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Title: EXPERIMENTAL AND MODELING ANALYSIS OF A GROUND SOURCE HEAT PUMP SYSTEM

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Corresponding Author: Dr carla montagud, Ph.D

Corresponding Author's Institution:

First Author: Carla Montagud, PHD

Order of Authors: Carla Montagud, PHD; Jose Miguel Corberán, Professor; Félix Ruiz-Calvo, Dip, Ing.

Abstract: This paper presents the evaluation of the performance of a ground source heat pump system monitored plant providing heating/cooling to an office building located in the Universitat Politècnica de València in Spain. The system was designed using GLHEPRO software and it has been monitored since 2005. Once a ground source heat pump has been designed, it is important to analyze its performance along the years after its construction and check whether the design was appropriate and the simulation predictions were consistent with real experimental measurements. This paper first presents the impact of the GSHP system in the ground thermal response. The simulations obtained in GLHEPRO software will be analyzed and compared to experimental measurements. The second purpose of this work is to compare the performance simulation results of a complete ground source heat pump system model built in TRNSYS, with the experimental measurements which have been registered and collected for one cooling day. Numerical predictions and experimental results are compared and discussed.

ELSEVIER
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Valencia, July 30th 2012

Subject: Article Submission.

To whom it may concern,

Considering two crucial elements, efficiency and sustainability, the Institute for Energy Engineering (IIE) has clearly established itself as an outstanding reference in the field of energy efficiency, modeling and optimization. The Institute's scientific production is represented not only by different activities carried out by the research groups working at the IIE, but also by the results attained from numerous R&D projects, being of special interest the articles published in high impact scientific journals and the presentations delivered in most relevant international forums.

Following this dissemination policy, and as member of the Thermal Engineering Area within the IIE, I accompanied to this letter the research manuscript, including some of the results of the ground source heat pump systems line of research.

This paper presents the evaluation of the performance of a ground source heat pump system, providing heating/cooling to an office building. The impact of the GSHP system in the ground thermal response is analyzed and compared to GLHEPRO software simulation results. It has been observed from experimental measurements that the ground has a stronger recovery capability than expected when compared to GLHEPRO results, which allows the water temperature coming from BHE present a periodic evolution along the years, being the mean water return temperature of the BHE equal to 20ºC for every year of operation and confirming well designed and balanced GSHP systems as a good alternative. In parallel, a complete model of the system was built in TRNSYS and experimentally validated, so that it is able to reproduce the behavior of the real installation taking every influence into account and makes it possible to develop control strategies to optimize the system energy performance.

Finally, I take this chance to show my gratitude for you taking the time to review the manuscript. Hoping it will be successfully accepted and published, I remain at your disposal to provide any further documentation required to clarify any issue aroused.

Sincerely yours,

Carla Montagud Montalvá, Ph.D.
Instituto de Ingeniería Energética
(Institute for Energy Engineering)

UNIVERSIDAD POLITÉCNICA DE VALENCIA
Camino de Vera s/n, Edificio 8E, bloque F, 5ª, 46022 Valencia, Spain
Phone: 34 963879910. Fax: 34 963877272
E-Mail: carmonmo@iie.upv.es

RESPONSE TO REVIEWERS

RESPONSE TO REVIEWER #1:

Thank you very much for your corrections. They have been addressed in the revised manuscript as requested. Please find below our **answers in bold** next to your comments.

The paper offers detailed insight in monitoring and modeling a ground source heat pump system providing heating and cooling to an office building in Spain. The system and its monitoring are precisely described. The modeling procedure is explained and verificated. Although the content of the paper is not very innovative, there are plenty of interesting details merged in one paper and the topic is of particular interest for the research community.

Due to the precise and extensive description, the paper is quite long but seems to be appropriate in length. The article is clearly laid out. Figures and tables describe the data accurately and are of good quality. The overall level of the English is good.

Nevertheless, some (minor) revision could be incorporated before the paper is accepted:

(i) Introduction, page 3, line 75: Yes, there really are few references on the validation of experimental models of reversible ground source heat pumps or BHE used as heat sink and heat source, but please name these references. You might want to refer to:

a. J. Nußbicker-Lux, W. Heidemann, H. Müller-Steinhagen: VALIDATION OF A COMPUTER MODEL FOR SOLAR COUPLED DISTRICT HEATING SYSTEMS WITH BOREHOLE THERMAL ENERGY STORE, EFFSTOCK 2009, Stockholm, Sweden, June 14-17 2009
b. D. Bauer, W. Heidemann, H. Drück: Validation of a groundwater flow and transport modeling tool for borehole thermal energy stores based on FEFLOW, INNOSTOCK 2012, Lleida, Spain, May 16th- 19th

Done.

(ii) Section 3.3, page 10, line 274ff: This BHE model (DST) was developed for large BHE fields. When simulating only a few BHE, the Superposition Borehole Model (SBM) for TRNSYS gives better results. Both models cannot simulate the transient behavior of BHE in a timescale shorter than a few hours because they assume a steady state condition of all heat transfer processes inside the borehole. The TRNSYS model EWS (vertical borehole heat exchanger) accounts for transient processes inside the borehole and might be the better model for these simulations.
Thank you very much for your suggestion and comments. At this moment, we don't either have the SBM model for TRNSYS or the EWS model. But we will try to get them and use them for future research studies.

(iii) Section 3.4, page 11, line 300ff: I would suggest to add a nomenclature to the paper. The legend of Figure 7 is difficult to understand. **Done. It has been added after the Introduction section.**

RESPONSE TO REVIEWER #2:

Thank you very much for your corrections. Please find below our **answers in bold** next to your comments.

Reviewer #2:
I like the basic idea of this article. Ground source heat pump installations are a good alternative for heating and cooling systems at present and will be key in the future. But it is of most importance that the installations are well designed and have a high seasonal performance factor. Monitored installations allow to analyze their impact in the ground thermal response, and make it possible to compare experimental measurements with simulation software predictions. This paper satisfactorily presents the comparison between GLHEPRO software predictions and the experimental measurements for a long period of time, which in my opinion is very useful and informative, as it allows the experimental validation of the original design of the installation. On the other hand, I find it very interesting to have a complete TRNSYS model also validated with experimental data, which makes it possible to develop control strategies and analyze the influence of different parameters in the energy performance of the system and compare it with experimental results. The methodology and the results satisfactorily support the conclusions.

The nomenclature is missing and it should be added at the beginning of the paper after Introduction. This would make the paper more comprehensive**. Done.**

Suggested referees:

Álvaro Montero, Ph.D
Universidad Politécnica de Valencia
Dept. of Applied Physics
Camino de Vera, s/n, ed. 8E, escalera F, 2ª planta
46022 VALENCIA (Spain)
e-mail: almonter@upvnet.upv.es

Julio Martos, M.Sc.
Escola Tècnica Superior d'Enginyeria
Dpt. Enginyeria Electrònica
UNIVERSITAT DE VALÈNCIA
Avinguda de la Universitat s/n
46100 Burjassot - VALENCIA (Spain)
e-mail: julio.martos@uv.es

Ivan Valencia-Salazar, M.Sc.
Instituto Tecnológico de Veracruz
Dept. of Electrical Engineering
Miguel Ángel de Quevedo, 2779
91860 VERACRUZ (Mexico)
e-mail: ivvasa@itver.edu.mx

Pedro D. Sanz Martínez, PhD.
Instituto del Frío-ICTAN (CSIC)
C/ José Antonio Nováis, 10.
28040 Madrid,(Spain)
e-mail: psanz@if.csic.es

David Alfonso-Solar, M.Sc.
Universidad Politécnica de Valencia
Dept. of Electrical Engineering
Camino de Vera, s/n, ed. 8E, escalera F, 2ª planta
46022 VALENCIA (Spain)
e-mail: daalso@die.upv.es

Manuel Alcázar-Ortega, Ph.D.
Instituto de Ingeniería Energética
Universidad Politécnica de Valencia
Camino de Vera s/n, Edificio 8E, bloque F, 5ªplanta
46022 Valencia, (Spain)
e-mail: malcazar@iie.upv.es

***Highlights (for review)**

Analysis of an existing GSHP installation > Ground thermal response analysis using GLHEPRO software> A complete TRNSYS model is validated > Results satisfactorily match experimental measurements>Model as a tool for developing optimization control strategies

EXPERIMENTAL AND MODELING ANALYSIS OF A GROUND SOURCE HEAT PUMP SYSTEM

Carla Montagud (*), José Miguel Corberán, Félix Ruiz-Calvo

Universitat Politècnica de València, Institute for Energy Engineering
Camino de Vera, s/n, edificio 8E, escalera F, 5ª planta. 46022 Valencia (SPAIN)
(e-mail: carmonmo@iie.upv.es)

Abstract

This paper presents the evaluation of the performance of a ground source heat pump system monitored plant providing heating/cooling to an office building located in the Universitat Politècnica de València in Spain. The system was designed using GLHEPRO software and it has been monitored since 2005. Once a ground source heat pump has been designed, it is important to analyze its performance along the years after its construction and check whether the design was appropriate and the simulation predictions were consistent with real experimental measurements. This paper first presents the impact of the GSHP system in the ground thermal response. The simulations obtained in GLHEPRO software will be analyzed and compared to experimental measurements. The second purpose of this work is to compare the performance simulation results of a complete ground source heat pump system model built in TRNSYS, with the experimental measurements which have been registered and collected for one cooling day. Numerical predictions and experimental results are compared and discussed.

Keywords: Ground Source Heat Pump Systems, Experimental measurements, Thermal impact on the ground, Numerical modeling analysis.

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[*] Corresponding Author: Carla Montagud. Institute for Energy Engineering. Universitat Politècnica de València. Camino de Vera, s/n, edificio 8E, escalera F, 5ª planta. 46022 Valencia (SPAIN). Telf. +34 963 879 910 Fax: +34 963 877 272 email: carmonmo@iie.upv.es

1. Introduction

The interest in using the ground as a source of thermal energy storage has grown considerably in the last few years. Ground coupled heat pumps are recognized by the U.S. Environmental Protection Agency as being among the most efficient and comfortable heating and cooling systems available today. These heat pumps represent a good alternative system for heating and cooling in buildings, [1] when compared to conventional systems. For domestic applications, the objective is basically to use the natural ground temperature as a heat source during the heating mode and as a heat sink during the cooling mode.

The European work programme for energy supports technology development and demonstration of ground source heat pumps aiming at increasing the coefficient of performance of the heat pump and the overall system in order to reduce the electricity consumption and extend its usage in Europe and particularly to the Mediterranean regions. Ground-Med is a collaborative project which aims at demonstrating innovative ground source heat pump solutions in eight buildings located in eight Mediterranean EU member States (Portugal, Spain, France, Italy, Slovenia, Romania and Greece). It is a five years duration project and the first period started in January 2009.Twenty four European organizations join the Ground-Med consortium, including research institutes and universities, heat pump manufacturers, industrial associations and energy consultants. The coordinator of this project is CRES (Centre for Renewable Energy Sources) from Greece. The main objective of Ground-Med is to demonstrate that a measured seasonal performance (SPF) higher than 5 can be obtained. In order to evaluate the energy efficiency and the performance of the Ground-Med heat pump systems, all the sites are going to be instrumented and monitored for the evaluation of the daily performance of the heat pump and the whole system. Further description of the project is given in [2].

In order to avoid a decrease in the system energy performance, the ground temperature change around the boreholes should be kept small, and this strongly depends on the accuracy of the borehole heat exchangers (BHE) design in a ground source heat pump (GSHP) installation. In order to better understand the behavior of a system and assist in the design, it is advisable the use of simulation models. Experimental validation of design models for thermal facilities is the subject of a considerable amount of research works, like in [3], where an experimental validation of the variable refrigerant volume (VRV) air conditioning system was carried out on the basis of the building energy simulation program, Energy Plus. The differences between average monitored and predicted data for the total cooling energy and power use were proved to be within 25.19% and 28.31%, respectively. In the present work, the software used to model the Gecool plant is TRNSYS (Transient Systems Simulation Program) [4]. TRNSYS software is one of the most flexible modeling and simulation tools, which can solve very complex problems from the decomposition of the model in various model components (types) interconnected. One of the TRNSYS main advantage for the modeling and design of ground source heat pumps is that it includes components for the calculation of building thermal loads, specific components for heating and cooling (HVAC), heat pumps and circulation pumps, modules of borehole heat exchangers and thermal storage, as well as climatic data files which make it a very suitable tool to model a complete air conditioning installation to provide heating and cooling to a building.

Some of the models describing the behavior of thermal facilities have been implemented as modules for the TRNSYS software tool. Its experimental validation is also a field of strong research activity. There are several papers that experimentally validate models for the design of air conditioning systems for heating and cooling: in [5], the experimental validation of a TRNSYS model used to calculate the thermal behavior of buried deposits for hot water thermal storage was carried out and deviations between experimental measurements and simulation results were lower than 5%. Other research studies are focused on the experimental validation of new modules developed in TRNSYS, like in [6] where predicted performance of a grid connected photovoltaic system using TRNSYS was compared with measured data, and deviations found took values from 8% to 10%. However, there are very few references on the validation of experimental models of reversible ground source heat pumps or BHE used as heat sink and heat source. In [7], a validation of a computer model developed in TRNSYS for solar coupled district heating systems with borehole thermal energy storage was done. The installation was equipped with Borehole Thermal Energy Stores (BTES) which were charged and discharged by means of borehole heat exchangers. The correlation between measured and calculated heat quantities was good (<5%). On the other hand, in [8], the validation of a groundwater flow and transport modeling tool for (BTES) based on FEFLOW software [9] was done. The numerical model was validated against measured data of two BTES with and without groundwater flow, and predictions for the outlet water temperature from the BTES presented a maximum deviation of 1 to 2 K.

With regard to the ground source heat exchangers numerical modeling, a variety of codes are currently used as tools for the design of borehole heat exchangers. In the USA, GLHEPRO, [10], is one of the most known software tools developed as an aid in the design of vertical borehole-type ground loop heat exchangers used in geothermal heat pump systems, and has been validated experimentally and against more detailed models as presented in [11].

Research in heat pump systems coupled to the ground and operating reversibly is very recent. In [12], a dynamic simulation of a complete GSHP system was performed using the TRNSYS simulation software. Results obtained from a 10 year simulation period showed that the maximum difference found between the water temperature coming from the ground loop and the experimental measurement was about 0.5 K.

The performance of a ground source heat pump system for heating and cooling has also been analyzed in previous research works. In [13], experimental measurements are used to test the performance of a ground source heat pump system at different operating conditions and the main performance parameters are presented for one month of operation.

The present work is focused on the energy analysis and modeling of a geothermal experimental plant located in an institutional building at the Universitat Politècnica de València, València, Spain. The system consists of a water to water reversible heat pump coupled to the ground. It was built under the framework of a European project ‘Geocool’ (Geothermal Heat Pump. for Cooling-and Heating. along European Coastal Areas) whose main purpose was to adapt ground coupled heat pump technology to cooling dominated areas.

The execution of this experimental plant was completed at the end of year 2004, starting on February 2005 the regular operation of the air conditioning system. The system has been fully monitored since then and research studies have been undertaken in the framework of Ground-med project, as the Universitat Politècnica de València is one of the RTD partners in the project.

One of the main innovative contributions of this study consists in the analysis of the impact of the system design and operation in the ground thermal response for a 5 year operational period. In order to determine whether the BHE is well designed, the impact of the GSHP system in the ground thermal response will be analyzed using GLHEPRO software, and simulation results will be compared to experimental measurements.

The second purpose of this work is to compare the performance simulation results of a ground source heat pump system model developed in TRNSYS with the experimental data collected in the data acquisition system of the Geocool installation. Numerical predictions and experimental results are compared and discussed for one day of operation. In comparison to previous research works, it consists of a very detailed model including not only the BHE model and the hydraulic circuit components but also the distribution of the air conditioned zones in the building that allows analyzing not only the system energy response at different working conditions but also the impact in the user comfort. Therefore, it can be used in future research works for developing control strategies.

Nomenclature

COP	Coefficient of performance [-]
c_p	Specific heat at constant pressure [J/kg·K]
$\dot{m}$	Mass flow rate [kg/h]
NFC	Number of fan coils in operation [-]
$\dot{P}$	Power consumption [W]
$\dot{Q}$	Instantaneous thermal loads [kW]
T	Temperature [ºC]

Subscripts

EC	External circuit (ground loop)
exp	Experimental measurement
FC	Fan coil
IC	Internal circuit (building)
in	Input
out	Output
space	Air conditioned space
V_1	Fan coil first position velocity
V_2	Fan coil second position velocity
V_3	Fan coil third position velocity

2. Materials and methodology

This paper first presents the layout of the system, and describes the instrumentation employed. After introducing the system, the impact of the GSHP system in the ground thermal response is analyzed. A study is done using GLHEPRO software, where the mean monthly values for the water return temperature from the ground are calculated for 25 years of operation. In order to do so, the design characteristics of the ground heat exchanger, ground thermal properties and the monthly energy load extracted/injected to the ground calculated from experimental measurements are introduced into GLHEPRO. In parallel, a complete model of the building and the system has been developed in TRNSYS. The paper presents the main characteristics of the global model as well as for the main system components. A comparison between the obtained experimental results and the ones calculated with the model is presented and discussed. Finally a set of conclusions of the whole study are presented.

3. Results and discussion

3.1. System description

The overall heat pump system consists of a heat pump, an indoor circuit and an outdoor circuit as shown in Figure 1(a).

The system consists of a reversible water to water heat pump which uses as external heat source a closed loop ground heat exchanger. The nominal heating and cooling capacities are 18 kW (45ºC return /16ºC return) and 14 kW (30ºC return/12ºC return) respectively. The operation of the heat pump is governed by an electronic controller which, depending on the building water return temperature, switches on/off the heat pump compressor. The external circulation pump is controlled by the heat pump controller which activates the external pump 60 seconds before compressor activation. The GSHX itself consists of six vertical boreholes connected in a balanced parallel configuration. Each borehole has a depth of 50m and contains a single polyethylene U tube of 25 mm internal diameter, with a 70mm separation between the upward and downward tubes. The borehole overall diameter is 150 mm. The six boreholes are arranged in a 2x3 rectangular grid ($18m^2$), with a 3m separation between boreholes. All boreholes are filled with sand and finished with a bentonite layer at the top to avoid intrusion of pollutants in the aquifers.

The building (see Figure 1(b)) which is heated and cooled, comprises approximately 250 m^2 floor area and includes a corridor, nine offices (located on the east façade of the building), a computer room and a service room with office equipment and other internal loads. The building loop consists of a series of 12 parallel connected fan coils, an internal hydraulic loop and a water storage tank (160 liters).

A network of sensors was set up to allow monitoring the most relevant parameters of the system. Temperature sensors are used to measure the inlet and return temperature for each hydraulic circuit. The mass flow rate for each circuit is measured by means of a coriolis flow meter. The power consumption associated with the compressor and external pump, the internal pump and fan coils are measured by two separate power meters. The temperature sensors are four wire PT100 with accuracy ±0.1 ºC. The mass flow meters are Danfoss Coriolli meters, model massflo MASS 6000 with signal converter Compact IP 67 and accuracy <0.1%. The power meters are multifunctional power meters from Gossen Metrawatt, model A2000 with accuracy ±0.5% of the nominal value. Data from this sensor network is collected by a data acquisition unit Agilent HP34970A with plug-in modules HP34901A.

In order to better understand the behavior of the system, the performance of the installation during a typical day in July will be analyzed. Figure 2 shows the evolution of the inlet and outlet temperatures in the indoor and outdoor circuits.

As shown in Figure 2, the water temperature sent to the outer loop, TINEC (ground source heat exchanger) reaches a maximum value of 32 °C. The ground return temperature to the condenser, TOUTEC, takes values around 27 ºC. This is typical in cooling season during the summer when the soil has warmed up during the month of May and June, and the daily thermal load is very high especially at noon. It can also be observed that the outlet water temperature from the ground, TOUTEC, gets higher values as the day passes by, due to an increase in the total thermal energy injected into the ground. Regarding the internal circuit, it can be observed that the heat pump is supplying the chilled water to the system at a temperature, TINIC, around 9 °C. The heat pump switches off when the return temperature, TOUTIC, takes values around 12 º C, and starts up when the return temperature is around 14 ºC. The system automatically turns off from 22:00 to 07:00 hours every day.

3.2. Analysis of the GSHP system impact on the ground thermal response

The system has been fully monitored for several years since 2005. For the purpose of the present work, it is considered that the parameter that better represents the impact of the system in the ground thermal response is the outlet water temperature from the borehole heat exchanger (BHE), in such a way that an increase in the ground temperature due to an imbalance of thermal loads, would make the outlet water temperature from the BHE be higher, leading to a performance degradation of the unit. Water temperature coming from the ground is collected every minute in the data acquisition system. Figure 3 shows the mean monthly values for the outlet water temperature from the BHE calculated as the average of the mean daily values for each month.

The natural ground temperature is used as a heat source during heating mode and as a heat sink during cooling mode; so during the heating season, the higher the heat extracted from the ground, the lower will be the outlet water temperature of the borehole heat exchanger, TOUTEC, and vice versa. Taking a look at year 2008, it can be noticed that the water temperature starts at 17.44ºC approximately in January and decreases a little until March which means that the ground has been cooled down during heating operation. Then, due to a lower amount of extraction heat, it increases from March until May. This is typical in Mediterranean climates like in Valencia, where the heating energy demand is very low at spring time, leading to a smaller amount of heat extracted from the ground and allowing the ground to recover. In May the heat pump is switched to cooling mode. Water return temperature increases along the cooling season until September because the ground is being heated up during cooling mode operation.

It must be pointed out that at university, summer holidays take place mainly in August and this is why, during this month, the ground recovers due to a lower energy demand. In October it decreases a little due to a lower cooling load in the building. Finally, the heat pump is switched to heating mode again in November and water return temperature starts decreasing.

All in all, it can be observed from Figure 3 that the return water temperature from the BHE starts taking values of 17 ºC at February 2005 and after 5 years of operation, February 2010, the value is the same. Looking at the maximum water temperatures coming from the ground in July, it can be noticed that the variation is very low from year to year. So, it is concluded that the balance between the amount of extracted heat during winter, the injected heat during summer and the periods where the ground recovers due to a lower energy demand in spring time, August holidays and in autumn, let the ground reach a balanced state which can be observed in the last three years of operation. It can be observed that the mean water return temperature remains constant along the five years of operation at 20ºC approximately. This means that in this unbalanced case (cooling dominated) the BHE is well designed in such a way that the ground thermal response is not affected.

It can be noticed in Figure 3 that there are some months where no data was available due to maintenance operations, some problems with the data acquisition system, and some periods where the installation was stopped in order to carry out other research activities such as the tune up of a thermal response test mobile facility as described in [14].

A study was done using GLHEPRO software to compare measured values with numerical predictions. Using GLHEPRO, the mean monthly values for the water return temperature from the ground were calculated for 25 years of operation. In order to do so, the design characteristics of the ground heat exchanger, ground thermal properties and the monthly energy load extracted/injected to the ground calculated from experimental measurements were introduced into GLHEPRO. Values for ground thermal properties (conductivity of 1.6 W/mK and volumetric heat capacity of 2.25 MJ/m3K) were estimated with a Thermal Response Test performed at Geocool heat exchanger. These values are compatible with laboratory analysis performed on soil samples although in both cases a high uncertainty (around 20%) in the estimation of the ground thermal conductivity was observed. Measurements of the ground temperature were undertaken at Geocool plant and the registered values were around 18.5ºC (see [15-16] for details).

Figure 4(a) presents the energy loads injected/extracted from the ground and Figure 4(b) presents the value of the peak heating and cooling loads calculated as the maximum instantaneous values registered for each month for year 2010. It should be pointed out that the GLHEPRO considers all the years identical, which is not totally true in reality. However, as the air conditioned spaces correspond to an institutional building located in a university, the thermal energy demand in the building won't be very different from year to year because the daily activity of the users (professors) would not vary dramatically, and the weather in Valencia is very mild; therefore, the average thermal load would be approximately the same from year to year.

Energy loads injected/extracted from the ground were calculated from experimental measurements for year 2010. The heat transferred from the heat pump to the external circuit (BHE), is estimated from the values of the inlet, T_{INEC}, and outlet, T_{OUTEC}, water temperatures and the water flow rate $\dot{m}_{EC}$ at the external circuit (measured with four wire PT100 temperature sensors and a Coriolis meter). Instantaneous thermal loads are obtained by the energy balance from inlet to outlet of the external heat exchanger using expression 1:

$$\dot{Q}_{EC}(t)=\dot{m}_{EC}c_p\left(T_{INEC}(t)-T_{OUTEC}(t)\right) \tag{1}$$

Because all measurements are taken in one minute intervals, the injected/extracted load into the ground is defined as the integral of expression (1) for each month. Finally, Figure 5 shows the predicted results obtained in GLHEPRO for the mean monthly water temperature coming out of the borehole heat exchanger (BHE).

Simulation results from GLHEPRO software show that during the first five years of operation, the water temperature coming from the ground would increase around 0.7K, reaching a 1.12K increase after 25 years of operation. As it has been observed in practice, the ground has a stronger recovery capability than expected which allows the water temperature coming from the ground present a periodic evolution along the years.

Two influences arise from the observation of experimental measurements: the underground water effects and the ground recovery due to holiday periods. On the first place, it must be pointed out that the underground water level in Valencia is around 3.5m depth, which means that the ground is practically saturated of water and there is a strong possibility of having induced convection heat transfer currents. The high uncertainty observed when determining ground thermal conductivity can also be understood from this underground water effect. On the other hand, during the weekends, the installation is stopped letting the ground recover from Friday until Monday every week.

3.3. System model in TRNSYS

In order to understand the dynamics of the system and to fully characterize its operation and assist in the design, a complete model of the building and the system has been developed in TRNSYS. The model fully describes the building and the whole system of water production (at the refrigeration unit), the fan coils operation, and the heat injection/extraction to the ground. The main characteristics of the global model as well as the models of the main components of the system will be presented.

Previous studies were undertaken using a quasi-steady state mathematical model of the installation developed in EES [17] incorporating an adequate model for every system component which was validated by comparison with experimental data.

Figure 6 presents the scheme of the system model built in TRNSYS, where the main components of the system can be observed: Building, internal hydraulic circuit and fan coils, internal buffer tank, heat pump, and the ground loop.

The vapor compression software package IMST-ART was used to model the performance of the GSHP as a standalone system, [18]. Sensitivity studies using the validated IMST-ART heat pump model facilitated the production of system performance maps of heat pump capacity and compressor power consumption as a function of building and ground water return temperatures for different mass flow rates. These heat pump performance maps were correlated using polynomial equation fits, which were incorporated within the TRNSYS model, [19]. The control setting of the water return temperature and the dead band for the micro-chiller as well as water flow rates at the internal and external circuits were also recorded and set from experimental data. Construction data as well as internal gains due to occupancy, light, computers, infiltrations and ventilation were taken into account in the TRNSYS model of the building.

The internal circuit consists of the internal tank, the hydraulic circuit and the fan coils. The outlet water temperature from the heat pump to the internal circuit is conducted to the fan coils. Each fan coil is coupled to one office in the building. The air temperature of the room in the building will change as a result of the energy balance between the heat exchanged in the fan coil and the building energy losses or gains. Then, the calculated room air temperature will be an output of the building and a feedback input to the fan coils control system.

The outdoor loop was also modeled in a detailed way. It consists of the borehole heat exchanger, and the external hydraulic circuit components such as water pipes and the external circulation pump. The control of the external circulation pump was also implemented in TRNSYS: the control signal for the compressor and the external circulation pump were programmed to be the same, so that, the external circulation pump works cycling with the compressor. The ground source heat exchanger was modeled using a TRNSYS type (DST model) specially developed for dynamic simulation of ground heat exchangers [20], where all the geometrical data of the BHE was implemented as well as the values for ground thermal properties such as conductivity and volumetric heat capacity.

TRNSYS models for fan coils in heating and cooling mode (including dehumidification) were considered as well as the control of the fan coils, which can be individually regulated by means of a thermostat. Users can easily select the temperature and fan speed by changing the control board settings: looking at the collected data, it was possible to estimate the number of fan coils in operation, the comfort temperature selected by users and its position (1, 2 or 3). Each position corresponds to a different air flow velocity; being the first position the minimum (see more details in [14]). This information was implemented in the model and the consumption was estimated as a function of the number of fan coils running and their position as it is indicated in expression 2.

$$\dot{P}_{FC} = 0.083 \cdot NFC_{V3} + 0.055 \cdot NFC_{V2} + 0.02 \cdot NFC_{V1} \tag{2}$$

Where $\dot{P}_{FC}$ corresponds to the fan coils power consumption, NFC_{V1} is the number of fan coils working on the first position, NFC_{V2} is the number of fan coils working on the second position, and NFC_{V3} is the number of fan coils working on the third position.

The control for each fan coil is governed by a three way valve that allows the heating/cooling water to be modulated through the fan coil. The valve is controlled by the thermostat of the room. This control system was also implemented in TRNSYS. Weather data for Valencia was considered and also the working schedules for the operation of the system including holidays and weekends.

3.4. Model Validation

After building the model of the whole system, a validation was undertaken by comparing model predictions and experimental data taken from the UPV GSHP installation. Figure 7 compares model predictions for space and water temperatures against experimental data for a typical heat pump cycle period for the 29th of July of 2009.

It can be observed from Figure 7 that model predictions for space and water temperatures at the internal circuit (building) are well adjusted to experimental data. The duration of the ON/OFF cycles is approximately the same, which means that the building energy demand is well adjusted to reality. Regarding the space air temperature, upper and lower set point temperatures are also well adjusted in the model as well as the switch ON/OFF time of the fan coils. As shown in Figure 7, steady state water temperatures calculated in the model match perfectly with experimental measurements; therefore, as the COP of the heat pump is a function of the water temperatures coming from the ground and the building, it will be very well adjusted by the model. A comparison between the electrical consumption model predictions and the experimental measurements is presented in Figure 8 and Figure 9 for the compressor and the fan coils respectively. It can be observed in Figure 8, that the heat pump model developed in TRNSYS reproduces, with an average deviation of 2%, the performance of the unit along the day for each cycle. The highest deviation would take place for the first minutes of each cycle which correspond to the transient process when the compressor switches ON.

Figure 9 shows the comparison for the fan coils consumption along the day. It can be observed in Figure 9 that the fan coils consumption registered in the experimental measurements varies along the day, as it depends on the users' daily activity and the occupancy levels in the air conditioned offices; while on the other hand, the fan coils consumption obtained in TRNSYS simulations is constant during the day. This is because in TRNSYS, the fan coils are modeled to work continuously while the installation is running (15 hours during the day). The number of fan coils which are switched ON was fixed in the model as well as their position. For the same cooling day (hot day in summer), the number of fan coils working resulted in: three of them working on the third position, eight running on the second position (the most usual one), and one switched off. Nevertheless, it can be observed in the TRNSYS model that the average fan coils consumption is well adjusted. Further improvements will be implemented in the model to randomly vary the position of the fan coils along the day in order to better reproduce the real behavior of the users.

It should be pointed out that the model reproduces quite accurately the behavior for one operational cooling day. Future work will be carried out to check the model adjustment for several days along the year for heating and cooling mode, as well as the model predictions for a long period of time, for instance, a five years simulation period.

The model developed can be finally used as a tool for predicting the system thermal response and the impact in the users' comfort when varying several working parameters such as internal circuit mass flow rate, set-point temperature and temperature bandwidth of the heat pump control, building space set-point temperature and building space temperature bandwidth. The results obtained in these sensitivity studies could be used to develop control strategies in order to optimize the system energy performance and ensure users' comfort along the year.

4. Conclusions

This paper presents the evaluation of the performance of a ground source heat pump system, providing heating/cooling to an office building. The system has been fully monitored along several years up to now and experimental measurements have been collected since 2005.

The impact of the GSHP system in the ground thermal response is analyzed. Mean return water temperature from the BHE was chosen as the parameter that best represents the impact of the system in ground thermal response and its evolution along the five years operation of the system was studied. A study was done using GLHEPRO software where the mean monthly values for the water return temperature from the ground were calculated for 25 years of operation.

It has been observed from experimental measurements that the ground has a stronger recovery capability than expected when compared to GLHEPRO results, which allows the water temperature coming from BHE present a periodic evolution along the years, being the mean water return temperature of the BHE equal to 20ºC for every year of operation and confirming well designed and balanced GSHP systems as a good alternative.

In parallel, a complete model of the system was built in TRNSYS and a comparison between experimental measurements and simulation results has been made for one operational day in cooling mode. The model predictions of the internal circuit water temperatures (building) and the external circuit (ground loop) are very well adjusted to reality being water temperatures on steady state very well predicted by the model, and therefore being the COP of the heat pump well characterized. The duration of the ON/OFF cycles is approximately the same, which means that the building energy demand is well adjusted to reality. Regarding the space air temperature, upper and lower set point temperatures are also well adjusted in the model as well as the switch ON/OFF time of the fan coils. With regard to the electricity consumption, fan coils average consumption was well adjusted by the model, although a randomly sequence variation of fan coils position would better represent the real occupancy of the users. The compressor consumption was well predicted by the heat pump model developed in TRNSYS presenting an average deviation of 2%, and being the highest deviation for the transient process when the compressor switches ON.

Further studies are to be developed and presented by comparing simulation results obtained in GLHEPRO, TRNSYS and experimental measurements, for a 5 years simulation period.

Finally, the complete TRNSYS model presented in this work can be used as a tool to develop control strategies in order to optimize the system energy performance and ensure users' comfort along the year.

Acknowledgment

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Figure captions

Figure 1. GSHP system (a) GSHP system schematic (b) Building plan

Figure 2. Daily temperature evolution at the internal and external circuits

Figure 3. 2005-2010 temperature measurements at the outlet of the external circuit

Figure 4. Monthly energy load profile exchanged with the BHE: a) Base loads (kWh) b) Peak loads (kW)

Figure 5. GLHEPRO 25 years of simulation results: mean monthly BHE outlet water temperature

Figure 6. System complete model built in TRNSYS

Figure 7. Comparison of system model predictions with experimental data: water temperatures

Figure 8. Comparison between model predictions and experimental data: compressor consumption (kW)

Figure 9. Comparison between model predictions and experimental data: fan coils consumption (kW)

Figure 1

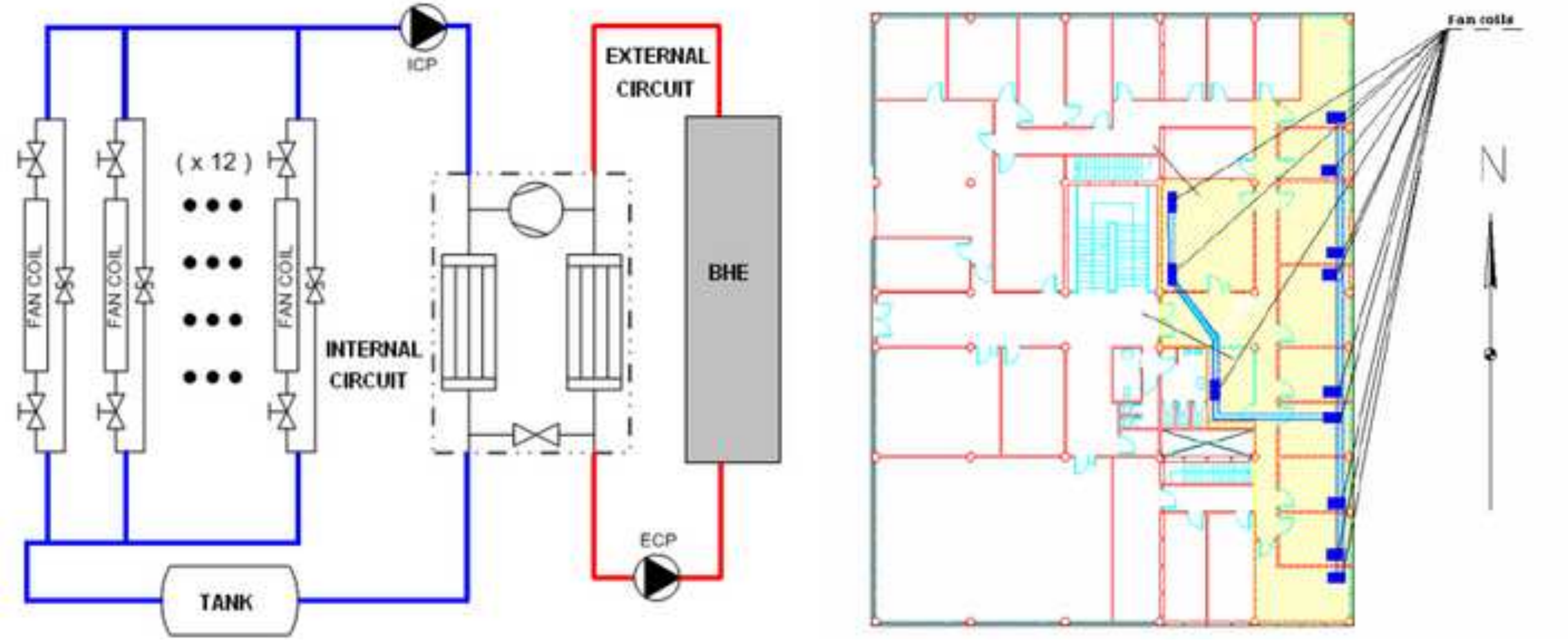
ICP
EXTERNAL CIRCUIT
FAN COIL
FAN COIL
(x 12)
FAN COIL
INTERNAL CIRCUIT
BHE
ECP
TANK
Fan coils
N

Figure 2

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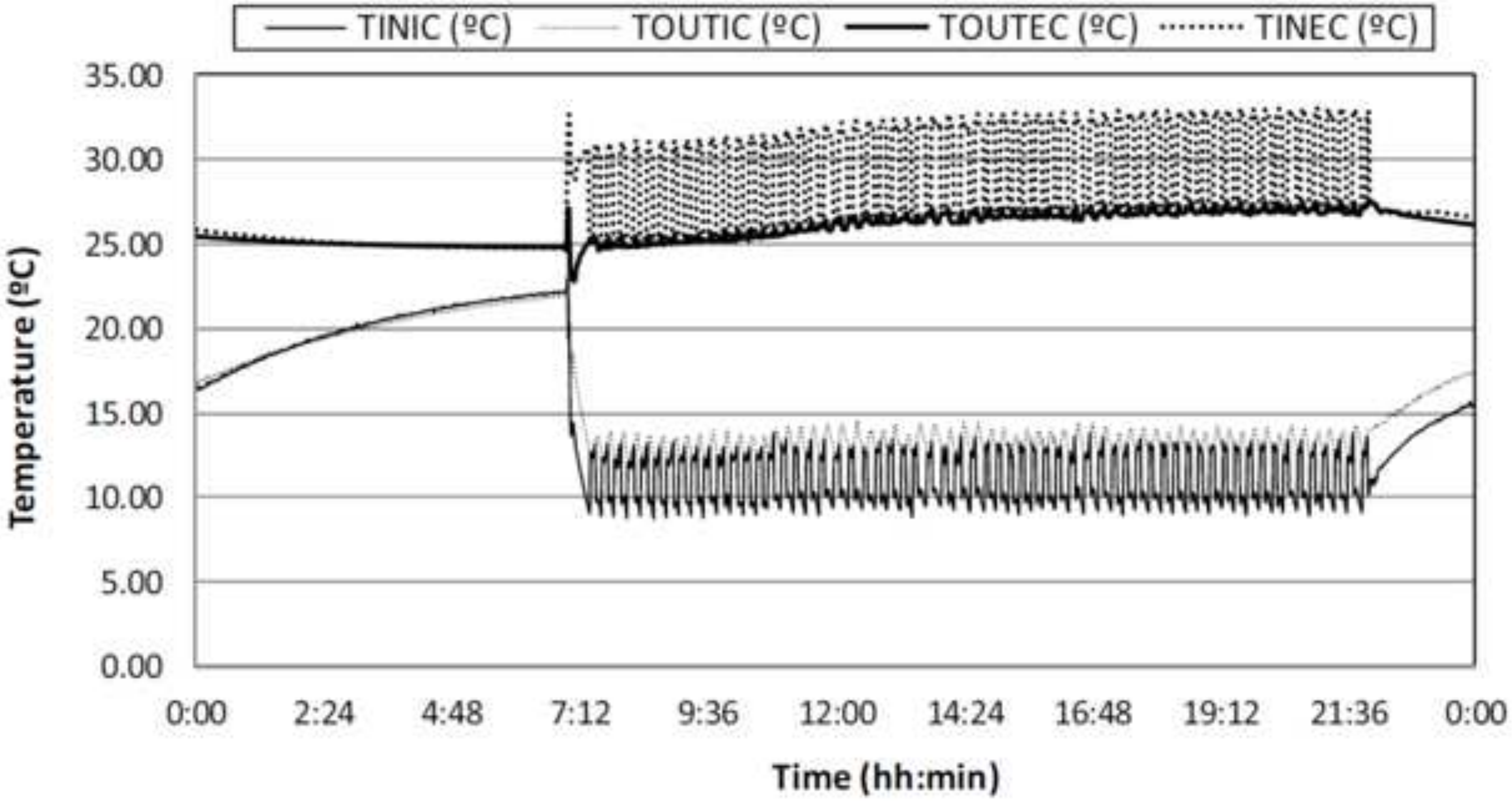

Figure 3

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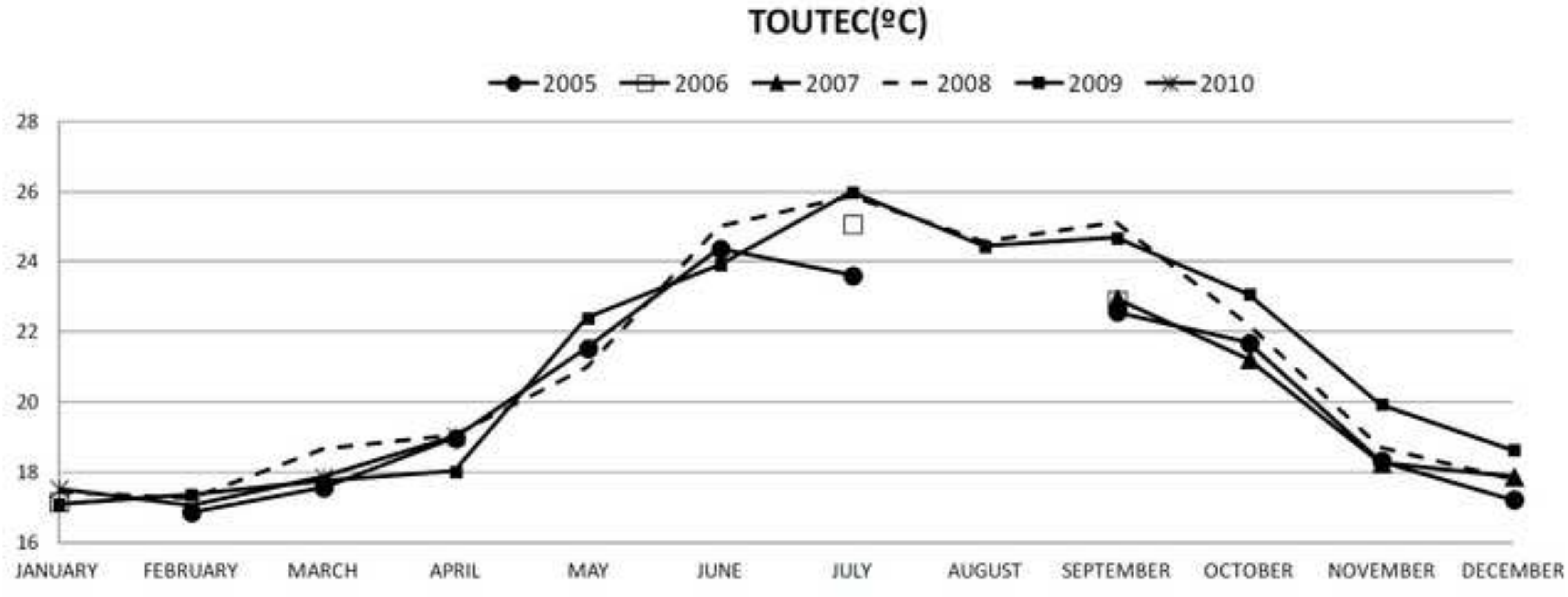

Figure 4

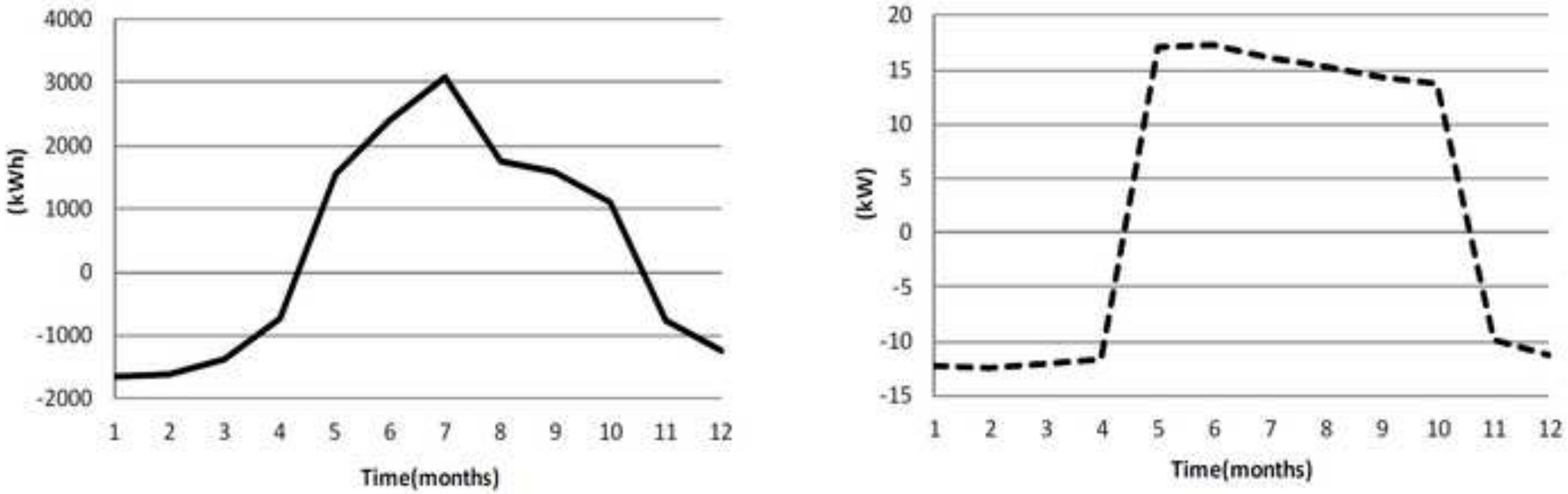
(kWh)
4000
3000
2000
1000
0
-1000
-2000
1
2
3
4
5
6
7
8
9
10
11
12
Time(months)
(kW)
20
15
10
5
0
-5
-10
-15
1
2
3
4
5
6
7
8
9
10
11
12
Time(months)

Figure 5

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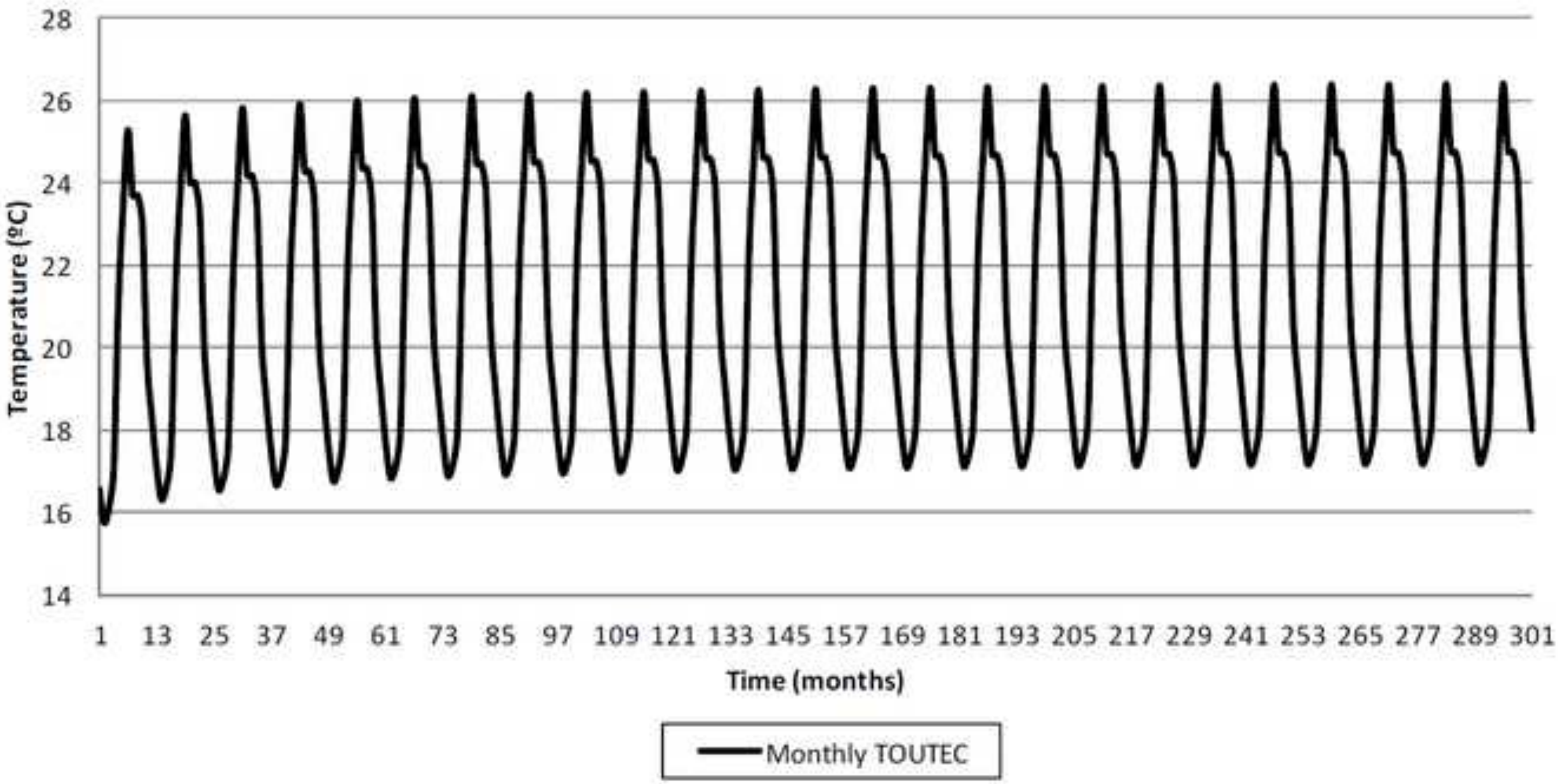

Figure 6

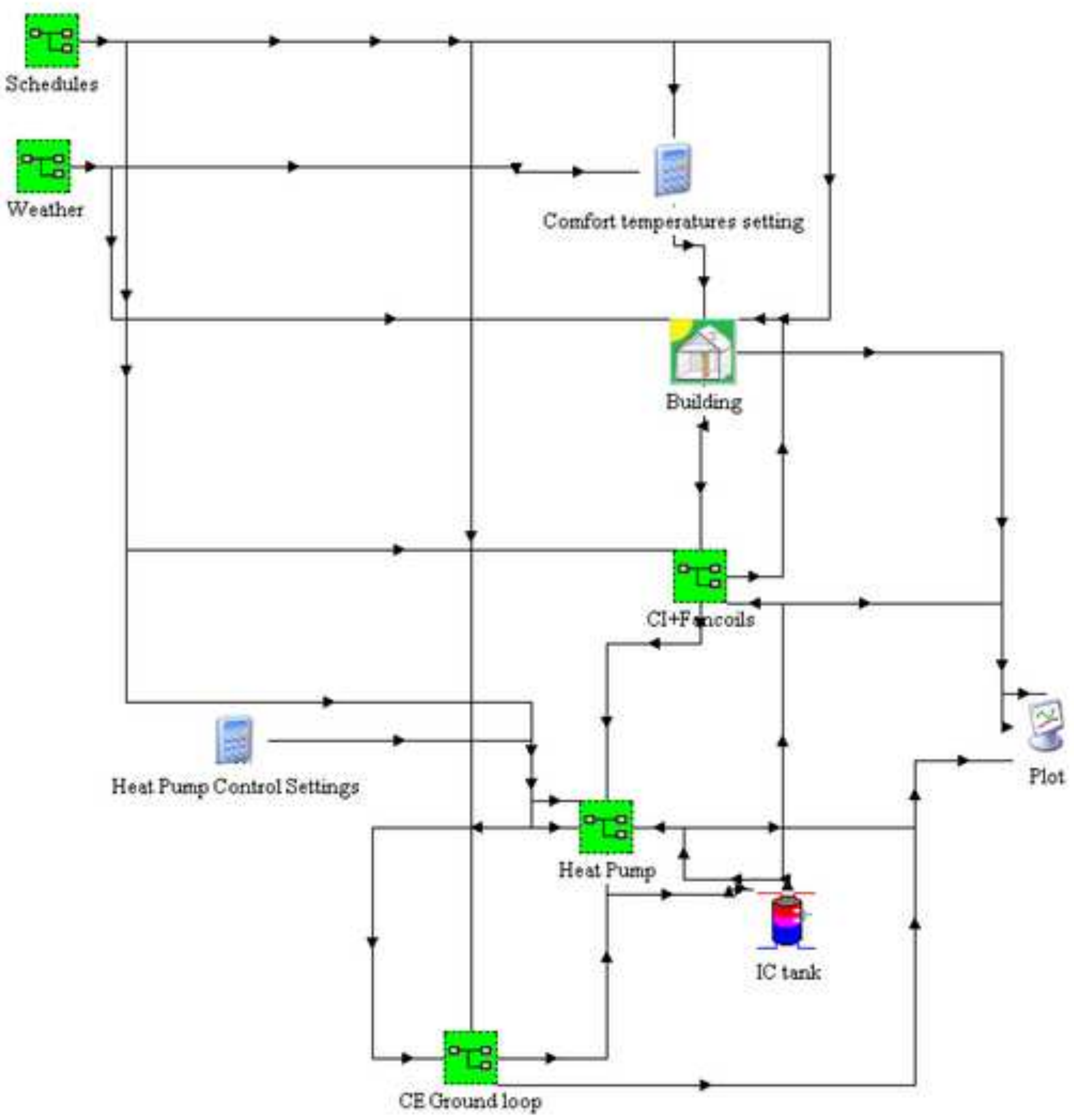
Schedules
Weather
Comfort temperatures setting
Building
CI+Fancoils
Plot
Heat Pump Control Settings
Heat Pump
IC tank
CE Ground loop

Figure 7

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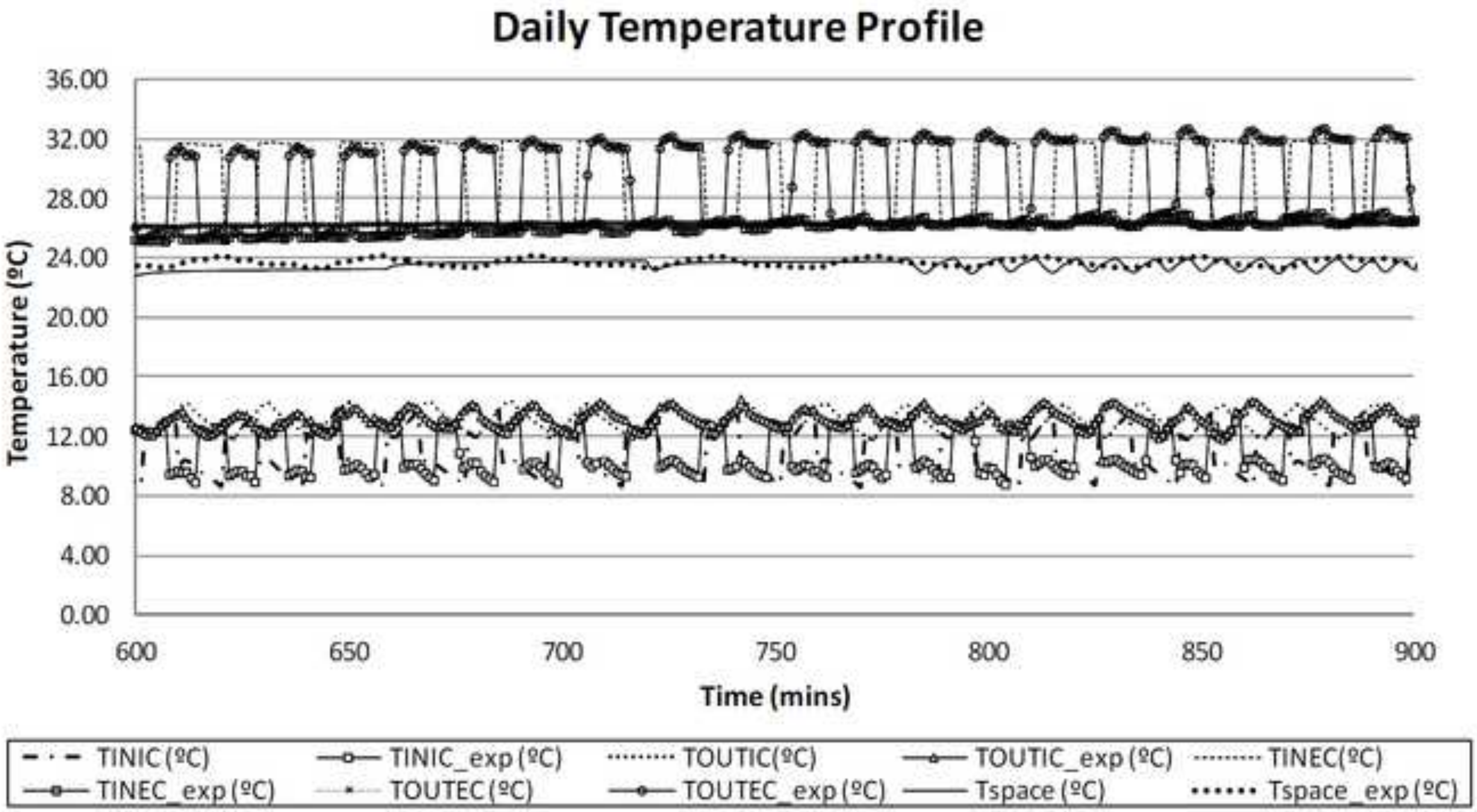

Figure 8

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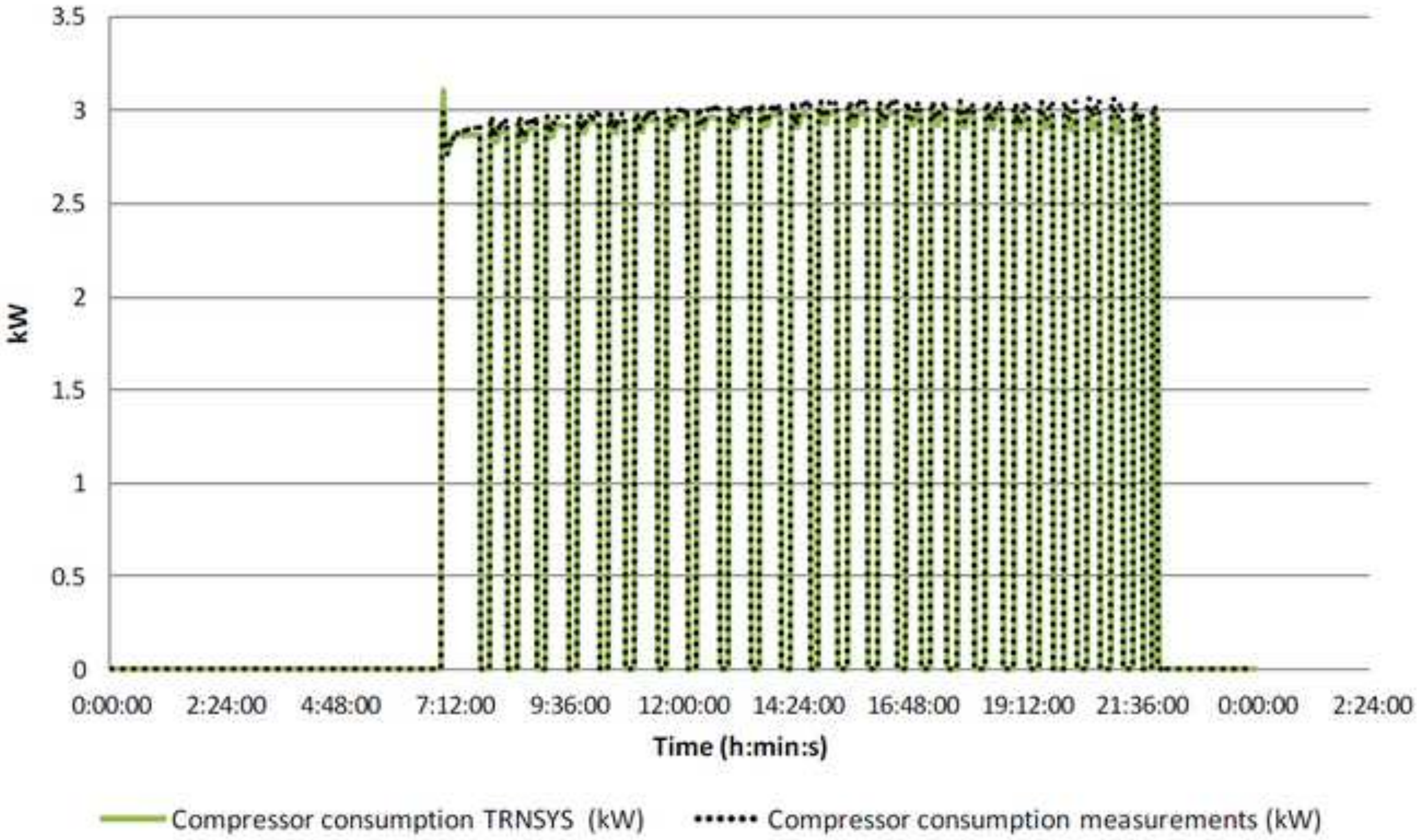

Figure 9

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