Department of Mechanical and Aerospace Engineering

IMPACT OF PHASE CHANGE MATERIALS ON ENERGY SAVINGS OF RENWABLE ENERGY TECHNOLOGIES

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Signed: - Date: - 8th September, 2012

Abstract

The possibility of energy and operational cost savings with application of phase change thermal/heat storage was investigated in this report. Model of a 2-storey detached house representative of typical UK dwelling with average insulation employing an air source heat pump for domestic water and space heating was simulated. The model was divided into three zones, living, non-living and loft. The living zone represents the living room and dining, the non-living zone, the bedrooms, toilets and baths and the kitchen while loft zone represents the loft. Model of the domestic hot water tank is stratified and has provision for incorporating phase change material. A base case model with no PCM in DHW tank was simulated for decreasing on/off set time duration to obtain a minimum on/off set time for running heat pump such that DHW temperature drop below 40^{o}C is in experienced for a percentage of occupied period (averaged over simulation week/period) not greater than 15%. This set time was set as starting point for simulating models with phase change material incorporated into the DHW tank. Simulations were run for 12.5%, 25% and 37.5% of DHW tank volume of PCM and for reducing on/off set time duration as well as back shifting on/off set time away from peak energy demand period into off peak period in order to explore the possibility of taking advantage of the different and lower energy tariff for off peak period for energy cost savings. Back shifting on/off set time into off peak period for models with PCM using the same number of hours as for the minimum obtained for the base case, 7 – 16, yielded energy cost saving of 32.8 pence/day, 22.75% less but energy consumption increase of 5.23%, for on/off set time 3 – 12, 12.5% PCM, being the on/off set time with maximum percentage of occupied period DHW temperature dropped below 40^{o}C. 50.55pence/day, that is 35.06%, was obtained as maximum energy cost saving while average daily energy consumption increased from 13.95kWhr to 15.04kWhr, (7.81%), for back shifting to 1 – 10, 37.5% PCM while reducing on/off set time duration and back shifting resulted in maximum energy cost savings of 111.06pence/day (77.2%) and 6.34kW/day (52.83%) reduction in energy consumption when compared with the minimum base case (no PCM) on/off set time.

Dedication

This work is dedicated to God almighty, whose grace and mercy made it possible for me to embark on the programme and to finish. It is also dedicated to my wife, Kemi and my daughter, Eden, the two blessings of God I have not come to fully appreciate.

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I wish to acknowledge and appreciate God for his love, grace, mercy and provision for me throughout the period of the programme. I appreciate my wife and daughter for enduring and taking care of each other while I was away. I am grateful to Iya Remi, my mother, for her constant love and prayers, and for yielding herself to be used of God to bless me. I am grateful to my mother-in-law for her support. I appreciate sister Nike, who has been more of a sister than an in-law. I also appreciate Mama Sunday (Eye Jiyegbe), my siblings and other members of my extended family for their support and understanding.

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1 Introduction

1.0 Background

1.0.1 Energy

Modern man, in a lot of respect, differs from his primitive ancestors, especially, in energy use. World total energy consumption was put at $7.575 \times 10^4 MJ$ in 2005 (Energy Information Administration, 2007). With over six billion population, this is equivalent to every individual having 90 men do heavy industrial labour non-stop all day.

Because energy has the ability to make possible the provision of comfort, transportation and production of food and material goods, it has become essential to our way of life, a veritable ingredient in everyday human life. So much so that it is used as a yardstick with which a country's development is measured, the per capital energy consumption.

There is an ever increasing demand for energy due to increase in use and demand for labour saving devices, population increase, industrialisation, e.t.c., leading to increase in energy production and search for more sources and resources, often exceeding capacity of local resources to cope.

Energy is defined as the capacity to do work. It is present or inherent in very object or substance in nature, in cells, atoms, molecules, nuclei and in nuclear forces and interactions. According to the energy equation $E = mC^2$, matter is energy and energy is matter.

It is dormant and reserved while it remains in the cells, atoms, molecules and nuclei as chemical, internal molecular and nuclear energy, but is consumed when it performs or is employed to do work: mechanical work, to move unit mass over unit distance, electrical work, to move a charged particle (electron) through an electric field, thermal work, to cause unit increase in temperature of a substance and release of electromagnetic radiation (visible light, gamma rays, x-rays, radio waves, etc).

It is inter-convertible from one form to the other, more easily when it is being used up, from the stored, reserved form, to work, and from one type of work to another. It is however not quite easily converted from work to the stored form. And this all that can be done to energy, convert from one form/type to the other. Energy can neither be created nor destroyed! It can only be converted from one form/type to another or transferred.

The ease of conversion (or transfer) depends on the materials and systems employed – A boiler for converting chemical energy stored in natural gas to thermal work which raises temperature of water, a battery operated light bulb for converting chemical energy stored in batteries to thermal energy (work) for raising temperature of bulb filament and electromagnetic radiation as light (energy), and a thermal power plant, through a number of conversion processes and stages, for converting stored chemical energy of fuels (like natural gas) to electrical work (energy).

A thermal power plant begins to consume energy once the burners are lit and the fuel ignited. Energy is utilised here (for steam power plant) to raise temperature of water and change it from liquid to gas (steam) (i.e. thermal work). The turbine converts or changes the work (energy) from thermal to mechanical in the spinning shaft which is further converted or changed into electrical work (energy) by the electric motor (alternator). This energy has been consumed and its usefulness depends on how easily it can be further converted into other forms/types of work (energy), retained (or kept from dissipating) or converted back to the stored form for use/consumption at a later time. This has been the major challenge of energy utilisation and availability.

The readiness or effectiveness with which an energy converter or consumer converts energy from one form to the other is referred to as its efficiency. It is the ratio of output energy to the input energy, whether or not the form/type is similar or different after conversion. Every energy conversion process or transfer involves some losses or wastages and is never at 100%. This is due to limitations imposed by structural, molecular and thermodynamic constraints on substances and materials. The coils within an electric motor will always warm up as a result of the resistance to flow off electricity by copper. This is necessary for inducing magnetic force needed for moving the armature and producing rotation of the shaft. The shaft, in turn, will warm up due to friction resistance in the bearings and so on. Also, the molecules of the material used to construct a heat exchanger will, of necessity, take up some of the heat energy before it flows across to the receiving substance (like water), which will in turn also take up some before passing it on. This energy taken up represents 'work' that has to be done on atoms and molecules of the substance for it to perform the required task.

1.0.2 Energy Storage andConservation

As stated above, energy consumption for a power plant begins as soon as the burners go on. If not utilised for any particular purpose, the energy, now converted to thermal energy (work), is dissipated, taken up, in the molecules of air in the atmosphere. It is wasted because it was not utilised.

Energy storage affords opportunities for better utilisation and management of energy and energy resources. Wastages can be reduced considerably as energy systems would not necessarily have to be designed for maximum load but for an optimum that is some mid-way between highest and lowest demand. Excesses during periods of low demand can be stored away and utilised to meet up supply during periods of high energy demand. This way energy demand and supply profile can be levelled.

It is particularly useful in renewable energy systems technology and applications like solar, wind, wave and tidal energy, which are intermittent. Storing up energy produced during periods of high resource availability provides opportunity for extending supply and making it appear continuous, if energy in store can sufficiently meet up demand during periods of low or no resource availability.

Energy storage (or rightly put, energy reservation) refers to means or methods of keeping energy in the stored or dormant form (holding off consumption or dissipation), converting work (energy) back to stored form, or delaying its dissipation by temporarily storing for use at a later time in order to prevent or reduce its wastage or useless dissipation.

Holding off consumption, that is keeping in the stored, dormant form implies not employing it to perform work. Not using energy is almost an impossible task in this industrialised energy intensive age. Electrical energy (work) can easily be converted back to the stored form (chemical energy) via electrolysis or kept from dissipating in charge and electrical capacitors. Thermal and mechanical energy (work), on the other hand, can only be converted into temporary stored form or kept (temporarily) from dissipating, as internal (heat) energy via change of phase from solid to liquid or liquid to gas, or increase in temperatures of a substances with high specific heat capacity, for thermal energy (these are non natural processes. Plants naturally convert thermal, and radiant energy, from the sun into stored chemical energy via photosynthesis), and by employing a rotating object with large mass, a flywheel, or as internal energy in compressed air/vapour or pumped water storage for mechanical energy (work).

The substances employed for these storages are often in unstable states, which can only be maintained if substance/material is isolated from the environment or surrounding, from frictional forces, otherwise the work is dissipated and utilised or wasted as substance returns to stable state. Keeping storage substance/material in isolation is not always easy to achieve due also to thermodynamic, structural and environmental constraints.

Although electrical energy (work) can be converted back to the stored form it is not without some losses as ‘work’ has to be done (energy dissipation) on the atoms and molecules of the storage substance to change their configuration into the form that enables them store energy. Maximum theoretical efficiency for electrolysis is between 80 – 94% but between 50 – 70% in practice, and drops as the substance cycles between dissipation and storage over a period of time until the substance is no longer able to change back to the energy storing form.

Because of the difficulty and attendant losses associated with attempts to convert work (energy) back to the stored energy form, coupled with the fact that it may only be possible with electrical form/type, and that it is almost impossible not to consume energy at all, preventing dissipation for a period of time seems to be the option for reducing or preventing energy wastage with wide applicability.

1.0.3 Thermal Energy/Heat Storage

The ease or readiness with which heat/thermal energy can be reserved or kept from dissipation, temporarily, depends, to a large extent, on the quantity to be stored, storage temperature and the length of time for which it is to be stored. Storing at low temperatures (often referred to as low grade heat, below 100°C) can easily be done for considerable lengths of time (up to 48 hrs), whereas storing at higher temperatures (high grade heat, above 100^oC) for long periods is more difficult to achieve and requires rather complex systems to effectively keep the heat (energy) from dissipating. Also, storing heat (energy) in high temperatures allows large quantities to be stored but with increased possibility of wastages or losses (wasteful dissipation) due to high temperature differences.

Heat/thermal (energy) can be stored employing three basic methods or ways: in elevated temperatures of substances with high thermal mass (specific heat capacity), by change of phase of a material from, say solid to liquid or liquid to gas or by reversible chemical reaction of some substances that absorb large amount of heat during either the forward or reverse reaction and releases stored heat in the reverse or forward reaction. The first method is referred to as sensible heat/thermal storage (SHS), the second, latent heat/thermal storage (LHS) and the third chemical heat/thermal storage.

Sensible heat storage involves changes in the temperatures of the material storing the heat. Here, advantage is taken of the relatively high specific heat capacity of the storage material. This term refers to the amount of heat/thermal energy required or needed to raise the temperature of the substance by one unit. For example, specific heat capacity of water is about 4.2kJ/kgK, about 3.35kJ/kgK for concrete and about

0.42kJ/kgK for steel. This means that for every degree (Kelvin) rise or fall in temperature of water 4.2 kJ of heat/thermal energy is absorbed or released; 3.35kJ for concrete and 0.42kJ for steel.

Latent heat/thermal storage involves no change in temperature, utilising the energy taken up or given out by a substance as it changes from one phase to the other, the process occurring at the same temperature. The heat (energy) absorbed is utilised to break the strong molecular structure and bond of more compact configuration phase, say solid, and cause transformation into a less compact configuration phase, say liquid. The energy (heat) is released when the substance returns to the initial phase and the molecular bonds reform. This heat/energy is usually very large in comparison to that required per unit mass for sensible heating. Latent heat of vaporisation of water is 2260 kJ/kg and between 260 and 285 kJ/kg for steel.

The ratio of energy (heat) required for phase change to that required for temperature change is relatively large for many known substances, about 80 for water. That is, 80 times more energy (heat) is needed to cause water to transform from liquid to gas than is needed to raise the temperature of liquid (or gaseous) water by 1 degree. This implies that water, employed for latent heat storage, can store 80 times more heat (energy) than the same quantity employed for sensible heat (energy) storage. This also means that 80 times less quantity and space will be required for the same quantity/amount of heat (energy).

Important factors about a thermal storage system are the amount of energy that can be stored, the amount stored per unit volume, the volumetric energy capacity, and the length of time over which it can be stored with acceptable losses. Volumetric energy capacity is usually high for materials with high density. If specific heat capacity is high, large amount of heat can be stored in relatively small amount of material, which affords the advantage of small storage space. For sensible heat storage, amount of material required to store an appreciable amount of heat/energy is relatively large, even for high density materials, making it difficult to take advantage of small storage space.

Latent heat/thermal storage allows storage of more heat/energy per unit mass and volume, making storage system smaller, lighter and more compact. The reduced size also means heat loss is reduced as heat loss is proportional to surface area. The fact that phase changes occur at relatively constant temperatures implies that difference between heat (energy) storage and heat (energy) delivery temperatures need not be large and heat (energy) supply and delivery will occur at relatively constant temperatures, which also reduces or limits heat (energy) loss to the surrounding (Farid, et al., 2004). Also fluctuations in supply can be effectively smoothed out by application of heat storage (Münster & Lund, 2007).

The process of heat storage or absorption ceases for sensible heat storage when storage material temperature reaches temperature at which heat is being delivered to it. Latent heat storage, on the other hand, continues until all material completely changes phase. More heat can even be stored if phase change temperature is lower than heat delivery temperature, this time as sensible heat, combining both types of heat storage methods.

Phase change materials for latent heat/thermal energy storage affords great opportunities for energy and cost savings and the potential for their development and advancement, implementation and integration is immense (Baker, 2008).

1.0.4 Phase Change Heat storage materials (PCMs)

For most phase change energy storage applications the solid-liquid phase is the most widely employed, primarily because of the ease of handling solid and liquids relative to gases, and because heat transfer to and from PCMs involve some conduction, which is better in solids and liquids.

There are two main divisions or classes of phase change materials used for thermal energy storage: organic and inorganic. Organic materials are paraffin, fatty acids, esters, alcohols, and glycols while inorganic materials include water, salts and salt hydrates of metals, alkalis, metals and alloys, and eutectic mixtures.

The paraffins stand out among organic PCMs and are often classed separately. They are waxes and viscous oils. They have a high latent heat of fusion, low vapour pressure, little or no sub-cooling and are chemically stable. They are readily available, non corrosive and safe but their application is limited by low thermal conductivity, flammability and large volumetric change after phase change.

Organic non-paraffinic PCMs have high melting points, similar to those of paraffins, as well as low thermal conductivity and volume change. They are majorly toxic, poisonous and unstable at high temperatures, as well as being very expensive.

Inorganic phase change materials have relatively high latent heat, high thermal conductivity and low volumetric change, with salt and salt hydrates ranking best. They (salts and salt hydrates) have high volumetric thermal storage capacities, sharp melting points and are readily available. Some are corrosive to some metals and other not so corrosive. However, a suitable combination of phase change material and metals is largely possible.

A major problem with salt hydrates (and many other inorganic phase change materials) is super-cooling upon freezing due to weak nucleation properties and phase segregation which is caused by incongruent melting. As the hydrates melt anhydrous salts separate from the aqueous solution and settle to the bottom because of higher density. When re-solidification begins, it usually starts at the interface between anhydrous salt and precipitate forming a contact barrier that prevents complete rehydration. The method adopted to tackle this problem is to mix the salt hydrate with nucleating and gelling agent

Eutectics are mixture of two or three inorganic compounds that have definite melting/freezing points, which enables them to melt and freeze without separating. The mixture could contain only salts, salt hydrates, alkalis or mixture of two or all. Their sharp melting points allow melting and freezing of all components to occur simultaneously.

Table 1.1 Properties of some PCM used for domestic applications (source Cabeza et al. (2011))

Product	Type	Melting temperature(^{o}C)	Heat of fusion (kJ/kg)	Thermal conductivity (W/m K)	Source
RT 20	Paraffin	22	172	0.88	Rubitherm GmbH
Climsel C23	Salt hydrate	23	148	–	Climator
E23	Salt hydrate	23	155	0.43	EPS Ltd
Climsel C24	Salt hydrate	24	108	1.48	Climator
TH 24	Salt hydrate	24	45.5	0.8	TEAP
RT 26	Paraffin	25	131	0.88	Rubitherm GmbH
RT25	Paraffin	26	232	–	Rubitherm GmbH
STL 27	Salt hydrate	27	213	1.09	Mitsubishi Chemical
S27	Salt hydrate	27	207	–	Cristopia
AC 27	Salt hydrate	27	207	1.47	Cristopia
RT 27	Paraffin	28	179	0.87	Rubitherm GmbH
RT 30	Paraffin	28	206	–	Rubitherm GmbH
E28	Salt hydrate	28	193	0.21	EPS Ltd

Latent heat thermal storage systems (using phase change materials) employed for home and office heating purposes offer huge benefits and opportunities for reducing cost and CO_2 emissions by buildings, enhancing building ability to stabilize and maintain steady internal temperature conditions (Turnpenny et al, 2000 and 2001; Halford & Boehm, 2007; Heim & Clarke, 2004). Acting as heat resistors and entrapment, they store up heat that would have ordinarily been wasted for later use during periods of high heating demand. This can help smoothen out energy demand peaks and reduce overall heating energy demand. According to (Arteconi, et al., 2012) phase change energy storage is capable of ensuring energy security, efficiency and environmental quality.

1.0.5 Domestic Energy Consumption

Energy is used in the home for a variety of purposes from food preparation and preservation to entertainment and environment control. It is reported that buildings consume around 40% of the total energy produced and between 42% (Henze, 2005) and 60% (Wyse, 2011) of this is used for indoor environment control. In the UK, 30% of total energy is utilised in the domestic sector with 83% employed for heating and cooling purposes (Boardman, et al., 2005).

Domestic heating in the UK is done mostly with gas fired boilers. Crozier-Cole & Gareth (2002) reported that about 18 million units are fitted into UK homes, representing about 68% of residential properties in the UK (Kane & Newborough, 2006).

In spite of their high efficiencies gas fired boilers are still a major contributor to global CO_2 emissions because they burn fossil fuels. Mounting global cry for reduction in CO_2 emission and the looming end to fossil fuel availability, coupled with environmental considerations and strict emission restrictions, has led to research into alternative renewable sources of energy, especially in the residential sector, because they have the potential to reduce residential emission of pollutants and CO_2 attributed to electricity and heating. It has also prompted many countries to put in place policies and incentives aimed at encouraging deployment of renewable energy technology systems (International Energy Agency, 2002).

This type of heating system (gas fired boilers) has more or less reached its peak in terms of performance and efficiencies, which is close to 100% (Barbieri, et al., 2011), a reason Kane & Newborough (2006) and De Paepe, et al (2006) infer is responsible for move of research efforts at achieving more carbon savings and CO_2 emission reductions into co-generation and micro-CHP systems for domestic application as well as heat pumps for domestic heating (White, 2009). After all, very, little improvements can be made, especially to the efficiency, by further research work.

1.0.6 Heat Pumps

Heat pumps have been identified as strong contender for reducing carbon emissions in the UK domestic energy sector (Singh, et al., 2010). They are considered as having the greatest potential for reducing domestic heating and power CO_2 emissions (Cockroft & Kelly, 2006), with capability, also, for reducing overall primary energy consumption and is one of the products promoted under the EU Ecolabel scheme with potential to reduce negative environmental impact (European Union (EU), 2010). This is primarily due to their durability, long useful service life (like normal refrigerators) and potential for financial gains and reduced cost savings from using the technology for heating in comparison to conventional domestic heating systems. A further reduction would be possible, also, if any excess produced during periods of low heat demand can be stored and utilised to make up during periods of high demand.

Heat pumps are basically refrigerators with the heat absorbing part (evaporator) located outside and the heat emitting (condenser) part located indoor. In a typical refrigerator a compressor works on a substance, the refrigerant, and causes it to remove, extract, absorb heat from food and other stuffs kept in the compartment and to give out this heat at the back (or at the sides in some cases) outside of the box/compartment. A heat pump has the same components and works in the same way except that heat removal is from the outside of the house, the house acting as the refrigerator box or compartment. Heat is now rejected into the house (box or compartment). Simply put, the system removes heat energy from the low temperature outdoor and delivers heat at a higher temperature to the indoor whose temperature is also high.

There are different types of refrigeration systems employed for domestic heating. The common type is the vapour compression refrigeration system that operates on the simple saturated vapour compression cycle. It utilises a mechanical compressor to compress the refrigerant vapour leaving the evaporator, thereby increasing its temperature and pressure, and driving it round the system: to the condenser where it rejects heat as it condenses, changing from vapour (gas) to liquid, to the expansion devise where it expands from high pressure to low pressure, the temperature also changing from high to low, to the evaporator where it absorbs heat as it evaporates changing from vapour (gas) to liquid and back to the compressor for the process to be repeated. The compressor requires energy to drive it, usually obtained from the grid or a prime mover, as the case may be.

Another type, the vapour absorption refrigeration system, utilises what is sometimes referred to as a thermal compressor. There is no mechanical compression of refrigerant. Rather a substance that has high affinity for the refrigerant, a strong carrier, is employed to absorb refrigerant vapour from the evaporator. A solution pump drives this strong refrigerant-carrier solution through a secondary circuit embedded between the evaporator and condenser. The secondary circuit is open to the primary circuit through an absorber, to the evaporator, and generator, to the condenser. The generator is heated and the heat drives out the refrigerant at high temperature and pressure from the solution. Refrigerant flows onward to the condenser while the weak refrigerant-carrier solution returns through a secondary expander to the absorber where it can absorb more refrigerant and begin another cycle. The refrigerant proceeds as it does in the vapour compression system, rejecting heat in the condenser, expanding in the expansion devise and evaporating in the evaporator. The process/cycle continues with the carrier absorbing refrigerant again in the absorber and on to through the solution pump.

Refrigeration technology is not new and the system still consumes as much energy and emits as much CO_2 as conventional refrigerators (vapour compression) because it also runs on electricity. Its application (heat pump) as an energy saving (or renewable energy) technology however, results from its sourcing input energy (heat) from a cheap and abundant source (Hepbasli & Kalinci, 2009) and, more importantly, the amount of total energy (heat) rejected (or delivered to demand) compared to energy consumed for the purpose, its ‘thermal’ efficiency or Coefficient of Performance (COP). The ratio is usually greater than 100% (sometime up to 200%); implying that more energy is produced than is consumed, producing more heat for the same quantity of energy consumed in comparison to gas fired (or electric) boilers (Kim, et al., 2004).

Although an increase in deployment of heat pumps could be regarded as adding more electrical load to the network, the greater than 100% efficiency is an indication of a lower overall energy load.

The vapour compression system is the most widely utilised for domestic applications. This can be further sub-divided into two types according to and named by where heat is removed or absorbed (the same categorisation is possible for vapour absorption systems).

1.0.7 Air Source Heat Pump (ASHP)

As the name implies it sources or absorbs heat from outside/atmospheric air. Installation is quite easy and simple. It consists of two units, outdoor unit consisting of the expander, evaporator and compressor and located outdoors and the indoor unit, the condenser, located indoors. The indoor unit can be inconspicuous but the outdoor unit occupies a rather conspicuous location on the building side.

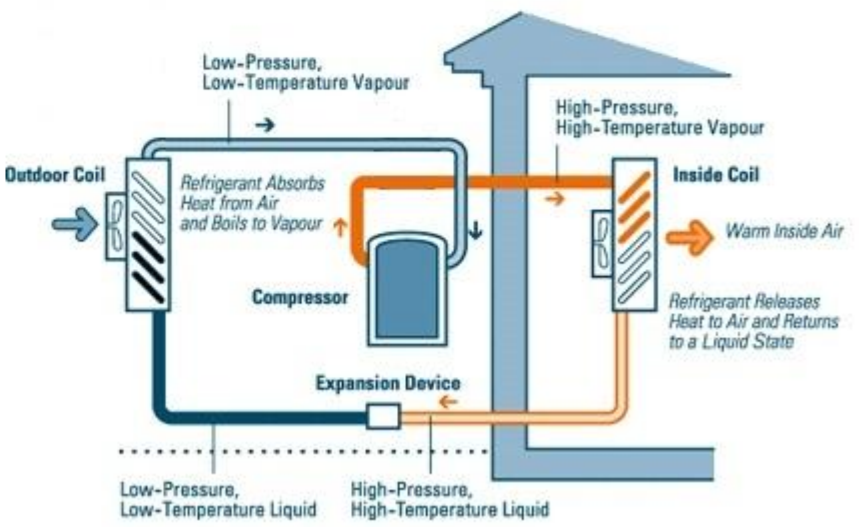

Figure 1.1 Arrangement of components of an Air Source Heat Pump (REUK.co.uk, 2012)

Fans or blowers blow air over the evaporator from which the refrigerant absorbs heat. The condenser may be arranged to heat water in a hot water storage tank or simply provided with a fan or blower to blow air over it, which is transferred through vents round the house. They can also be placed or installed under floor slabs to provide under floor heating.

Performance of heat pumps, and efficiency, is dependent on heat supply temperature, refrigerant used and more importantly on evaporator temperature (Kara, et al., 2008), which is influenced/affected by atmospheric air temperature and weather conditions, and decreases as air temperature drops. System efficiency, and effectiveness, for air source heat pump can decrease below 100% during very cold seasons like winter. The evaporator may freeze up if atmospheric temperatures fall to and below 5^{o}C.

They are relatively easy to install, and require little maintenance but often regarded as noisy. Although the hum of the compressor and fan/blower is quite noticeable, noise levels from air source heat pumps are still below 56 decibels (Building Performance Centre, 2011).

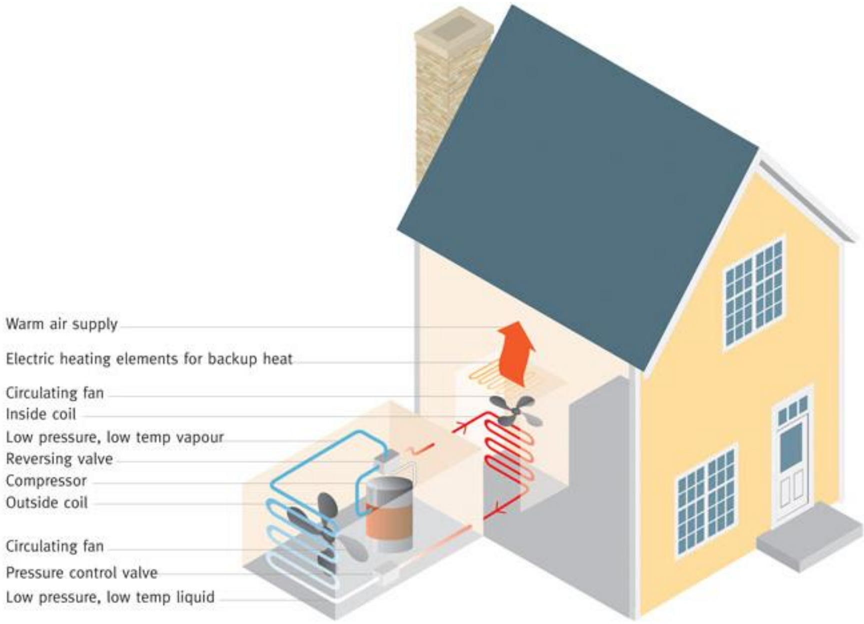

Figure 1.2 Air Source Heat Pump (Pro Enviro Limited, 2012)

1.0.8 Ground Source heat Pumps (GSHP)

This type of heat pump absorbs heat from the ground, using the earth as heat source. They are sometimes referred to as Geothermal Heat Pumps. It employs loops of pipes buried in the ground to extract heat from same. The entire system, except the evaporators, is located indoors. The condenser, similar to air source heat pumps, can be arranged to heat water, provided with a fan/blower to circulate warm air round the house or installed in floor slabs for under floor heating.

The absence of a second blower for the evaporator means lower energy consumption for this type of heat pump, and compressor power requirement is quite low due to the moderate evaporating temperature the system is designed to operate in compared to air source heat pumps. Also, because the compressor is located indoors, the types used are designed to produce low noise levels.

Its performance is not so heavily impacted by weather conditions as ground temperatures are relatively stable, slightly varying with air temperature with a lag that is depth dependent, so that greater depths see less variation (Jenkins, et al., 2009). Notwithstanding, it is able to function at relatively high efficiencies even in mid winter, offering potential for a higher coefficient of performance (COP) compared to air source heat pumps (White, 2009). But its performance can also reduce tremendously in very severe, cold winter when the ground freezes.

A major drawback for this type of heat pump is the difficulty of achieving excellent thermal contact between evaporator and the ground due to irregular shaped stones and rocks underground and the relatively high cost of installation with the ground coil alone taking up between 30% and 50% of total cost (Building Research Establishment Sustainable Energy Centre, 2009). Also sufficient space required for installing it is usually not always available and the cost of drilling boreholes in the absence of large expanse of land is relatively high.

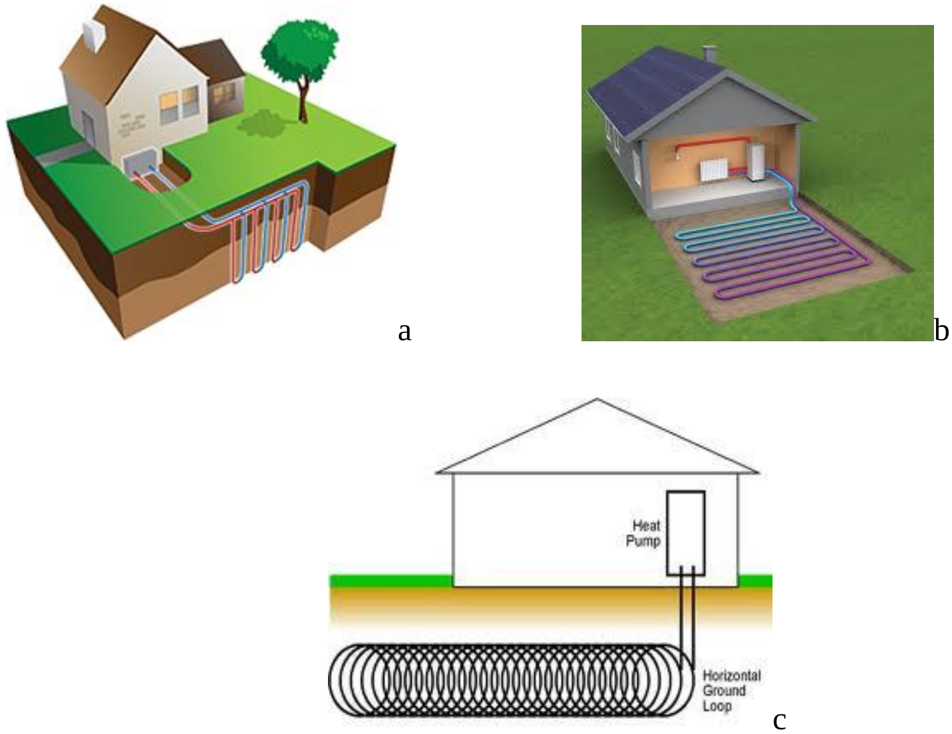

Figure 1.3 Ground Source Heat Pumps showing different configurations of evaporator underground – a) vertical loop (South West Energy Services Limited, 2012), b) horizontal loop (Carbon Zero, UK, 2011) and c) spiral loop (Sunray Solar Limited, 2011)

Although heat pumps produce (or supply) more energy (heat) than is consumed, implying reduced energy demand, they still suffer from some imperfections and produce some wastes. Boait et al (2011) suggest underloading as one of the reasons for low efficiency of heat pumps, particularly in the UK. Most times they are run continuously, installers' recommecdations being the reason given by home owners for this (Boait, et al., 2011).

According to Izquierdo-Barrientos et al (2012), Muruganantham et al (2010) and Hong et al (2012), opportunities abound in operation of heat pumps heating systems for energy and cost savings, as well as electrical network stabilisation by both manipulation of operation period/time for back shifting from peak to off-peak periods and application of thermal buffering. However, manipulation of demand is also important, according to Wyse (2011), to ensuring steady and reliable energy supply.

As suggested by Arteconi et al (2012), “thermal energy storage can be used for electrical loads management if coupled with electrically driven heating and cooling systems” like heat pumps (vapour compression systems) as a means of flattening the load profile, smoothening out demand fluctuations, thereby reducing operation/running time/period and resulting in further reduction in cost and energy, and imposed load on electricity networks.

This forms the basis for this research work, to investigate possibilities of saving energy and cost by manipulating start and stop time of a heat pump heating system employed for space and water heating and incorporating a phase change heat storage materials into the system.

1.1 Aims, Objectives and Scope

1.1.1 Aim

To assess ability of PCM to improve effectiveness of renewable energy technology and to effect reduction in energy cost.

1.1.2 Objectives

1) Review state of the art of PCMs and applications for domestic thermal energy storage
2) Review renewable energy systems for domestic application to assess application and deployment PCMs incorporated into the systems
3) Using an integrated model for a house/dwelling employing air source heat pump heating system with phase change material integration, test effectiveness of system with and without phase change material.

1.1.3 Scope

The scope of this work entails assessing the impact of phase change materials on improving performance of air source heat pump supplying heat to a 2-storey detached UK house with average insulation, using ESP-r simulation software to simulate models of the building and its energy systems.

2 Literature Review

2.1 Peamble

The survey of literatures examines works on renewable energy sysyems deployment and application for carbon emission redunction and energy and cost savings undertaken with application of both experimental and theoretical methods. The literatures cut across micro-generation and heat pump applcation and comparisons of different types of technologies for domestic application, and implemtation of various control strategies.

2.2 Renewablenergy systems

Roselli et al, (2011) reported on the energy production and economic and environmental implications of deploying small scale cogeneration systems which they propose as one of the option for introduction of more efficient technologies into the energy sector for achieving the 2020 renewable and emission targets set by the EU. One of the advantages of small scale cogeneration systems for power generation, according to them (Roselli, et al., 2011), is the avoidance of network loses experienced with large centralised power stations.

They reported that a variety of small single family to medium commercial units driven by reciprocating internal combustion engines and capable of supplying between 1.0 – 10kW electric power and 2.0 – 26kW thermal power are available in the market and are being deployed while the sterling engine prime mover types are yet to be developed commercially. They compared a number of sample systems with conventional gas-fired boiler system supplying heat and power plant system that supplies electricity. They found and concluded that net primary energy savings and CO^2 reductions were possible with reciprocating internal combustion engine based micro-cogeneration systems.

In the same vein, Peacock & Newborough (2005) investigated practical application of different prime-mover specification and control strategy for Stirling engine and Fuel cell based CHP for annual energy and CO_2 emission estimation for single dwellings in the UK by employing detailed minute by minute electricity and gas consumption data for a period of 1 year. In their study, they analysed contributions to thermal and electrical demand of test residential apartments met by Stirling engine micro-CHP and Fuel cell micro-CHP, as well as electrical export to the grid, employing different control strategies - unrestricted thermal surplus, restricted thermal surplus, restricted thermal surplus but part-load and unrestricted thermal surplus. They found that running the system under restricted thermal surplus strategy produced the best results - CO_2 reduction above 2.5kg/day in winter and between £90 and £99 total savings. Unrestricted thermal surplus strategy produces more heat than can be stored by the conventional thermal store available in the test residents leading to a smaller total savings, £52, and even more CO_2 emissions than non-CHP base case. While running under restricted thermal surplus but part load strategy reduces amount of thermal surplus (and wastages) produced, it also reduces the proportion of electrical and heating demand met by system and amount exported to the grid. But it increases number of switching events, which affects durability of system negatively. Total savings in the case was £90. Running under restricted thermal surplus strategy (full load), however, supplied a significant proportion of both thermal and electrical demand, with high electrical export but higher surplus thermal energy, especially during summer, and gave a total savings of £99.

They concluded from their findings that thermal requirements of the dwellings were better matched by applying the restricted thermal surplus but part load strategy, however, CO_2 reduction is smaller than that obtained with the restricted thermal surplus (full load) case.

An implication of this would be that storage of the excess thermal energy produced, for example during summer, to offset thermal deficit at other periods could improve upon total savings and CO_2 emissions.

2.3 Energy Storage and Phase Change Materials

The possibility of energy savings from storing exsess energy was investigated by Heim & Clarke (2004) who developed a phase change materials (PCMs) model and incorporated into ESP-r by adding effect of phase change transition to the energy balance equations. Employing special materials concept used in ESP-r to model active building elements, they introduced thermo-physical properties of the Gypsum PCM as special material properties used for the modelling. This allows homogeneous treatment of the properties which vary with temperature.

They conducted numerical simulations for a multi-zone passive solar building with high glazing and natural ventilation, and employed PCM impregnated gypsum plaster board for internal room lining. They compared with a similar building model but without PCM impregnated plaster board walls. Analysis of results reveals that incorporation of PCM resulted in effective reduction of heating energy demand during the heating period/seasons. They concluded that the relatively small difference in resultant room temperatures was due to the small latent heat of the PCM and thinness of the walls. The findings however showed the potential of PCM to impart and stabilize internal temperatures and to store energy for use later during the heating season and reduce heating energy demands.

In a report by Halford & Boehm (2007) studies on a strategy to shift air conditioning load away from peak period using encapsulated PCM installed within wall (or ceiling) insulation was described.

They developed a model in which the phase change temperature and latent heat are treated as parametric properties. They modelled the ceilings and walls as three-layer plane wall with the PCM sandwiched between two insulations. Independent variation to the thickness of each layer is possible to enable creation of different configurations.

Two different baseline conditions were established for comparisons with case with PCM impregnated walls to permit identification of the various components of PCM load shifts: ‘mass but no phase change’ and ‘insulation only’.

Their findings show maximum peak load reduction of between 11% and 25% for comparison with ‘mass but no phase change’ case and between 19% and 57% load reduction for comparison with ‘insulation only’ case. Their results also show that changes in mean ambient temperature imparts the optimal position of the phase transition layer relative to the inside wall, suggesting a relationship between performance and off-peak re-solidification of PCM.

Also, Izquierdo-Barrientos et al (2012) conducted a study on effect of embeding PCM in external walls of building with the use of a one-dimensional transient heat transfer model.

Three scenarios/configurations were considered due to the effect of the PCM on wall thermal behaviour, with, (1) PCM placed interior to the insulator, (2) exterior to insulator and the third has the insulator replaced by PCM. Because the PCM layer added resistance to heat flow and to be able to make proper comparisons, a base case model with an additional layer whose properties are similar to that of the PCM layer in a solid state was introduced.

Employing different wall configurations wherein the location of PCM within wall is varied as well as phase transition temperatures, and also varying wall orientation, they ran numerical simulations, using finite difference technique, for two different time periods covering 6 winter and 6 summer days.

They observed that there was no significant effect on heat losses during the winter simulation periods for all the various conditions but large differences were observed during the summer periods. This they attributed to high radiant fluxes during summer. They also observed that inclusion of PCM in the external walls further increased the thermal inertia of the walls, which led to increased thermal load during the day and reduced load during the night.

They concluded finally that although total heat gained or lost was not significantly affected, proper selection of PCM is capable of reducing maximum amplitude of instantaneous heat fluxes in and out of buildings and thereby reduce energy requirements for HVAC systems. Their work demonstrates the ability of phase change materials to act as heat resistors and entrapment, enhancing building ability to maintain steady internal temperature conditions.

Turnpenny et al (2000 and 2001) in two different reports described the design, construction and testing of a cooling system that incorporates heat pipes embedded into a phase change material (PCM). They employed one dimensional mathematical heat transfer model for sizing the units.

An average sized room in an existing building with a large south-facing window that receives considerable solar gains in the summer was used for the experiment. They reported that the room had to be partitioned to bring the size down to 16 m^2 of floor area. Heat pipes with longitudinal fins along one end and inserted (the finned end) into PCM to make single units were arranged in a circle and mounted close to the ceiling below a ceiling fan located at the centre of the experimental study room The fan blows air downwards over the heat pipes. Extractor fans draw cool air during the night, guided through the room and over the heat pipes to remove heat absorbed by PCM during the day.

Result analysis reveal heat transfer rates of between 80 and 200 W per unit, sufficient to absorb solar heat gains and prevent room temperature from rising to uncomfortable levels. They did a comparison of their results with previous works on alternative cooling systems and conventional air conditioning system and concluded that a latent heat storage system offers better benefits in terms of reducing cost and CO_2 emissions.

The effect of integrating thermal energy storage device into a domestic space heating system employing a solar heater assisted heat pump by a using two non-linear partial differential equations, one for material storage temperature and the other for the heat transfer fluid, for its modelling was similarly evaluated by Badescu (2003).

Thermal energy storage system was employed for storing heat from the solar heater, which is subsequently delivered to the evaporator of a vapour compression heat pump.

They reported that heat supply to the heat pump evaporator was rapid for thermal energy storage (TES) with smaller mass (quantity).This, they reported, was due to rapid increase in temperature as a result of heat saturation of the small amount of storage material. They conclude that this was a disadvantage with the use of small amount of material for large quantities of heat, because ‘the amount of stored energy is smaller than for more massive units’ (Badescu, 2003).

In a study by Muruganantham et al (2010), impact of a new class of organic based phase change material, BioPCM, manufactured by Phase Change Energy Solutions (PCES) Incorporated, on energy consumption, peak load shifting and energy savings was evaluated. They constructed two similar sheds with one having the BioPCM embedded in the walls, ceiling and floor and tested, over a year, in Phoenix Arizona. Both sheds had total thermal resistance of $13.49^{o}C/W$ (with PCM) and $13.33^{o}C/W$ (without PCM). They commented that a thermal resistance difference of 1% was not sufficient enough to interfere with or affect results and findings.

Results show differences in energy consumption between 9% and 29.25%, with the largest difference, 29.25% occurring in November, as well as shifts in peak power consumption. This occurred only in the summer months, with maximum of 60 minutes occurring in June. They attributed the lack of shift of peak load in the other (season) months to insufficient time for PCM to change phase as a result of short sunlight hours. They reported that this was also responsible for energy savings, especially in winter. The incomplete melting and solidification of the PCM allowed it exhibit its highest thermal capacity, implying that it was able to prevent and reduce heat from flow across it from and to the interior. Heat stored was also available for the evening and night periods. They also reported a cost saving of 30%.

Similar to the findings of Izquierdo-Barrientos et al (2012), these results show capability of PCMs to trap heat and enhance building ability to maitain steady internal temperatures. It also shows clearly, possibility of energy and cost savings by proper control strategy.

2.4 Energy Demand/Load shifting and Control

Hong, et al., (2012) assessed the possibilities of manipulation start and stop times for a heat pump for better electricity network management. Using ESP-r to model two types of buildings with each having two variants of thermal fabrics representing present UK housing standard and passive house standards, both heated by air source heat pumps, they ran simulations, altering the start times of the heat pumps, adjusting zones and hot water temperature set points and adding two types of thermal buffering.

Result analysis reveals, for the current building standard fabric, advance times of between 1.5 and 2.5hrs for both before zone resultant and hot water temperatures dropped below 18 and 40^{o}C respectively. They reported that the buffering did little to increase advancement time. Maximum obtained was 2.5hrs, and this resulted in increasing heat pump energy consumption by 37%. There was little improvement in advance time for the passive house standard fabric simulation but a significant reduction in energy consumption of about 76%.

They observed that increasing zone and hot water temperatures also did not improve on advance time; rather it increased energy consumption by between 30 and 70%, the latter being for the passive house standard fabric.

They reported a maximum advance time of 6 hours after introducing additional/supplemental heating to boost hot water temperatures to 60^{o}C. This resulted in an energy increase of 70%.

They concluded that to obtain an operating time/period shift sufficient to effect a flattening of peak electricity consumption would only be possible with improved thermal insulation and buffering.

They observed that CO_2 emission reductions and primary energy savings due to micro-CHP deployment depended on reduction in total electricity consumption and hence on proportion met by micro-CHP and that imported from the grid. They concluded that these are better achieved by operating the systems to satisfy heating demands.

Similarly, Boait et al (2011) conducted a study to investigate how appropriate control regimes can improve performance and coefficient of performance of heat pumps as well as increase energy savings in dwellings. They modelled a building and heat pump combined and validated with a number of pre 1980 houses in Harrogate Borough council, Yorkshire.

The houses, they reported, have been upgraded with cavity-wall insulation, double-glazing and additional loft insulation fitted with ground source heat pumps used for space and water heating. They also reported that all the heat pumps run continuously, being a manufacturer's recommendation. This, they concluded, allows opportunities for energy savings to be missed and suggested a need for a control system capable of determining suitable setback periods and implementing it, as well as possible implementation procedures.

2.5 Heat Pump Heating Systems

Employing procedure set out in directive 2007/742/EC of the European Parliament, Fernández-Seara et al (2012) did an evaluation of system and main components performance of a ground source heat pump investigated by using a water-glycol heater as ground source for the evaporator and a condensing section cooling water loop for demand.

The condensing section consisted of two series connected heat exchangers, one serving to cool refrigerant from superheat temperature to condensing temperature (the 'desuperheater') and connected to the hot water storage tank and the other serving as condenser and linked to the water loop for space heating. Water and water-glycol flow were controlled by pumps and mass flow recirculation loops while a 3-way electronic valve regulates "desuperheater" water flow.

Results show impact of evaporator temperature as well as condenser temperature on performance and compressor power consumption, COP rising with evaporator temperature but dropping or reducing with condenser temperature. Power consumption also increased with both evaporator and condenser temperatures. Temperature increase from 0 -15^{o}C for evaporator produced 8% increase in power consumption while cooling water (condenser) temperature increase form 25 – 45^{o}C caused an increase of 35% in power consumption.

The findings of their research shows the significance of an important factor for performance and preference for ground source heat pumps over air source heat pumps, especially for cold temperate regions such as the UK. It also shows a likely disadvantage in use of heat pumps for high temperature heating, being more effective at low condensing temperatures.

3 Methodology

3.1 Model Description

The investigation was carried out using ESP-r software, a building energy modelling tool for dynamic internal environment modelling and simulation to model a detached 2-storey detached building employing air source heat pump water heating system and separated into three zones, living, non-living and loft. The model represents details of building geometry, fabric materials, occupants and equipment heat gains, air leakages and heating system. The heating system, comprising an air source heat pump and domestic hot water storage tank, which has provision for inclusion of phase change materials, are treated as components and represented by networks. A stratified tank model is employed for the domestic hot water storage tank.

The modelled building is an average insulation building with total floor area of 139.9m^2. It is a 2-storey detached building divided into three zones representative of the living room and dining, the living zone, the bedrooms, kitchen and toilets, the non-living zone, and the loft designated as loft in the model. It is heated by an air source heat pump that provides space and water heating.

The living and non-living zones have an overall areas of 33.9m^2 and 106m^2 respectively. Power rating for the air source heat pump is 8kW. It has a base power consumption of 10W and operates between 65^{o}C and 90^{o}C, heat in and heat out temperatures respectively. Its operation is controlled by time actuator according to on/off time settings and temperature actuator set to cycle on when water temperature reaches 50^{o}C and cycle off when it reaches 55^{o}C. Volume of domestic hot water tank is 0.144 m^3.

Heat is removed from heat pump through a primary/main heat exchanger with water as coolant. This is channelled to wall mounted plate heat exchangers, radiators, to supply space heating for the zones. It branches off to an immersion heat exchanger inside the hot water storage tank before reaching the radiators for domestic water heating (figure B2). Flow is controlled by two circulation pumps, one to remove water from heat pump heat exchanger and the other, on the branch off to storage tank, to circulate water through the tank.

Water return from radiators flows to the heat pump heat exchanger joined by return from hot water tank immersion heat exchanger. Two 3-way temperature actuated valves control water flow between flow and return for both storage tank and radiator. The strategy employed is such that domestic hot water is maintained above 40^oC, so heat supply to the domestic hot water storage tank is given priority.

ESP-r allows adjustments and manipulation of zones and plant and systems component, composition and controls of occupied periods, occupant and appliance casual heat gains, system start and stop times, sensor and actuator parameters, as well as capacity of hot water tank and water draw. The control most germane to this project is the on/off start/stop set times times for heat pump for manipulation of both running time/period and duration, and amount of phase change material included in the domestic hot water storage tank to investigate effect of phase change heat storage on domestic hot water supply and cost of providing energy for the purpose. Occupied period set for the simulation is between 8:00 am and 11:00pm (8.00 – 23.00)

UK weather data for 1994 was used for the simulations.

3.2 Experimental Procedure

The heat pump on/off set time controls for the base case model, without PCM, were adjusted to reduce the running/operation time while keeping start time one hour before beginning of occupied period and predominantly in the peak period (with one hour off peak at beginning) for series of simulations to obtain minimum run time/duration before hot water temperature drops below 40^oC for a time duration not greater than 15% of total occupied period and for which it does not drop below 38^oC for longer than 10% within the 15% of total occupied period.

15% of occupied period was chosen because it was assumed that this would amount to 2.25 hrs (2 hr 15 min) (15% of 15 hrs of occupied period, 8am – 11pm) during which the temperature drop is assumed to be almost unnoticeable, if the difference is not more than 2K, which is the reason for 38^{o}C as the bottom margin temperature.

A further criteria is set for minimum run time/duration for which temperature drop 40^{o}C occurs close to the end of occupied period, 7pm – 11pm (19.00 – 23.00), which is when hot water consumption rates for most dwellings is expected to decrease, progressively, toward the end of occupied period (Energy Saving Trust, 2008).

Simulations were repeated for the minimum run time/duration obtained above but back-shifted away from peak electricity demand period into off peak period. This was to identify maximum back-shifting time possible before hot water temperature drops below 40^{o}C, applying the criteria set above.

This minimum run/operation time/duration is used as determinant for the likely minimum energy consumption and cost of providing sufficient heating for domestic hot water and set as maximum for testing with inclusion of phase change material.

Using the minimum on/off set time/duration obtained in the procedures above as maximum, further simulations were run for base case model but with phase change material incorporated into the domestic hot water storage tank in a series of two-step procedures. First, on/off set time duration was reduced during the peak period by 2hr while maintaining the ‘on’ or start set time for the initial base case and shifting the ‘off’ or stop set time backwards by 2 hours. Second, the initial ‘off’ or stop set time is restored and the ‘on’ or start time is shifted backwards by 2hours. A 2 hr gap is used because difference is significantly small to be noticed over 1 hour gap.

The twin procedure is repeated for series of reducing on/off set time durations. In so doing, a fixed, progressively reducing, on/off set time duration is moved or shifted backwards and forward until entire heat pump operation was reduced to 3hrs and in the off peak electricity demand period only. Simulations were done for a week in January for winter, being the coldest season of the year.

The procedures above were carried out for inclusion of phase change materials into the domestic hot water tank to make up 12.5%, 25% and 37.5% of its volume. Only whole units PCM can be utilised because it is encapsulated. Unit volume is 0.003m^3, while diameter and length are 0.088m and 0.4932m respectively.6 units therefore make up 12.5% of volume of domestic hot water storage tank, 12 units, 25% and 18 units 37.5%. Also, since the PCM models are set to occupy the upper part of the tank 18 units seem the highest that can be incorporated into the tank to avoid the risk of having too little water in the upper part of the tank. The phase change temperature is set at 41.5^{o}C.

The results are analysed for effect on hot water temperatures, actual heat pump operating time and energy consumption, and cost estimate for running system to provide heating.

The result analysis did not focus much attention on zone temperatures because of the difficulty of keeping them up even for 15 hour run/operation time/duration for heat pump. This is due primarily to the sample accommodation being of average insulation. Heat loss through building fabric is relatively high, so attention was focused on domestic hot water.

Cost of electricity for powering heat pump was determined from minute by minute real power consumption taken over the entire simulation week and averaged to obtain average daily cost. Average peak and off peak energy rates for economy 7 electricity tariffs, obtained from EDF Energy (2010), that is 11.57p/kWh and 4.86p/kWh respectively, are utilised in the equations below:

$$Energy\ cost\ per\ minute\ (peak) R_{m1} = \frac{P_1}{60} \times E$$

$$Energy\ cost\ per\ minute\ (off\ peak) R_{m2} = \frac{P_2}{60} \times E$$

$$Ave\ consumption\ per\ minute, R_m = \frac{\sum R_{m1} + \sum R_{m2}}{D_{tn}}$$

$$Energy\ consumption\ per\ day\ R = \frac{R_m \times 60 \times 24}{1000}$$

P_1= peak energy cost (p/kWh)

P_2= off peak energy cost (p/kWh)

E= minute energy consumption (kW/min)

R_{m1}= peak energy cost per minute (p/min)

R_{m1}= off peak energy cost per minute (p/min)

R_m= average energy cost per minute (p/min)

R= energy cost per day (p/day)

D_{tn}= total data over simulation period

Actual operating time and energy consumption for heat pump were obtained from the simulation plant results and averaged over the simulation week/period.

While running simulations for these specific on/off set times: 1-8, 1-10, 3-10 and 5-8 all for 12.5%PCM, and 3-10 for 37.5% PCM ESP-r encountered some errors and problem with the model which made results obtained for them unreliable They have been excluded from the result analysis and are the blanks in the results table of appendix A and gaps in some of the result charts.

It is believed that the results and data obtained from simulations of other on/off set times are sufficient enough to make valid conclusions without these erroneous results.

4 Result Analysis and Discussion

4.1 Base case

Simulations for the base case model (without PCM) with reducing on/off set time duration obtained a 7 hours reduction possibility (figure 1). Hot water temperature remained above 40^{o}C for approximately 85% of the entire occupied period, averaged over the week-long simulation period, and below 40^{o}C for exactly 14.53%. It also remained above 38^{o}C for 8.44% of period. Figure 4.1 shows the hot water temperature profile for the 7 hour reduced operating period (7 – 16).

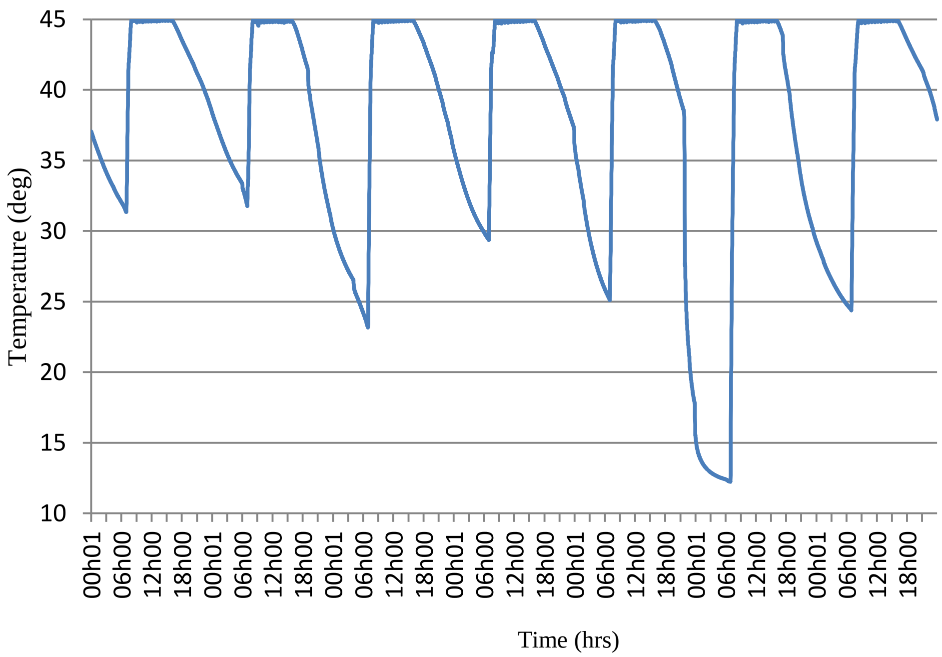

Fig. 4.1 - DHW temp profile over simulation period for on/off set time 7 - 16 (no PCM)

The gully in day 6 of hot water temperature profile for simulation week (fig 4.1 above) is due to high hot water draw in the middle of the night (between 12am and1am) when heat pump was off and there was no heating (fig 4.2). This is significant because it is a determinant, throughout the exercise, of the percentage of occupied period that the hot water temperature would fall below 40°C.

This on/off set time (7 – 16) gives total on/off set time duration of 9 hours for the heat pump. Actual operating time is 38.45 hours for the entire simulation week and 5.49 hrs as daily average operating time. This yields 144.2 pence as average daily cost of energy (144.2 p/day or £1.44/day).

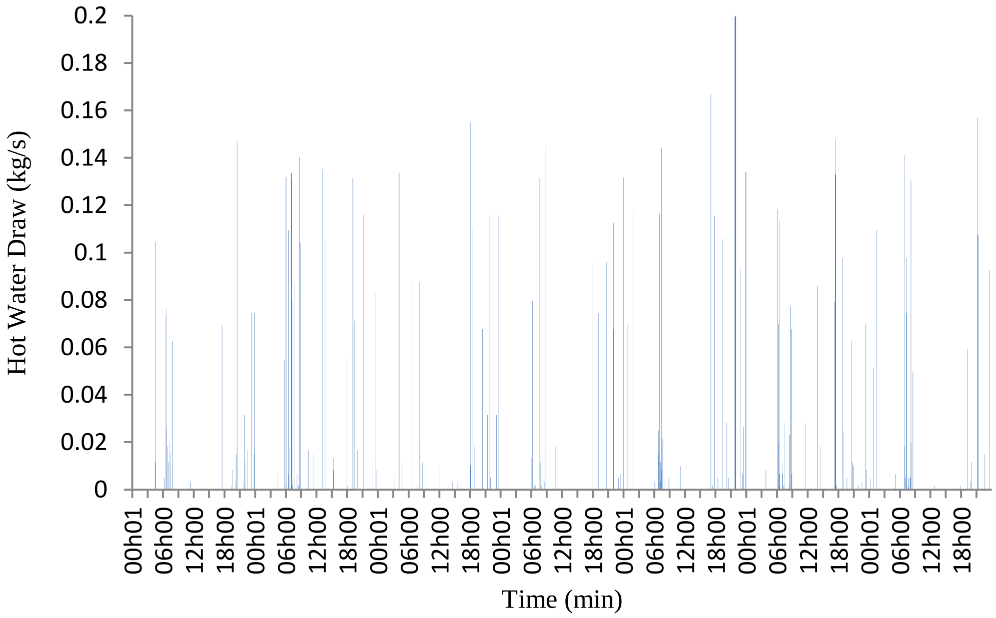

Fig. 4.2 - Profile for DHW Draw for on/off set time 7 - 16 (no PCM)

4.2 Effect of Reducing on/off set time Duration

Reducing the on/off time 7am to 4pm (7 – 16) by two hour intervals with 7am remaining as the ‘on’ or start time, that is, 7 – 14, 7 – 12 and 7 – 10, for durations of 9, 7, 5 and 3 hours, respectively, produced the hot water temperature profiles shown in figures 4.3 – 4.5.

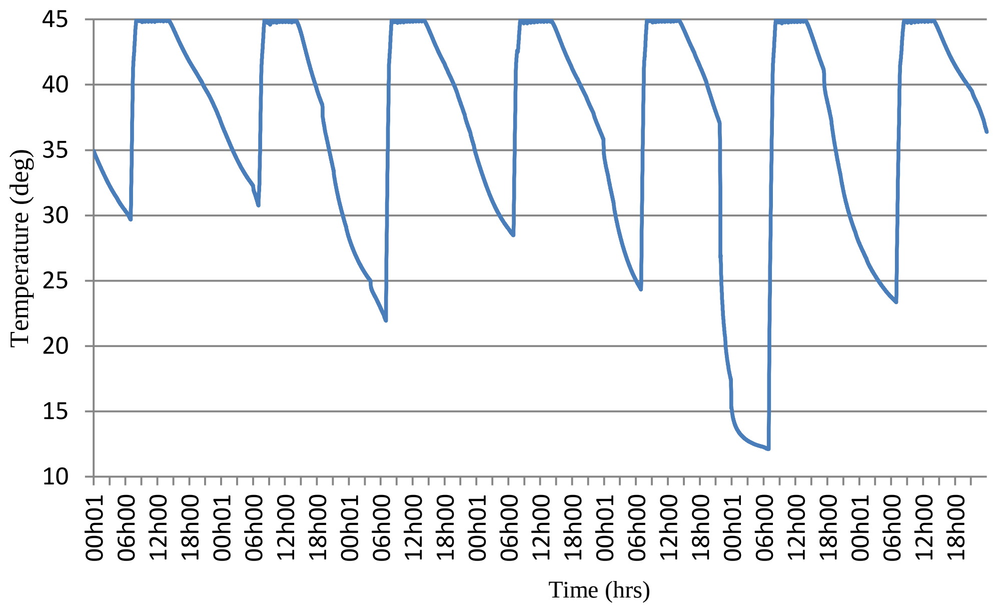

Fig. 4.3 DHW temp profile over simulation period for oon/off set time 7 - 14 (no PCM)

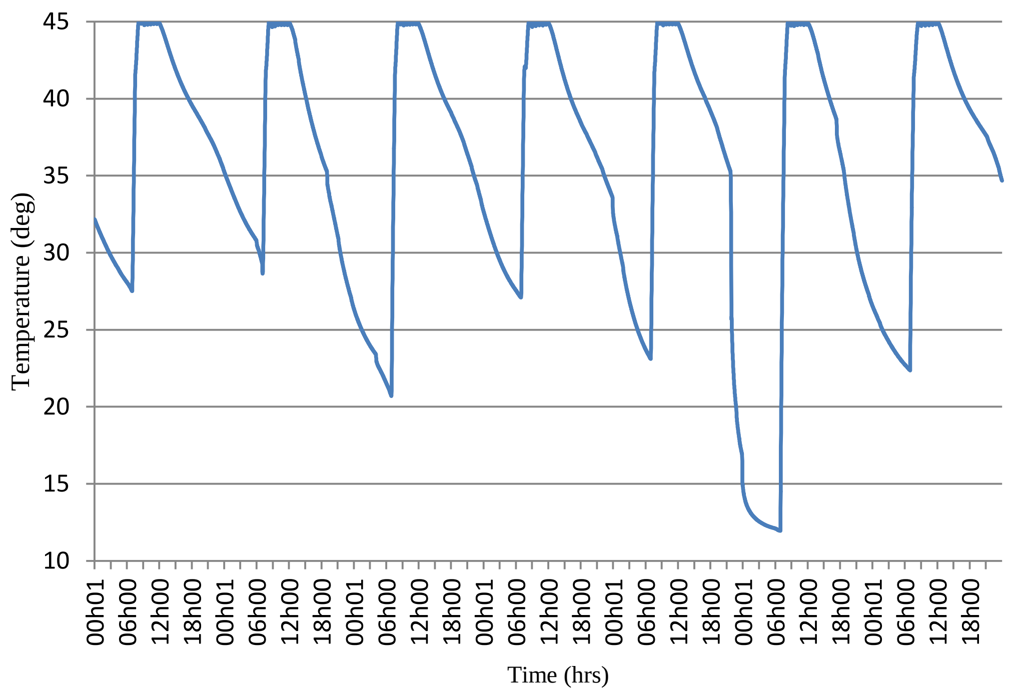

Fig 4.4 DHW temp profile over simulation period for on/off set time 7 - 12 (no PCM)

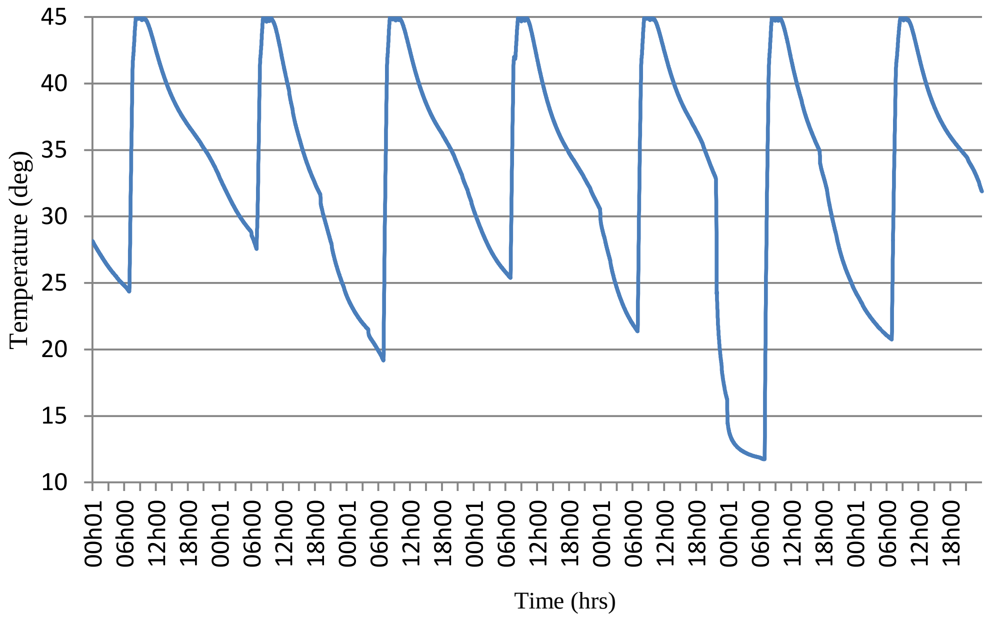

Fig 4.5 DHW temp profile over simulation period for on/off set time 7 - 10 (No PCM)

The effects of these on percentage of occupied period that hot water temperature falls below 40^{o}C and on actual operating time for heat pump are shown in figures 4.6 and 4.7. As expected, percentage of occupied period that hot water temperature dropped below 40^{o}C increased from 14.52% for initial case (7 – 16) to 24.92% for on/off set time 7 – 14, 43.16% for on/off set time 7 – 12 and 63.91 for on/off set time 7 – 10 while average heat pump daily operating time reduced from 5.49hrs for on/off set time 7 – 16 to 4.45hrs for on/off set time 7 – 14, 3.45hrs for on/off set time 7 – 12 and 2.33hrs for on/off set time 7 - 10.

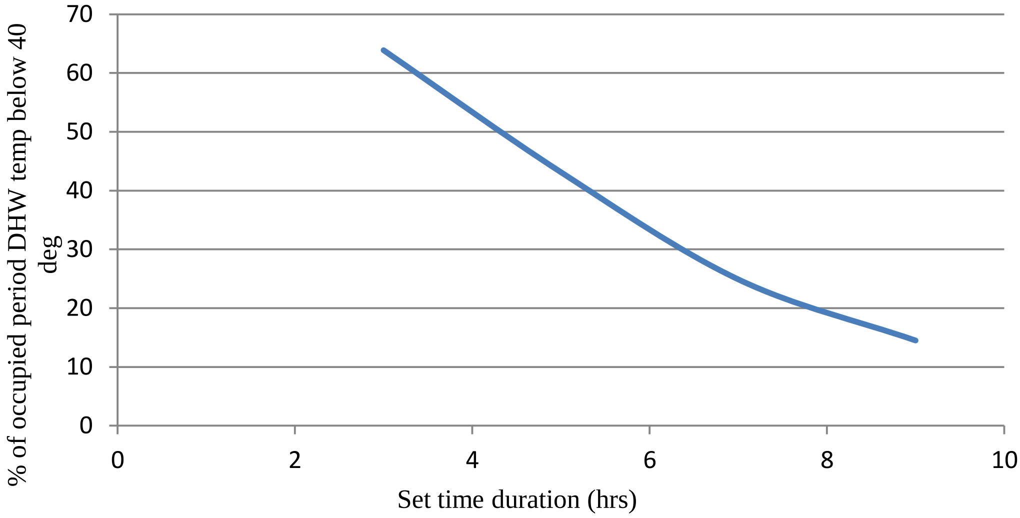

Fig 4.6 Effect of reducing set time duration (start time at 7am) on % of occupied period hot water temp < 40 deg

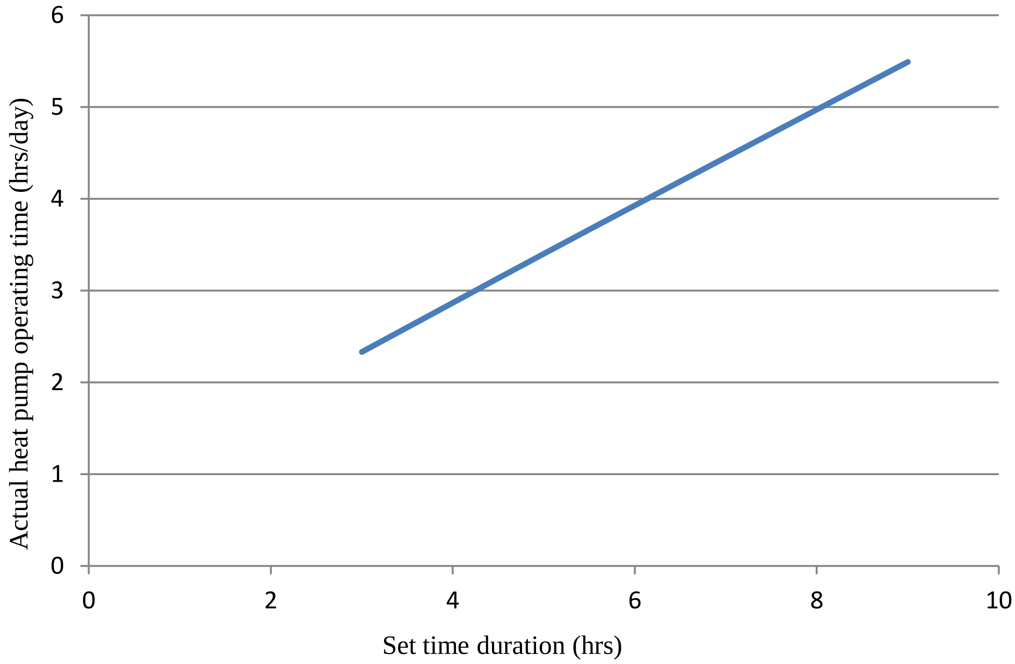

Fig 4.7 Effect of reducing operation set time on actual daiily operating time for heat pump

4.3 Effect of Back Shifting (no PCM)

The minimum set time duration of 9 hours was back shifted by 2-hour intervals away from peak period into the off-peak period (note that initial on/off set time used as base contained one hour of off-peak operation). The on/off set times are 5 – 14, 3 – 12 and 1 – 10. The domestic hot water temperature profile for each on/off set time and effect on percentage of occupied period that hot water temperature dropped below 40^{o}C and on actual operating time for heat pump and are shown in figures 4.8 – 4.12.

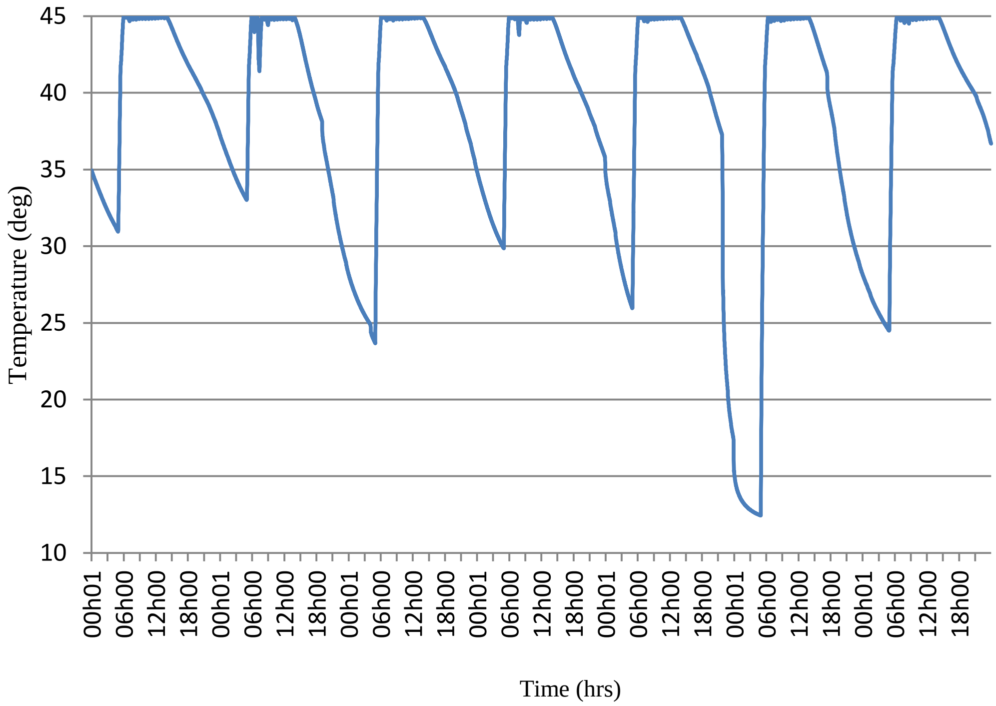

Fig. 4.8 DHW temp profile over simulation period for on/off set time 5 - 14 (no PCM)

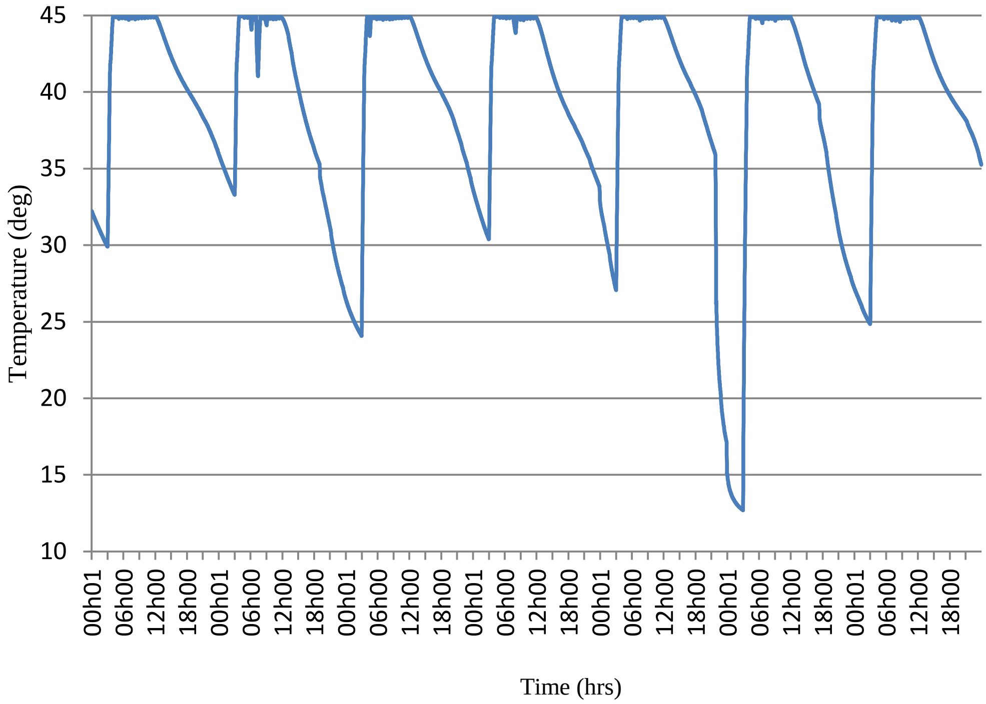

Fig 4.9 DHW temp profile over simulation period -on/off set time 3 - 12 (no PCM)

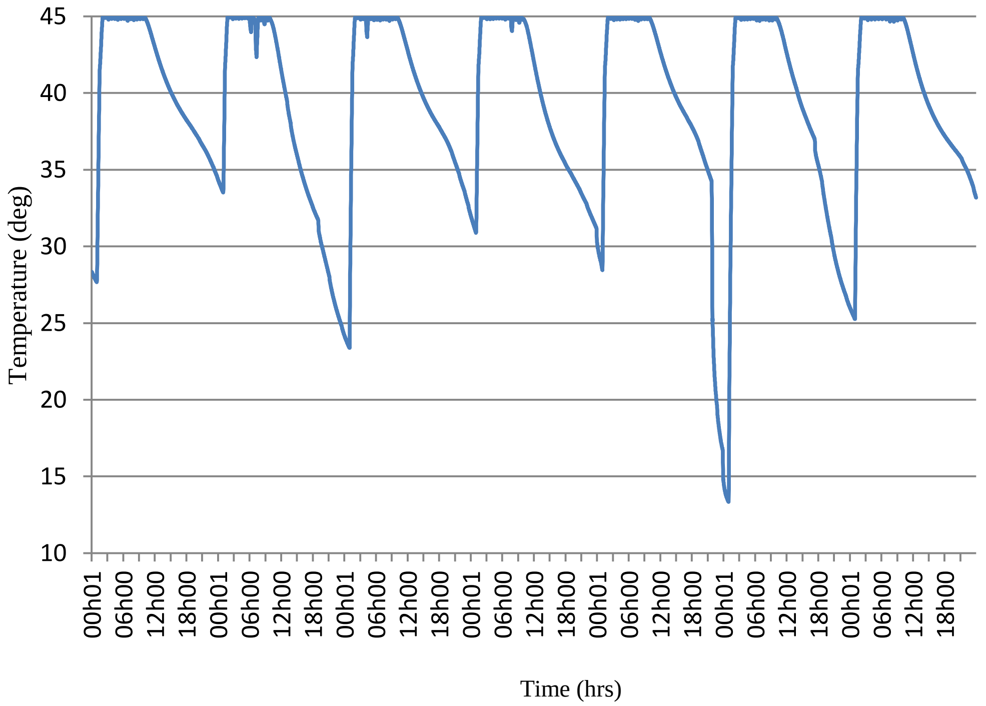

Fig 4.10 DHW temp profile over simulation period - on/off set time 1 - 10 (no PCM)

It is pertinent to note that the width of the gully in day 6 of domestic hot water temperature profile for simulation week reduces as set time is shifted backwards from the initial base case and heat pump start time and it draws close to the period of high hot water draw. It is however not able to cause hot water temperature to stay above 40^{o}C longer because stop time, and heat pump off time is equally shifted backwards away from the period of high hot water draw. It appears to have a more negative impact on hot water temperature and actual operating time for the heat pump, as show in figures 4.11 and 4.12.

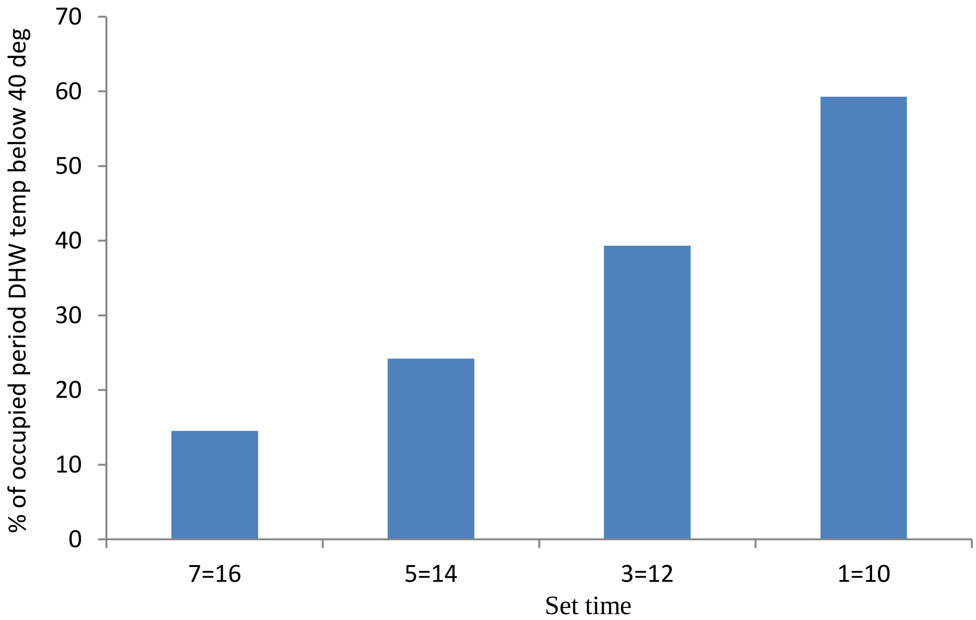

Fig 4.11 Effect of bach shifting set time duration on % of occupied period DHW temp < 40 deg (no PCM)

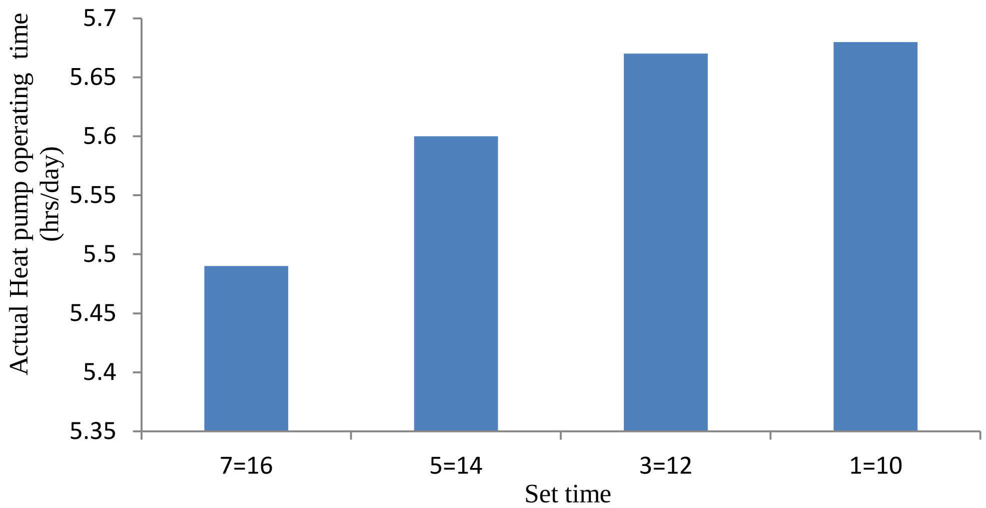

Fig 4.12 Effect of bach shifting set time duration actual heat pump operating time (no PCM)

Percentage of occupied period with hot water temperatures below 40^{o}C increases from 14.52% to 24.22%, 39.35% and 59.29% for on/off set times 7 – 16, 5 – 14, 3 – 12 and 1 – 10 respectively. As shown in figure 4.12, the heat pump is working more, due to its starting earlier in the mornings and into the night when temperatures are still relatively low. The implication being that the system is experiencing more heat loss and energy wastage.

4.4 Effect of Back Shifting with PCM

Back shifting from on/off set time 7 – 16 to 5 – 14 without PCM resulted in hot water temperature dropping below 40^{o}C for 24.22% of occupied period and below 38^{o}C for 14.13%. With this as starting point for test case models, incorporating phase change materials, a comparison is made with the same on/off set times of 5 – 14, 3 – 12 and 1 – 10 with proportion of PCM to DHW tank volume of 12.5%, 25% and 37.5% for each set time. Temperature profiles for the domestic hot water temperature for each of the set times and percentage of PCM are shown in figures 4.13 – 4.20

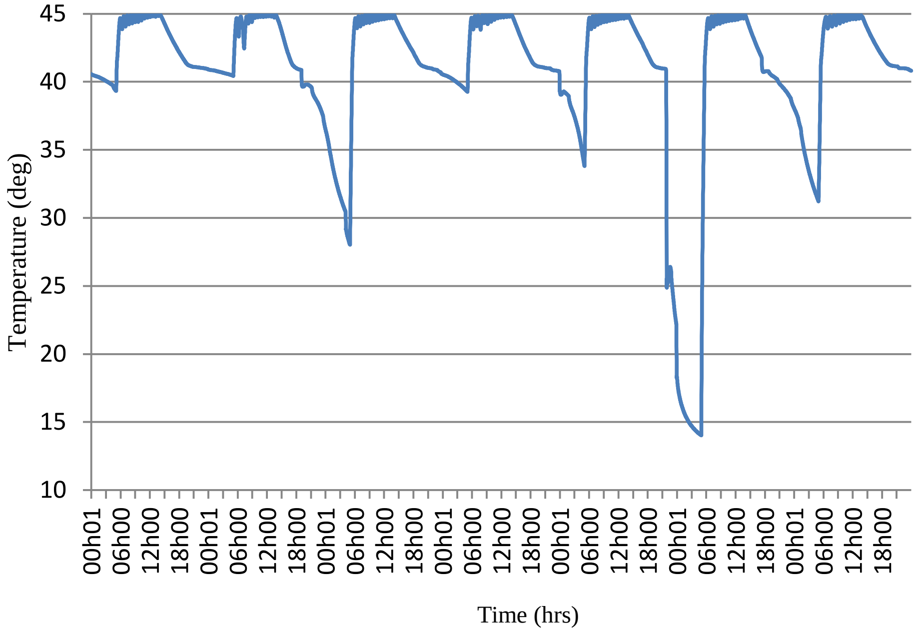

Fig 4.13 DHW temp profile over simulation period (5 - 14 , 12.5% PCM)

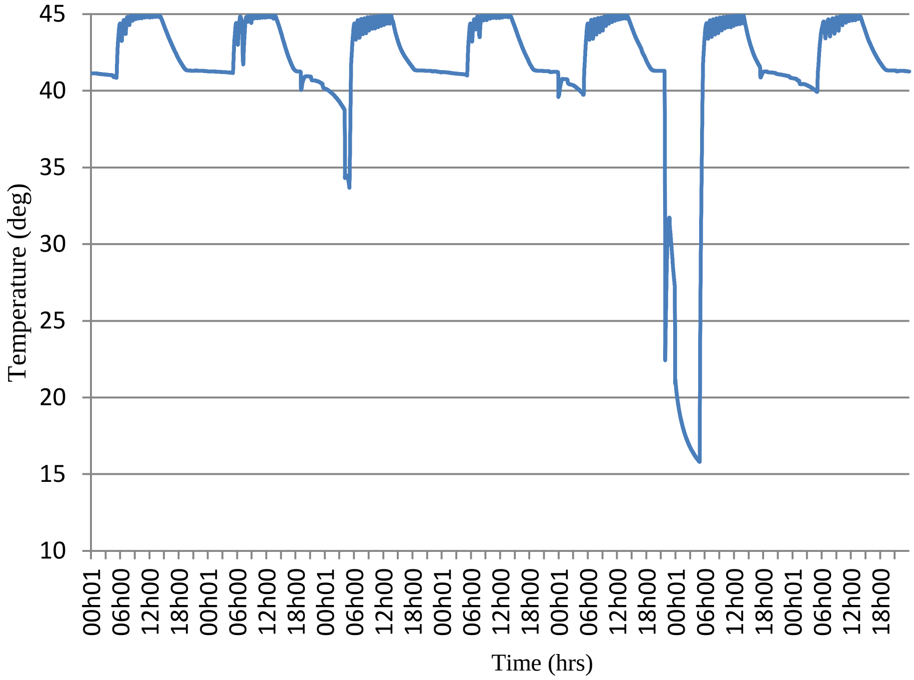

Fig 4.14 DHW and Buffer tank water temp profile over simulation period (5 - 14, 25% PCM)

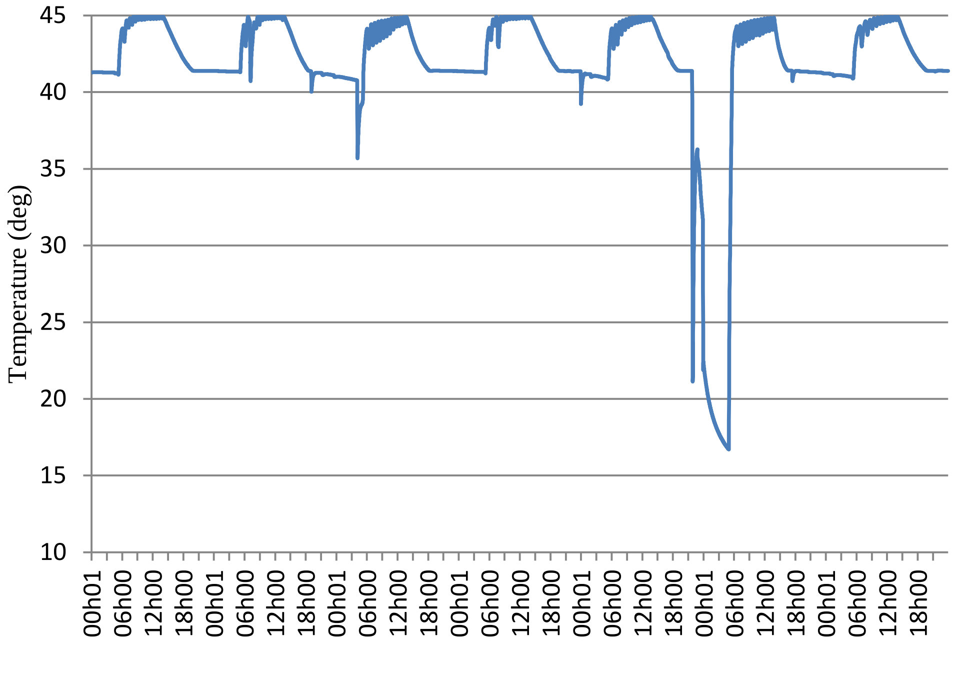

Fig 4.15 DHW tank water temp profile over simulation period (5 - 14, 37.5% PCM)

An obvious and important observation here is the progressive closure of the temperature drop gullies in the hot water temperature profiles present in the no-PCM cases, figures 4.8 – 4.10, present after heat pump switches off, with increasing percentage of PCM (figures 4.13 – 4.20). This is an indication of the effectiveness of phase change material to bridge heat/thermal energy supply gap and maintain hot water temperature above set point for a considerably long length of time and high percentage of the occupied period.

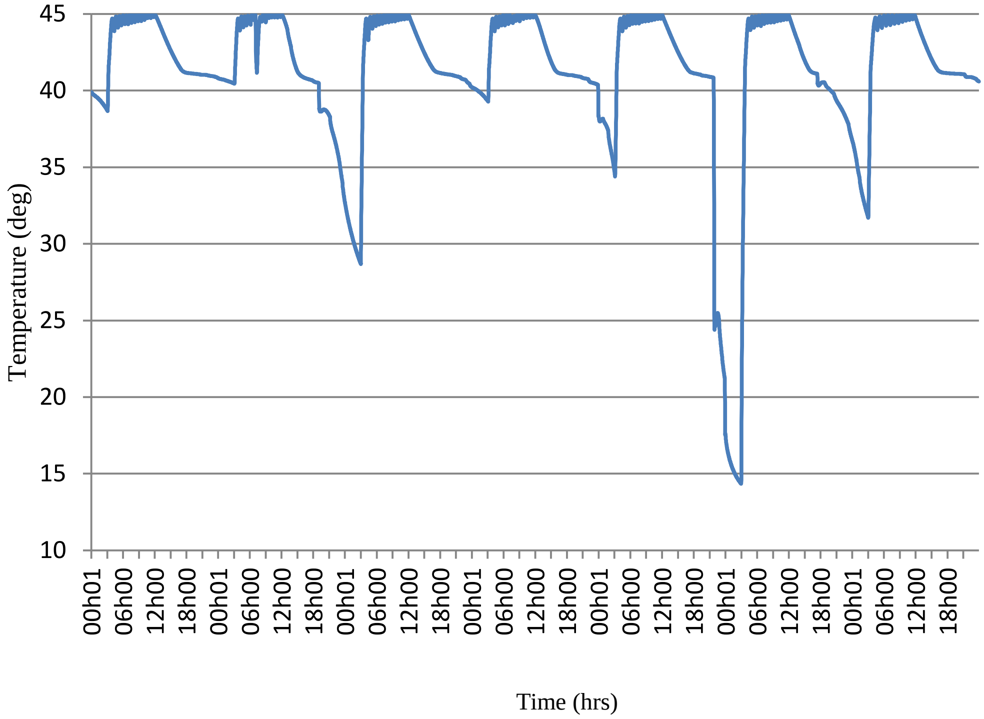

Fig. 4.16 DHW tank water temp profile over simulation period (3 - 12, 12.5% PCM)

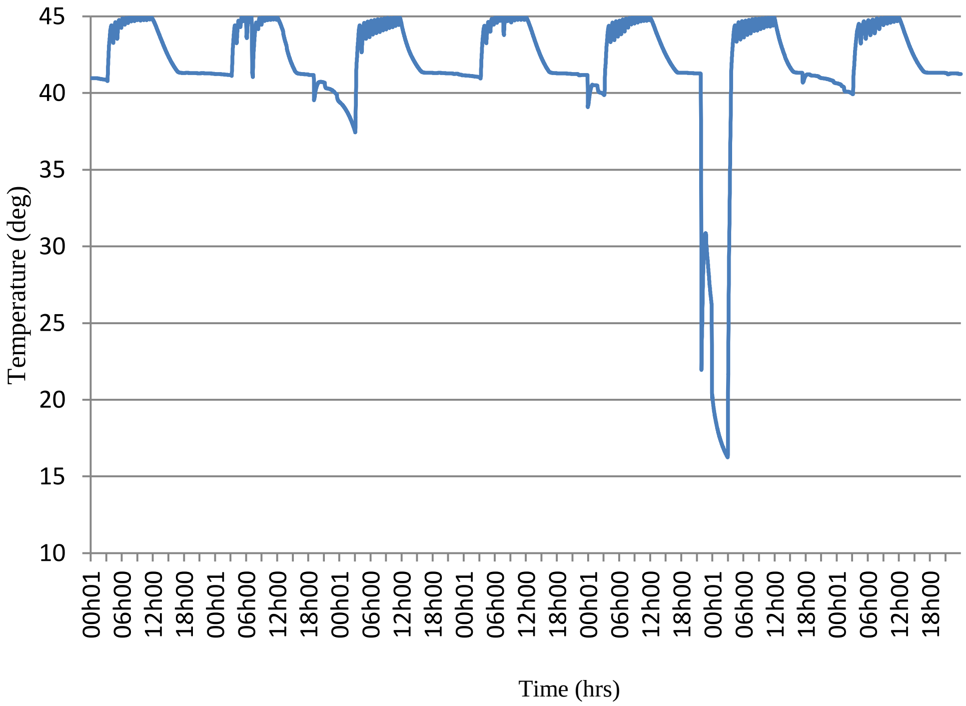

Fig 4.17 DHW tank water temp profile over simulation period (3 - 12, 25% PCM)

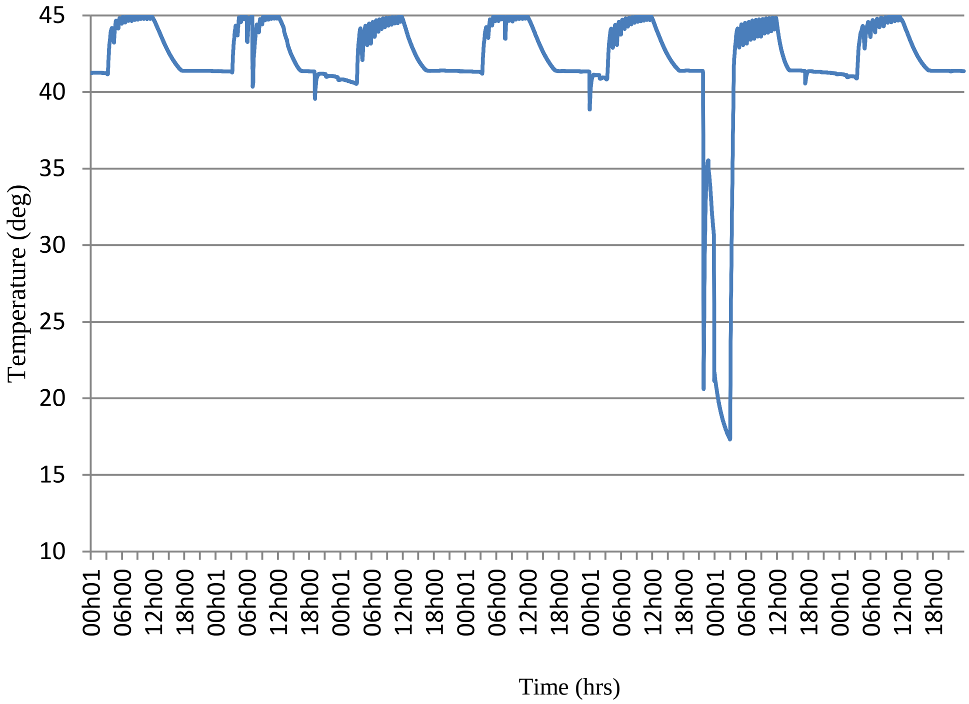

Fig 4.18 DHW tank water temp profile over simulation period (3 - 12, 37.5% OCM)

A similar trend as with the no –PCM base case of gradual reduction of width of the gully in day 6 of hot water temperature profile for simulation week is observable. The reduction in these cases, have a positive effect on percentage of occupied period that hot water remained above 40^{o}C, (figure 4.22). With PCM extending heat availability beyond the off time of heat pump slope of temperature drop is much gentler, almost horizontal, and sufficient to keep hot water temperatures up till heat pump's next 'on' or start time.

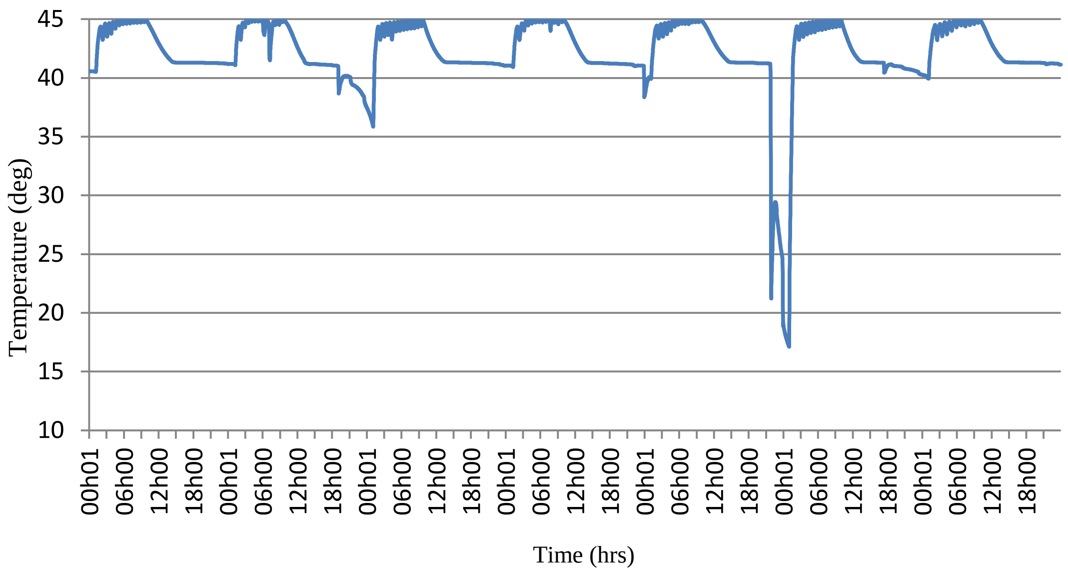

Fig 4.19 DHW tank water temp profile over simulation period (1 - 10, 25% PCM)

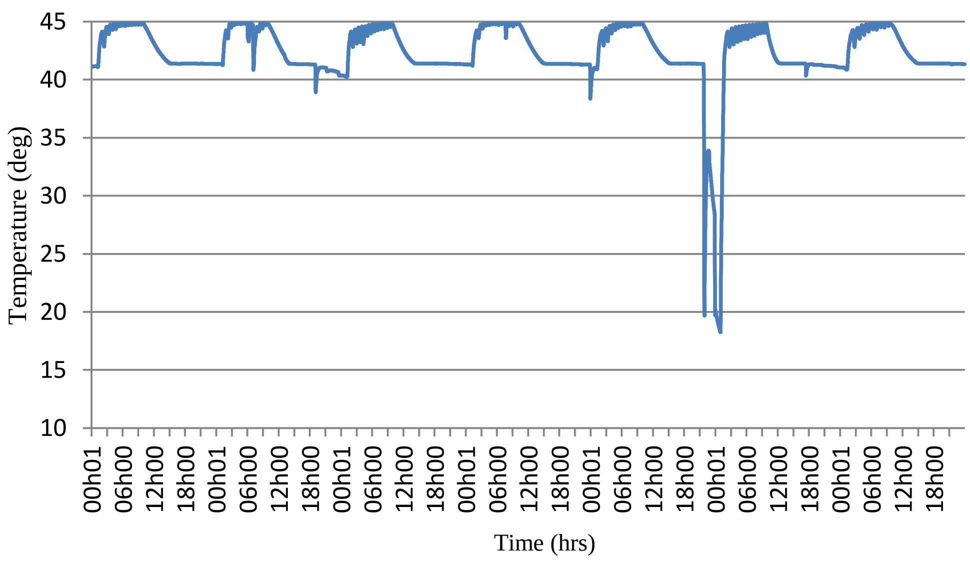

Fig 4.20 DHW tank water temp profile over simulation period (1 - 10, 37.5% PCM)

4.5 Comparison between no-PCM and PCM cases (Back Shifting)

Consequence of back shifting on cost of running heat pump, percentage of occupied period hot water temperature dropped below 40^{o}C, actual operating time for heat pump and average daily heat pump energy consumption is compared for the base cases (no PCM) and test cases with different proportions of PCM in domestic hot water tank in figures 4.21 – 4.24.

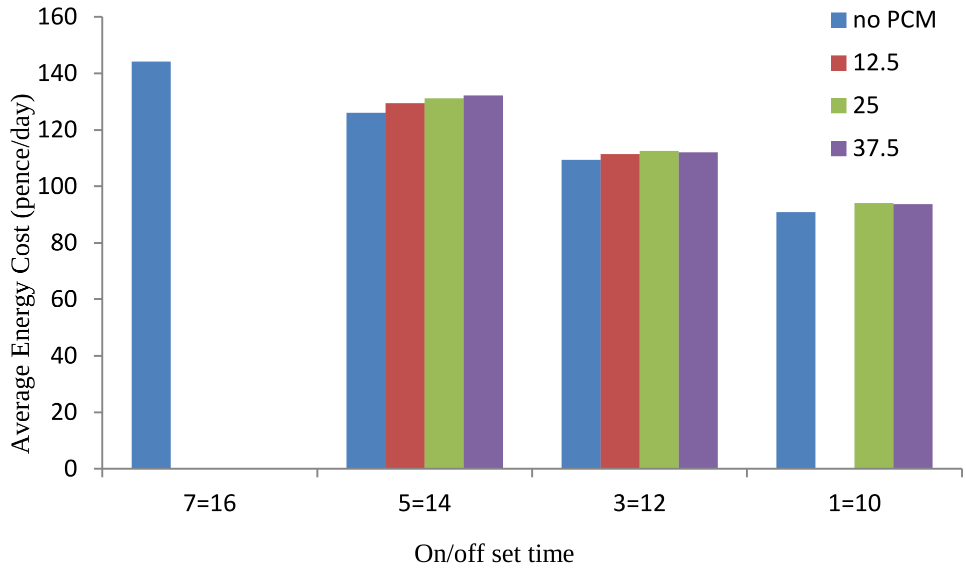

Fig 4.21 Comparison of back shifting effect on energy cost for no-PCM and different percentage of PCM in DHW tank

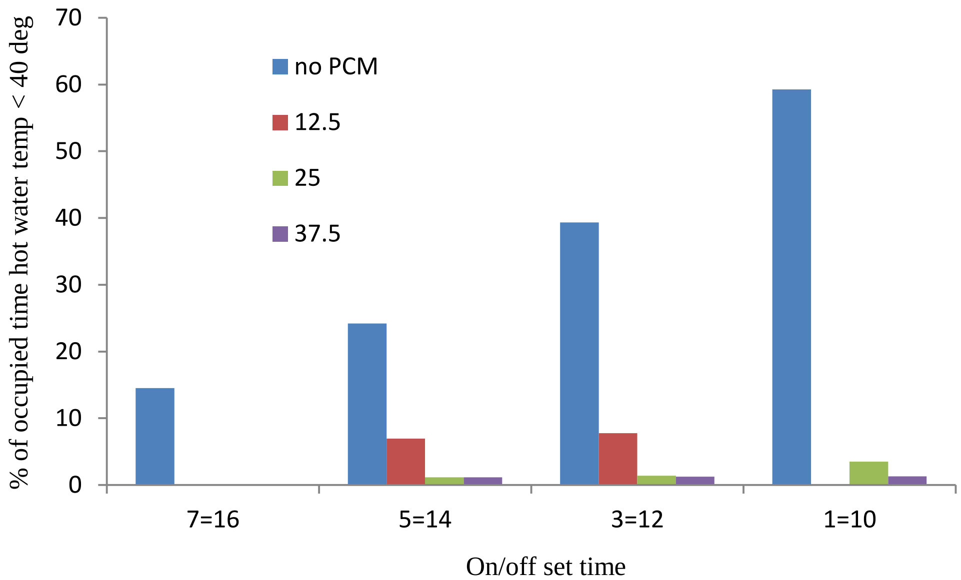

Fig 4.22 Comparison of back shifting effect on % of occupied period water temp < 40 deg for no-PCM and different percentage of PCM in DHW tank

Maximum percentage of occupied period that hot water temperature dropped below 40^{o}C for the test cases (back shifting constant on/off set time duration) with PCM is 7.77%, occurring for on/off set time of 3 – 12, 12.5% PCM. Average energy cost and heat pump energy consumption for this set time are 111.4 pence/day and 14.68kWh/day respectively. Compared with 7 – 16 on/off set time for the base case with no PCM (being the only case with hot water temperature remaining above 40^{o}C for the assumed proportion of occupied period criteria) (144.2pence/day energy cost and 13.95kWh/day energy consumption) gives a cost reduction of 32.8 pence daily average and energy consumption increase of 0.73kWh/day. These amount to a cost savings of 22.75% daily average but energy consumption increase of 5.23%.

Lowest energy cost obtained for on/off set times that meet the set criteria, is 93.65 pence/day for on/off set time of 1 – 10 and 37.5% PCM. Hot water temperature was below 40^{o}C for 1.32% of occupied period and daily average actual operating time and average daily energy consumption for the heat pump are 5.92hrs and 15.04kWh respectively. Average daily energy cost reduced by 35.06% while average energy consumption increased by 7.81%.

The on/off set time, 1 – 10, amounts to heat pump working for 7 hours during off peak energy demand period and only 3 hours during the peak period. Implication of this is that although energy consumption by heat pump increased much of the energy is consumed in the low energy tariff period, indicating possibility of energy cost saving off peak operation though energy consumption rate is higher.

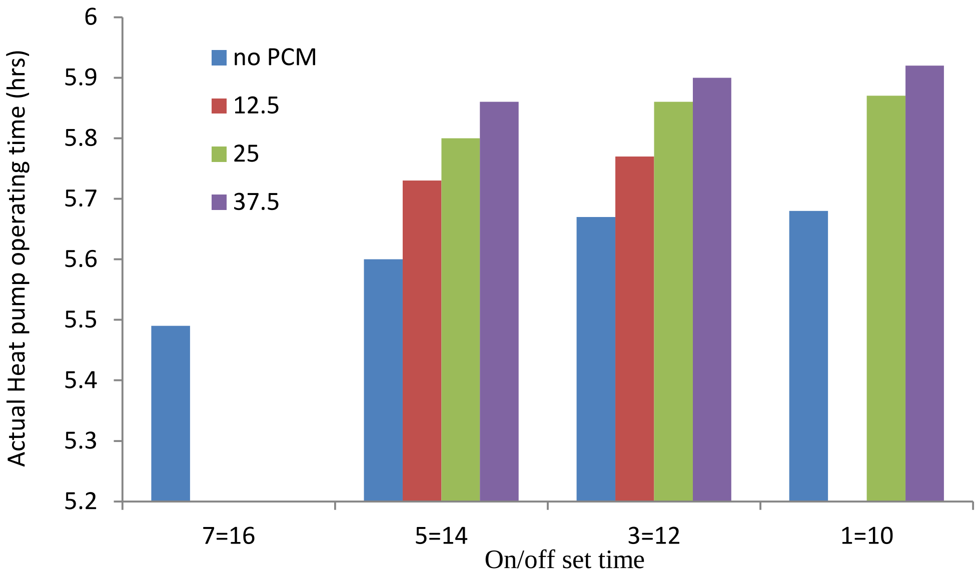

Fig 4.23 Comparison of back shifting effect on actual heat pump operating time for no-PCM and different percentage of PCM in DHW tank

Figures 4.23 and 4.24 show the increase of actual operating time for the heat pump and average daily energy consumption with back shifting and also with increasing percentage of PCM for the test cases from 5.49hrs/day and 13.95kWhr/day respectively for base case to maximums of 5.92 and 15.04kWhr.day respectively for the on/off set time 1 – 10 with 37.5% PCM. This is similar for the base cases, without PCM.

As with the base cases, it can be attributed to heat pump having to work for longer duration due to its mid-night and early morning start-ups and the heat loss experienced. This is coupled with additional heating required to cause change of phase, the latent heat absorbed by PCM while melting.

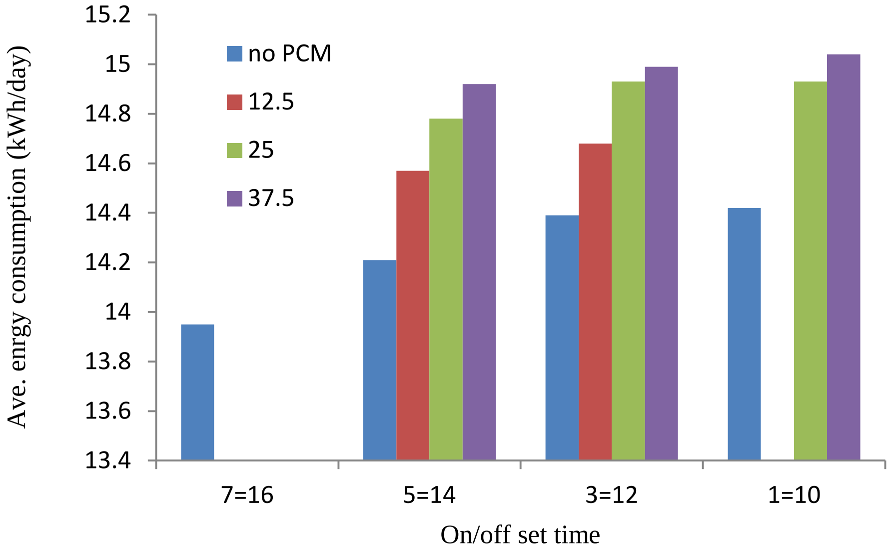

Fig 4.24 Comparison of back shifting effect on average heat pump energy comsumption for no-PCM and different percentage of PCM in DHW tank

This notwithstanding, energy cost appears low because as 'on' or start time for heat pump is moved backwards into the off peak period the hours of off peak operation increases, thus bringing down cost of running heat pump because of the different and lower energy tariffs for off peak periods.

4.6 Back Shifting Combined with Set Time Duration Reduction

Further reduction of on/off set time duration as well as heat pump start/on time back shifted or moved back further into the off peak energy demand period for more off peak operation hours for the heat pump produced results represented in figures 4.25 – 4.28.

This indicates the impact of phase change materials on in enabling system to take advantage of the difference in energy tariffs between peak and off peak periods for energy cost reduction.

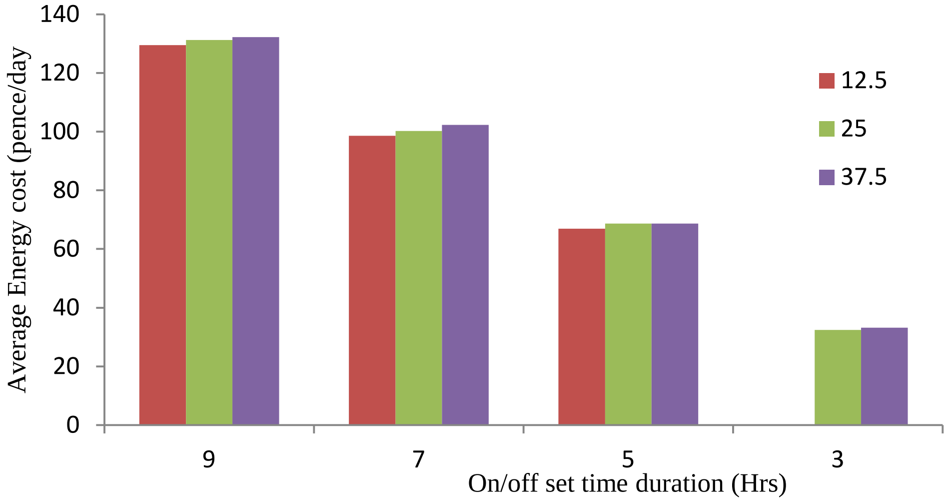

Fig 4.25 Effect of reducing set time duration with 5am as starting time on cost at different % of PCM

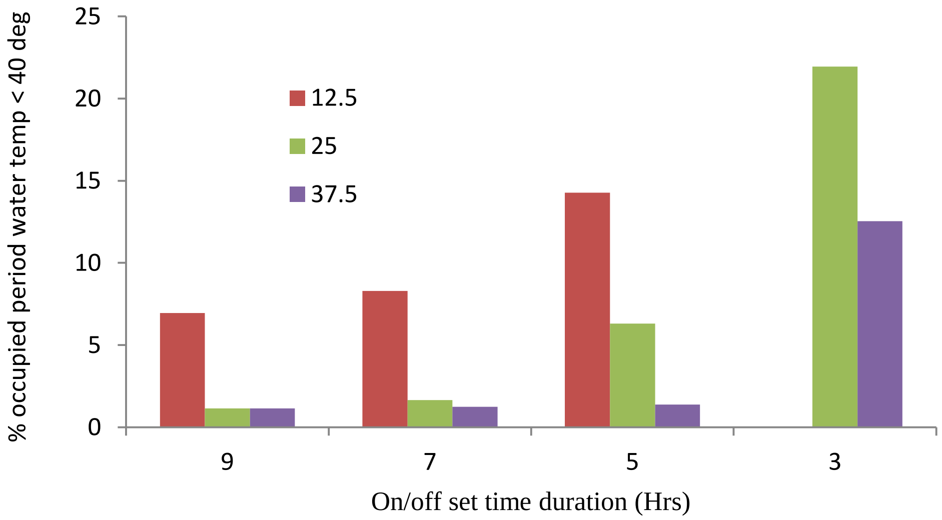

Fig 4.26 Effect of reducing set time duration with 5am as starting time on % occupied period water temp < 40 deg at different % of PCM

Figure 4.25 shows energy cost, reducing with reducing on/off set time duration but rising with increasing proportion of PCM for each of the set time duration. The increase with proportion of PCM, although minimal, is attributable to the additional heating requirement for increased volume (quantity) of PCM while decrease with decreasing set time duration is due to reduced operating time and average daily energy consumption for the heat pump as depicted in figures 4.27 and 4.28. The relationships between actual heat pump operating time as well as average daily energy consumption and set time duration, and between them and proportion of PCM are similar to that for cost.

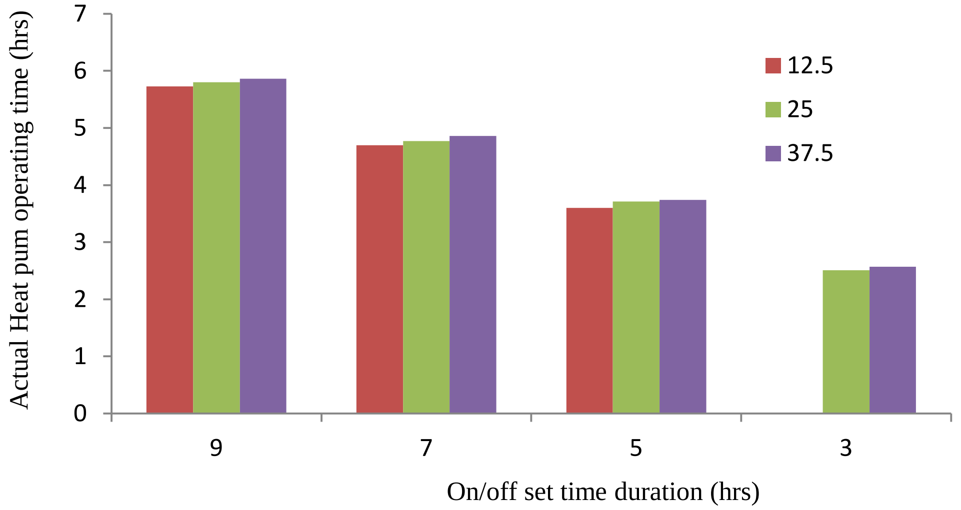

Fig 4.27 Effect of reducing set time duration with 5am as starting time on heat pump actual operating time

Reverse is however the case between percentage of occupied period that hot water temperature falls below 40^{o}C and both set time duration and proportion of PCM. It increases as set time duration reduces but reduces with increasing proportion of PCM. This is because additional PCM permitted more heat energy to be stored, enabling heating system to maintain hot water temperature above 40^{o}C for longer.

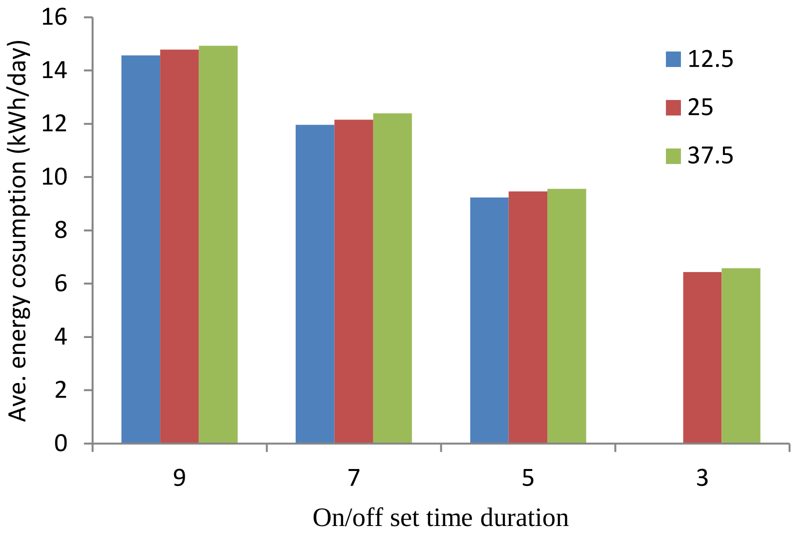

Fig 4.28 Effect of reducing set time duration with 5am as starting time on heat pump energy consumption

4.7 Combined Effect of on/off Set Time and Proportion of PCM

A final comparison is done for effect of on/off set time and duration, as well as proportion of PCM, on energy cost, percentage of occupied period water temperature dropped below 40^{o}C, actual operating time and energy consumption for heat pump. They are represented in figures 4.29 – 4.32.

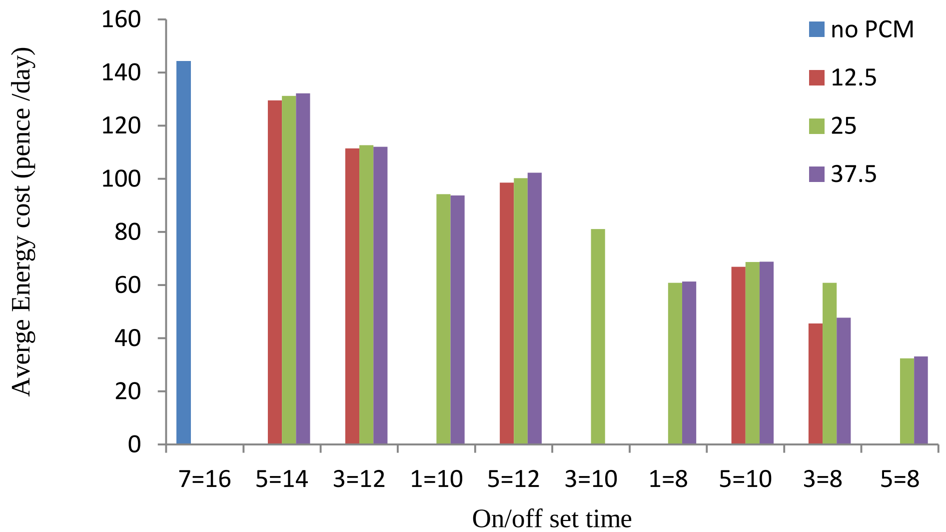

Fig 4.29 Comparison of Effect of on/off set time and % PCM on energy cost

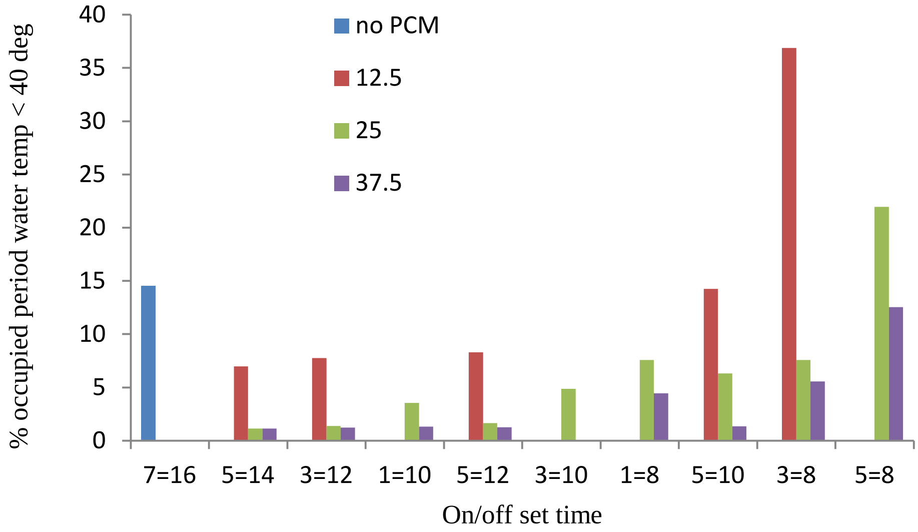

Fig 4.30 Comparison of Effect of on/off set time and % PCM on % occupied perion wter temp < 40 deg

Figures 4.29 – 4.32 show the pattern of results obtained from the toggling back and forth described in the methodology. It can be seen, from figure 4.29, that energy cost reduces as on/off set time moves back or is back-shifted with fixed on/off set time interval as well as with reducing on/off set time duration but increases with increasing proportion of PCM.

Actual heat pump operating time and average daily energy consumption however increase with back shifting and proportion of PCM but reduces with reducing on/off set time duration (figures 4.31 and 4.32).

The only anomaly is the on/off set time 3 – 8 where cost rises between 12.5% and 25% PCM but drops between 25% and 37.5% PCM. The reason is not exactly clear and the only reasoning at this time is that there could be a glitch in the model or iterations which may have affected the output results. The anomaly is however absent in the case of effect on percentage of occupied period hot water dropped below 40^{o}C (figure 4.30).

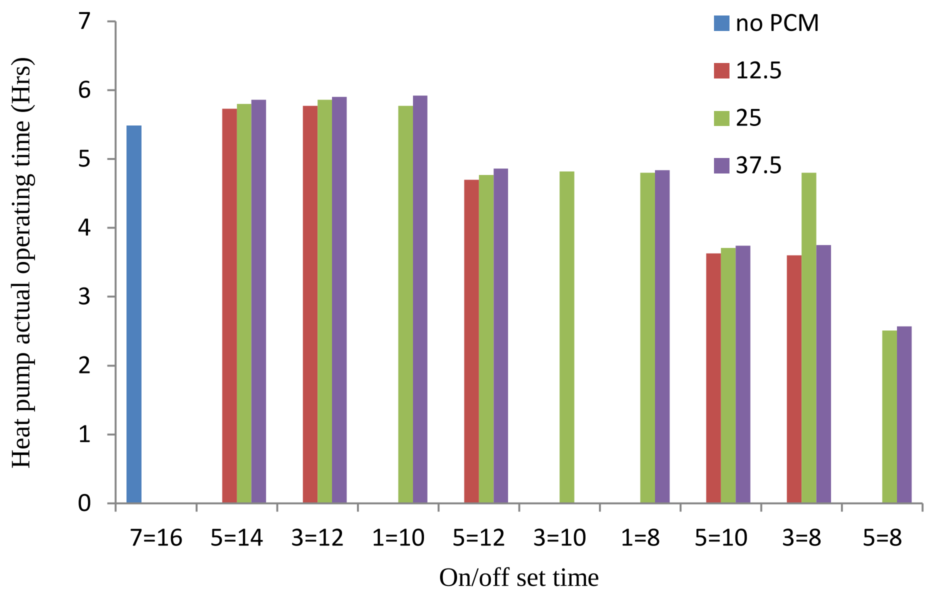

Fig 4.31 Comparison of Effect of on/off set time and % PCM on heat pump actual operating time

The lowest average daily energy cost obtained is 33.14 pence, for on/off set time 5 – 8 at 37.5% PCM in domestic hot water tank. This on/off set time compares well with the initial base case no PCM on/off set time of 7 – 16 in terms of percentage of occupied period that water temperature falls below 40^{o}C. Both are close to the 15% mark. Interestingly, this on/off set time is entirely in the off peak energy demand period and average daily energy consumption is considerably lower than that for the base case, 6.58kWh/day (the true lowest energy cost, shortest operating time for heat pump and lowest energy consumption was obtained for on/off set time 5 – 8, 25% PCM but the percentage of occupied period that hot water temperature falls below 40^{o}C for this set tine is outside the criteria of 15% set at the beginning).

This shows that there is high possibility of running system only in the off peak period and saving huge sums on heating energy with incorporation of phase change materials. Hot water temperature profile for on/off set time 5 – 8 at 37.5% PCM is shown in figure 4.33.

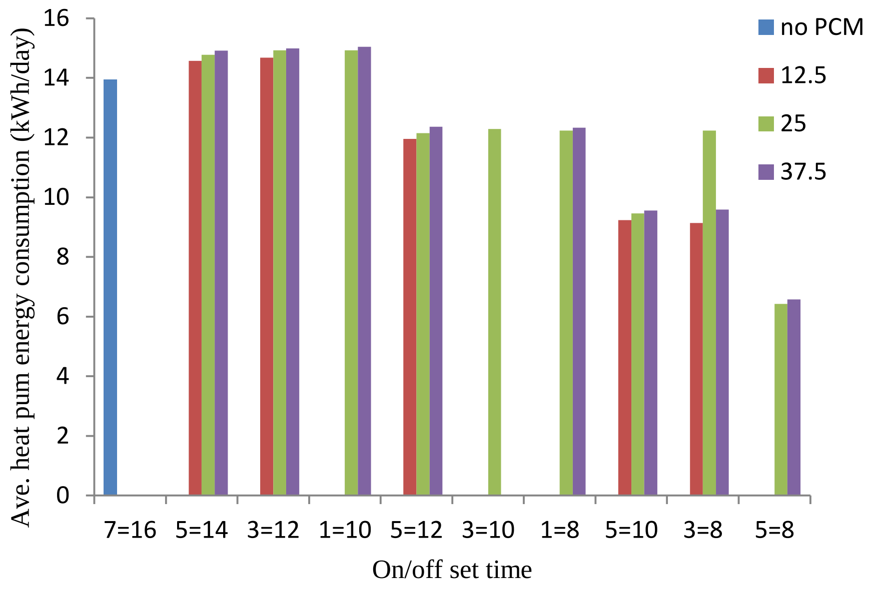

Fig 4.32 Comparison of Effect of on/off set time and % PCM on heat pump energy consumtion

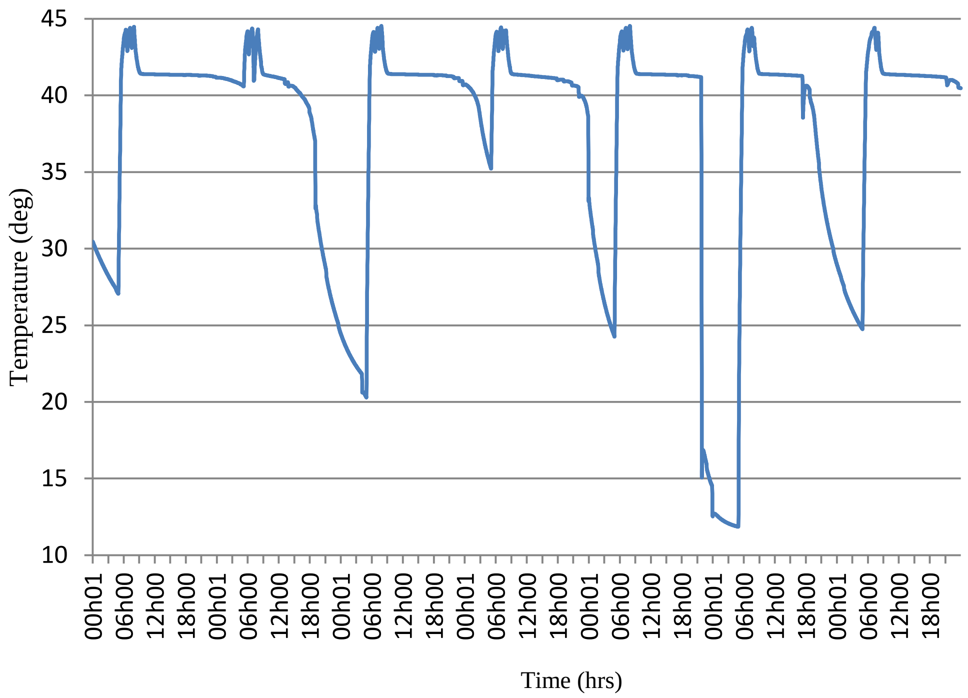

Fig 4.33 DHW tank water temp profile over simulation period (5 - 8, 37.5% PCM)

Average daily energy cost and energy consumption difference of 111.06 pence and 7.37kWh/day respectively, are obtained from comparing the two cases, which sums to 77.2% and 52.83% savings on energy cost and consumption respectively.

The next lowest average daily energy cost is obtained for on/off set time 3 – 8, 37.5% PCM (domestic hot water temperature profile is shown in figure 4.34). Actual heat pump operating time for this set time is 3.75 hrs higher than actual heat pump operating time and energy consumption for on/off set time 5 – 8 but with hot water temperature below 40^{o}C for 5.55% of the occupied period. This implies that water temperature is maintained above 40^{o}C for a much longer period. Average daily energy cost and average daily energy consumption are7.73 pence and 9.59kWh respectively. Energy cost and energy consumption are 44.03% and 45.74% respectively, higher than average daily energy cost and energy consumption for 5 – 8 but 66.9% for cost and 31.25% for energy consumption, less than that for the initial base case (7 – 16, no PCM).

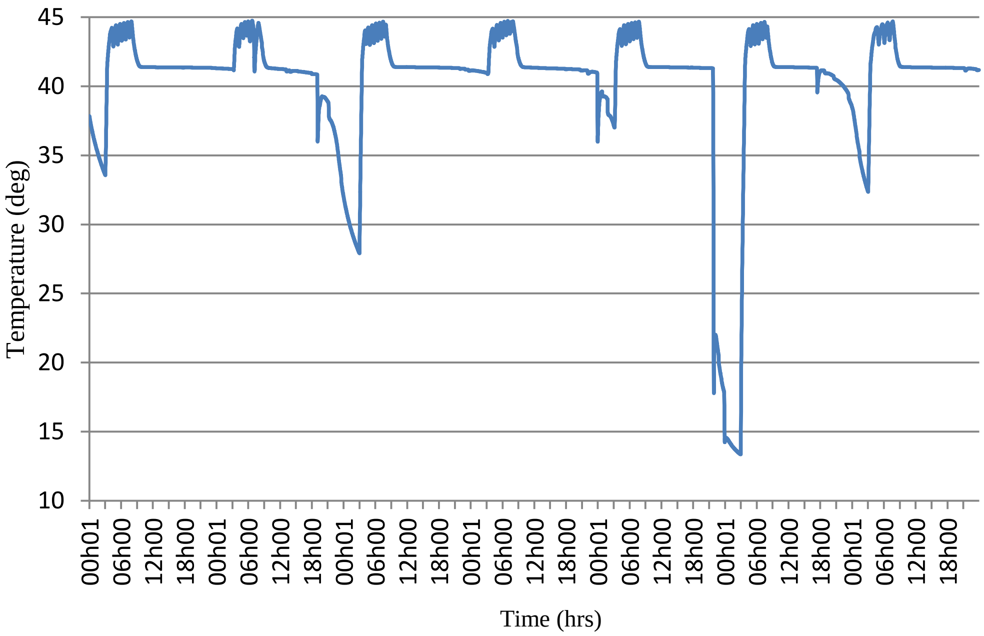

Fig 4.34 DHW tank water temp profile over simulation period (3 - 8, 37.5% PCM)

5 Conclusion and Recommendations

5.1 Conclusion

The objective of this research work is to assess the probability that phase change energy storage materials can lead to energy savings when applied to or with renewable energy systems. If any, renewable energy systems are the most likely candidates for energy storage, being mostly intermittent in nature.

The work was done employing models for a detached UK building with average insulation and utilising an air source heat pump for heat supply for domestic water heating and space heating. Simulations were run for a winter week over a range of on/off set times and durations, and proportion of phase change materials in domestic hot water storage tank.

Results show that inclusion of phase change materials causes heat pump to work or remain on, or cycle on longer due to additional heating required to cause change of phase. Results also show that shifting operating period backwards also results in increasing actual operating time of heat pump as depicted by rise in heat pump operating time and energy consumption from 5.49hrs/day and 13.95kWhr/day respectively for base case with no PCM to a maximum of 5.92 and 15.04kWhr.day respectively for on/off set time 1 – 10 with 37.5% PCM, while reducing the on/off set time duration results in less actual operating time for heat pump.

Reducing on/off set time duration resulted in a reduction of heat pump operating time and average energy consumption but they increased with proportion of PCM in DHW

The proportion of increase of actual operating time of heat pump and average energy consumption as on/off set time, that is, operating period is moved backwards, as well as with increasing proportion of phase change material is considerable small when compared to the reduction experienced due to reducing on/off set time duration, resulting in overall reduction in actual heat pump operating time and energy consumption, from 5.49hrs/day and 13.95kWhr/day, operating time and energy consumption respectively, for the base case (7 – 16 on/off set time) to 2.51hrs/day and 6.43kWhr/day, operating time and energy consumption respectively, for on/off set time 5 – 8 with 25% PCM. This reflects on the maximum average daily energy cost savings and energy consumption reduction, of 77.2% and 52.83% respectively obtained for on/off set time of 5 - 8, 37.5% PCM, which agrees with the criteria set at the beginning.

Overall effect of the application of phase change materials, therefore, is the potential for back shifting operating period away from peak energy demand period to off peak period and reducing total operating period, with eventual effect on reduced energy cost and consumption.

5.2 Recommendations

This research work was conducted using simulation software that employs iterations of near actual conditions. Some assumptions are also made that may not be completely accurate. Phase change simulated has properties that closely resemble actual materials.

Further work could be on acquiring data for properties and behaviour of market available phase change materials to be modelled for simulation in order to make the results more realistic.

A practical approach to the problem could be examined with the aim of establishing and validating models and confirming modelling results.

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Appendices

Appendix A Results Tables

Table A1 Effect of back shifting on energy cost computed from simulation result

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	144.2	-	-	-
5=14	126.1	129.5	131.2	132.2
3=12	109.4	111.4	112.6	112
1=10	90.87	-	94.17	93.65

Table A2 Effect of back shifting on % of occupied period DHW temperature dropped below 40^{o}C computed from simulation result

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	14.52	-	-	-
5=14	24.22	6.96	1.14	1.14
3=12	39.35	7.77	1.38	1.24
1=10	59.29	-	3.53	1.32

Table A3 Effect of back shifting actual heat pump operating time computed from simulation result

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	5.49	-	-	-
5=14	5.6	5.73	5.8	5.86
3=12	5.67	5.77	5.86	5.9
1=10	5.68	-	5.87	5.92

Table A4 Effect of back shifting heat pump average daily energy consumption (kWhr/day) computed from simulation result

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	13.95			
5=14	14.21	14.57	14.78	14.92
3=12	14.39	14.68	14.93	14.99
1=10	14.42		14.93	15.04

Table A5 Effect of reducing on/off set time duration on energy cost computed from simulation results

On/off set time duration	% PCM		
	12.5	25	37.5
9	129.5	131.2	132.2
7	98.56	100.2	102.3
5	66.88	68.65	68.71
3	-	32.39	33.14

Table A6 Effect of reducing on/off set time duration on % of occupied period DHW temperature dropped below 40^{o}C computed from simulation results

On/off set time duration	% PCM		
	12.5	25	37.5
9	6.96	1.14	1.14
7	8.3	1.65	1.25
5	14.27	6.3	1.37
3	-	21.95	12.55

Table A7 Effect of reducing on/off set time duration actual heat pump operating time computed from simulation results

On/off set time duration	% PCM		
	12.5	25	37.5
9	5.73	5.8	5.86
7	4.7	4.77	4.86
5	3.6	3.71	3.74
3	-	2.51	2.57

Table A8 Effect of reducing on/off set time duration pump average daily energy consumption (kWhr/day) computed from simulation results

On/off set time duration	% PCM		
	12.5	25	37.5
9	14.57	14.78	14.92
7	11.96	12.15	12.39
5	9.23	9.46	9.56
3		6.43	6.58

Table A9 Combined effect of on/off set time back shifting and duration reduction on cost computed from simulation results (7-16 only for no PCM)

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	144.2	-	-	-
5=14	-	129.5	131.2	132.2
3=12	-	111.4	112.6	112
1=10	-	-	94.17	93.68
5=12	-	98.56	100.2	102.3
3=10	-	-	81.07	-
1=8	-	-	60.85	61.29
5=10	-	66.88	68.65	68.71
3=8	-	-	-	47.73
5=8	-	-	-	33.14

Table A10 Combined effect of on/off set time back shifting and duration reduction on % of occupied period DHW temperature dropped below 40^{o}C computed from simulation results (7-16 only for no PCM)

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	14.52	-	-	-
5=14	-	6.96	1.14	1.14
3=12	-	7.77	1.38	1.24
1=10	-	-	3.53	1.32
5=12	-	8.3	1.65	1.25
3=10	-	-	4.86	-
1=8	-	-	7.58	4.45
5=10	-	14.27	6.3	1.34
3=8	-	-	-	5.55
5=8		-	-	12.55

Table A11 Combined effect of on/off set time back shifting and duration reduction heat pump average daily energy consumption (kWhr/day) computed from simulation results (7-16 only for no PCM)

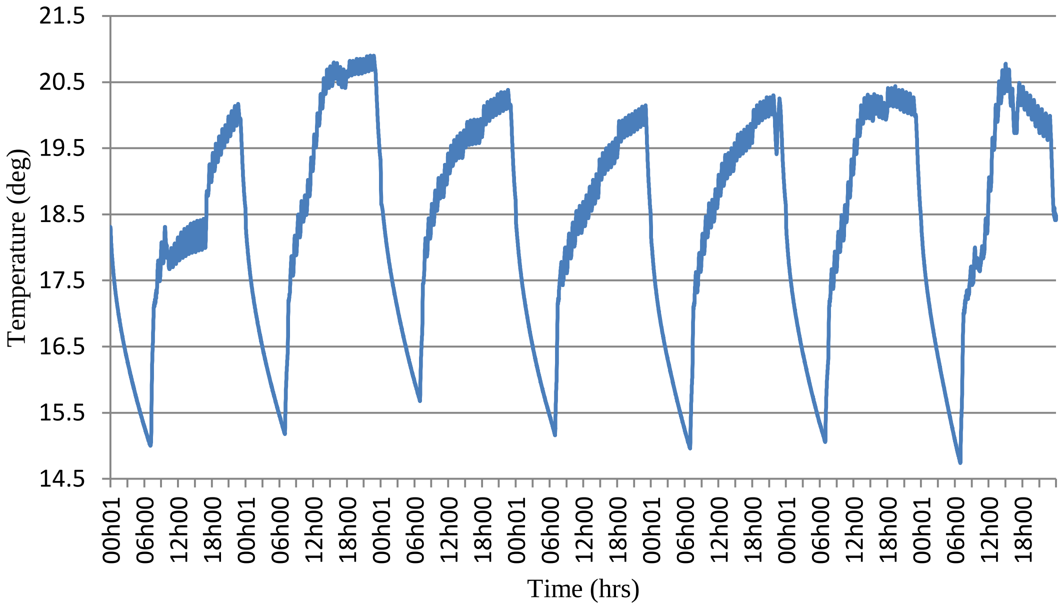
On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	5.49	-	-	-
5=14	-	5.73	5.8	5.86
3=12	-	5.77	5.86	5.9
1=10	-	-	5.77	5.92
5=12	-	4.7	4.77	4.86
3=10	-	-	4.82	-
1=8	-	-	4.8	4.84
5=10	-	3.63	3.71	3.74
3=8	-	-	-	3.75
5=8	-	-	-	2.57

Table A12 Combined effect of on/off set time back shifting and duration reduction actual heat pump operating time computed from simulation results (7-16 only for no PCM)

On/off set time	no PCM	% PCM		
		12.5	25	37.5
7=16	13.95			
5=14		14.57	14.78	14.92
3=12		14.68	14.93	14.99
1=10			14.93	15.04
5=12		11.96	12.15	12.36
3=10			12.29	
1=8			12.24	12.33
5=10		9.23	9.46	9.56
3=8		9.14	12.24	9.59
5=8			6.43	6.58

Appendix B

Figure B1 Living zone temperature profile for on/off set time 7 -23 (no PCM)



Living zone temperature profile for on/off set time 7-23 (no PCM)

Figure B2 Cut-out picture of EDF Energy prices sheet showing Economy 7 tariffs (source EDF Energy, 2010)

EDF ENERGY

R77ECO.IH.AG.03/10.V16(SNO)

DOMESTIC ENERGY PRICES EXCLUDING VAT

TARIFF	YOUR REGION / Refer To Notes Below	EAST MIDS	EASTERN	LONDON	MANWEB	MIDLANDS	NORTHERN	NORWEB	SCOTTISH HYDRO	SCOTTISH POWER	SEEBOARD	SOUTHERN	SWALEC	SWEB	YORKSHIRE
ELECTRICITY															
Standard	1,3														
Band A (900 kWh p/a)*		17.50p	16.71p	17.86p	18.40p	16.90p	19.23p	16.48p	18.57p	18.14p	16.33p	18.67p	18.80p	17.36p	18.96p
Band B kWh		10.36p	9.94p	10.89p	9.92p	10.49p	9.33p	9.99p	10.23p	10.21p	11.20p	10.50p	10.37p	11.79p	9.37p
Economy 7	1,3														
Band A (1000 kWh p/a)**		22.83p	17.66p	19.64p	21.11p	21.20p	22.73p	18.79p	24.45p	23.56p	19.33p	21.36p	20.93p	18.27p	22.67p
Band B kWh		10.95p	11.05p	11.78p	11.64p	11.73p	10.82p	11.87p	10.44p	11.95p	11.85p	12.06p	11.86p	13.25p	10.68p
Night kWh		4.71p	5.34p	4.70p	4.60p	4.86p	4.93p	4.69p	5.40p	4.85p	4.64p	4.72p	4.59p	4.96p	4.79p
Economy 10^#	1,3														
Band A (1000 kWh p/a)***		23.78p	18.17p	20.40p	21.76p	21.25p	N/A	19.08p	24.69p	23.92p	19.94p	22.07p	21.64p	20.26p	23.11p
Band B kWh		11.70p	11.51p	12.40p	12.16p	12.01p	N/A	12.34p	10.57p	12.21p	12.38p	13.02p	12.82p	15.39p	11.44p
Economy kWh		5.96p	6.16p	5.34p	5.35p	4.91p	N/A	4.77p	6.57p	5.70p	5.54p	4.79p	4.65p	5.05p	4.83p
GAS^															
Standard	2,3,4														
Band A (2680 kWh p/a)†		7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p	7.000p
Band B kWh		2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p	2.891p