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A Taxonomy of Fabric Integrated Thermal Energy Storage

A review of storage types and building locations

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Abstract: Thermal energy storage incorporated into the fabric of buildings provides the opportunity to significantly reduce the energy load of those buildings, improve the use of energy from renewable sources and take maximum advantage of off-peak electricity tariffs. If this kind of thermal storage is integrated into the structure of the building itself, the internal space of the building is not compromised.

In this paper, the authors present a taxonomy of currently available fabric-integrated thermal energy storage solutions based on a review of existing literature. The aim of this study is to map the range of extant design solutions for fabric-integrated thermal storage in buildings and detect any omissions in this range of designs.

The taxonomy presented in this paper takes into consideration the interaction between the storage of thermal energy and the thermal zones of buildings, the methods and medium used to store thermal energy, and the storage temperature. Also considered here are the different architectural integration options, which the authors present through a catalogue of possible thermal energy storage locations.

This paper argues that an active storage system provides a link for active participation in the energy network. Active storage allows the charge and discharge of the thermal energy stored within such buildings when the energy is available and/or economically valuable. This kind of active participation is not possible with passive storage techniques.

Keywords: Fabric integrated thermal energy storage (FITS), Active storage system, Passive storage system

1. INTRODUCTION

Thermal Energy Storage (TES) in buildings is used to store energy as heat or cold, making it available when needed. TES can radically alter the timing of a buildings' energy demand, can enhance the use of renewable energy sources (Lehmann et al., 2007) and take advantage of off-peak energy supply (Basecq et al., 2013) and can perform also as the energy collector (AIA-Research-Corporation, 1976). However, many obstacles exist with regards to integrating and operating heat storage systems in future buildings and communities, one of the most significant is competition for space - as dwelling sizes reduce (Robert-Hughes, 2011), floor area is at a premium and the space penalty associated with conventional hot water storage acts as a barrier to its uptake; this problem becomes more acute if heat needs to be stored over longer time periods than is done at present. Storage in the future may need to migrate away from the traditional hot water tank at seen at present, towards media such as phase-change materials and storage that makes better use of the existing space and thermal mass in and around buildings, including large scale community storage. If this uses existing elements of construction, without compromising internal space, such as using structural or constructional elements for energy storage, this becomes fabric integrated thermal storage (FITS). However, the effective operation of FITS, within the context of a low carbon future featuring multiple heterogeneous heat sources and active energy network participation raises significant engineering and social challenges.

1.1. Methods for FITS

Thermal energy can be stored physically as sensible heat storage and latent heat. The first is based on specific heat of the storage material, such as concrete or hot water, while the second one is based on the heat of phase transitions (Cabeza et al., 2015). The FITS can be coupled or decoupled from the building' thermal zones depending on insulation level and position. Charging and discharging of FITS, can be passive or active. With passive storage, the heat is stored without mechanical input, using solar gains, convection or temperature difference, whilst active systems require a system for heat generation and transfer. The passive storage systems or technologies are normally integrated as part of the building structure, which is the case of thermal mass or shading devices (Navarro et al., 2016a). In an active storage system the heat is transferred using distribution fluids, such as air or water, with forced convection (Navarro et al., 2016a), or by using electricity. Air and water based-systems can either be used for cooling or heating while direct electric systems are used for heating. In some cases the charge and discharge can be a combination of active charge and passive discharge or vice versa, and the thermal energy can be stored in a HVAC system, in the building fabric or outside the building structure (Heier et al., 2015).

There are a small number of reviews on thermal storage systems in buildings, with reduced emphasis on the potential of FITS. Basecq et al. (2013) present a review on short-term storage systems for buildings based on concepts such as passive and active systems, storage materials and system performance. Heier et al. (2015) focus on combining TES in residential and commercial buildings by reviewing storage technology such as passive and active systems. Navarro et al. (2016a) and Navarro et al. (2016b) reviewed passive and active TES systems that are integrated in buildings, and classify the integration based on the storage location. Considering these works, this paper addresses the application of passive and active FITS in buildings through a taxonomy of extant designs solutions. This is done to identify existing solutions and omissions in this range of designs.

2. TAXONOMY OF FITS SYSTEMS

The AIA Research Corporation (1976) provides one of the first storage taxonomies, presenting a set of diagrams of passive FITS systems, illustrating different storage methods, materials, locations and thermal energy distributions. Mazria (1979) and Anderson (1984) validate these initial diagrams by producing new illustrations based on a review of researches on passive FITS systems. Later, Howard and Fraker (1990) continue a taxonomy of passive FITS systems by illustrating FITS systems with direct, indirect and isolated gains. Focusing on the application of phase change materials (PCM) in buildings, Zhang et al. (2007) present illustrations on latent storage in passive FITS systems. In these initial taxonomies, considerable amount of the sensible storage with solid materials is integrated into the building fabric. This integration is included in structural elements such as walls, floors, roofs and foundation walls, or in interior elements such as internal walls, vertical solar louvers, internal floors or ceilings. FITS systems with liquid storage material are integrated in external or internal walls using filled-water drums, tubes and transwalls. Similarly, these systems are included on roofs by using filled-water bags, while the passive latent heat storage systems are located in walls, floors, roofs, ceilings and windows. However, these taxonomies are limited to passive FITS systems, and therefore a new taxonomy that includes active FITS systems is necessary.

A new taxonomy was developed from the existing taxonomies and from the research studies examined in this paper. The relation of the storage to the internal zone of the buildings was organized in coupled, semi-decoupled and decoupled storage, according with the storage temperature, type of system and heat distribution types such as air and water base distribution and electric activation. The coupled FITS systems include passive and active systems while the semi-decoupled and decoupled FITS systems are mainly active.

3. COUPLED ACTIVE FITS SYSTEMS WITH AMBIENT TO LOW TEMPERATURE

The majority of previous studies describe coupled systems. There is preponderance for studying active systems, with air and water as the distribution fluid (rather than using electricity). The studies either employ sensible or latent storage, and most sensible storage use concrete as the storage material.

3.1. FITS Systems with Air Base Distribution

TES active systems in buildings are not a new concept. In ancient Rome the hypocaust was used as a heating system, and similar concepts that also uses air as the heating fluid such as the Chinese Kang and the Korean Ondol systems are still used (IEA-ECBCS-Annex44, 2009).

Floors

Chen et al. (2010) studied a ventilated concrete slab (VCS) integrated in a low energy solar house. The thermal storage was activated using warm air collected by a roof photovoltaic/thermal (BIPV/T) system, and the heat was release by passive means. It was found that at winter, on a clear sky day and with outside temperatures around 0°C, the VCS was able to store 9.12kWh of heat supply by the BIPV/T system. It was also able to store thermal energy during several clear sky days without overheating. Ekrami et al. (2015) also studied a VCS that works in conjugation with a ventilated sand bed accommodated under the VCS, and both systems stored thermal heat from the BIPV/T, which later was used to preheat an air-to-water heat pump system. The heat pump supplied the heated water for space conditioning using the hydronic floor and walls, and for domestic hot water. The preliminary thermal analysis showed that the hydronic walls could be used for thermal energy storage using a BIPV/T and air source pump system.

Multiple Locations, Interior Walls, Interior Floors, Ceilings and Columns

Chen et al. (2016) studied the thermal performance of three different configurations of ventilated building-integrated thermal energy storage systems, which could be implemented on walls and on floors. The systems were reported as being able to improve the thermal performance of the zone with reduced energy consumption due to the thermal energy stored. Through an experimental investigation, Dermardiros et al. (2015) looked into the use of latent thermal energy storage system in air ventilated panels. The system contained a macro-encapsulated PCM panel that was activated using warm or cold air, which flowed along the panel core. This design could be implemented as partition walls or could be incorporated as part of a ceiling.

Columns are a potential location for thermal energy storage. Unalan and Ozrahat (2014) looked into this structural element by investigating the use of multi-storey buildings columns for heating using stainless steel pipes embedded on concrete columns with circulating heated air. The vertical thermal storage has active charge and passive discharge, by using stainless steel pipes embedded on concrete columns with circulating heated air. It was found that at winter the charging time to achieve the required heat loads value for a flat was dependent on air temperature and airflow velocity values.

3.2. FITS Systems with Water Base Distribution

Hydronic systems were initially utilised during the 1930's in Switzerland, by embedded steel pipes in concrete floors (IEA-ECBCS-Annex44, 2009). Later, in the 1990's in Mid-Europe, these systems appeared as an energy efficient and economic possibility for heating and cooling of buildings (Lehmann et al., 2007).

Floors

Reynders et al. (2013) compared the use of a hydronic floor and a wall radiators system. The study assessed the use of electricity for heating and the application of local electricity production through storing thermal energy into the building structure. The floor heating system provided the lowest energy needs and had the lower internal air temperature oscillations. Several studies focused on the use of latent thermal storage. Through an experimental investigation Zhou and He (2015) compared four systems with different thermal storage, such as latent (PCM) and sensible (sand), and with different heating pipes, such as polyethlene coil and capillary mat. The authors found that the capillary mat could provide room temperature within comfort zone in a shorter period of time that the polyethlene coil. Also through an experimental investigation, Zhang et al. (2016) considered a new radiant floor system with solar collector and a vertical latent thermal energy storage device. This study showed that the system was able to improve the indoor thermal comfort under different winter weather conditions, providing temperatures of 5°C to 7°C higher than a room with no heating. The vertical latent energy storage device could store excess solar energy for two consecutive mornings, and could increase the usage of solar energy by 30%. The system was self-sufficient when the received solar radiation was greater than 15MJ/m^2.

Exterior Walls and Ceilings

Several researches investigated the performance of hydronic walls using particular heat sources. Li et al. (2016) studied the energy saving potential of an exterior wall system that used a ground source heat exchanger to charge the system with cold or heated water, while the discharge was passive. It was reported that the heat loss and gains through the walls were minimized due to the water temperature of the system. However, the soil temperature at different climates had a great effect on the system' energy saving potential. Romaní et al. (2017) undertook an experimental study on a radiant heating system in a heavy brickwork wall with a ground source heat pump. It was found that the radiant wall produce maximum energy savings of around 40% when using a set point of 22°C. The system was able to operate with off-peak electricity but, because of the slow response, this system was not able to operate in occupancy schedules. Atienza Márquez et al. (2017) explored the use of a radiant floor heating system combined with a fan-coil heating system. It was reported that the system was able to provide good thermal comfort during the heating season, and produced the best performance when both heat distribution systems work in conjugation. Through an experimental study Koschenz and Lehmann (2004) tested a thermally activated latent storage ceiling panel with passive discharge. This panel could be incorporated in lightweight constructions or used in retrofit projects. It was found that due to high latent thermal capacity of the paraffin, 5 cm microencapsulated paraffin (25% by weight) and gypsum could provide good thermal comfort in an office building. It was concluded that renewable energy sources such as night cooling could be used with this system.

3.3. FITS Systems with Electric Activation

Floors

Various studies investigated use of off-peak electricity to charge the FITS, and some of these researches combine active charge and passive charge by using direct solar gains. Through a numerical model, Athienitis (1997) investigated the thermal performance of a radiant concrete floor heating system with direct solar gains. The author reported that by increasing the floor thickness from 5 cm to 10 cm, the heat demand was reduced by around 20% but the surface temperature was 1.5°C higher than the allowable temperature of 29°C. However, when the system was fully charged during the off-peak periods, additional direct solar gains during the day could cause overheating. This could be avoided by increasing the thermal mass or by using individual night and day set points. Athienitis and Chen (2000) studied the heat transfer in floor heating systems using a three-dimensional model. The thermal impact produced by storage material such as concrete and gypcrete was investigated, as well as the effect of floor full or partial coverage using hardwood or carpets. It was found that a surface area with sun exposure could reach temperatures up to 8°C higher than a shaded floor surface area. It was also reported that the energy demand could be reduced with the solar passive gains received by the storage system.

Research on the thermal behaviour of electric heated floors was conducted by Amir et al. (1999) using a mathematical model. The study compared the thermal performance of a sensible storage with a latent storage charged with off-peak electricity. Both thermal storage systems were in a concrete structure, the sensible storage used water while the latent storage used paraffin. It was reported that the latent storage show greater thermal storage capacity with a reduced amount of volume, with a daily storage surface amplitude temperature of 1.3°C, while the sensible storage value was 3.8°C. Through a simulation study, Li et al. (2009) also investigated an electric floor heating system combined with a latent heat storage. The system was charged with off-peak electricity and the discharge was passive. It was found that the new form-stable PCM storage provided good temperature regulation with energy costs reduction, and that the system performance was affected by the heating mode and the latent storage thickness.

Recently, a thermal energy storage system composed by an electrically heated floor for building load management was investigated by Thieblemont et al. (2016). The parametric study using TRNSYS examined concrete thickness, and also the location of wires and insulation. It was reported that in a cold climate, an electrically heated floor system could use up to 84% of the energy load during off-peak periods, while providing good thermal comfort. Concerning the system design, it was found that insulation below the storage reduced heat losses to the ground, while using insulation above the storage increased the heat losses to the ground and prevents heat transfer to the room. Regarding the system performance, it was affected by the location of the electric cables and storage thicknesses but values greater than 18 cm had no additional benefit.

Walls

LeBreux et al. (2009) proposed a controller to operate a hybrid storage system based on anticipatory and regulation strategies. The storage system had an interior wall with embedded electric resistance and an adjacent sunspace. The system stores solar heat through passive charge, and off-peak electricity through active charge. The authors reported that the controller shows superior performance than traditional control systems. The storage system was maintained with a constant performance, and within the thermal comfort range. The electricity demand for space heating was reduced of which 95% was off-peak electricity.

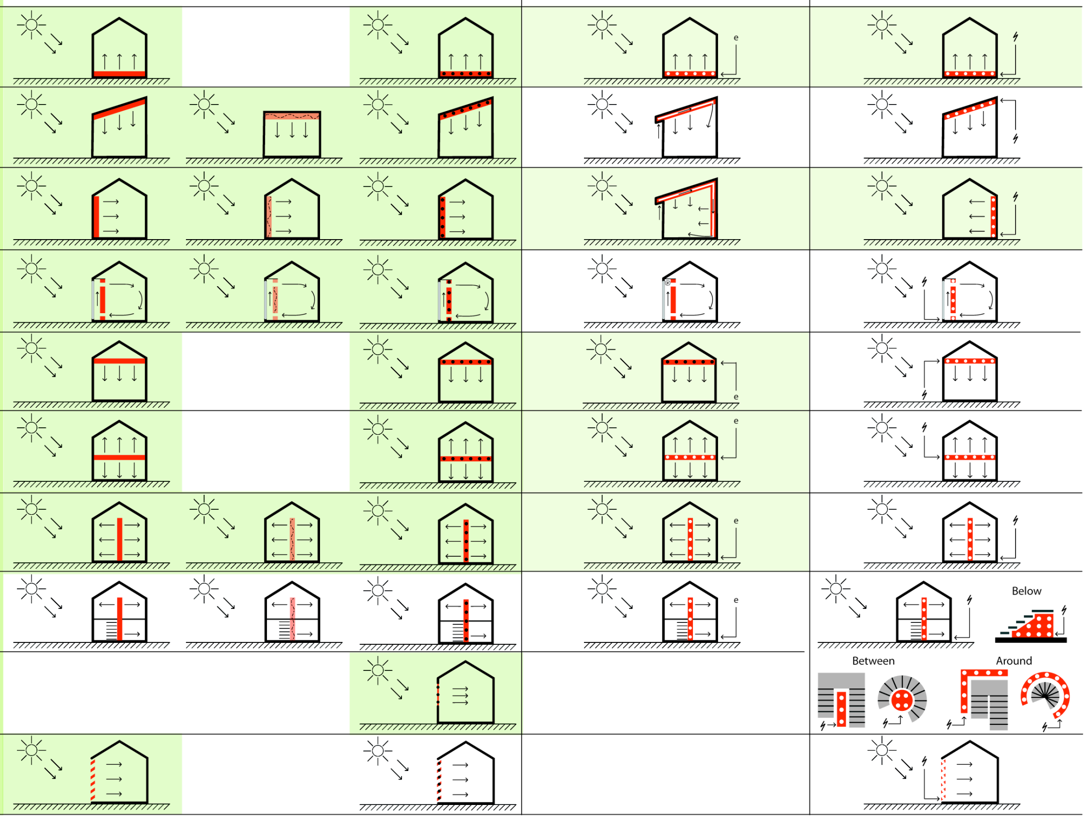
3.4. New Taxonomy of Coupled FITS Systems

The new taxonomy of coupled FITS systems illustrated in Table 1 includes passive and active systems. The taxonomy of passive FITS systems are based on the existing taxonomies, while the taxonomy of active FITS systems are based on above research studies.

The passive systems use storage temperature ranging from ambient to low temperature up to 30°C and are presented as sensible and latent storage systems. The active coupled systems include low storage temperatures up to around 40°C and are presented according with the storage activation process and, therefore, organized by distribution fluids, such as air and water, and electricity.

Table 1. Taxonomy of FITS – coupled storage systems

Storage Location	Passive Charge & Discharge			Hybrid Charge & Discharge	Active Charge & Passive Discharge
	Passive FITS			FITS system with air or water distribution	FITS system with electric cables
	Sensible Storage		Latent Storage	Sensible or latent Storage	Sensible or Latent Storage
	Solid	Liquid	PCM	Solid or PCM	Solid or PCM
	Ambient to Low Temperature up to 30°C			Low Temperature up to 40°C	Low Temperature up to 40°C
Floor					
Roof					
Exterior Wall					
Trompe Wall/ Double Facade					
Ceiling					
Interior Floor					
Interior Wall					
Staircase & lift areas (wall, column or void areas)					
Window					
Shading Device					



Passive FITS systems locations based on previous taxonomies | Active FITS systems locations based on reviewed studies | Potential active FITS systems locations

4. SEMI AND DECOUPLED FITS SYSTEMS WITH AMBIENT TO HIGH TEMPERATURE

The potential advantage of a semi-decouple and decoupled system is that storage temperatures may be much high and thus the potential amount of storage is increased. In a FITS concept, this may be advantageous in terms of having higher storage capacity and an ability to control both charge and discharge.

4.1. FITS Systems with Water Base Distribution

Foundation Piles and Retaining Walls

Foundation piles and retaining walls are below-ground thermal energy storage systems, which are part of a building foundation, are decoupled from the building thermal zones and work as the heat exchanger. Generally, the energy source is geothermal when an energy foundation pile length is greater than 20 m. These systems also work as a storage medium. However, as pointed by Loveridge and Powrie (2013), in the case of concrete piles most studies do not consider the heat storage potential within the pile. These systems work with ambient temperature storage that is dependent on the mean ground temperature of a particular location. Nevertheless, there is a great potential to use medium to high storage temperature values.

Through an experimental study Wood et al. (2010) analysed the heat pump performance and ground temperature of piled foundation system for residential buildings. This system used 21 concrete piles with 10 m depth each. During the heating season, it was found that seasonal performance factor of the heat pump was 3.62, and the piles no longer affected the ground temperature at a distance of 5 m. Moon and Choi (2015) also analysed the heating performance of a ground source heat pump with energy piles and energy slabs. The energy pile system of 150 piles with a depth of 13.8 m, while the energy slabs had 10 horizontal pipes with a length of 180 each. It was found that the heating capacity of these systems exceeded the expected capacities. The energy pile system had greater thermal performance than the energy slab system. The minimum coefficient of performance of the heat pump was 4.2 for energy pile system and 4.5 for the energy slab system. Recently, the use of a thermo-active diaphragm wall was investigated by Sterpi et al. (2017). It was reported that the retaining wall system benefited from the large surface in contact with the ground. It was found that the thermally induced mechanical effects do not seem to be harmful to the geotechnical and structure safety. However this research points out that its use requires further studies to avoid unanticipated overstress conditions.

4.2. FITS Systems with Electric Activation

The number of researches on FITS with medium storage temperature values up to 70°C are limited and there is a lack of research using values above these. By increasing the storage temperature values the storage capacity also increases, moving from short-term or small period such as hours to longer energy storage periods such as days or weeks. However, the TES system has to be thermally decoupled from the living areas since the parasitic losses from the storage system will contribute to unwanted heat gains. Therefore, the FITS requires a great level of insulation and the mechanisms to charge and discharge have to be active. Consequently, as illustrated in Table 1, the possible locations for fabric integration are reduced. Nevertheless, the potential for new research is greater, and additionally these systems can be linked to the grid allowing active participation of thermal storage.

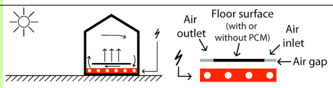
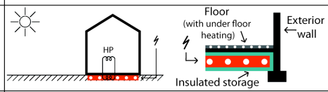
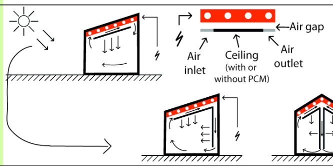
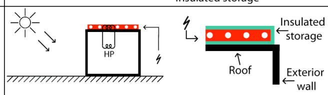
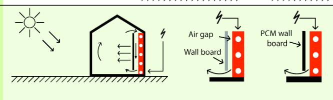
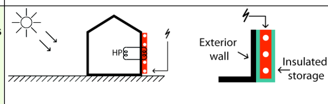
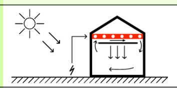
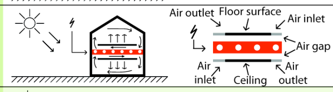
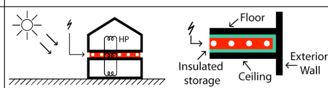
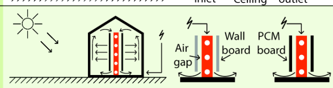
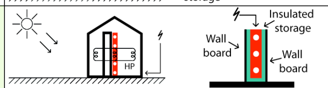
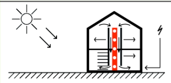
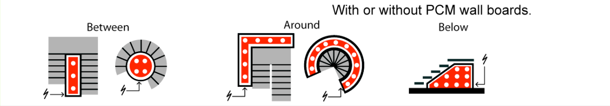
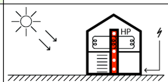
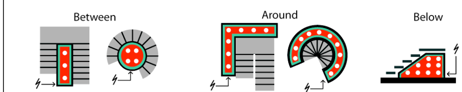
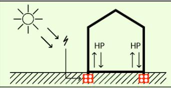
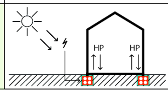
Floors, Exterior Walls and Suspended Ceilings

Laouadi and Lacroix (1999) used a mathematical formula to study the thermal performance of a latent heat storage unit with electric heat source, which worked as a ventilated heating panel with active charge and passive/active discharge. The units could be applied on horizontal or vertical surfaces, such as ceilings or walls. This system used two types of heat discharge: a forced convective heat that occurs with the air passing through an air channel, and a passive radiant heat discharge from the panel that separates the storage unit from the living space. The system operational temperature were set between 35°C and 50°C. It was report that the unit could be used to store electric energy as thermal heat during off-peak periods providing sufficient heat for the living areas. Lin et al. (2005) proposed an under floor heating system with PCM. The system stored thermal heat using off-peak electricity, the storage temperatures were between 55°C to 70°C and the discharge was passive. It was found that the system could provide a uniform indoors air temperature and it was confirmed that off-peak electricity could be used to charge the latent storage.

4.3. New Taxonomy of Semi-decoupled and Decoupled FITS Systems

The new taxonomy of semi-decoupled and decoupled systems is illustrated in Table 2. These systems are active FITS systems. The semi-decoupled systems use medium storage temperatures up to 70°C with electric activation, while the decoupled systems are best used with temperatures greater than 70°C. Concerning the storage locations, FITS systems were organized based on previous research, adding new locations such as staircases and lifts multistory dwellings.

Table 2. Taxonomy of FITS – semi-coupled and decoupled storage systems

Storage Location	**Active Charge & Passive or Active Discharge**		**Active Charge & Discharge**	
	FITS system with electric cables		**FITS system with electric cables**	
	Sensible or latent storage semi-decoupled from the living areas		**Sensible storage decoupled from the living areas**	
	Solid or PCM		**Solid**	
	Medium Temperature up to 70°C	**Notes**	**Medium to High Temperature above 70°C**	**Notes**
Floor		The floor surface can be suspended over a semi-insulated storage. The warm air can be introduced into the living areas through floor openings. PCM floor surfaces such as tiles can be used to avoid overheating.		Total insulated storage decoupled from the thermal zone.
Roof		Roof semi-insulated thermal storage with suspended ceiling to avoid overheating. The use of fans is necessary to distribute the heat. PCM ceiling boards can be used to avoid overheating.		A Roof total insulated storage decoupled from the thermal zone.
Exterior Wall		A wall panel separates the semi-insulated storage from the living zones to avoid burnings or overheating. The heated air can be stopped from entering the rooms by closing the wall vents. PCM boards can be used to avoid overheating.		Total insulated storage decoupled from the thermal zone.
Ceiling		Similar to the Roof system. PCM boards can be use to avoid overheating.		
Interior Floor		PCM tiles can be used to avoid overheating of the floor surface. PCM ceiling boards can be used to avoid overheating near the ceiling.		Total insulated storage decoupled from the thermal zone.
Interior Wall		Similar to the Exterior Walls. The storage can be semi-isolated from the living areas. This allows higher temperature storage. With or without PCM wallboards.		Total insulated storage decoupled from the thermal zone.
Staircase & lift areas (wall, column or void areas)	 	Similar to Interior Walls.The semi-insulated storage is detached from the stairs. Wall boards with air gap and with air circulation. Possible positions: around, between or below the stairs. With or without PCM wall boards.	 	Total insulated storage decoupled from the thermal zone.
Foundation pile & retaining wall		**FITS System with Water Base Distribution** **Ambient to Lower Temperature**		

Active FITS systems locations based on reviewed studies   Potential active FITS systems locations and designs

5. CONCLUSIONS

Thermal energy storage (TES) in buildings has the potential to contribute to the reduction of buildings thermal loads, maximise the use of renewable energy sources and allowing the use of off-peak electricity tariffs. Fabric-integrated thermal storage (FITS) can be coupled or decoupled from the building' thermal zones based on insulation levels and positions. Decoupled TES allow higher temperature storage, which results in a greater storage capacity but also requires active charge and discharge. Active FITS systems can be changed using distribution fluids such as air and water, or by using electric cables.

This taxonomy shows that most research on FITS has focussed on coupled systems and the majority of the studied systems use air and water has the distribution fluid. Therefore, the number of researches that use electricity to charge a FITS system is comparatively small - the greater the storage temperature, the fewer are the available studies. The majority of the studies of sensible storage use concrete as the storage material, and some of the studies compared or combine sensible and latent storage.

With this taxonomy the quantity of possible locations for FITS decrease when the storage temperature increases from ambient to high temperature values. However, these are of interest. Firstly, there is a lack of investigation focus on semi-decoupled and decoupled FITS with higher temperature storage. Secondly, these systems will require additional research on storage design to avoid parasitic losses. Lastly, since the charge and discharge are active, new control mechanisms can be investigated for both change and discharge which may have benefits to energy supply systems and the building users. Contrary to passive storage techniques, an active storage system offers an opportunity for active participation in the energy network. It allows the charge and discharge of FITS systems when the energy is available and/or economically valuable.

6. ACKNOLEDGEMENTS

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