

## The Engineering Doctorate (EngD) in Environmental Technology

- Four year course in which the student is based in industry, conducting a research project that is beneficial to the sponsor company.
- Research must focus on sustainable technologies. Initially a very general topic is defined and then focused onto a specific research question.
- Two journal papers must be published, and fourteen weeks worth of courses passed, in order to qualify for the doctorate.

## General Abstract

The aim of this research is to increase the use of phase change materials in the built environment and thereby reduce the overall energy consumption and associated carbon emissions of buildings. The research began with the general aim of identifying ways in which energy storage could be used to reduce a building's carbon emissions. Energy storage can lead to carbon emission reductions in three ways: Reduction in energy demand, increased energy efficiency and increased use of intermittent renewables. Energy storage systems are broken down into electricity storage, which results from restricted conversion, and thermal storage, which results from restricted flow. Thermal storage is further broken down into passive and active storage. Phase change materials have applications in both passive and active systems. There are several opportunities for research into using latent thermal storage in the built environment. The most promising areas for research in latent thermal energy systems are: Improvements in the heat transfer between the space and the PCM, optimisation of existing PCM-based systems and demonstration of certain systems efficacy through testing of occupied buildings or simulation.

## Technical Abstract (Focus on Phase Change Materials)

The destructive consequences of climate change and the resulting requirement to reduce carbon emissions is generally accepted. Phase change materials have a large number of potential active and passive applications for managing, and therefore saving energy, in the built environment. However, so far only a limited number of PCM installations have emerged. This is due to; the ignorance and risk-aversion of designers, the cost of the systems and some current technical limitations. This EngD will focus on one or more of these factors in order to increase utilisation of latent heat storage systems. Ignorance and risk aversion can be combated through reliable demonstrations of efficacy in occupied buildings or with simulation. The cost of systems can be reduced in various ways including container removal through shape-stabilisation. The technical limitations of low cycle-life and fire risk, can be overcome through selection of organic PCMs and appropriate mitigation techniques, respectively. Heat transfer may be enhanced through the following: Addition of highly conductive particles, fibres or expanded graphite; promotion of convection currents in the liquid phase when melting; addition of conductive fins or increasing the number of heat exchange loops in active systems.

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## 1. Why is reduced energy consumption important?

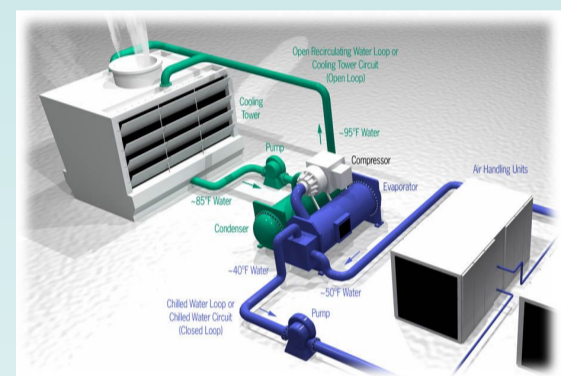
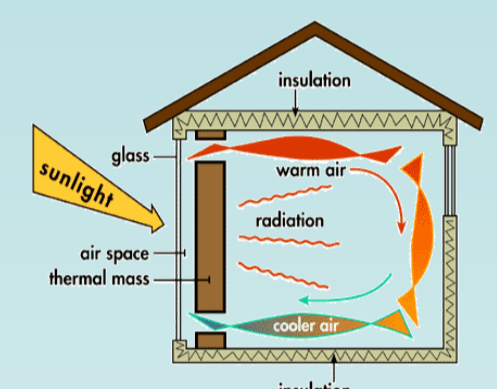
Reducing energy consumption in any system will reduce running costs and lower carbon emissions. With the causes and damaging effects of climate change firmly established, developing more ways to reduce carbon emissions is of paramount importance. In Europe over 40% of energy used, and the consequent CO<sub>2</sub> emitted, results from energy consumed by building services. Reducing this energy load will have a dramatic impact on European energy consumption.



## 2. How can energy storage help?

Energy storage can reduce consumption in the following ways:

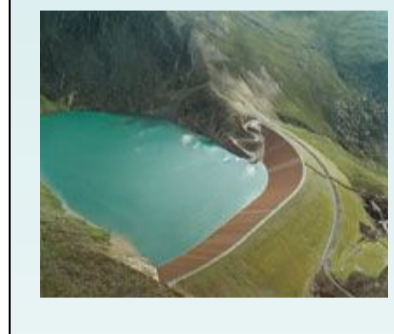
1. Reducing energy demand at the point of use. E.g. Storing thermal energy in the building fabric for supplementary heating or cooling.
2. Increasing the efficiency of many types of device. E.g. Operating chillers at night to make use of the lower condensing temperatures.
3. Allowing intermittent renewable energy sources to generate a greater proportion of national energy consumption. E.g. Wind power.



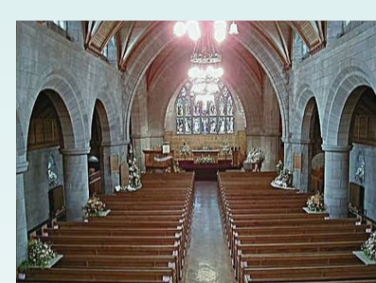
## 3. General Energy Storage Theory

Energy storage is defined as the restricted conversion or flow of energy that confines it to some vessel, or medium, for some period of time.

Restricted conversion is achieved through balancing the fundamental physical forces acting in a system. This type of storage is normally used in the storing of electricity. Examples are: Batteries, in which a balancing of electromagnetic forces is manifested as chemical storage; and pumped hydro storage, in which gravitational potential energy is balanced with the electromagnetic forces which are manifested as the solidity of the reservoir bed and dam.



Restricted flow is achieved in two ways. One is the insulation of a medium from the surrounding environment. E.g. The lagging on a domestic hot water tank. The second is the utilisation of a medium with large thermal mass and a specified conductivity that has a direct thermal interaction with its local environment. E.g. The stone that makes up the fabric of a church building.



## 4. Thermal Energy Storage

In the UK 41% of CO<sub>2</sub> emissions associated with buildings is due to heating. Globally 45% of residential and commercial buildings' energy demand comes from cooling. It is clear therefore that reducing the energy required for occupants' thermal comfort will greatly reduce overall energy consumption. By controlling the heat flows in a building, through storage, the required energy can be reduced.

This is a strong motivation for researching and developing thermal energy storage devices and media. There are two types of thermal energy storage system; active and passive:

**Active storage systems** refer to those that are thermally isolated from the environment they are intended to interact with. This requires an intermediate heat transfer fluid to actively transport heat between the storage vessel and the environment.

**Passive storage systems** are in direct contact with the environment that they are intended to thermally interact with.

There are also two types of thermal energy storage medium, that are commonly used; sensible and latent.

An example of **sensible thermal energy storage media** is the solid fabric of a building.

Examples of **latent thermal energy storage media** are; ice, which can be used for space cooling, or paraffin wax which could be incorporated into the building fabric for passive storage.

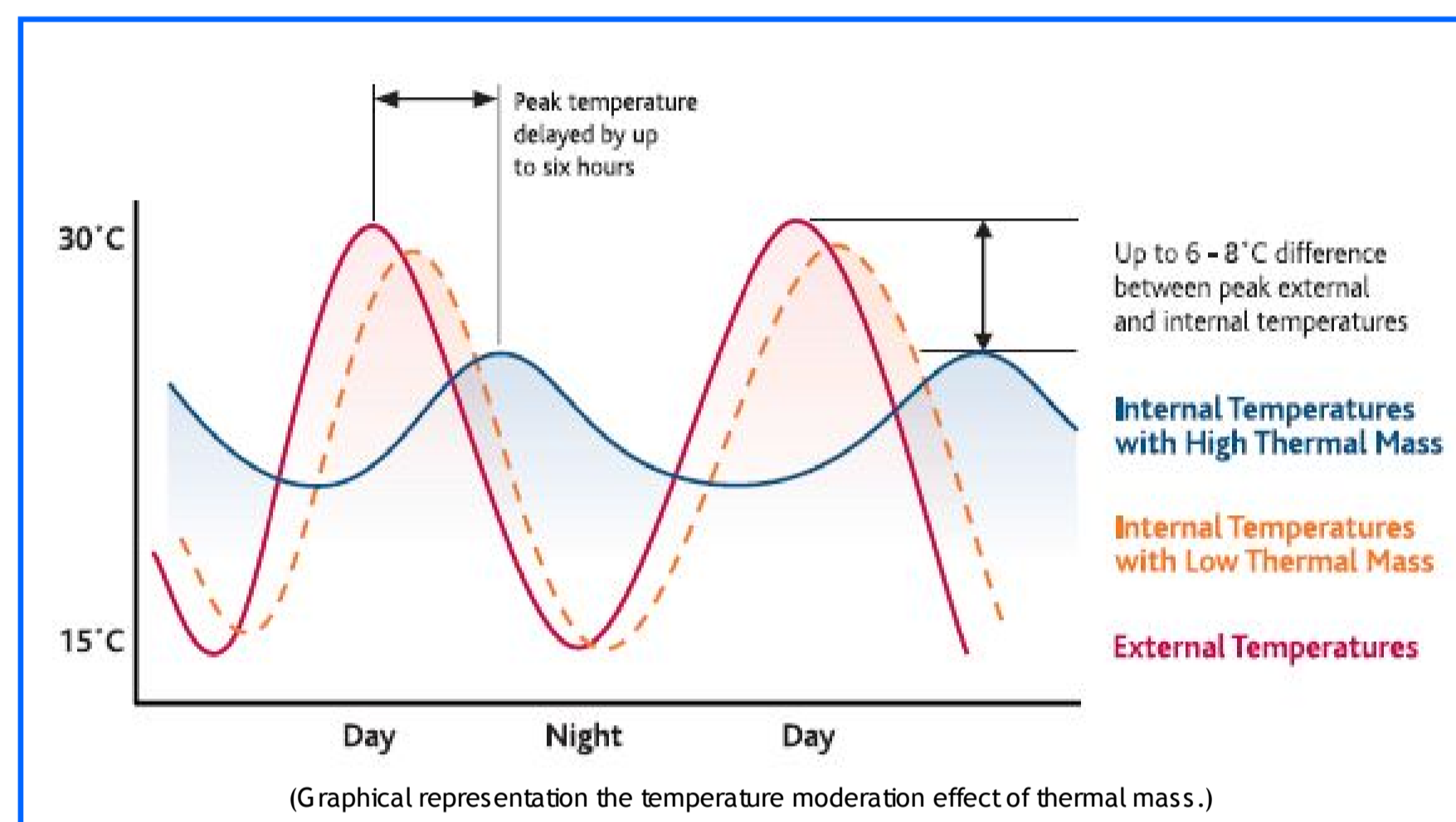
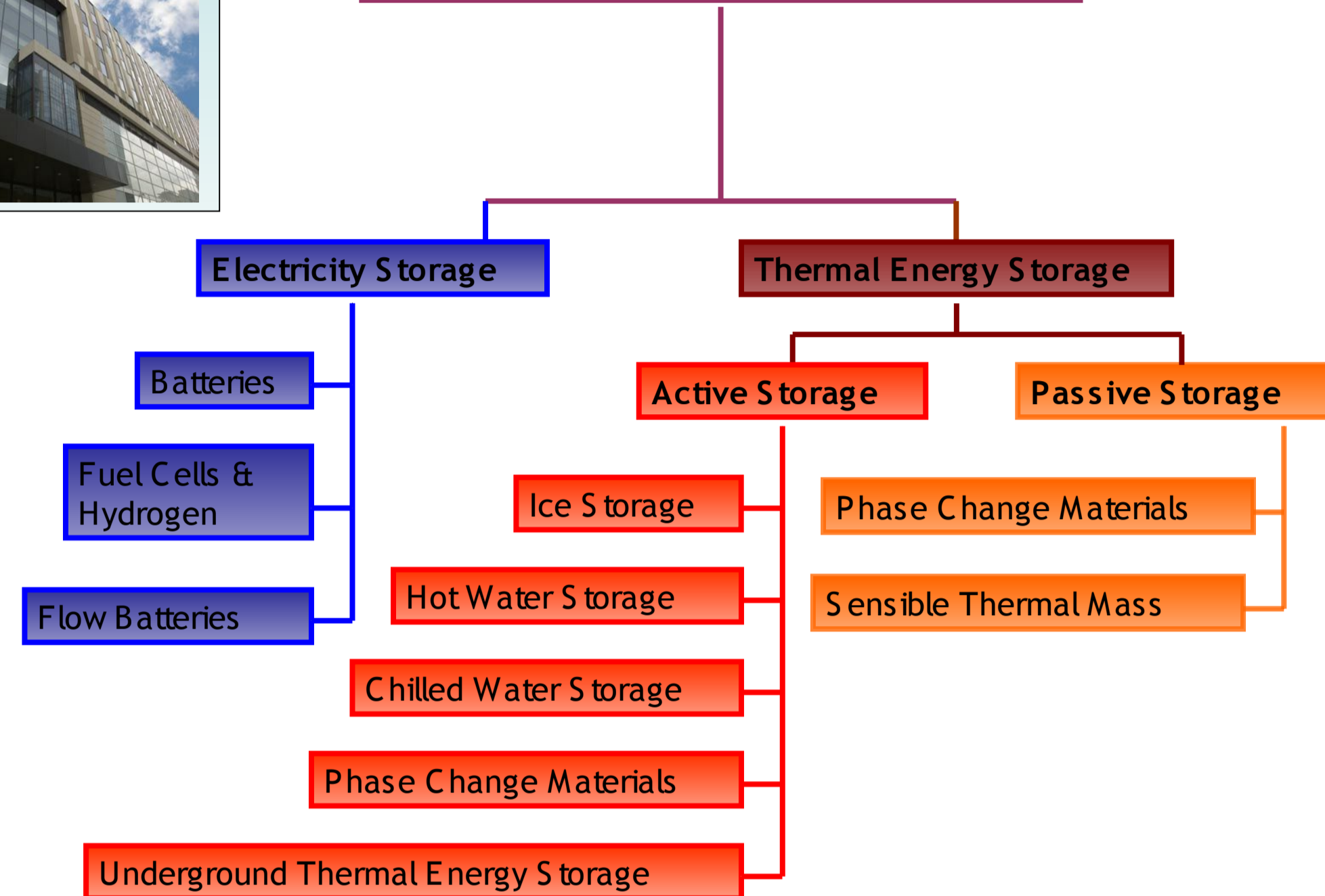
## 5. Phase Change Materials

In the built environment phase change materials (PCMs) refer to those materials that can be used to usefully store heat through a change of phase from solid to liquid and vice versa. They are generally divided into three types of material as shown in the table below. (This excludes ice storage which has largely different applications.)

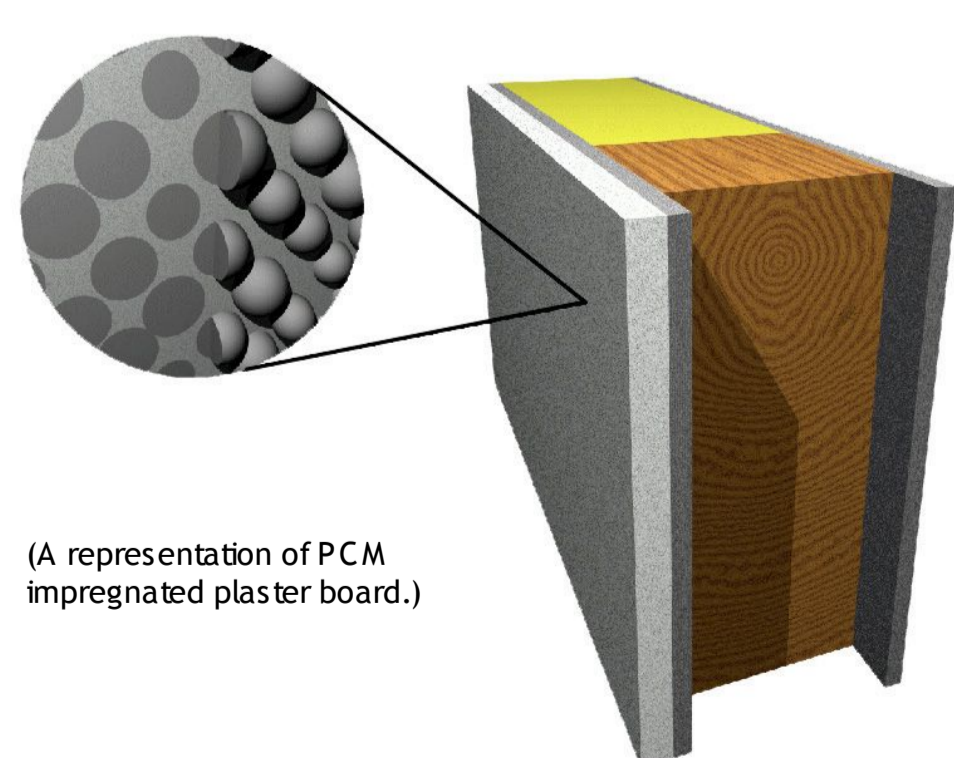
There are several properties that a PCM should have in order for application in the built environment to be feasible. These are:

- Appropriate phase change temperature.
- High change of enthalpy near temperature of use.
- High thermal conductivity in liquid and solid phases (but not always.)
- Low density variation.
- High density.
- Small or no undercooling.
- Chemical stability.
- No phase separation.
- Compatibility with container materials.
- Non-toxic, non-flammable, non-polluting.
- Cheap and abundant.

## Categories of Energy Storage Technology and Media for the Built Environment



PCM Type	Notes	Advantages	Disadvantages	Examples	Melting Temperature (°C)	Heat of fusion (kJ/kg)
Organic	Further categorised as paraffins and non-paraffins.	No corrosives. Low or no undercooling. Chemical and thermal stability.	Lower phase change enthalpy. Low thermal conductivity. Inflammability.	Butyl Stearate	19	140
				Paraffin C16-C18	20-22	152
				Capric-Lauric acid	21	143
				Dimethyl sebacate	21	120
				Polyglycol E600	22	127.2
				Paraffin C13-C24	22-24	189
				(34% stearic acid + 66% capric acid)	24	147.7
				1-Dodecanol	26	200
				Paraffin C18 (45-55%)	28	244
				Vinyl Stearate	27-29	122
				Capric Acid	32	152.7
				RT 20 (Paraffin from Rubitherm GmbH)	22	172
				RT 26 (Paraffin from Rubitherm GmbH)	25	131
				RT 25 (Paraffin from Rubitherm GmbH)	26	232
				RT 30 (Paraffin from Rubitherm GmbH)	28	206
RT 27 (Paraffin from Rubitherm GmbH)	28	179				
RT 32 (Paraffin from Rubitherm GmbH)	31	130				
Inorganic	Further categorised as salt hydrates and metallics.	Greater phase change enthalpy. Lower cost.	Undercooling. Corrosion. Phase Separation. Lack of thermal stability.	KF4H2O	18.5	231
				Mn(NO3)2.6H2O	25.8	125.9
				CaCl2.2H2O	29	190.8
				LiNO3.3H2O	30	296
				NaSO4.10H2O	32	251
				Clmsel C23 (Salt hydrate from Climator)	23	148
				Clmsel C24 (Salt hydrate from Climator)	24	216
				STL 27 (Salt hydrate from Mitsubishi Chemical)	27	213
				S27 (Salt hydrate from Cristopia)	27	207
				TH 29 (Salt hydrate from TEAP)	29	188
Clmsel C32 (Salt hydrate from Climator)	32	212				
Eutectic	A minimum-melting composition of two or more components, which melt and freeze congruently.	Subject to the disadvantages of their constituents. (These may be organic-organic, organic-inorganic or inorganic-inorganic compositions.)	Subject to the disadvantages of their constituents. (These may be organic-organic, organic-inorganic or inorganic-inorganic compositions.)	66.6% CaCl2.2H2O + 33.3% MgCl2.6H2O	25	127
				49% CaCl2 + 4.3% NaCl + 0.4% KCl + 47.3% H2O	26.8	188
				47% Ca(NO3)2.4H2O + 53% Mg(NO3)2.6H2O	30	136
60% Na(CH3COO).3H2O + 40% CO(NH2)2	30	200.5				



## 6. Phase Change Materials: Passive Applications

An obvious comparison for PCMs in passive applications is that of sensible thermal mass. Both can absorb excess heat from a space and release it when temperatures fall. As a result, both can reduce minimum and maximum temperatures and both can reduce heating and cooling loads but due to the fact that PCMs absorb and emit heat at one temperature, or transition zone, there is a much greater potential for steady internal temperatures around the thermal comfort zone. Added to this, they have an energy density an order of magnitude higher than sensible storage materials, which makes them smaller, lighter and easier to install. PCMs therefore have a great potential for effectively tracking thermal comfort conditions.

The different types of passive applications researched are numerous. Included are:

**Wallboards:** Easily retro-fitted boards that moderate temperatures and reduce cooling load. Commercially available in the form of the Dupont Energain panel.

**Shutters:** Solar radiation that is absorbed by the PCM shutters is emitted to the room at night when the shutters are closed. Not commercially available.

**Building Blocks:** Blocks impregnated with PCM can increase the thermal mass of a building significantly. Not commercially available.

**Floor Heating:** By incorporating PCMs into floors, the heating load resulting from solar gains can be delayed by several hours. Not commercially available.

**Ceiling Boards:** These boards can perform the same function as wall boards but have the advantage of being placed at the hottest part of the room. Not commercially available.

**Air Conditioning:** By flowing air passed solid PCM blocks, the air temperature can be reduced to comfortable levels. Commercially available as CoolDeck with PCM from Climator.

**Trombe Walls:** Walls that are located behind south facing windows to absorb solar radiation and reduce heating load. PCM trombe walls are lighter and smaller than their concrete counterparts. Not commercially available.



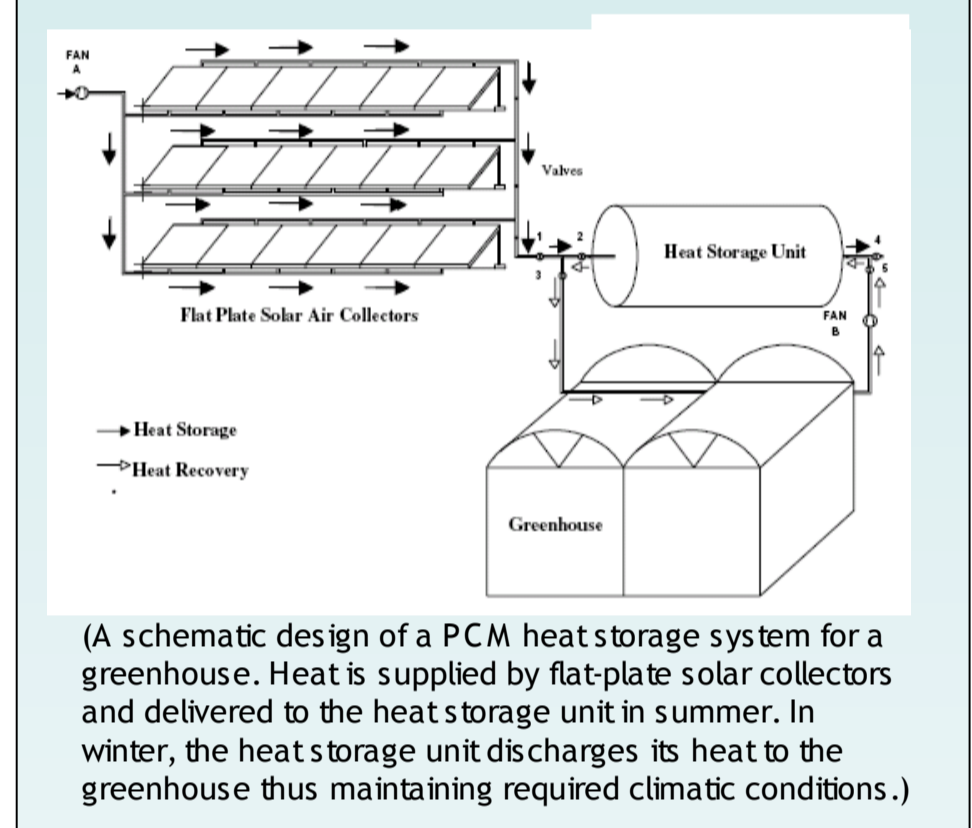
## 7. Phase Change Materials: Active Applications

There are many examples of PCMs being used in active applications. These include:

**Solar Absorption Cooling:** Solar energy may be converted to thermal energy in water, contained by a solar collector. If this energy is then used to drive an absorption cycle, cooling is produced which can be used to cool a space. However, because the sun doesn't constantly shine and is not perfectly in phase with cooling loads, thermal energy storage is needed to fill any gaps. This can be provided by PCMs.

**PCM heat pump system:** Using PCM storage, a heat pump system may be reduced in size through more constant operation.

**Seasonal Heat Storage:** A large enough PCM store can be used to balance the difference in temperatures between the seasons. This has been researched particularly for greenhouses where constant climatic conditions are desired.



## 8. Barriers to PCM Installation

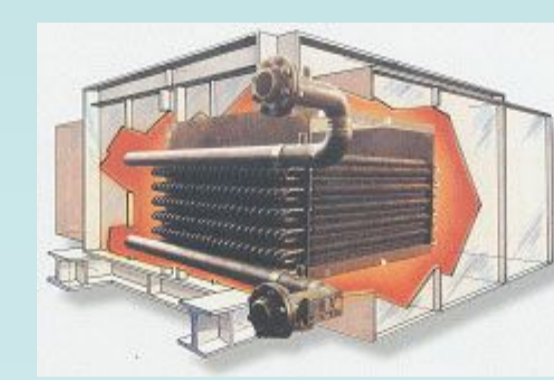
PCM use is currently limited because of:

- Risk of leakage through expansion.
- Risk of fire.
- Low internal heat transfer rate.
- Low cycle-life.
- Perceived efficacy of the system.
- Cost of the system

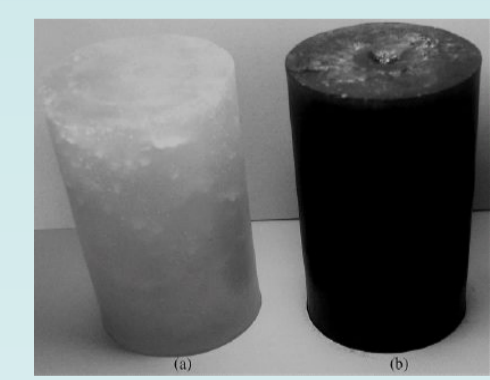
## 9. Improving Heat Transfer

The great technical limitation on the increased application of PCMs for thermal storage is their low conductivity, especially in the liquid phase. For example paraffins have a typical thermal conductivity of 0.21 - 0.24 W/mK. This means that the charging or discharging of the PCM is slow which results in an unreactive system that absorbs only a small amount of the excess heat available. The various methods for improving heat transfer are:

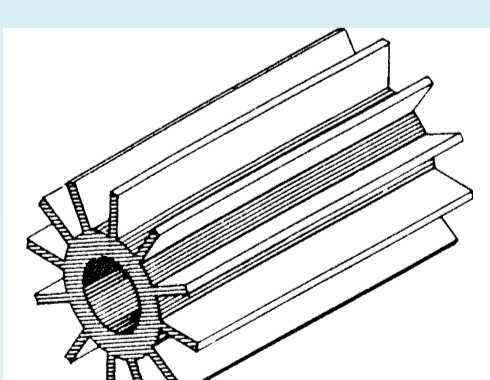
• Greatly increasing the heat exchange surface area to volume ratio. This is the strategy taken by DuPont in the design of their 'Energain' panels. The same principle is exploited thermal storage units are filled with many loops of heat exchange pipe to carry the heat exchange fluid (normally water) to as much of the PCM as possible.



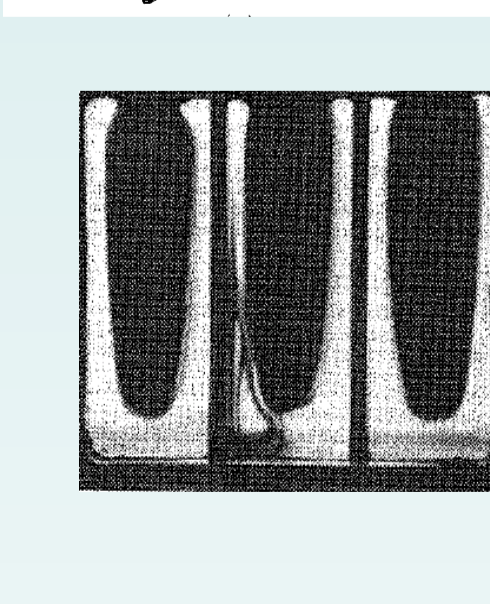
• Adding highly conductive particles, fibres or expanded graphite. The picture opposite shows two blocks of paraffin wax. The one on the left is pure. The one on the right contains 10% expanded graphite which has stabilised the shape and increased conductivity by a factor of 4.



• Increasing the internal surface area through the addition of such elements as fins or metal foams. The major drawback here is the additional costs in materials and manufacture.



• Promoting convection currents to more effectively transfer heat when the substance enters the liquid phase, when heated. The picture opposite shows partly melted paraffin in a finned container - liquid in white, solid in black. One of the convection currents is indicated some additive dye in the central chamber.



## 10. Looking Forward...

The information presented here strongly indicates that thermal energy storage in PCMs can reduce carbon emissions from buildings. The question therefore is:

**What can be done to increase the likelihood of PCMs being specified for heating and/or cooling systems?**

Of the six barriers to installation listed, the cost, the perceived efficacy and the low internal heat transfer are most important. The three others may be dealt with as follows: Risk of leakage through expansion can be mitigated through improved container design and so is subsumed under 'Development' below. Cycle life is effectively infinite for organic PCMs but there is a risk of fire, however, this can be easily mitigated as the flash-point for paraffin is low.

So, three basic approaches for research present themselves:

• **Development - improve/optimize operation.** For many PCM applications the system is sufficiently complex and under-developed to warrant optimisation studies. The most obvious area for improvement is internal heat transfer as a low rate of internal heat transfer is the dominant limiting factor in any PCM-based system's efficacy. It may well be that the optimal method for increased heat transfer is application dependent and so here lie several opportunities for study.

Another opportunity here is to try to find ways to improve the heat transfer between the space and the PCM. Ideally, the moment the temperature in a space rises above the transition temperature of the PCM, the associated excess heat is removed, so that in effect the temperature of the room can never significantly rise above the PCM transition temperature. Further attempts to approach this ideal may be fruitful.

2) **Demonstrate efficacy to engineers and architects.** With certain systems being shown to be operationally successful and cost-effective, the lack of uptake in PCM technology is likely to be due to ignorance and/or a risk-averse attitude from building designers. This may be overcome through demonstrations of the success of PCM-based systems. Most convincingly this would take the form of detailed and reliable studies of occupied buildings. Failing this, a demonstrably reliable simulation would go some way to convincing designers - the difficulty here being the reliable modelling of the PCM itself.

3) **Reduction in cost.** Any design alteration that leads to a reduction in cost (particularly capital costs) would make these systems far more attractive. One study of a free-cooling system with PCM located in the ventilation ductwork showed that the PCM itself only constituted 17% of the total system cost. Clearly then a cost reduction is not seriously limited by raw materials. Developments, such as shape-stabilisation with expanded graphite, suggest that an increase in conductivity and a decrease in container cost can be achieved simultaneously.

## Glossary

**Absorption Cycle** - A refrigeration process, driven by heat (not compression) and using two fluids; one refrigerant and one absorbant.

**Active Storage Systems** - Those systems that are thermally isolated from the environment they are intended to interact with.

**Batteries** - Electricity storage devices in which chemical energy is converted to electricity through the reaction of electrodes with the electrolytes they are submerged in.

**Building Services** - The provision of water, lighting, ventilation and temperature control that make a building habitable.

**Chiller** - A device for actively cooling an occupied space.

**Cooling** - In the context of building services this normally refers to the cooling of an occupied space, as opposed to the cooling of objects.

**Coolth** - The difference in internal energy between a medium and its surroundings, when that medium is colder than the surroundings. Often treated as a form of stored energy.

**Condensing Temperature** - The temperature to which a refrigerant is cooled upon reaching the condenser in a refrigeration cycle.

**Cycle Life** - The number of times that a storage device can be fully charged and discharged before it degrades significantly in storage capacity.

**EngD** - See 'The Engineering Doctorate in Environmental Technology' box in the abstract bar.

**Flow Batteries** - Electricity storage devices in which chemical energy is converted to electricity through the reaction of two liquids on inert electrode surfaces.

**Fuel Cells** - Electricity generation devices in which oxygen and hydrogen combine to form water.

**Heat Pump** - A device that effectively converts low temperature heat into higher temperature heat through a vapour compression cycle.

**Lagging** - The insulation surrounding thermal storage devices or pipes.

**Passive Storage Systems** - Those systems that are in constant thermal contact with the environment they are intended to interact with.

**Phase Change Material (PCM)** - A material that has a solid liquid transition temperature/zone, and high latent heat capacity, such that significant thermal storage can be achieved.

**Pumped Hydro Storage** - An electricity storage system that converts the gravitational potential energy, of an elevated mass of water, when that water is released.

**Solar Collector** - A device that facilitates the heating of a fluid by solar radiation.

**Sustainable Technologies** - Those technologies whose widespread use can be sustained indefinitely without significantly damaging the environment for future generations.

**Thermal Comfort** - The state of mind which expresses satisfaction with the thermal environment.

**Thermal Mass** - The material in a building that has relatively high specific heat capacity and can therefore regulate temperature.

**Underground Thermal Energy Storage** - The process whereby the ground in the region beneath a building is used for the storage of thermal energy, to be recovered at a later time.