Optimisation of an HVAC system for energy saving and thermal comfort in a university classroom

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Abstract

In university classrooms with air conditioning systems, as well as in conference rooms, thermo-hygrometric and air quality requests must deal with high energy consumption of the plant system. The whole plant management is sometimes critical due to the particular conditions of use of the rooms where the ventilation rate demand and thermal loads may change consistently during daily occupation. In this work an existing HVAC system unit is analyzed, serving two classrooms with a single zone distribution. The HVAC system is set to work with an external air supply at a constant rate, and includes air treatment sections with heating, cooling and vapour humidification. Experimental measurements of both thermal comfort parameters and real operating conditions of the HVAC unit gave information about critical aspects of the whole building-plant system design and management. In this work an energy dynamic simulation of the building-plant system using Energy-Plus software has been realized. After a proper calibration of the model based on experimental measurements, a dynamic simulation is used to carry out plant management strategies (e.g. free cooling, variable set points for intermediate occupational condition, mixing of the external air with recycled air, etc.) that combine energy savings with better indoor comfort. Several design alternatives are modelled through Energy-Plus to predict energy performance improvements associated with a different set of HVAC system configuration. Simulation results indicate up to 60% energy savings.

1. Introduction

Air conditioning plants are very energy consuming systems, especially in summer periods where the control of internal humidity assumes an important role for hygrothermal comfort conditions. The possibility to adopt specific management controls of the plant system as a function of the effective occupation of each classroom can lead to an important reduction in the energy consumption. However, the effectiveness of adopted solutions is strongly dependent on external climatic conditions, especially when the HVAC system is connected to air condensing chillers for cooling water, as in the case study. Energy modelling of a building-plant system can be very difficult and can provide reliable results only if a detailed knowledge of the thermal characteristics of materials and plant components are available. Simulations of existing cases need a control or "calibration" with experimental measurements of physical parameters during the analysed period of study.

2. Description of case study

2.1 The building envelope

The investigated classrooms are two adjoining rooms with the same internal dimensions (L=14.0 x W=8.85 x H=3.50 m) located on the first floor of the Faculty of Engineering's new building in Bologna. Each one has a maximum occupancy of 96 students. Main external loads come from the external windowed façade (triple glazing for the lower fixed ribbon, quadruple glazing for the upper moveable ribbon, both with solar control properties in the outer glazing layer), oriented on the north-west side and protected by a solar screen on the top of the building, (Fig. 1 and 2).

Floor and opaque wall surfaces border internal conditioned areas, except south-east ones that are exposed to an unconditioned corridor

Fig. 1 – External view of the building

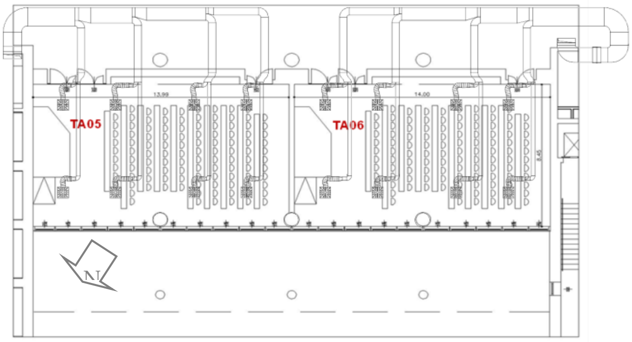

Fig. 2 – Plan of classrooms

2.2 HVAC System

The classrooms are conditioned by a single zone Air Handling Unit (AHU) of 8500 m³/h (constant air volume fan) where the inlet air (from ceiling air diffusers) is controlled by a thermostat that detects the temperature of the mixing air extracted from both classrooms (set point at 26°C). Typical operating conditions in summer provide a cooling coil section at a fixed temperature of about 14°C (connected to an external water chiller) and a post-heating coil section (powered by a gas boiler used also for hot water production). Scheduled times are from 6 am to 8 pm (Mon-Fri) and from 6 am to 2 pm (sat).

2.3 Thermal comfort conditions

During part of the summer period some experimental measurements were carried out in order to evaluate the internal comfort conditions that are correlated to actual operating conditions of the AHU unit, by means:

- measurements of climatic parameters;
- questionnaires to students in different periods.

Results of PMV index evaluated from microclimatic measurements are comparable to results of questionnaires (Fig. 3), showing a small prevalence of slightly heating near windows in the afternoon period due to the thermal radiation of the glazed surfaces.

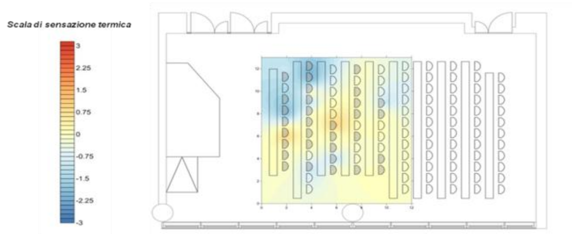

Fig. 3 – PMV map based on questionnaires (internal set point of 24°C)

The internal air distribution is quite uniform, even if little differences of the air temperature are detected; probably, those differences are due to asymmetric position of extraction grids.

The designed AHU can maintain a correct internal set point on both classrooms only when the same occupancy levels occur (same thermal loads); for a number of students, which differs from one classroom to the other, discomfort conditions occur in winter and summer periods, giving a general overheating condition in one of the two classrooms.

3. Energy modeling

Dynamic simulations are performed with “EnergyPlus” (version 7.2) software (energy calculation) and the corresponding “Legacy OpenStudio” plug-in (geometrical input data). The first step was the “calibration” of the energetic model of the building-HVAC plant system comparing the predicted data with the experimental measurements.

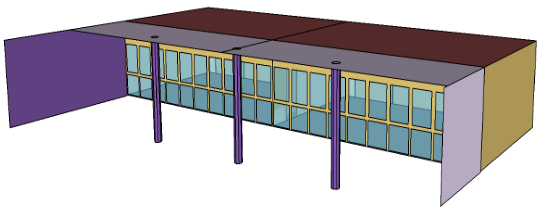

Fig. 4 – Sketch of simulated thermal zones

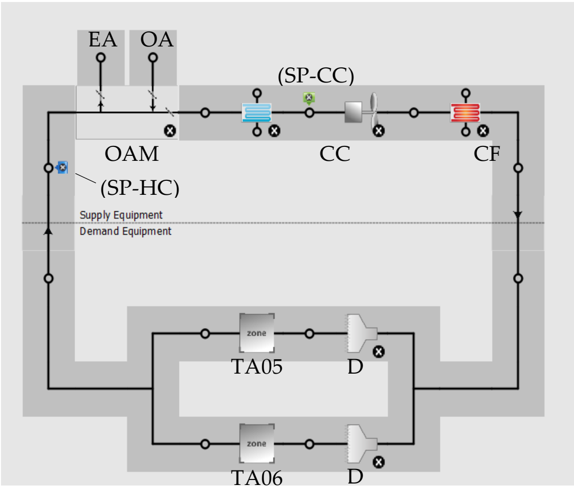

Fig. 5 - Model of the HVAC system

Figure 5 Legend:

CC	cooling coil
(SP-CC)	cooling coil dew point temperature controller
HC	post-heating coil
(SP-HC)	post-heating coil temperature controller
OAM	outdoor air mixer
EA	exhaust air
OA	outdoor air
TA05	TA05 classroom
TA06	TA06 classroom
D	diffusers

Then simulations are performed in order to evaluate energy consumption of the HVAC system both in the actual configuration, and using technical solution proposals to improve the plant system's efficiency. Fig. 4 shows the geometrical model of the building while fig. 5 shows the simplified model of the HVAC system. Due to the complexity of the water chiller and gas boiler plants, used also for other rooms and offices in the building, they are modelled in order to simply supply the cooling and heating coils with the power they need at each time step calculation (5 min).

3.1 Calibration of the energetic model

The calibration of the model was not easy to achieve because of uncertainties about some thermal characteristics involved in the building envelope and, in addition, because of the non-uniform temperature of air in rooms caused by a not perfect balancing of the air inlet jets.

Due to our priority of energy analysis of the HVAC system, the model has been refined to achieve good correlation on internal temperatures and inlet temperatures. Fig. 6 and fig. 7 show measured and predicted temperature trends through days with a changing in set point temperature (27°C), used in the questionnaires experience.

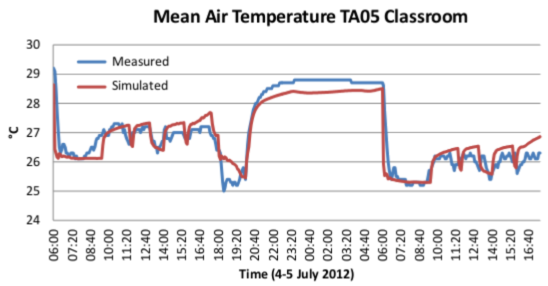

Fig. 6 – Comparison between predicted and measured mean indoor air temperature

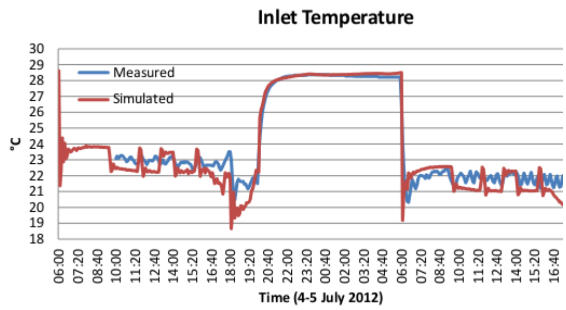

Fig. 7 – Comparison between predicted and measured inlet air temperature

Concerning the mean radiant temperature, there is a discrepancy of about 1°C between measured and predicted data (Fig. 8).

This discrepancy is due both to some simplifications adopted in roof/ceiling and corridor modelling, and also to specific conditions of experimental measurements performed with the globo-thermometer. However, these results are deemed satisfactory for the purpose of this work.

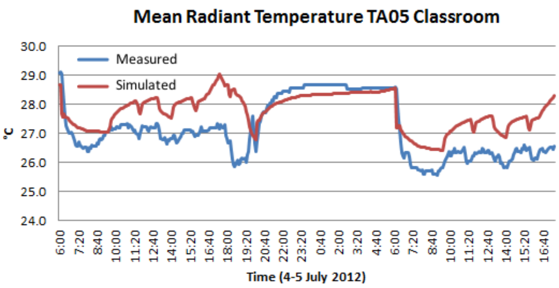

Fig. 8 – Comparison between predicted and measured mean radiant temperature

4. Energy optimisation of the hvac system

The energy consumption of the HVAC system is mainly related to the high air flow rate and to the low saturation temperature of the cooling coil; these situations, especially the second one, cause high energy consumption for the post-heating process when low internal thermal loads occur.
In table 1 the basic setting parameters for actual situation (simulation starting point) are reported.

OCCUPANCY (BOTH CLASSROOMS)	Mon-Tue 20% Wed 100% Thu-Fri 80% Sat 10%
AHU OPERATION	Mon-Fri 06.00-20.00 Sat 06.00-14.00
INLET OUTDOOR AIR	100%
FIXED TEMP. COOLING COIL	13,5°C

Table 1 – Basic setting parameters for simulation starting point (actual situation - AS)

SOLUTION S1	
INLET OUTDOOR AIR	60%
SOLUTION S2	
FIXED TEMP. COOLING COIL	15°C

SOLUTION S3	
INLET OUTDOOR AIR	60% (with 100% occup.) 30% (with 50% occup.) 12% (with 20% occup.) 6% (with 10% occup.)
SOLUTION S4	
AHU OPERATION	Mon-Fri 07.00-20.00 Sat 07.00-14.00
AHU'S FAN OPERATION	Mon-Fri 05.00-06.00 Sat 05.00-06.00 (only if outside dry bulb temperature < 23°C)

Table 2 – Changed setting parameters to simulate different solutions (proposals from S1 to S4)

In order to reduce global energy consumption, four different managing solutions are analysed and compared to the actual situation (AS). Maintaining the AHU actual air flow rate of 8500 m^3/h, the following cases are analysed (changed parameters are reported in Tab. 2):

S1 reducing the amount of external air flow to the minimum value of 7 l/s per person, as required to reference national standard (UNI 10339): the external air flow rate is than reduced to 60% of the total air flow;

S2 increasing the condensation set point temperature of cooling coil at values ≥ 15°C: this case results an increasing of indoor humidity, but not above 60% in the case of maximum occupancy of each classrooms;

S3 controlling the recirculated air flow of the AHU on the basis of the effective occupancy level of each classrooms;

S4 using free cooling in the first morning hours depending on the effective external air temperature.

C combining solutions S2, S3 and S4.

Each of the proposed solutions refers only to a different setting of one or more components of the existing AHU.

Further solutions concerning changes on components of the air handling unit are then analyzed.
First we considered a new smaller fan, designed

for a constant air flow rate of 4850 m^3/h (which is enough to ensure the indoor air quality in conditions of full occupancy, as stated by UNI 10339 standard) and re-sized cooling and post-heating coils accordingly to the new air flow rate. Therefore, simulations with the new AHU are performed (new simulation starting point - NSP), applying the same previous managing solutions (respectively named S2R, S3R, S4R, CR). In the re-statement of the third solution (S3R), the correspondence between inlet outdoor air and occupancy is properly adjusted: both parameters have now the same percentages.

Lastly, it is supposed to modify the original concept of the HVAC control, adopting a multi-zone solution, where the single post-heating coil on the AHU is replaced by two half-power ones, located just upstream of the distribution air ducts of each classroom. A single thermostat for each classroom controls the power delivered from the corresponding post-heating coil, in order to maintain the internal set point at 26°C.

5. Simulation results

The evaluation of effective energy advantages for each proposed solution must be evaluated as a function of the specific temporal period of the analysis and correlated climatic data.

A first analysis related to a shorter and warm period (25^{th}June – 1^{st} July week), shows that all four solutions are effective energy savers, especially S3 where the high re-circulated air carries out a lower cooling coil energy consumption (Fig. 9). Adding the advantages related to a higher cooling coil temperature and the free cooling to this solution, the best performance is achieved (combination C of solutions from 2 to 4).

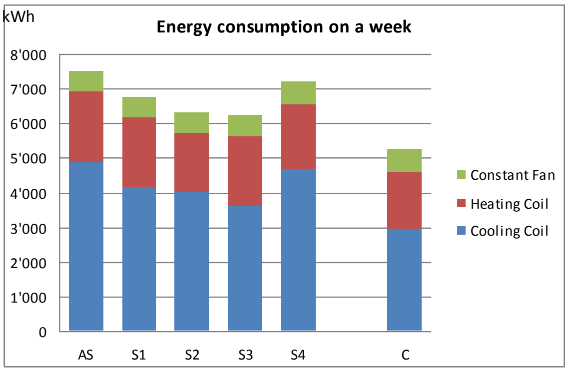

Fig. 9 – Energy consumption on a warm week (25th June - 1st July, IGDG weather data)

Energy saving of almost all solutions is higher when the period is warmer. Results from simulations run over the same week, but with the EPW climate data file built on the basis of measured 2012 data (detected by means of a weather station during the experimental measurement campaign), show improvements in energy saving, except in case S2 (Fig. 10 and Tab. 3).

	AS	Energy saving (%) SOLUTIONS				
		S1	S2	S3	S4	C
IGDG	7’533 kWh	10.1	16.0	17.2	4.5	30.3
2012	8’302 kWh	13.4	14.0	25.4	5.1	38.0

Table 3 – Energy saving (%) for solution proposals respect to global consumption of the actual situation (AS) over two different warm weeks

Simulations were also performed over the whole cooling season, from 15^{th} May to 30^{th} September, considering that the HVAC system is switched off from 1^{st} to 20^{th} August (as scheduled by the school in the summer). Default EnergyPlus weather data for Bologna were used (resulting from the Gianni De Giorgio collection – IGDG).

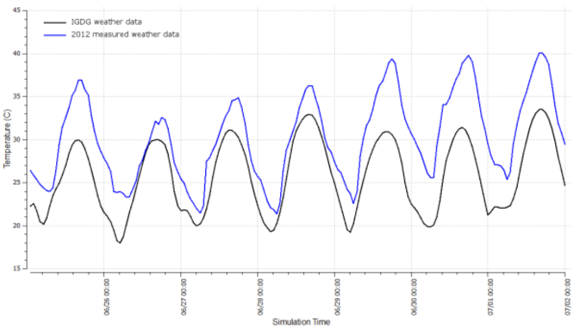

Fig. 10 – Comparison between IGDG and measured 2012 outdoor dry bulb temperature

Analysis of simulations over a whole summer season give a substantial difference on proposed solutions with respect to results obtained during the warm week previously analysed. From fig. 11 it can be seen that only in the middle of the season are climatic conditions advantageous for cooling strategies, while in other periods (the initial month and the last 15 days) when external temperatures are lower than the internal set point (26°C) energetic performances are worse than the actual situation. As shown in Fig. 12, solutions with air recirculation (S1 and S3) provide higher cooling coil consumptions. Only S2 solution is better than the initial situation AS.

But just simply looking at the energy consumptions of each components of the AHU, an improper design of the HVAC system should be pointed out: high values of the external air flow rate causes too high energy demands not only for the cooling coil but also for the post-heating coil.

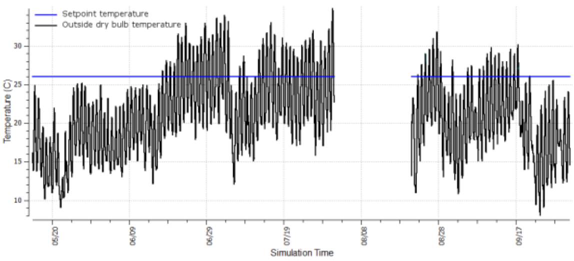

Fig. 11 – Outdoor dry bulb temperature (from IGDG climate data) compared to internal set point temperature

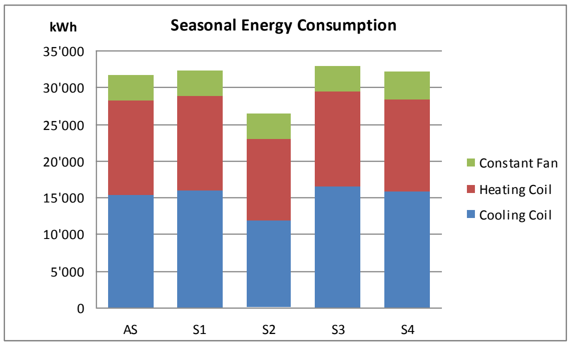

Fig. 12 – Energy consumption over standard cooling season (15th May - 30th September, IGDG weather data)

Now the reduced design air flow rate of 4850 m^3/h is assumed, strictly meeting the minimum renewal requirements. Of course energy consumption is cut down and, with reference to the starting point of the actual situation, the savings are even greater, up to a maximum of 59.6% for the combined proposal in the warm week period (fig. 13 and table 4). Similar results are obtained over the standard cooling season (Fig. 14).

If the AHU works with a reduced air flow rate, more attention should be paid to the regulation of diffusers in the classrooms so that the inlet air jet at a lower temperature does not cause conditions of local discomfort for the occupants.

		SOLUTIONS				
	AS	NSP	S2R	S3R	S4R	CR
IGDG	7'533 kWh	45.4	54.4	51.8	47.2	59.6

Table 4 – Energy saving (%) for solution proposals respect to global consumption of the actual situation (AS) over the same week, but with the reduced total air flow rate (4'850 m3/h)

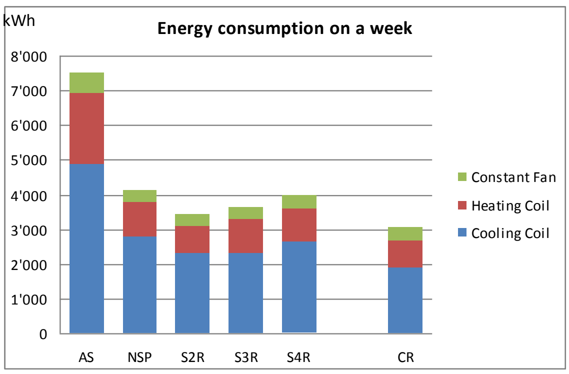

Fig. 13 – Energy consumption on a warm week with reduced total air flow rate (25th June - 1st July, IGDG weather data)

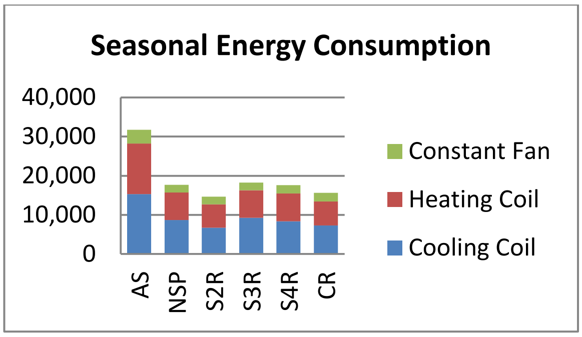

Fig. 14 – Energy consumption over standard cooling season with reduced total air flow rate (15th May - 30th September, IGDG weather data)

5.1 Comfort conditions

The actual configuration of the HVAC system can achieve comfort conditions in both classrooms only when they have the same occupancy level, because of the single heating coil controlled by the common return air temperature. However, a different number of students is very often present in the two classrooms, especially in the summer period.

Fig. 14 shows that different occupancy levels (100% in TA05, and 10% in TA06) give mean air temperature differences between the two zones higher than 2 °C, and produce little discomfort in both classrooms.

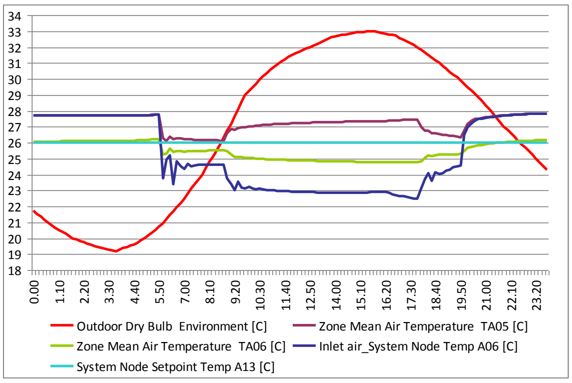

Fig. 15 - Trend of temperatures in a typical warm day when asymmetric occupancy occurs, for HVAC system in actual configuration

The replacement of the AHU fan could bring about energy savings, but would not improve HVAC system performance in terms of internal comfort when an asymmetric occupancy occurs.

Instead, the HVAC configuration with the two separated post-heating coils would be able to ensure comfort conditions even for asymmetric occupancy levels. Fig. 15 shows that the same previous different occupancy levels (100% in TA05, and 10% in TA06) are now correctly obtained.

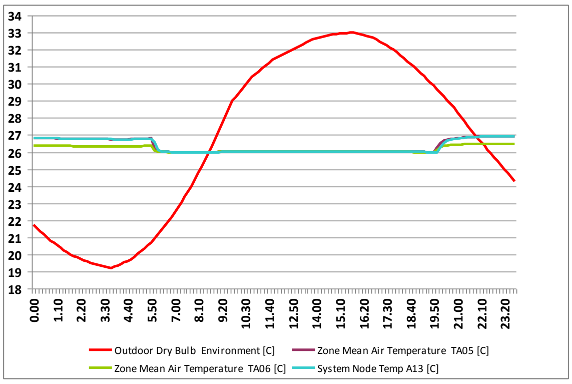

Fig. 16 – Trend of temperatures in a typical warm day when asymmetric occupancy occurs, for HVAC system configuration with split heating coils

6. Conclusion

Dynamic simulations software are very important tools for the energy analysis building-plant systems not only in design process but also in management decision for improve energy saving in existing buildings.

In the case study of a typical HVAC plant designed for hygrothermal and air quality control in university classrooms located in Bologna, energy simulations gave important information for the best setting of the air handling unit and for the evaluation of energy efficient solutions. Energy saving solutions must be evaluated depending on the effective external climatic conditions and daily scheduling of HVAC system.

Problems of the existing plant are related to excessive air renovation causing high energy consumptions and a lack of control of internal temperature of two classrooms treated as a single zone, creating discomfort when different occupancy of two rooms occurs.

The main and simplest solution is to increase the recirculating air flow rate (as for S1 and S3 solutions) that is an efficient strategy only if it is directed to reduce cooling loads. While in warmer summer periods this solution gives high energy savings (25%), no advantages are present in a seasonal analysis.

Other solutions analysed are the increasing of the cooling coil dew point temperature (controlling the internal humidity) and reducing the volume total flow rate. Combining all those solutions, simulation results indicate up to 60% energy savings for a typical summer week in Bologna and 53% for a seasonal cooling period.

Further improvements can be achieved with a variable cooling coil dew point temperature controlled by the measurements of the internal relative humidity.

References

UNI 10339, 1995: Impianti aeraulici per il benessere: Generalità, classificazione e requisiti

EERE Energy Plus