THERMAL ENERGY STORAGE OPPORTUNITIES FOR RESIDENTIAL SPACE COOLING: A TECHNOLOGY TO MANAGE DEMAND RESPONSE AND REDUCE CUSTOMER COSTS

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ABSTRACT
Cool thermal energy storage could become one of the primary solutions to manage peaks, low load factors, electrical power imbalance between daytime and nighttime, and to offer the possibility to reduce electricity costs for the customer. This kind of storage uses off-peak power to provide cooling capacity by extracting heat from a storage medium. Typically these systems use refrigeration equipment to create at night a reservoir of cold liquid or solid material. During the day, the reservoir is tapped to provide cooling capacity. To evaluate the opportunities of storage it is necessary to have accurate load models.
The problem of modeling of cool thermal storage is addressed in this work. The proposed load model rely on information about the physical characteristics of an hypothetical load at the residential sector of customers. Some simulation results are shown and some demand responsive alternatives are also proposed in the work.

Keywords: Demand-Responsive policies, thermal energy storage, energy-efficiency.

1. INTRODUCTION

New products, viable management techniques and better control look to achieve an interesting balance between optimum service and energy savings. Specifically there is a considerable potential for improving the energy efficiency in the four consumer sectors: residential, commercial, industrial and transportation. Several studies have estimated that electricity savings potential in some sector can reach 40%.
Unfortunately, energy costs are generally perceived a small fraction of total cost. For a lot of customers, there are doubts as to whether the new technologies –for example, technologies with a higher first cost such as cool or heat storage- even save energy, and they are reluctant to spend time and money in these energy-efficient projects.
Moreover a problem arises in last decades: the continuous growth experienced in the demand of residential electrical systems (about 30% of demand growth from 1997 to 2001 in the southeast of Spain). This growth is important because in Spain and in other European Union countries, typically about 25% of annual electric energy demand is attributable to residential loads (more than 70% of residential energy use is for Air Conditioning, Space Heating and in a minor extend for water heater). Thus, it seems reasonable to try to influence the customer demand patterns through Demand-Side incentives in order to obtain several objectives: minimizing peak summer demand, improving load factor in residential feeders and substations, improving system operation and maximizing quality of service.
On the other hand, the competition in the new deregulated electricity and gas markets has decreased in some extend the electricity costs for medium and large customers and those energy efficiency improvements have become less profitable. From the authors viewpoint there will be a growing interest on customer Demand Side Bidding (DSB) in the next years, due to the flexibility and elasticity in the customer demand achieved through load control and energy efficient policies. Thus these policies can even be more profitable after the complete deregulation process allowing the customer participation in the new deregulated energy market structure.
Moreover energy efficiency and demand management, because of the increasing prominence of environmental issues in our societies, is a very useful tool from public authorities to face to increasing pressure to solve pollution related problems. It is difficult to assess the total effects of power plants emissions – greenhouse gases and volatile organ compounds-, but it is also clear that European Community (EC) will like to reduce these emissions. Under the Kyoto Protocol, the EC committed itself to reducing its emissions by 8% during the period 2000-2012 in comparison with their levels in 1990.
The purpose of this paper is to present the possibilities of residential cool storage systems through a Physically Based Load Model (PBLM).

2. DEMAND MANAGEMENT AND THERMAL ENERGY STORAGE

Last decades, direct control of water heaters was the most usual Demand-Side Management strategy for energy storage, mainly in the USA and France. Water Heaters are turned on at least for periods of from six to eight hours and turned off during the peak periods, and perhaps also switching on during the flats periods. The technology and cost for control of Thermal Energy Storage (TES) loads are not significantly different than for Air Conditioning (AC) or Heat Pump (HP), but the operating procedures however are quite different due to the capacity of loads to store energy and then to profit a control in longer periods without the degradation of customer service.

But a problem arises in this strategy: water heater load profiles with direct load control show a large payback after the control period ends. To mitigate this effect, two ways are suitable: large storage capacity (at about 100 or 200 liter) is advisable to the customer or a detailed load model to predict and to correct the load demand during the payback.

An alternative to promote energy nighttime abundance is through electrification and the use of storage space heating or cooling into markets that would have been served at present by other fuel - agriculture, residential customers- or conventional electric appliances. This concept is not a new one because between 1990 and 1995 the number of electrical thermal storage programs in the residential sector of some developed countries has grown threefold and the number of installations has grown six fold [1]. Despite such rapid growth the total number of installations to date is a very small percentage of the potential market, even for the thermal energy heat storage -the most common and reliable technology-. Several reasons explain this fact in developed countries: the first cost of TES loads, the volume of tank storage required and the absence of incentives from utilities and public authorities since the new regulated market started in these countries.

Also it is interesting to note here that the cost and the weight are correlated to energy storage capacity. Why these loads ought to store heat only during night periods? Because this is easier than direct control of ETS, but the technology to do it is well known. The possibility of these loads to store energy (is the same problem for water heaters) in flats demand hours can be developed by aggregators and medium customers.

On the other hand, storage AC technology offer similar options, mainly in summer peak systems, but practical applications are currently largely limited to non-residential installations. Utility-prompted residential installations are, for all intents and purposes, limited to prototype or small scale research activity. For commercial customers (hotels, railway stations, airports) heat or cool storage seem more suitable in this moment.

In this work we deal only with residential cool storage, and perhaps it presents a major opportunity for equipment vendors and engineering firms of the European Union. It is very important to note at that several developing nations are experiencing from 5 to 10 percent annual summer peak demand growth, and so cool storage could be an interesting way to accomplish a global strategy to solve this problem in the near future.

3. THERMAL ENERGY STORAGE TECHNOLOGIES

There are different types of cool storage technologies based on several combinations of storage media, charging and discharging strategies in a basis time period, and service priorities. The main media for cool storage are water, ice and eutectics salts. Perhaps the most interesting option for a small customer is ice storage systems. These systems can be classified into ice harvesting, ice-on-coil (internal melt or external melt), ice slurry and encapsulated ice options [2].

The second criteria is charging/discharging strategies. Independently of the storage technology, the cool storage system can be designed to provide full storage or partial storage, this last option can be performed with load-leveling or demand-limiting options. Finally from the point of view of the load service priority the system can be operated on a chiller-priority or storage-priority basis whenever the thermal load in the dwelling is less than design options.

Originally, the applications cool storage technologies were developed for integration with chilled water cooling systems that typically serve larger buildings, or as a way to reduce air admission temperature in combustion turbine generators to increase plant efficiency –and capacity to generate more power in summer peaks-. At present residential-sized cool storage technologies have also been developed but cost economies of scale have been difficult to overcome in the residential market. For example in 1994 the Sacramento Municipal Utility District (SMUD) developed a successful residential program for 518 residential units (for a typical 150 square meter house) achieving annual energy savings of about 5 MWh (shifting 2 to 3 kW of summer peak) and with interesting customer savings of about 800$/yr [3].

Cool storage systems furnish a number of advantages for users, aggregators or commercial agents, such are:

- Reduced equipment size, space and weight (compressor kW rated power) due to operating at more hours at full load (with higher COP or EER ratios) and at nighttime lower condensing temperatures (higher Carnot efficiency). This reduce customer utility bills profiting lower power tariffs and improving power conversion efficiency.
- Improves load reliability, due to the possibility to maintain load service when some power distribution system failure appears. Also fire-protection should be considered when chilled water storage is present.
- Energy Services Companies can reduce its summer demand peak, improve the load factor, defer system expansion costs and improve competitive position over gas fired alternatives (through added of-peak sales when storage is present).

Unfortunately, a lot of problems to achieve successful implementation of cool storage alternatives appear, for example:

- The first cost of cool storage system is higher than the cost of a conventional HVAC appliance.
- The system design and maintenance.
- Loss of efficiency due to tank losses during storage periods
- Engineers have a little background in this technology

3.1 Ice storage technologies

Ice storage systems are a way to gain summer peak capacity by shifting the on-peak load to off-peak hours, and an opportunity for users to reduce electrical costs. Cool storage systems uses ice because ice can store, using the latent heat of fusion of water, up to 335 kJ/kg during melting and freezing . This supposes an advantage face to chilled water systems because they can store only about 42kJ/kg, i.e. about one eight the capacity per kg of an ice storage system (this system uses only the specific heat of the water). Thus, ice it requires less space, can provide colder air to the dwelling and can reduce duct and fan sizes, while consuming more chiller energy, of course. For this reason ice storage is an useful option for storage where space for storage is limited such are the cases of smaller commercial or residential buildings.

There are two basic types of ice storage: static systems (ice building) and dynamics (ice harvesting). In general, as in the case of heat storage [3], static systems are simpler, more compact, and less costly than dynamic systems.

A. Static systems: these systems can be open systems or closed systems. The cold refrigerant is circulated through a pipe coils submerged in an open water tank as shown in figure 1. During the charging cycle the ice is formed on the pipe coils until a satisfactory thickness is achieved. During discharging operation, the chilled water is circulated to the ice reservoir and is chilled to the melting ice.

B. Dynamic systems: dynamic ice harvesters or spray slush-ice systems, use a water (or 75% water 25% glycol solution) supply and plates or tubes suspended over the storage tank. During the charging cycle, the ice is formed on the tubes or plates and is periodically ejected into the storage tank. The discharging operation is similar than in static systems.

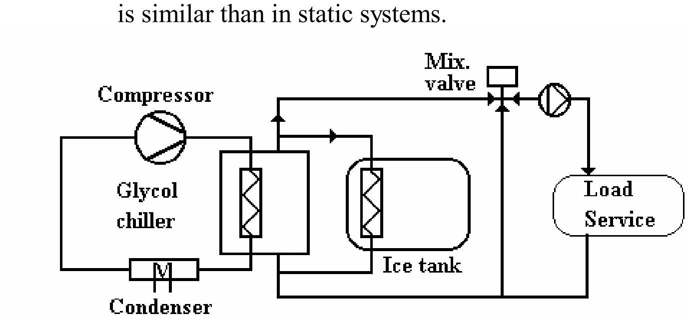

Figure 1. TES with internal melt system

The most promising alternative for cool storage seems to be glycol systems. These ice storage systems freeze water by circulating ethylene or propylene glycol through storage tanks. The main advantages of these systems are: first their simplicity (few accessories are needed and conventional water chillers can be used), the second the simplicity of control schemes, and of course the volume and space requirements. The main drawback is the need to include a heat transfer system that uses glycol rather than water [4], [5].

3.2 Phase change materials storage technologies

As it can be posed in previous paragraph ice storage systems have an important problem: the lower efficiency of chillers at lower temperatures required by ice storage systems. This problem can be solved through the use of phase change materials (paraffin, eutectic salts,…). These material are salts developed to change from liquid to solid phase at higher temperatures (for example about 8°C) which allows the improvement of chiller efficiency. Besides, phase-change materials also store about three times more KJ/kg than a conventional chilled-water storage system.

3.3. Operating strategies

Basically, there are three policies to operate TES cool storage systems: full storage, load leveling and demand limiting. These strategies will be described in the simulation example .

Full storage systems are designed to meet all peak and flat demand periods -cool demand service- from tank storage, i.e the chiller operates in valley hours (for example from 11pm to 7am). Obviously this type of systems results in larger and more expensive storage units compared with partial storage systems. Also this strategy presents an important drawback: the possibility of peak demand increasing in residential users.

From the other side, partial storage systems (load leveling and demand limiting) meet only a part of the cooling load from storage tank, so the rest of service requirements are achieved from the chiller in peak demand periods. The difference from load leveling and demand limiting systems are the chiller operation. In load leveling systems the chiller operates at the same rate during the all the time. In demand limiting systems, the operation of chiller is decreased when electrical tariffs are high (peak periods). The advantage of these systems are lower necessities for storage, rate power of chiller, and peak demand reduction in residential customer.

4. DEMAND-RESPONSIVE POLICIES

The new regulation process suppose a change in the relationship of utilities and their customers. Unfortunately and despite news in the press and elsewhere that suggest otherwise, the number of products that have been brought into competition for small users – residential and commercial- appear to be quite small in the future. The only way to participate in new deregulated (or re-regulated) markets [6] appears to be for residential users through energy aggregators and Demand Side Bidding (DSB).

Thus some promising initiatives, and pilot projects have been tested in the last three years: the so called Demand Responsive Policies (DRP) [6], [7]. These policies are the way to promote some customer participation in the new electricity market (at present limited to medium and large customers). DSB and DRP are changing the traditional concept (1985) of DSM from "policies driven by utilities to obtain a change in consumer demand" to policies where the customer is the main driving force to change in its own demand.

Also, these DRP policies are far from traditional DSM objectives and drawbacks. From the user viewpoint, DRP policies will be focused on the customer time of use rather than the magnitudes of electricity, searching for customer benefits (for example through participation in ancillary and settlement markets). From societal viewpoint, the greater elasticity of demand in some users will benefit significantly all the user because the price will be lower for all the user, participants or not (equity principle, usually not reached in older demand side programs).

But also, policies to achieve flexibility in customer demand present benefits for electrical energy systems because this "negative demand" or "distributed generation" should be an interesting reliability tool in the near the future.

At present, the rate of market penetration of these policies are very limited, in spite of the fact that deregulated electricity industry incentives for demand response seem to be greater than in the old traditional industry. The main barriers for DRP are:

1) The necessity of improved metering, communication and computer technologies to perform bids.
2) The lack of a clear policy from governments and System Operators to include demand and supply policies on an equal foot
3) The necessity of engineering tools to evaluate bid availability

The first barrier should be overcame. In our days such a communication and control system may have applications from beyond electricity affecting the control of a lot of parameters related to user activities (heating, lighting, ventilation, maintenance…) or also affecting natural gas and water uses. The demand and supply participation in the new markets on an equal basis is only a political question, because this premise is a basic rule for any free market.

The use of load control strategies to modify demand curves has been used since early sixties in the last century, but their objectives need to evolve from the Supply-Side and Direct Load Control (DLC) in traditional DSM programs to those that implies the voluntary participation of the demand through to reduce load in medium or short term, for example to alleviate networks constraints. It is therefore necessary to change old policies and concepts, to develop new specific policies, and improve tools to manage, forecast and evaluate the possibilities to perform bids for load reduction in new regulated market scenarios. Some of these demand control strategies proposed are shown in table I.

Policy	Load	Control strategies
Demand Limiting	AC, HP Dimmable Lighting	Cycling Dimming ballast
Demand Filling	TES(total/partial storage) AC, HP Water Heaters Water Heaters Pumps	Cycling, Preheating Precooling
Demand shifting	TES(total/partial storage) Water Heater	Shift primary source Dual sources)
Damp demand reduction	TES (partial storage) Dimmable lighting	Dimming ballasts, Control of storage
Demand Reserve	AC, HP Dimmable Lighting	Shed load, Dimming ballasts

Table I. Demand Responsive policies.

Each responsive policy has different objectives according to implementation necessities. For example an user who expects to offer a demand package reduction should control the demand of only the appropriate kind of load: HVAC, ECTS, lighting, etc. It is well known, from DSM experiences described in the bibliography [8], that some payback period follows up any control action. To reduce payback is necessary to apply additional actions –with ETS or lighting loads-, as proposed in table I.

The understanding of these policies should help us to asses the possibilities and availability of energy offers for each end use and specific load. If the inherent storage reservoir is not full the converter will produce cool to low room temperature and to produce ice in the reservoir during the night (demand filling). In valley or peak hours the control mechanism switch off the converter and it will use the cool stored in the tank to condition the house.

Obviously, after a normal use and depending on external weather, the state of cool reservoir will be easily known. In this way we would evaluate energy offers in medium term (we known the hours we need to refill the tank reservoir), and we will define what are the hours during the day to accomplish this task. Thus, the load has full availability to offer bid for a day ahead market. We used two state variables to perform this assessment: the load service (temperature) and the reservoir filling.

For example the possibility to perform energy offers for such a load is more difficult to evaluate for ancillary or balancing markets, due to the high probability that the converter was off and the load works stand alone with the heat capacity of its internal storage. If this is not the situation, the converter would be easily controlled to off state. Thus the load availability for this load is not full operative in these situations. Note here that the rate of load switching is very low (switching period up to 24 hours).

On the contrary, for a conventional heat pump, there is not intrinsic storage and the external storage can only maintain load service for a few minutes (note the rate of switching for these loads are from 10 to 15 minutes). For short term, the customer could be sure that the load will be on and its demand can be managed by load control (demand limiting) and so an offer can be performed for example in real time if the ISO has some network constraint or some imbalance. For example damp reduction policies are suitable to reduce oscillations due to payback after a demand limiting policy is exerted. In this case the possibility to store cool is higher for partial storage.

5. SIMULATION EXAMPLE: RESIDENTIAL COOL STORAGE ASSESSMENT.

In this section we present an example of TES cool storage design with basic calculations and considerations for an hypothetical system serving a familiar housing.

The characteristics of the house are: Total area at about 91 m^2, four bedroom (11.54 m^2, 10.79 m^2, 8.785 m^2 and 10.32 m^2),a kitchen (10 m^2) and the living-room (20,895 m^2)

The total area to cool is 72.33 m^2. The thermal load is obtained through physical modeling accounting for thermal losses (conduction, convection) of the dwelling, solar radiation, air infiltrations, etc [9]. The result is shown in figure 2 and the thermal requirements are: Peak thermal load 8.2 kW and daily thermal energy load of 135.2 kWh

Figure 2 shows the total electric load for the house studied in the design day (a typical peak summer day).

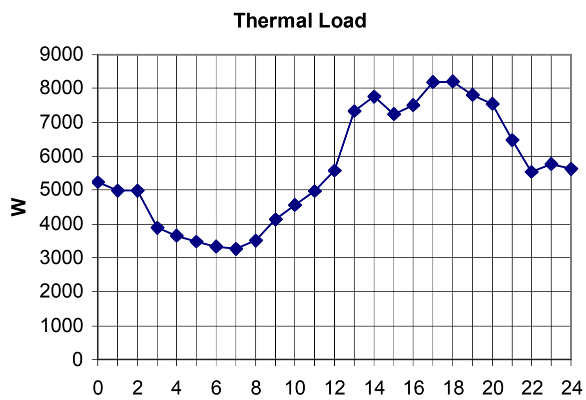

Figure 2. Thermal load for a residential customer

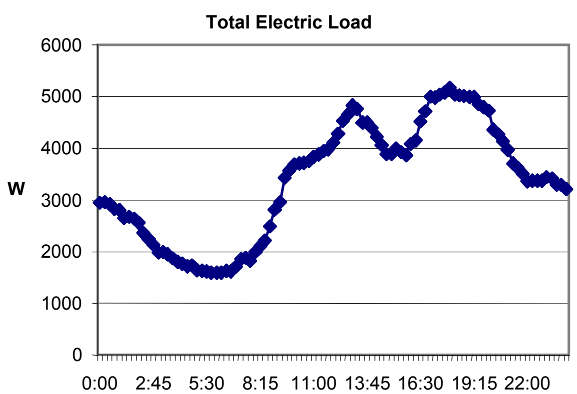

Figure32. Electrical demand in the summer peak day

The chiller and storage sizes are calculated based on the requirement that the total integrated capacity of the refrigeration plant must equal the total integrated cooling load plus any losses. (Here losses are considered insignificant). This means the equality of areas below two curves: the chiller operation curve and the thermal profile. Such equality is reflected in the general expression used to calculate nominal chiller size:

$$\text{Nominal chiller size} = \frac{\text{Total cooling load}}{H_{chrg}CR_{chrg} + H_{DConp}CR_{DConp} + H_{DCoffp}CR_{DCoffp}}$$

where:

H_{chrg} : storage charging time
CR_{chrg} : chiller's capacity ratio when charging storage
H_{Dcconp} :direct cooling during on-peak period (hr)
CR_{DConp} :chiller's capacity ratio when direct cooling during on-peak period
H_{DCoffp} :hours direct cooling during off-peak period
$C_{RDCoffp}$:chiller's capacity ratio when direct cooling during off-peak period

If the resulting nominal chiller size is greater than the cooling load for any hour in direct cooling mode, the chiller size must be recalculated. For this fact, capacity ratios must be substituted for appropriate rates so an iterative process is needed to equal areas and obtain the exact chiller needed.

	Full Storage		**Load Leveling**		**Demand Limiting**	
	Ch. Water	Ice	Ch. Water	Ice	Ch. Water	Ice
H_{chrg}	8	8	8	8	8	8
H_{Dccomp}	0	0	6	6	6	6
H_{DCoffp}	0	0	10	10	10	10
CR_{chrg}	1	0.7	1	0.7	1	0.7
CR_{DComp}	0	0	1	1	0.5	0.5
$C_{RDCoffp}$	1	1	1	1	1	1

Table II. ETS storage periods and performance

The required storage capacity is calculated with the following expression:

$$\text{Storage capacity} = \text{Total cooling load} - (TC_{DConp} + TC_{DCoffp} + TH_{DCchrg})$$

where:
TC_{Dconp} : total capacity when direct cooling during on-peak
TC_{DCoffp} :total capacity when direct cooling during off-peak
TC_{DCchrg} :direct cooling while simultaneously charging

The chiller and storage sizes for the modeled house are shown in table III.

Storage	**Storage medium**	**Chiller (W)**	**Storage (kWh)**
Non-storage		8200	-------------
Full Storage	Chilled Water	16896	103,2
	Ice	24137	103,2
Load Leveling	Chilled Water	5947	15,6
	Ice	6958	7,0
Demand Limiting	Chilled Water	6858	22,9
	Ice	8136	13,6

Table III Chiller and storage sizes.

The chiller operation for each strategy using ice is also shown in figures 3 (full storage) and 4 (load leveling).

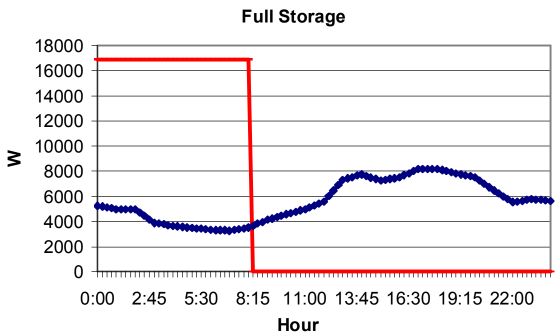

Figure 3. Full storage and thermal loads

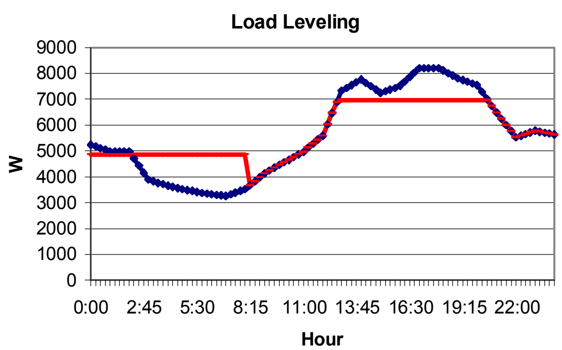

Figure 4. Load leveling and thermal loads

Table IV shows the effects on power and energy demand for our residential user due to each strategy of storage. Notice full storage alternative translates the peak from daytime to nighttime, and increases the peak (106% with ice storage). From this table, it can be shown that load leveling appears as the most interesting alternative due to shift load and peak demand reduction.

Operation strategy	Kind of storage	Peak saving (%)	Demand filling (%)
Full storage	Chilled water	- 85.4	71.2
	Ice	- 106.1	81.6
Load leveling	Chilled water	27.5	10.8
	Ice	15.2	7.8
Demand limiting	Chilled water	16.4	15.8
	Ice	0.8	12.9

Table IV. Impacts of storage alternatives in load curve

The annual savings in the customer electricity bills are estimated through residential Spanish tariff. The cost of nighttime demand (8 hours) is about 50% of daytime period (see table V).

Operation strategy	Kind of storage	Savings (€)
Full storage	Chilled water	13183.2
	Ice	12057.8
Load Leveling	Chilled water	3701.1
	Ice	2442.7
Demand limiting	Chilled water	4712.4
	Ice	3518.3

Table V. Impacts of storage alternatives in load curve

Notice savings in full storage is higher than in partial storage alternatives, this fact is due to the tariff selected. Also, it seems necessary to take into account the first cost of each alternative. These first costs are shown in table V.

Storage system	Non storage	Full storage		Load Leveling		Demand limiting	
		Water	Ice	Water	Ice	Water	Ice
Chiller	1384	2838	5148	1005	1513	1158	1766
Storage	-	1316	2541	199	146	292	283
Total	1384	4155	7690	1204	1659	1450	2050
Savings	0	-2770	-5884	180	-274	-67	-665

Table VI. Conventional and storage system costs comparison

It can be stated again that load leveling alternative seems the most interesting from electrical and economical point of view. Finally in figure 5 is shown the effect of cool storage load in demand curve.

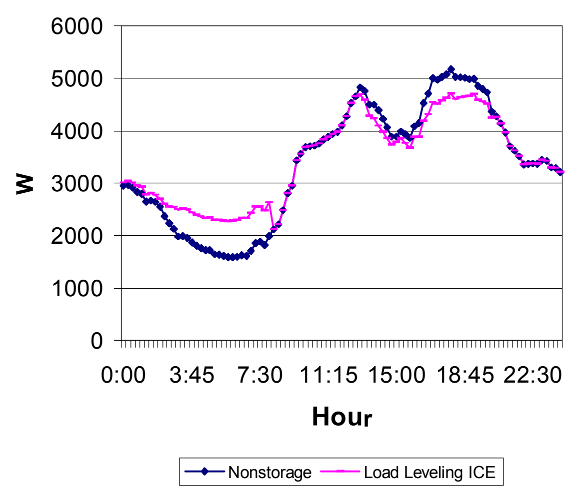

Figure 5. Effects of storage in customer load curve

6. CONCLUSIONS

Cool storage technologies, such are ice, chilled water, or phase-change material can help user, utilities and system operator to balance or reduce the electrical power consumption in a fairy way. The technology is straightforward and well proven for medium thermal necessities, and the savings and opportunities should be substantial. Perhaps cool storage is one of the most powerful tools available to aggregators and distributors for cutting operating costs and to promote a more efficient energy use in residential and commercial customers, and so to obtain a valuable benefit for our society in this century.

7. AKNOWLEDGEMENTS

The authors would like to thank to the Ministerio de Ciencia y Tecnología of Spanish Governement for supporting this research under the Project DPI2001-2779-C02-01, as well to thank the European Union for their support in this research.

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