Energy and Buildings 123 (2016) 17–33

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Energy improvement of office buildings in Southern Europe

A. Kyritsis [a,*], E. Mathas [a], D. Antonucci [b,c], M. Grottke [d], S. Tselepis [a]

[a] Centre for Renewable Energy Sources and Saving (C.R.E.S.), Dept. of Photovoltaic Systems and Distributed Generation, 19th km Marathonos Av., 19009 Pikermi, Athens, Greece
[b] EURAC, Institute for Renewable Energy, Viale Druso, 1/Drususallee 1, 39100 Bolzano, Italy
[c] Faculty of Science and Technology, Free University of Bolzano, 39100 Bolzano, Italy
[d] WIP Renewable Energies, Sylvensteinstrasse 2, 81369 Munich, Germany

ARTICLE INFO

Article history:
Received 17 September 2015
Received in revised form 11 March 2016
Accepted 13 April 2016
Available online 22 April 2016

Keywords:
Balanced energy buildings
Active energy-saving measures
ICT
Intermittent RES
Electricity and
Thermal storage systems

ABSTRACT

This paper highlights the potential of adapting the energy profile of conventional office buildings in Southern Europe into a profile of Balanced Energy Buildings. The proposed energy adaptation does not only aim to satisfy the electricity consumption on an overall annual basis using intermittent renewable energy sources (RES), but seeks for a better instantaneous match of the on-site demand of the building with the production from RES. The self-consumption of locally generated clean electricity shall be maximized and peaks in energy transactions between building and grid are to be reduced. The aforementioned targets are pursued with the utilisation of intermittent RES (mainly solar PV systems in Southern Europe), active energy-saving techniques supported by ICT (Information & Communication Technology) technologies and energy storage systems. Beyond this, attention is given to the indoor climate comfort.

1. Introduction

The energy consumption of a building depends on many factors, such as the kind of building use (e.g. residential or non-residential), the utilization profile, the climatic conditions, the thermal transmittance of the building materials, the architecture implemented (bioclimatic/passive or classical), the aging, the type and efficiency of heating/cooling systems installed and the behavior of building's users (internal comfort settings, application of energy saving principles, etc.). In addition, and unlike domestic buildings, the rest of the building stock presents highly heterogeneous characteristics of energy consumption, according to type of use [1–4].

Several scientific groups studied energy-intensive aspects of functional behavior of buildings and suggested applied solutions to increase their energy efficiency, utilizing techniques such as passive solar design, natural cooling and ventilation, heating and cooling using geothermal and/or solar heat systems. The aforementioned solutions in combination with the use of low thermal transmittance building materials and RES technologies, led initially to low-energy buildings and then to Zero (or nearly Zero) Energy consumption Buildings (ZEB, NZEB) and Life Cycle ZEB (LC-ZEB) [5–10].

A ZEB building produces the energy consumed during a year by utilizing RES. However, it is still connected to the Low Voltage (LV) grid. i.e. the building supplies or absorbs energy to/from the network serving the energy balance, as it is defined by the equilibrium of RES power generation and electricity consumption [7,11]. Although the building limits its energy dependence and operation burden on the grid (with reduced electricity needs and therefore reduced transport electric losses), it can adversely affect the quality of voltage (in case of widespread application of ZEB), since it causes repetitive sequences of production/consumption high peaks to the grid [12]. It is worth noticing that the Directive on Energy Performance of Buildings, suggests that from 2018 onwards, all new public buildings (owned or rented) should behave close to "ZEB" [13]. Last but not least, considering that the most favored reporting period for the calculation of energy autonomy is the annual basis, it is evident that the energy self-sufficiency occurs in an accounting basis and not in real time.

This work focuses on the improvement of the energy behavior of buildings that are used as offices, a sector that covers approximately 23% of the total surface of non-domestic buildings in the EU-28 [14,15]. The proposed energy improvement does not only provide social-economic benefits to building users and managers (bringing important reductions in energy bills and CO_2 emissions),

* Corresponding author.
E-mail addresses: kyritsis@cres.gr (A. Kyritsis), emathas@cres.gr (E. Mathas), Daniele.Antonucci@eurac.edu (D. Antonucci), matthias.grottke@wip-munich.de (M. Grottke), stselep@cres.gr (S. Tselepis).

http://dx.doi.org/10.1016/j.enbuild.2016.04.032
0378-7788/

but also provide benefits to distribution network operators (reducing electricity needs and achieving better instantaneous match of the on-site demand of the building with the production from intermittent RES). More specifically, the selection criteria for the energy improvement were the following two:

The energy improvement seeks to achieve more than 20% energy savings in annual consumption incorporating ICT concepts and known solutions from the literature [16–21], as well as to satisfy thoroughly the electrical demand of the building (on an overall annual basis) utilizing intermittent RES. Initially, a methodology is introduced in order to measure and evaluate the energy behavior of the building, then energy saving measures are selected, and finally average savings and comfort impact are evaluated. The results are presented in an indicator format allowing for a direct comparison of findings with those of other buildings of similar use. The most common international indicators are the density of energy consumption per unit of surface area and volume (kWh/m^2, kWh/m^3) or per occupant of the building (kWh/occ). Furthermore, the heating/cooling degree-days (HDD/CDD) are used in order to compare measured magnitudes with those of corresponding subsequent periods. The HDD and CDD are useful for the computation of the savings on heating/cooling systems (kWh/m^2 × DD_factor), since they limit the impact of other factors independently from the intervention (e.g., weather, utilization).

On the other hand, the energy improvement pursues a better instantaneous match of the on-site demand of the building with the production from intermittent RES. In more detail, the self-consumption of locally generated clean electricity shall be increased and peaks in energy transactions between building and grid are to be reduced. These aspects are very important for the electrical grid undisturbed operation and will become more critical in the near future where the electricity generation will shift from few and large classical dispatchable units to many smaller intermittent RES, while several buildings will behave as ZEB, causing energy redirection conditions [22–25]. Thus, electricity and/or thermal storage systems are considered in order to smooth power peaks in production and demand due to the frequent switch on/off character of heating/cooling systems.

The results presented in the next sections stem from the application of the aforementioned energy improvement at the building of the Department of PV systems and Distributed Generation (Dept. of PVs & D.G.), belonging to the Greek Centre for Renewable Energy Sources and Saving (CRES).

2. Building characteristics—data acquisition and utilization

The CRES premises are located at Pikermi—Athens (37°59.57′19″N, 23°55.38′ 60″E).The building which houses the Dept. of PVs & D.G occupies a total area of 300 m^2 and has a volume of 1290 m^3. The building was constructed according to the bioclimatic architecture rules, while the layout allows the formation of five fully-equipped offices with working space for eight persons. Two of them are equipped with working space only for one person (Office type 1), while the other three can accommodate two employees (Office type 2). Offices occupy only 12% of the total area of the building. The rest of the area is divided into three laboratory spaces (which are equipped with appropriate research equipment for conducting measurements in PV panels, batteries and electronic converters), a corridor and a kitchen. The power demand of the building is normally below 30 kW (including heating/cooling system operation) due to the stochastic use of laboratory equipment. Looking at Fig. 1, which shows the building's electric plan, the loads are served via three separate low voltage (LV) lines. The first three-phase line – through the distribution panel termed 'Instruments'– serves the electric loads of laboratories, part of the electrical needs of offices (lighting and fan coils) as well as other loads of the building (corridor lighting, kitchen equipment, etc.). The second single-phase distribution panel termed "U.P.S." feeds selected electrical loads in the building (computers, printers and security lighting), while the third distribution panel termed 'Heating/Cooling System' serves exclusively the "Interklima" heating/cooling Heat Pump (H.P.) system (model MPCA-013-HSD) having a nominal power of 14.3 kW$_{el}$ (54 kW heating power and 46.7 kW cooling power). The Interklima system provides heating and cooling to the building and comprises twin compressors and a circulator pump of 2.2 kW$_{el}$. The second compressor is activated only when the thermal load exceeds 50% of the overall heat pump system rated power.

Furthermore, the building features a ten year old solar PV system with a total capacity of 21.8 kWp composed of three subsystems: i) a 10.35 kWp subsystem (slope 30°, orientation 22.5°SW), ii) a 6.72 kWp subsystem (slope 45°, orientation 0°S) and iii) a 4.73 kWp subsystem (slope 90°, orientation 22.5° SW).[1] The selection of slopes and orientations of subsystems was not based on maximizing annual production, but to demonstrate various options for the integration of solar PV into buildings, as well as to provide shading to the building (especially during the summer period). The annual energy production of the PV system is estimated to be roughly 24 MWh and the relative production index is 1.1 MW$_{el}$/kWp. The produced energy is not consumed directly in the building but is fed into the grid via a separate 20 kV/400 V transformer, as shown in Fig. 1 (Feed in Tariff scheme). The next sections explore the solar PV system operation in a Net Metering status in order to assess the possibility of adapting the building's energy profile to the proposed model of Balanced Energy Buildings.

In order to explore the possibility of total or selective (partial) energy balance between electric loads and PV energy production as well as the possibility of limiting the peaks on the building's power exchanges, power analyzers were installed on all building's electrical supply points as well as on the PVs Distribution Board. Fig. 2 shows the power analyzers (used for the monitoring of power flows and the development of building's electricity profile), the sensors used to record external and internal environmental conditions of the building in areas that were selected as reference positions, as well as the monitoring system for the basic operating characteristics of the heating/cooling system. Data access is accomplished in real time on the Internet together with data storage and processing capability via the digital transmission platform "FAR ECHO" of FAR Systems [26]. The web based "FAR ECHO" energy monitor enables a detailed study of time series of both electric power consumption and PV system production, internal conditions (temperature, humidity, brightness, CO_2 concentration levels, presence) and the building's external environmental conditions (temperature, humidity, wind direction and speed, solar radiation and rain precipitation). The data are stored as five minute average values, a resolution which is satisfactory for a sufficient correlation between the energy production, the energy demand and the environmental conditions.

A full data series of the year 2013 was recorded as a reference period. The findings obtained were used to select the energy saving measures for the building and for programming the intelligent energy-saving controllers (based on the SmartStruxure^{TM} series made by Schneider Electric). Then, after incorporating the energy saving interventions, a full data series was recorded for the year 2014 as well.

[1] Installation realised in the framework of the EU funded FP5 project "PV Enlargement".

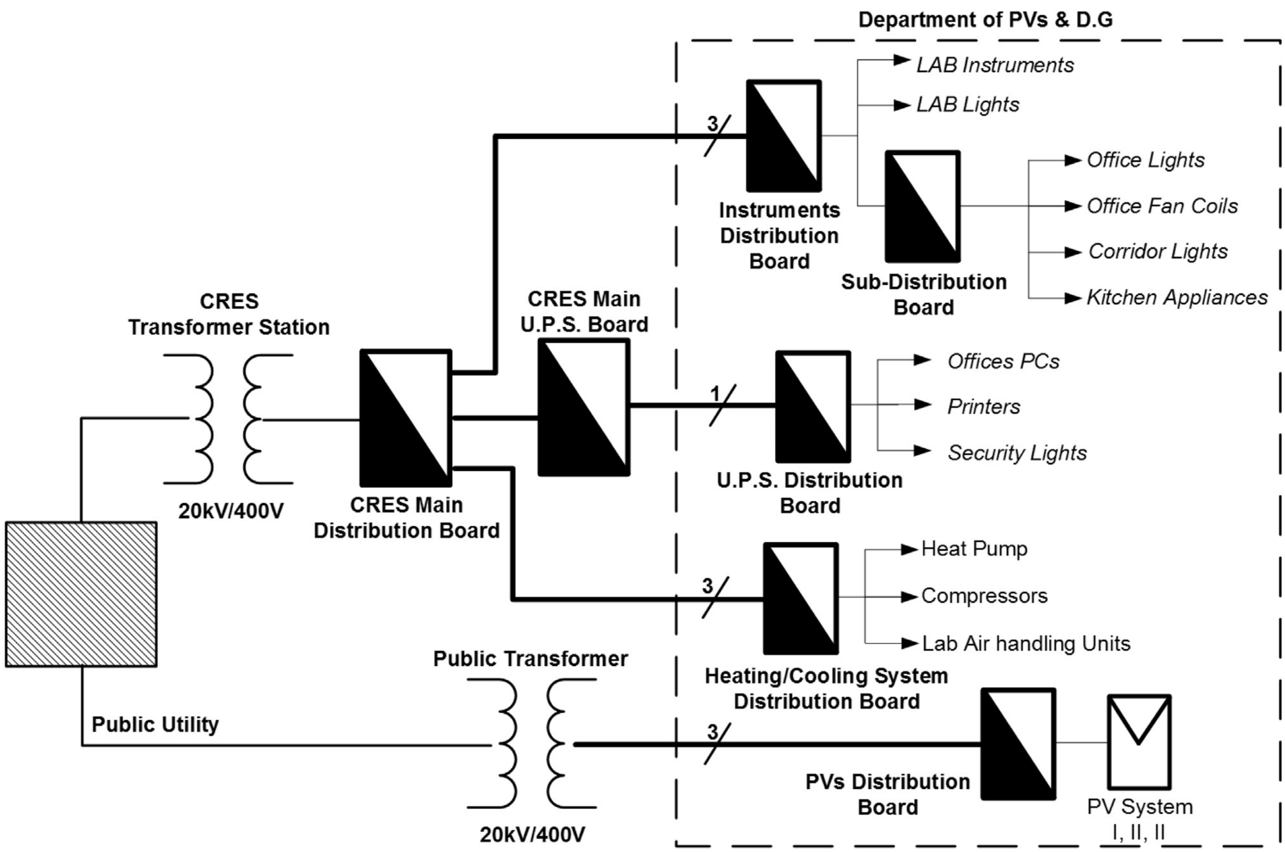

Fig. 1. Power supply plan of building.

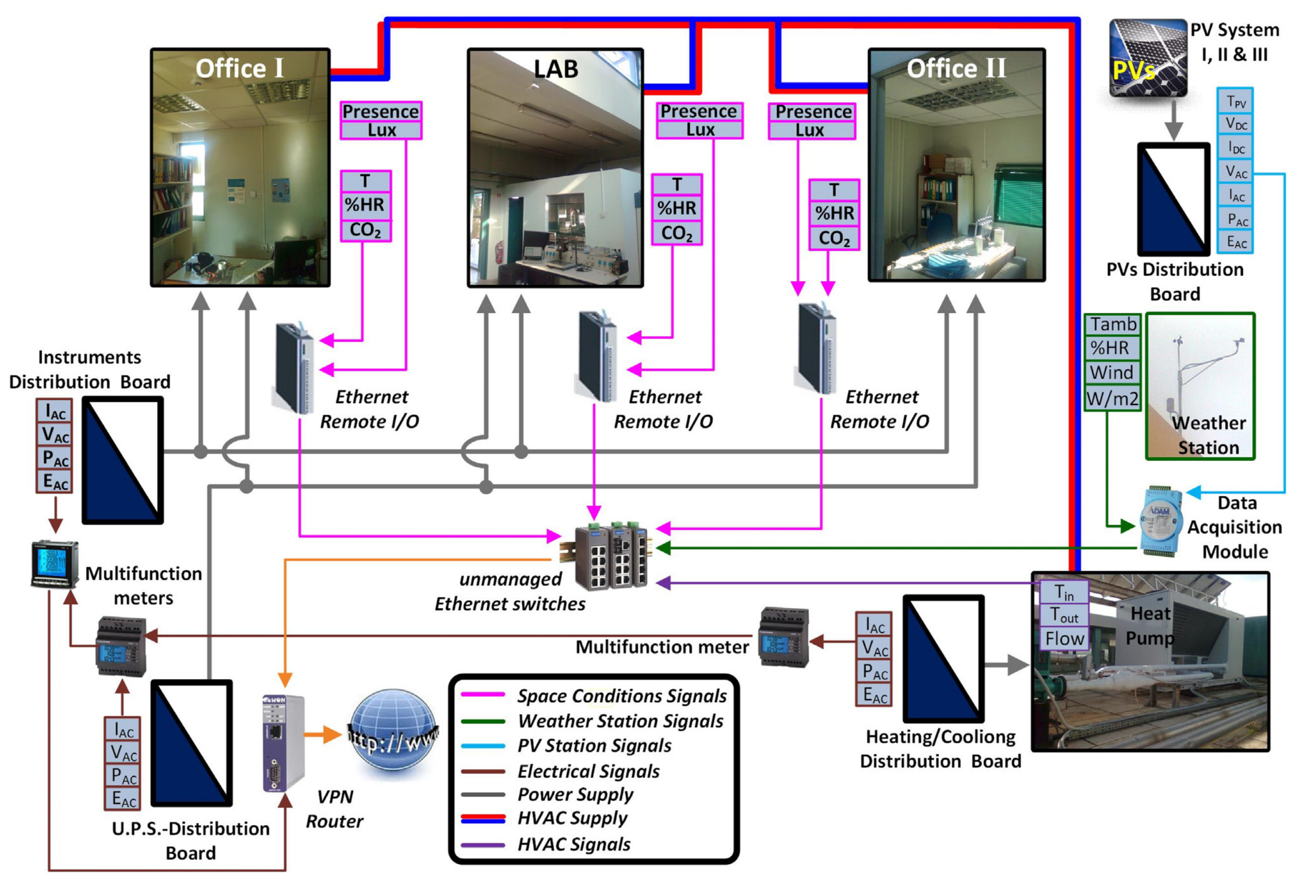

Fig. 2. Plan showing the position of the power analyzers and sensors used to monitor power flows, internal and external environmental conditions of the building.

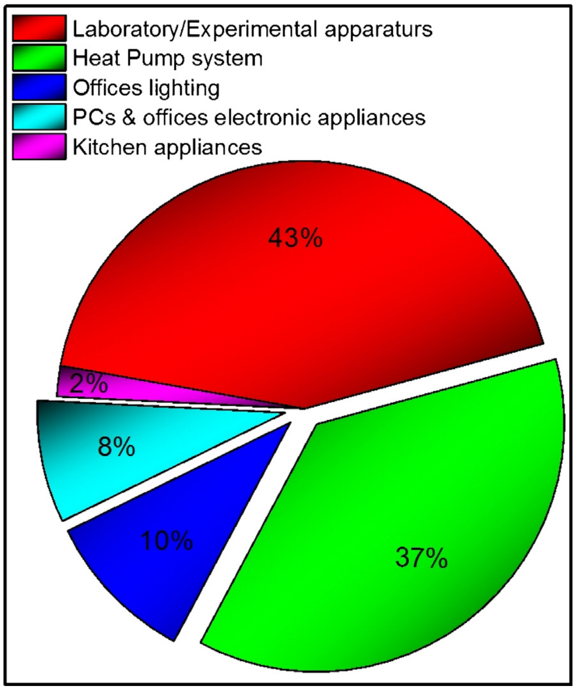

Fig. 3. Allocation of the electricity consumption for the baseline year.

3. Energy data evaluation and saving measures for energy upgrade

This section presents the main conclusions drawn after a thorough analysis of the time series of electric power consumption and PVs production, for the base year 2013, as well as the energy saving measures that have been adopted to improve the energy efficiency of the building.

On the basis of energy density indicators per unit area, the total electricity consumption for the baseline year 2013 was 59 kWh/m^2/year, of which almost 37% was spent on the electricity powered heating/cooling system, 8% in loads that are served from the uninterruptible power supply (U.P.S.), 53% in lab as well as in the lighting and general plug loads of the building (Lights and Appliances) and the remaining 2% in kitchen appliances. The kitchen appliances consumption was not measured but estimated according to the power consumption and the utilization profile of each apparatus. In accordance with the studies [27,28], for office buildings that have improved the efficiency of lighting, heating and cooling, the plug load energy use for computers and office equipment it can represent a large amount of the total electricity use. Considering that the U.P.S. system in the Dept. of PVs & D.G serves almost exclusively computer systems, printers, etc., it is presumed that computers and electronic appliances consume almost 8% of the total energy consumption. At this point it should be noted that the building did not house a server station. Furthermore, the offices lighting consumption was not measured but calculated according to the power consumption of each lighting fixture, the ballast efficiency (high-performance magnetic ballasts—class B1) and the lighting profile of each office. The lighting profile (measured in hours) of each office was calculated using the data of the monitoring equipment. According to the full data series for the lighting operation hours of the year 2013, the energy consumed in the offices lighting was almost 10% of the total energy consumption and thus the laboratory/experimental apparatus consumed the rest 43% of the total energy consumption. Fig. 3 shows the allocation of the electricity consumption for the baseline year.

The energy produced by the PV system was 79 kWh/m^2/year, while at a monthly level was always higher than electrical consumption, with the exception of the winter months. The most energy intensive month of winter 2013 was January, where the net energy transactions with the electric network did not exceed 2.3 kWh/m^2 (for the whole month). Consequently, the bioclimatic architectural design of the building and PVs sitting serve the requirements of “nearly ZEB” not only on an annual basis, but in addition for nine calendar months. Moreover, according to the baseline year data, it is evident that real time instantaneous self-utilisation of PV generated electricity is difficult to be achieved with load control/shift techniques, since laboratory loads are not flexible and they are governed by the personnel’s daily activities. Last but not least the solar PV system output self-utilisation on an overall annual basis was calculated to be 53%, while the minimum and maximum values on a monthly base were 22% (in May 2013) and 89% (in January 2013) correspondingly.

As regards to the energy consumption of the heating/cooling Heat Pump system, it is difficult to adopt general recommendations for its reduction, since it strongly depends on factors such as the heating/cooling system technology, piping network size and the climate zone of the building. In this work we did not examine the possibility to reduce the thermal needs by improving the building thermal envelope, but we decided to use motorized three way valves on the building’s fan-coils. Three way valves activation is governed by intelligent controllers and ICT devices, taking into account presence/absence in the building’s spaces, the room’s temperature and a temperature reference setting. It is worth noticing that the aforementioned control was performed in two of five office rooms only. Thus, the savings obtained relate only to the ICT system installed in selected rooms. The saving on building level is calculated by extrapolating the achieved savings on the two office levels to 5 offices. Considering that office buildings typically operate at 10% to 40% below heating/cooling system designed capacity, a better operation setting of the heat pump was pursued by trimming both the temperature and the flow rate of the water [7,25,29]. Specifically, lower temperatures in the evaporator lead in a lower cooling capacity, and the effect of ambient temperature is a significant change in the power requirements for compressor operation [30,31]. Thus in case of cooling operation, the water outlet temperature was set at 10 °C compared to the initial value of 7 °C increasing the system cooling capacity by 5.7 kW (at 35 °C ambient temperature), as well as the cooling generation efficiency. Moreover, a small decrease on the water flow approximately by 15% compared to the previous set point (the initial value was set to the maximum water flow value of the system—10041 L/h-), resulted in increased heat pump system efficiency [19,32]. Unfortunately, the volume of the already installed water tank (220 L) is small compared to the theoretical needed volume, resulting in frequent on/off operation of the compressor. Specifically, assuming: a) a desired H.P working interval of 60 min, b) the maximum H.P. output (as given by the manufacturer in BTU/HR), c) the minimum heat load of the building (calculated according to DIN 4701) and d) the allowable temperature difference of 2.5 °C, then the recommended capacity of the water tank should be roughly 1300 L [30,31]. Fig. 4 depicts the Heat Pump based cooling circuit water temperatures in a typical hot summer day after application of the new temperature set point. The maximum temperature difference at input and output of cooling circuit was never higher than 2.5 °C (during working hours), while the deviation between the real temperature of the cold water and the set point temperature was always lower than 1.5 °C. Correspondingly, for the heating operation, the water outlet temperature was set at 40 °C compared to the initial value of 45 °C, leading to increased system heating capacity by 1.3 kW (at 7 °C ambient temperature – reference value –) and decreased absorbed

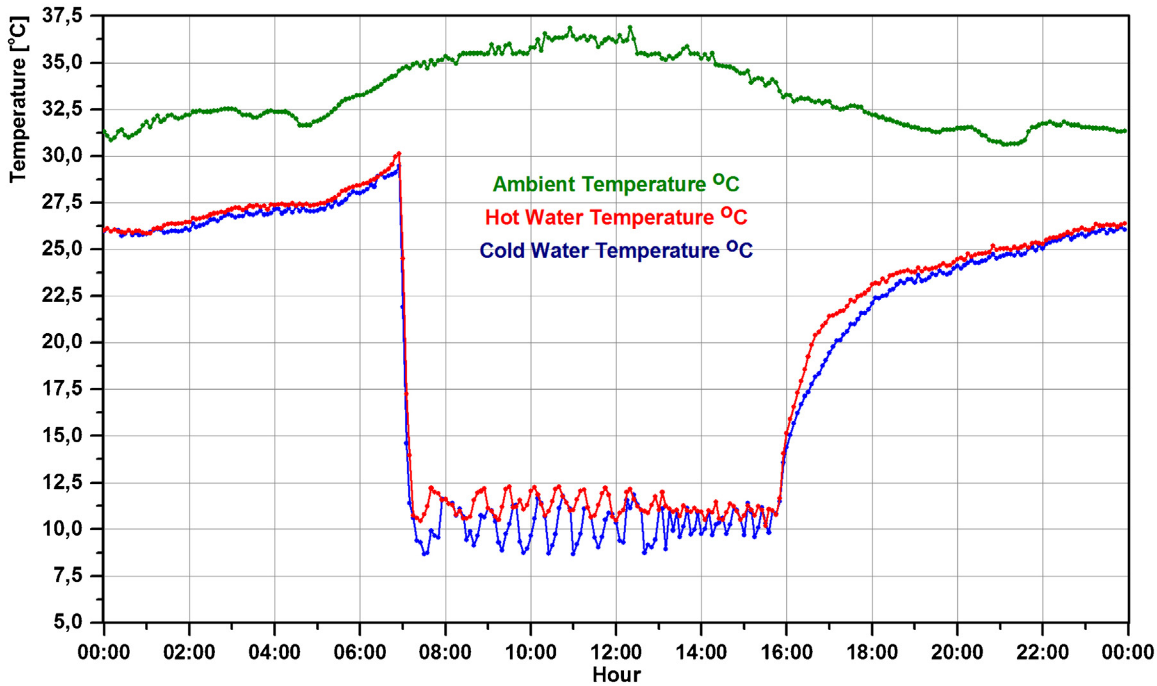

Fig. 4. Daily cooling circuit water temperatures (in/out) profile during summer time.

peak electricity power by, 1.8 kW. Furthermore, the piping network of lab spaces is switched off automatically if labs are not used for more than two hours. A further increase in heating/cooling system savings can be achieved if the ventilating speed of the fan coils are controlled with optimized PID controllers (appropriate selection of proportional and derivative coefficients) [33]. Currently, the ventilating speed can only be adjusted between three speeds.

Additionally, in order to reduce lab space's cooling needs during the summer period, it was decided to maximize natural cooling intervals utilizing the bioclimatic features of the building and ICT devices. Specifically, during night-time, ambient temperature is compared with the temperature of the warm air-mass trapped in the lab's ceiling level height and if the measurements of the wind speed and rain detector allows, skylight windows are opened to provide natural cooling. Comparison of internal and external building temperature is done with an hysteresis logic in order to avoid unnecessary activations/de-activation of skylight windows. Finally, suitable control functions are used in order to avoid opening of skylight windows in a case of fire.

Authors in several works have identified that lighting energy demand constitutes a consumption component with high energy saving potentials, [17,20,34–36]. In this work the energy saving measure selected was the installation of lighting control based on occupancy sensors and offices brightness values. The adaptation of the operating behavior of the lighting fixtures in offices led to the establishment of a minimum tolerable brightness of 300 Lux (level at which they are activated in case of presence in the office), while they are disabled in absence or when the difference between the actual value of office brightness compared to the fixture luminosity (measured in total lack of natural lighting) leads to a result higher than 400 Lux. A further increase in savings can be achieved if the fluorescent lamps of offices are replaced with LED luminaires.

In order to limit electrical consumption of office plug loads, energy saving functions on screens and printers were activated, while at the same time, the operating time of PCs in full function is reduced for time intervals were are not in direct use (devices switched to low power mode after 5 min of inactivity) [17,27]. As it concerns the new energy efficient electronic devices it seems that there is no room for improvement [2].

At this point it should be noted that the energy saving measures are governed by "SmartStruxure^{TM} series" intelligent controllers, while thanks to the presence of the monitoring equipment it is possible to perennially improve their operation.The selected saving measures are not radical solutions but technically, functionally and economically feasible for all buildings that undergo major renovation. The saving measures are possible to be applied either at the whole building or at a renovated part only. The impact of these measures on the energy performance of a building depends on many factors such as the building envelope, the extent to which the building is illuminated with natural light, and the Life-Cycle cost of alternative high-efficiency solutions.

4. Saving quantification and comfort impacts

What follows next is the evaluation of electrical savings results as well as comfort aspects, following the application of the selected improvement measures for one complete year (2014). The consumption is divided into two components on the basis of which energy efficiency is improved: the heat pump and both lighting and building electrical appliances.

Generally, in Pikermi the HDD and CDD vary significantly from one year to the other and the average variance could be higher than 25% as shown in Fig. 5. High variations of HDD and CDD may lead to high variations in annual energy figure normalizations. For this reason, it was decided not to consider the average of Degree Days of a long period (8 years) but only of the last two years: 2013/2014 and 2014/2015. In these last two years the Degree Days profiles are almost similar (8% difference- the value of degree days considered in the evaluation is 1036,943).

The calculations of HDD and CDD are made according to the European Environment Agency (EEA) which calculates HDD as:

$$(18 - \mathrm{T}) \times \mathrm{d}$$

where:

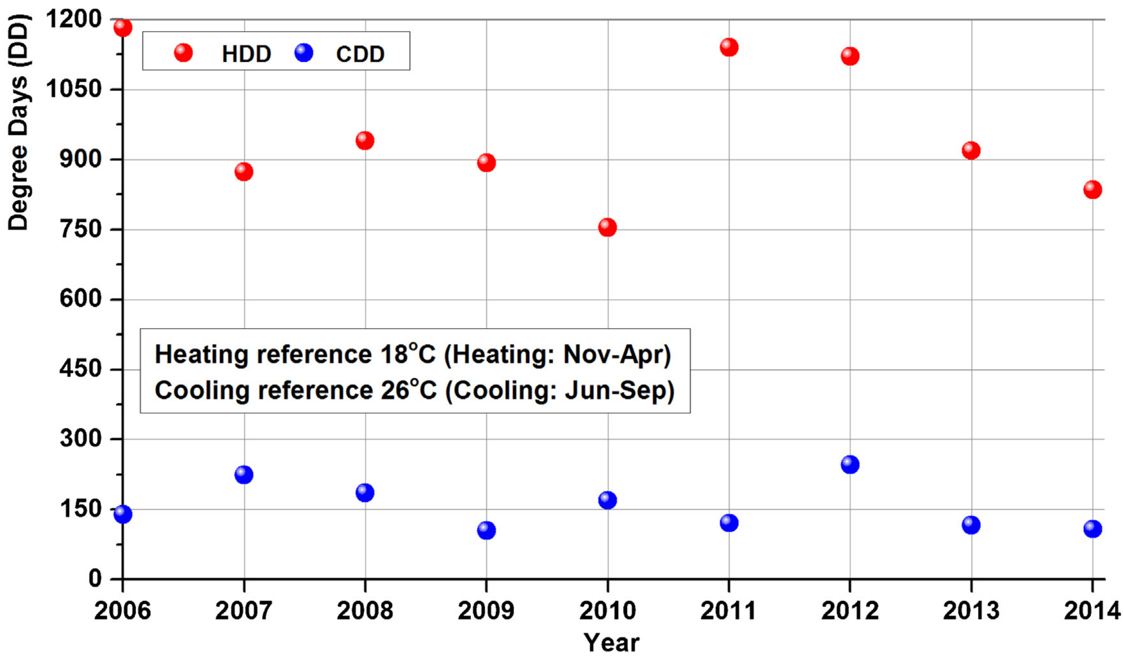

Fig. 5. Heating Degree Days (HDD) and Cooling Degree Days (CDD) of the last 8 years in Pikermi.

T: is the indoor daily average temperature in Celsius. It could be calculated as the average of the hourly monitored indoor temperature. Only values less than or equal to 15 °C are considered. Therefore, if T is higher than 15 °C, the value of HDD is 0.

d: number of days

Similarly, the CDD is a measure of how much (in degrees), and for how long (in days), the outside air temperature is above a certain level set at 26 °C. Different from the HDD calculation, all the values of outdoor temperature above the 26 °C are considered to calculate the CDD [37].

Fig. 6 shows the monthly energy comparison of the heat pump between the baseline period (from February 2013 to January 2014) and the reporting period (from February 2014 to January 2015) normalized with the DD factor. DD factor represents both the Heating and Cooling Degree Days factor for a specific evaluation period and it is calculated as the ratio between the DD of the selected month and the DD average of the same month in the current and previous year. It is evident from the study of Fig. 6 that the heating/cooling system has strong seasonal trends as a consequence of Southern Europe climatic characteristics (limited operation in spring and autumn due to mild weather). The application of improvement measures on the heat pump shows a general reduction of energy consumption in almost all months. The high consumption during June 2014 is due to a week's missing data whereas in November 2014, the HDD factor together with the different occupancy profile of the building caused lower consumption in this month.

For this reason, an average evaluation has been done considering the average value of electricity consumption during the heating and cooling season and presented in Fig. 7. In this way the big variance of Degree Days in some months has been leveled in the average value. By comparing the two periods, the energy saving reached is almost 17%. As it has been mentioned, the ICT control was installed in two selected rooms. By extrapolating the achieved savings on the two office level to 5 offices, the saving on building level is calculated to be 23%.

As far as the consumption of offices lighting is concerned, the saving of almost 25% showed in Fig. 8, is related solely to the reduction of the lighting operation hours due to the applied lighting control. The indicators of lighting consumption and energy saving in Fig. 8 were calculated considering only the surface area of offices (only 12% of the total area of the building).

Additionally, an assessment of Indoor Environmental Quality (IEQ) has been performed. The evaluation of IEQ takes into account only values of indoor temperature and humidity during the occupied hours of the building. Specifically, the internal comfort evaluation is based on the ASHRAE 55–2010. According to this, standard comfort is achieved for points inside the thermal zone (blue box for heating period and red box for cooling period). Each point is a combination between the operative temperature [°C] and the humidity ratio (gm water/gm of Dry Air). In CRES building, these graphs are based only on monitored data and due to the high cost of the monitoring system, only the air temperature of the room has been monitored. The operative temperature has been substituted by air temperature that can be a reasonable indicator of thermal comfort [38–41]. The hourly data are filtered based on hours with high activity (between 10am and 4pm) and presence of employee. According to the ASHRAE graphs (Figs. 9–12) the adaptation of the system was beneficial in the Office 2 for both, the heating and the cooling period.

In the Office 1 there is an improvement of the indoor comfort only during the cooling period while during the heating season the occupant of the office prefers to have a low temperature inside (less than 20 °C) penalizing the ASHRAE comfort graphs but not the satisfaction of the occupant. Occupants in both rooms were fully satisfied with the thermal control. Internal conditions are not fully covered in comfort windows for both years, but nevertheless the improvement/change after the application of improvement techniques is visible. Last but not least, during the course of the measuring campaign, the median values of CO_2 ranged from 350pm to 500 ppm in all offices and they never reached the alert threshold of 1000 ppm.

Figs. 13 and 14 depict the typical temperature profile in the course of a day and in the course of a week, respectively, of the office type 1 for February 2014. A typical day has been calculated as the average of all hourly values for each different day of the month and visualized in a daily and weekly graph. Analyzing in detail these graphs, it is noticed that during the first hours of each day, the temperature of the room is always lower than 18 °C. Mon-

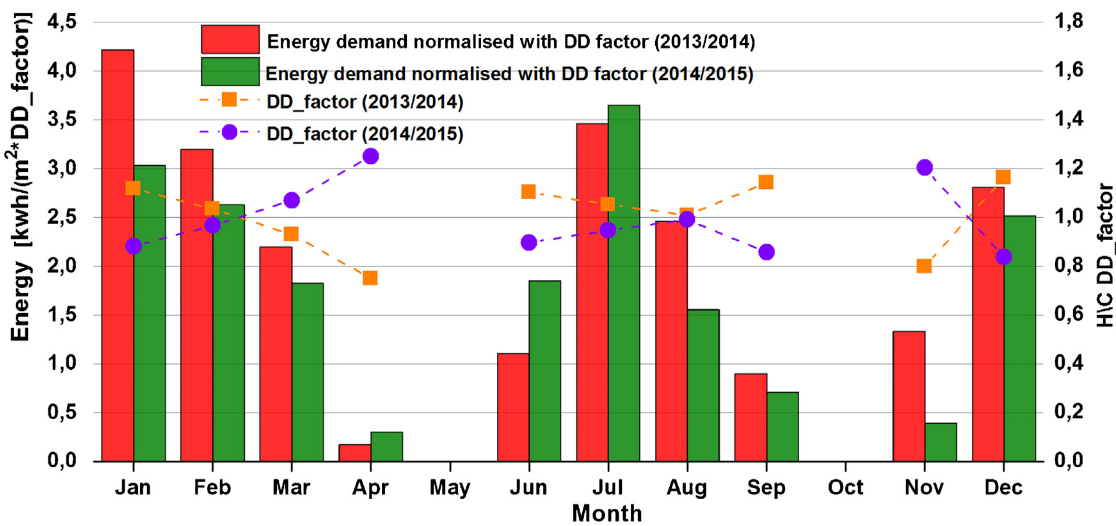

Fig. 6. Monthly heat pump energy demand before (February 2013–January 2014) and after (February 2014–January 2015) the activation of saving techniques normalized by the square meters of the building and the Heating and Cooling (H\C) DD factor.

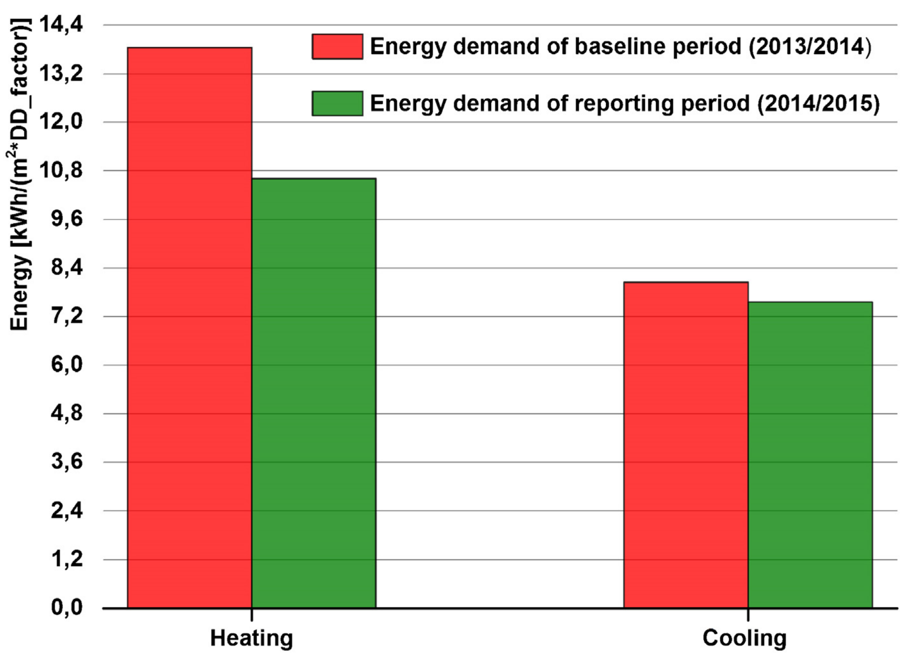

Fig. 7. Energy demand during baseline and reporting period both for Heating and Cooling season.

day is a critical day because the temperature in the early morning is always lower than the temperature of the other days. This situation is explained by considering the thermal production profile of the heat pump. Indeed the heat pump starts after the arrival of the first employee, resulting in a lower output of thermal energy than required to heat the building especially during the morning. Similar results were obtained for the office type 2 and for different seasons.

5. Increase of solar pv system output self-utilisation

In this section, an effort is made to define if and how the heating/cooling system can be matched with the production profile of a solar PV system. Initially, an electricity storage solution is presented which compensates the peaks in energy transactions between building and grid, while at the same time it increases the self-utilization of the solar PV system (PVs) output. Thereafter, a second approach is investigated, which is based on thermal energy storage systems.

5.1. Batteries—the electrochemical storage concept (esc)

Considering that PVs and Dept. of PVs & D.G. building is a representative case of building with local PVs production for Southern Europe, it was decided to focus on sunny summer days were PVs electricity production and air-conditioning systems demand take place simultaneously. However, it was found that even in such days there is significant energy exchange between the building and the public grid. This scenario was identified as a typical local (on-site) summer scenario for Southern European building cases with PV installations. It is worth noticing that during the specific time frame, electrical power systems encounter high electricity demand peaks, while the highest one takes place during midday and night (both due to the increased use of cooling systems). According to grid oper-

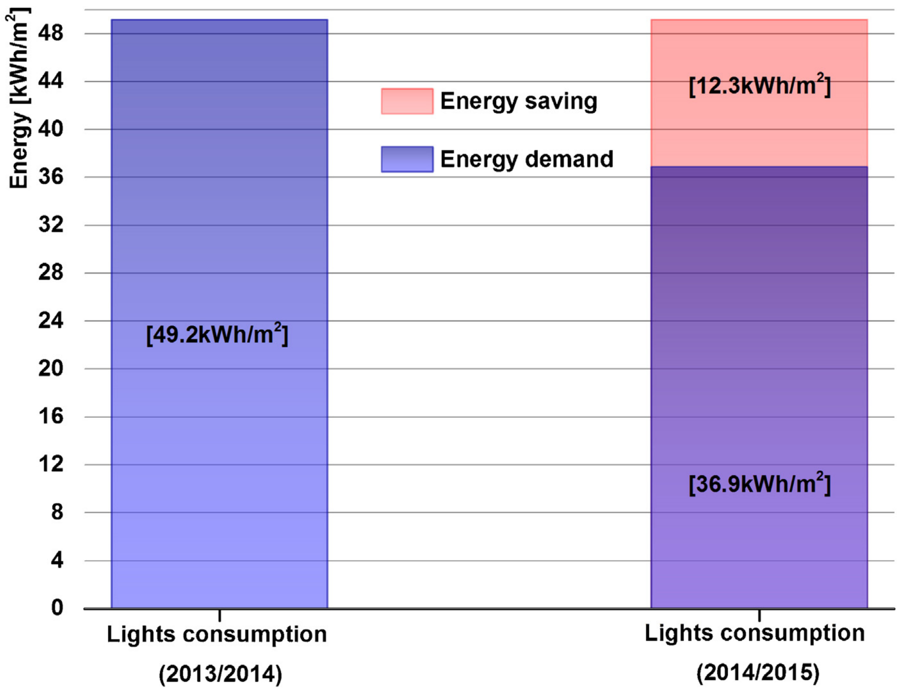

Fig. 8. Electricity consumption of lights during baseline (2013/2014) and reporting period (2014/2015).

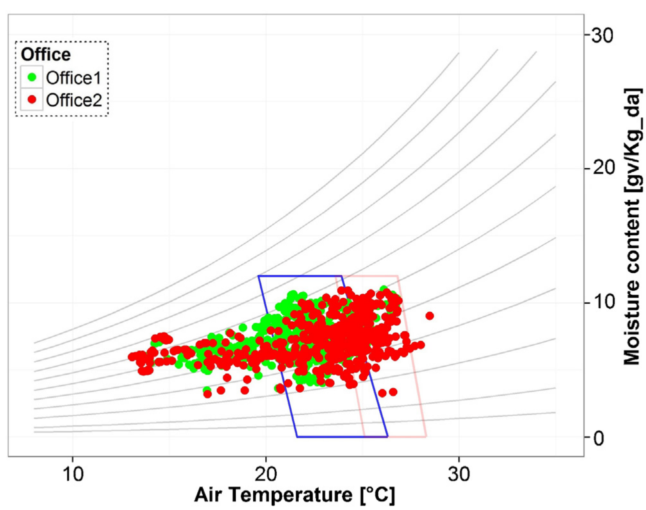

Fig. 9. Comfort zone during the heating period (2013). Each dot point is the hourly evaluation of air temperature and moisture content for two offices. The blue box represents the best comfort area during the heating season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ators, these demand peaks can possibly cause outage conditions for the electrical grid.

Assuming that PVs operate in a Net Metering scheme, Fig. 15 presents the power exchange profile of the building at PCC (Point of Common Coupling) on a typical summer day (during building working hours). A typical summer day has been created as the average of all working days of the summer. The building's power exchange profile is shown, resulting from the aggregation of the real data recorded by power analyzers at the inputs of i) Instruments Distribution Board, ii) Heating/Cooling System Distribution Board and iii) PVs Distribution Board). Power analyzers and the corresponding electrical board are illustrated in Figs. 2 and 3. It is recalled here that the electricity consumption and production data are stored as five minute average values, thanks to the presence of the monitoring equipment. Considering that the peak to peak fluctuation is almost 20 kW, voltage quality issues may arise on local LV electricity grids, depending on the LV distribution grid capacity and the consumption and/or production profile of the consumers that are connected to the same distribution transformer. Although it could not be argued that the peak demand occurs at the same time for all consumers that are powered from the same distribution transformer, we can certainly argue that PVs output maximum production occurs simultaneously for similar oriented solar PV arrays.

Fig. 16 shows the electricity consumption of the building on a typical summer day, as well as the energy output of PVs (real measurements). The electric consumption is divided into two components: a) Heat Pump system consumption in cooling operation (real measurements) and b) sum of lighting consumption (calculated according to the power consumption of each lighting fixture, the ballast efficiency and the lighting profile of each office), U.P.S. and other electrical loads of the building (real measurements).

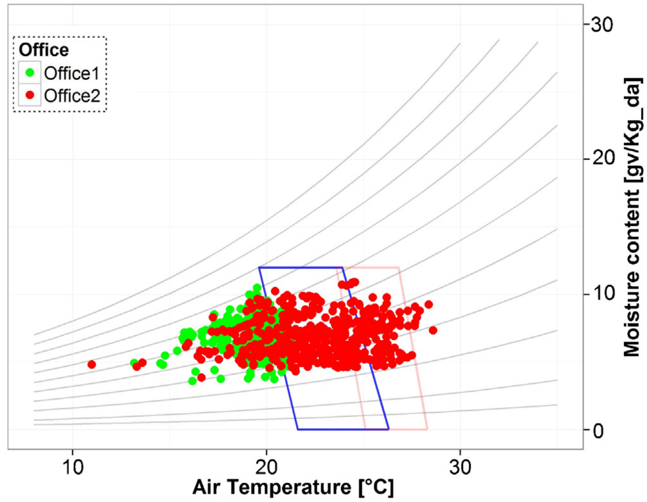

Fig. 10. Comfort zone during the heating period (2014). Each dot point is the hourly evaluation of air temperature and moisture content for the two offices. The blue box represents the best comfort area during the heating season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

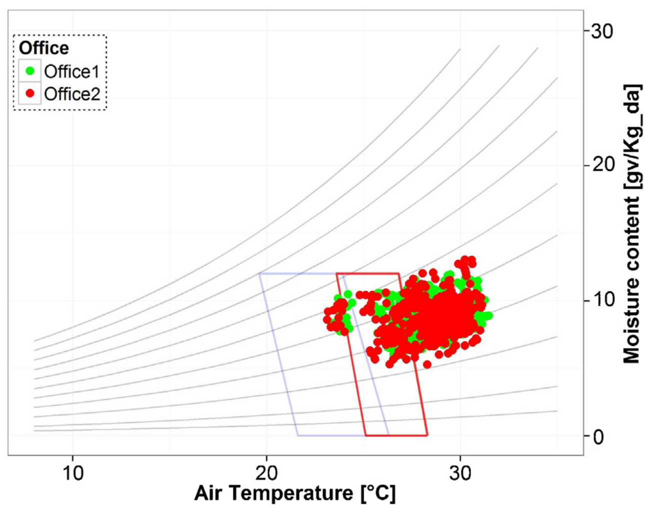

Fig. 11. Comfort zone during the cooling period (2013). Each point is the hourly evaluation of air temperature and moisture content for the two offices. The red box represents the best comfort area during the cooling season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

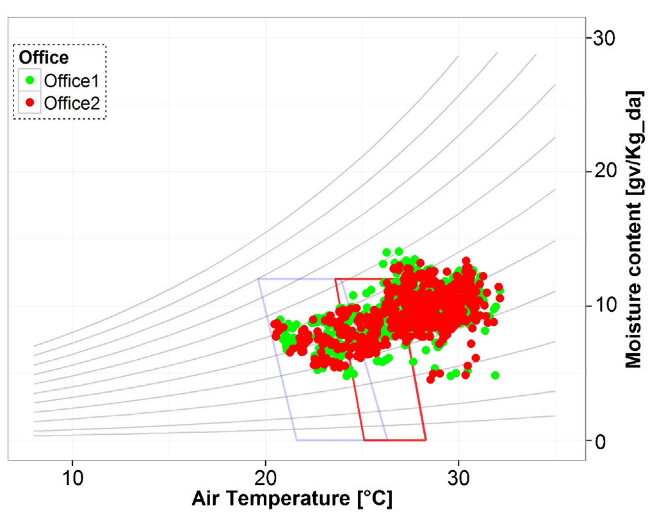

Fig. 12. Comfort zone during the cooling period (2014). Each dot point is the hourly evaluation of air temperature and moisture content for the two offices. The red box represents the best comfort area during the cooling season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

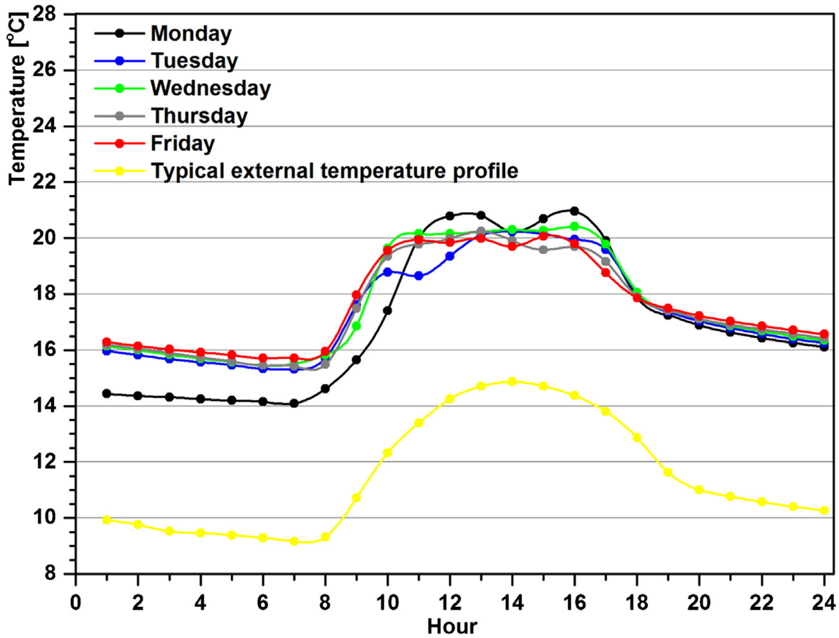

Fig. 13. Typical day of indoor temperature in the office 1 together with typical external temperature during February 2014. The lines depict the average of all hourly values for each different day of the month together with the typical external temperature profile.

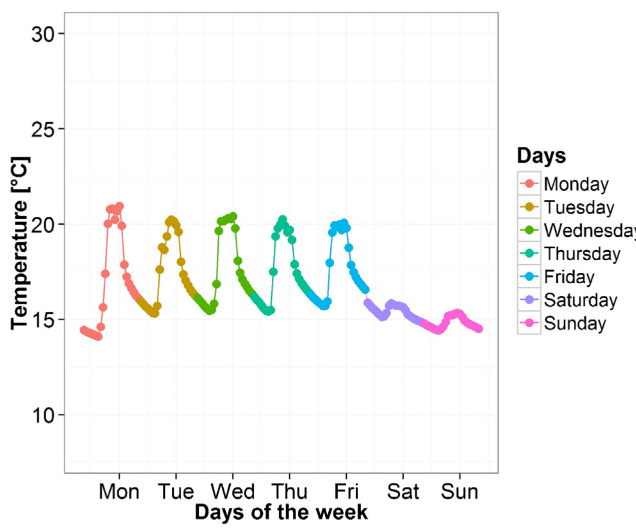

Fig. 14. Typical week of indoor temperature for the Office 1 during February 2014. Each colour of the line represents the typical day profile of temperature for each day of the week.

The real measurements, shown in Fig. 16, are derived from the three aforementioned power analyzers, plus the one installed at U.P.S. distribution Board. The study of this figure shows that the Heat Pump system operation demonstrates an acute intermittent character, affecting the overall daily profile of the building's electricity consumption, a fact that is also confirmed in Fig. 17 (red color line). On the contrary, the second component of the building's energy consumption remains almost constant and therefore does not adversely affect the quality of voltage and power of the electric network. The building total consumption profile (red color in Fig. 17) is derived from the aggregation of the real data recorded by the installed power analyzers

Fig. 18 shows the electric components and the necessary control signal of the ESC that is investigated/simulated in order to increase PVs output self-utilization and compensate peaks of the heating/cooling instantaneous consumption. The working principle of the proposed system is the following: At the beginning of Heat Pump system operation, the H.P. is fed by the PV system (through the grid-tied inverter) and the distribution LV grid. This supposes that the batteries have not got enough amount of stored energy. During H.P. non-working interval, the PVs energy is stored to the batteries by using an AC/DC charging converter. In the next operating cycle, the heating/cooling system will be powered by the batteries (through the battery inverter), PVs (through the grid-tied inverter) and possibly from the mains (in case the energy stored is not enough to meet electrical demand—usual in winter months). In time intervals with high solar irradiation, excess PV capacity (above the batteries capacity) will serve the rest of building loads, while the surplus energy will be injected into the grid. The controler estimates the duration of the next H.P. working interval by using the cold and hot water temperatures, the water flow and

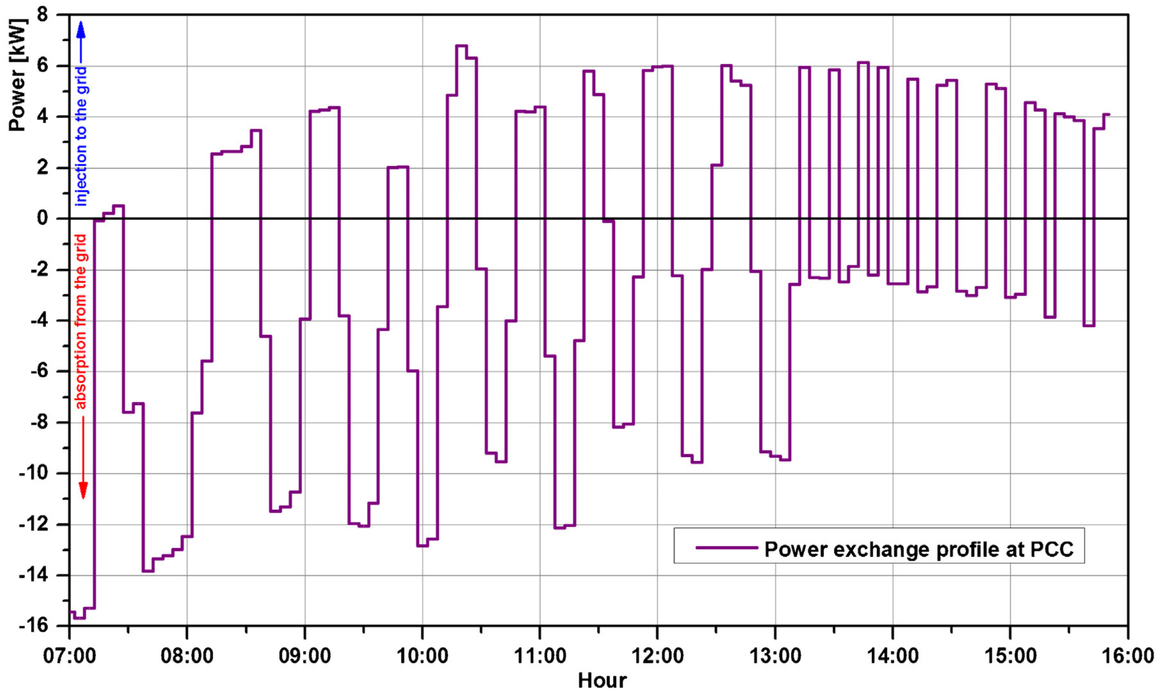

Fig. 15. Power exchange profile of the Dept. of PVs and D.G. building at the PCC. Positive values reveal that the power flows from the building to the L.V. grid, while negative values reveal that the building absorbs energy from the L.V. grid.

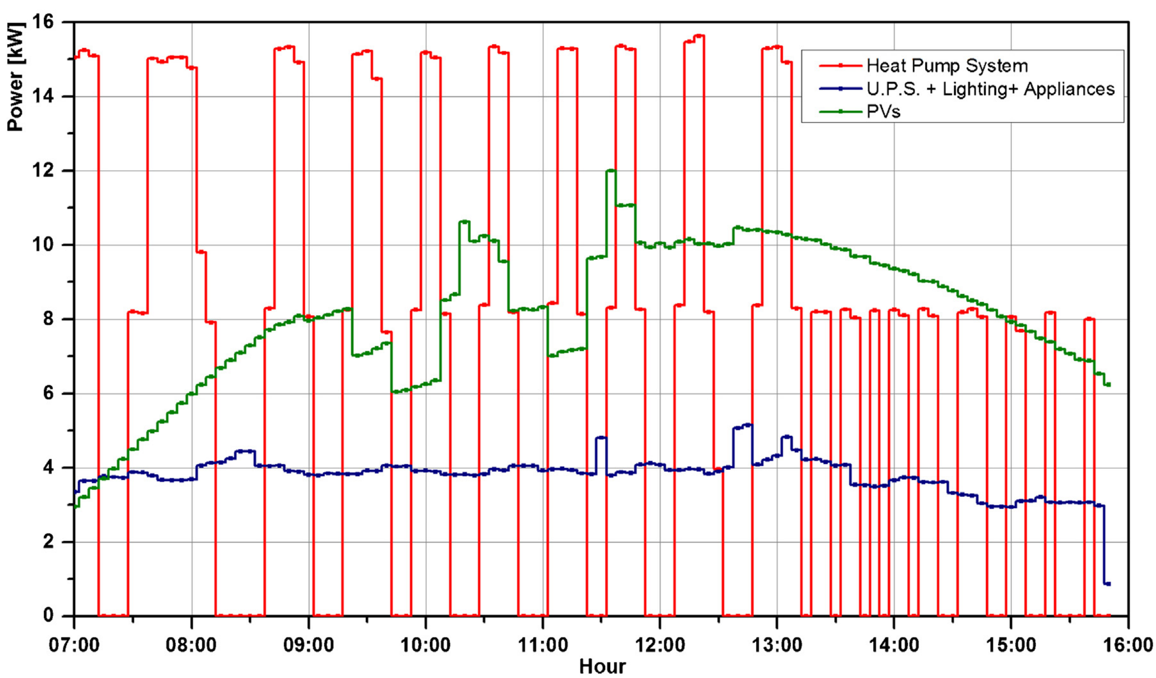

Fig. 16. Building's energy consumption components (Heat Pump system, lighting, UPS and other electrical loads of the building), and PV production on a typical summer day. A typical summer day has been created as the average of all working days of the summer.

their values from the previous H.P. operation interval, as well as the temperature values inside and outside the building [42–44].

The simulation result of the application of the proposed system in the total electricity consumption of the building is shown in Fig. 17 with green color (calculated/simulated values). The simulation model (developed on MATLAB/Simulink) does not approach the building power consumption and PVs production on a physical device level but as a power production and consumption times series (as recorded by the installed power analyzers). The authors in works [43,44] have proposed detail models for heating/cooling systems and some electrical appliances, based on device's physical parameters. Such models were not used since the aim of the simulation was to investigate possible elimination or reduction of peaks in energy transactions between building and grid and not to simulate the building loads in detail. Considering the measurements of the baseline period for PVs (stored as five minute averages values), the heating/cooling system switch off time intervals and the readings from power analyzers no 1, 2 (shown in Fig. 16), the energy that

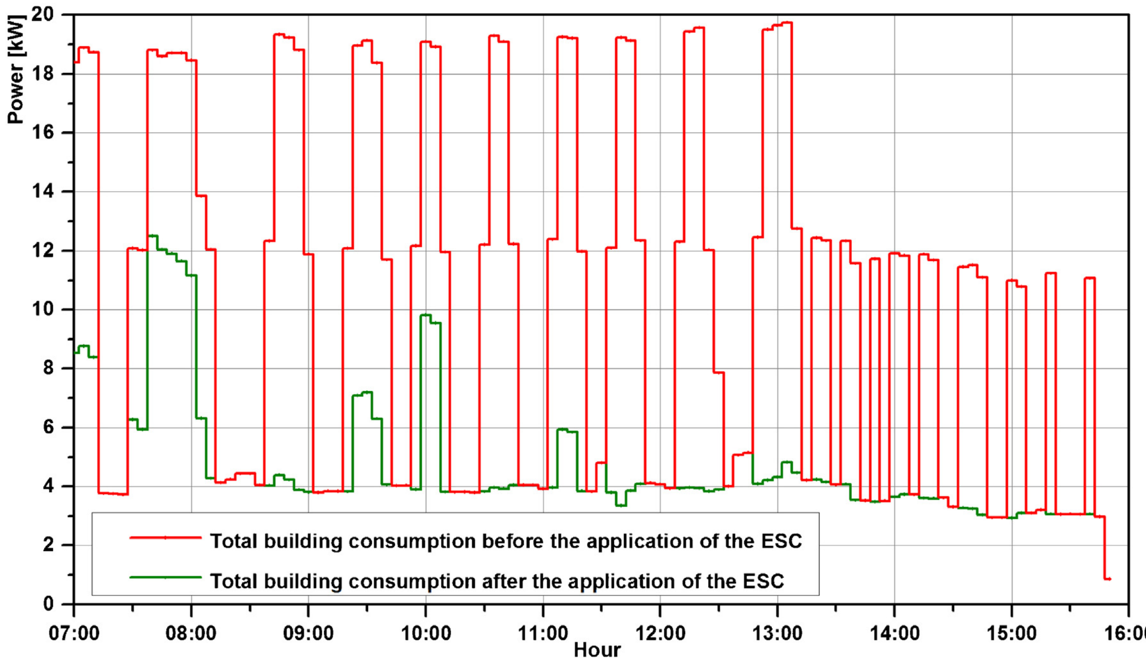

Fig. 17. Total building electric consumption before (red) and after (green) the application of the ESC. (For interpretation of the references to colour in this figure legend and text, the reader is referred to the web version of this article.)

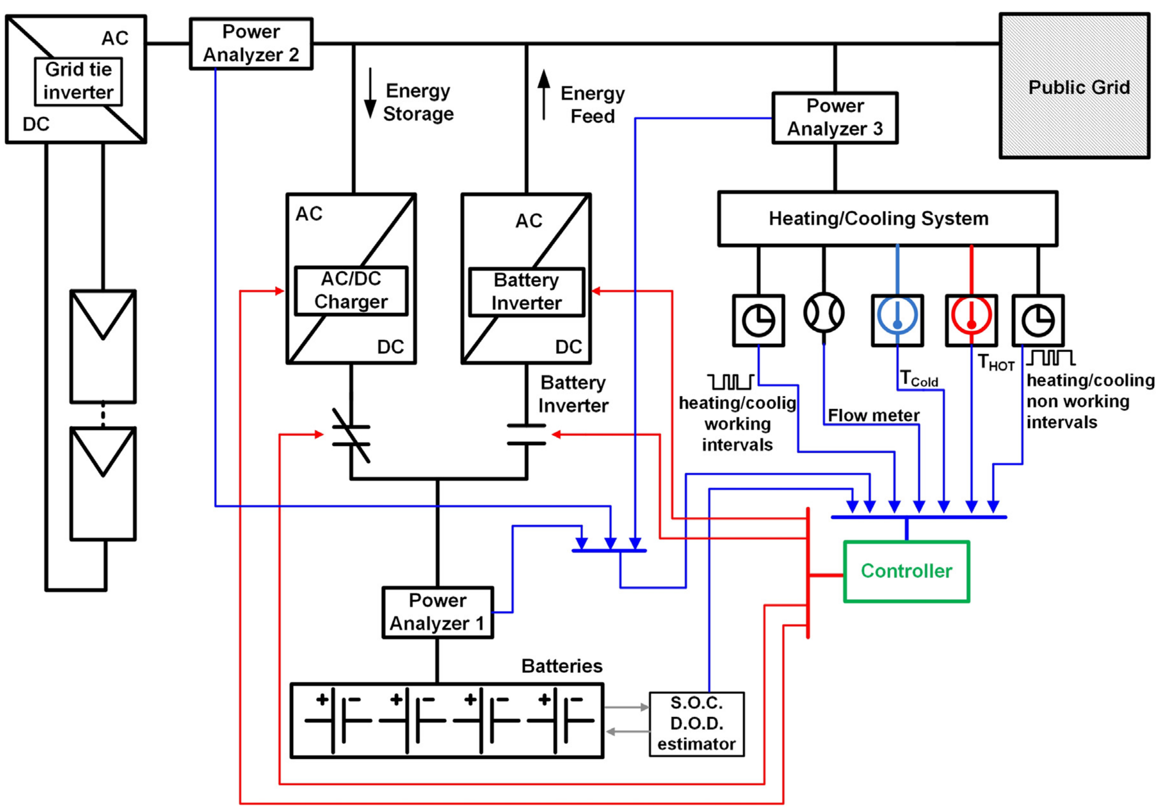

Fig. 18. ESC to limit peaks in Heating/Cooling system energy transactions and increase self-utilization of PVs output.

is stored in batteries between two consecutive operating cycles of H.P. system is calculated. For simplicity it was assumed that the efficiency of both AC/DC charging converter and battery inverter were unary. On each operating cycle of H.P, the battery inverter does not equally distribute the stored energy during H.P. operation interval (this would be preferable in case of H.P system with single compressor), but attempts to eliminate the importing energy from the grid considering the reading from power analyzers no 1, 2 and 3 (shown in Fig. 18).

A graphical representation of this simulation model is shown in Fig. 19. Considering that solar irradiation is not constant during a day, this means that the available PV power and thus the batter-

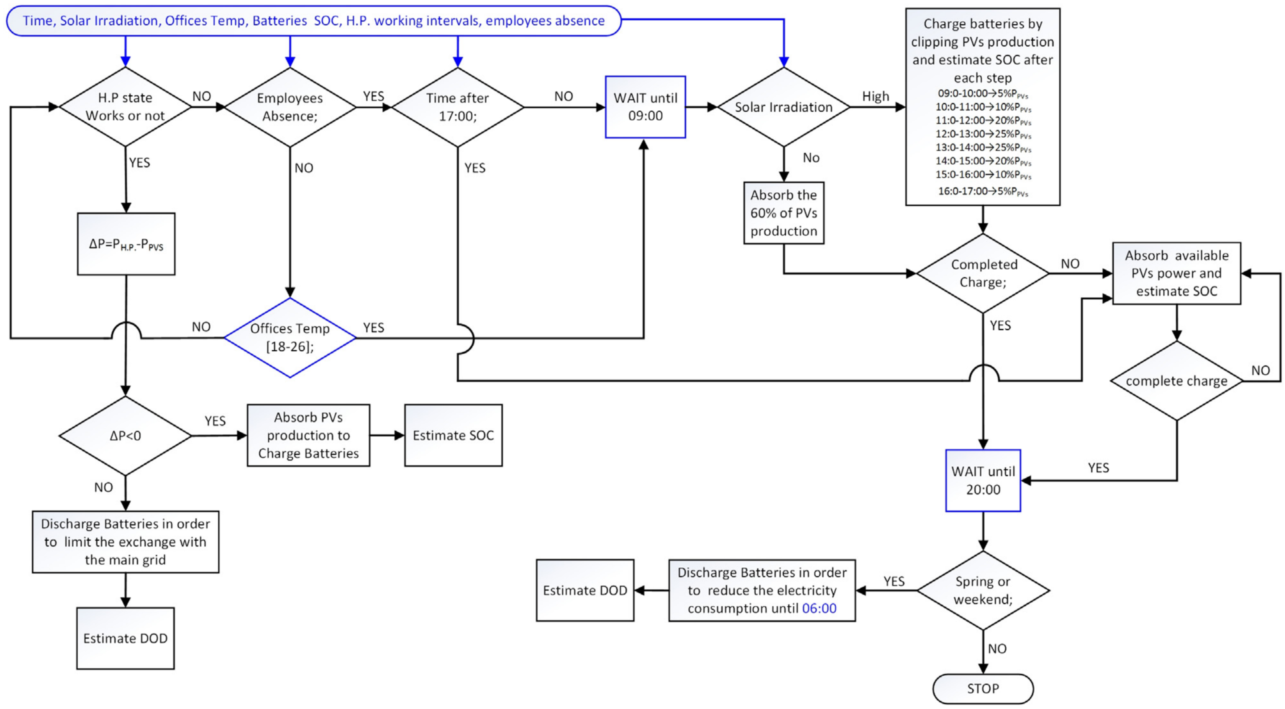

Fig. 19. Graphical representation of the simulation model.

ies power are subject to fluctuations. Thus, in order to decouple the Heat Pump system from the aforementioned power fluctuation, these variations are met by the public grid. Although, the measurements of the baseline period are adequate for the simulation model, the implementation of a real system requires the development of a real time controller, which measures the aforementioned power flows and controls the PV-power in order to balance the self-consumption and limit the exchange with the main grid. Considering that power flows correspond to a common three phase system, the expensive power analyzers can be replaced with common commercial current transducers. Thus, by using current measurements from the PV inverters together with Heat Pump and batteries currents, the entire system can be monitored. Last but not least the estimation of SOC is very important, since it reflects the battery performance and protects batteries from overdischarge and improves the battery life. Many techniques (with poor accuracy and good reliability) for estimating the SOC can be found in literature [45–48]. According to the records of the baseline period, the maximum energy that could be stored in batteries between two consecutive operating cycles of H.P. will never exceed the value of 3 kWh. Thus, a 10kWh storage system was simulated in order to limit the depth of discharge (DOD) and to increase the lifetime expectancy of battery operation.

The proposed solution could be implemented by using converters that are already available on the market (with proper intervention/programming in control logic) such as the SMA inverter “Sunny Island 8.0H (6.0 kW, 48 V_{DC}, 115A_{DC})” which costs roughly 3500 €. The specific converter is able to feed the heating/cooling system with 8000 W/9100 W/11000 W for 30 min/5 min/3 s correspondingly, while the maximum battery charging current is equal to 145A (referring to a battery nominal voltage value equal to 48 V). Fig. 18 illustrates one AC/DC charger and one Battery inverter in order to clarify the operation of the proposed solution. Additionally, the cost of a Flooded Lead-Acid (FLA) 10 kWh battery bank is roughly 2000 €.

Nevertheless, during summer months, the ESC system should charge the batteries after the PVs and D.G. department working hours, since there is sufficient high insolation (which is confirmed by Fig. 16). The stored energy could be used either to serve partly the building electrical loads during the night (a case that will be next discussed) or to serve the first operating cycle of heating/cooling in the morning.

Certainly in periods with reduced PV energy production (winter period), or even in cases of variable sunshine (passing of clouds) the benefits from the use of photovoltaic systems are severely limited, as it holds with all intermittent RES. Regarding springtime and autumnal months as well as bank holidays and weekends where the building consumption reaches the lowest annually electricity consumption values (there is no need for heating or cooling), the energy storage system could be used in order to store energy from PVs (during time intervals with high solar irradiation) and serve the building electrical loads during the night. Specifically, the building electrical needs (mostly lighting and some PCs) during the night (20:00pm–06:00am) are roughly between 12–15 kWh.Thus, during the aforementioned time intervals, the operation profile of the proposed ESC system is amended. More specifically, the charging operation is performed around the solar noon (clipping symmetrically the PV production between 5% and 25%), while the discharging operation starts at 20:00 (trying to keep the electricity consumption steady and as low as possible considering the SOC and DOD status of the batteries). A graphical representation of this simulation model is also presented in Fig. 19

Fig. 20 shows PVs production based on real measurements (red color), PVs clipped production according to aforementioned storage profile (green color-simulation results), as well as the stored energy for a typical day of spring (purple color-simulation results). All power components referring to average hourly values, while a typical spring day has been created as the average of all days of the spring. Consequently, Fig. 21 illustrates the building average hourly power demand with (green color–simulation results) and without (red color-real measurements) the application of the proposed energy storage system. At the end of discharge time the batteries are not emptied in order to limit DOD value and prolog battery life.

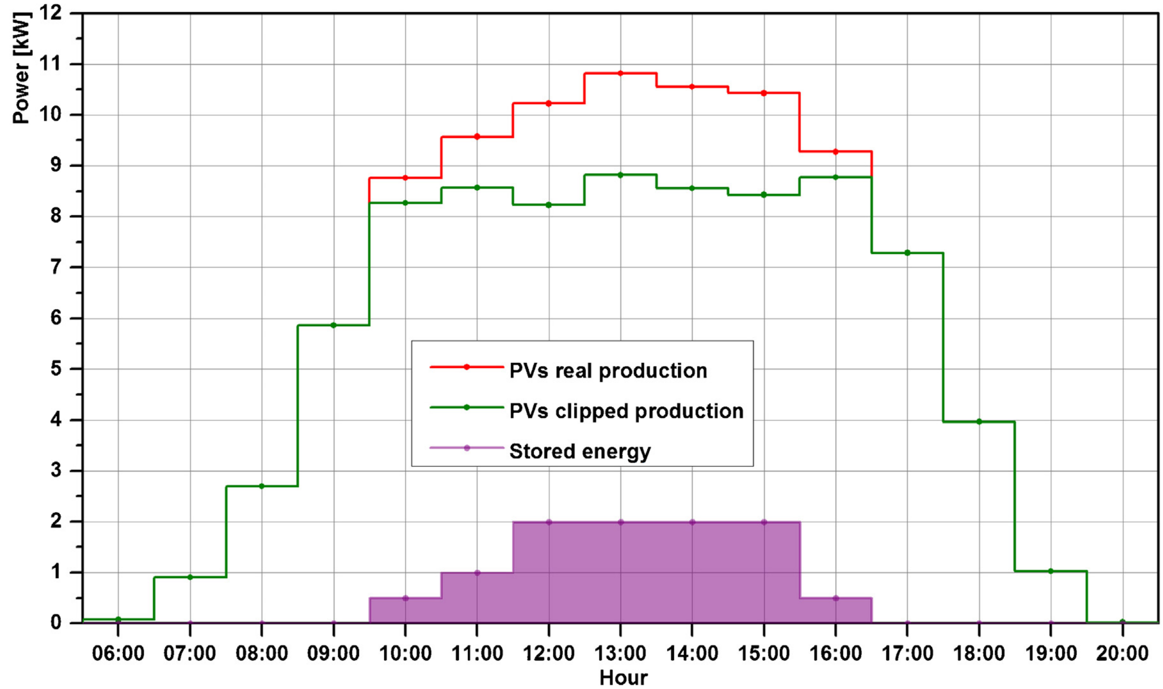

Fig. 20. PVs real production (red), PVs clipped production (green), stored energy (purple) for a typical day of spring. A typical spring day has been created as the average of all spring days. (For interpretation of the references to colour in this figure legend and text, the reader is referred to the web version of this article.)

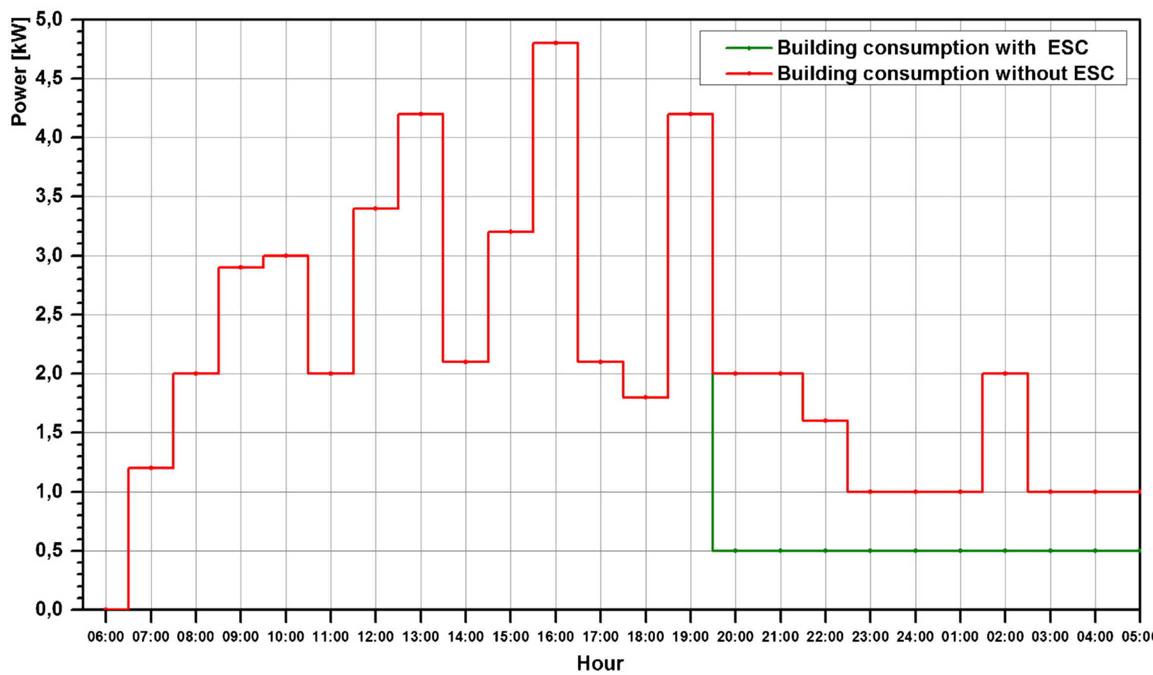

Fig. 21. Building hourly average power demand with and without the use of the storage system for a typical day of spring. A typical spring day has been created as the average of all spring days. (For interpretation of the references to colour in the text, the reader is referred to the web version of this article.)

5.2. *Water tank—the thermal storage concept (tsc)*

Newly constructed buildings could be equipped with heating/cooling systems using variable speed motors (systems with motors powered via inverters or multi-level compressor systems), in order to reduce peaks in consumption and respond better to actual cooling/heating needs. These systems cost almost 70% more compared to single or twin compressors heat pumps (353 €/$kW_{thermal}$ and 205 €/$kW_{thermal}$ correspondingly—the costs are referring to systems with nominal cooling power lower than 50 $kW_{thermal}$), but they exhibit a smoother operation profile. Fig. 22 illustrates the above remark. Specifically, the blue color (real measurements) refers to the currently installed twin compressor H.P. consumption curve, while the green line (simulation results) represents the consumption profile of a H.P. system which supports variable load operation. Considering the records from the baseline period, it is evident that the nominal electric power of the variable speed heating/cooling system should be approximately equal to

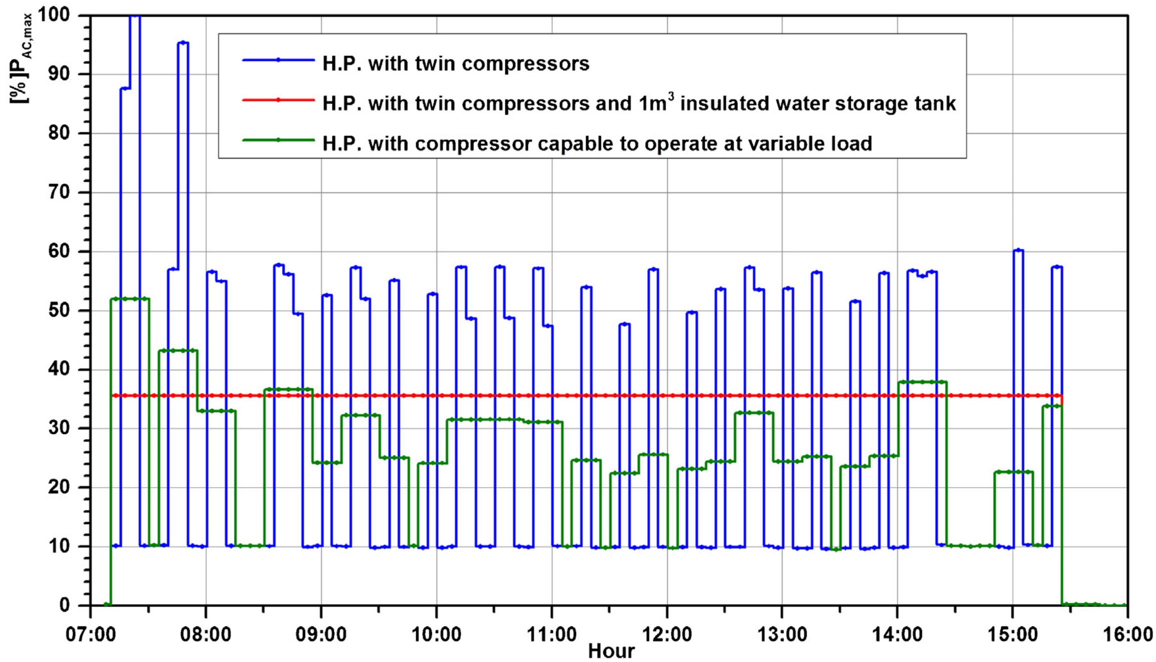

Fig. 22. Consumption profile of a Heat Pump system with: a) twin compressors (blue), b) compressor capable to operate at variable load (green) and c) constant operation point for all working hours (red). (For interpretation of the references to colour in this figure legend and text, the reader is referred to the web version of this article.)

50–60% (≈10 kW$_{el}$) of the currently installed H.P system (including the electric power of the circulator pump).

But there is an even more economical option: Fig. 22 presents in red color (simulation results) the consumption curve of the currently installed heating/cooling system in combination with a thermally insulated water tank of 1 m^3 (in parallel connection with the H.P.) in order to avoid frequent on/off operation of the compressor. The capacity of such a water tank is calculated following the calculation procedure that is presented in section 3. The amount of the water that circulates in fan coils and tubes is calculated to be less than 50 L per cycle. Considering the records from 2013 it is expected that in such a scenario the H.P. system could work at 50% constant power level (one compressor only) during the building working hours, and it would provide heating/cooling for the water tank. An independent circulation pump would circulate the water between the tank and the fan coils. For new systems, the nominal twin compressor capacity could be reduced by 50–60% of the already installed without any switch off/on during building working hours, thus presenting a very smooth energy demand curve. Moreover, such a system reduces peaks in electricity demand of the H.P. system during start-up periods by 50% (as it is shown in Fig. 22). Table 1 summarizes the total cost of all three scenarios (for all cases a constant C.O.P. value equal to 3 is assumed). The simulated results (green and red line of Fig. 20) are based on the record power consumption and production time series, as well as on the calculation of the average electricity amounts for matching the same thermal needs on predefined time intervals. More specifically, assuming that all three heating/cooling systems have equal COP values, it is deduced that the three systems have to consume equal amount of electricity in order to serve the same thermal load. The consumption time series of the currently installed twin compressor Heat Pump system were recorder during both the baseline and reporting period, thanks to the presence of the monitoring equipment. Afterwards, considering the consumed electrical energy during the working intervals of the currently Heat Pump system as well the non-working time intervals, it is possible to calculate the nominal electric power of both alternative heating cooling systems (variable speed H.P. system—twin compressors H.P. system with 1 m^3 insulated water storage tank).

Table 1
Different Heating/cooling system configurations and corresponding costs.

Heating/Cooling configuration	Twin compressors (current configuration)	Compressor capable to operate at variable load	Twin compressors and 1 m^3 insulated water storage tank
Nominal electric power (kW$_{el}$)	14.3	10.0	6.0
HVAC cost (€/kW$_{thermal}$)	205	353	205
1m^3 insulated tank (€)	0	0	2500
Extra circulation pump (€)	0	0	1000
Total cost (€)	9500	10590	7805

5.3. COMPARISON OF ESC and TSC solutions

By importing data from the reference year to the ESC simulation model, it is evident that batteries will be cycling approximately 2.7 MWh for the heating/cooling system during heating/cooling periods and 2.4 MWh to supply appliances during night time. In other words the proposed ESC system could feed the building with approximately 5.1 MWh which are derived from the PV system. Thus the solar PV system self-utilisation increases to 74.5% on an overall annual basis. Such electrochemical storage systems may become a viable solution in the near-term but system costs are still too high.

On the other hand, the water tank concept is of benefit only during heating/cooling operating periods (8 months) while for the rest of the period the thermal storage is idle.

The cost of the ESC system with medium Lead-Acid batteries is roughly 5500 € (without considering the B.O.S. – balance of system – cost, e.g. cables, circuit breakers, fuses), while the cost for the adaptation of the existing twin compressors H.P. system to the water tank concept is roughly 3500€. The final choice between the two aforementioned solutions depends mainly on the market prices of electricity, the consumption profile of building during the night and the matching between PVs capacity and the water tank size. Last but not least, the proposed ESC seems to be a preferably solution for future smart electricity grids [23,24].

6. Conclusions

This work presents practices for improving electric consumption in office buildings, aiming in the achievement of Balanced Energy Buildings, in smoothing their electrical power peaks and increasing their RES self-utilization. The energy saving reached when applying energy efficiency measures is almost 23% for the heating/cooling system and 25% for the lighting of the building. Furthermore, a thermal storage system is proposed which reduces peaks in heating/cooling system demand by at least 50% and is economically viable already today. Electrochemical storage systems may become a viable alternative in the near-term but system costs are still too high. The thermal storage tank solution may be considered as very attractive for new buildings since it leads to smaller heating/cooling systems and at the same time, to smoother consumption profiles on the PCC.

Acknowledgements

This work was co-funded under the ICT Policy Support Programme (ICT PSP) as part of the Competitiveness and Innovation Framework Programme (CIP) by the European Community [49].

References

[1] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: a review article, Energy Build. 39 (3) (2007) 249–257 (ISSN 0378-7788).
[2] N. Giorgos Spyropoulos, Constantinos A. Balaras, Energy consumption and the potential of energy savings in Hellenic office buildings used as bank branches—a case study, Energy Build. 43 (4) (2011) 770–778 (ISSN 0378-7788).
[3] D.A. Asimakopoulos, M. Santamouris, I. Farrou, M. Laskari, M. Saliari, G. Zanis, G. Giannakidis, K. Tigas, J. Kapsomenakis, C. Douvis, S.C. Zerefos, T. Antonakaki, C. Giannakopoulos, Modelling the energy demand projection of the building sector in Greece in the 21st century, Energy Build. 49 (2012) 488–498 (ISSN 0378-7788).
[4] A. Sfakianaki, M. Santamouris, M. Hutchins, F. Nichol, M. Wilson, L. Pagliano, W. Pohl, J.L. Alexandre, A. Freire, Energy consumption variation due to different thermal comfort categorization introduced by European standard EN 15251 for new building design and major rehabilitations, Int. J. Vent. 10 (September (2)) (2011) 195–204 (ISSN 1473-3315).
[5] Mattheos Santamouris, Dionysia Kolokotsa, Passive cooling dissipation techniques for buildings and other structures: the state of the art, Energy Build. 57 (2013) 74–94 (ISSN 0378-7788).
[6] M. Kapsalaki, V. Leal, M. Santamouris, A methodology for economic efficient design of net zero energy buildings, Energy Build. 55 (2012) 765–778 (ISSN 0378-7788).
[7] A.J. Marszal, P. Heiselberg, J.S. Bourrelle, E. Musall, K. Voss, I. Sartori, A. Napolitano, Zero energy building—a review of definitions and calculation methodologies, Energy Build. 43 (4) (2011) 971–979 (ISSN 0378-7788).
[8] Luis Pérez-Lombard, José Ortiz, Christine Pout, A review on buildings energy consumption information, Energy Build. 40 (3) (2008) 394–398 (ISSN 0378-7788).
[9] Patxi Hernandez, Paul Kenny, From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB), Energy Build. 42 (6) (2010) 815–821 (ISSN 0378-7788).
[10] Moncef Krarti, Alexandre Deneuville, Comparative evaluation of optimal energy efficiency designs for French and US office buildings, Energy Build. 93 (15) (2015) 332–344 (ISSN 0378-7788).
[11] M.T. Iqbal, A feasibility study of a zero energy home in Newfoundland, Renew. Energ. 29 (No. 2) (2004) 277–289.
[12] S. Kilkis, A new metric for net-zero carbon buildings, in: Energy Sustainability Conference, Long Beach, California, 2007.
[13] The Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, Off. J. Eur. Union 53 (2010).
[14] EU, Energy in Figures-Statistical Pocket Book, Publication Office of the E.U., Luxembourg, 2014.
[15] M. Economidou, et al., European Buildings Under the Microscope-A Country by Country Review of the Energy Performance of Buildings, Published by Buildings Performance Institute Europe (BPIE), October, 2011 (ISBN: 9789491143014).
[16] M. Santamouris, E. Dascalaki, Passive retrofitting of office buildings to improve their energy performance and indoor environment: the OFFICE project, Build. Environ. 37 (2002) 575–578.
[17] Marie-Claude Dubois, Åke Blomsterberg, Energy saving potential and strategies for electric lighting in future North European, low energy office buildings: a literature review, Energy Build. 43 (10) (2011) 2572–2582 (ISSN 0378-7788).
[18] Kaoru Kawamoto, Yoshiyuki Shimoda, Minoru Mizuno, Energy saving potential of office equipment power management, Energy Build. 36 (9) (2004) 915–923 (ISSN 0378-7788).
[19] Luis Pérez-Lombard, José Ortiz, Juan F. Coronel, Ismael R. Maestre, A review of HVAC systems requirements in building energy regulations, Energy Build. 43 (February–March (2–3)) (2011) 255–268 (ISSN 0378-7788).
[20] Ashish Pandharipande, David Caicedo, Smart indoor lighting systems with luminaire-based sensing: a review of lighting control approaches, Energy Build. 104 (1) (2015) 369–377 (ISSN 0378-7788).
[21] Y. Sun, S. Wang, F. Xiao, D. Gao, Peak load shifting control using different cold thermal energy storage facilities in commercial buildings: a review, Energy Convers. Manage. 71 (0) (2013) 101–114.
[22] Omar Ellabban, Haitham Abu-Rub, Frede Blaabjerg, Renewable energy resources: current status, future prospects and their enabling technology, Renew. Sustain. Energy Rev. 39 (2014) 748–764 (ISSN 1364-0321).
[23] F. Blaabjerg, J.M. Guerrero, Smart grid and renewable energy systems, International Conference on Electrical Machines and Systems (ICEMS-11) (2011) 1–10, 20–23 August.
[24] Y.K. Penya, C.E. Borges, J. Haase, D. Bruckner, Smart buildings and the smartgrid, IECON Proceedings (Industrial Electronics Conference) (2013) 113–117.
[25] Lu Lu, Wenjian Cai, Lihua Xie, Shujiang Li, Yeng Chai Soh, HVAC system optimization-in-building section, Energy Build. 37 (1) (2005) 11–22 (ISSN 0378-7788).
[26] http://www.farsystems.it/nqcontent.cfm?a_id=2360.
[27] A.C. Menezes, A. Cripps, R.A. Buswell, J. Wright, D. Bouchlaghem, Estimating the energy consumption and power demand of small power equipment in office buildings, Energy Build. 75 (2014) 199–209 (ISSN 0378-7788).
[28] NBI, 'Plug Load Best Practice Guide—Managing Your Office Equipment Plug Load', New Buildings Institute, 2012, 2016.
[29] Teshome Edae Jiru, Combining HVAC energy conservation measures to achieve energy savings over standard requirements, Energy Build. 73 (2014) 171–175 (ISSN 0378-7788).
[30] John Siegenthaler, Heating with Renewable Energy, first edition, Associate Professor Emeritus, Mohawk Valley Community College, Utica, NY, 2016 (ISBN-13: 9781285075600).
[31] John Siegenthaler, Modern Hydronic Heating: For Residential and Light Commercial Buildings, third edition, Associate Professor Emeritus, Mohawk Valley Community College, Utica, NY, 2016 (ISBN-13: 9781428335158).
[32] E. Djunaedy, K. Van Den Wymelenberg, B. Acker, H. Thimmanna, Oversizing of HVAC system: signatures and penalties, Energy Build. 43 (2–3) (2011) 468–475.
[33] A.P. Wemhoff, Calibration of HVAC equipment PID coefficients for energy conservation, Energy Build. 45 (2012) 60–66 (ISSN 0378-7788).
[34] A. Boyano, P. Hernandez, O. Wolf, Energy demands and potential savings in European office buildings: case studies based on EnergyPlus simulations, Energy Build. 65 (2013) 19–28 (ISSN 0378-7788).
[35] P. Hanselaer, C. Lootens, W.R. Ryckaert, G. Deconinck, P. Rombauts, Power density targets for efficient lighting of interior task areas, Light. Res. Technol. 39 (2) (2007) 171–184.
[36] X. Guo, D.K. Tiller, G.P. Henze, C.E. Waters, The performance of occupancy-based lighting control systems: a review, Light. Res. Technol. 42 (2010) 415–431.
[37] http://www.eea.europa.eu/data-and-maps/indicators/heating-degree-days-1.
[38] A. Matzarakis, B. Amelung, Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans, in: M. Thomson, R. Garcia-Herrera, M. Beniston (Eds.), Seasonal Forecasts, Climatic Change and Human Health. Advances in Global Change Research, 30, Springer, Netherlands, 2008, pp. 161–172, http://dx.doi.org/10.1007/978-1-4020-6877-5_10.
[39] Weilin Cui, Guoguang Cao, Jung Ho Park, Qin Ouyang, Yingxin Zhu, Influence of indoor air temperature on human thermal comfort, motivation and performance, Build. Environ. 68 (October) (2013) 114–122 (ISSN 0360-1323).
[40] A. Kumar, I.P. Singh, S.K. Sud, Thermal comfort feelings assessment based on digital signal processor, Int. J. Recent Trends Eng. 5 (2009) 395–404.
[41] O. Seppanen, W.J. Fisk, Q.H. Lei, Room Temperature and Productivity in Office Work, Lawrence Berkeley National Laboratory, Lawrence Berkeley National Laboratory, 2006 http://escholarship.org/uc/item/9bw3n707.
[42] F.Noris D.Antonucci, U. Filippi Oberegger, A. Gasparella;1, Estimation of the water flow rate and energy consumption of a central heating system in an office building using system identification, in: 2nd IBPSA-Italy Conference of the International Building Performance Simulation Association, Bolzano, Italy, 2015 (04.-06.02.2015).

[43] Xiaofei He, Zijun Zhang, Andrew Kusiak, Performance optimization of HVAC systems with computational intelligence algorithms, Energy Build. 81 (2014) 371–380 (ISSN 0378-7788).
[44] Fan Tang, Andrew Kusiak, Xiupeng Wei, Modeling and short-term prediction of HVAC system with a clustering algorithm, Energy Build. 82 (October) (2014) 310–321 (ISSN 0378-7788).
[45] J. Chiasson, B. Vairamohan, Estimating the state of charge of a battery, IEEE Trans. Control Syst. Technol. 13 (3) (2005) 465–470.
[46] K.S. Ng, C.S. Moo, Y.P. Chen, Y.C. Hsieh, State-of-charge estimation for lead-acid batteries based on dynamic open-circuit voltage, in: Proceedings of the 2nd IEEE International Power and Energy Conference (PECon '08), Johor Bahru, Malaysia, 2008, pp. 972–976 (December).
[47] V. Surendar, V. Mohankumar, S. Anand, Vadana D. Vadana, Estimation of state of charge of a lead acid battery using support vector regression, Procedia Technol. 21 (2015) 264–270 (ISSN 2212-0173).
[48] Rui Xiong, Hongwen He, Fengchun Sun, Kai Zhao, Evaluation on state of charge estimation of batteries with adaptive extended kalman filter by experiment approach, IEEE Trans. Veh. Technol. 62 (1) (2013) 108–117.
[49] See: www.smartbuild.eu.