to-air horizontal heat exchangers; ground cooling; passive cooling; school building

Corresponding Author: Mr. Giacomo Chiesa, M.D.

Corresponding Author's Institution: Polytechnic of Turin

First Author: Giacomo Chiesa, M.D.

Order of Authors: Giacomo Chiesa, M.D.; Marco Simonetti, PhD; Mario Grosso, professor

Abstract: The present study aims at presenting the results of 12 months long monitoring campaign of an earth-to-air horizontal heat exchangers (EHXair-hor) system in a school complex, Imola, Italy. With more than two kilometres of buried pipes, it represents the biggest Italian application of this technology. Considerable differences between inlet and outlet air temperature have been noticed both in winter and in summer. Air temperature and humidity rate have been represented over a psychrometric chart while the energy performance of the system was based over data analyses on sensible heat exchange.
The monitored results have been compared with three other cases presented in literature in order to verify parameters' values of different EAHXs in various climates and design conditions.

Cover Letter

To Whom It May Concern,

The main reasons on which is based the application for publishing a paper on the results from a monitoring campaign regarding a earth-to-air horizontal heat exchange ($EHX_{air\text{-}hor}$) system applied to a School building located in Italy are highlighted as follows.

Data on ground cooling systems are mostly available from simulation and theoretical analyses in literature worldwide. Very few monitoring data can be found and only related to small plants and specific parameters such as EHX effectiveness and inlet-outlet air temperature. No experimental data on the effect of EHX systems on soil temperature variation in time are available.
Information and data presented in the proposed paper contribute to reduce this lack of data being characterized by the following unique features:

- dimension of the $EHX_{air\text{-}hor}$ system with about 2 km of buried pipes;
- two-year long series of data on soil temperature for both intermittent and continuous system operating mode;
- $EHX_{air\text{-}hor}$ operation in a real functioning complex building;
- integration of the $EHX_{air\text{-}hor}$ system with a high performing controlled mechanical ventilation plant;
- representation of data in psychometric plots as a mean to evaluate summer and winter system performance in comparison to potential comfort conditions.

Kind regards.

The paper's authors
Mario Grosso, Giacomo Chiesa, Marco Simonetti

***Highlights (for review)**

Information and data presented in the proposed paper are characterized by the following unique features:

- dimension of the $EHX_{air\text{-}hor}$ system with about 2 km of buried pipes;
- $EHX_{air\text{-}hor}$ operation in a real functioning complex building
- integration of the $EHX_{air\text{-}hor}$ system with a controlled mechanical ventilation plant
- use of psychometric plots in comparison to potential comfort conditions

See table 1 for design performance parameters and results from monitoring

A 3-field Earth-Heat-Exchange System for a School Building in Imola, Italy: monitoring results

Giacomo Chiesa[1] , Mario Grosso[2]*, Marco Simonetti[3]

[1,2]Department of Architecture and Design, Polytechnic of Turin, Viale Mattioli 39, 10125 Torino, Italy
[3]Energy Department, Polytechnic of Turin, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy
[1]PhD student, [2]Associate Professor, [3]senior research assistant
*corresponding author. Tel. +39 0110904376; e-mail address: mario.grosso@polito.it - [1]giacomo.chiesa@polito.it, [3]marco.simonetti@polito.it

Abstract

The present study aims at presenting the results of 12 months long monitoring campaign of an earth-to-air horizontal heat exchangers ($EHX_{air\text{-}hor}$) system in a school complex, Imola, Italy. With more than two kilometres of buried pipes, it represents the biggest Italian application of this technology. Considerable differences between inlet and outlet air temperature have been noticed both in winter and in summer. Air temperature and humidity rate have been represented over a psychrometric chart while the energy performance of the system was based over data analyses on sensible heat exchange.

The monitored results have been compared with three other cases presented in literature in order to verify parameters' values of different EAHXs in various climates and design conditions.

Keywords: earth-to-air horizontal heat exchangers; ground cooling; passive cooling; school building

1. Introduction

During the last decades, application of sustainable design solutions and technologies for indoor climate control (ICC) in architecture has been gradually spreading among building operators, following a breakthrough process - from the pioneer stage of the 70's of the last Century, through large demonstration projects at urban scale in the 90's, to integrated passive & hybrid ICC systems nowadays [1]. Parallel policies on sustainability have been implemented by EU, national and local government bodies including directives, laws, and regulations with the effect of rising 'green sensibility' among building users. However, this process has been focused mainly on energy conservation for space and water heating rather than for cooling and ventilation [2], for which, instead, a rising interest is evident in the recent years. This interest depends on two main aspects. Firstly, the expansion of air conditioning demand has significantly increased global electrical consumption and peak power demand in summer, requiring new power plants for electrical energy production [3 & 4] as well as increasing the cost of peak electricity. Secondly, global attention for reducing climate-change-inducing greenhouse gasses emissions is stimulating the diffusion of passive cooling solutions that are non fossil fuel dependent while assuring comfort conditions. As a matter of fact, among the various energy sources, electricity is characterised by the highest GHG emission factor in Countries – as Italy – with a prevalent oil-dependent energy mix. Moreover, oil reserve peak is approaching and costs for energy supply - both economical and environmental - will increase considerably [1]. All these factors will promote the application and diffusion of low energy technologies particularly for electricity end use as the ones related to HVAC systems.

2. **Horizontal earth-to-air heat exchangers.**

$EHX_{air\text{-}hor}$ systems are not everyday technologies and only in the last years several monitored cases have been presented in literature [5] [8] [9] [10]. Nevertheless, $EHX_{air\text{-}hor}$ systems are particularly interesting because of their low maintenance and operational costs [8].

Examples of $EHX_{air\text{-}hor}$ systems design methodologies could be found in [6] and [7]. The GAEA software represents a simple effective approach to dimension and evaluate the energy contribution of an $EHX_{air\text{-}hor}$ system [11], while TRNSYS [12], ENERGYPLUS [13] and other thermal dynamic models can be used for more accurate and detailed simulations [14] [15] [16]. A simplified parametric approach to be used as a preliminary design tool is described in [6, pp.431-436]. Critical aspects of $EHX_{air\text{-}hor}$ systems are: an increase of relative humidity of outlet air, with high water wapor condensation rate, in summer (as opposed to a decrease in winter); land occupancy; the thermal capacity and diffusivity of the soil. Analyses on thermal soil capacity and thermal saturation due to continuous use have been described in [6] although a monitoring of two $EHX_{air\text{-}hor}$ systems at the same boundary conditions would be necessary in order to obtain reliable results regarding soil long-term thermal discharging. In addition, there is a lack of data on the thermal behaviour of $EHX_{air\text{-}hor}$ systems in different seasons and climates, although long time monitoring results have been presented in [8] and [9]. Only a few analyses have been made about specific and relative air humidity rates in spite of the fact that water vapour is an important variable for comfort analysis. A thorough work on this topic is presented in [17].

3. **Imola's School Building Case Study**

The monitored EHXair-hor system is located in Imola (BO), Italy in the High School Building "L. Orsini" (completed in 2008), which is characterized by a gross floor area of 4800 m^2 and has 18 classrooms. Several sustainable energy-saving technologies were designed and installed, in addition to the $EHX_{air\text{-}hor}$ system. In particular vertical Solarwall® air-collectors is coupled with the $EHX_{air\text{-}hor}$ in winter.

3.1. Description of Imola's $EHX_{air\text{-}hor}$ system.

Imola's $EHX_{air\text{-}hor}$ system is composed of three fields each with a different number of 70-m-long horizontally buried pipes (12 – 12 – 8) made of rigid polyethylene for a total length of 2240 meters.

All the fields supply air to a dedicated AHU connected to other 3 AHUs placed in the basement, out of the six (two AHUs are placed on the roof and supplied by the Solarwall® air collectors) which form the mechanical controlled ventilation system.

In winter, the $EHX_{air\text{-}hor}$ fields work as an alternative system to the Solarwall® air collectors. This switching is based on a inlet air temperature control. In summer, the Solarwall® collectors are by-passed while the $EHX_{air\text{-}hor}$ system is activated on a fixed daytime schedule related to the operation of the night mass cooling system, which is also under monitoring.

Each $EHX_{air\text{-}hor}$ field comprises the following components: an uptake chamber; a collector duct for distributing air into tubes; twelve or eight parallel pipes comb-like connected to the collector ducts; a collector duct of outlet air; a condensation chamber; a terminal connection duct. Each terminal connection duct merges to an air mixing chamber. All chambers can be inspected. Ducts and pipes are made of rigid polyethylene with a special treatment in order to prevent moulds. Uptake, condensation and mixing chambers are made of reinforced concrete with a special surface treatment based on a nontoxic finishing for water containers. External elements of uptake chambers are made of low solar radiation absorption material, inlet openings are provided with a 100 mm grid device to avoid rain and rats infiltration. An anti-dust filter (class G4) is installed before the distributing collector duct. In every chamber a sump is present to collect infiltration or condensation water, while in the condensation chambers, catch basins bring collected water directly to the drainage system. (Figure 1)

Ducts and pipes are positioned on a sand layer with a 6,5 ‰ constant slope . Connections between pipes and collector ducts are blended in order to reduce friction losses. Every tube presents expansion joints. The average depth of tubes is 2,61 meters while the distance among pipes in the same field is 110 centimetres.

3.2. Performance of the $EHX_{air-hor}$ system

In the design phase, the annual energy performance of the $EHX_{air-hor}$ system was evaluated using the software GAEA. As the maximum number of parallel tubes in GAEA input is ten, separated analyses have been elaborated for each field. Moreover, for the 1st and the 2nd field the simulation results based on ten tubes were converted to the actual number of tubes (twelve) using a proportional approach. Soil properties used in the simulation are: type of soil - sand; density - 1780 kg/m^3; heat capacity - 1,39 kJ/(kg K); thermal conductivity - 0,93 W/(m K); ground water level - 6 m [6].

The system could treat 40'500 m^3/h, which is the demand for a full occupancy of the school building to comply with the ventilation requirement defined by a national law (minimum ACH of 2.5 Vol/h [18]).

The design characteristics of each field are the following:

1st field – 12 pipes of 70 m each; maximum total airflow rate of 15'200 m^3/h; maximum air velocity of 5 m/s; uptake chamber area of 1,4 m^2; distance from building of 6 m; total pipe pressure loss of 410 Pa.

2nd field – 12 ducts of 70 m each; maximum total airflow rate of 15'200 m^3/h; maximum air velocity of 5 m/s; uptake chamber area of 1,4 m^2; distance from building of 30m; total pipe pressure loss of 420 Pa.

3rd field – 8 ducts of 70 m each; maximum total airflow rate of 10'100 m^3/h; maximum air velocity of 5 m/s; uptake chamber area of 1,0 m^2; distance from building of 6m; total pipe pressure loss of 350 Pa.

In Table I, design performance parameters of the EHXair-hor system are shown with a comparison to results from monitoring when applicable.

4. **Monitoring: methodology and results**

Data on the $EHX_{air-hor}$ system are available since May 2010 and are here elaborated.

4.1. Characteristics of the monitoring system

The monitoring system of Imola's $EHX_{air-hor}$system is composed of 49 sensors that allow for measuring air and soil temperatures, air humidity rates and air velocities. Each field has two sensors outside the uptake chamber (air temperature and humidity rate) and three sensors in the terminal connection duct (air temperature, air humidity rate and air velocity). A more accurate monitoring system was installed along the first field. Seven pipes are provided by air velocity and air temperature sensors, localised near the exit of the pipes. Six sensors of temperature were installed along two pipes in order to record the air temperature trend along the duct length. Ten temperature sensors were buried in the ground at different levels of depth and distance form tubes (figure 2) in order to check soil temperature variation over time. Graph n°1 illustrates the output temperature values from the main sensors of the 1st field (inlet air, outlet air and ground temperatures of different soil sensors) during a period from May 2010 to September 2011. The farthest available sensor from pipe of soil temperature is used as a reference ground temperature.

4.2. Data collection and first processing.

Monitoring data are collected at various intervals depending on the variable considered: air velocity and humidity, every hour; air temperature, every 15 minutes (for that reason hourly data have been generated from the mean inlet and outlet operating time air temperatures). The hourly ground temperature has been averaged over values measured every 15 minutes. A similar approach is described in [8]. Average daily values have also been calculated using the same procedure. Volumetric airflow rate is calculated with reference to the air velocity hourly values proportionally to the effective operating time.

4.3. Data analyses

The monitored temperatures have been summarized on an inlet-outlet temperature diagram (graph 2) in order to elaborate the characteristic line according to [7]. As the $EHX_{air\text{-}hor}$ system is also operating during neutral period, several values are localized between the heating and cooling part of the graph (12 °C < T_{in} < 22°C [8]).

4.3.1. Effectiveness of the $EHX_{air\text{-}hor}$ system

The effectiveness of Imola's $EHX_{air\text{-}hor}$ system was checked using Scott, Parson and Koehler's expression [3, p. 216] and [8]:

$$\varepsilon = (T_{in} - T_{out}) / (T_{in} - T_{soil}) \qquad (1)$$

Equation (1) was also used to validate the collected data, neglecting outlet air temperature values lower or higher than the ground temperature, respectively, in summer and winter, due to the location of the soil temperature sensors which could be influenced by the building and/or the $EHX_{air\text{-}hor}$ system itself [8]. As only a few monitoring data are not-validated by equation (1), the ground temperature chosen as a reference can be considered acceptable although a position farther from the building and the buried pipes shall be taken for future monitoring. In addition, equation (1) could not be applied when the values of the three temperature variables within the equation converge, i.e., when the $EHX_{air\text{-}hor}$ system is thermally neutral and, therefore, could be bypassed.

Imola's $EHX_{air\text{-}hor}$ system effectiveness values were calculated for various reference months and time intervals as shown in graphs 3 and 4, where data of single variables such as inlet and outlet air temperature, soil temperature, and volume airflow are shown as well. Annual values have been elaborated in order to study both the relation between difference in temperature ($T_{out} – T_{in}$) in graph 5 and the distribution of the hourly frequencies in graph 6.

4.3.2. Water vapour content of air

Knowledge of the water vapour content of air is particularly important in $EHX_{air\text{-}hor}$ systems as Imola's one since the favourable variation of sensible heat generated by them has an increase in air humidity as a draw back, which seems to occur during the cooling period. Being not possible to measure directly the quantity of water vapour in a mass unit of dry air, i.e., the title (x), it has to be calculated.

The following expression was used to calculate the title (x) [19]:

$x=0,622*(p_v/(p-p_v))$ [kg/kg] (2)

where:

p is the total air pressure in the pipes [Pa]

p_v is the vapour pressure [Pa]

The total air pressure in a pipe (p),was calculated adding the atmospheric pressure (assumed as 101325 Pa) to the dynamic pressure p_{dyn}:

$p_{dyn} = ½ \rho v^2$ [pa] (3)

where:

$\rho=353.118/T[K]$ [kg/m^3] [6] (4)

v is the air velocity [m/s]

$p_v=\phi*p_{vs}$ [Pa]

$\log_e p_{vs} = ((A*t)/(B+t)) + C$ [-] (5)

where [20]:

A = 22,376 B=271,68 C=6,4146if -40°C < t < 0°C

A=17,438; B=239,78 and C=6,4147 ; if 0°C < t < +40°C

ϕ = relative humidity [%]

4.3.3. Psychrometric analysis

Both sensible and latent heat exchange need to be considered when evaluating the effect of hybrid ventilation systems as the $EHX_{air\text{-}hor}$ ones on indoor comfort, while only a few examples could be found in literature taking humidity into account [17]. It is useful for this purpose a representation of monitored and calculated data, as described above, on inlet and outlet air temperature and humidity – both relative and absolute, i.e., the title X – related to Imola's $EHX_{air\text{-}hor}$ system on psychrometric diagrams 1 and 2.

In the cooling mode, diagram 1 shows a remarkable decrease in air temperature with an increase in relative humidity (ϕ), while absolute humidity (x) decreases when dew point is reached in the tubes. In some measures, a growth registered in the absolute quantity of water vapour is probably due to previous local water condensation or possible water infiltration. Both phenomena have been already mentioned in literature [21]. In summer, Imola's $EHX_{air\text{-}hor}$ system outlet air might need a de-humidification treatment while air outlet temperature is satisfactorily low. In some case, a mixed use of external air and $EHX_{air\text{-}hor}$ outlet air could represent a good solution as occurs in Imola's $EHX_{air\text{-}hor}$ system, where the ground treated air is mixed with external air (maximum 20% of total air) taken from an uptake unit localized on the roof through a dedicated duct. In the neutral period, between cooling and heating modes, air temperature and humidity values are much less dispersed than in the heating and cooling ones. Imola's $EHX_{air\text{-}hor}$ system is conceived in order to be used in a flexible way: each AHU can work using external air directly when the buried pipes system is not suitable for comfort conditions. Moreover, controlled natural ventilation can be used in every moment when appropriate and a single room switch can stop mechanical ventilation. During the neutral period, it is important to make the operating schedule dependent on the external air temperature in order to use the most efficient energy solution.

4.3.4. Energy balance of Imola's $EHX_{air\text{-}hor}$

The energy balance of Imola's $EHX_{air\text{-}hor}$ was calculated using the sensible heat exchange.

The power balance of sensible heat was calculated using the following equation [ASHRAE, 1985]:

$$Q_{sens} = A_{tube}\, v_{air}\, \rho_{air}\, c_{air}\, (T_{out} - T_{in}),\ [W] \tag{6}$$

where:

A_{tube} = section area of the terminal connecting duct [m^2]

v_{air} = hourly averaged air velocity measured at the end of the collector duct of outlet air [m/s]

ρ_{air} = hourly averaged air density [kg/m^3], calculated as described in § 4.3.2

c_{air} = specific heat of air [1000 J/K]

T_{out} = absolute hourly averaged temperature of outlet air [K]

T_{in} = absolute hourly averaged temperature of inlet air [K]

A positive or negative value of Q_{enth} means that Imola's $EHX_{air\text{-}hor}$ adds heat on, or subtracts heat from, the incoming external air. Integrating Q_{enth} over a period yields the energy balance for that period.

This methodology was used in order to calculate the sensible energy balance of the other two Imola's $EHX_{air\text{-}hor}$ system fields. A summary of such results are presented in table I.

In graphs 7 and 8 is shown the daily sensible energy balance of Imola's $EHX_{air\text{-}hor}$ system first field divided by the tube length and the temperature difference between T_{in} and T_{soil} [kW/mK]. Such result has to follow the dynamic of the volumetric flow rate. Graph 7 illustrates a reduction in daily sensible energy balance/length and difference in temperature in relation to volumetric flow values probably due to a progressive rising of soil temperature.

4.3.5. COP of Imola's $EHX_{air\text{-}hor}$

In order to estimate the additional electric consumption of every field the pressure drops have been theoretically calculated, assuming pressure loss coefficients from literature.

According to these results it is possible to calculate the COP of the system using:

$$COP = Q_{cooling}/E_{el} \tag{7}$$

where

$Q_{cooling}$= summer cooling energy from EHX

E_{el}= added electric energy demand for EHX

COP according to air velocity follows an almost linear trend. This fact suggests that the system, in standard conditions, presents an utilisation factor lower than 100%. As it is suggested in graph 9, most part of the cooling effect happens in the first third of pipes and for this reason an increasing in air velocity doesn't affect significantly the outlet temperature.

Graph 10 shows the monthly averaged temperatures along the third tube of the first field; differences between the slopes of lines are related to the cooling power of the system.

.

4.4 Comparison with other monitoring results presented in literature

The Imola's $EHX_{air\text{-}hor}$ monitoring results are compared to the ones from other systems found in literature [8] as shown in table 2.

In particular, the ratio of temperatures (R_t):

$$R_t = (T_{out,max} - T_{out,min}) / (T_{in,max} - T_{in,min}) \tag{8}$$

has been calculated according to [8].

Averaged annual COP values have been calculated as follows:

$$COP = (Q_{heating} + Q_{cooling}) / E_{el} \quad (9)$$

As shown in Table 3, EAHX systems could be considered effective systems for pre-heating and cooling indoor air. This type of systems performs remarkabley high regardless of climate conditions, but COP is strictly dependent on pressure losses and airflow rate. Hence, systems' performance is dependent dependent on design characteristics.

The comparison shows a good agreement with other monitored data [8], thus supporting the quality of Imola's systems.

5. **Conclusions**

This paper shows the results of 12 months long monitoring of an earth-to-air exchangers systems made of three fields of horizontal pipes located in central Italy (Imola's $EHX_{air-hor}$ system). Data analyses on both enthalpy and sensible heat exchange were carried out in order to evaluate the energy performance of the system as well as its effect on indoor comfort. Results show that Imola's $EHX_{air-hor}$ system is very effective over outlet temperature both as pre-heating and cooling ventilation mode although treatment of humid air is needed during summer. During thermally neutral periods an extension of non-operating hours for Imola's $EHX_{air-hor}$ system might be considered in order to reduce the use of electrical energy for fans. Adaptive and flexible strategies are essential for an effective use of passive/hybrid ECS technologies in building [22]. In addition, more testing need to be considered in order to calibrate fans power and treated quantities of air. A considerable difference in air velocity values has been noticed between measurements and design calculations; for that reason a targeted investigation has to be carried out in the future.

A considerable difference in the output values from the 2nd and the 3rd field has been monitored, which is probably due to site's characteristics and number of ducts.

The comparison with other cases [8] shows that the EAHXs' performances are effective in different climate and design conditions.

Bibliography

[1] Matteoli, L, Pagani, R (eds). 2010. CityFutures: Architecture Design Technology for the Future of the Cities, Hoepli, Milano.

[2] Grosso, M.. 2006. ‘La Certificazione Energetica degli Edifici sul Fabbisogno di Raffrescamento’, *Il Progetto Sostenibile*, vol 4, no. 10-11, pp. 38-45, Edicom Edizioni, Monfalcone (GO).

[3] Givoni, B.. 1994. *Passive and Low Energy Cooling of Buildings*, Van Nostrand Reinhold, New York.

[4] Santamouris, M.. 2007. ‘Preface: Why Passive Cooling?’, in Santamouris, M (ed.), *Advances in Passive Cooling*, pp.xix-xxxii, Earthscan, London.

[5] Grosso, M., Raimondo, L.. 2008. “Horizontal air-to-earth heat exchangers in Northern Italy: testing, design, and monitoring”, *International Journal of Ventilation*, pp. 1-10, Volume 7, Number 1, June 2008, Veetech Ltd.

[6] Grosso, M., 2011. Il Raffrescamento Passivo degli Edifici in Zone a Clima Temperato, 3rd edn, Maggioli, Rimini.

[7] Pfafferott, J., Walker-Hertkorn, S., and Sanner, B.. 2007. ‘Ground Cooling: Recent Progress’, in Santamouris, M (ed.), *Advances in Passive Cooling.*, pp.190-227, Earthscan, London.

[8] Pfafferott, J., 2003. ‘Evaluation of Earth-to-Air Heat Exchangers with a Standardized Method to Calculate Energy Efficiency’, *Energy and Buildinds*, vol 35, pp. 971-983, Elsevier, London.

[9] Hollmuller, P., Lachal, B.. 2005. ‘Buried Pipe Systems with Sensible and Latent Heat Exchange: Validation of Numerical Simulation Against Analytical Solutions and Long-Term Monitoring’, *Proceeding of the 9th Conference of International Building Performance Simulation Association*, pp. 411-418, Ecole Polytechnique de Montréal, Montréal.

[10] Musskopf, D., Sattler, M.. 2006. ‘Natural Ventilation through Buried Pipes in a Small School in Viamão (Brazil)’, *Proceeding of the 23rd Conference on Passive and Low Energy Architecture*, PLEA, Geneva, Switzerland.

[11] Benkert, S., Heidt, F.D., and Schöler, D.. 2011. *Calculation Tool for Earth Heat Exchangers GAEA*, Department of Physics, University of Siegen, Germany.

[12] TRNSYS, *Transient System Simulation Program*, Solar Energy Laboratory, University of Wisconsin-Madison, WI, USA.

[13] EnergyPlus 4.0. 2009. Building Energy Simulation Program. US Department of Energy, USA,.

[14] Lee, K.H., Strand, R.K.. 2006. ‘Implementation of an Earth Tube System into Energy Plus Program’, *Proceedings of SimBuild 2006*, August 2-4, MIT, Cambridge, MA, USA.

[15] Darkwa, J., Kokogiannakis, G., Magadzire, C.L., and Yuan, K.. 2011. ‘Theoretical and Practical Evaluation of an Earth-Tube (E-Tube) Ventilation System’, *Energy and Buildings*, vol 43, pp. 728-736, Elsevier, London.

[16] Trombe, A., Serres, L.,.1994. ‘Air-Earth Exchanger Study in Real Site Experimentation and Simulation’, *Energy and Buildings*, vol 21, pp. 155-162, Elsevier, London.

[17] Kopecký, P.. 2008. ‘Hygro-Thermal Performance of Earth-to-Air Heat Exchangers: Numerical Model, Analytical and Experimental Validation, Measurements in-situ, Design’, PhD Thesis, Ćeské Vysoké Učení Technické v Praze, Praha.

[18] Grosso, M., Voerzio, M. 2008. ‘Il Raffrescamento Passivo degli Edifici Scolastici’, *Il Progetto Sostenibile*, vol 6, n° 17-18, pp. 52-61, Edicom Edizioni, Monfalcone (GO).

[19] Çengel, Y.A.. 1997. *Introduction To Thermodynamics and Heat Transfer*, McGraw-Hill, New York.

[20] CETIAT. 1976. *Tables de l’Air Humide*, CETIAT, Villeurbanne.

[21] Hollmuller, P., Lachal, B.. 2001. ‘Cooling and Preheating with Buried Pipe Systems: Monitoring, Simulation and Economic Aspects’, *Energy and Buildings*, vol 33, pp. 509-518, Elsevier, London.

[22] Nicol, F., Roaf, S.. 2007. ‘Progress on Passive Cooling: Adaptive Thermal Comfort and Passive Architecture’, in Santamouris, M (ed.), *Advances in Passive Cooling.*, pp.1-29, Earthscan, London.

Table 1

1st field	Design – GAEA (1 year)	Measured (may 2010-april 2011)
Averaged air flow rate	15’200 m^3/h	4948 m^3/h
Averaged air velocity (ON)	5 m/s	2.4 m/s
Annual gain (heating)	55042 kWh	78318 kWh
Annual gain (cooling)	8826 kWh	26268kWh
Averaged air velocity (ON cooling)		2.6 m/s
Add. electrical absorption (calc.)		1330 kWh (cooling)
COP (cooling)		19.7
Average specific cooling power		8.6 W/m
2nd field		
Averaged air flow rate	15’200 m^3/h	1265 m^3/h
Averaged air velocity (ON)	5 m/s	0.6 m/s
Annual gain (heating)	54432 kWh	10994 kWh
Annual gain (cooling)	8965 kWh	12677 kWh
Averaged air velocity (ON cooling)		1.2 m/s
Add. electrical absorption (calc.)		220 kWh (cooling)
COP (cooling)		57.6
Average specific cooling power		4.2 W/m
3rd field		
Averaged air flow rate	10’100 m^3/h	3784 m^3/h
Averaged air velocity (ON)	5 m/s	1.8 m/s
Annual gain (heating)	35442 kWh	34427 kWh
Annual gain (cooling)	6556 kWh	28646 KWh
Averaged air velocity (ON cooling)		3.3 m/s
Add. electrical absorption (calc.)		7135 kWh (cooling)
COP (cooling)		4
Average specific cooling power		14.2 W/m

Table 1: $EHX_{air\text{-}hor}$ system

	IMOLA 1st field	IMOLA 2nd field	IMOLA 3rd field	DB Netz DG [8]	Fraunhofer ISE [8]	Lamparter [8]
Rt [K/K]	0.33	0.33	0.38	0.28	0.47	0.36
ε [-]	0.76	0.77	0.69	0.94	0.77	0.80
COP[kWh/kWh]	38	103	43	88	29	380
n° ducts	12	12	8	26	7	2
Lenght of ducts [m]	70	70	70	67-107	95	90
Diameter [m]	0.25	0.25	0.25	0.2-0.3	0.25	0.35
Depth [m]	2.6	2.6	2.6	2-4	2	2.3
Mean air flow [m3/h]	4948	1265	3784	10300	7000	1100
Air speed [m/s]	2.4	0.6	1.8	2.2	5.6	1.6
Pressure loss at mean air flow [Pa]	257 (calculated)	22 (calculated)	141 (calculated)	40 (measured)	166 (measured)	12 (calculated)

Table 2: comparison between data of Imola's monitoring and three other monitorings reported in [8].

Nomenclature			
ε	effectiveness, [-]	R^*	perfect gas constant
T_{in}	temperature of air entering the connecting duct [°C]	p_a	dry air pressure [Pa]
T_{out}	temperature of outlet air [°C]	φ	humidity rate [%]
T_{soil}	soil temperature [°C] – not influenced by the $EHX_{air-hor}$	p_{vs}	vapour saturated pressure [Pa]
X	Water vapour in mass unit of dry air [kg/kg] - title	h	specific enthalpy [kJ/kg]
p_v	vapour pressure [Pa]	A_{tube}	section area of the terminal connection duct [m^2]
p	total pressure in the pipes [Pa]	h_{out}	specific hourly enthalpy of air getting out from the connecting duct [kJ/kg]
p_{dyn}	dynamic pressure [Pa]	h_{in}	specific hourly enthalpy of air getting entering the connecting duct [kJ/kg]
ρ_{air}	air density [kg/m^3]	Q_{sens}	power balance of sensible heat [kW]
v_{air}	hourly air velocity [m/s]	c_{air}	specific heat of air [1000 J/K]
M_a	dry air mass flow rate [kg/s]	COP	Coefficient of performance
R_t	Ratio of temperatures [K/K]	E_{el}	Added electric energy demand [kW]

Table 3: nomenclature

Figure

Figure 1. General plan of the $EHX_{air-hor}$ system

Figure 2. $EHX_{air-hor}$ system: 1^{st} field – Localization of the soil temperature sensors.

Graph 1. Imola's $EHX_{air-hor}$ system: 1^{st} field – monitoring data for inlet and outlet air temperature, and soil temperature (hourly averaged) during the period: 1^{st} may 2010 – 30^{th} April 2011

Graph 2. Imola's $EHX_{air-hor}$ system: temperature diagram and regression line of the three fields. (1^{st} May 2010 – 30^{th} April 2011)

Graph 3. Imola's $EHX_{air-hor}$ system 1^{st} field - monitored data on 15' time intervals: effectiveness, inlet and outlet air and soil temperature (July 2010)

Graph 4. Imola's $EHX_{air-hor}$ system 1^{st} field. monitored data on hourly intervals: effectiveness, inlet and outlet air and soil temperature (January 2011)

Graph 5. Imola's $EHX_{air-hor}$ system 1^{st} field – temperature-effectiveness (1^{st} May 2010 – 30^{th} April 2011)

Graph 6. Imola's $EHX_{air-hor}$ system 1^{st} field – effectiveness – hourly frequencies (1^{st} May 2010 – 30^{th} April 2011)

Diagram 1: psychrometric diagram from May 2010 to September 2010 - 1^{st} field. The graph clearly illustrates the effect of $EHX_{air-hor}$ systems in compressing temperature values. It also reports the difference in the specific enthalpy values for the cooling period.

Diagram 2: psychrometric diagram from the 15th of October 2010 to the 15th of April 2011 - 1st field. The graph clearly illustrates the effect of $EHX_{air\text{-}hor}$ systems in compressing temperature values. It also reports the difference in the specific enthalpy values for the heating period.

Graph 7. Imola's $EHX_{air\text{-}hor}$ system 1st field – Daily-averaged sensible power balance for tube length and difference in temperature (T_{in}-T_{soil}) [kW/mK]. (July 2010)

Graph 8. Imola's $EHX_{air\text{-}hor}$ system 1st field – Daily-averaged sensible power balance for tube length and difference in temperature (T_{in}-T_{soil}) [kW/mK]. (January 2011)

Graph 9. Averaged temperature profile along a single tube (1st field, 3rd pipe). The 70% of the air to earth exchange occurs in the first third of the tube suggesting that the system length is not completely used.

Graph 10. Temperature profile along a single tube (1st field, 3rd pipe). The graph illustrates the thermal charge of soil caused by the $EHX_{air\text{-}hor}$ system.

Figure 1
Click here to download high resolution image

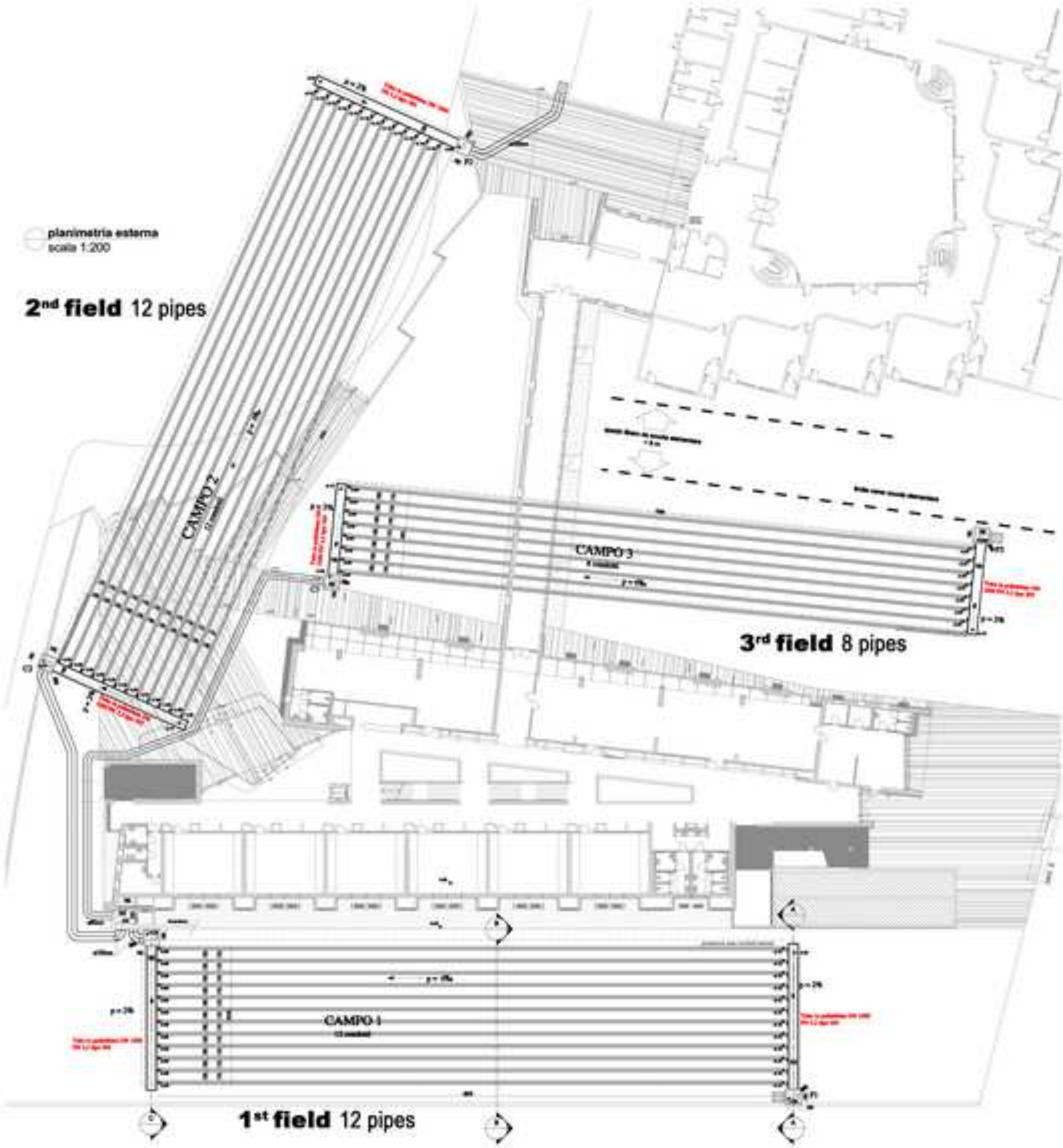
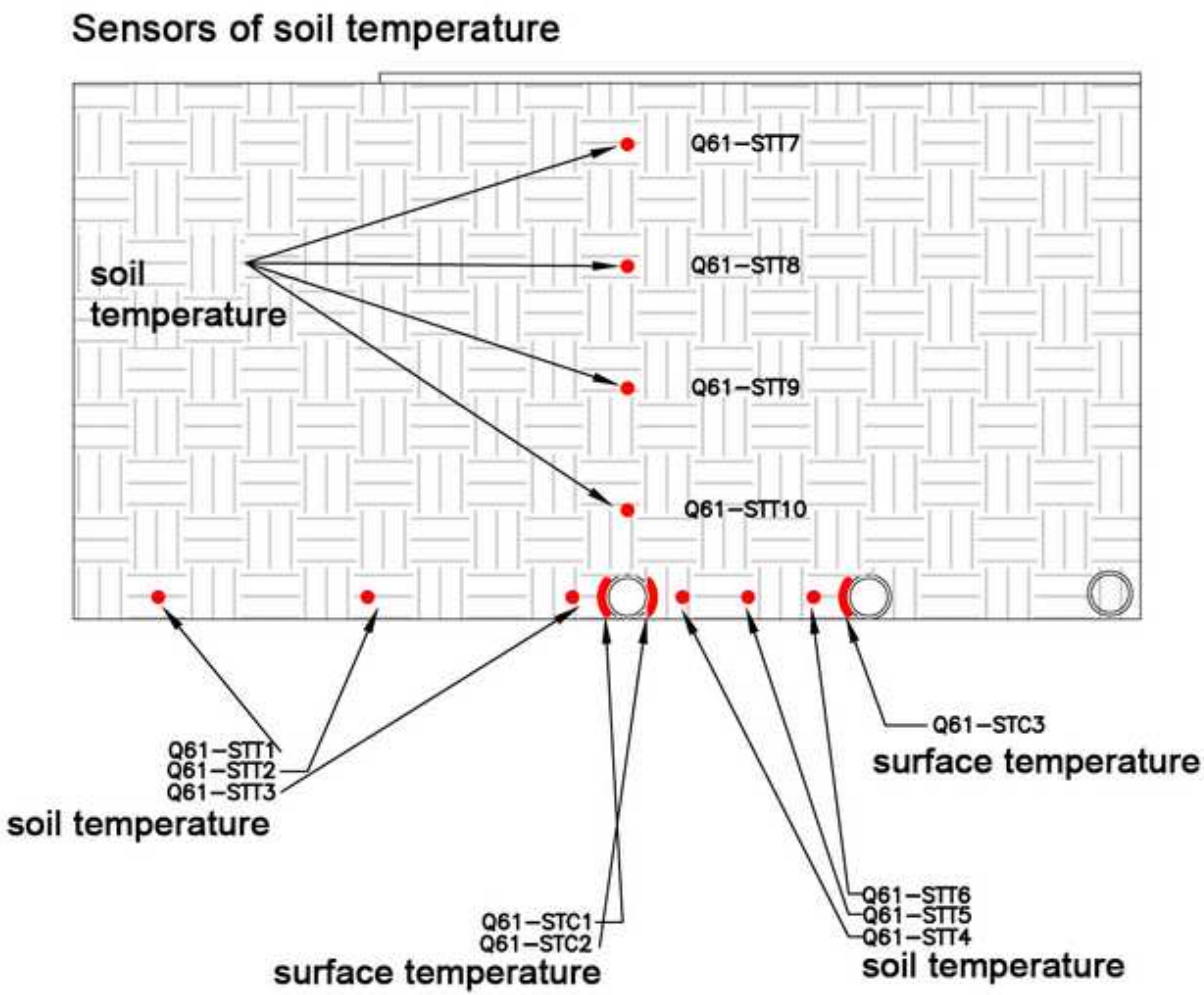
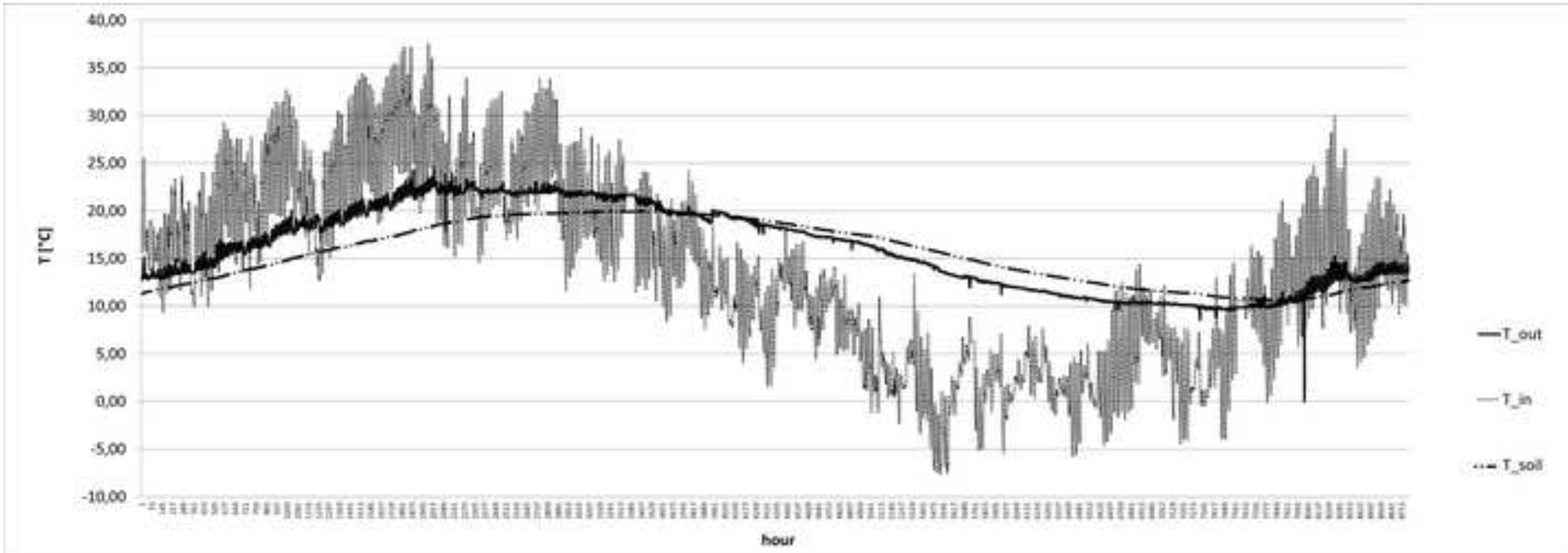


Figure 2
Click here to download high resolution image

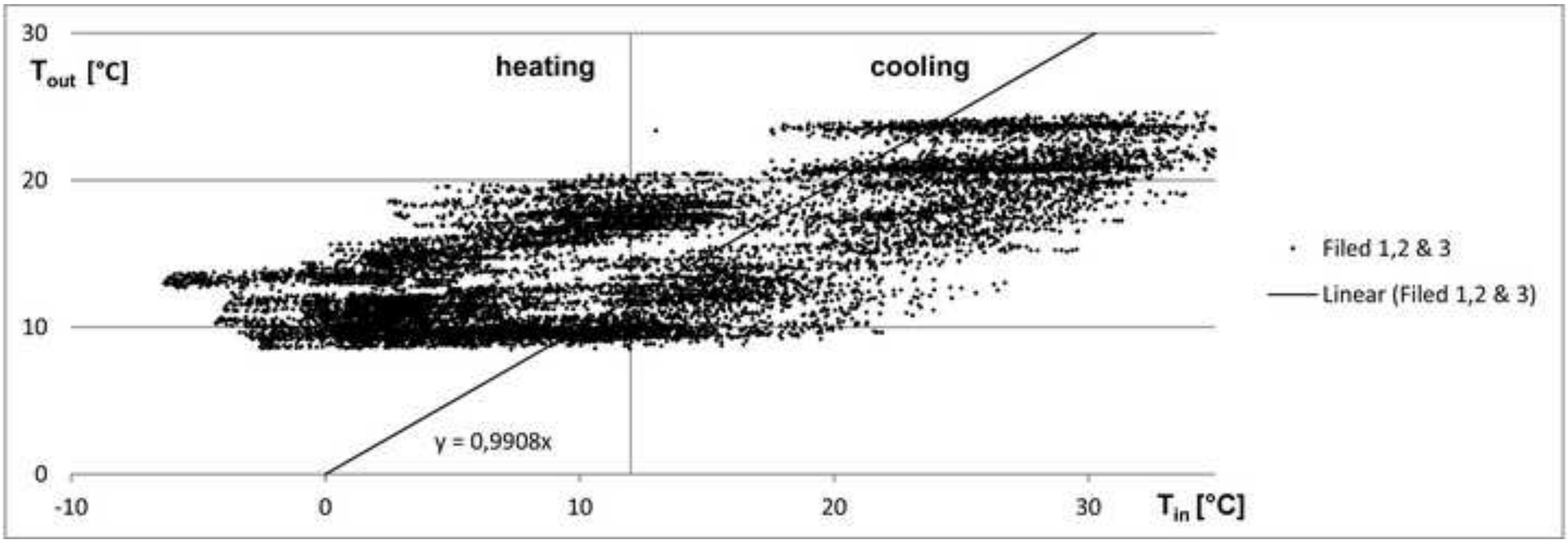


graph 1
Click here to download high resolution image



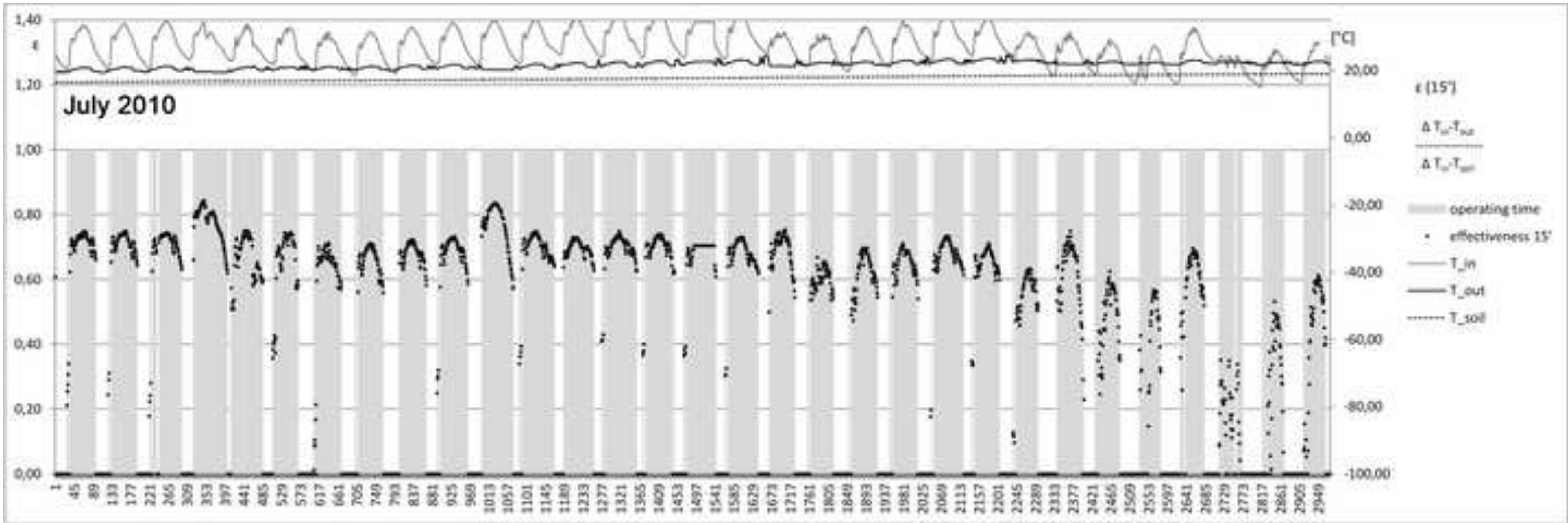
graph 2

Click here to download high resolution image



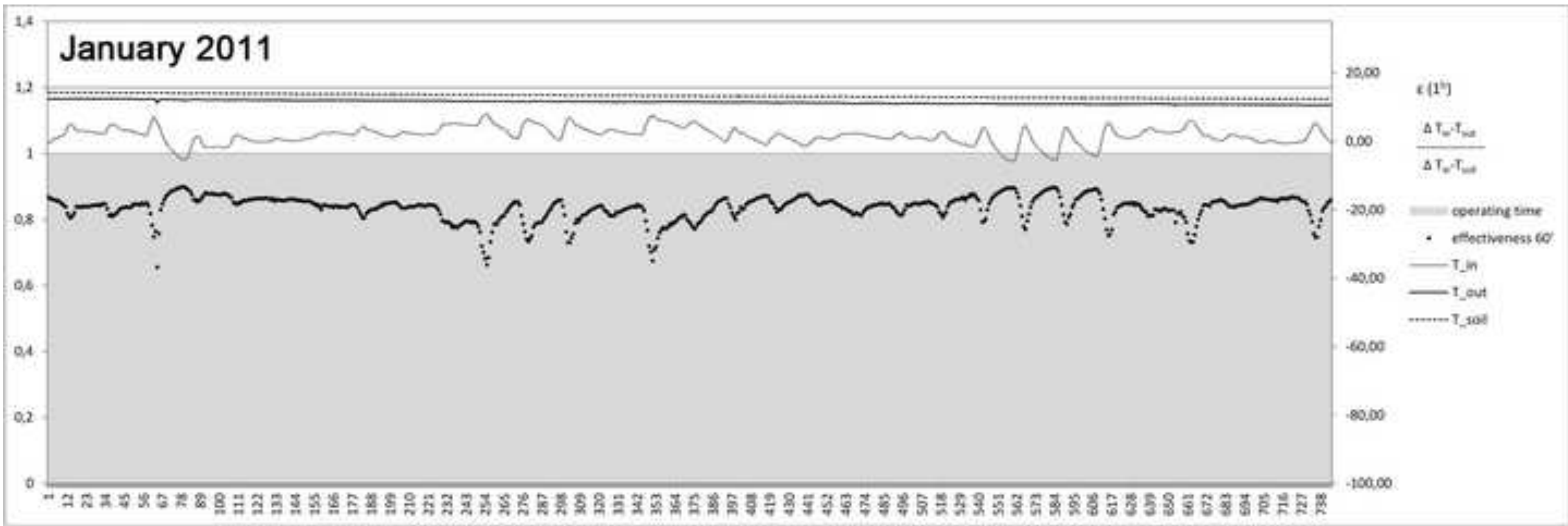
graph 3

Click here to download high resolution image

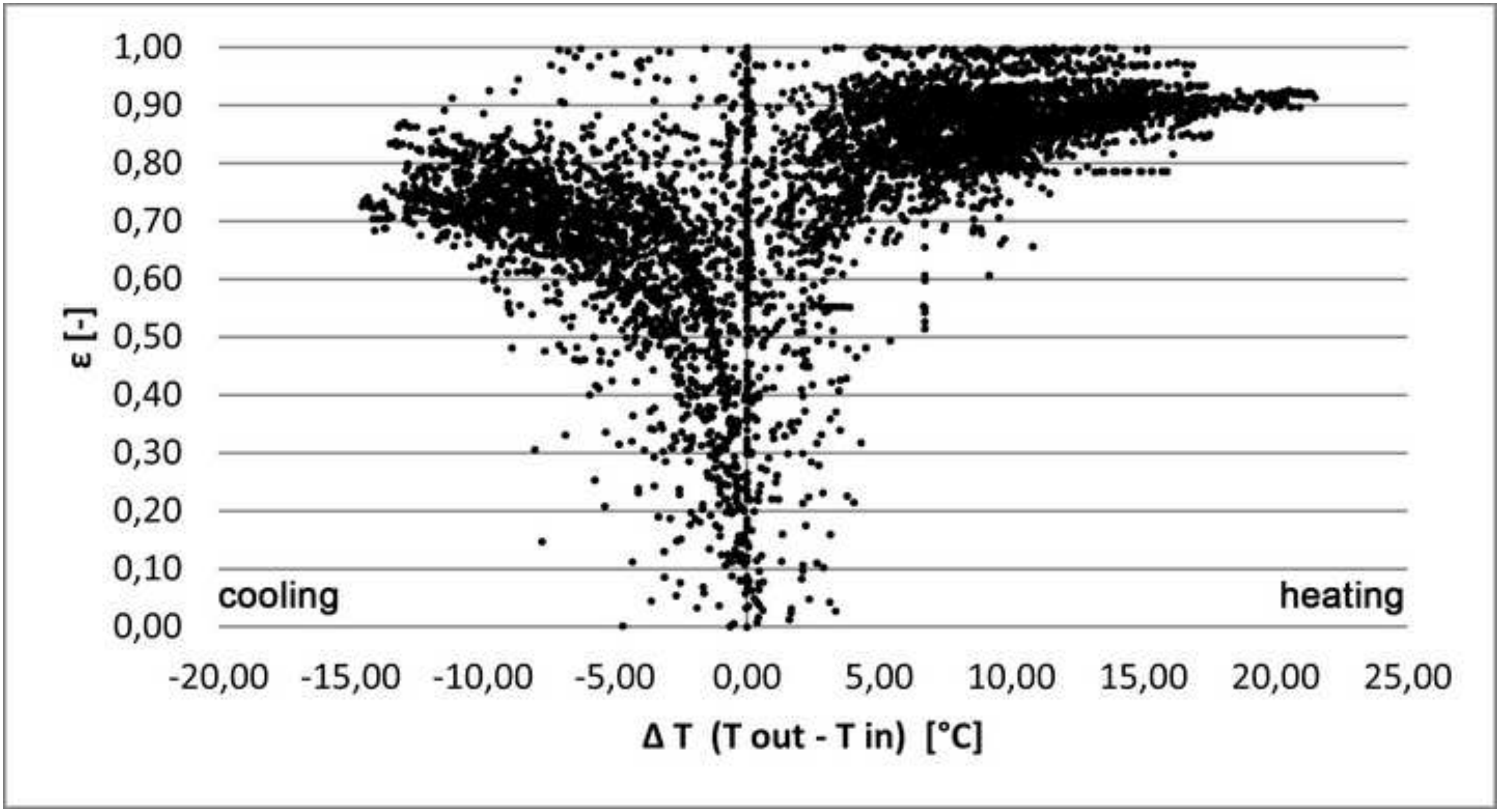


graph 4

Click here to download high resolution image



graph 5
Click here to download high resolution image



graph 6
Click here to download high resolution image

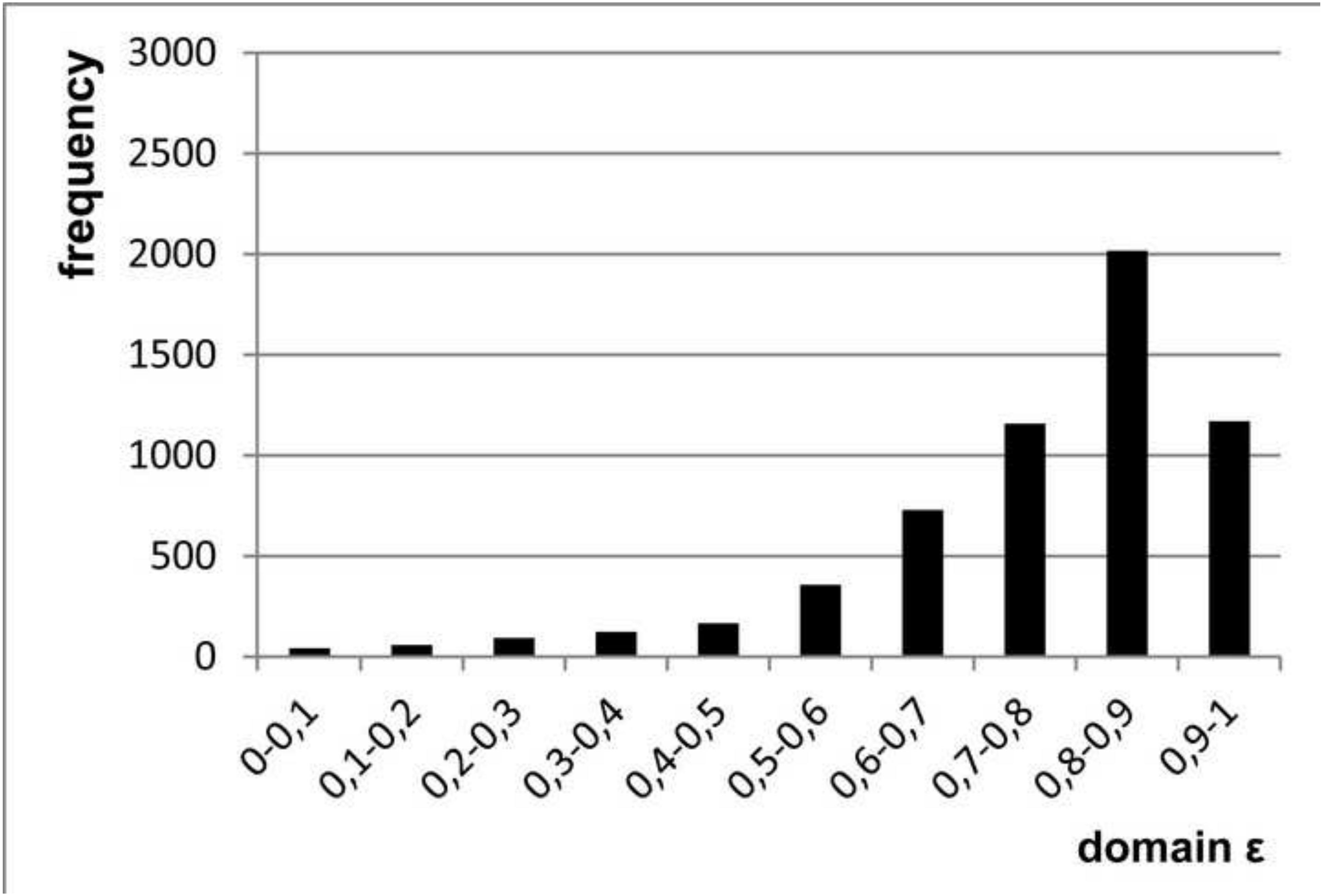


diagram 1

Click here to download high resolution image

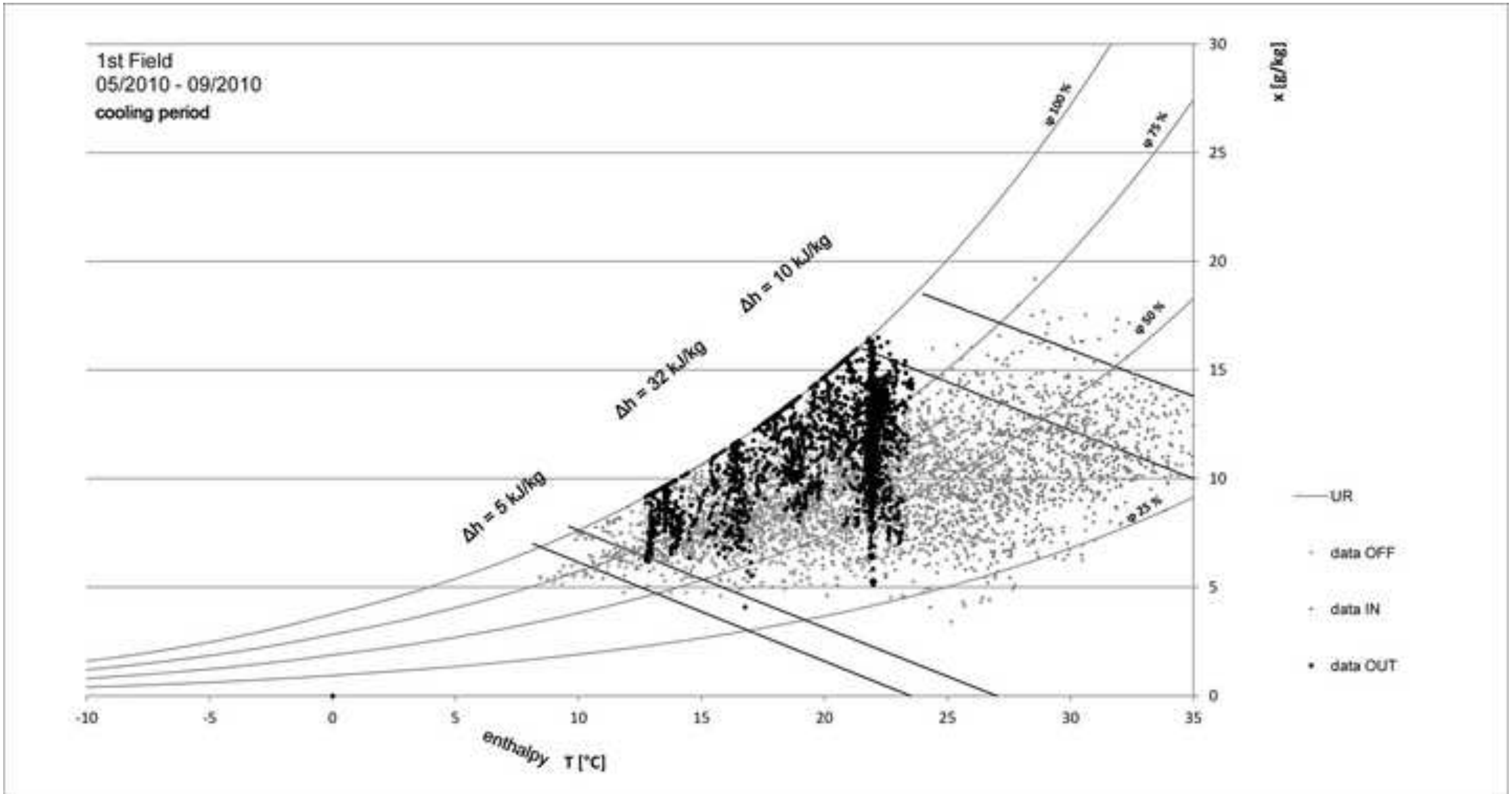
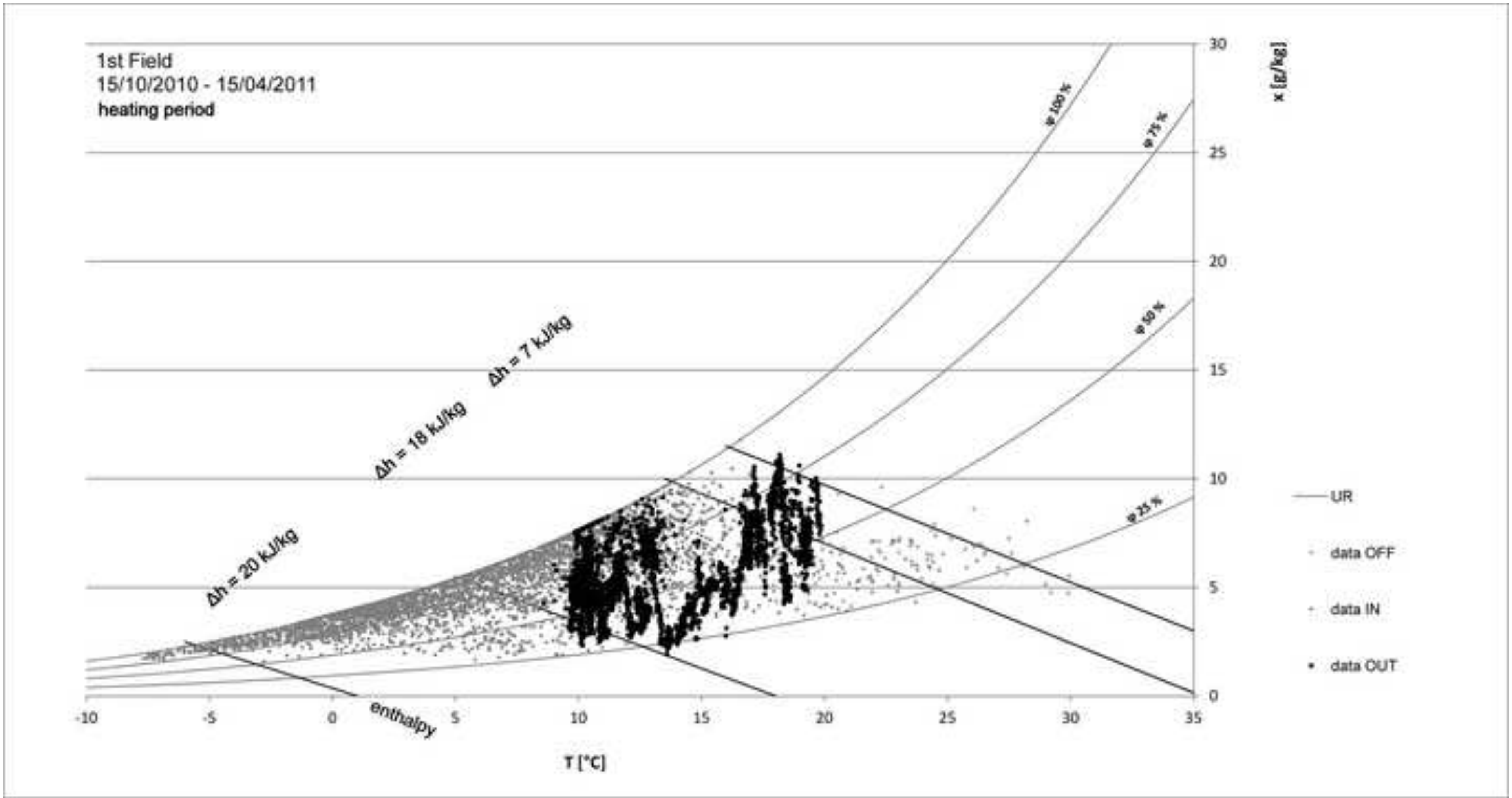
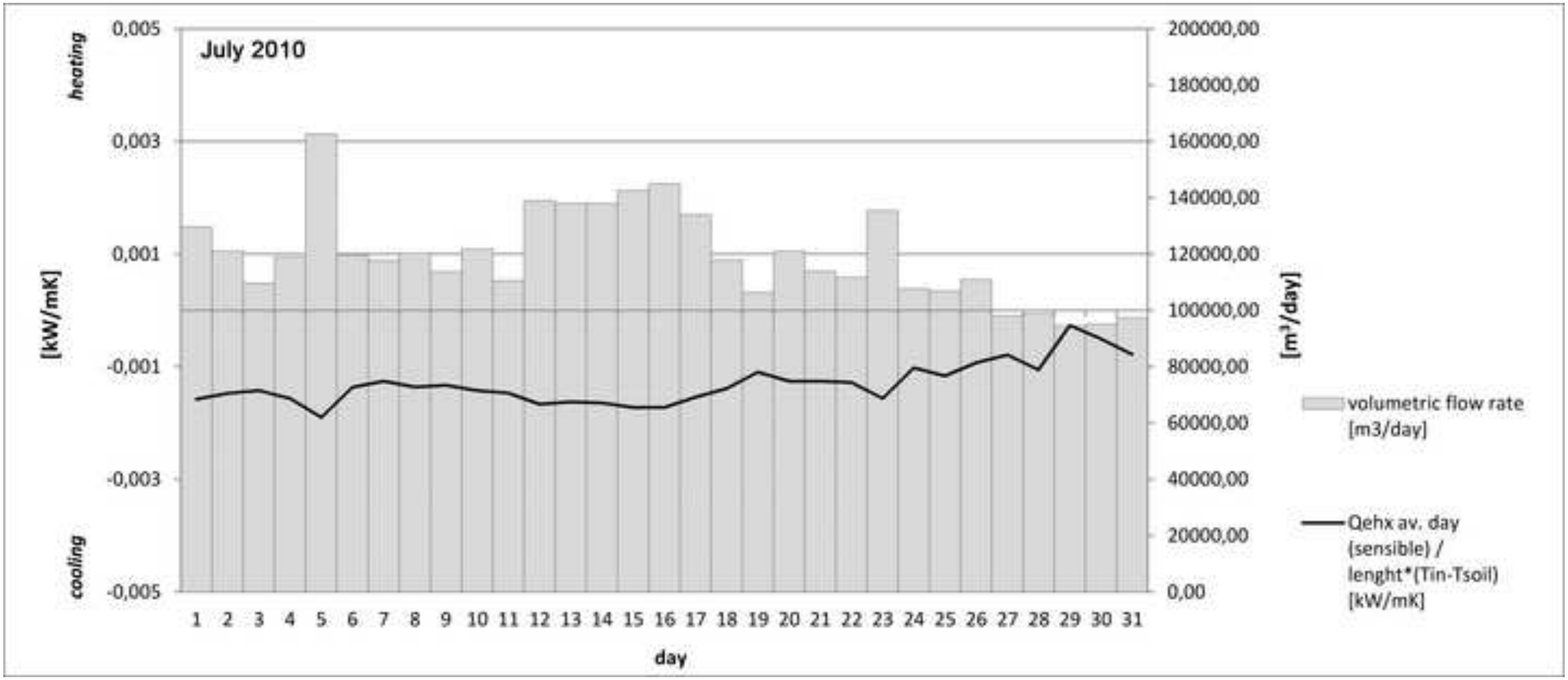


diagram 2

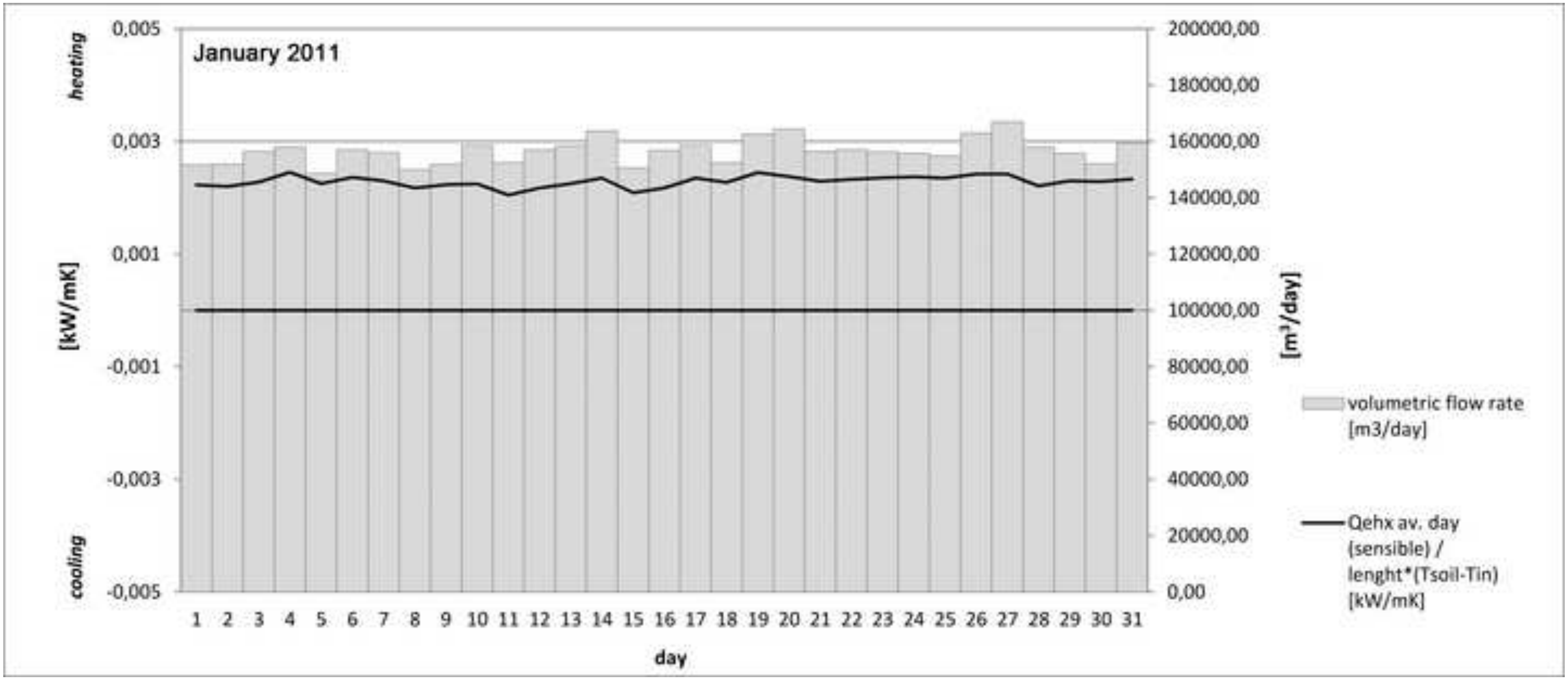
Click here to download high resolution image



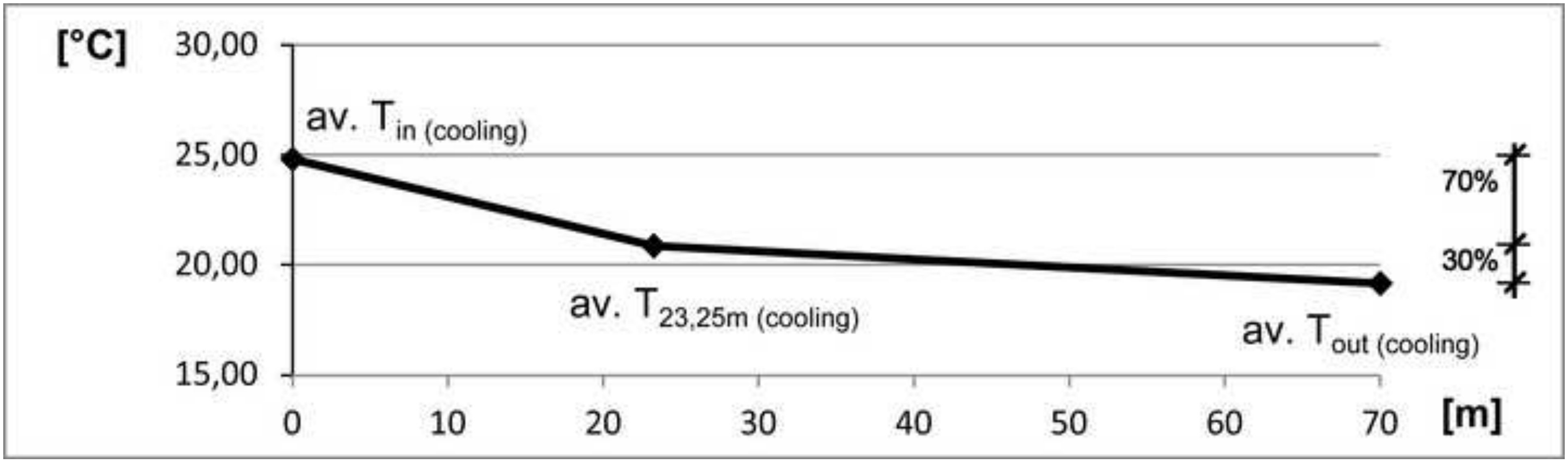
graph 7
Click here to download high resolution image



graph 8
Click here to download high resolution image



graph 9
Click here to download high resolution image



graph 10

Click here to download high resolution image