Assessing the energy performance of HVAC systems in the tertiary building sector by on - site monitoring

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Proceedings of the 6th International Conference on Improving Energy Efficiency in Commercial Buildings: IEECB Focus 2010

13th - 14th of April, 2010, Frankfurt am Main (Germany)

Editors: Angelica MARINO, Paolo BERTOLDI

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Executive summary

Buildings are large consumers of energy and consequently responsible for a big share of green house gas emissions. The electricity consumption of the tertiary and residential sectors represented 57% of the total energy consumption in EU-27 2007. Moreover, from 1990 to 2007 the final energy consumption of the building sector grew 12%, while the electricity consumption in the building sector grew 53% during the same timeline.

The strong development of the tertiary sector, particularly in the New Member States, has a considerable influence on the growing energy consumption. Furthermore, it is estimated that ca. 20% of the worldwide electric energy consumption is used for lighting. The electricity consumption used for lightning is estimated to grow by 2-3%/year in developed countries.

Energy conservation and the application of energy efficient measures has increasingly become a focus of the building industry as a means of mitigating the environmental impacts of energy consumption, reducing building operating costs as energy costs escalate, raising the propriety value and attracting more selective tenants. Moreover, improving energy efficiency offers the largest and most cost effective mitigation opportunities in the buildings sector. A broad range of best practice examples demonstrates that it is possible to achieve up to 80% energy savings at low or no extra costs.

However, despite an increased awareness of commercial buildings energy consumption and the options and positive financial performance of energy efficiency measures for propriety developers and owners, the adoption of energy conserving and efficiency measures is lower than expected.

Studies shows that the energy consumption of buildings is generally underestimated, while the costs of energy efficiency and energy conservation measures are generally considerably overestimated. Furthermore, the Principal-Agent dilemma present in the building sector due to the distance between the propriety developer and propriety owner and the energy consumer (the tenant, who pays the energy costs) makes investment decisions in energy conservation and efficiency measures complex.

Following the success of the previous IEECB conferences[1], Messe Frankfurt with the scientific collaboration of the European Commission Joint Research Centre organised the sixth International conference on Improving Energy Efficiency in Commercial Buildings (IEECB’10).

The sixth IEECB’10 took place on the 13th and 14th of April, 2010 in Frankfurt during Light+Building, the International Trade Fair for Architecture and Technology in Frankfurt, Germany.

The IEECB'10 brought together players from the sector, including commercial buildings’ investors and property managers, energy efficiency experts, equipment manufacturers, service providers (ESCOs, utilities, facilities management companies) and policy makers. IEECB'10 provided a forum for the participants for knowledge and experience sharing for learning about the latest development in the sector and of course, for networking.

The two days conference offered two session tracks, one session track focused on programmes, policies, and best practice and a second track more technology oriented with the presentation of state-of-the-art equipment and systems. Stakeholders' decision criteria in energy efficiency investment and the market based instruments and economic barriers were analysed together with the relevant legislative framework of the building sector. A number of programmes and policies were analysed, such as the GreenLight programme, the European Energy Service Initiative and SELINA.

Studies of the electricity consumption in the European service sector were also presented as tools and models for the analysis of energy consumption in buildings and the impact of energy conservation measures. State-of-the-art equipment and systems were introduced such as lighting technology, HVAC auxiliary equipment, ICT & office equipment.

It emerged from the conference that a lack in understanding of the relevance of energy consumption in buildings is coupled with a lack of confidence in adopting energy conserving and energy efficient

[1] IEECB’98 in Amsterdam, IEECB’02 in Nice, IEECB’04, and IEECB’06 and IEECB'08 in Frankfurt.

measures. Nevertheless, interest is still growing for energy efficient solutions. A stricter regulatory framework (such as energy efficiency building codes and labelling standards) is needed to increase the demand for energy conservation and efficiency solutions on the market. On the other hand, the interest for and the impact of voluntary programmes is stronger where organisations voluntary commit to reduce their energy consumption by adopting energy conservation and efficient measures (such as the GreenBuilding programme).

It is hoped that the availability of this compendium will enable a large audience to benefit from the presentations made at the conference. Potential readers who may benefit from this book include energy and environment researchers, engineers and equipment manufacturers, policy makers, energy agencies and energy efficiency programme managers, energy supply companies, energy regulatory authorities.

We hope the conference proceedings will be a valuable contribution to disseminate information and best practices in policies, programmes and technologies to foster the penetration of highly efficient buildings in the commercial sector.

The Editors,

Angelica Marino
Paolo Bertoldi

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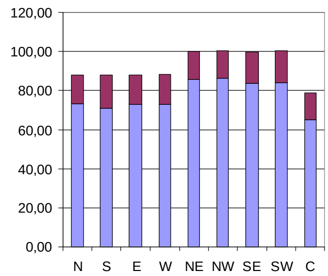
in enhancing the potentialities of the low energy strategy used. Further research on the morphological coefficients should focus more on this aspect.

Table 2. Parameters used for the simulations.

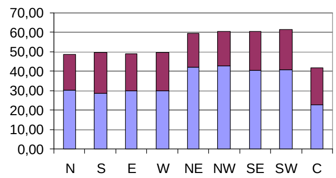
	Unit	**Trad.syst.**	**TEK07**	**LE**
U-value external wall	*W/m²/K*	1.2	0.15	0.15
U-value roof	*W/m²/K*	0.60	0.13	0.13
U-value floor on ground	*W/m²/K*	0.50	0.18	0.18
U-value windows, glazed walls and roofs	*W/m²/K*	2.4	1.2	1.2
Air-tightness	*ach*	3.0	1.5	0.6
Heat recovery system efficiency	-	0.7	0.7	0.85
Occupancy	*persons/m²*	0.1	0.1	0.1
Cooling set point temperature	*°C*	26	26	26
Heating set back temperature	*°C*	18	18	18
Lighting load	*W/m²*	8	8	8
Equipment load	*W/m²*	11	11	11

If the respect of even more exigent Low energy standards – LE – permits a further reduction of the heating consumption, on the other hand the increased need for cooling partially compensate this benefit, questioning the convenience of using compact shapes and super-tight envelopes if not combined with a proper strategy for ventilation, passive cooling or solar control (figure 8).

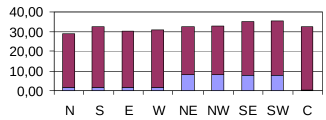
Figure 8. Thermal demand of the 9 office units in case of different air-tightness.



a) 2,5 ach – traditional systems



b) 1,5 ach – TEK07



c) 0,6 ach – LE standard

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Assessing the energy performance of HVAC systems in the tertiary building sector by on-site monitoring

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Abstract

The paper discusses the collection and processing of energy performance data as part of the inspection of HVAC systems, aimed at identifying technically feasible and cost-effective Energy Conservation Opportunities (ECOs), as required by the European Directive on Energy Performance of Buildings (EPBD). Case studies developed by the IEE-funded HARMONAC project have shown that low-cost or no-cost ECOs - mostly related to system operation and management (O&M) - can be identified with an effective system monitoring. Building Management Systems (BMS) may be a powerful tool for this task, provided their HW and SW architecture is designed with adequate attention to energy monitoring. Dedicated instrumentation – such as temperature loggers and electricity meters – may also be employed as an alternative / integration to BMS monitoring. The paper also discusses the application of data analysis tools – such as “carpet plots” and “energy signatures” – to the identification of component malfunctioning, control problems, inadequate maintenance, or system schedule optimization, and to the evaluation of achieved energy savings. The final section of the paper is dedicated to the detailed *in situ* analysis of refrigeration equipment performance.

List of abbreviations

AHU: Air Handling Unit
BMS: Building Management System
COP: Coefficient of Performance
DHW: Domestic Hot Water
ECO: Energy Conservation Opportunities
EPBD: Energy Performance of Buildings Directive
HVAC: Heating, Ventilating and Air Conditioning
HP: Heat Pump
IEE: Intelligent Energy Europe
O&M: Operation and Management
RH: Relative Humidity
TXV: Thermostatic Expansion Valve
VRF: Variable Refrigerant Flow (heat pump)

Introduction

The Intelligent Energy Europe (IEE) funded HARMONAC project [1], due to completion in August 2010, is developing a set of inspection and energy audit procedures suitable for fulfilling the requirements of article 9 of EPBD [2], which establishes the mandatory inspection of HVAC systems of rated output above 12 kW. The procedures proposed by HARMONAC are now being tested by the project partners over a wide range of field trials and case studies throughout Europe.

One of the key points of the inspection procedure is the availability of reliable energy performance data of the main components of the HVAC system. This task is usually easy for heating only systems, such as gas boilers coupled to hydronic heating plants, but much more complex for systems delivering both heating and cooling. In the latter case, in fact, most system equipment (e.g., water chillers, cooling towers, air handling unit (AHU) fans, chilled / hot water pumps, fan coils, etc.) are electrically-driven, but the electricity consumption is seldom measured in a disaggregated way. Normally, the only available electrical consumption data are those measured at the main incomer; therefore, such data also include the contribution of lighting and appliances. One of the main problems that have been addressed by the HARMONAC team has therefore been the definition of energy data collection protocols, suitable for an effective inspection and energy auditing process of existing HVAC systems.

This paper presents the main findings obtained by the authors through the energy and performance monitoring of a set of tertiary buildings in Northern Italy, including laboratories, hospitals, and offices of different ages. HVAC systems that have been investigated include air, water, and air-water units (with fan coils or chilled beams), air cooled chillers, reversible heat pump (HP) systems of various characteristics: variable refrigeration flow (VRF) air-to-air HP, closed-loop ground source HP, open loop water to water HP.

A sample of case studies from the HARMONAC project are presented in this paper, as summarized in Table 1. Specifically, the following issues are discussed:

- How to obtain reliable and sufficiently disaggregated energy consumption data using the existing BMS, and which SW and HW features are required for this purpose.
- Data collection with low-cost dedicated instrumentation (electric meters, temperature and RH loggers, etc.) as an alternative or integration to BMS monitoring.
- Approaches to energy data processing - e.g. correlation of primary energy consumption with climatic conditions and occupancy characteristics - and determination of suitable energy performance indexes.
- Identification and assessment of cost-effective Energy Conservation Opportunities (ECOs) [3], which have been implemented in practice and checked in actual case studies: examples include modified operation schedules, improved control strategies, maintenance or improvement actions on specific HVAC components.

Table 1. Case studies: building and HVAC system characteristics

	Type / location	**Area (m^2)**	**Main HVAC system characteristics**
1.	Operating rooms NW Italy	300	15500 m^3/h outdoor air (15 ach) AHU 2 air-cooled chillers, 394 kW total output
2.	Office building NW Italy (Aosta)	3500	Air-and-water HVAC (four-pipe active chilled beams) 2 chillers + evaporative tower, 650 kW total output
3.	Office building NW Italy (Torino)	9400	Air-to-air reversible VRF heat pump, 600 kW heating, 550 kW cooling output. 5 primary air AHUs
4.	Public building NE Italy	4000	Two-pipe fan coil system, no mechanical ventilation open-loop groundwater-cooled chiller, 330 kW output
5.	Retirement home NE Italy (Trieste)	30000 heated 8000 cooled	Four gas/oil boilers, 6823 kW output 3 chillers + evaporative towers 1468 kW total output
6.	Office building NW Italy (Genova)	8600	Air-and-water HVAC (two-pipe active chilled beams) 2 chillers + evaporative tower, 1868 kW total output

Results indicate that primary energy savings typically in the 5%-25% range, and up to 60% in peculiar circumstances, may be reached by applying low-cost (or no-cost) measures identified by analysing data that are acquired with dedicated instrumentation, or are provided by a BMS that has been properly designed, installed and commissioned for energy monitoring.

The final section of the paper discusses the experimental method that may be applied for a detailed *in situ* analysis of the energy performance of chillers and heat pumps. This approach - which requires the installation of a portable dedicated instrument, and skilled personnel for interpretation of results - may be a very powerful diagnostic tool for identifying equipment defects such as low refrigerant charge, fouled evaporator / condenser, poor compressor efficiency, etc.

Data collection and processing

Hardware and software requirements of BMS

Most tertiary buildings of new construction, or undergoing radical refurbishing, are now being equipped with sophisticated and powerful computer-based Building Management Systems (BMS), which monitor and control mechanical and electrical equipment such as lighting, power supply, fire prevention, security, and HVAC [4]. BMS can effectively perform energy metering (fuel consumption, electrical energy input to specific components, delivered energy to fluid networks), provided the energy metering functions are clearly indicated among the design specifications of the BMS in terms of installed instrumentation (electricity meters, temperature sensors, fluid flow meters, etc.), and SW characteristics. Our experience indicates, however, that adding such capability to an existing BMS implies very high costs and technical problems that are sometimes impossible to overcome.

The experience gained in using existing BMS for HVAC energy monitoring has yielded several hints which may eventually lead to a complete specification. The following is a non-exhaustive list of recommendations to the designers and installers:

- Electric meter characteristics (type of data collected, accuracy, data storage) and number (e.g. separate chillers + cooling tower, pumps, AHU).
- Thermal energy meters: specifications for hot water and chilled water flow rate and temperature measurements.
- Environmental data measurements: indoor and outdoor air temperature and RH.
- Time coding: the data acquisition time interval should be specified by the user, typically in the range from 15 minutes up to 1 hr, depending on the type of data; the time sequence of collected data should never be interrupted, which means that, if for any reason the data are not collected at a given time, a conventional figure should be recorded. Daylight saving time should be managed in a non-ambiguous manner.
- Data format: the correspondence between data and physical quantities should be clearly specified with alphanumeric codes that make the identification easy to the inspector.

Data collection with dedicated instrumentation

As an alternative or integration to BMS monitoring, specific data may be collected with dedicated instrumentation. Ambient temperature and relative humidity (RH) data are easily obtained with stand-alone, battery powered loggers. Status loggers should be used to monitor, at relatively low cost, the operation schedule of small fixed power appliances, such as constant speed electric motors of HVAC equipment (typically, constant flow fans and water pumps, fan coils, etc.). The logger simply logs the on/off status of the component by a magnetic field sensor or a single current transformer clamp.

More relevant electrical users should be monitored with energy meters that may be installed on the electric board. In recent plants, the electric meter may be already present, in which case it may be sufficient to connect the meter to a suitable data logger. The most sophisticated measurement units are the so-called “power / energy analyzers”, which can provide a complete set of data including active and reactive power, power factor, and the corresponding energy values over a specified integration interval. Power quality analyzers may also provide information on the waveform (e.g. the total harmonic distortion). A summary of the instrumentation characteristics is given in Table 2.

Table 2. Metering instruments utilized

Instrument	Typical values logged	Acquisition time	Memory	Cost (€)
Electrical power meter	kW, kWh, VAh, PF	15 minute	1 year	300-1000
T/RH logger (stand-alone)	°C, RH (%)	1 hour	6 months	120-250
Status logger (ON/OFF)	On/Off status	1 second	8000 COV(*)	100
(*) COV = Change of value				

Analysis of energy monitoring data

As discussed above, the monitoring process should typically yield the disaggregated values of primary (electric) energy consumption of the main system components. These values are supplemented with a suitable set of environmental and occupancy data, recorded over the same time scale, that are likely to influence the system energy demand. The level of disaggregation of the acquired data varies significantly from case to case: in some buildings, the total electrical consumption was only available (i.e. the typical “billing data” provided by the electric utilities), while in other cases the BMS allowed the separate measurement of the energy input to the main HVAC sub-systems (e.g., dedicated meters for: chillers and cooling towers; water circulation pumps; and Air Handling Units). For some HVAC systems, dedicated equipment was installed for a detailed analysis of “critical” components, such as the AHU of the operating block of a hospital.

The availability of such data sets makes it possible to perform an energy analysis, based on the so-called “data-driven” modeling approach. According to ASHRAE [5], data-driven methods for building / HVAC energy analysis may be classified into three broad categories (Black-Box, Calibrated Simulation, or Gray Box), depending on the type of available data and goals of the analysis. Furthermore, the mathematical approach may vary depending on the basic assumptions, such as steady-state vs. dynamic modeling, or single-variate vs. multivariate regression, etc. In this research, a steady-state, single-variate approach has been applied, considering the daily (or weekly) mean outdoor temperature as the independent variable, and the corresponding daily (or weekly) primary energy consumption of the specific equipment (or system) under investigation. The reason for this choice is that outdoor temperature is the most readily available climatic variable for the inspector, and is also likely to have the main influence on HVAC primary energy consumption. This is a crucial aspect of the inspection process: to be able to get the maximum information from readily available data that may be useful for ECO identification and assessment.

Another useful tool for energy data analysis is the so-called “carpet plot”, which provides a visually grasping representation of temperature or energy consumption trends over long time periods: time of day is indicated on the y-axis, while the day is represented on the x-axis; the value of the variable under observation is encoded, at any time and date, as a colour or shade of gray according to a specified scale [6]. Even if the information provided by the carpet plot is rather qualitative, it allows a meaningful and quick interpretation of the overall system performance in time. This may be particularly useful for identifying anomalous situations, such as excessive energy consumption in non-occupancy periods which may be caused by unwanted equipment operation, or unsatisfactory temperature values due to poor control.

An example of best practice in building and HVAC system data monitoring

Case study n. 6 is an insightful example of best practice in building and HVAC system monitoring. The 16 floor office/laboratories tower, built in 2003, hosts the headquarters of a company that designs and produces communication systems. The building is equipped with an air-water, two-pipe active chilled beams HVAC system; mechanical ventilation is provided by three AHUs. The building is connected to a district heating network. The cold generators are two water chillers (with screw compressors and evaporative towers) rated at 934 kW cooling capacity each, with a maximum electrical input of 207 kW. The building is equipped with an electrical consumption metering system, connected in parallel to the BMS (but functionally independent), which logs the following data at a 15 minutes sampling rate:

- Global electrical income
- AHU electrical consumption
- Chilled water pumps electrical consumption
- Chillers electrical consumption
- Total thermal energy to the building (from the district heating)
- Thermal consumption for space heating
- Thermal consumption for DHW
- Total water consumption
- Evaporative towers water consumption

The logged data were helpful to analyze in detail the HVAC sub-systems consumption and schedule. A sample of results is presented in the following graphs. Figure 1 represents the breakdown, over one year of operation, of electrical consumption into three terms: i) chillers; ii) water pumps; iii) AHUs and small VRF units; iv) non-HVAC uses. As expected, the chiller consumption exhibits a marked variation from month to month (with a maximum in July), while the consumption associated to other equipments are virtually constant over the year. The temperature-dependence of chiller consumption is clearly visible in the regression analysis of Figure 2, while for the AHU the consumption is virtually temperature-independent (the slight positive slope of the regression line is likely to depend on the small VRF systems that are measured with the AHU fans).

Figure 1. Electrical uses breakdown based on annual monitoring

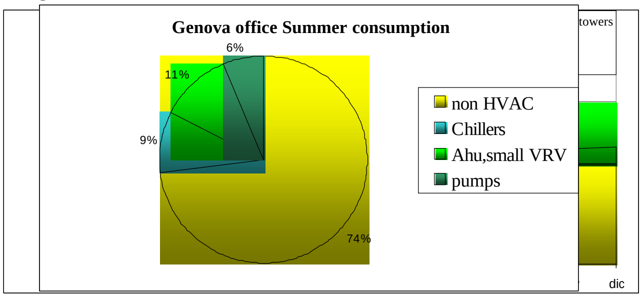
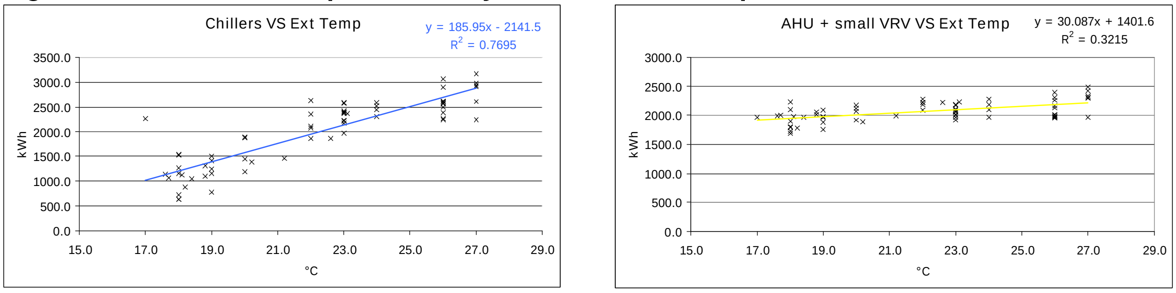
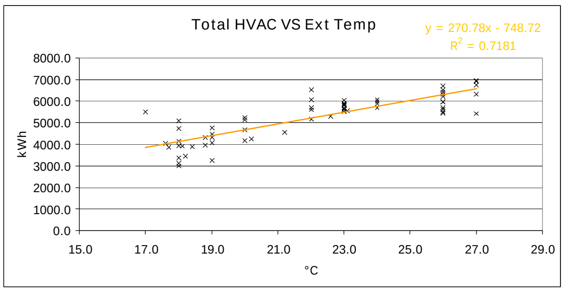


Figure 2. Electric consumption vs daily mean external temperature for different users

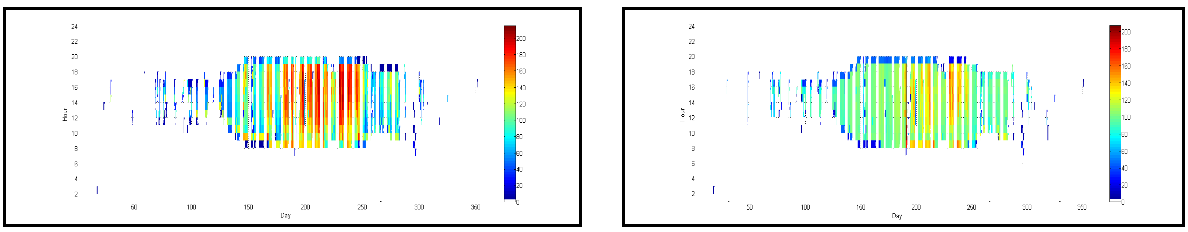




- Top left: Electric input to chiller compressors, evaporative tower pumps, chilled water pumps
- Top right: Electric input to AHU fans and small direct expansion VRF units
- Bottom left: Electrical consumption to all HVAC components

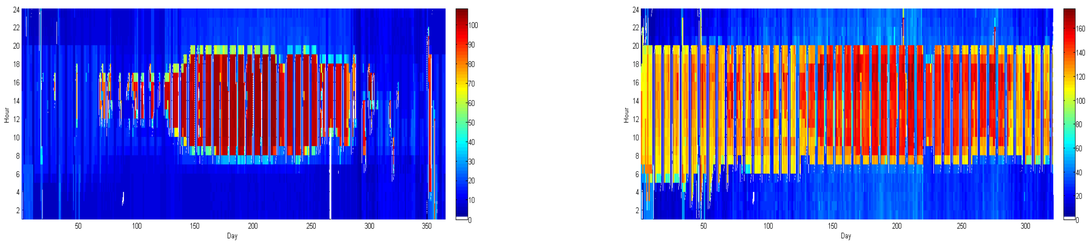
Carpet plots are also used to represent in a single graph the data collected over one year at a sampling rate of one hour; the colour scale refers to hourly energy consumption in kWh. The two plots of Figure 3 allow a quick appreciation of the control strategy applied to the two chillers.

Figure 3. Carpet plots of chiller electric consumption (unit A, left; unit B, right)



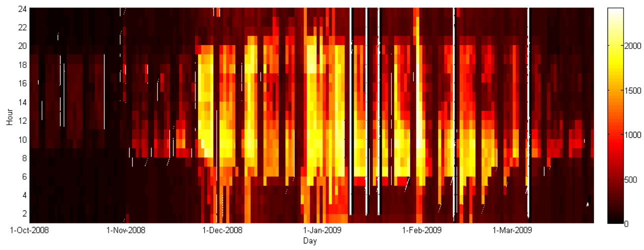
The plots of fig. 3 reveal that, in the periods of maximum cooling load, unit A operates at maximum power, while unit B operates at partial load; however, when the demand is lower, both units work at partial power. This type of information is extremely useful in evaluating the efficacy of the control strategy being applied, both in terms of energy efficiency and system maintenance procedure. The carpet plots of figure 4 refer to pumps (chilled water and cooling tower water) and to AHU fans and secondary circuits pumps consumption. The first plot permits to clearly identify the period of pump operation, while the electric consumption is virtually constant when the pumps are on. The AHU electric consumption, however, basically depends on the ventilation needs, which are linked to the occupancy period of the building.

Figure 4. Carpet plots of electric consumption of pumps (left) and AHUs (right)



One last example of carpet plot is shown in figure 5, which refers to the thermal energy measured at the secondary side of the heat exchangers interfacing the building's hot water circuits to the district heating network. Here the plots provide a clear picture of the thermal load over the entire heating season (October 1st to March 31st).

Figure 5. Carpet plots of thermal energy at secondary side of district heating heat exchangers



Evaluation of Energy Conservation Opportunities

Table 3 summarizes the ECOs that have been identified and evaluated as part of some of tje case studies of Table 1, with an assessment of expected energy savings. All ECOs belong to the O&M (Operation & Maintenance) category and may therefore be implemented at virtually no-cost.

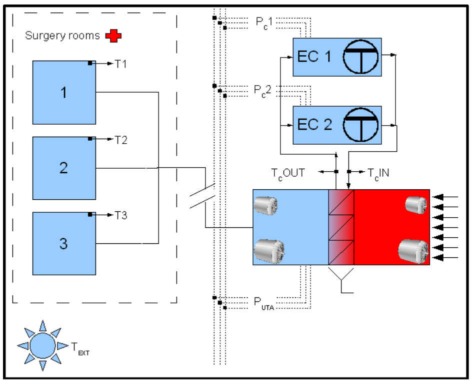
Table 3. Examples of ECOs assessed on measured data

	ECO description	Potential savings
1.	Avoid simultaneous heating and cooling	61.5% on winter chiller consumption
2.	Improvement of chiller control	8-15% on annual chiller consumption
3.	Shut off chiller when not required	30% on annual chiller consumption
4.	Shut off VRF system when not required	26.7% on weekly winter VRF consumption
5.	Reducing operation time of chiller	6.2% per hour of daily operation reduction

Case Study 1: Inspection and monitoring of the operating rooms of a general hospital

The experimental setup for the monitoring of the three operating rooms is shown in Figure 6. The graphs in Figure 7, representing the indoor and outdoor temperature values measured over a five week period in November – December, indicate that the HVAC system does not always allow a satisfactory temperature control during surgical activities (i.e. T > 22°C), even with low outdoor temperatures and with the chiller continuously operating at about 25% load. This circumstance can be better appreciated in the carpet plot on the right part of the figure.

Figure 6. Operating room HVAC monitoring experimental setup



EC1: electric chiller no. 1

EC2: electric chiller no. 2

P_c1: active power of EC1

P_c2: active power of EC2

T_cIN: cold water supply temperature

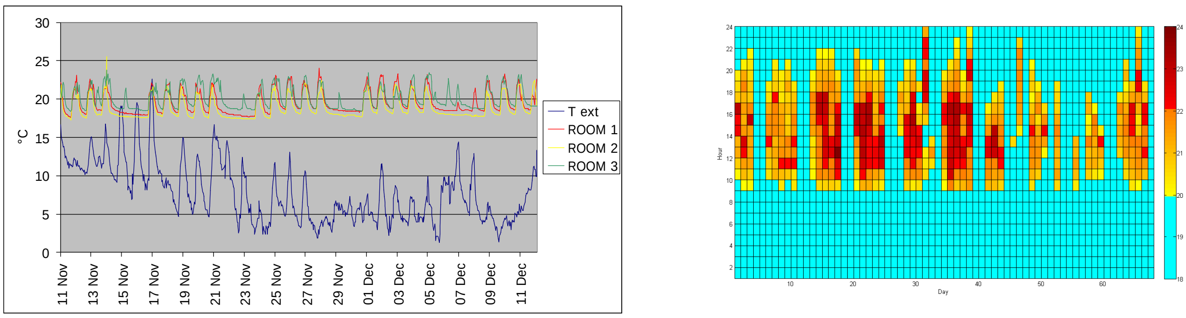
T_cOUT: cold water return temperature

P_{UTA}: AHU fan active power

T1-T3: temperature and RH of surgery rooms 1-3

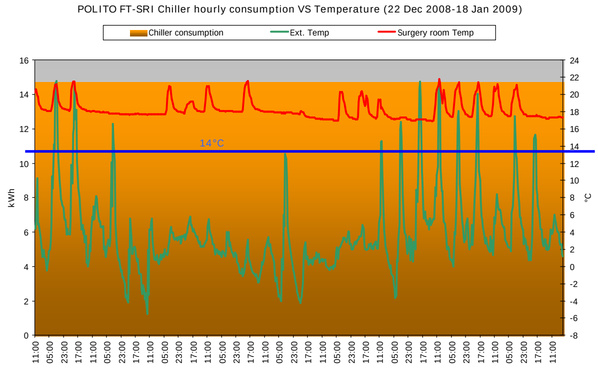
T_{ext}: outdoor temperature

Figure 7. Outdoor and operating room temperatures and carpet plot of room temperature.



Potential energy savings with improved chiller control is assessed with medium term measurements, carried out from December to February. This ECO consists of avoiding simultaneous heating and cooling and shutting off the chiller when outdoor temperature falls below a set level, which, for typical cooling load values, was assumed 14°C. Over the investigated four-week period (Fig. 8), the chiller electric consumption occurring when the external conditions satisfy the requirement for free cooling is 4879 kWh, i.e. the 61.5% of total chiller consumption (7979 kWh). Extrapolating these figures to the entire year, and taking into account the results of a similar analysis performed in case study n. 2, savings of 8-15% in annual chiller consumption may be expected in comparable climatic conditions.

Figure 8. Outdoor / indoor temperature - chiller electric consumption (December – January)



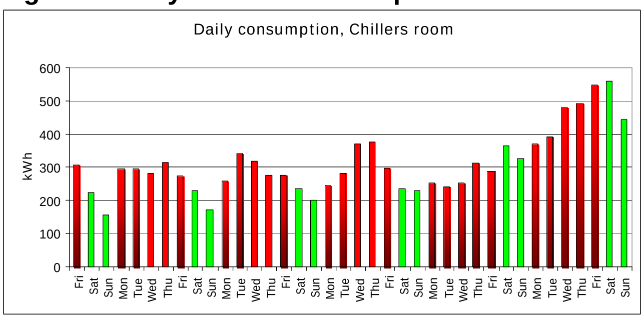
Case study 2: Inspection and monitoring of an office building of recent construction

The inspection of a new office building in NW Italy indicates a relatively high HVAC electric consumption, in spite of state-of-the art system components and building envelope, particularly in relation to the climatic conditions of the site. In fact, BMS monitoring data show that about 39% of the total summer electric consumption (51 kWh/m^2) may be attributed to the central cooling plant (20 kWh/m^2), 96% of which due to chillers and cooling tower and 4% to water circulation pumps. These results suggest that significant savings may be achieved by improved chiller control and scheduling.

More detailed analyses performed in the winter season reveal, for example, that simultaneous heating and cooling take place in the AHU under specific circumstances. A detailed monitoring over the January – May period indicates that an improved control strategy, capable of switching off the chiller and exploiting direct free cooling with outdoor air when the outdoor temperature permits, may lead to a 35% reduction in central cooling plant consumption over the investigated five months period.

Another identified ECO is the possibility of turning the cooling plant off at night and during weekends: the BMS data in fact reveal no significant differences in chiller energy consumption between occupied and non-occupied periods (Figure 9). During the monitored January – May period, about 40% of the consumption occurs in the workdays (7:00-18:00) and the remaining 60% during weekends and at night. Spot measurements made during one working day in summer yield opposite percentages: 61% (7:00-18:00) and 39% (rest of day). Extrapolating similar analysis performed in case study n. 3 in which a VRF system was monitored over several seasons with different operating schedules, savings on the order of 30% in annual chiller consumption may be expected in comparable climatic conditions.

Figure 9. Daily electric consumption of central cooling plant: workdays and weekends



Case study 3: Long-term BMS monitoring of VRF heat pump system

The case study concerns a XVII century building in Torino, which was almost entirely rebuilt after World War II. In 2006, a radical refurbishment of the building services has been completed by the ESCO in charge of the energy service contract and a new modular air-to-air VRF (Variable Refrigerant Flow) reversible heat pump system was installed, consisting of 16 external units and 150 fan coil internal units. Mechanical ventilation is provided to some areas only by five AHUs fed by air-cooled water chillers and gas-fired condensing boilers. A BMS performs complete monitoring and management of the building services (HVAC, fire prevention, security, lighting). Energy performance data acquired by the BMS have been recorded and stored since 2005.

The data records indicate that, in the initial operation period, the HVAC system was running 24/24 hrs – 7/7 days; the operating schedule was subsequently optimized by introducing nighttime and weekend system set-back criteria. The effects are clearly seen in the graphs of Figure 10. The weekend set-back is reflected in the greatly reduced consumption on Saturday and Sunday, and in increased system consumption on Monday; the night set-back determines an increase of the hourly energy demand in the morning period of working days. Referring to typical winter conditions, the following electric energy consumption reductions are achieved: 9% on working days and 85% on weekends, yielding a 26.7% weekly saving.

The effects of modified system operation are also well visible in a carpet plot representing the time trend of total electric energy consumption (Figure 11): the plot on the left side refers to a period in which the operation schedule of the VRF system is well defined and stable, while the plot on the right side basically reveals a continuous operation, in which night-time or weekend setbacks are not clearly applied.

Figure 10. Daily and hourly electric energy demand of VRF system with different schedules

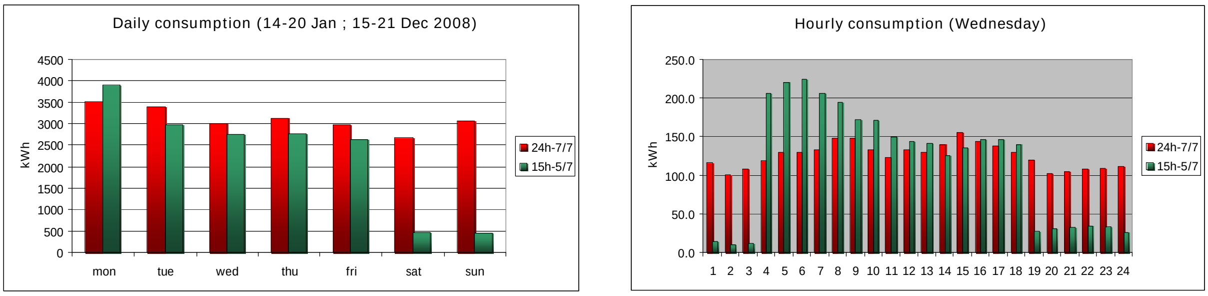
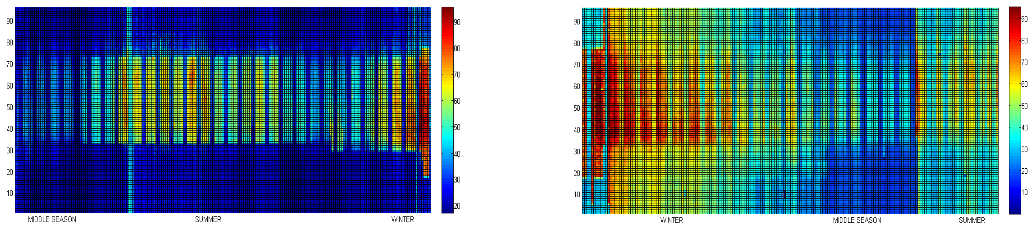


Figure 11. Carpet plots of total electric energy consumption with different VRF schedules

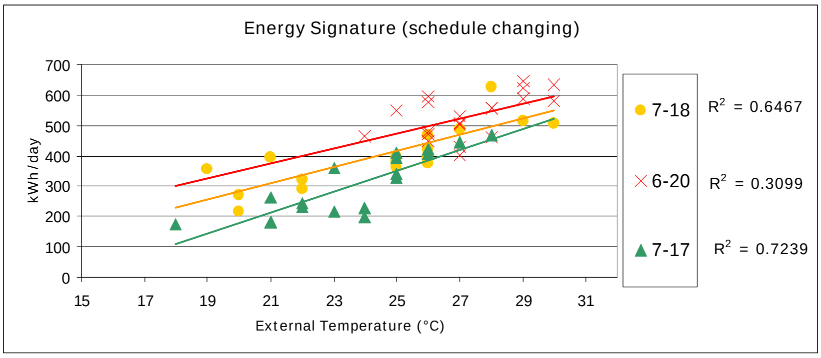


Case study 4: Effect of the operating schedule on a chiller electric consumption

The case study considers a public building equipped with a two-pipe fan-coil system, installed at the time of building construction (1970), coupled to a gas boiler and water-cooled electric chiller; the latter unit was replaced in 2002 and is in good overall maintenance status. In consideration of the low thermal capacity of the building, the study was focused on assessing the effect of a reduced system operational schedule. An electric meter was installed on the chiller, to measure the hourly consumption; the chiller operates six days a week (at reduced load on Saturdays), while it is completely shut off on Sundays.

Three different operating schedules, each applied for about four weeks, were adopted to investigate the effects of varying the chiller on-period: A: 11 hrs ON (7:00-18:00); B: 14 hrs ON (6:00-20:00); C: 10 hrs ON (7:00-17:00). The monitoring results are summarized by the three energy signatures of Figure 12, each referred to one of the chiller operation schedules. The temperature dependence of electric consumption is fairly linear, with acceptable correlation coefficients (particularly for schedules A and C), and exhibits comparable trends, ranked as expected for increasing operation ON-times. Taking into account the statistical distribution of temperatures, it that, by reducing the chiller operation time from 14 hrs/day (B) to 11 hrs/day (A), a 20.7% reduction of chiller mean daily consumption was achieved; a further reduction to 10 hrs/day (C) increased the savings to 22.1%. These values correspond to average savings of 6.2% per hour of daily operation reduction.

Figure 12. Chiller electric consumption vs daily mean external temperature



Refrigeration equipment performance analysis

The experimental analysis of water chiller or heat pump performance requires specific instrumentation which allows the measurement of the thermodynamic conditions of the refrigerant fluid and the electric input to the compressor and auxiliaries. The instrument that was used by the authors [7] is equipped with refrigerant fluid pressure gauges (compressor inlet and outlet) and temperature sensors (refrigerant temperature at compressor inlet / outlet, and condenser outlet; secondary water at condenser inlet / outlet); the temperature sensors are clamped on the fluid pipes, while the pressure gauges must be connected to the dedicated ports present in most refrigeration equipment. In addition, the instrument is connected to two power meters, to log the electrical consumption of up to two compressors. A data base of the thermodynamic properties of the refrigerant fluid is provided, yielding the refrigerant saturation temperature values corresponding to the measured pressures. This allows the determination of meaningful operative parameters, such as vapor superheating at the evaporator outlet, and fluid subcooling at the condenser outlet. For the estimation of the isentropic efficiency of the compressor, an assumption must be made on heat exchange in the compression phase.

The above data make it possible to draw the actual thermodynamic cycle and to calculate the enthalpy difference between compressor inlet and outlet: based on this figure, and by estimating the electric and mechanical efficiencies of the compressor and motor, it is finally possible to determine the system COP and refrigeration flow rate, using the measured value of the electric energy consumption of the compressor motor. The above described instrument may therefore be employed both as an energy evaluation and diagnostic tool, for identifying system faults such as evaporator or compressor fouling, insufficient refrigerant charge, or poor compressor efficiency. These defects can be readily corrected with maintenance actions, therefore achieving significant energy savings [8].

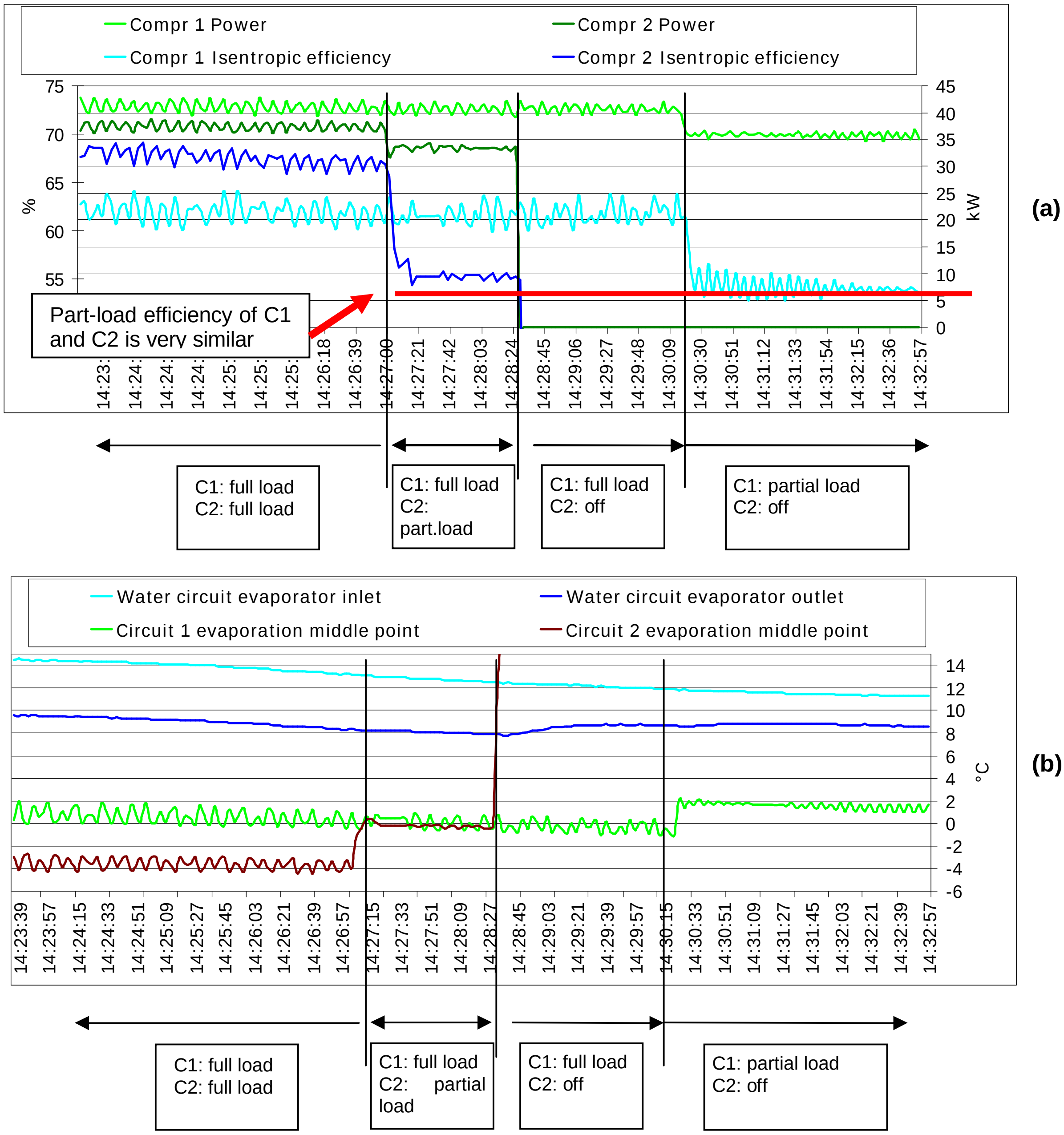
Case study 4: Performance analysis of an open-loop water-condensed electric chiller

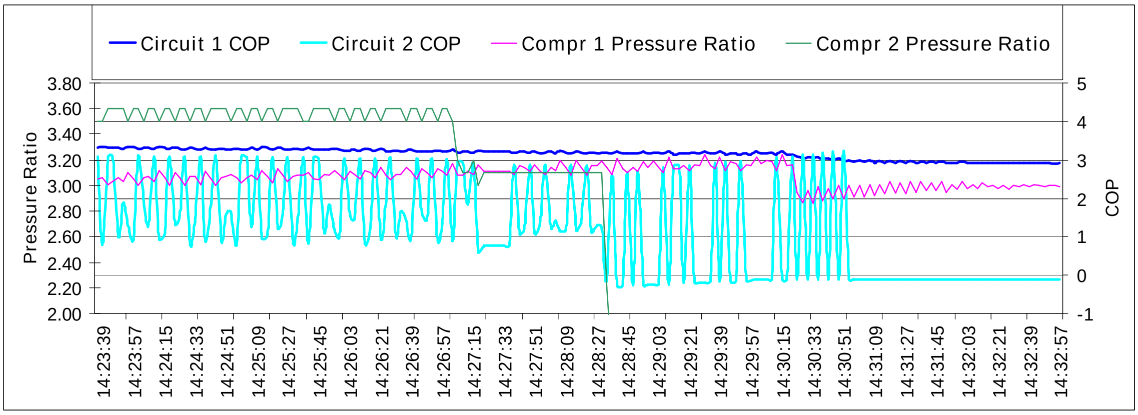
The first analysis presented in this paper was performed on the electric chiller of case study n. 4. The unit assessed is a water condensed chiller, using underground water as the cooling medium. The unit consists of two refrigerant circuits, each including compressor and evaporator, connected to a single condenser. The compressors are of the reciprocating type, with multiple cylinders and suction and discharge valves, and can operate at two load levels, thus allowing four degrees of partialisation. Previous to the performance assessment, the HVAC system was inspected following the HARMONAC guidelines and inspection methodology. The inspection results, for the considered chiller, showed a good state of maintenance. No sign of oil leakages was detected. Prior to the test the unit was considered perfect. The assessment data (Figures 13), however, showed that some operating parameters were critical, and that the unit performance was not always satisfactory.

Figure 13a shows the electric power input and the isentropic efficiency of the two compressors under different load conditions. Figure 13b shows, for the same operating conditions, the chilled water temperatures at the evaporator's inlet and outlet, and the refrigerant fluid temperature in the two evaporators. Finally, Figure 13c indicates the two circuits COP and compression ratio. The experimental data reveal that:

- At full load, the power input to compressor n. 1 (C1) is very close to its nominal value (39.45 kW), while the corresponding value for compressor n. 2 (C2) is about 10% lower; in terms of isentropic efficiency, C2 is about 5% more efficient than C1. At partial load, the performance difference between C1 and C2 is very small, both in terms of isentropic efficiency and input power (see Fig. 13a). Probably, the lower C2 performance at full load is caused by problems in the cylinders that are disconnected at part load.
- Circuit 2 is likely to have a low refrigerant charge, which explains the lower evaporation temperature (around – 4°C, with risk of freezing at the water side, see Fig. 13b), and unstable COP values, caused by continuous flash evaporation (Fig. 13c); the same graph also indicates that C2 has a higher pressure ratio than C1. A correct charge would increase the evaporation temperature with an increase in COP on the order of 3-5%/K.
- Other monitoring results (not shown in the graphs) also reveal an excessive superheat at the evaporator's outlet, which may be corrected by adjusting or replacing the expansion valve.

Figure 13. Case Study 4: Chiller parameters logged



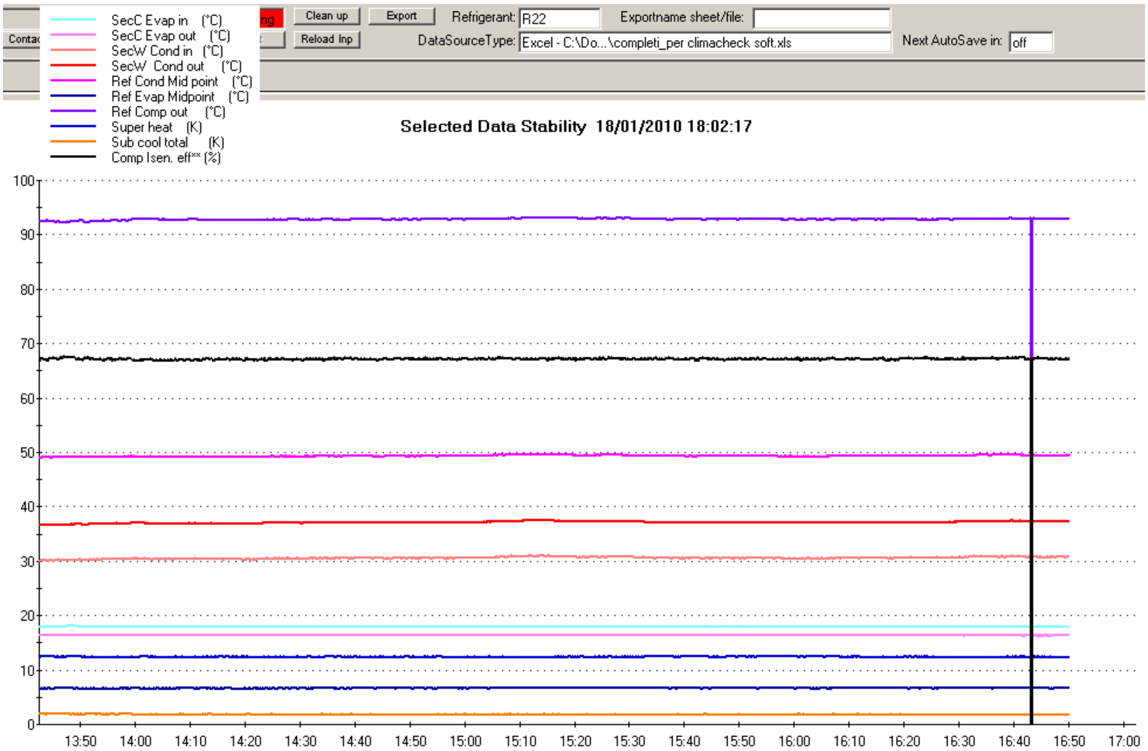


(c)

Case study 5: Performance analysis of an water-condensed chiller with evaporative tower

The second analysis refers to the electric chiller of Case Study n. 5. The unit assessed is a water condensed chiller installed in 1996. The unit is composed by two refrigerating circuits, served by two compressors, two condensers and a single evaporator. The compressors are of the reciprocating type with multiple cylinders and suction and discharge valves. Results are presented in Figure 14.

Figure 14. Case Study 5: Chiller parameters logged



The analysis shows that:

1. The ΔT in the evaporator between evaporation dew point and cool water outlet is very high, more than 10 K. A good system would have 3-5 K. The high value of the ΔT is probably caused by the high value of the superheat (12.4 K). Decreasing the value of the superheat appears to be a good solution to increase the temperature of evaporation. Experimental data indicate that for every degree of evaporation increase, the capacity and COP increase almost by 3-5% [7].
2. The ΔT in the condenser between outlet gas temperature and condensing water outlet is very high, more than 10 K. A good value for a new condenser would be 2 K and an adequate value