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Ice based energy storage integration with solar PV power plants for cooling energy

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This paper gives aspects of the design of Cooling Thermal Energy Storage (CTES) for cold storage refrigeration and building air conditioning plants, powered/integrated through Solar Photo Voltaic (SPV) power. Ice based CTES are useful when there is mismatch between the availability of the energy source (grid tied centralized system or roof top decentralized system) and the air conditioning/ refrigeration application period. In both grid power with time of the day metering or SPV powered systems in integrated as well as in decentralized SPV, the source-load mismatch is handled through an ice storage system. The ice storage system not only helps with operation under decoupled source-load environment but gives the benefits of reduction in maximum output power, average power and energy consumption by 20-40 % as compared to conventional systems in centralized as well as decentralized environments.

Keywords : *Refrigeration, air conditioning, solar photovoltaic, cooling thermal energy storage, ice storage, energy efficiency, power reduction.*

1.0 INTRODUCTION

Inherent stochastic variation in the power generation pattern of SPV calls for energy storage for smoothening of the supply curve. An alternative to the costly electric storage systems is the cooling thermal energy storage based on ice as a storage medium.

Of the several ways of integration of ice based storage into solar photovoltaic plants, two very promising techniques are:

- Solar powered cold storage plants to smoothen grid tied power plants.
- Solar powered room air conditioners with ice storage to smoothen the supply of solar powered roof tip decentralized plants.

2.0 COLD STORAGE PLANTS- SPV POWERED WITH ENERGY STORAGE

Typical power utilization pattern of cold storages is that there is initial power for reducing the temperature of the cooling space and the products stored, down to the required level. Once the steady state cooling temperature is reached, then the power requirements are reduced only to power for top up. Coupled with the renewable source the power to top up needs to be minimized through good thermal insulation, temperature control and automatic control of the power source.

A typical Indian cold chain consists of the following:

- Past harvesting packing

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- Transfer to cold storage facility
- Pre-Cooling
- Cold storage
- Chilled / Refrigerated transfer
- Packing
- Distribution
- Sale

2.1 Background of cold storage in India

The cold chain as it is called is centered around cold storages for short term storage of products of agricultural, horticultural, poultry, fishery, dairy, etc. Cold storages are an important vehicle for conserving and value addition of agricultural products. Banks encourage cold storages wherein 70% capacity is available on rentals to farmers and rest for own use.

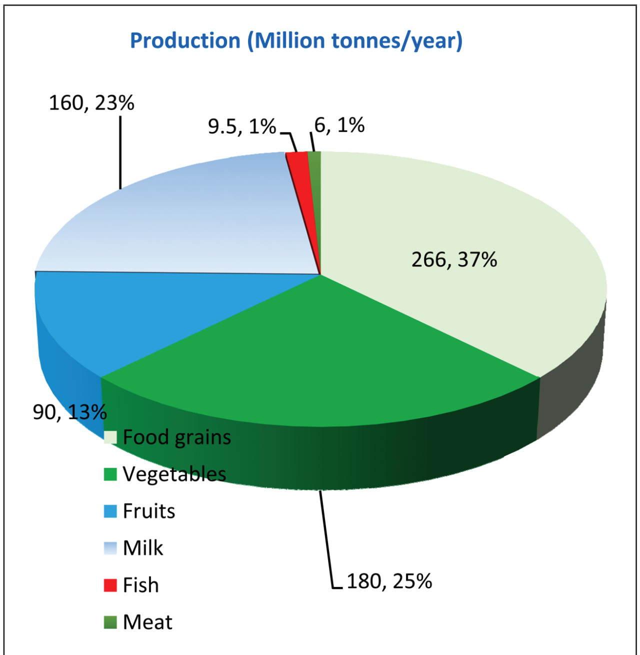

FIG. 1 INDIAN FOOD PRODUCTION FOR 2014-15

The various measures of Govt. of India and public-private participation has contained the wastage to 5.8 % for fruits and 18 % for vegetables. Being the largest producer of fruits, largest producer of milk and second largest producer of vegetables in the world, India is having a growth rate is around 3-5 % per annum for various products. The present production is given in F

The cold storage network business is estimated at Rs. 33,000 crores of which 85 % is accounted by cold storages and 15 % by transportation. The growth rate prospects are high because of good incentives (51 % for FDI). Sector wise, 95 % of the cold storages are in the private sector. Product wise, nearly 90 % of the cold storages are catering to storage of potatoes. Zone wise, over 50 % of the capacity is located in the Northern zone. State wise, UP and West Bengal account for over 60 % of the capacity.

The standard Indian economical capacity is 5 kilo tonnes. Presently, Indian's cold storage capacity is 30 million tonnes (7000 individual cold storage units), accounting for 1.2 GW or 0.5 % of the installed electrical capacity and 6.7 % of the gross produce. A comfortable cold storage coverage for India is 20 % of the produce requiring a growth rate of 12 % up to 2020 to achieve a capacity of 70 million tonnes (2020) and subsequently 11.5 % up to 2030 to achieve 200 million tonnes (2030). The corresponding electrical load in 2020 would be 2.74 GW and in 2030 would be 7.8 GW.

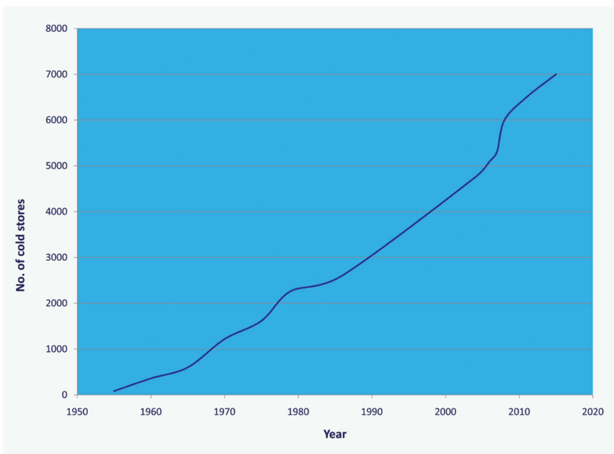

FIG. 2 GROWTH OF THE NUMBER OF COLD STORAGES IN INDIA

Figures 2 and 3 give the growth of number of cold storage units and cold storage capacity in India {data for 1955 to 2011 from [1]}. Presently the installed capacity is 27.7 million tonnes with 6500 nos of units. The growth rate in reference to the 1955 base level index is around 12.1 %/year. However, with reference to 2004, the growth is only 5.2 %/year. The growth is almost dovetailing with the product growth indicating that additional percentage capacity addition is not being added.

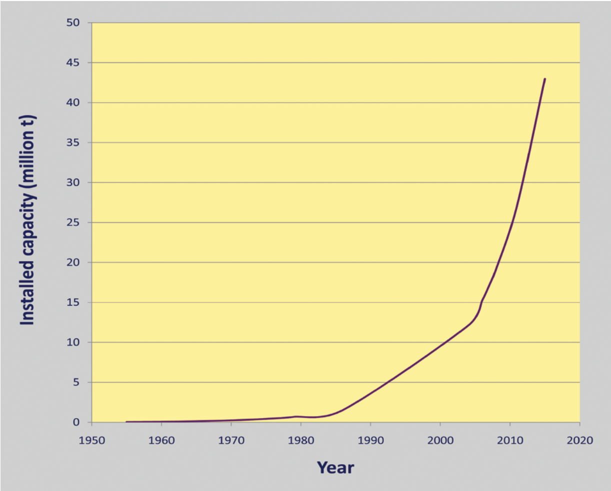

FIG. 3 INSTALLED CAPACITY OF COLD STORAGES IN INDIA

To achieve this level of cold storage capacity, first of all, the issues of weak conventional grids (frequent power disruption, power fluctuation and power cuts) must be addressed through renewable power (solar photovoltaic). Also, the energy efficiencies (kWh/m^3/year) for Indian cold storages (majority working on ammonia as refrigerant) for chilled systems (0 to 10 °C) and refrigerated systems (-18 to -25 °C) need to be brought on par with international practice through reinforcement of insulation, containment of infiltration, efficient controls and retrofitting with solid state variable frequency drives for major motors.

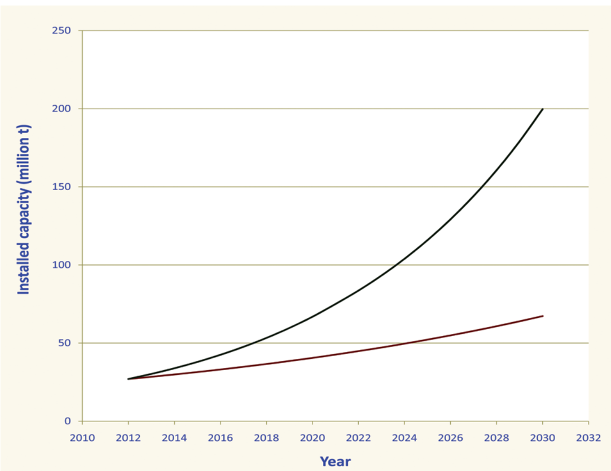

FIG. 4 PROJECTED GROWTH OF COLD STORAGE CAPACITY AT PRESENT RATE (5.2%) AND REQUIRED RATE (12 %)

Figure 4 gives the projected growth of cold storage capacity and Figure 5 shows the projected growth of electric capacity due to cold storage units at present rate (5.2%) and required rate (12 %).

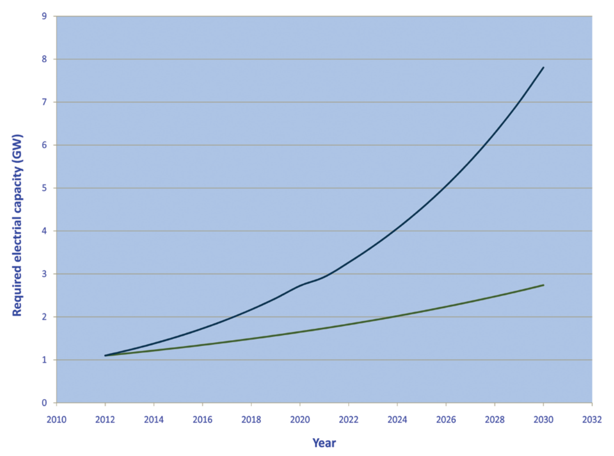

FIG. 5 PROJECTED GROWTH OF ELECTRIC CAPACITY DUE TO COLD STORAGE UNITS AT PRESENT RATE OF GROWTH (5.2 %) AND REQUIRED GROWTH RATE (12)

2.2. Types of cold storages in India

The following categories types of cold storages are popular in India:

- Small cold storage (export oriented)
- Frozen foods (refrigeration)
- Ripening chambers for fruits

The National Horticultural Board of Govt. of India has classified the cold storages into the following categories:

- Bulk cold storages for storage of fresh horticulture products which do not require pre-cooling [2]
- Multi-commodity Cold storages for short term and long-term storage of fresh horticulture products, which require pre-cooling and varying storage requirements [3]
- Control Atmosphere Storages (CAS) [4]

The technical standards and protocols have been brought out to facilitate growth of cold storage capacity in India [2-4].

The commonly used cold storage designs (based on production of cooling effect) are:

- Coils at the top (bunker type)
- Floor mounted air conditioning unit with diffuser type coils at various heights.
- Plate and fin coil type air conditioning units with sandwich panel construction.

Of the three, the first is of the oldest design and the third is of the most modern design with best energy efficiency.

Based on temperature of the cooling space, mechanical refrigeration equipment [2-4] can be classified as:

- Class A (+ 12 °C and 0 °C)
- Class B (+ 12 °C and - 10 °C)
- Class C (+ 12 °C and - 20 °C)
- Class D (≤ 0 °C)
- Class E (≤- 10 °C)
- Class F (≤- 20 °C)

Pre-cooling reduces the cold storage load brings in uniformity and improves product utilization efficiency (reduction in wastage). The following options are available for pre-cooling cooling in cold storage units:

- Ceiling air coolers (located inside cold storage)
- Floor mounted air coolers (located inside cold storage with ducts at the top)
- Insulated air coolers (located outside at the top side with air ducts inside the cold storage)
- Insulated air coolers (located outside at the top side without air ducts)
- Air curtain type air coolers (located at one end inside the cold storage without any ducts)
- Penthouse mounted insulated air coolers (mounted above at the centre)

The majority of the cold storages (95 %) fall in the range of medium temperature or frozen as:

- Medium temperature products: 0 to 10 °C.
- Frozen products: -18 to -25 °C.

The working fluid in the majority of the systems (> 98 %) is presently ammonia (R717).

The efficiency of the air circulation system is determined by the temperature difference between the coldest and warmest zones which must be within 2 °C. Stratification or sectionalization of temperature indicates poor air circulation.

The core technology for refrigeration of cold storages is the vapor compression systems. Vapour absorption systems though becoming popular and limited in their number of installations. Depending on the arrangement in the cold rooms, three types of popular compression systems are:

- Diffuser type: for low heights.
- bunker type
- Fin coil type

Based on the energy source and operational principle, cold storage systems can be classified under the following sub-systems:

- Source power plant - grid electrical power, captive diesel electric power, renewable solar photovoltaic (SPV) or wind electric power, thermal power from process steam, solar concentrating collectors, etc. In the case of diesel back up for vapor compression systems, the energy consumption is nearly 0.3-0.35 litres/kWh of electric power generated. The flue gases are let out at 400-450 °C without any application.
- System power plant- vapor compression system (VCS)- reciprocating/screw compressors, vapor absorption system (VAS).

The basic parameters of cold storages in India are given in Table 1.

TABLE 1			
BASIC PARAMETERS OF COLD STORAGES			
Sl. No.	**Particulars**	**Units**	**Values**
1	Volume of cooling space to weight conversion	m^3/t	2.2-3.4
2	Air circulation before set point is reached	$m^3/h/t$ of product	160-170
3	Air circulation after set point is reached	% of design capacity	20.0-40.0
4	Cooling capacity	TR/1000 m^3	2.80-4.0
5	Margin in design cooling load	%	10.0-30.0
6	Ventilation air changes per day before set point is reached	no./day	6.0-8.0
7	Ventilation air changes per day after set point is reached	no./day	1.8-2.0
8	Operating period before set point is reached	h	16.0-18.0
9	Operating period after set point is reached	h	8.0-10.0
10	Loading rate of new product for cold	% of total capacity	4.0-6.0

2.3 Sizes of cold storage units

The sizes of Indian cold storage plants are generally given on the basis of weight (tonnes of product processed) whereas in Western countries the sizes are given volumetrically (m^3 of cooling space). The conversion rate between weight and volumetric basis varies between 2.2 to 3.4 m^3/t. Typically the conversion factor is 3.4 m^3/t. This must not be mistaken with density but is a form of bulk density including space for housing of evaporator coils, air circulation and physical movement for navigation inside the cold storage, etc.

The 5000 t (17000 m^3) is considered as an economical size for Indian conditions. The largest size of the controlled atmosphere storage (CAS) is around 20 kt while that of refrigerated cold storage is 12 kt.

2.4. Operational mode and energy consumption

While in western countries cold storages are operated all year round (8760 h/year), in India majority of the cold storages are seasonal for short term storage of food products. The operational cycle is around 4-6 months.

The annual operation of cold storages in India can be classified as:

Peak period (high energy consumption)
Holding period (medium energy consumption)
Lean period (low energy consumption)

Gurmit Singh (2010) [5] has brought out the performance of cold storages under the three different conditions of operation. The peak pull down period is dependent on the loading rate which is normally 4-6 % of the total capacity. Typically a 5 % loading rate (of the total capacity) gives a peak period of 20 days.

The characteristics of the cold storage during the three operating phases are given in Table 2. Usually a larger capacity is selected for achieving faster pull down but the part load efficiency will be poorer if the capacity control at part load is not through solid state load controls. If the capacity control is achieved through cylinder unloading no substantial savings can be observed during the holding and lean periods.

TABLE 2

CHARACTERISTICS DURING THE THREE PHASES OF OPERATION.

Sl. No.	Particular	Units	Pull down period	Holding period	Lean period
1	Period of operation	months/year	0.67	1.5	6
2	Hours of operation per day	h/day	20	18	12
3	Cooling load (approximate)	%	100	40	20
4	Electrical power loading (approximate)	%	100	50	30
5	Specific power	kW/TR	1.18	1.46	1.86
6	Cooling capacity	TR/1000 m^3	6.73	2.63	1.31
7	Electrical power	kW/1000 m^3	7.95	3.84	2.45
14	COP	dimensionless	3.8	3.4	2.6

The energy consumption during the peak period is dependent on the condition of pre-cooling. Pre-cooling (from ambient conditions to the vicinity of 0 °C) can bring down the energy consumption during the peak phase of cooling. The various methods of pre-drying are as follows [6]:

- Forced-air
- Hydro
- Vacuum
- Water spray
- Ice
- Room

Of these the hydro drying and forced air drying are most successful and energy efficient as they are of low energy intensity involving fan power in place of compressor power. Forced cooling (induced draft)can be achieved at 2.5-4.0 m^3/s per tonne of product.

The breakup of the thermal cooling load is accounted for by the following factors:

- Transmission through walls, roof and floor
- Product heat generation
- Internal electrical heat generation
- Infiltration
- Defrost heat generation (removal of ice from evaporator)
- Design margin

In well-designed systems, the heat transmission, internal electrical generation, infiltration and defrost heat generation must be minimized to the extent possible. If ice is formed over the evaporator, then it will retard the cooling capacity resulting in loss of energy efficiency.

The energy consumption during the holding and lean periods is dependent on the status of insulation, air tightness (infiltration/ingress of into the system) and the operational temperature controls. In the event of these factors being good, the on time to total time ratio of the refrigerant compressors will be reduced thereby not only reducing the energy consumption but also enhancing their life.

2.4.1 Specific energy consumption

Specific energy consumption (SEC), the annual energy consumption/volume of cold storage in kWh/m^3/year, is the standard energy efficiency index used internationally. In the case of India where the operation is seasonal, the monthly consumption is extrapolated to annual value to obtain comparative results of deemed SEC. The SEC is dependent on the installed characteristics of the system especially the heat gain from various sources (useful and not-useful), minimization of situations of defrosting, etc. The on time to total time ratio of the system is purely dependent on the thermal ingress in the system.

The SEC can be broadly classified for two types of systems:

- Chilled: 0 to +10 °C
- Frozen: -18 to -25 °C

The SEC (kWh/m^3/year) is given for refrigerated units by Paul Singh for USA data [7] by the fit,

$$SEC = 1369.3V^{-0.2275} - 5.56$$

V is the volume of the cold storage space in m^3.

The SEC of chilled storage systems is given in Table 3 and those of refrigerated systems are given in Table 4. Figure 6 gives the frequency distribution of SEC of cold storages in Europe. In Indian conditions where there are no all year round operations the annual data must be extrapolated from the experimental values of 3-4 months to 8760 hours/year. This is termed as deemed energy consumption.

TABLE 3

SEC OF CHILLED STORAGE SYSTEMS

Sl. No.	Chilled cold storages (0 to + 10 °C)	SEC (kWh/m^3/year)
01	Europe range	30-125
02	Europe average	43.5
03	US range	30-52
04	US average	33.5
05	South Africa (2005)	53.5
06	South Africa (2012)	37.62
07	Netherlands	30-110
08	India (pull down period)*	47.7-63.5
09	India (holding period)*	46.1-62.7
10	India (lean period)*	35.0-54.8

*deemed annual consumption

TABLE 4

SEC OF REFRIGERATED STORAGE SYSTEMS

Sl. No.	Frozen cold storages (-18 to -25 °C)	SEC (kWh/m^3/year)
01	Europe range	50-425
02	New Zealand, UK & US [8]	40-140
03	USA best practice value	30-60
04	US Refrigerated warehouses (1997)	56.20
05	US Refrigerated warehouses (2012)	32.30
06	UK	99-124
07	Netherlands	50-325
08	India (pull down period)*	50-100
09	India (holding period)*	50-70
10	India (lean period)*	40-60

*deemed annual consumption

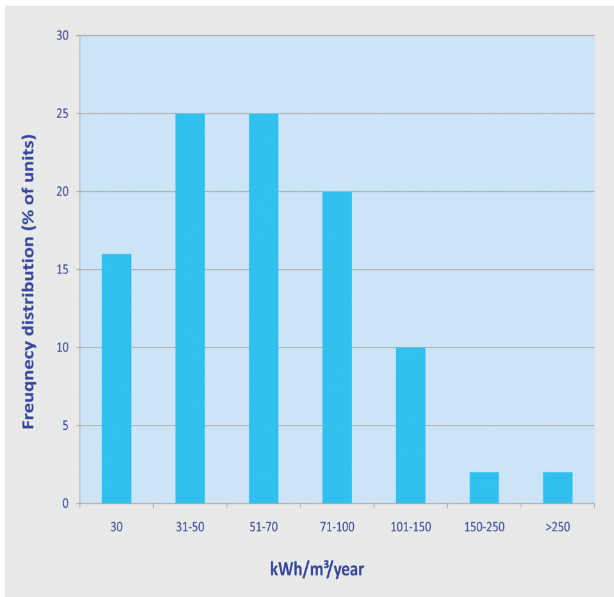

FIG. 6 SPECIFIC ENERGY USE ACROSS ALL COLD STORES IN EUROPE.

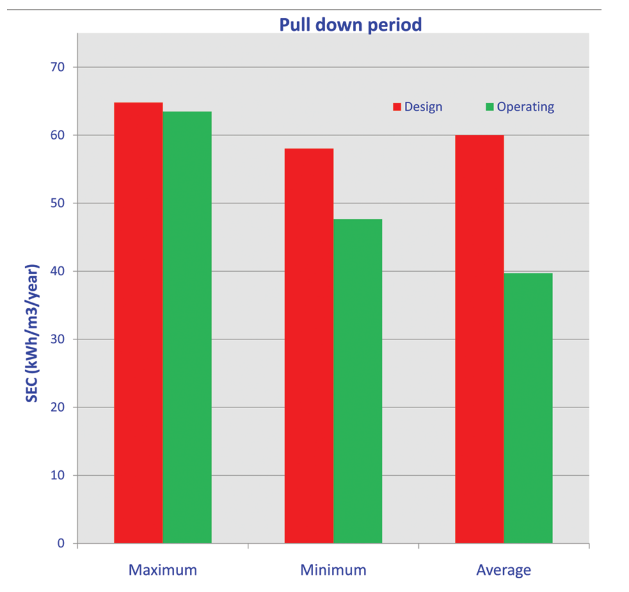

FIG. 7 SEC OF COLD STORAGES IN INDIA DURING PULL DOWN PERIOD.

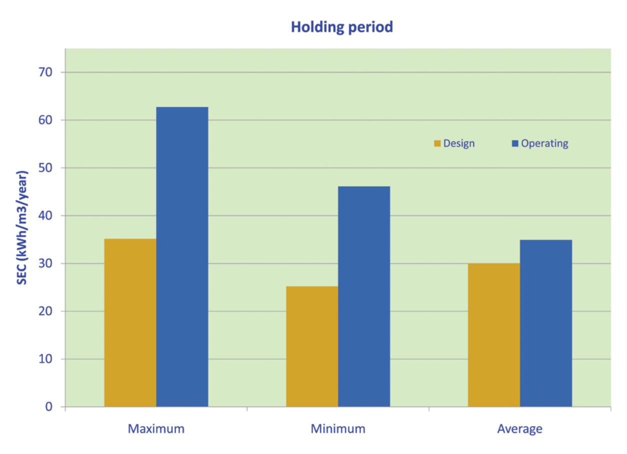

FIG. 8 SEC OF COLD STORAGES IN INDIA DURING HOLDING DOWN PERIOD

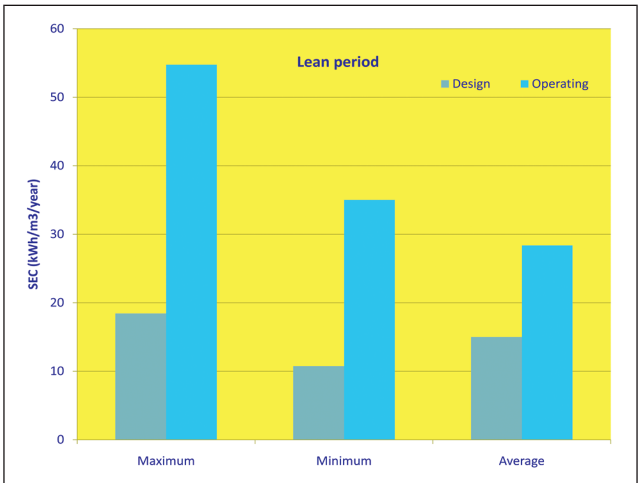

FIG. 9 SEC OF COLD STORAGES IN INDIA DURING LEAN DOWN PERIOD.

It has been shown from various studies that the ambient temperature variations do not significantly affect the all year round energy consumption. The data indicates that the SEC of Indian units are far too high on account of thermal insulation and infiltration. The low values in few cases are due to factors like unscheduled power cuts which cannot be considered on par with normal operation. The isentropic efficiency of the compressors and the motor efficiencies; and the use of variable frequency solid state drives also play a role in determining the inherent efficiency of the cold storage systems.

2.5 Power balancing of SPV with energy storage

Solar photovoltaic power (SPV) has now become cost competitive and achieve grid parity as compared to other power sources. Mono crystalline or polycrystalline silicon SPV modules are suited for the cold storage industry because of their long life of 25+ years and their degradation is restricted to 0.8-1%/year. SPV power can be integrated to cold storage plants of 5 kilo tonnes as the primary power source without any back up power from grid or diesel plant.

Decoupling of electric power generation pattern and the cold storage operating pattern can be achieved by decoupling of time domains of cold storage chiller (or evaporator) operation and fan operation. This decoupling results in reduced electric power input (30-40 %), reduced electrical energy input (20-40 %) and more effective cooling rates.

Cold storage with (cold thermal energy storage) CTES referred to as CS-CTES is a means of balancing the mismatch between the load curve and the solar generation curve. The peak power input is critical in SPV powered plants where the plant capacity directly determines the maximum power and energy generation. The focus of this paper is on integration of ice based CS-CTES with SPV power source with its peculiar variable power generation profile different from other power sources.

CS-CTES plant configuration using ice build/melt systems. Presently there are systems with chilled water as the main cooling effect carrier to air circulating units (ACUs) which further convey the cooling effect through chilled air. Alternatively, there are systems where the refrigerant (NH_3) from the evaporator itself carry the cooling effect till the room where it is finally dispersed by a ventilation fan (variable refrigerant flow (VRF) systems).

CS-CTES systems can be configured as follows:

- Option for cooling through either Direct chiller operation (without CTES) (chilled water scheme or VRF scheme) or ice build and melt operation.

Cooling through Ice build and melt operation only without cooling through direct chiller operation (VRF scheme is not applicable here)

External ice build and melt system

Internal ice build and melt system

In an ice build and melt system, the working fluid for transferring the cooling effect is a mixture of water and antifreeze agent (viz. ethylene glycol or propylene glycol) in mass fraction of 75 % /25 %. Methylene glycol has a specific heat of 3.77 kJ/kg°C (water: 3.77 kJ/kg°C) and viscosity of 3.2 mPas (water: 1.5 mPas).

In an external ice build and melt system the chilled water (plus antifreeze liquid) is part of the melt system and is exchanged between (a) chiller and the ice storage system for ice build process and (b) the ice storage system and a heat exchanger for ice melt process. A secondary fluid is used to transfer the cooling effect from the heat exchanger into the air handling unit (AHU). In the internal ice build system the chilled water (plus antifreeze liquid) is circulated between (a) the chiller and ice storage system during ice build process and (b) ice storage system and the AHU during the ice melt system.

By creation of an off peak 'refrigeration lake' of cold liquid ammonia at low pressure through minimization of temperature stratification, the energy efficiency of the system can be enhanced by 10-12 %.

Load balance is achieved by using excessive energy for charging ice forming chillers. Ice has a latent heat of fusion of 333 kJ/kg and energy density of 92 kWh/m^3 as compared to 37 kWh/m^3 for paraffin and 63 kWh/m^3 for phase change salts.

2.6 Results and discussions (cold storage plants)

Table 5 gives the characteristics of SPV system to be integrated for energizing the cold storage plant of 5 kilo tonnes.

TABLE 5

CHARACTERISTICS OF SOLAR PV SYSTEMS FOR COLD STORAGE UNITS OF 5000 T

Sl. No.	Particular	Units	Value
1	Capacity	tonnes	5000
2	Capacity	m^3	17000
3	Specific power	kW/TR	1.18
4	Cooling capacity	TR/1000 m^3	10.0
5	Electrical power	kW/1000 m^3	11.80
6	Hours of operation per day	h/day	20
7	Annual hours of operation	h/year	4000
8	SEC (maximum) (design) (deemed)	kWh/m^3/ year	103.37
9	SEC (maximum) (operating) (deemed)	kWh/m^3/ year	93.03
10	Electrical power (load)	kW	200.6
11	Cooling capacity	TR	170.0

12	Daily energy requirement	kWh/day	4012.0
13	Daily energy expenditure (solar period)	kWh/day	2300.0
14	Daily energy expenditure (ice storage for non-solar period)	kWh/day	1750.0
15	Average solar load	kW	169
16	Area of crystalline silicon SPV panels	m^2	4600.0
17	Capacity of SPV plant	kW	573.0

Figure 10 gives the electrical generation pattern of SPV and load pattern of cold storage system of 5000 t. The energy storage is through creation of ice and cold liquid ammonia at low pressure under adiabatic conditions of storage.

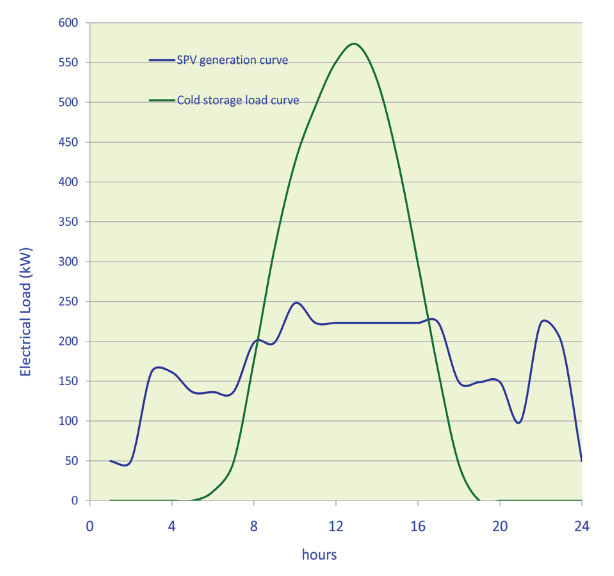

FIG. 10 ELECTRICAL GENERATION PATTER OF SPV AND LOAD PATTER OF COLD STORAGE SYSTEM OF 5000 T.

SPV with ice storage system gives an energy saving of over 20 % besides reducing the cost of battery storage to overcome the load mismatch.

3.0 AIR CONDITIONERS WITH ICE STORAGE SYSTEMS

3.1 Air conditioners scenario

The air conditioners (ACs) based on vapor compression cycle can be classified into:

- Room air conditioners: split and unitary air conditioners (1-3 TR)
- Duct and package air conditioners: 3-15 TR
- Central air conditioners: > 15 TR

The majority of the air conditioners are split air conditioners (1-3 TR) and in the central segment the chillers sizes are 100-200 TR for commercial buildings and 900-1500 TR (for industrial AC applications). Most of the central machines in the large capacities are based on screw compressors.

The commonly used refrigerants for the air conditioners are:

- R134A (CH_2FCF_3)
- R410A (CH_2F_2/CHF_2CF_3) (50 %/50 %)
- R290 (propane)

While the smaller units use R 134A the larger units use R 410A.

The sectors which use the air conditioners are the domestic sector where unitary (window) and split systems are used; and the commercial sector where both split as well as the central systems are in use. The annual sale of ACs is around 3-4 million units/year and annual sales is around Rs. 30,000 crores. The annual physical growth of the AC sector is 14 %. Energy efficiency improvement is growing at the rate of 3 % which implies that the power growth is around 11 %. Table 6 gives the national scenario of the contribution from air conditioning segment.

Table 6: National scenario of the contribution from air conditioning segment

TABLE 6					
NATIONAL SCENARIO OF THE CONTRIBUTION FROM AIR CONDITIONING SEGMENT.					
Sl. No.	**Particulars**	**Units**	**Domestic sector**	**Commer-cial sector**	**Total**
01	Percentage of total national power shared by building sectors (domestic and commercial sectors) as a whole (all loads including AC loads)	%	22	9	31
02	Total national power shared by building sectors (domestic and commercial sectors) as a whole (all loads including AC loads)	GW	58.30	23.85	82.15
03	Percentage share of AC loads in the total loads of the domestic and commercial sectors	%	50	60	NA
04	Percentage of total national power shared by AC loads alone in domestic and commercial sectors	%	11	5.4	16.4
05	Actual national power shared by AC loads in domestic and commercial sectors	GW	29.15	14.31	43.36
06	Percentage share of domestic and commercial AC loads in the national power scene	%	67	33	100
07	Energy share of AC loads in the national energy scene	TWh	96	64	160
08	Energy share in AC loads from the domestic and commercial sectors in the national energy scene	%	5.88	3.92	9.80
09	Peak load occurrence in AC loads in domestic and commercial sectors		night	After noon	NA
10	Installed capacity of AC in India on a national level	million TR	≈15	≈7	≈22

Figure 11 shows the load variation with months for a commercial building in Delhi. It is clear that the variation is from 60 % in winter to almost 160 % of the average value during the summer months. This can be attributed to AC loads.

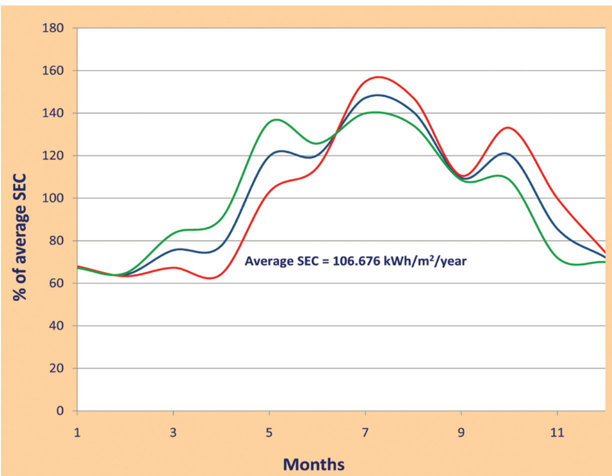

FIG. 11 BUILDING LOAD VARIATION LOCATION: DELHI

The Ac power in the commercial sector account for 9 % which gives a total of 31 % of the national share of the power. However, when it comes to energy the contribution from ACs is quite low (hardly 10 %) because of the low load factor of the ACs. While the power ratings of ACs are high their load factors are low due to seasonal usage, weather conditions and non continuous use only during certain hours of the day. In the domestic sector 70 % of the ACs are unitary (window) and the balance of split. In the commercial sector the break up of unitary and split are 50 % each. Among the central air conditioners nearly 28 % are in the range of 100-200 TR and used for commercial building load and nearly 26 % are of 900-1500 TR and used for industrial air conditioning applications. The balance air conditioners come in varying sizes from 50 TR to 2000 TR.

However, on the overall load scenario of the various regional grids, the winter and summer loads do not show any perceivable differences. This means that the AC loads do not impact the national grid significantly in terms of additional loads or load peaks. When SPV systems are installed, their inherent variation in the energy generation pattern calls for energy storage which can be accomplished by ice based storage.

3.2 Concepts of ice based energy storage

Integration of ice based energy storage systems into air conditioning plants were under experimentation or over twenty five years but only very recently good technological success has been achieved on the hardware front. The advantages of integration of conventional AC units with cooling thermal energy storage (CTES) are reduced power (30-40 %), reduced energy consumption (20-40 %) and more effective cooling rates [9,10]. This is especially critical in solar photovoltaic (SPV) powered plants where the plantcapacity determines the maximum power and energy generation. AC with CTES referred to as AC-CTES is a means of balancing the mismatch between the load curve and the solar generation curve.

AC-CTES de-couples normal AC operation into refrigerant chiller operation and AHU operation thereby SPV panel size is considerably reduced. The vapour compression cycle and chilled water cycle are decoupled from AHU fan power. When operating on grid power AC-CTES operates on grid power and during the peak period for SPV generation. Thereby steady load is provided.

AC-CTES systems can be configured as follows: Direct chiller operation and ice build operation separately

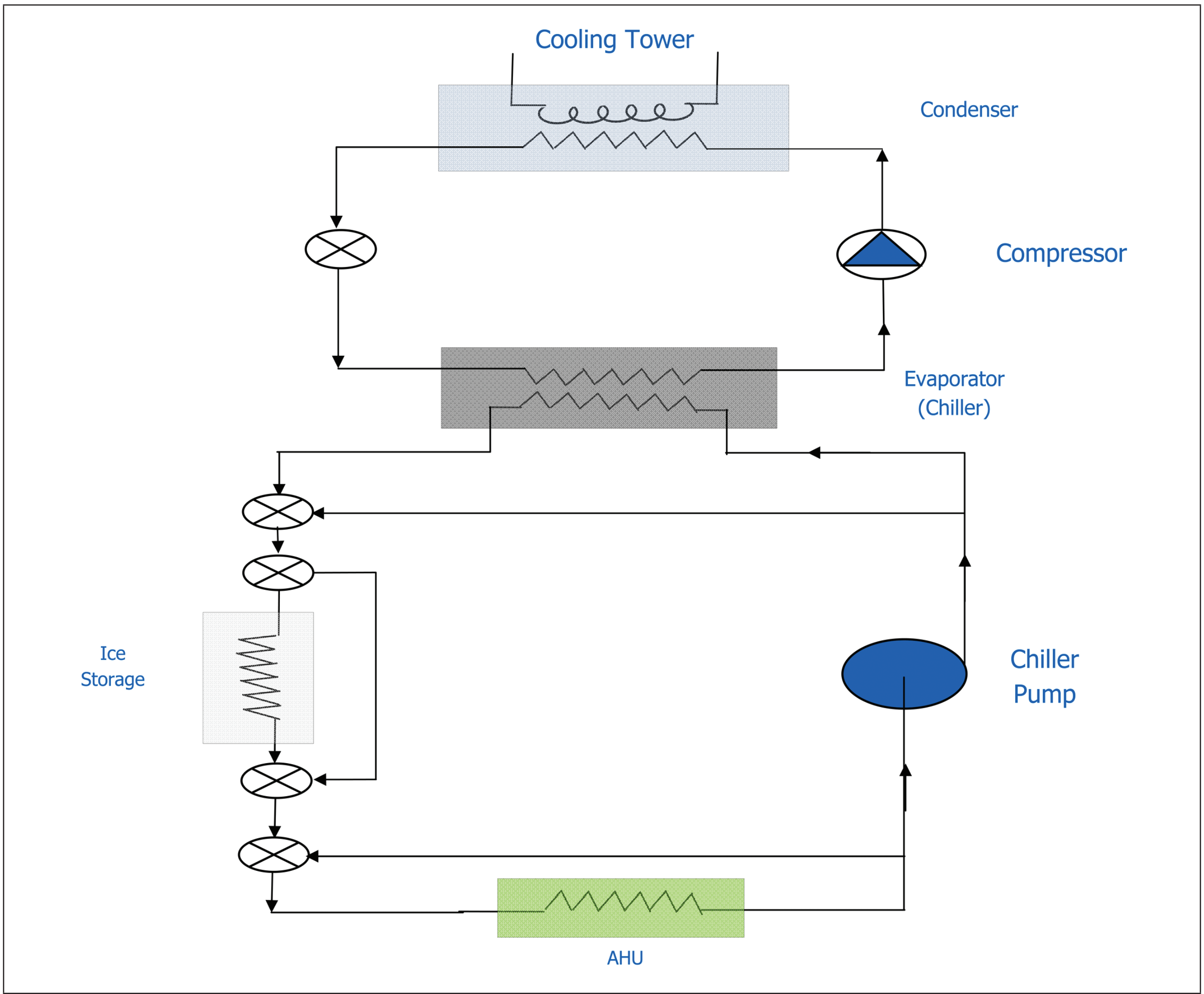

FIG. 12 VIEW OF A AC-CTES SYSTEM

- Ice build and ice melt operation only
- External ice build and melt system
- Internal ice build and melt system

In an external ice build and melt system the chilled water (plus antifreeze liquid) is part of the melt system and is exchanged between (a) chiller and the ice storage system for ice build process and (b) the ice storage system and a heat exchanger for ice melt process. A secondary fluid is used to transfer the cooling effect from the heat exchanger into the Air Handling Unit (AHU).

In the internal ice build system the chilled water (plus antifreeze liquid) is circulated between(a) the chiller and ice storage system during ice build process and (b) ice storage system and the AHU during the ice melt system.

Both systems have advantage and disadvantages and overall system can built any one concept.

Figures 12 & 13 give schematics of AC-CTES system. Figure 14 gives a comparison of AC and AC-CTES system. Figures 15 & 16 gives schematics of external and internal ice build and melt systems.

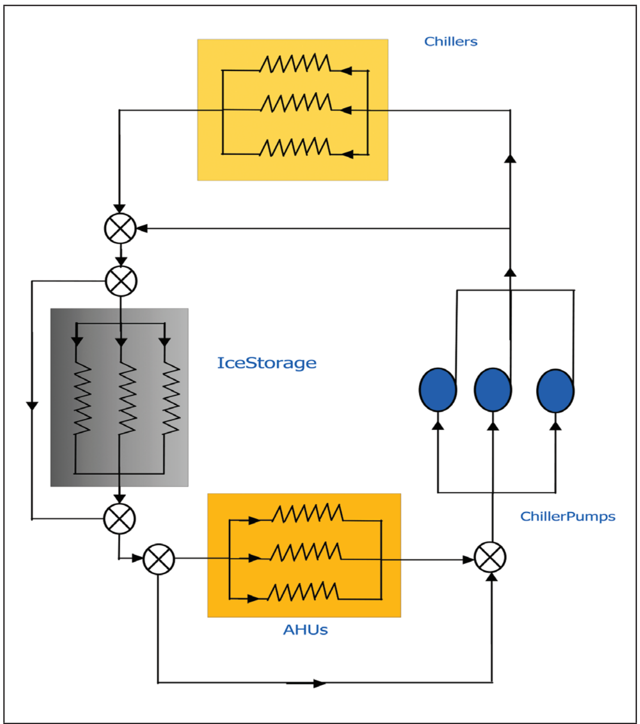

FIG. 13 CHEMATIC OF AN AC-CTES SYSTEM

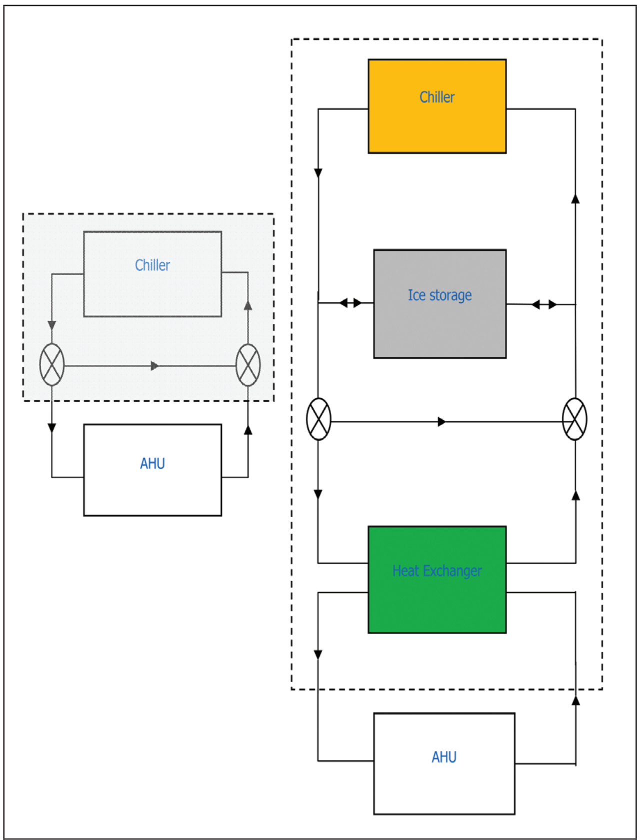

FIG. 14 COMPARISON OF AC AND AC-CTES SYSTEM

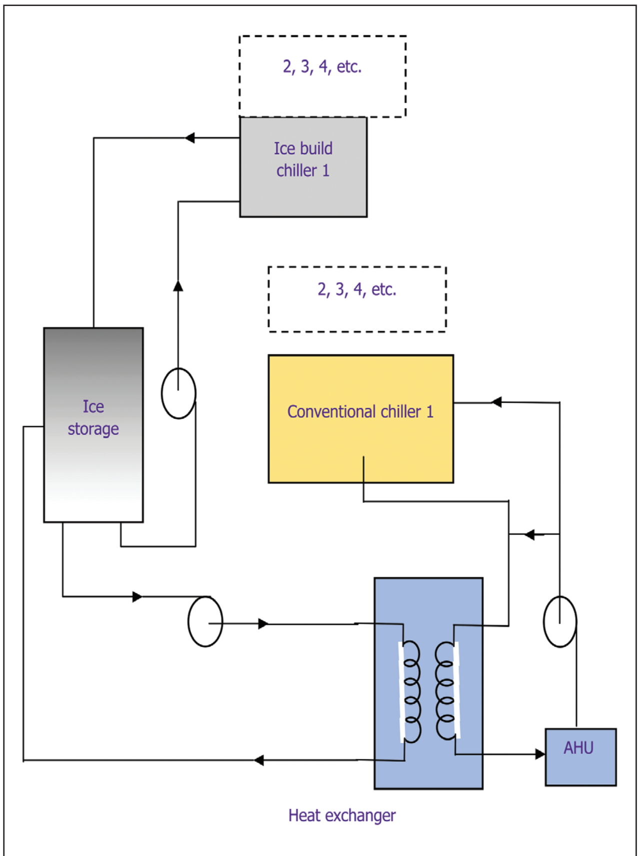

FIG. 15 EXTERNAL ICE BUILD AND MELT SYSTEM

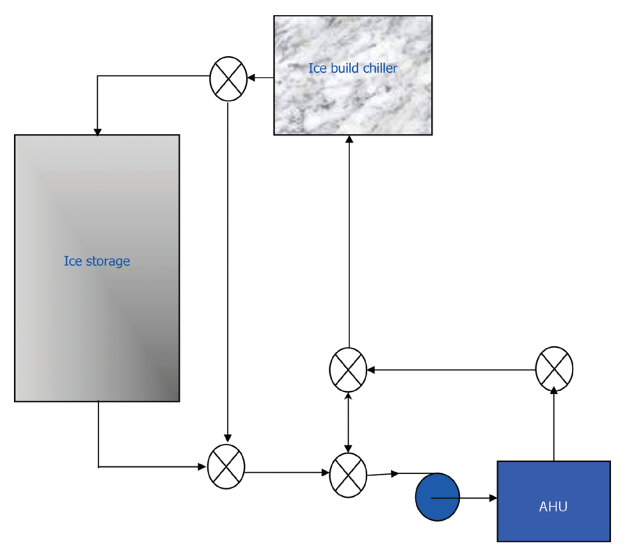

FIG. 16 INTERNAL ICE BUILD AND MELT SYSTEM

SPV power is available as a parabolic output and only for 12 hours in a day. For providing electrical power in the non-sunshine period, electrical energy storage is required in the form of battery banks. The energy efficiency of electrical energy storage is 80 % which calls for 20 % additional generation to meet the load. If the AC-CTES system is available, the storage of electrical energy in battery banks is totally avoided. Further during the sunshine period, the excess energy can be used for the ice freeze process. During the non-sunshine period the ice melt process will provide the cooling effect. With AC-CTES systems, the chilling (cooling effect generation) and the cooling effect utilization are de-coupled. As a result only those equipment associated with chilling are used during the ice freeze process and equipment with AHU operation will be used in the ice melt process. Thus the total power at any time of operation is much lower than the simultaneous chilling and AHU operation of conventional ACs.

3.3 Indices of energy efficiency

Energy efficiency in air conditioners (AC) (of which compressors are the primary energy consuming components) is basically achieved by closed loop communication and tracking of the load. Energy conservation does not imply compromise of the demand load. Load could however be optimized by tuning the temperature and humidity but essentially the load has to be met and the demand fulfilled. Three important interrelated indices of energy efficiency [11] are:

- SP (Specific electric power) (kW of electric power input per tonne of refrigeration =kW/TR) [1 TR=3.516 kW]
- EER (energy efficiency ratio) = cooling load (kW)/electric input (kW) which is expressed on the basis of p.u., it is generally in the range of 2.3 to 3.1.
- COP (coefficient of performance) is given by the ratio 3.516/SP

Table 7 gives the break-up of the specific power of major power consuming equipment in 500 TR central AC plant [11].

AS mentioned under cold storages, the internationally accepted annual performance index is the SEC (specific energy consumption) in kWh/m^2/year. As per the Energy Conservation Building Code of India [45], the energy efficiency of buildings must be within 120 kWh/m^2/year for AC buildings and 25-40 kWh/m^2/year for non AC buildings. The AC contribution can be taken as 80-90 kWh/m^2/year. The AC power is benchmarked at 25 W/m^2.

The on time to total time ratio is ratio of the period under which the AC plant is in operation and drawing full active power to the total time period under consideration (24 hours/day; 720 hours/month or 8760 hours/year). This is a temperature dependent factor and is designed to be around 0.3 for the of ambient temperature of 33-34 ºC. As the temperature shoots up, this ratio also increases. Theoretically this ratio should be zero when the ambient temperature matches with the comfort temperature of 23 ºC but invariably the building inside temperature will be several degrees higher than the outside ambient temperature because of greenhouse and heat trap.

3.4 Ice based cooling thermal storage systems (CTES) for AC plants

The working fluid for transferring the cooling effect is a mixture of water and antifreeze agent (viz. ethylene glycol or propylene glycol) in mass fraction of 75 % /25 % [12]. Methylene glycol has a specific heat of 3.77 kJ/kgºC (water: 3.77 kJ/kgºC) and viscosity of 3.2 mPas (water: 1.5 mPas).

Ice is formed and stored in a static heat exchanger vessel called as Ice storage tank which are characterized by their freeze rate (kW) and melt rate (kW). Under 100 % capacity the ice storage contains 65 % ice and 35 % liquid. The storage efficiency is nearly 95 %. The cold thermal loss is 1-5 %/day. The thermal capacity of ice storage systems are 1.8-2.4 kW/m^3ºC These can operated under unlimited charge-discharge thermal and deterioration of the working fluid is not an issue. In the external ice form and melt system the ice forming liquid itself (chilled water with glycol) is circulated into a heat exchanger for transferring the cooling effect and from these it is indirectly transferred to the AHU. The circulating fluid carrying up to 15 %ice does not decrease the convective heat transfer coefficient. Mixtures in excess of 15 % ice retard the heat transfer coefficient with any benefit in temperature difference. In the internal ice form and melt system the chilled water with glycol is circulated in the heat exchanger tubes of the ice storage tank and the ice forming mixture is always inside the tank and is not circulated.

The power plant for the ice forming is the ice making chiller- a centrifugal chiller which is slightly different from the conventional chiller in that it has two different exit water set points. The controls are set such that the entering chilled water drops to below exit set point and operates at the maximum capacity in ice making mode. Conventional chillers respond to cooling load changes through capacity control.

3.5 Results and discussion (Ac with ice storage system)

The case of a 100 TR system with and without AC-CTES. Table 7 gives a typical temperature profile of AC-CTES with conventional AC systems.

Figure 17 shows the use of conventional AC system with SPV. Figure 18 shows the use of AC-CTES with SPV. Figure 19 shows the use of AC-CTES with conventional grid power. Basically, with the use of AC-CTES the maximum power is reduced because of de-coupling chilling and AHU operation. Table 8 gives the power rating during the ice freeze and ice melt processes.

Some design curves for AC-CTES are also presented. Figure 20 gives the relationship between cooling capacity and volume of storage system. Figure 21 gives the chilling capacity with flow rate of chilled water. Figure 22 gives storage mass for different chiller outlet temperatures. Figure 23 gives ice making chiller capacity for different chiller outlet temperatures.

The chiller capacity and storage tank freeze capacity have to be matched as indicated in Figure 24.

In the operation of AC-CTES with SPV the power input is reduced and also the energy consumption is lower as compared to conventional AC operation. In grid power operation, the non-peak period can be used for ice free processes.

The specific power is reduced from 1.84 kW/TR for a conventional system to 1.15 kW/TR during the ice freeze phase and 0.69 kW/TR during the ice melt phase.

Table 7: Typical temperature profile of AC-CTES and conventional AC systems.

TABLE 7

TYPICAL TEMPERATURE PROFILE OF AC-CTES AND CONVENTIONAL AC SYSTEMS.

Sl. No.	Fluid	Location	Normal System (ºC)	Ice storage system (ºC)
1	Refrigerant	Chiller inlet	1 to 2.2	-9 to -11
2	Refrigerant	Chiller outlet	2 to 5	-5 to -6
3	Chilled water	Chiller inlet	8 to 9	2 to 3
4	Chilled water	Chiller outlet	4 to 5	-5 to -6
5	Chilled water	Ice build storage inlet	-	-5 to -6
6	Chilled water	Ice build storage inlet	-	-1 to -2
7	Ice water mixture	Ice water storage system	-	-1 to -2
8	Chilled water	AHU inlet	-	-2 to -3
9	Chilled water	AHU outlet	8 to 9	2 to 3
10	Chilled air	AHU outlet	12 to 14	7 to 8
11	refrigerant- chilled water	ΔT across chiller	4.0	4.0
12	Cold chilled water-ice system temperature	ΔT across ice build system	-	4.0
13	Chilled water-air	ΔT across chiller water-AHU for ice use	5.5-6.5	10.0-11.5

TABLE 8

POWER RATINGS DURING ICE FREEZE AND ICE MELT PROCESSES.

Sl. No.	Electrical load			Conventional AC	Ice freeze process	Ice melt process
	Cooling capacity		TR	100	100	100
		Nos	kW/TR	kW	kW	kW
1	Compressors	1	0.894	89.4	89.4	
2	Chiller pumps	1	0.11	11	11	11
3	Condenser pumps	1	0.11	11	11	
4	Cooling tower fans	1	0.036	3.6	3.6	
5	AHR fan motors	6	11.52	69.16		69.16
		Total	1.8416	184.16	115.0	80.16

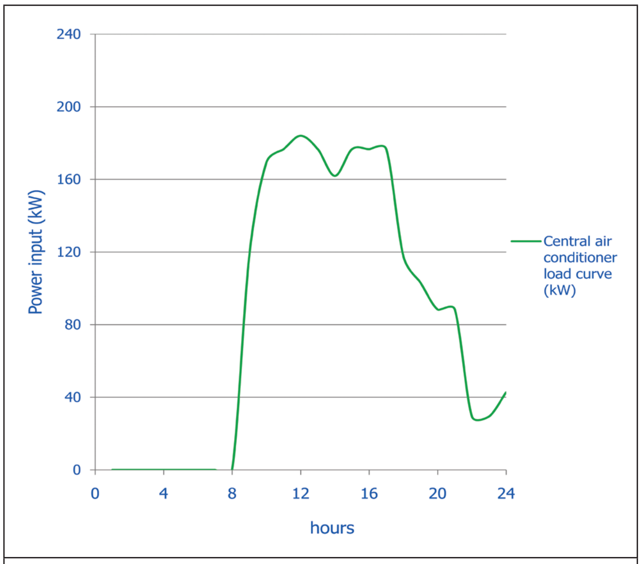

FIG. 17 AIR CONDITIONING COMMERCIAL LOAD CURVE

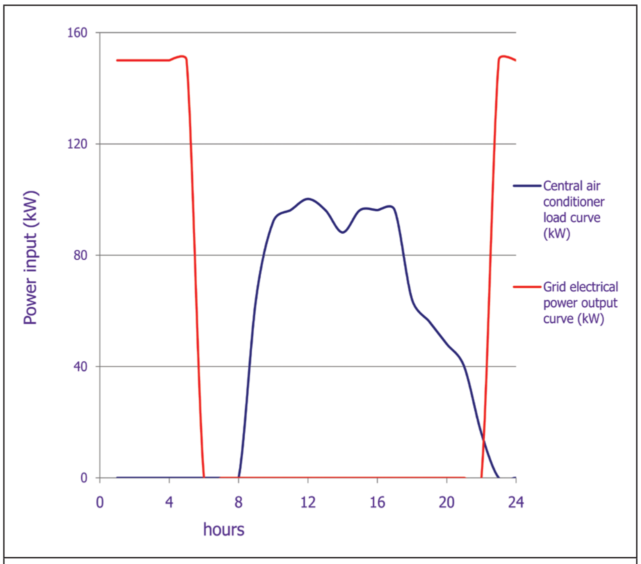

FIG. 19 AIR CONDITIONING COMMERCIAL LOAD CURVE

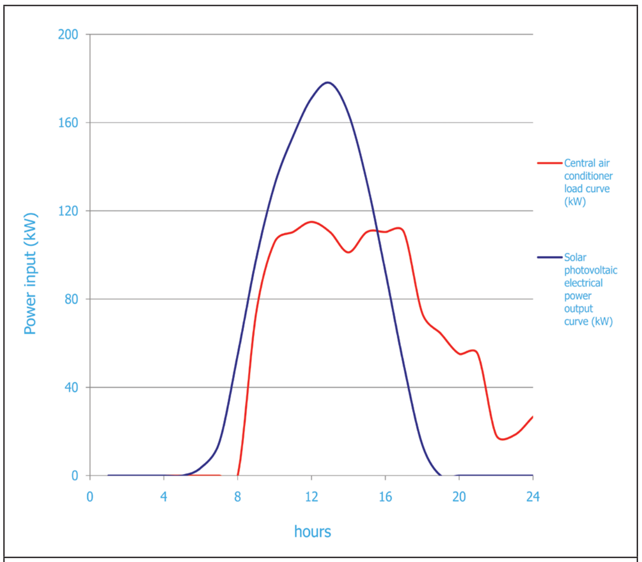

FIG. 18 AIR CONDITIONING COMMERCIAL LOAD CURVE WITH ICE STORAGE

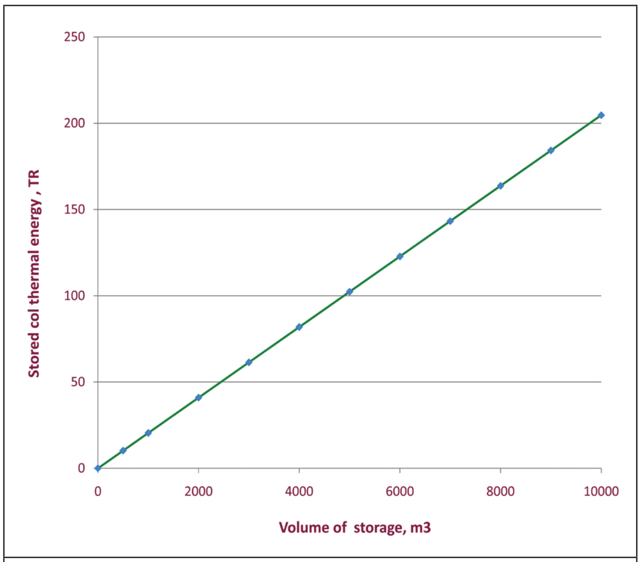

FIG. 20 COOLING THERMAL ENERGY STORAGE CAPACITY

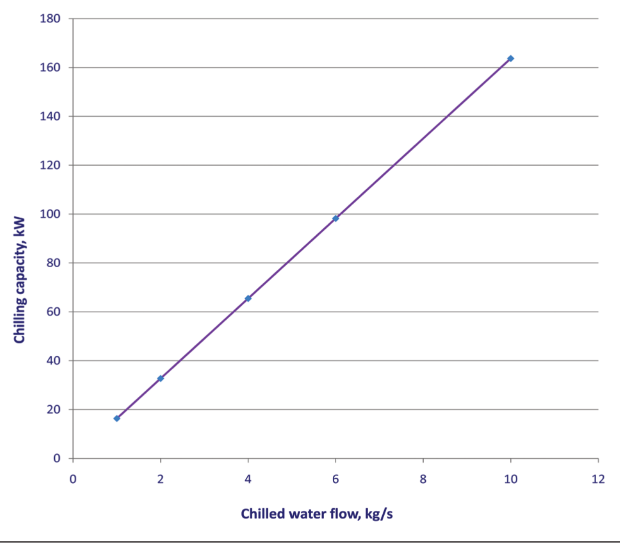

FIG. 21 CHILLER CAPACITY AS A FUNCTION OF CHILLED WATER FLOW RATE

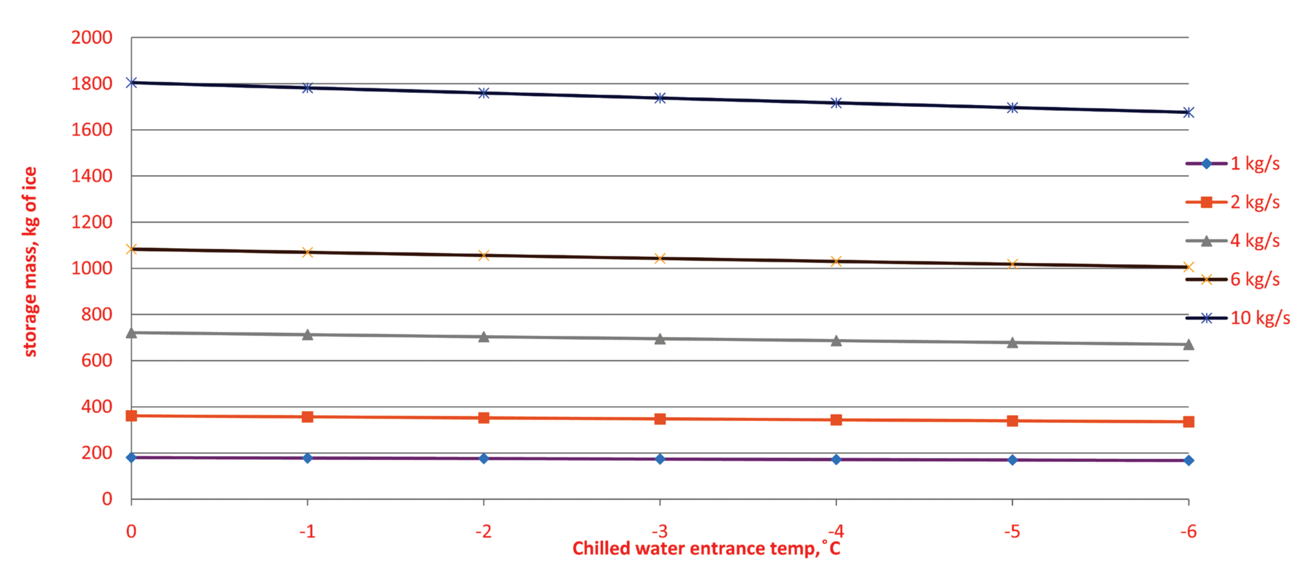

FIG. 22 STORAGE MASS OF ICE

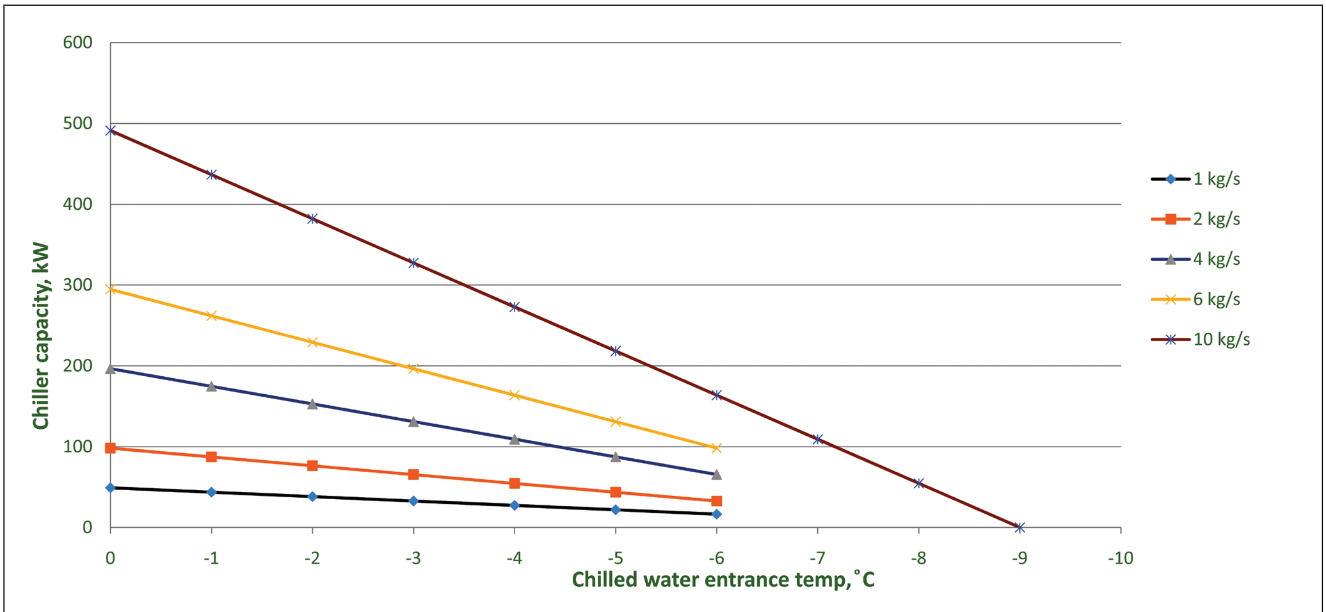

FIG. 23 CHILLER CAPACITY WITH CHILLED WATER ENTRANCE TEMPERATURE

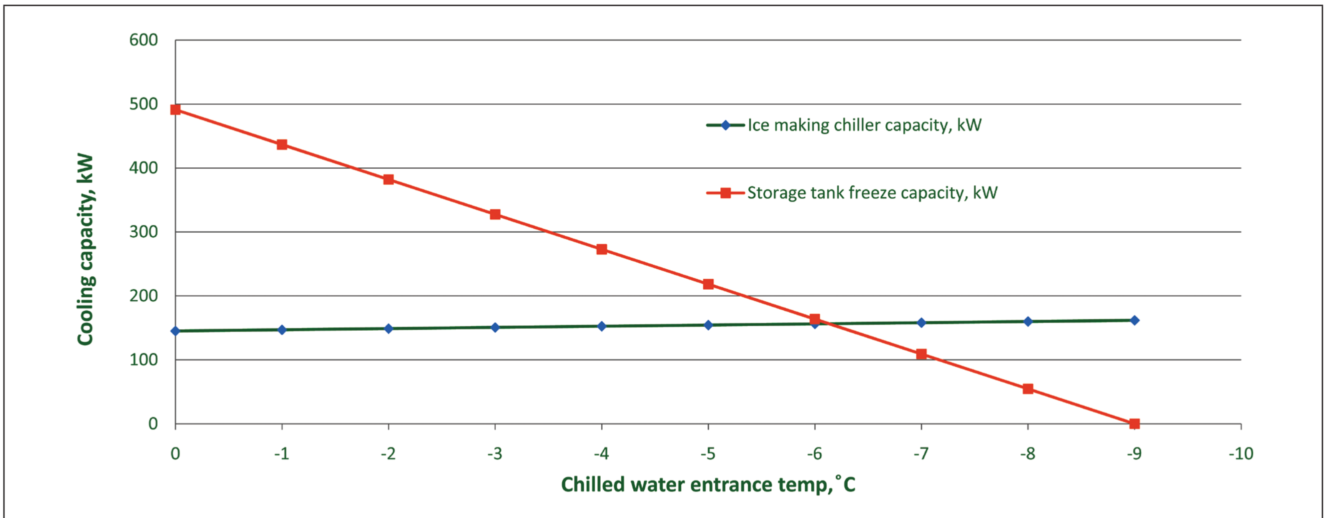

FIG. 24 BALANCE OF STORAGE TANK FREEZE CAPACITY AND HILLER CAPACITY

4.0 CONCLUSIONS

The conclusions of the cold storage based energy storage are:

The present Indian cold storage capacity is drawing a power of 1.2 GW or 0.5 % of the installed electrical capacity. Considering a good growth, the electrical load due to cold storages would be 2.74 GW in 2020 and 7.8 GW in 2030.

The energization of cold storage plants by solar photovoltaic (SPV) with ice storage is financially feasible for units of standard Indian economical capacities 5 kilo tonnes.

For a cold storage plant of 5 kilo tonne, a solar PV plant of 573 kW is required. The energy generated is 4054 kWh/day out of which 2301 kWh/day are utilized directly and 1753 would have to be used in mode of thermal ice storage and cold liquid ammonia at low pressure. The energy storage capacity of cold storage units can be utilized for supply balancing from grid tied SPV plants.

A traditional 100 TR system consumes 2015 kWh/day for meeting a commercial AC load curve. If ice storage system is used along with SPV the energy consumption is reduced to 1260 kWh/day for the same load. The average electrical load is reduced from 83 kW for traditional system to 52.5 kW for the SPV system using AC-CTES. A grid connected AC-CTES system consumes 1050 kWh/day to meet the same load curve and the average electric power is 43 kW.

For SPV operation AC-CTES systems are essential for minimizing the capital costs of the source as the peak SPV array capacity is reduced from 83 kW down to 52.5 kW.

A number of commercial window and split AC-CTES products have come into the market [13] and the technology is matured to a reliability level for wide scale usage. The technology is applicable to both large ACs as well as window and split ACs.

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