CLIMA 2000 ’97, TOPIC 9: *“Modelling and Experimental Approaches”* , P93

COST-EFFECTIVE DESIGN OF THERMAL ENERGY STORAGE COMPONENTS FOR HVAC PLANTS

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Summary

This paper compares the results obtained with the simplified sizing methodologies for thermal energy storage components usual in HVAC current practice and those obtained from an optimised procedure based on hourly simulations.

The PC version of the building energy analysis programme DOE2.1E was used in energy simulations of a central hospital in Lisbon, as part of an energy audit. The audit enabled the simulation model to be calibrated. Based on this model, the sizing of energy plant alternatives including thermal energy storage systems with ice banks or chilled water storage were determined.

It was concluded that the usual practices of sizing storage systems are quite ambiguous. The best methodology involves determining power and energy consumed on daily and annual terms, variable functional strategies throughout the year and corresponding costs in relation to energy supplier tariffs.

1. Introduction.

A central hospital in Lisbon, with about 76,000 square metres of floor area, ordered an energy audit (CCE, 1996), with the objective of identifying all the economically justified energy conservation opportunities (ECO’s), including the total restructuring of its central energy plant.

For modelling energy needs for this building, the PC version of the building energy analysis programme DOE2.1E. was used (Hirsh, 1996). The audit enabled the simulation model to be calibrated and the simulation results produced breakdowns of energy consumption into sources and uses as well as analysis of the essential ECO’s in the building envelope, HVAC systems and thermal energy producing central plant.

The Board of the hospital was also considering to make a considerable investment in the global renovation of the building and of its special facilities, including the generalisation of space cooling to the whole hospital. Hence the systems module of the model was developed to cover this new goal, including some pertinent ECO’s, such as substitution of electric resistance heating and scheduled control for HVAC. Some alternatives for the type of central plant concept were studied, including co-generation and chilled water storage.

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This paper is based on the auditing and retrofitting case of the hospital unit, but uses the final model produced to compare the results obtained with the sizing methodologies usual in the HVAC design industry related to thermal storage and those obtained from an optimised procedure based on hourly simulations (DOE2.1E).

Some suggestions are made for future DOE2 updates in order to improve its capacity to simulate thermal energy storage systems.

2. Sizing methods and economical analysis.

Most often, the design of thermal storage plants follows quite simple procedures, thus leading to several undesirable consequences. A study conducted in three European countries (CCE *et al.*, 1996) reports the conclusions that have been found from a survey on installations, suppliers and project engineers. Some of the most important are the following:

a) Partial storage was the preferred strategy.
b) In spite of the express goal of reduction of chiller capacity, designers do not put enough trust in storage systems. So, they install excessive chiller capacity, resulting in less economical returns.
c) The design process is usually very basic, based only on a Design Day which is the yearly peak cooling day, on a daily charging cycle and on partial storage load levelling strategies.
d) Commercial ice storage is the storage technology generally adopted.
e) Economic analysis of the storage systems was always absent in the project documentation. Often, the only justification consisted of comments about electrical tariffs and efficiency advantages, and some balancing between avoided chiller cost and storage cost.
f) Design engineers do not take advantage of the possibility of larger temperature difference in the secondary circuit when using ice banks.
g) The commissioning process is very simplified in most of the cases.
h) Most of the installations are not properly monitored and there is no optimisation of operating conditions.
i) Due to the lack of monitoring, there is no account of savings. So, building owners do not really know how their return on investment stands, although they apparently think that storage systems are economical.

It was concluded that, in current HVAC practice in the three countries covered by the survey, there is no realistic assessment of thermal storage systems during design, as it requires tools not readily available to project engineers: detailed hour-by-hour simulations are not generally used except by large design firms.

The implementation of a system on the basis of the design day without a year-long assessment will lead to unbalanced installations. This will force system operators to develop the best annual running strategy on their own. Fortunately, when those procedures are used, there is a tendency to install 100% of the initial nominal chiller power, and so, the load will be always satisfied. However, the storage will become redundant and it is often soon abandoned. In this case, investment costs are obviously much higher than needed.

2.1 Sizing Methods

When project engineers use simple design methods, even when they use commercial software, the monthly peak cooling day constitutes the only information that is normally used for thermal storage projects. The day with the maximum peak cooling load constitutes the design day. The sizing process usually follows the procedure described next.

1 - Quick sizing process.

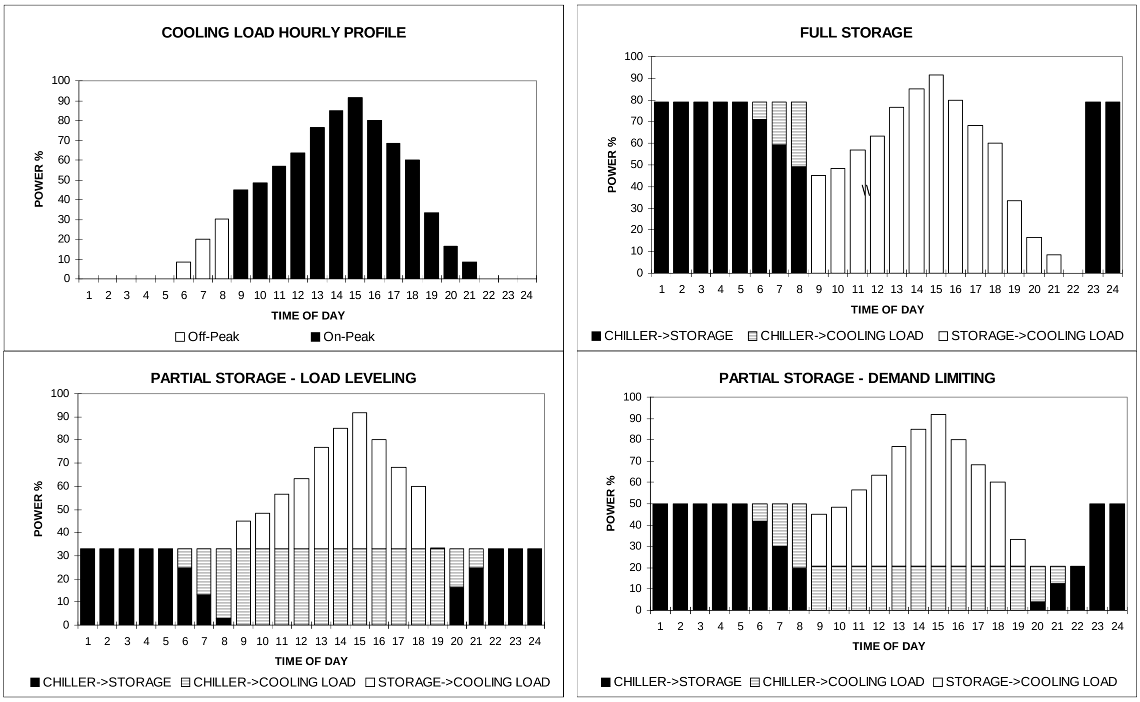

Fig 1 - a) Peak Cooling Day example. b) Full Storage strategy. c) Partial Storage Load Levelling strategy. d) Partial Storage Demand Limiting.

This is the ASHRAE reference methodology (ASHRAE, 1993). This is a method for initial evaluation of cool storage systems and for preliminary selection of system components based on the design day with chiller priority. The chiller size and storage capacity are calculated based on the total system cooling load, given number of hours in charging and discharging modes, chiller capacity when on direct cooling on-peak period, chiller capacity when charging storage, chiller capacity when direct cooling during off-peak period, and operating strategy (full storage, partial storage demand limiting or load levelling). Fig. 1 shows the results from this method on a hourly basis for the various operating strategies for a given Design Day.

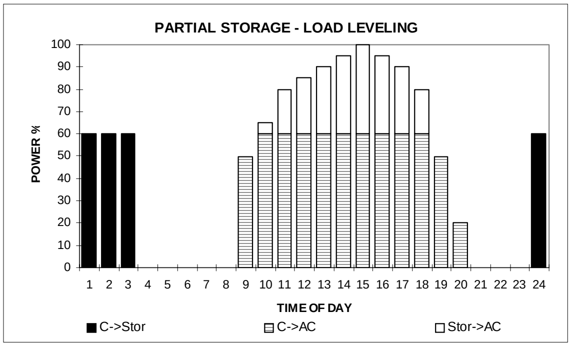

Fig. 2 - Partial Storage Load Levelling, "60% method"

When partial storage is used, several arrangements chiller size-storage capacity are possible, depending on the number of hours allowed for charging and the schedule for discharging. When applying this method, designers often size the storage system based on a heuristic decision, which leads to a chiller power of about 60% of the Maximum Cooling

Project Demand Power, and a storage capacity calculated from a peak shaving area resulting from the cooling load profile and the load met by operation of the chilling equipment. The final sizing relies on simple spreadsheet and graphical analysis. In this case, the number of hours allowed to charge and discharge is an output, and not a design specification.

2 - Final sizing

Typically, manufacturers of cool storage devices, e.g. internal melt ice on coil and encapsulated ice, provide performance data for their products. It is often possible to run an hourly simulation for the design day including the specific characteristics of the thermal storage device, circuits temperatures, chiller placement in relation to storage tank (upstream, downstream and parallel), and chiller priority and obtain a more precise estimate of system performance.

The sizing process most often stops here, even if the only accurate economical analysis possible is the simple comparison between the price of avoided chiller power against the price of the cool storage system.

2.2 Economical analysis methods.

In an attempt to obtain some form of annual evaluation of the system, and in spite of the lack of information about building behaviour, a very simplified yearly analysis is sometimes performed based on a proposed equivalent number of days simulating the whole cooling season. Two alternative analyses can be made depending on the amount of information available:

a) If the only load profile available is for the design day, yearly analysis is carried under a scenario of the Design Day representing all operating days in Summer.
b) If the twelve monthly peak day profiles are available, the analysis can be extended to a full-year based on the number of equivalent full-load days during each month.

Both simplified scenarios may tend to promote cool storage if the number of equivalent full-load days is overestimated. However, when partial storage strategy is the option for the peak design day, the system may work in full storage mode for most of the non-peak days, depending on the importance of the internal loads in the overall cooling load. Hence, the analysis would not account for additional savings associated to lower energy consumption during the higher on-peak cost of electricity and, thus, in reality the results have the usual tendency to be adverse to adoption of cool storage.

There are other methods which account for the various peak cooling load profiles for each month, namely the hot day, the cool day, the typical workday and the typical non-workday (COOLAID, 1991). However, the amount of work necessary to produce those 48 cooling day profiles is not far different from what is required for a complete yearly analysis and, thus, it is avoided by designers most of the time.

Hourly-based energy simulation in buildings, which may overcome all the drawbacks previously listed, is rarely used in the three countries, other than in research or very special large projects. This situation thus usually leads to non-optimised sizing and operational modes for the storage systems that have been installed in most cases.

3. Hospital Case Study.

3.1 Building Energy Analysis.

The following case study is based on a real energy audit exercise carried for a hospital unit. The PC version of the building energy analysis programme DOE2.1E, currently supported by the Lawrence Berkley Laboratory, USA, was used in this work. DOE2 predicts the hourly energy use and energy cost of a building given hourly weather information, occupancy schedules, the description of the spaces and zones in the building, its HVAC equipment and utility rate structure. Building heat transfer relies on the concept of response factors, weighting factors and transfer functions for accounting for the thermal inertia effects of building fabric and occupational trends like lighting, occupancy and equipment use.

The building is 10 storeys high, consisting of two main blocks linked by three intermediary blocks, with a total useful floor space of 76,000 m^2. The building includes a Medical Faculty (10,000m^2). A general view of the building is shown in Fig. 3 and in a schematic representation of the model obtained by reading the data file of one of the applications of DOE2.1E (Fig.4).

Fig. 3 - Frontal view of the hospital.

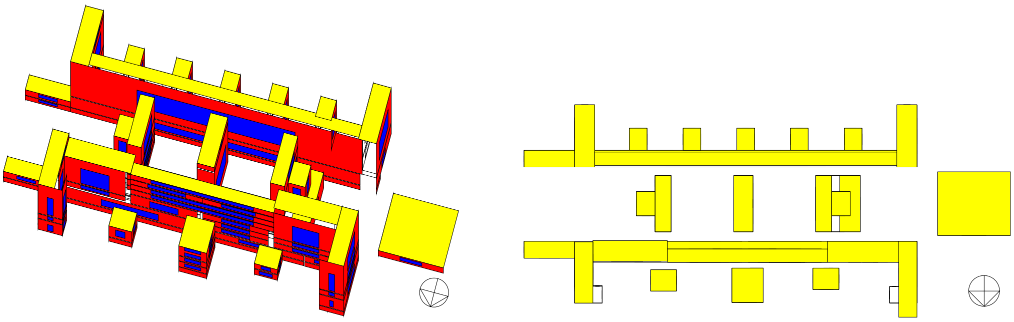

Fig. 4 - Isometric and plan views from DOE2.1E model obtained with DrawBDL (Huang, 1994).

Zoning was established taking into account the following criteria:

a) the characteristic internal gains of each space e.g. occupation, lighting and equipment densities and schedules. The space types considered for the Faculty were: classrooms, auditoria, laboratories and offices. The space types considered in the Hospital were: consultation, urgency, infirmaries, laboratories, surgery block, offices, dinning-hall, visitor-reception and warehouse.

b) differences in external shading, including the building self-shading, and for similar orientation (north, south, east, west, intermediate).

c) unconditioned spaces and system type for the conditioned spaces:
    1. Heating only by baseboards.
    2. Heating and Cooling with Packaged Heat-Pumps.
    3. Package air-conditioning plus baseboard-heating.
    4. All-air system with chilled water and electric heater.
    5. Two-Pipe Fancoil and electric heater.

Application of these criteria resulted in a total of 43 zones for the simulation model.

The existing building systems have an installed capacity of 4.5 MW for heating and 1.9 MW for cooling. Cooling is presently limited to high risk units and certain other departments. It is provided by chillers (0.8 MW), and by others numerous individual window units (1.1 MW). Heating is provided throughout the whole building and consists of electric radiators (3.8 MW) and individual heat pump units (0.7 MW).

Comfortable room temperature can be obtained during cold days but it is more difficult to keep during hot days, despite the high thermal inertia of the building and the presence of effective window shading.

Service hot water (SHW) is produced by electrical water heaters with individual capacities between 30 and 500 litres, with a total installed electrical capacity of 2.7 MW, though with relatively low simultaneous usage.

Steam, produced in central boilers, is used in the kitchen, laundry and for sterilisation of equipment.

The hospital consumes around 14,300 MWh of electricity and 740 tons of fuel, per year, for a total of 4,878 tons of oil equivalent (toe), with annual energy costs of almost 270 million PTE[1], 90% of which corresponds to electricity costs, as shown in table 1.

Table 1. - Energy consumption and use

	Electricity	Thick-fueloil	Burner-oil
PRIMARY ENERGY			
-toe	4 146	717	15
-%	85%	15%	0%
APPLICATIONS	Space Heating and Cooling, SHW, lighting and equipment	kitchen, laundry and sterelization	incinerator

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[1] Indicative rates (Nov. 1996): USD $1.00 = 155 PTE , 1 ECU = 195 PTE

Electricity is widely used in the building (indoor environmental control, lighting, elevators, hospital equipment and SHW) and, thus, a special attention had to be devoted to reduce its consumption and replace it by other more efficient energy sources before proceeding with an optimisation of its central plant.

The audit also included an inventory of the thermal characteristics of the building, as well as an inventory of production and distribution of steam, thermal and electrical systems plus annual schedules of occupation, equipment, illumination and infiltration.

3.1.1 Model Tuning.

3.1.1.1 Principles

As shown in Table 1, electricity is the sole relevant parameter for the DOE2 model tunning: the indoor environment is thermostatically controlled in most of the space, and the other fuels are not significant as they are only used for very specialised services. So, to calibrate the model output (electricity consumption), experimental verification was made at three levels:

1. The electricity consumption of major individual equipments and major zones (equipment and lighting) were individually monitored to obtain accurate hourly electrical consumption to be used in the model.

2. The output of the DOE2 model was carefully compared to the overall electrical consumption and peak demand, by zone and overall, for a period of four days.

3. Overall monthly electric consumption and peak power predicted by the DOE2 model were compared with real data.

3.1.1.2 Description

Throughout the period of field work (about one and a half months), total electrical consumption at the utility meter was monitored as well as in selected zones (e.g., infirmaries, administrative area and intensive care units), several electrical water heaters, some elevators and chillers. The partial metering of electrical use were integrated in such a way that the overall sum was equal to the total electrical consumption profile registered during the monitoring period. Thus, consumption associated to equipment, lighting, SHW and other users were adequately characterised.

This information was used to create the input data file for DOE2.1E and to calibrate the model as closely as possible with respect to the monthly and annual use pattern of electrical energy.

Global energy consumption was obtained from electric bills from 1993 to 1995. The average monthly energy consumption was taken as the mean for the period, to dilute climatic influence, as it was impossible to obtain real weather data for that period and the TMY data available for Lisbon had to be used for the simulation. In relation to the taken demand power values, two criteria were used: the average value of homologue months and the maximum value of the same month.

Fig. 5 shows that the level of correlation between energy consumption and taken power values is very high in terms of monthly values.

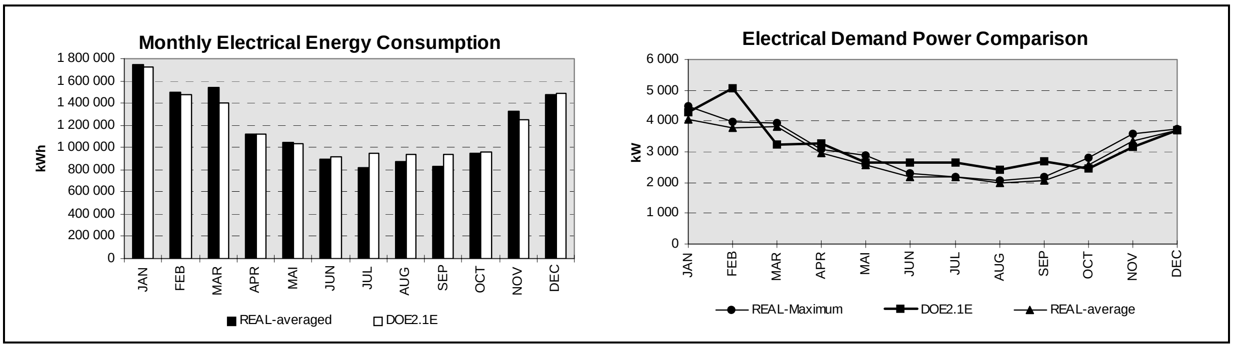

Fig. 5 - Measured energy consumption compared to the output of the DOE2 model for the hospital.

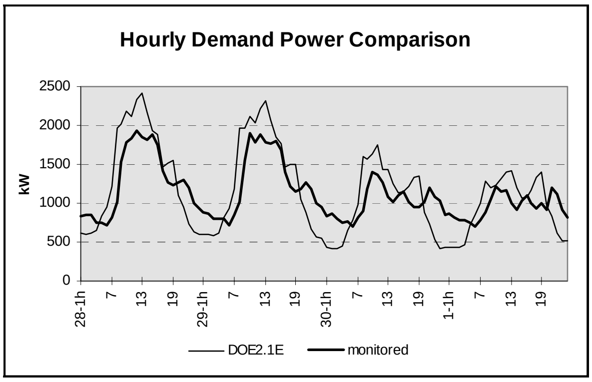

Fig. 6 - Measured and simulated global electrical use patterns.

There was also an attempt to obtain a correlation between the average electrical consumption profile in the total meter of the Hospital and the simulation profile obtained via the model. Comparing four whole days (two weekdays and one weekend) as shown in Fig. 6, it is visible that certain random variables such as the use of individual electrical water heaters and meteorological conditions are responsible for some differences, but there is quite a good similarity in the daily evolution pattern of the use of electricity. In relation to the accumulated consumption of electricity in this period, the difference between the average values and those obtained through simulation was only 4%, which is quite acceptable given all the uncertainties involved in the model.

Thus, the simulation model may be considered valid, as the sole variable predicted by the model closely matched the measured data during the audit as well as electricity bills available on record. This model thus is a good basis for the process of energy accounting in respect to the present use of electricity and to the identification of ECO's, namely the study of the potential for thermal energy storage.

3.1.2 Results.

Based on this model, it was possible to establish how electricity was used in the hospital on a yearly basis, as shown in Fig. 7.

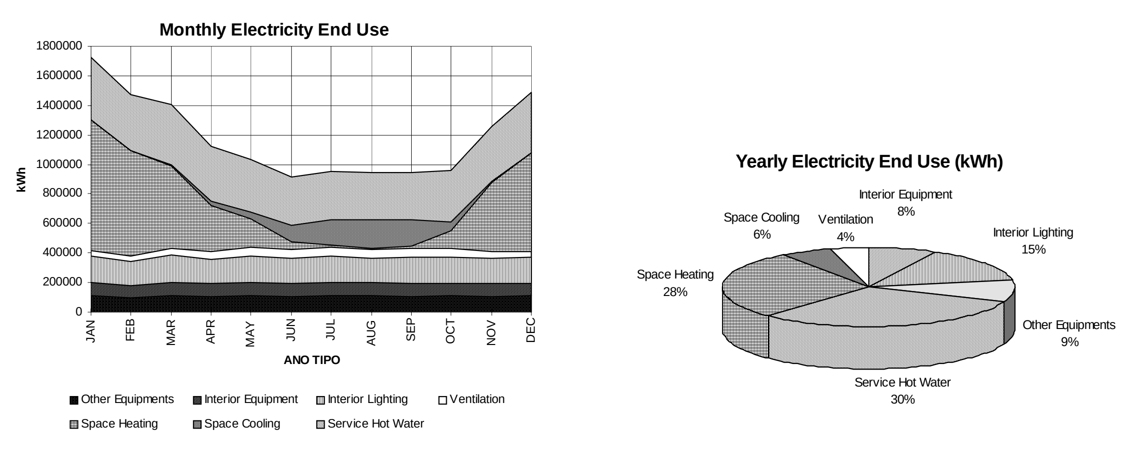

Fig. 7 - Total and Monthly consumption of electricity by end-use.

3.2 Implementation of Thermal Storage within a scenario of generalisation of space cooling.

In this scenario, the only one where cool storage has any meaning, the conditioning of the spaces would be carried out by a four-pipe fan-coil network. The existing all-air conditioned spaces would be maintained, but their air-handling units would be retrofitted with a four-pipe system. The interior reference temperatures are 22ºC in Winter and 24ºC in Summer, without humidity control. The present amount of fresh air intake of the all-air conditioned spaces would be maintained, and one air-change per hour was adopted for the other spaces.

Heat production, for both space heating and service hot water production would take place in gas boilers. Cold water would be produced in chillers located in the central station. In the discontinuously occupied spaces, systems would be turned off outside of occupied periods.

The systems and the physical plant were sized with an hourly simulation with DOE2.1E for a whole year. The design cooling and heating loads were 4.8 MW and 4.6 MW, respectively.

An aspect worthy of note is that, despite the generalised cooling in the whole hospital, this scenario achieved a smaller overall energy consumption and energy costs (3,493 toe, 185 million PTE), than the present situation resulting from scheduled control of non-occupied spaces and replacement of electricity by natural gas for space heating and production of service hot water.

This scenario constitutes the **base case** for the study of a cool-storage option**.** The monthly peak cooling day is shown in the Fig. 8. The September peak cooling day load will be used as a the Design Day profile.

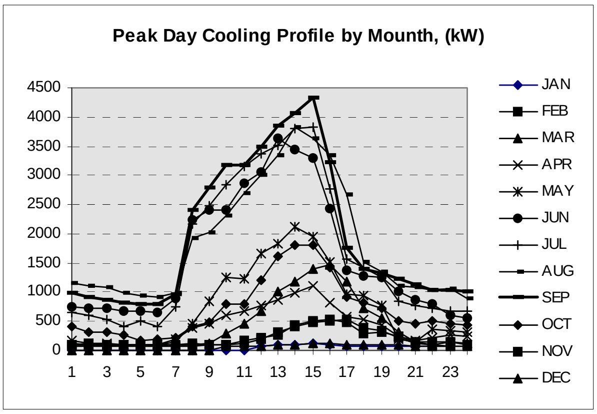

Fig. 8 - Maximum daily profile cooling load for each month.

The general characteristics are:
Total Electrical Energy Consumption:
7,097,599 kWh/year
Maximum Electrical Power Demand:
2,600 kW
Chiller Cooling Power: 4,800 kW
(Maximum Cooling Load: 4,343 kW)

The yearly analysis scenarios that follow illustrate the implications of the simplified procedures that were described in section 2, in comparison with the hourly simulation performed with DOE2.1E.

For this building chilled water could be a reliable system because there is available space and there is room for a good aesthetic integration. Ice storage was also a technology to consider.

Partial storage was the only option studied because a full storage design strategy is most attractive where on-peak demand charges are high or where the on-peak period is relatively short, which is not the case here. Partial Storage Load Levelling for chilled water storage was studied from a departure point obtained with the 60% method previously described. Partial Storage Demand Limiting for ice storage was also not pursued because the storage capacity size would be excessively large. For Chiller Water Demand Limiting scenario, an arbitrary 1,200 kW maximum chiller operation was imposed.

As there is a net cooling load twenty four hours a day in summer, the chiller must be operating during the night time anyway. Thus, the chiller power must be high enough to meet the hourly charging storage load and the building load. For this reason, for the case #2b below, chiller power could not be reduced. The storage capacity was also initially calculated from the 60% method, bearing in mind the nigh-time cooling load.

The pay-back period for all the studies was determined taking into account four variables: balances of cost of energy consumption and demand power, reduction in chiller power (15 kPTE/kW) and cost of storage (3 kPTE/kWh for ice storage and 2.7 kPTE/kWh for chilled water storage, plus a 2,500 kPTE fixed cost for the control system). The same utility rate was used for all the cases. The charging period allowed is from 11:00 PM to 8:00 AM, the off-peak period for the hospital throughout the year.

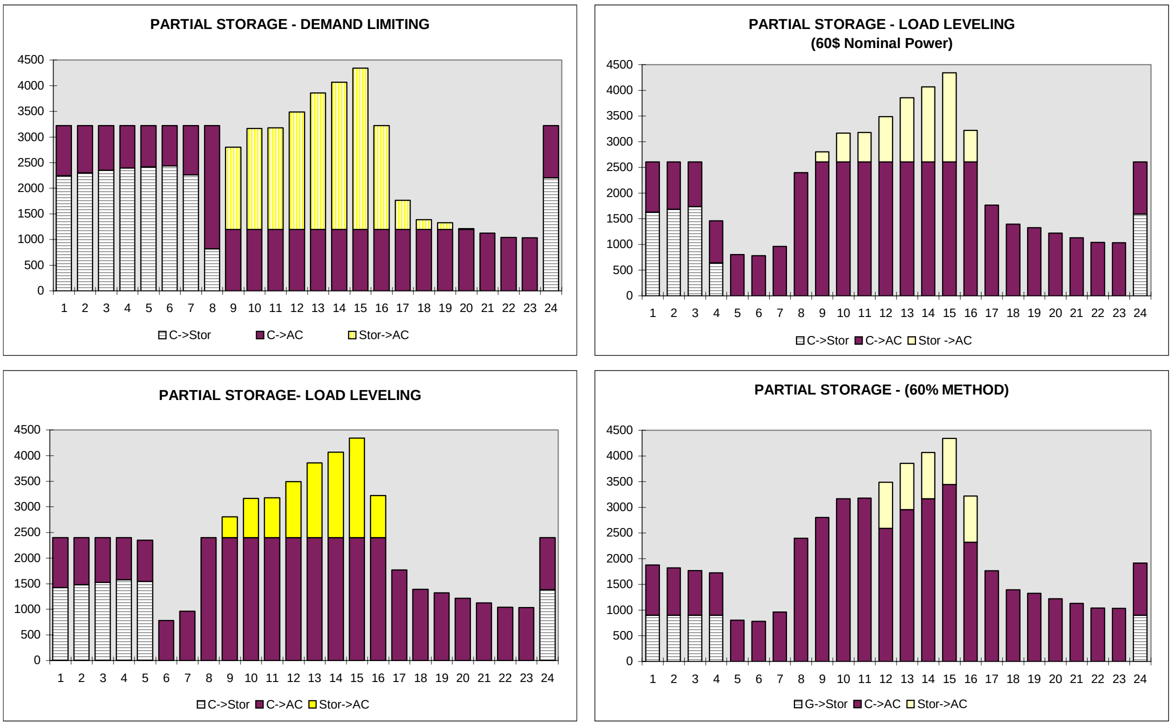

Fig. 9 -

a) **Case study #1a:** Chilled Water Storage, Partial Storage Demand Limiting (ASHRAE method).

b) **Case study #1b:** Chilled Water Storage, Partial Storage Load Levelling (60% method).

c) **Case study #2a:** Ice Storage, Partial Storage Load Levelling (ASHRAE method).

d) **Case study #2b:** Ice Storage, Partial Storage (60% method)

The yearly simplified economical analysis will be carried under two scenarios: Design Day representing the operating days from July to September (E1), and the Monthly Peak Day Profile as representative of the operating days of each month (E2). For the last scenario, chiller or storage priority will be applied in each month depending on which is the best choice.

For all cases where quick sizing method was used, there was no allowance for changes in chiller behaviour (COP) as outdoor conditions changed, except a reduction of 40% in the Nominal Capacity in Charging Ice Storage Mode. The DOE2 model, however, considers corrections for partial load regime, capacity and efficiency as a function of the entering water/air temperature in the condenser and of the leaving water temperature in the evaporator. In the DOE2 model, it was also possible to adapt the best strategies for each day of the year (chiller and storage priority, or combined) as function of the hourly cooling load.

In the DOE2 model, initial chiller and storage sizing also derives from the respective quick sizing analysis. An iterative process was then followed (chiller size fixed and capacity storage allowed to change). When capacity storage changed more than 10%, chiller size was allowed to change 10%. When all hourly loads were satisfied by the system, the solution was accepted as the best to be selected. Then, a sensitivity study involving control strategy was done which led to the best economical trend.

Table 1 - Summary of Results.

	Case #1a	**Case #1b**	**Case #2a**	**Case #2b**
Description	Chilled Water Demand Limiting	Chilled Water Load Levelling	Ice storage Load Levelling	Ice Storage
Quick sizing method	ASHRAE	60% method	ASHRAE	60% method
Chiller Power Charging Period (kW)	3,221	2,606	3,998 * 0.6	4343 *0.6
Chilling Power Discharging Period, (kW)	1,200	2,606	2,399	4343
Storage Capacity (kWh)	19,433	7,300	8,934	4,500
Energy consumption related to Base Case, scenario E1, (kWh)	plus 21,150	less 95	plus 21,507	0
Pay-back scenario E1, (year)	10 (13)*	**	16 (19)*	17 (17)*
Energy consumption related to Base Case, scenario E2, (kWh)	plus 208,107	plus 87,000	plus 166,103	plus 84,869
Pay-back, scenario E2, (year)	37 (12)*	**	33 (18)*	*** (16)*
DOE2 analysis				
Maximum Chilling Power Charging Period (kW)	3,600	3,300	4,200	4,800
Maximum Chilling Power Discharging Period (kW)	1,200	3,300	4,200	4,800
Storage Capacity (kWh)	23,000	8,000	15,000	4,500
Energy consumption related to Base Case, (kWh)	less 186,362	less 117,899	less 53,042	less 4,956
∆ Electrical Power Demand (kW)	less 905	less 282	less 588	less 130
Pay-back, year	4.2	< 1	5,4	3,4

* Pay-back without demand power cost consideration, **Decreasing cost of chiller equals capacity storage cost
*** No economical savings.

Although the quick sizing method generally predicts higher energy consumption the necessary for the base case, energy costs are reduced because consumption is moved to off-peak hours, thus, translating into savings and a positive pay-back.

However economic and energy data given by quick sizing with simplified economical analysis are very different from those resulting the detailed DOE2 simulation. The economic and energy savings obtained with the quick sizing/simplified economical analysis methods are thus quite dubious, because a good annual assessment is not possible. Two major causes were identified for these differences:

a) The use of peak load days does not take into account the savings achieved in days when cooling loads are smaller.
b) A sizing method based only upon demand cooling load is not able to correct the real capacity availability of the chiller nor its real efficiency, as both strongly depend on the real temperature of both hot and cold sources. The night-time running of the chiller and load levelling are major factors to improve overall efficiency which are not accounted for in the simple procedure.

Nevertheless, the DOE2 model does not take into account other important heat transfer variables, such as inlet and outlet temperatures of primary and secondary circuits, charging and discharging rates as a function of the energy stored in the tank and secondary fluid flow rate, as well as configuration of the storage plant (series flow storage chiller upstream or downstream, and parallel flow). Moreover, one often used strategy, that decides storage priority, chiller priority or combined for the day as a function of the outside temperature at a given hour (e.g. 8:00 AM) cannot be easily simulated in DOE2, as it only allows for control based on cooling-load magnitude.

4. Conclusions

From the results shown, it can be concluded that:

a) Sizing a storage system on the basis of only design day method does not permit any meaningful thermal and economical analysis.

b) Quick sizing procedures may be interesting for an initial sizing, but they must not be the basis for an economical analysis, because some degree of guessing will be required for simulation of the behaviour during a whole year. The resulting economical analysis is not reliable and a suitable control strategy cannot be defined.

c) Initial sizing on the basis of the reduction to 60% of maximum cooling power seems to lead the best pay-back period, despite the higher initial investment cost and the smaller energy savings.

d) Using an annual overall assessment of the HVAC plant, as with detailed hourly-simulation tools, will permit the prior establishment of suitable control strategies, and a good awareness of the thermal and economical impact of alternative solutions.

e) There is an obvious need for the development of more accurate simplified design methodologies, as the use of detailed hour-by-hour simulations is not the most suitable means for initial design of thermal storage systems nor for the final design of systems for smaller buildings, due to costs and time required to prepare the simulations.

5. Acknowledgements

This work would not have been possible without all the elements obtained from CCE about “St.Maria Hospital Energy Survey” and THERMIE project “Promotion of the Use of Cooling Storage Systems” financed by the Commission of the European Union, DGXVII.

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