Thermal energy storage (TES) systems for greenhouse technology

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22.1 Introduction

The FAO *Statistical Yearbook 2013* states that global crop production has increased threefold over the past 50 years, largely through higher yields per unit of land and crop diversification. The global per capita food supply rose from about 2200 kcal/day in the early 1960s to over 2800 kcal/day by 2009. Currently 12.5% of the world's population is undernourished [1]. The vast majority of underfed people live in developing countries. Greenhouses provide sustainable environments to grow crops in almost any location. Local production, increased yields per area, longer harvest periods, and better controlled growing environments all make greenhouses a feasible solution in disadvantaged areas where heat is not readily available. The total world greenhouse vegetable area in 2013 is 411,262 hectares spread over 127 countries [2]. Growers strive to maximize yields and to minimize their expenses. Heating is the major cost involved in greenhouses, and this is usually done by burning fossil fuels. Adverse environmental effects of fossil fuels, i.e. climate change and growing concern for energy security, make the use of renewable energy sources more urgent than ever. Solutions need to better exploit renewable energy sources and better energy efficiency. The intermittent characteristics of many renewable energy sources can be compensated by using thermal energy storage (TES) systems that match supply and demand better.

Since the 1970s TES systems have proven to be significant tools to increase energy efficiency in contrast to conventional energy systems [3]. TES systems provide alternative heating and cooling solutions to decrease consumption of electricity and fossil fuels and also replace mechanical cooling devices. Greenhouses need a lot of thermal energy, and a significant portion of its costs is heating. Therefore they can get major benefits from TES.

22.2 Greenhouse heating and cooling

Greenhouses are transparent buildings designed to utilize solar radiation and provide optimum growing conditions for plants. The 'greenhouse effect' is the basis of

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greenhouse operation. Short wave solar irradiation entering the greenhouse is re-radiated as infrared radiation (IR) by the materials inside the greenhouse and trapped inside by the cover material (Figure 22.1). Thus heat accumulates in the greenhouse. The sun is the main source of energy gain in greenhouses. When solar gain is not enough or in excess to meet the requirements of plants grown in the greenhouse, climatization is required. Moisture and heat are vital for the growth of all plants. Heating, cooling and/or humidity control are employed when conditions in the greenhouse do not meet optimum growth conditions.

22.2.1 Heating systems in greenhouses

Heating systems in a greenhouse are basically designed to meet the heat losses. The systems used can be classified into three main groups [5]:

- unit (forced air) heaters
- central heaters
- radiant heaters.

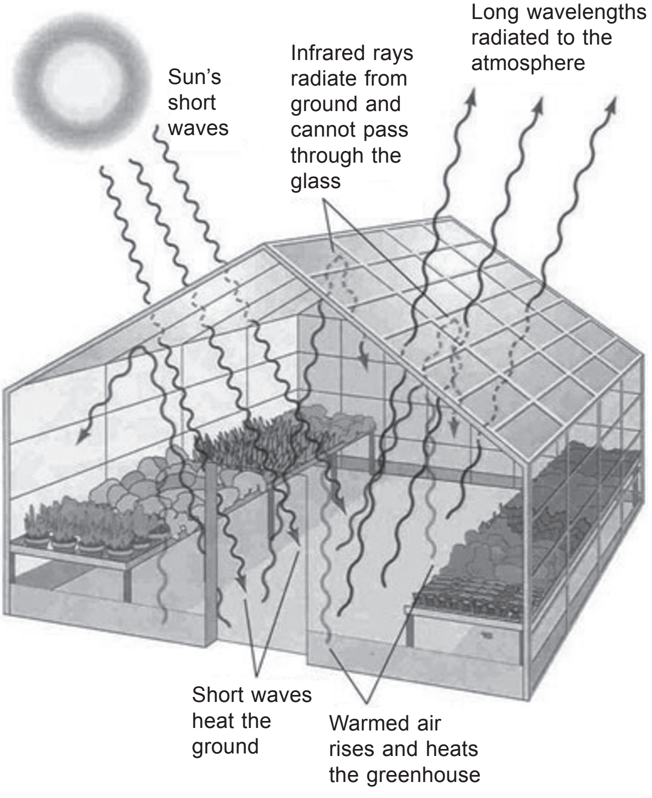

Figure 22.1 Modes of energy transfer in a greenhouse [4].

Unit heaters consist of multiple individual heaters placed overhead and have fan-driven distribution systems. Each has a combustion chamber and heated air is blown from rear to front by a fan. Fuel oil, kerosene, liquid petroleum (LP) gas, or natural gas is used as fuel.

Central heaters use one or more boilers in a central location and distribute steam or hot water into the greenhouse through pipes. Distribution pipes can be placed in a number of ways depending on the growing technique. Overhead pipe coils are placed above the plants. In-bed pipe coils are placed along the edges of ground beds, beneath benches, within ground beds or inside the concrete floor. This type of placement allows heat to be close to the plant.

Radiant heaters use steel pipes filled with hot gas suspended over plants along the greenhouse. Overhead aluminium reflectors bounce IR down to the ground and plants so that heat is not absorbed by the air, and it reaches the plants, ground and shelves. Radiant heaters are more fuel efficient and can burn natural gas or propane [5].

22.2.2 Cooling systems in greenhouses

Commercial cooling systems in greenhouses comprise three main groups: ventilation (forced or natural), shading (reflecting) and evaporative cooling. For shading or reflecting, special curtains that reduce total heat gain in the greenhouse are used. Such curtains can be automated to optimize solar radiation when it is needed most. A shading cooling system can help reduce the indoor temperature without auxiliary energy. They also reflect a considerable amount of energy which could be stored.

22.2.3 Humidity control in greenhouses

Controlling humidity in a greenhouse is crucial for optimum growth conditions of any plant. The humidity level in the greenhouse is a function of temperature and closely related to the heating and cooling system. The high humidity in combination with lower irradiation level in the winter is dangerous for the plant as well as the low humidity in combination with high irradiation level in summer [6]. In the conventional greenhouse, the easiest way of controlling high humidity is by ventilation. On colder days, this has to be combined with heating to sustain the required temperature. Humidifying and cooling can be done at the same time in evaporative cooling systems. For reducing humidity or dehumidification two methods are used: refrigerative or sorptive. Refrigerative-based systems remove moisture in a condensation mechanism by using coils [7]. In sorption systems, the air is dehumidified using desiccant substances instead of coils. Hence, freezing the coils in low temperature and humidity conditions can be avoided [8]. A combination of desiccant and cooling-based dehumidification systems will be the most efficient method because the limitation of each method will be compensated by their respective advantages [9].

22.3 Thermal energy storage (TES) technologies for greenhouse systems

The main thermal energy storage (TES) technologies that are used for various heating and cooling applications may be listed as [10]:

- Underground thermal energy storage (UTES)
  - aquifer thermal energy storage (ATES)
  - borehole thermal energy storage (BTES)
  - cavern thermal energy storage (CTES)
- phase change materials (PCM)
  - organics
  - inorganics
  - ice
- chemical reactions
- water tank.

UTES systems are usually preferred for seasonal storage, whereas water tanks, PCM and chemical reactions are used for short-term storage. There are different opportunities of benefiting from TES in greenhouses for seasonal and/or short-term purposes. In the review by Sethi and Sharma [11], important existing TES for greenhouse heating and cooling systems are classified as follows:

- heating system
  - water storage
  - rock bed storage
  - PCM
  - movable insulation (thermal screens/curtains)
- cooling system
  - ventilation (natural and forced)
  - shading/reflection
  - evaporative cooling (fan-pad system, mist/fog and roof cooling)
- composite system for heating and cooling
  - BTES
  - ATES.

The closed greenhouse concept introduced in the last decade maximizes the benefit from solar energy through seasonal TES [12]. A closed greenhouse can collect almost three times its own annual heating demand [7]. A semi-closed greenhouse concept may be more applicable considering the need for extra energy for ventilation. In the semi-closed greenhouse, a large part of the available excess heat can still be stored through TES. It is possible to integrate a ventilation system with TES in order to use fresh air as a rapid response indoor climate control system. A detailed energy analysis of these concepts can be found in Vadiee [4, 7] and Vadiee and Martin [13].

There are also greenhouse heating and/or cooling systems that use heat pumps coupled with TES. These systems are usually called ground source heat pumps (GSHPs). In GSHPs earth is used as a heat source during heating mode and as a heat sink during cooling mode. When used with seasonal TES, heat pumps can increase the benefits from TES for a longer period. The use of PCM on the condenser and/ or evaporator side of the heat pump is another alternative heat pump application for greenhouses. The most common TES options for greenhouses will be discussed below.

22.3.1 Underground thermal energy storage (UTES) systems for greenhouses

Underground soil and/or rocks can provide a large, invisible and isolated storage volume. UTES systems (Figure 22.2) use the heat capacity of this volume to store thermal energy from any natural or artificial source for seasonal or diurnal applications. UTES is an option for greenhouses because they produce excess heat in the summer and require heating in the winter. UTES can provide both heating and cooling; however, there are also systems that provide only one or the other. The three main sections of UTES systems are the thermal storage system itself, the thermal exchanging unit (not required in direct heating), and the thermal distribution system.

22.3.1.1 Aquifer thermal energy storage (ATES)

ATES involves the free cooling or heating from an aquifer – natural groundwater basins. They use groundwater as the medium of heat transfer between an external energy source and the aquifer. The groundwater has a constant temperature normally related to the mean annual temperature of the site. During the winter, natural or artificial cold is stored in the cold side of the aquifer while pumping away heat from

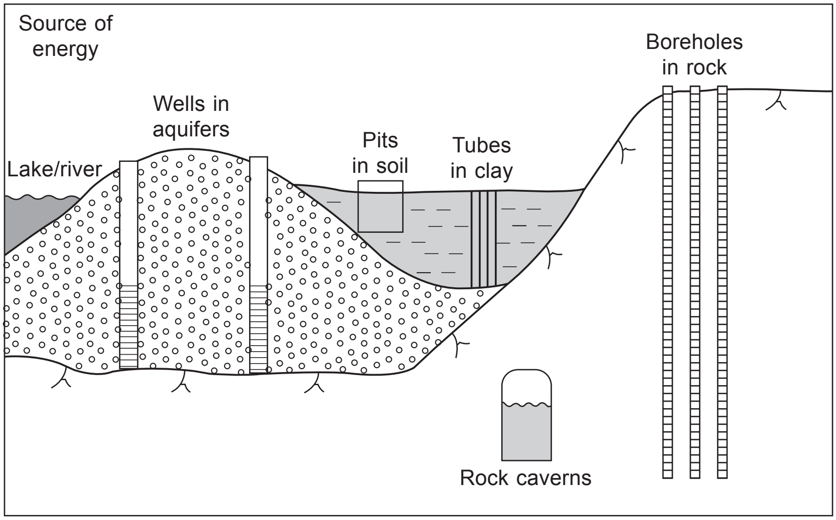

Figure 22.2 UTES systems [14].

the warm side. During the cooling season the stored cold is pumped back and the waste heat from the cooling process is stored in the warm side. A heat exchanger transfers the heat or cold from the groundwater loop to the user. For greenhouses heat accumulated in the greenhouse is used as the source of energy that is stored with ATES. This operation is shown schematically in Figure 22.3 [15]. The heat distribution system in the greenhouse is adapted to each ATES system. The aquifer is connected by conventional water wells, one or several at each side. Their spacing must take into consideration groundwater flow velocities and the temperature of the aquifer; therefore, they should be determined by detailed pre-investigation. In many cases the ATES systems combine heating and cooling, often by using a heat pump for extended heat or cold production. A supplemental heating system such as a boiler where the temperature is raised may be necessary depending on the climate conditions. The main reason that makes aquifer storage attractive is the large saving of energy, with a small amount of driving energy producing a very large return.

22.3.1.2 Borehole thermal energy storage (BTES)

If no suitable aquifer is present, or it is not possible to use the existing aquifer due to regulations, BTES can be an alternative system that uses the subsoil for thermal energy storage. In a BTES system, thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes. The boreholes are equipped with different types of borehole heat exchangers (BHE), where the boreholes act as heat exchangers within the ground. The most common BHE is a single U-tube made of plastic pipes. Horizontal piping can be used to avoid high drilling costs, but influence of outside climate conditions is more effective and should

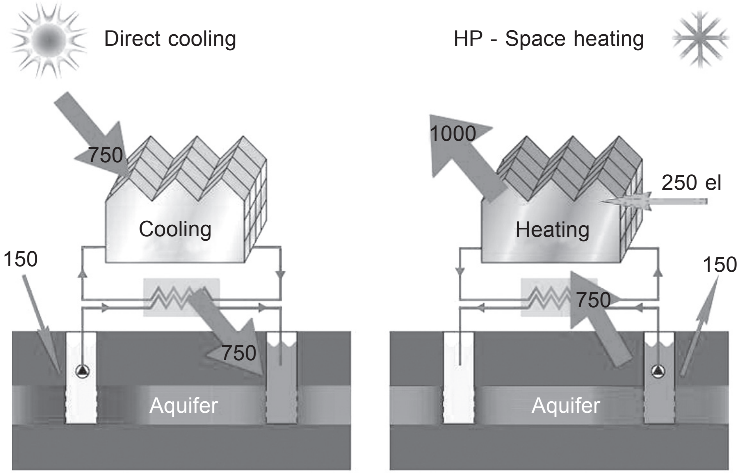

Figure 22.3 ATES system for greenhouses. Courtesy of IF Tech International BV, The Netherlands.

be used with care. Heat or cold is delivered or extracted from the underground by circulating a fluid in a closed loop through the boreholes. The fluid often contains an antifreeze to allow the system to operate below the freezing point. As in the ATES system, connection of the greenhouse with the borehole field is accomplished with heat exchangers in the greenhouse distribution system.

22.3.1.3 Cavern thermal energy storage (CTES)

The other option for UTES involves man-made structures. These are used when existing aquifer and sub-soil conditions are not favourable. They are called cavern thermal energy storage (CTES), covering all kinds of ‘cavities’ underground. The first is a tank buried underground where an insulated tank is filled with water. The other storage option is pit thermal energy storage in which a pit is dug, lined, and filled with water or water/gravel. Underground caverns that may be found in natural karstic formations or abandoned mines can also be alternatives that can be used for UTES.

22.3.2 Phase change material (PCM)

Phase change materials with high latent heat storage capacities and isothermal application opportunities can be used in active or passive greenhouse systems. The alternatives for using PCMs in greenhouses are as follows:

- active systems
  - diurnal storage in combination with heat pumps
  - diurnal storage with solar collectors
  - peak shaving with seasonal storage systems
- passive systems
  - passive storage with the greenhouse covering material
  - passive storage to control temperature of the plants and to protect from frost.

Depending on the way PCMs are used, different materials with different phase change temperatures and encapsulation techniques may be needed [16].

22.3.3 Water tanks

Water tank storage is the most well-known and commonly used technology. It can be used for seasonal and diurnal applications, though the size of the seasonal storage tank would be very large and therefore may not be economical. The choices of tank and insulation materials are the main factors that affect the efficiency and cost of the tank. There are different structures that can be used inside the tanks to enhance the stratification for higher efficiency use of TES. In greenhouses, water tanks are commonly used not only for back-up storage for the heating system, but also to collect rainwater.

22.4 Case studies for TES in greenhouses

22.4.1 UTES

22.4.1.1 The Netherlands

The Netherlands is one of the leading countries in ATES systems in the world. The first pilot ATES greenhouse system was built in 2002 followed by a first full-scale application in 2003. More than ten closed or semi-closed greenhouse projects with ATES/HP system were in operation by 2009 [15]. Figure 22.4 shows the concept of ATES used in closed greenhouses in The Netherlands. The observations from these projects are [15]:

- semi-closed greenhouses are more economical than full-closed greenhouses for the Dutch climate (200–400 W/m^2 cooling capacity instead of 600–800 W/m^2)
- yield increase per m^2 is approximately 10% for tomatoes and a similar increase for cucumbers
- an ATES/HP system provides approximately 20–30% savings in primary energy use for the Dutch climate
- standard greenhouse with combined heat and power (CHP) and boiler is more economical at present gas prices (ca. €0.25/m^3) and feed in rates (ca. €0.07/kWh).

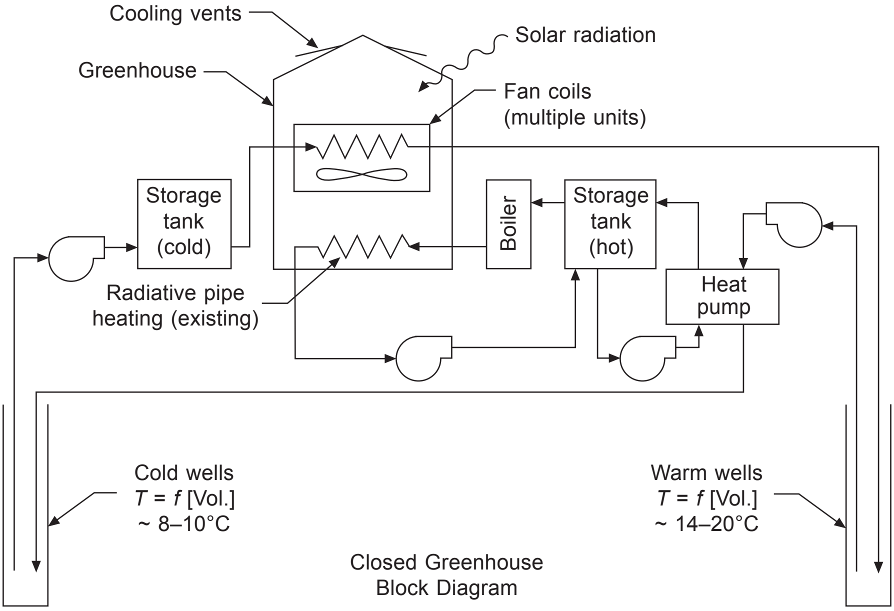

Figure 22.4 Closed greenhouse concept using ATES. Courtesy of Leidos Canada Inc.

22.4.1.2 Turkey

The ATES system has been utilized for the first time in the heating and cooling of a greenhouse in a Mediterranean climate [17, 18]. Two separate greenhouses with PE covers, each having an area of 360 m^2 at Cukurova University have been used in this project. The first has been heated and cooled by ATES. In the second control greenhouse a conventional heating system has been used without any cooling. Figure 22.5 shows the basic concept of the ATES system. Two groups of wells, each having a cold and a warm well combination, operated for each greenhouse. Each group had a well with a depth of 80 m and casing diameter of 0.40 m.

The basic concept of the ATES system utilized the heat stored from summer to heat the greenhouse during winter, as well as the cold stored in winter for cooling during summer. The greenhouse is the 'solar collector' to store heat on sunny days. Temperatures in the greenhouse varied between 40–60ºC about 6 hours/day for 5 months in this climate. Winter air colder than 10ºC is the source for cooling. In summer, the fan coils transferred heat from air in the greenhouse to groundwater extracted from the aquifer for heat storage. In winter, these units distribute the heat stored in the aquifer to the greenhouse. Perforated polyethylene air ducts assembled at the exhaust of the fan coils distributed and extracted the air from the greenhouse. Based on the mass of fresh fruits, the product yield of tomatoes in the ATES greenhouse was 40% higher than those for the conventional greenhouse. During total operation of the ATES system in 2005–2006, no fossil fuel was used for heating. ATES made it possible to cool the greenhouse in a period when under normal Mediterranean climate conditions production would have halted. Thus, the yield from the harvest was increased further. The conventional greenhouse was heated using fuel oil No. 6. For the ATES system electricity was used to run the

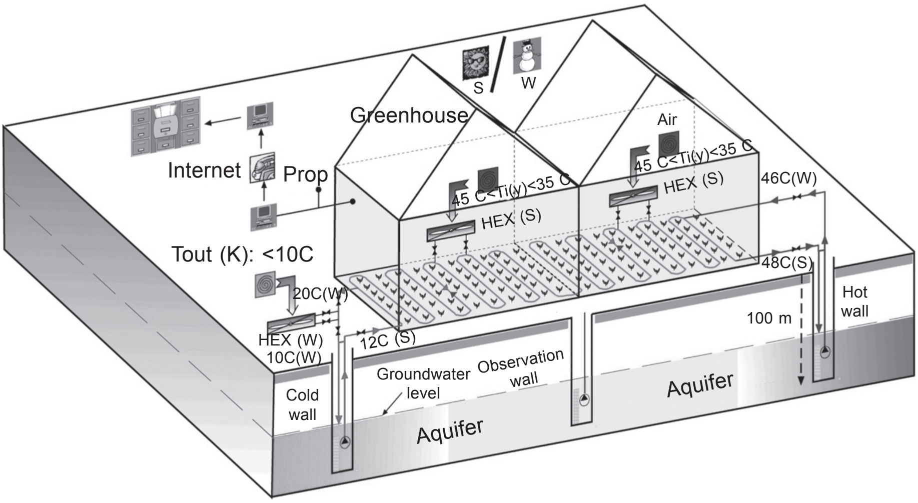

Figure 22.5 Schematic diagram of ATES greenhouse in Cukurova University, Turkey [16].

fan coils and pumps for groundwater circulation. The coefficient of performance (COP) for the ATES system for heating and cooling for this period were 7.6 and 3.2, respectively. Total investment cost for both greenhouses were almost the same and energy cost for ATES was 34% less than the conventional, making ATES the more viable choice for greenhouse heating and cooling. Economic benefit resulting in higher yield is not included in the calculations. The market price for tomatoes varies during the year. Tomatoes were harvested earlier with the ATES system. With ‘zero’ fossil fuel consumption, leading to 68% energy conservation, a 20–40% increase in product yield depending on season and short payback time of less than a year, the ATES system shows a very high potential for greenhouse climatization.

Another demonstration greenhouse was set up in Turkey by Ege University in Izmir [19]. Their demonstration included a GSHP and a vertical borehole storage system, supplemented by flat plate solar collectors. Heat was distributed in the greenhouse by forced air over a fan coil. The ground loop comprised a borehole 50 m deep containing a single U-tube, and polyethylene piping filled with a 10% ethylene glycol mixture. A GSHP with a 4 kW capacity provides the heating and cooling at a 72% exergy efficiency based on a product/fuel scale with a COP of 2.8. In addition to the heat pump, a flat plate, 1.82 m^2 solar collector added thermal energy to the ground loop. Overall, it was found that this combination system operated at a 68% exergy efficiency, with a COP of 2.6 but was not sufficient to heat the greenhouse at peak heating loads (i.e., when the outside temperature is very low); a backup heating system is needed. The most cost-effective method for improving the system’s effectiveness was by upgrading the greenhouse heat distribution system to a conduction, near-plant heating system.

22.4.1.3 Norway

For the greenhouse in Mære Agricultural College in Norway, a climatization system for a closed greenhouse combining BTES, 100 kW heat pump and short-term dynamic storage unit [20,21] was studied. In summer, surplus heat was stored in the BTES. Stratified borehole field design facilitated better performance. A 150 m^3 water tank was used for short-term dynamic storage. With a variable speed pump, just enough cold water from the cold tank was supplied to the heat exchanger circuit filled with ethylene glycol. The fan coils were operated to keep the greenhouse just below maximum allowable temperature. After one year of operation 90% savings in fossil fuels was achieved [20].

22.4.1.4 Switzerland

In Geneva, Switzerland, a study was undertaken to compare three greenhouses with different heating systems; one conventional using a natural gas boiler, one with a tank storage system, and the other with an underground, borehole storage system [22]. It was concluded that the storage systems did not negatively impact the productivity of the harvest. The greenhouses with tank and underground storage were found to offset the energy by 13% and 11%, respectively. These systems were thought to be reaching approximately 25% of their storage potential; therefore, theoretically the energy offset could be four times that observed. It was predicted that an economically feasible outcome in a similar climate (averaging 17.5°C) would be a 25% energy offset. The underground storage was found to operate with a COP of 5.8 while the tank storage had a COP of 1.7. This latter number was concluded to be a fault of the design and not inherent to the tank storage.

22.4.1.5 USA

A study in the United States by the Geo-Heat Center focused on the economic feasibility of meeting the heat demands of greenhouses with a GSHP in both open and closed loop configurations as compared to natural gas heating systems. Climate data from Boston, Dallas, Denver, and Seattle was used to determine the heating needs of a 4047 m^2 fiberglass greenhouse. It was found that at natural gas costs of \$0.21–0.35/m^3, BTES systems emerge as economically feasible and at natural gas prices exceeding \$0.53/m^3, BTES systems become economically feasible [23].

22.4.1.6 Canada

Pacific Agricultural Research Centre in Agassiz, Canada, has installed an ATES system that supplied thermal energy for their greenhouses. It included seasonal energy storage and was employed for both heating and cooling. In this particular design, cooling towers were not needed and a natural gas boiler provided secondary heat when needed. It was found that the technology was less costly than conventional to build, and for operation costs about \$35,000 was saved annually. This represented 6000 GJ less energy consumption per year and a reduction in greenhouse gas emissions of about 300 tonnes per year. The project was not a ‘closed’ greenhouse operation [24].

22.4.1.7 Belgium

In the project GESKAS, two small research greenhouses were built at the horticulture research institute in Belgium [25]. The greenhouses were fully air conditioned and operated as small closed greenhouses for tomato growing. Crop behaviour, production rates and energy needs were monitored in comparison with two small reference open greenhouses equipped with traditional technologies. The results showed that closed greenhouses can provide higher yields (7–11%) and primary energy savings of 8–34% were possible. It was also reported that if energy was not used wisely in closed greenhouses, more energy could be consumed. There was a need for a heat pump and a compatible UTES system for optimum operation of this closed greenhouse.

22.4.2 PCM

PCM applications in greenhouses as summarized in Table 22.1 were in the pilot stage for greenhouses with areas between 20 and 500 m^2. Energy savings in the range of 20–51% were achieved in these studies. $CaCl_2.6H_2O$ was the PCM preferred for short-term heat storage in the majority of the studies. In only one of the studies given in Table 22.1 was seasonal storage of solar energy in paraffin wax [26] attempted.

Table 22.1 PCM applications in greenhouses

Greenhouse location	Area (m^2)	Plant	PCM	PCM mass (kg)	Reference	Remarks
Antibes, France	445	–	Eutectic mixture of NaOH and Cr_2N	–	27	20% saving
Yokohoma, Japan	352	Tomatoes	Mixture of Na_2SO_4 $.10H_2O$ Na_2CO_3. $10H_2O$ - NaCl	2500	28	8°C higher
Carolina, USA	100	–	$CaCl_2.6H_2O$	1200	29	5°C higher
Avignon, France	176	Tomatoes	$CaCl_2.6H_2O$	2970	30	30% saving
Canbera, Australia	20	Pot plants	$CaCl_2.6H_2O$	100	31	–
Nice, France	500	Roses	$CaCl_2.6H_2O$	–	32	51% saving
Montfavet, France	176	Lettuce-tomatoes	$CaCl_2.6H_2O$ +chlorides and nitrates	2100	33	7–8°C higher
Bet Dagan, Israel	200	–	$CaCl_2.6H_2O$	3000	34	–
Adana, Turkey	180	Strawberry	Paraffin wax	6000	26	40% saving

22.4.2.1 Turkey

A ground-source heat pump heating system project with a latent heat thermal storage tank, used for space heating in a 30 m^2 glass greenhouse was investigated in Turkey [35]. R-22 was chosen as a refrigerant cycling in the horizontal ground heat exchanger loop with a length of 246 m. The PCM was 300 kg of calcium chloride hexahydrate. Solar radiation and thermal energy from the heat pump provided heat to the indoor air and the PCM storage unit. According to the results obtained from October to May in the heating seasons of 2005 and 2006, the COP of the ground-source heat pump varied from 2.3 to 3.8 and the combined COP of the whole system from 2 to 3.5. It was pointed out that PCM storage contributed to the rational heat distribution in the greenhouse due to its nearly constant phase changing temperature.

Root zone heating with thermal energy storage in PCM to keep plant temperature at the optimum levels has been investigated for soil-less agriculture greenhouses without a heating system [36,37]. A system for night-time heating of the root zones of plants in pots at Çukurova University Horticulture Department research greenhouse was developed. The candidate PCMs appropriate for optimum conditions of the plants to be grown were determined as a 40% oleic acid- 60% decanoic acid mixture and α-oleic acid. Measurements at two different periods of November (for zucchinis) and March–April (for pepper) were carried out with the system developed. In the November period, when the greenhouse temperature was below optimum growth conditions, with 40% oleic acid 60% decanoic acid mixture, the root zone temperature in the pots with PCM was 1.9–1.2°C higher than the control. Between 6 March and 8 April, both PCMs were tested and the PCM mixture was observed to be more effective than the oleic acid. The maximum temperature differences with respect to the control attained in this period were 2.4°C and 2.1°C. Results show that the passive PCM system has been effective in controlling the root zone temperatures and avoiding the risk of putting plants under stress in periods when central heating is not used in the greenhouse.

22.4.2.2 Germany

In Berlin Botanical Garden, PCM panels were stacked to form a storage tower (Plate XIV between pages 316 and 317) [38]. During the day, solar heat from the roof was stored in panels filled with PCM, which released heat at night-time into the plant area. This resulted in considerable energy, CO_2 and cost savings [38].

22.4.2.3 China

In China, solar greenhouses are totally passive with no auxiliary heating in winter [39]. This type of greenhouse design is used mostly in Northern China with over 80% of the land area [39]. The north wall of the greenhouse is made of brick or other similar material, the south roof is transparent greenhouse cover and the north roof is non-transparent made of light materials, such as wood panels, aerated concrete slabs, or straw (Figure 22.6). This traditional design can be improved by adding

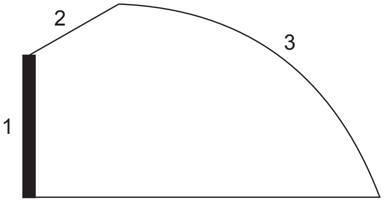

Figure 22.6 Schematic presentation of the Chinese greenhouse concept. 1: North wall made of brick or other similar material, 2: non-transparent north roof made of light materials, 3: south roof made of transparent greenhouse cover.

TES systems. The thermal performance of a greenhouse similar to the Chinese solar greenhouse design, but with PCM added in the north wall was modelled in Marrakesh under Mediterranean weather conditions. The results showed that with 32.4 kg of PCM per square meter of the greenhouse ground surface area, the temperature of plants and inside air were found to be 6–12°C higher at night-time in the winter period with fewer fluctuations. Relative humidity was found to be on average 10–15% lower at night-time [40].

22.5 Conclusions and future trends

Many greenhouses around the world can benefit considerably from TES systems. These benefits are: more manageable interior temperatures, increased yields, extended harvests, improved working conditions inside the greenhouse, energy savings, less reliance on fossil fuels, and CO_2 emissions reduction. The achieved sustainable benefits could result in more profitable greenhouse growing, and increased food production capacities would result in their spreading. Especially in developing countries, greenhouses would relieve the undernourished population with crops produced in an economic and more sustainable manner.

More demonstration greenhouses with TES would help determine better management strategies. Such examples would also reinforce the benefits observed in earlier studies. Various locations would necessitate the adaptation of this technology for different climate conditions. The result would be a proliferation of greenhouse TES technologies on a wider scale.

There exist many commercial applications of UTES systems in greenhouses with significant energy savings and short payback times. The trend in greenhouse development is from self-sufficient greenhouses to energy-producing greenhouses. With TES systems properly integrated into greenhouses, it will be possible to use greenhouses as energy sources for heating buildings near them. This concept is already under development in Denmark, Netherlands and Sweden [4, 41]. In future greenhouses, TES solutions can combine heating-cooling-dehumidification functions and provide poly-generation possibilities. Further research on the possibility of thermochemical energy storage and better development of phase change materials is needed for this option to be widely adopted in a more cost-effective manner.

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