CO_2 mitigation accounting for thermal energy storage (TES) case studies

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Abstract

According to the IPCC, societies can respond to climate changes by adapting to its impacts and by mitigation, that is, by reducing GHG emissions. No single technology can provide all of the mitigation potential in any sector, but many technologies have been acknowledged in being able to contribute to such potential. Among the technologies that can contribute in such potential, thermal energy storage (TES) is not included explicitly, but implicitly as part of technologies such as energy supply, buildings, and industry. To enable a more detailed assessment of the CO_2 mitigation potential of TES across many sectors, the group Annex 25 "Surplus heat management using advanced TES for CO_2 mitigation" of the Energy Conservation through Energy Storage Implementing Agreement (ECES IA) of the International Energy Agency (AEI) present in this article the CO_2 mitigation potential of different case studies with integrated TES. This potential is shown using operational and embodied CO_2 parameters. Results are difficult to compare since TES is always designed in relation to its application, and each technology impacts the energy system as a whole to different extents. The applications analysed for operational CO_2 are refrigeration, solar power plants, mobile heat storage in industrial waste heat recovery, passive systems in buildings, ATES for a supermarket, greenhouse applications, and dishwasher with zeolite in Germany. The paper shows that the reason for mitigation is different in each application, from energy savings to larger solar share or lowering energy consumption from appliances. The mitigation potential dues to integrated TES is quantified in kg/MWh energy produced or heat delivered. Embodied CO_2 in two TES case studies is presented, buildings and solar power plants.

Key words: CO_2 mitigation potential, Thermal Energy Storage (TES), Operational CO_2, Embodied CO_2,

1 Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), societies can respond to climate changes by adapting to its impacts and by mitigation, that is, by reducing Greenhouse Gas (GHG) emissions [1]. No single technology can provide all of the mitigation potential in any sector, but many technologies have been acknowledged in being able to contribute to such potential. Among these technologies thermal energy storage (TES) is not included explicitly, but implicitly as part of technologies such as energy supply (improved supply and distributions efficiency, renewable heat and power, combined heat and power, concentrated solar power, etc.), buildings (more efficient electrical appliances including heating and cooling devices, improved insulation, passive and active solar design for heating and cooling, etc.), and industry (heat and power recovery and advanced energy efficiency).

The benefits of TES may not be evident since their effects are not immediate in some cases or they are only appreciable under specific circumstances. A first attempt on accounting for TES potential energy savings and climate change mitigation was carried out by Arce et al. [2]. In this study, an overview of the TES potential in Spain and Europe was given by numerically demonstrating how TES can provide significant energy and environmental benefits on national and continental scales. The sectors considered were buildings (seasonal solar thermal systems, district/central heating, short term solar thermal systems, and passive cold systems) and industry and transport (combined heat and power, heating and cooling in industry, power stations and transport, and concentrated solar power plants). Results showed how the potential load reduction at the EU-level may be of 1,160,695 MWth during the next 10 years. Such impact can exert a strong influence over power capacities to be installed over that period. The share of Germany and Spain in this reduction is of 8% and 9%, respectively. Yearly potential energy savings at the EU-level were estimated to be 7.5%. Regarding electrical energy savings, Spain accounts for 20% of the overall savings at the EU, which amounts to a 0.1% of the electrical energy consumption. Finally, the estimated potential CO_2 emissions reduction in the EU averaged 5.5% (based on 1990 and 2005 levels).

To enable a more detailed assessment of the CO_2 mitigation potential of TES, across many energy intensive sectors, the group Annex 25 “Surplus heat management using advanced TES for CO_2 mitigation” of the Energy Conservation through Energy Storage Implementing Agreement (ECES IA) of the International Energy Agency (IEA) was formed. This group focussed on the CO_2 mitigation potential in several applications and presented case studies with integrated TES. This potential is shown as operational and embodied CO_2. The aim of this paper is to present the results of the comprehensive work conducted by the team members of Annex 25, carried out between 2011 and 2013. The details of each application are discussed; nevertheless numbers are hard to compare since TES is always designed in relation to its application, and each technology impacts the energy system as a whole (e.g. national, or EU level) to various extents.

In order to incorporate eco-objectives into the design process of a product, additional properties than the well characterized engineering properties are needed. These properties (like embodied energy or CO_2 footprint) include measures of the energy committed and carbon released into the atmosphere when a material is extracted or synthesised.

Embodied energy is the energy, excluding bio-fuels, that is used in making 1 kg of material from its ores and feedstock in an industrial production plant. The CO_2 footprint is the sum of all the contributions per unit mass of usable materials existing in a plant. In transport and in most industrial processes, there is a correlation, known as CO_2 factor, between CO_2 emissions and the energy consumption:

$$CO_2 \text{ footprint} \cong 0.08 \text{ Energy consumption}$$

A commonly used value is a carbon footprint of 500 g CO_2/kWh of electricity production, coming from a developed country with an energy mix of 75% fossil fuel, and a conversion efficiency of 38%, giving an oil equivalence of 7 MJ [3].

Due to the low precision of the eco-attributes related to energy and carbon footprint, it is accepted that there is an elevated uncertainty (of about 10 - 20% [3]) for decision making.

The CO_2 mitigation potential accounting is commonly carried out by counting the energy used/saved and translating that to tons of CO_2 using the CO_2 emission factor. But the CO_2 emission factor depends on the country and on the year under investigation. Usually, these issues are not considered, and authors only mention the country or group of countries where the CO_2 emission factor is used for, but scarcely the year. In this article, the CO_2 mitigation potential is shown using the operational and the embodied CO_2. Operational CO_2 refers to the mitigated CO_2 during the operation phase of the component/application while the embodied CO_2 refers to the CO_2 released into the atmosphere when the component/application is made.

Moreover, another key issue is the fact that CO_2 emissions influence is rarely considered when TES is studied in different applications.

2 Operational CO_2 accounting in TES case studies

A variety of technologies has been assessed in terms of the energy savings, and resulting CO_2 mitigation potential from integrating TES. The details of each application are further discussed below, followed by a summarizing assessment.

In the examples discussed below, different TES technologies are used, sensible heat storage and latent heat storage with phase change materials (PCM). In this section, each technology is assessed in their respective country. More detail in these technologies can be found elsewhere [4].

2.1 Refrigeration applications

A model to estimate the potential Spanish and European impact when using TES for cold production, in terms of energy consumption and CO_2 emissions reduction, was developed in a previous publication [5]. Table 1 shows all the cases analysed and the electricity savings due to the implementation. The total energy demand for cold applications in Spain and Europe was calculated, and after that the energy reduction and therefore CO_2 emissions mitigation was determined assuming a full implementation of the PCM (phase change materials) TES systems (Figure 1). Two scenarios have been studied, the low and the high scenario. The low scenario accounts for the lowest factors of electricity savings, while the high scenario accounts for the highest values of energy savings found in the literature.

Table 1. Potential electricity savings related in the maintenance of low temperature sensitive products [5].

Cases analysed	Sector	Authors	Electricity savings
Domestic refrigerators	Domestic and commercial sector	Azzouz et al. [6]	During normal working conditions, 10-30% COP
Domestic freezer		Gin et al. [7]	During defrost cycle by 8%, and by 7% during door openings
Domestic refrigerator (refrigerator and freezer)		Subramaniam et al. [8]	During normal working conditions by 8%
Refrigerated trucks (PCM on the walls)	Cold in road transport	Ahmed et al. [9]	Daily average reduction of the heat flux from the ambient to the refrigerated truck of 16.3%
Refrigerated trucks (novel refrigeration system incorporating PCM)		Liu et al. [10]	During normal working conditions between 6 and 38%, depending on the chosen scenario
Industrial refrigeration	Cold in industry	Cheralathan et al. [11]	During normal working conditions, 6-20% SEC (kW/TR)
Refrigeration plants		Wang et al. [12]	During normal working conditions, 4-8% COP

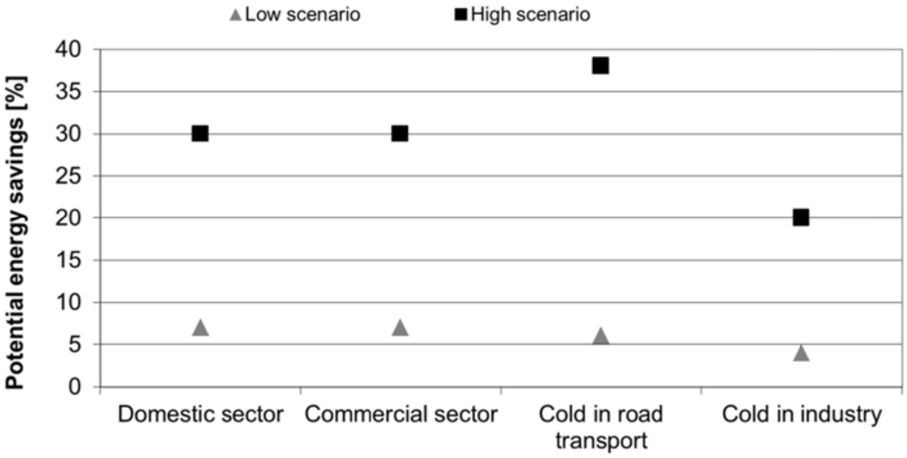

Figure 1. Potential electricity savings in cold applications using different scenarios [5].

Among the cold applications identified, the industry sector shows the highest potential of all the sectors analysed (Figure 2). Related to economical savings on their final energy consumption, Spain could save between 239 and 1,760 millions of € and Europe between 4,430 and 28,547 millions of €, depending on the scenario evaluated. However, these economical saving are over estimated as they do not include the capital cost of implementation of PCM-TES in the actual systems.

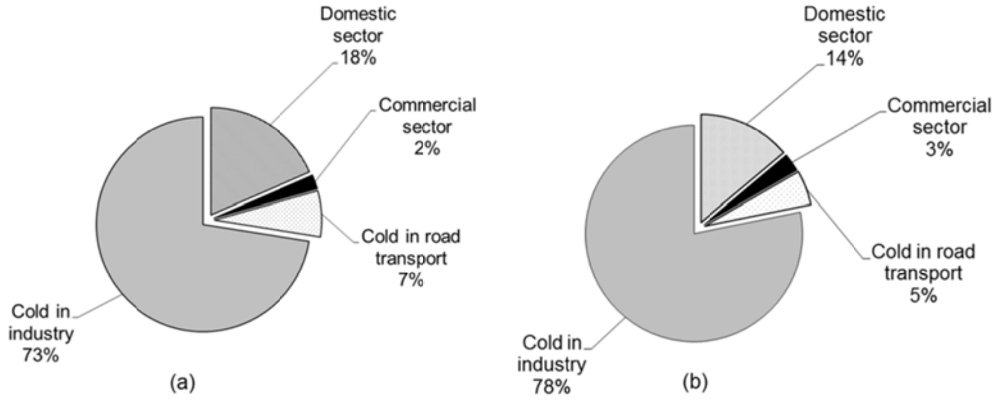

Figure 2. Distribution of the energy consumed yearly for cold applications in Spain (a) and Europe (b), 2008 [5].

Thus, in Spain, the annual CO_2 emissions from the cold storage and cold transportation systems may be reduced from 4% to 21%. In relation to European CO_2 emissions mitigation, these emission reduction values range from 5% to 22%. Even though on an overall level the impact of the implementation of PCM-TES systems is barely 1% compared to the total CO_2 emissions in 2008 in Europe, it could be much more important that it seems. One can realize that the domestic cold and some of the energy to industry is probably during peak hours and therefore produced with higher CO_2 factor. Then, the emission factors become much higher because here the marginal production factors have to be account instead of the energy mix factors being. Moreover, this implementation could come to alleviate the peak load and hence improve grid stability.

2.2 Solar power plants

Powell and Edgar [13] carried out a dynamic simulation for a TES unit used in a parabolic trough CSP system. The system considered is presented in Figure 3. According to these authors, the use of a thermal storage gives the system ability to provide power at a constant rate despite significant disturbances in the amount of solar radiation available. By contrast, a CSP system without thermal storage undergoes large fluctuations in power output, particularly during intermittent cloud cover. Adding a storage system increases the solar share of the power plant by as much as 47% for a base load thermal power output of 1 MW. This reduces the supplementary fuel requirement by as much as 43%.

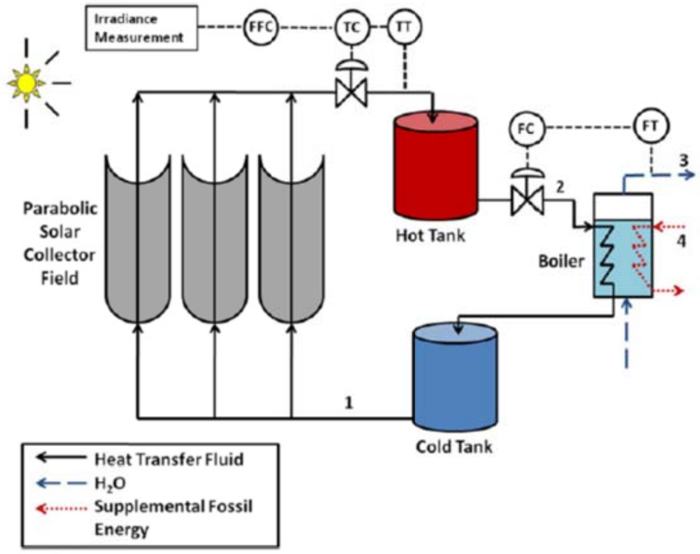

Figure 3. Two-tank direct TES system used with a parabolic trough solar collector field [13].

A summary of the results obtained by Powell and Edgar [13] are presented in Table 2. The results of these simulations show that, by adding 8 h of storage capacity, the solar share (the fraction of energy provided by solar) of the power plant can be increased by as much as 47% to levels over 70% on a sunny day. The improvements in solar share are more meagre on cloudy days. However, during intermittent cloud cover, the main benefit of thermal energy storage is the ability to maintain a constant power output by using the storage tank as a buffer between available energy and energy demand (Figure 4).

Table 2. Summary of results obtained by Powell and Edgar [13].

Variable	Clear day		Cloudy day	
	System w/o TES	System with TES	System w/o TES	System with TES
Solar energy delivered to load (MWh)	16.48	16.82	8.40	8.49
Supplemental fuel required (MWh)	12.58	7.18	15.78	15.51
Solar share (%)	47.6	70.1	34.3	35.4

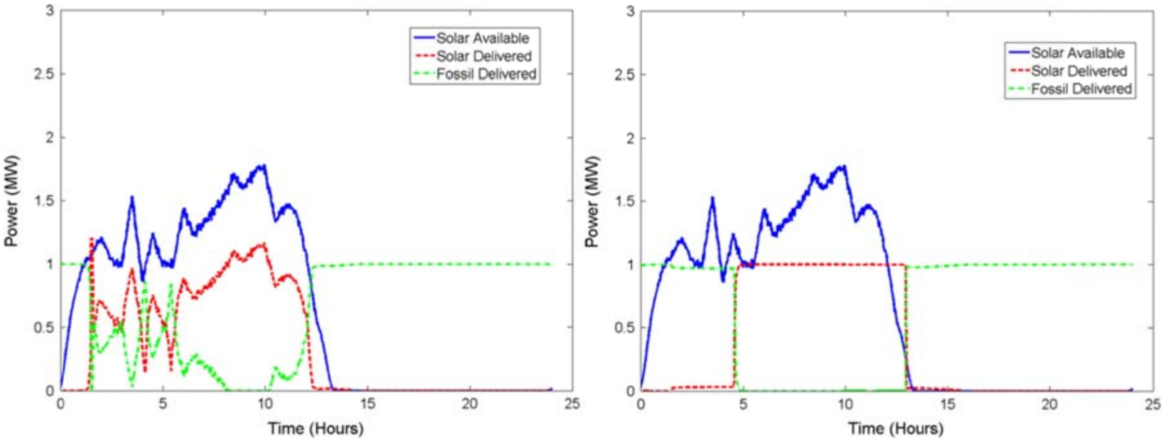

Figure 4. Total solar energy available and energy delivered to the load on a partly cloudy day for: left – system without storage; right – system with storage [13].

From results presented in Table 2, the mitigation of CO_2 emissions in a CSP plant when TES is implemented can be calculated as a function of the fuel used for hybridation (Table 3). Since the supplementary fuel requirement is reduced by 43%, CO_2 emissions will be also reduced by 43%.

Table 3. CO_2 emissions (tCO_2) in a 1 MW output CSP plant with and without TES.

Variable	Emission factor of the fuel considered, tCO_2/TJ	System w/o TES	System with TES
Supplemental fuel required (MWh)	---	12.58	7.18
CO_2 emissions (tCO_2)	Coal (94.6-96.1 [14])	4.28 – 4.35	2.45 – 2.48
	Natural gas (56.1 [14])	2.54	1.45
	Oil (73.3-77.4 [14])	3.32 – 3.51	1.89 – 2.00

2.3 Mobile heat storage in industrial waste heat recovery

Transport of heat by truck, train or boat, “heat on wheels”, is a promising supplement to the currently used systems of piped thermal energy distribution or of use of waste heat from industry (Figure 5). The concept requires that the heat can be stored in a material with a high energy density, i.e. a large amount of heat per unit of weight and volume. Mobile energy storage systems transported by truck may bridge the gap between heat source and demand site in cases where a pipeline-bound connection cannot be realized cost effectively.

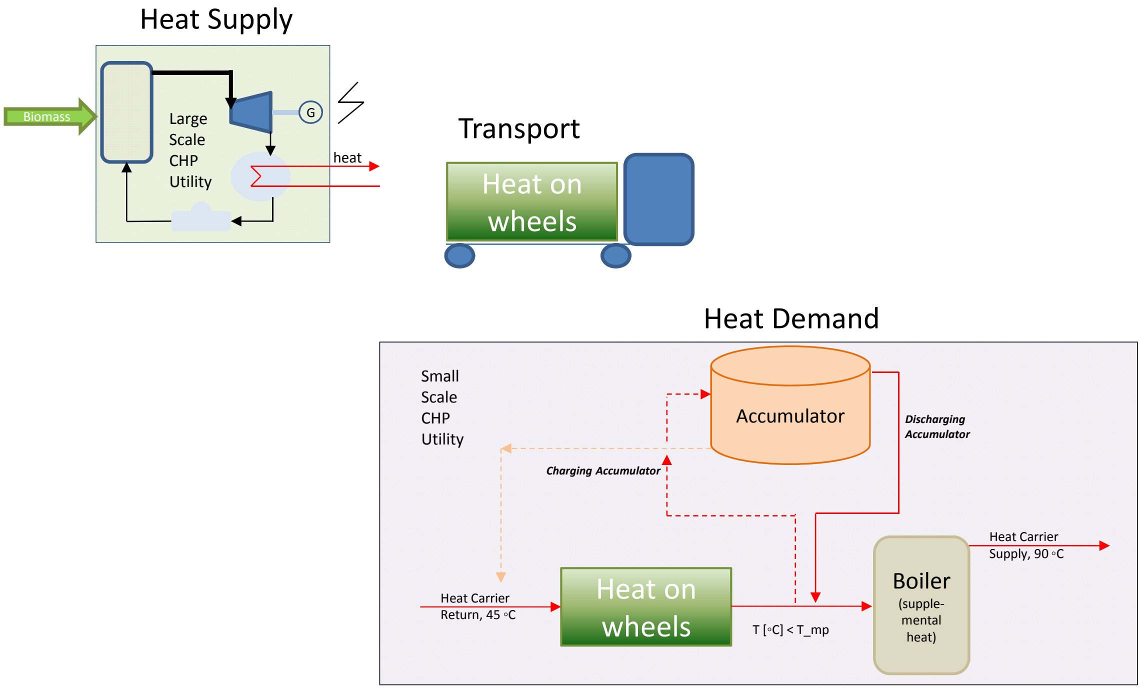

Figure 5. Schematic description of the heat on wheels concept [15].

Based on this result ZAE Bayern and its partner Industrieanlagen Hoffmeier GmbH have developed and built a prototype of a mobile storage based on an open sorption system, working with a packed bed of zeolite as adsorbent. A pilot plant with a waste incineration plant as a heat source and an industrial drying process as demand site was built (Figure 6). The system has been operated for about 50 cycles so far and the test period is still running.

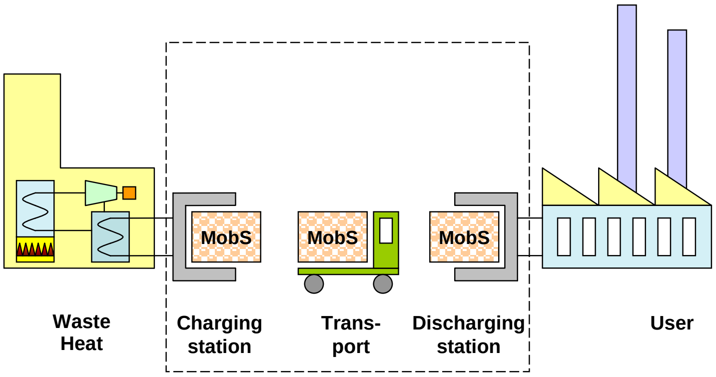

Figure 6. Principle of Mobile Sorption Heat Storage in Industrial Waste Heat Recovery [15].

Table 4 contains the necessary parameters to estimate the potential CO_2 mitigation achieved by this mobile sorption heat storage.

Table 4. Parameters for CO_2 mitigation accounting.

Storage	
Energy content per storage [MWh]	2.91
Storage efficiency	0.9
Boundary conditions	
Distance [km] (one way)	10
Auxiliary electric energy / cycle [MWh]	0.11
Specific fuel consumption truck [l/100km]	55
Annually number of storage handling	1,051
CO_2 emission factors	
gas [kg CO_2/MWh]	202
electricity [kg CO_2/MWh]	773
fuel (diesel) [kg CO_2/l]	2.64

The energy savings are equal to the amount of substituted gas (2.62 MWh) accounted as the energy content per storage (2.91 MWh) times the storage efficiency (90%). Multiplied with the corresponding CO_2 emissions factor, 530 kg CO_2 savings per storage can be achieved. However, CO_2 emissions due to auxiliary electric energy (85 kg CO_2) and the fuel consumption of the truck (29 kg CO_2), have to be subtracted, thus the total amount of CO_2 mitigation per container is 416 kg CO_2. Considering annual storage handling, the amount of CO_2 mitigation per storage container per year will be 437 t CO_2.

If 10 to 100 mobile heat storage systems could be established in Germany in the medium term the potential CO_2 mitigation in Germany would be around 4,000 – 40,000 tons CO_2 per year. This range refers to the physical potential of CO_2 mitigation while the other applications studied in this paper refer to technical potentials, as defined in [1].

Similarly, the transport of excess heat from a large-scale biomass- based combined heat and power plant to local smaller "boiler-based" utilities has been studied by the Swedish District Energy System. Initially, the market for heat transportation with truck (train or boat) was assessed by considering statistics on cities with population and connected to district heating systems. Other assumptions were that the single household on average is occupied by 2.5 persons and utilizes 20 MWh of heat per year.

Here, the market results show that smaller cities (between 200 and 10,000 inhabitants) with district heat already in place, generate a yearly heat demand of about 11 TWh. If the total demand would be provided by energy transport from the large CHP utility, the additional biomass-based power generation in these plants would amount to about 7 TWh. The effect on CO_2 mitigation on such scenario can be analysed as follows:

1. CO_2 mitigation is obtained through replacing heat and electricity generated by green alternatives. This is due to:
    a. Replacing heat from an oil-based boiler (approximately 300 g/kWh) by heat from biomass CHP.
    b. Replacing electricity from EU average mix (approximately 350 g/kWh), with zero CO_2-emission power from biomass CHP.

    For this case, the expected CO_2 mitigation is 5.8 Mt/year, which is about 10% of the present Swedish total annual CO_2-emissions.

2. CO_2 mitigation is obtained through the generation of electricity only since heat is normally generated in a local, smaller-scale biomass boiler.

    For this case, the expected CO_2 mitigation is 2.4 Mt/year for Sweden.

2.4 Passive systems in buildings

It is well known that the use of latent heat storage in building passive systems could reduce the energy consumption of the HVAC systems. These reductions have been analysed both experimentally and numerically.

In summer, during daytime the sunshine and high temperatures result in a heat wave penetrating the walls of the buildings (Figure 7). PCM absorbs the excess of heat through its melting process, delaying the heat wave penetrating the building, and also reducing its peak. During most of the day the room temperature remains comfortable and the cooling system consumes less energy. During night time, when outdoor temperatures become lower, the PCM releases the stored heat through its solidification process to both internal and external environments, keeping again the room temperature comfortable, closing the cycle and being ready for another daily use.

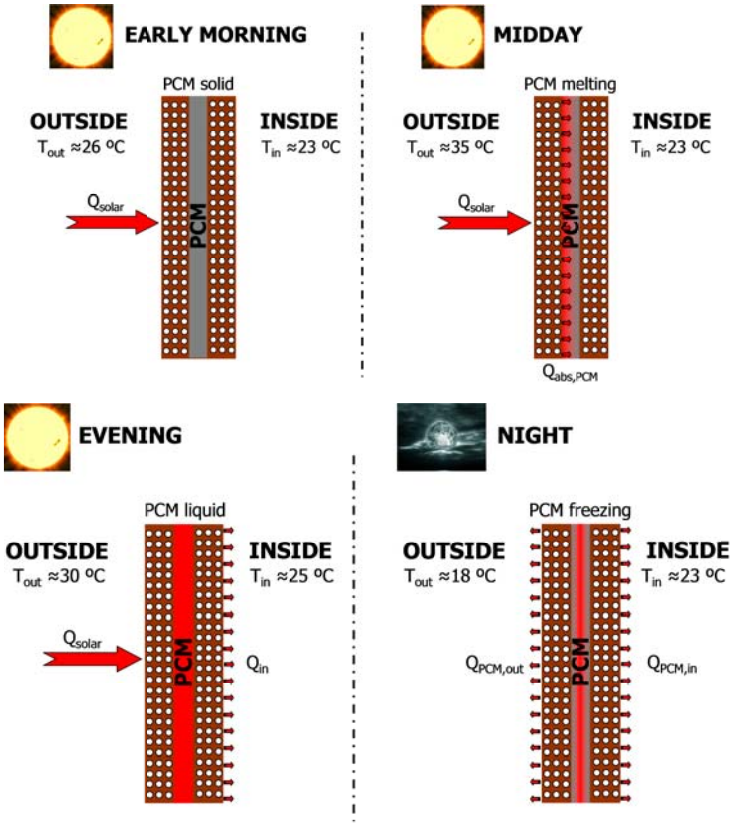

Figure 7. Operating principle of PCM in buildings [15].

Table 5 shows measured data of energy consumption and compares the energy performance of different cubicles located in Puigverd de Lleida (Spain) in order to quantify the energetic benefits of using PCM [16].

From the energy consumed in each cubicle, the CO_2 emissions to the atmosphere can be estimated. According to the Spanish electricity production share, a CO_2 emission factor of 238 g/kWh is used for this estimation.

Table 5 presents CO_2 emissions and electrical energy savings for different cubicles, considering a set point of 24 ºC during 90 days per year (cooling demand). The study presents the performance of a cubicle with traditional constructive system without insulation (REF), with 5 cm of polyurethane (PU), with polyurethane and PCM (RT27+PU), a system without insulation but with high thermal mass (Alveolar) and the same system with PCM (SP25+Alveolar). The constructive systems of the different cubicles are detailed in Castell et al. [16]

Table 5. CO_2 emissions to the atmosphere due to the electricity consumption in each cubicle [16].

	Electricity consumption (kWh/year·m^2)	CO_2 emissions (kg/year·m^2)	CO_2 savings (kg/year·m^2)
Reference	29.3	7.0	0.0
PU	14.3	3.4	3.6
RT27+PU	12.2	2.9	4.1
Alveolar	15.8	3.8	3.2
SP25+Alveolar	13.1	3.1	3.9

Moreover, the same experimental set-up was used to test the energy performance of a ventilated double skin facade (VDSF) with macro-encapsulated panels with PCM inside its air cavity. This system was designed to reduce the heating demand during the winter season. The VDSF acts as a solar collector during the sunny hours and once the PCM is melted and the solar energy is needed by the building heating demand, the heat stored is discharged to the inner environment as a heating supply. According to de Gracia et al. [17] the electrical energy required by the heat pump to maintain a set point of 21 ºC during heating season is reduced by 20.6% due to the use of this VDSF.

Table 6 quantifies the amount of CO_2 emissions that would be saved due to the use of PCM in this active system. An energy mix of 238 g CO_2/kWh is also considered in this case.

Table 6. CO_2 emissions to the atmosphere due to the energy consumed in each cubicle [17].

	Energy consumption ($kWh/year \cdot m^2$)	CO_2 emissions ($kg/year \cdot m^2$)	CO_2 savings ($kg/year \cdot m^2$)
Reference	191.8	45.6	0.0
VDSF	152.1	36.19	9.4

Moreover, the thermal performance of a single family house with and without PCM, impregnated in the gypsum board, was numerically investigated in 10 different cities around the world with different climates [18]. The paper discusses the influence of the climate in the potential that PCM can provide for energy savings. Table 7 presents the energy savings achieved under the different climate conditions.

Table 7. Electricity consumption of the house and the energy savings provided by the PCM [18].

Country	Energy per year (no PCM) [GJ]	Savings per year (with PCM) [GJ]	Savings per year (%)
Bogota	8.39	2.60	31
Quito	7.27	2.40	33
San Francisco	14.62	1.90	13
Auckland	13.64	1.50	11
Brisbane	14.00	1.40	10
Montreal	110.00	1.10	1
Madrid	27.50	1.10	4
Stockholm	45.00	0.90	2
Kuala Lumpur	15.00	-0.30	-2
Singapore	20.00	-0.40	-2

These savings in the electrical energy needed to achieve thermal comfort conditions during the whole year (set point of 20 ºC for heating and 23 ºC for cooling) represent reductions in the amount of CO_2 emitted to the atmosphere. According to IEA [19] the worldwide CO_2 emissions per kWh from electricity generation present slight variation during the last 20 years, presenting a value of 564 gCO_2/kWh for 2010. Moreover, the IEA report also provides the energy mix of each country. Table 8 presents the amount of CO_2 that has been saved at the different analysed locations if considering a global worldwide energy mix and a country ratio. One can see that for some locations, the amount of CO_2 saved is very different depending on the chosen CO_2 emission factor.

Table 8. CO_2 reduction from space heating and cooling considering a global worldwide energy mix [18].

City (Country)	CO_2 reduction [$kgCO_2$/year·m^2] Worldwide energy mix	CO_2 reduction [$kgCO_2$/year·m^2] Country energy mix
Bogota (Colombia)	1.59	0.50
Quito (Ecuador)	1.47	1.01
San Francisco (USA)	1.16	1.08
Auckland (New Zealand)	0.92	0.24
Brisbane (Australia)	0.86	1.28
Montreal (Canada)	0.67	0.22
Madrid (Spain)	0.67	0.28
Stockholm (Sweden)	0.55	0.03
Kuala Lumpur (Indonesia)	-0.18	-0.24
Singapore (Singapore)	-0.25	-0.22

A similar experimentation was carried out in a 4 m^2 floor area test cabin in Adana, with cooling and heating loads 2391 W and 665 W, respectively [20,21]. In this case, two microencapsulated PCM - Micronal 5001 (melting point 26 °C and latent heat 110 kJ/kg) and Micronal 5008 (melting point 23 °C and latent heat 110 kJ/kg) – were used to produce sandwich panels with insulation material Izopan. The south facade of the test cabin was lined with sandwich panel. Total amount of PCM used was 3.5 kg. The tests were carried out with PCM only, insulation only and sandwich panel linings. In summer, day-time temperature in the cabin was reduced by 2.5 °C in the case of using PCM only and 0.6 °C when only using insulation. Cooling loads were reduced by 7 % as a result of using PCM in the summer operation, which accounts for energy saving of 186 kWh/year. In winter, the average temperature inside the cabin was increased by 1.6 °C with PCM only, 1.3 °C with only insulation and 2.2 °C with sandwich panel (insulation together with PCM). Under these conditions, heating loads were reduced by 10% and 23% when PCM and sandwich panel were used, respectively. Energy conserved for heating was 292 kWh/year.

Calculating the heating using coal and air-conditioning using electricity produced from coal, the CO_2 mitigation in the cases presented in Table 8 was 0.5 ton/year as average.

2.5 Aquifer Thermal Energy Storage (ATES) for a supermarket

This was the first ATES project in Turkey and in Mediterranean climate. The gross area for the building was 1800 m^2 and 1400 m^2 of this area was air-conditioned. The peak loads for cooling and heating were 195 kW and 74 kW, respectively. The ATES system (Figure 8) contained two groups of wells - each at 100 m depth - connected to HVAC system [20,22]. In the cooling mode, groundwater from the cold well was used to cool down the condenser of the HVAC system and at the same time storing this waste heat in the aquifer through the warm well. Cooling with groundwater at around 18 °C - instead of outside summer air at 30-35 °C - decreased consumption of electricity significantly. The stored heat was recovered from the warm well in the heating mode, when it is needed in winter. The total energy that was stored in this operation is 0.4 MWh. A conventional system with air cooled condenser consumes 898 kWh/day to meet the peak cooling demand of 2400 kWh/day. The average COP is 2.67 for such a system. The ATES system started operation with cooling mode in August 2001. Using groundwater at 18°C yielded an average COP of 4.18, which was almost 60% higher than that of conventional system. Because of 60% higher COP, heat pump of the ATES system was down-sized, making the system more economically viable. The extra investment that was required for drilling of the wells was cancelled out with the decrease on investment of heat pump. With this performance ATES system consumed 574.2 kWh/day. Total annual electrical energy conservation introduced by ATES system was 118 MWh. Assuming that electricity is produced with coal, this would mean 113 ton/year of CO_2 mitigation.

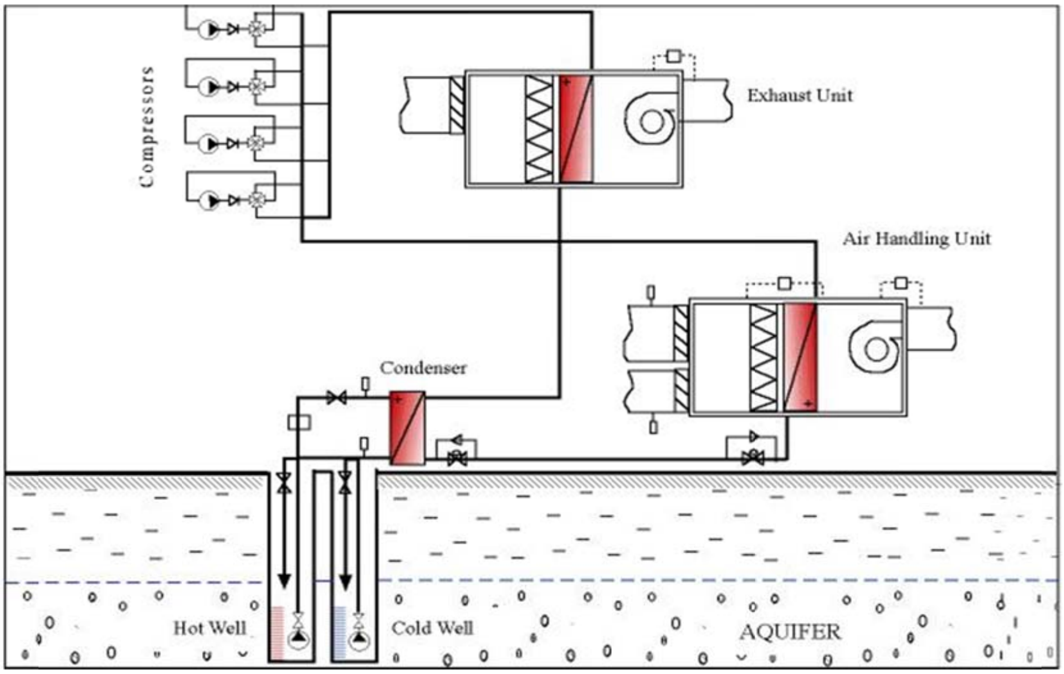

Figure 8. ATES system for supermarket [22].

2.6 Greenhouse applications

Energy management in commercial greenhouses aims at ensuring sustainable growth of fruits, vegetables, and ornamental plants. It is an issue that will become increasingly important as we address the need for sustainable energy services, conservation of water resources, and food production for all, in combine.

In 2007 two separate greenhouses with polyethylene covers, each having an area of 360 m^2 at Cukurova University (Turkey) research farm were used [20,23]. One of the greenhouses was heated and cooled by ATES technique and the other one with a conventional heating system and no cooling. Two wells- a cold and a warm well – were operated for the ATES greenhouse. The basic concept of the ATES system utilized the heat stored from summer to heat the greenhouse - as well as the cold stored in winter for cooling in summer. Greenhouse was the "solar collector" to store heat in sunny days. A schematic diagram of the ATES system is shown in Figure 9.

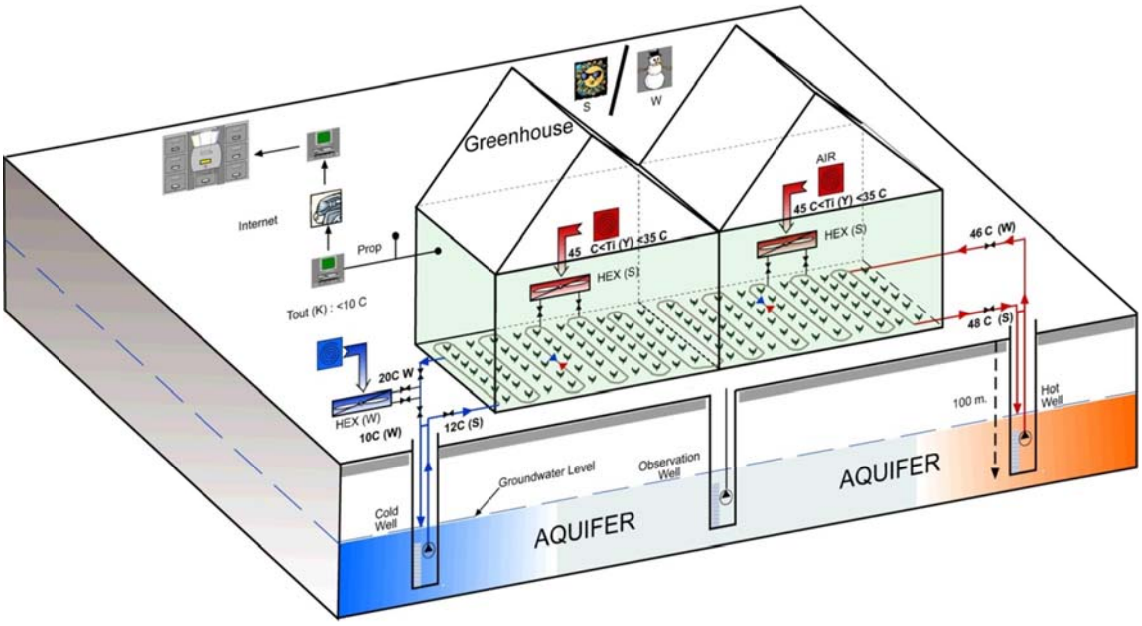

Figure 9. Schematic diagram of the ATES system for greenhouse [23].

Temperatures in the greenhouse varied between 40-60 °C about 6 hours/day for 5 months in this climate. Winter air colder than 10 °C is the source for cooling. The ATES system operated during 2005-2006 for 70 days storing heat and for 138 days heat recovery and cold storage. Total energy stored in the warm well in this period was 103.9 GJ. In this heat storage process, groundwater temperature increased from 18-20 °C to 30-35 °C. Heat stored was recovered in winter to heat the greenhouse, when inside temperatures were below 11 °C (minimum temperature allowable for growth of tomatoes). Total energy stored in the cold well during heat recovery was 76.0 GJ. Cold stored was recovered for cooling of the greenhouse for 32 days in spring 2006. When temperature inside the greenhouse exceeded 30°C, the ATES system was used for cooling. The product yield of tomatoes in the ATES greenhouse-in terms of fruit weight- was 40% higher than those for the conventional greenhouse. During the total operation of ATES system in 2005-2006, no fossil fuel for heating was consumed. Additionally, it was possible to cool the greenhouse in a period when under

Mediterranean climate conditions production would have been halted. Thus, the yield from the harvest was increased further. The conventional greenhouse was heated using fuel oil No.6. For the ATES system 3 MWh of electricity was used to run the fan coils and pumps for groundwater circulation. For 2005-2006 operation of the system, COP for heating and cooling were 7.6 and 3.2, respectively. Total energy conserved was 36 MWh/year.

Considering that greenhouses in Turkey are heated with fuel oil, 26 ton/year of CO_2 could be saved in every greenhouse. The total greenhouse area in Turkey was more than $7x10^7$ m^2 in 2005. With introduction of ATES systems in greenhouses, CO_2 emissions can be reduced by 5 million tons /year with an extra investment of 280 million USD. Accordingly 163 million USD worth of fuel oil would be saved per year.

Energy management in a greenhouse located in Nordic climate has also been considered, implementing the closed greenhouse concept [24]. Here, the summer excess heat is harvested instead of ventilated, stored and used at a later time, e.g. for winter heating through seasonal storage. For this study, the means of harvesting was by way of integration a PVT-panel as a shading device, generating electricity at the same time as collecting heat. This concept is schematically illustrated in Figure 10.

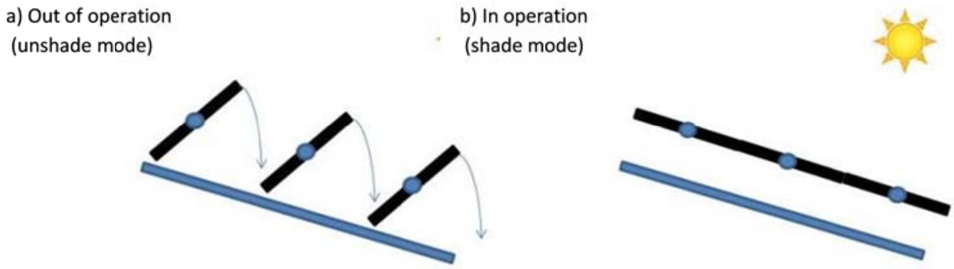

Figure 10. Schematic profile view of solar blind [24].

This concept was analysed based on annual energy performance using TRNSYS simulations. This showed that the harvested excess heat could be used to cover about 20% of the annual heating demand, at the same time as electricity was generated to cover about 20% of the electricity demand as well. Depending on the mode of heating/electricity generation that is replaced, these savings can be translated into an annual CO_2 mitigation as shown in Table 9.

Table 9. A comparison in CO_2 reduction for closed greenhouse with and without considering the solar blind system [24].

Conventional Greenhouse Energy Source →	**Biomass**	**Fuel Oil**	**Electricity**	**Natural Gas**
Closed Greenhouse without solar PVT blind	-11%	74%	62%	71%
Closed greenhouse WITH solar PVT blind	26%	83%	74%	81%

As shown, the values are also there for a closed greenhouse where the heat is not harvested using solar PVT blinds [25]. Then, more of the annual heating demand can be covered (over 50%) but no electricity is generated in the process. For this case, heat is collected at much lower temperature and thus an electrical heat pump is needed to adjust the temperature of the heat. Then, the closed greenhouse might even have a negative impact on climate mitigation if the harvested, stored excess heat would replace heat from a biomass boiler. This means the CO_2 emission is not reduced in comparison with the conventional greenhouses in this case. However, combining the closed greenhouse with the solar blind system such that a portion of the electrical demand is provided by the PVT panels, the CO_2 emission can be reduced by 26% as compared to a conventional greenhouse using biomass for heating. Furthermore, more than 74% CO_2 emission reduction can be achieved in case of using fuel oil, electricity and natural gas as the external energy source for heating purpose in the greenhouse. These numbers all assume the EU27 Energy Mix for Power Generation.

2.7 Dishwasher with zeolite in Germany

Open adsorption systems using water as adsorbate, zeolite as adsorbent and air as heat and mass carrier can be used for heating, cooling and thermal energy storage (TES). Drying processes are a promising field of application for open adsorption systems, since air can be dehumidified in an adsorption cycle. For example, the energy consumption of dishwashers can be reduced by means of an open adsorption system [26]. Therefore, the water heating phase of the main washing cycle has been used to desorb a packed bed of zeolites. The common water heating phase before the drying of the dishes has been omitted and replaced by an adsorption phase in which the dishes are dried by hot air. In this context the adsorption system was used as a thermally driven heat pump and a thermal energy storage system. The reduction of the energy consumption compared to a conventional dishwasher from about 1.05kWh to 0.80kWh per washing cycle leads to energy savings of about 24 % [26]. This innovative dishwasher is commercially available since November 2009.

The assumptions made in the CO_2 mitigation calculation of this system were: energy savings of 0.25 kWh per washing cycle and an average of 250 washing cycles per year with a dishwasher lifetime of 10 years. A CO_2 emissions factor of 0.5 kg CO_2/kWh was considered. An annual number of 1 million installed dishwashers with zeolite drying is considered in order to demonstrate the potential energy savings and CO_2 mitigation due to a wide application of this TES system. Calculated energy and CO_2 emissions savings are presented in Table 10.

Table 10. Energy and CO_2 savings due to an extensive use of a sorption storage system for dishwashers. Detailed boundary conditions are given in the text.

Savings	**After 1st year**	**After 10 years (cumulative value)**
Energy	62.5 GWh	3,440 GWh
CO_2 emissions	31,250 tons	1.7 megatons

Today, some dishwashers with zeolite drying only consume around 0.73 kWh of electricity per cycle and, hence, lie 10% below the limits for the top-grade energy efficiency class A^{+++} [27].

In a recent study by Santori et al. [28], a silica gel was investigated as an adsorbent material for the drying stage of a dishwasher. Tests of an optimized prototype showed an electric power consumption of 0.636 kWh corresponding to a reduction of energy consumption of about 40% compared with the standard cycle of an energy class A standard dishwasher (1.08 kWh according to [28]).

Therefore, assuming higher energy savings of 0.4 kWh per washing cycle and 250 cycles per year, the cumulative energy and CO_2 emission savings after 10 years would be approx. 5,500 GWh and 2.8 megatons per 1 million dishwashers, respectively.

3 Embodied CO_2 accounting in TES case studies

The embodied energy is the energy that must be committed to produce a unit mass of a material from whatever it is made from. It includes the embodied energy involved in the extraction, primary production, transformation, transport to its place of use and recycling [29]. Similarly to operational CO_2, to translate the embodied energy into embodied CO_2 in any application, the energy mix factor should be used.

3.1 Buildings

By using the CES Selector software the relation between the embodied energy vs. the CO_2 footprint of the primary production of several typical building materials can be plotted as shown in Figure 11 [30]. The same type of data can be obtained for the processing and recycling of the materials. But usually, more data is necessary to assess, compare and select different materials, and e.g. water usage in its production (Figure 12).

Jiao et al. [31] analysed different type of buildings and the materials involved. They reported that more than 90% of a building is concrete (Figure 13). The remaining 10% of materials, are brick, wood and steel among some others.

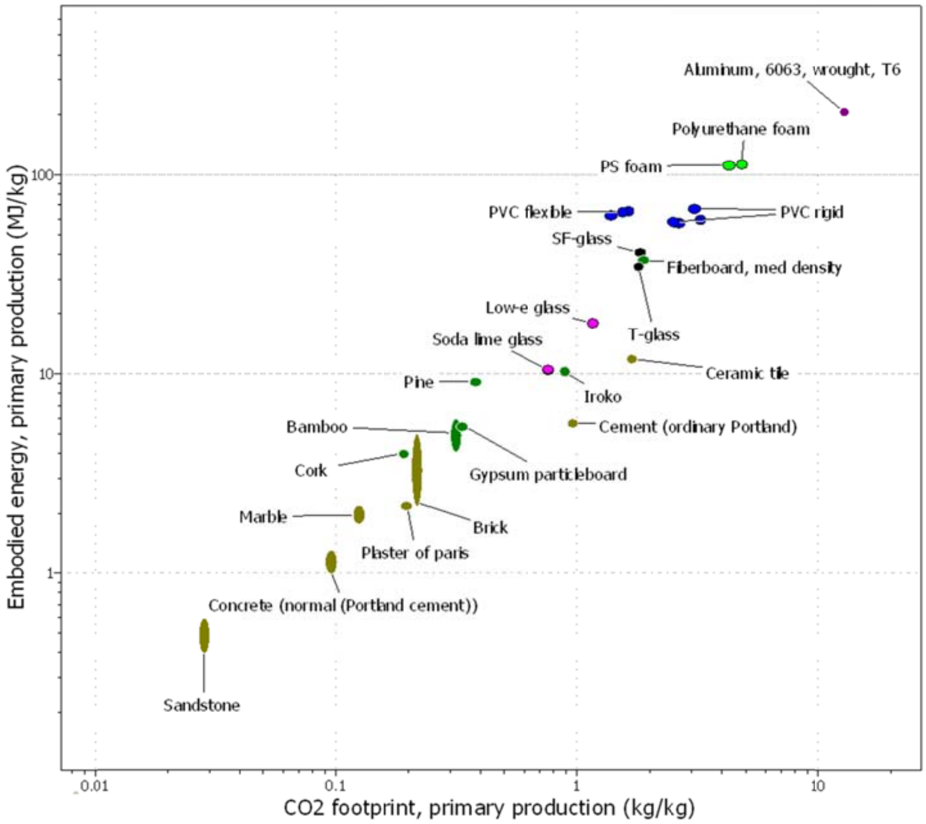

Figure 11. Embodied energy and CO_2 in typical building materials.

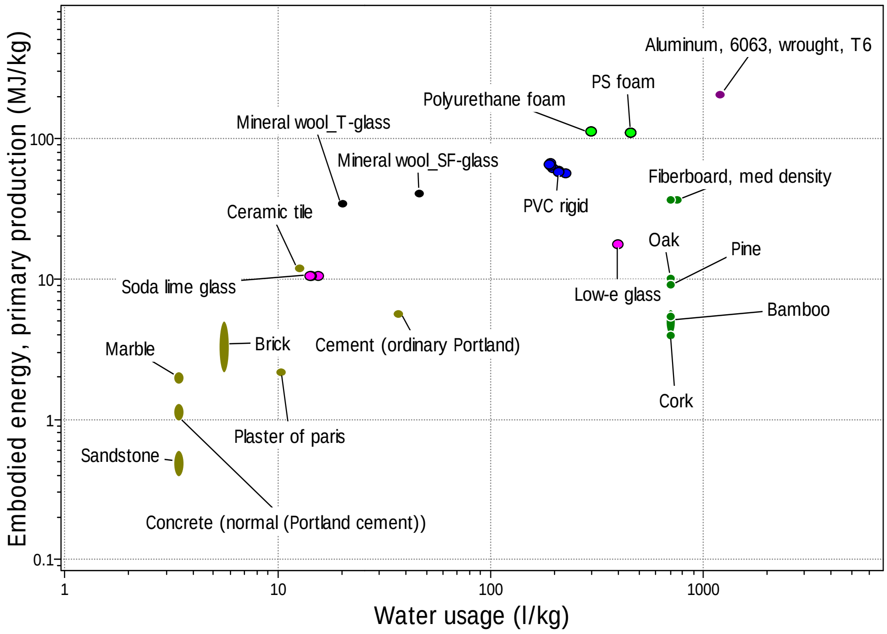

Figure 12. Embodied energy and water usage of typical building materials.

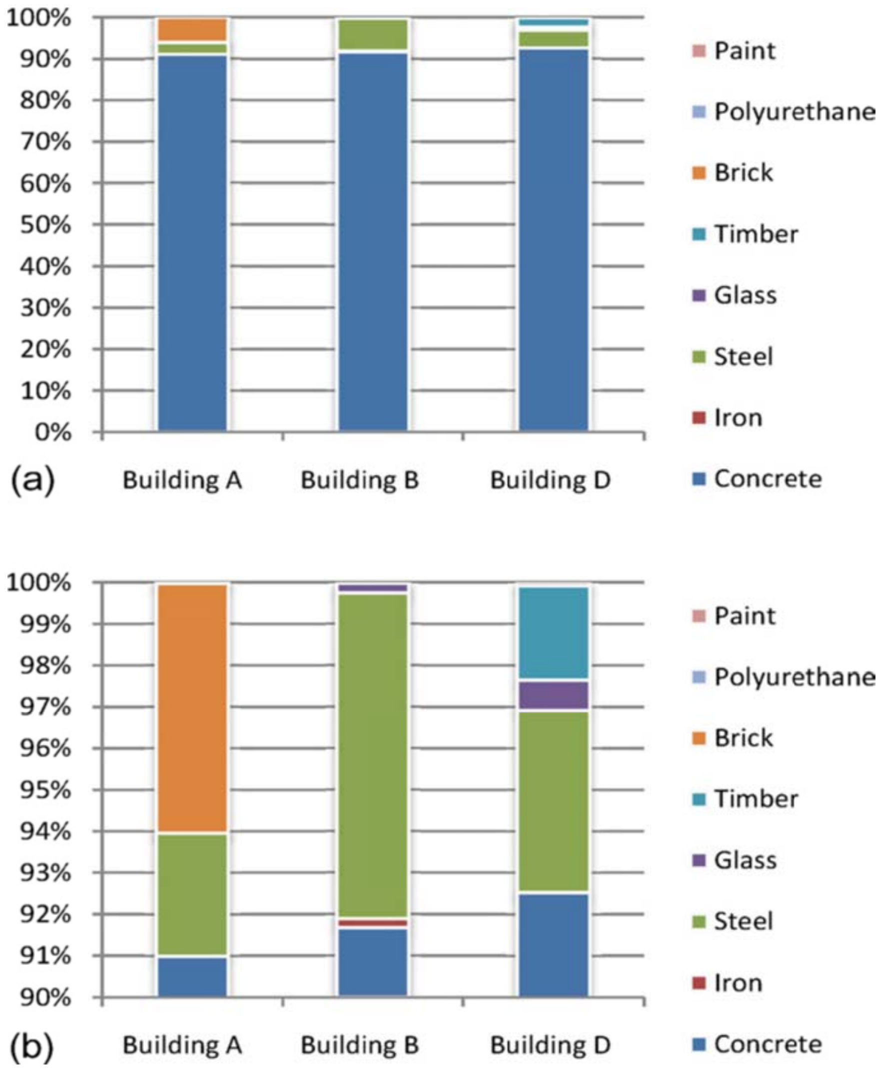

Figure 13. Quantity of materials in a building in % wt. [30].

Clements et al. [32] developed a comparison between the embodied and the operational energy in a building wall:

- The embodied energy (per m^2) can be written as:

$$E_{emb} = H_e \cdot \rho \cdot d$$

where H_e is the embodied energy [kJ/kg]; ρ is the density; and d is the thickness of the wall.

- The operational energy (per m^2) can be written as:

$$E_{use} = \frac{(T \cdot \tau) \lambda}{d}$$

where T is the degree-days per year [K·s]; τ is lifetime of the building, 100 years; λ is the thermal conductivity.

- Therefore, the total energy of a building is:

$$E_{lifetime} = E_{emb} + E_{use}$$

In order to use less energy in the buildings, this $E_{lifetime}$ should be minimized, therefore:

$$Minimum \;\; E_{lifetime} \Rightarrow E_{emb} = E_{use}$$

Giving an optimum thickness of:

$$d = \sqrt{(T \cdot \tau) \cdot \frac{\lambda}{H_e \cdot \rho}}$$

with a total life energy of:

$$E_{lifetime} = 2 \cdot \sqrt{(T \cdot \tau) \cdot (\lambda \cdot H_e \cdot \rho)}$$

Representing this for several materials, one can see that different materials give different energy use during their lifetime, for a given wall thickness (Figure 14). For instance a wall made with brick only; shows the highest lifetime energy, whereas the inclusion of insulation materials (PU foams) reduces the required thickness and the lifetime energy.

The use of PCM incorporated in the building materials makes them composite materials in which there is a change the properties of the original material like density and thermal conductivity. In this way, embodied energy of the composite will be also different. There is not reported data on the embodied energy of materials containing PCM, even though there is ongoing work to estimate it, in order to include some of these materials in a figure like Figure 14.

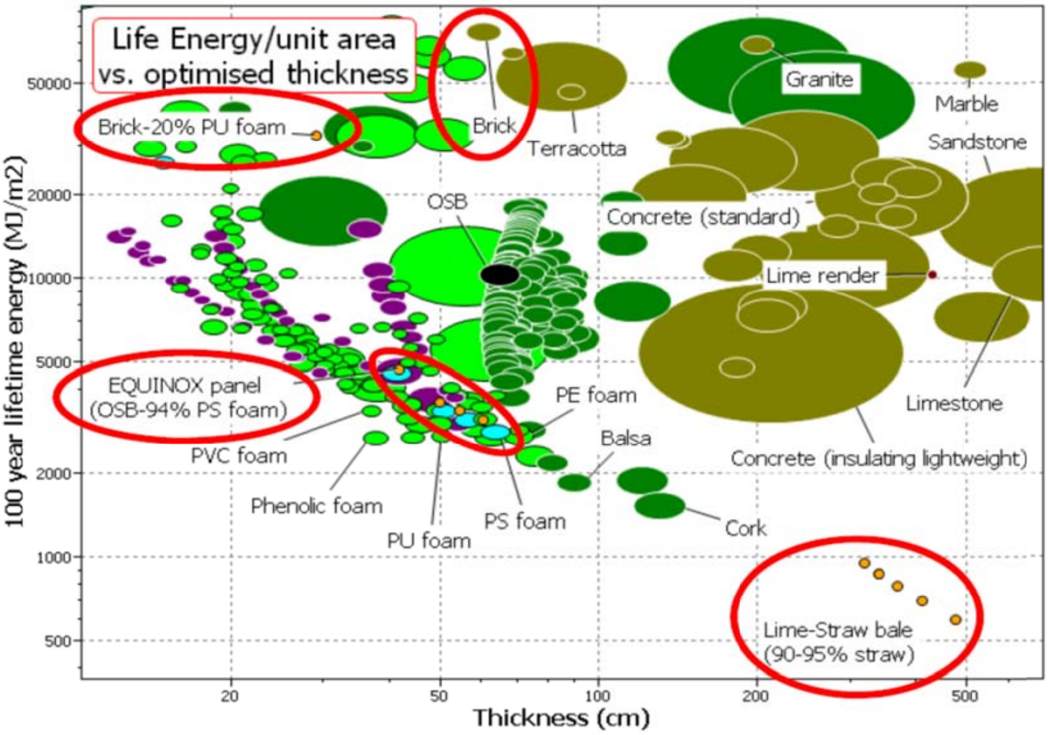

Figure 14. Lifetime energy per unit area vs. optimised thickness of a wall [32].

3.2 Solar power plants

Three different TES systems [33] to be implemented in CSP plants found in the literature have been environmentally analysed and compared during their manufacturing and operation life [33] (Table 11). For that, the embodied energy of the components of these three TES systems has been accounted. The embodied energy of a component is defined as the total energy inputs required to make it.

- System 1: Solid system. Sensible heat is stored in this system using high temperature concrete as storage material.
- System 2: Molten salts system. Heat is stored in liquid media by sensible heat; using molten salts based on a mixture of $NaNO_3$ and KNO_3.
- System 3: PCM system. Latent heat is stored using the same molten salts described system 2 but with different mixing ratio.

Table 11. Storage capacity and storage material used in each system [33].

	Solid system	**Molten salts system**	**PCM system**
Storage capacity (kWh)	350	$600 \cdot 10^3$	100
Storage material	High temperature concrete	60 wt% $NaNO_3$ + 40 wt% KNO_3	46 wt% $NaNO_3$ + 54 wt% KNO_3
Amount of storage material (kg)	26,757	$5{,}500 \cdot 10^3$	2,100

In this analysis the working conditions (temperature gradient, thermal characteristics of the TES materials, etc.) are not considered because this environmental analysis only considers the quantity of the components that form the TES system and their embodied energy.

In order to account for the embodied energy of these three TES systems, a database and a method should be chosen. It has to be taken into account, mainly, the suitability of the database with the components to be studied, the regional validity of the data, and the boundaries of the collected data. In the case of embodied energy, the energy of the extraction, manufacture, disposal, and transport must be considered. For that, EcoInvent database has been chosen. This database provides the needed data to perform environmental analysis that can be useful to determine the impact of the three case studies, between all of them, Cumulative Energy Demand (CED) accounts for the materials embodied energy.

Figure 15 to Figure 17 show the distribution of the most influencing components for the three systems. The most influencing component in solid system is the steel tubes of the heat exchanger. In the molten salts system, the storage component (KNO_3 + $NaNO_3$) is the most significant in the embodied energy accounting. The same trend is observed in the PCM storage system.

In all systems, the components used in the design can be divided into “storage materials”, the material that stores the heat, and “container materials”, the structural and building materials. Figure 18 shows the influence of them. Results show in the solid system, the storage material contribution to total embodied energy are the lowest (around 30 %). In the molten salts systems it is 70 % and 85% in the PCM system.

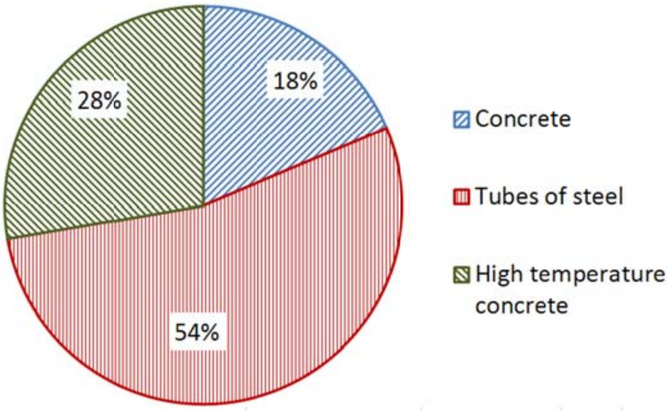

Figure 15. Distribution of the embodied energy most influencing components of the solid system [33].

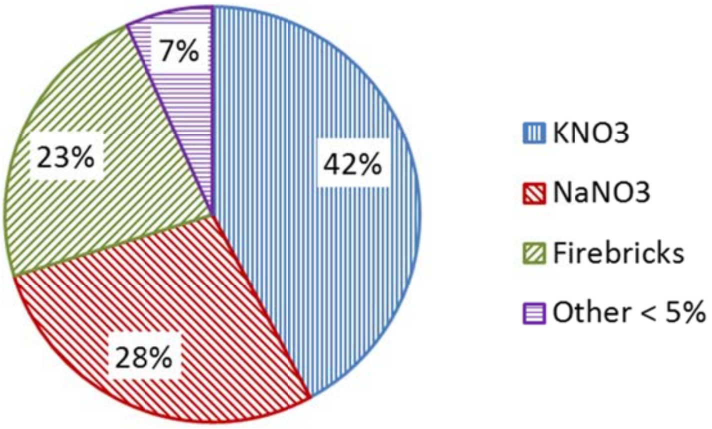

Figure 16. Distribution of the embodied energy most influencing components of the molten salts system ("Other < 5 %" includes all the components that affect less than 5 % in the total distribution) [33].

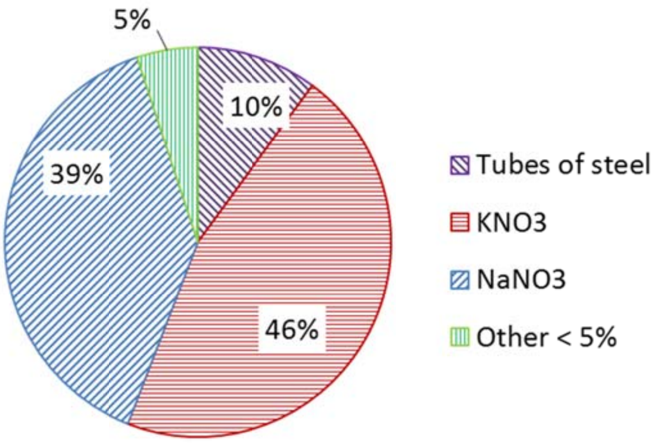

Figure 17. Distribution of the embodied energy most influencing components of the PCM system (“Other < 5 %” includes all the components that affect less than 5 % in the total distribution) [33].

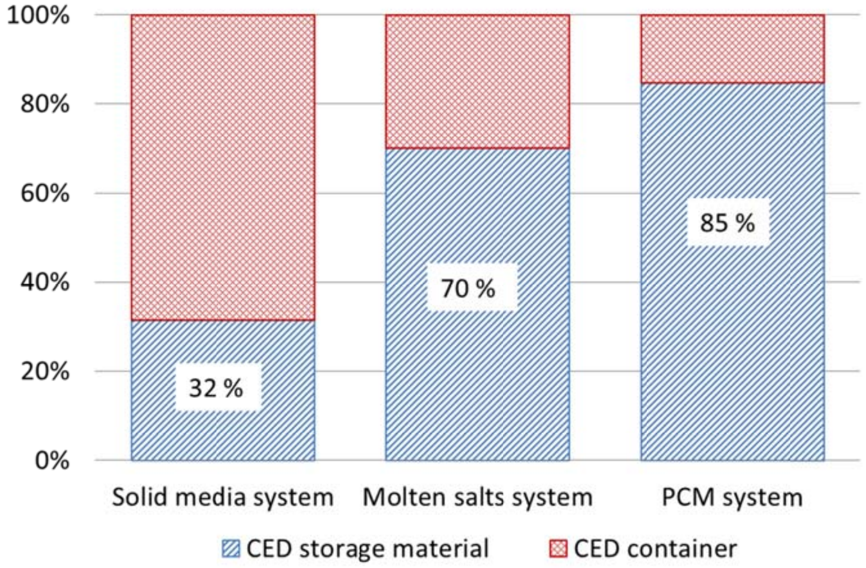

Figure 18. Influence of storage materials and container embodied energy for the three systems [33].

The major advantage of applying this method is that it represents an easy and understandable first environmental screening of the system. Also, it allows the assessment of changes of the system in terms of energy savings. Moreover, it is a global method, meaning that it can be applied to systems around the world. However, this last advantage represents also a big drawback because the energy needed to produce component is different depending on the region, and, this data nowadays is not available.

4 Discussion

A summary of the operational CO_2 mitigation potential of the case studies presented in this paper is presented in Table 12. When the mitigation potential is due to electricity savings, this potential would be very much influenced by the emissions factor, which varies from country to country and from year to year due to the change of the energy mix. Because of this, translating from electricity savings to CO_2 emissions savings is not possible and is not presented in this paper.

Moreover, due to the different reasons for mitigation, a quantitative comparison between the different case studies presented can only be done for each country and not in a general way as it would have been desirable in this paper.

Embodied CO_2 accounting in thermal energy storage has been done only for building materials and for a given case in solar power plants. If the building material is considered as TES material (due to the thermal inertia that can be given by that material), then aluminium and insulation materials are found as the material with higher embodied energy per unit mass, but since buildings usually have much more concrete than any other materials, concrete is the material introducing higher embodied CO_2 in most of today's buildings. Finally, different materials give different energy use during their lifetime when included in a building. This evaluation helps to account the lifetime energy of materials used in buildings.

On the other hand, embodied CO_2 accounting in solar power plants shown in this paper shows that this method can be used to decide where efforts need to be directed to decrease embodied CO_2 in a storage system (or any other energy system). Most researchers direct the efforts only to the storage material, while more CO_2 can be embedded in the container materials or other system components.

Table 12. Summary of CO_2 mitigation potential.

Application	**CO_2 mitigation potential due to integrated TES**	**Main reason for mitigation**
Refrigeration	25-125 [kg/MWh cold produced]	Electricity savings
Power plant with CSP	800-2000 [kg/MWh electricity produced]	Larger solar share
Heat on Wheels – industrial surplus heat for industrial drying in Germany	145 [kg/MWh heat delivered]	Replacing natural gas for industrial drying process
Heat on Wheels – CHP heat replacing local boilers in Sweden	300-500 [kg/MWh heat delivered]	Generating more biomass electricity in CHP plant, and replacing oil in local boilers
Indoor climate control of buildings – passive integration of TES	1-5 [kg/m^2-year]	Lowering energy demand for indoor comfort control (heating/cooling)
Active climate control of Supermarket in Turkey – Heat Pump + ATES	950 [kg/kWh consumed]	Saving electricity due to higher COP of Heat Pump
Closed Greenhouse with ATES (Turkey)	8 [kg/ MWh produced]	Electricity savings for heating
Dishwasher with zeolite	500 [kg/ dishwasher-year]	Lowering energy consumption from appliances

5 Conclusions

Thermal energy storage is one of the technologies with potential to reduce the GHG emissions as being part of technologies such as energy supply, buildings, and industry.

The CO_2 mitigation potential of real case studies which include thermal energy storage (TES) is assessed. The CO_2 mitigation potential is analysed by calculating the operational CO_2, which is the CO_2 mitigated during the operation phase of the component/application and the embodied CO_2, which is the CO_2 released to the ambient while the component/application is made.

When performing these types of environmental analysis it is important to keep in mind that they depend on the energy mix of the country and on the CO_2 emission factor. It should be highlighted that due to the low precision of the eco-attributes related to energy and carbon footprint, it is accepted that there is an uncertainty of about 10 - 20% for decision making.

The applications with TES presented in this article belong to the work performed in the group Annex 25 “Surplus heat management using advanced TES for CO_2 mitigation” of the Energy Conservation through Energy Storage Implementing Agreement (ECES IA) of the International Energy Agency (IEA).

In this paper a variety of technologies has been assessed in terms of the energy savings, and resulting CO_2 mitigation potential from integrating TES. Results are difficult to compare since TES is always designed in relation to its application, and each technology impacts the energy system as a whole to different extents. The applications analysed are refrigeration, solar power plants, mobile heat storage in industrial waste heat recovery, passive systems in buildings, ATES for a supermarket, greenhouse applications, and dishwasher with zeolite in Germany. The paper shows that the reason for mitigation is different in each application, from energy savings to larger solar share or lowering energy consumption from appliances. The mitigation potential dues to integrated TES is quantified in kg/MWh energy produced or heat delivered.

Finally, embodied CO_2 in two TES case studies is presented, buildings and solar power plants. It includes the embodied energy involved in the extraction, primary production, transformation, transport to its place of use and recycling. Similarly to operational CO_2, to translate the embodied energy into embodied CO_2 in any application, the energy mix factor should be used.

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References

1. IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups l, ll and lll to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
2. Arce P, Medrano M, Gil A, Oró E, Cabeza LF. Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe. Appl Energ 2011;88:2764-2774.
3. Ashby MF. Materials and the environment eco-informed material choice. 2nd ed. St. Louis, MO. Butterworth-Heinemann; 2012.

4. Advances in thermal energy storage systems. Methods and applications 1st Edition. Editor Cabeza LF. Woodhead Publishing. 2014.

5. Oró E, Miró L, Farid MM, Martin V, Cabeza LF. Energy management and CO2 mitigation using phase change materials (PCM) for thermal energy storage (TES) in cold storage and transport. Int J Refrigeration 2014;42:26-35.

6. Azzouz K, Leducq D, Gobin D. Enhancing the performance of household refrigerators with latent heat storage: An experimental investigation. Int J Refrigeration 2009;32:1634-1644.

7. Gin B, Farid MM, Bansal PK. Effect of door opening and defrost cycle on a freezer with phase change panels. Energ Convers Manage 2010;100:372-376.

8. Subramaniam P, Tulapurkar C, Thiyagarajan R, Thangamani G. Phase change materials for domestic refrigerators to improve food quality and prolong compressor off time. International Refrigeration and Air Conditioning Conference, Richmond (USA), 2010.

9. Ahmed M, Meade O, Medina MA. Reducing heat transfer across the insulated walls of refrigerated truck trailers by the application of phase change materials. Energ Convers Manage 2010;51:383-392.

10. Liu M, Saman W, Bruno F. Development of a novel refrigeration system for refrigerated trucks incorporating phase change material. Appl Energ 2012;92:336-342.

11. Cheralathan M, Velraj R, Renganarayanan S. Performance analysis on industrial refrigeration system integrated with encapsulated PCM-base cool thermal energy storage system. Int J Energ Res 2007;31:1398-1413.

12. Wang F, Maidment G, Missenden J, Tozer R. The novel use of phase change materials in refrigeration plant. Part 3: PCM for control and energy savings. Appl Therm Engineering 2007;27:2893-2901.

13. Powell KM, Edgar TF. Modeling and control of a solar thermal power plant with thermal energy storage. Chem Eng Sci 2012; 71:138-145.

14. IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

15. Annex 25 – ECES IA – IEA. Surplus Heat Management using. Advanced TES for CO2 mitigation. Final report. 2014.

16. Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick constructive solutions for passive cooling. Energ Buildings 2010;42:534-540.

17. De Gracia A, Navarro L, Castell A, Ruiz-Pardo A, Alvarez S, Cabeza LF. Thermal analysis of a ventilated facade with PCM for cooling applications. Energ Buildings 2013;65:508-515.

18. Zhu X, Behzadi S, Farid MM, Chen JJJ. The effectiveness of phase change materials for building application in different climates. In press.

19. CO_2 emissions from fuel combustion. Highlights. IEA Statistics. 2012 edition.

20. Paksoy H, Evliya H, Abaci Ş, Mazman M, Konuklu Y, TurgutB, Gök O, Yilmaz M, Yilmaz S, Beyhan B. CO_2 Mitigation With Thermal Energy Storage. Int J Global Warming 2009;1:253-269.

21. Konuklu Y, Paksoy HÖ. 2009. Phase Change Material Sandwich Panels for Managing Solar Gain in Buildings. J Sol Energy Eng 2009;131: 0410121-0410127.

22. Paksoy HÖ, Gürbüz Z, Turgut B, Dikici D, Evliya H. 2004. Aquifer Thermal Storage (ATES) for air-conditioning of a supermarket in Turkey. Renew Energ 2004;29:1991-1996.

23. Turgut B, Paksoy H, Bozdag S, Evliya H, Abak K, Dasgan HY. (2008). Aquifer Thermal Energy Storage Application in Greenhouse Climatization, World Renewable Energy Congress, July 19-25, Glasgow.

24. Vadiee A, Martin V. 2013, "Solar Blind System- Solar Energy Utilization and Climate Mitigation in Glassed Buildings", accepted for publication in Energy Proceedia, as part of ISES Solar World Congress, Cancun, 2013.

25. Vadiee A, Martin V. 2013, "Energy management strategies for commercial greenhouses", Appl Energ 2014;114:880-888.

26. Hauer A, Fischer F. Open Adsorption System for an Energy Efficient Dishwasher. Chem Ing Tech 2011;83:1-7.

27. BOSCH AND SIEMENS HOME APPLIANCES GROUP http://www.bsh-group.com/index.php?page=137733

28. Santori G, Frazzica A, Freni A, Galieni M, Bonaccorsi L, Polornara F, Restuccia G. Optimization and testing on an adsorption dishwasher. Energy 50 (2013) 170-176.

29. Cabeza LF, Barreneche C, Miró L, Martínez M, Fernández AI, Urge-Vorsatz D. Affordable construction towards sustainable buildings: Review on embodied energy in building materials. Curr Opin in Environ Sustainability 2013;5:229-236.

30. CES Selector 2012 software, Granta Design Limited, Cambridge, UK, 2012, www.grantadesign.com [accessed 4 August 2014]

31. Jiao Y, Lloyd CR, Wakes SJ. The relationship between total embodied energy and cost of commercial buildings. Energ Buildings 2012;52:20-27.

32. Clements A, Shercliff H. Thermal Performance of Laminated Materials for Buildings, J. Materials Education Symposium Cambridge University, April 5th 2013.

33. Miró L, Oró E, Boer D, Cabeza LF. Embodied energy in thermal energy storage (TES) systems for high temperature applications. Appl Energ 2014, in press.