Curr Sustainable Renewable Energy Rep (2016) 3:58–66
DOI 10.1007/s40518-016-0056-y

Solar Greenhouse With Thermal Energy Storage: a Review

Amritanshu Shukla[1] · **Atul Sharma**[1] · **Karunesh Kant**[1]

Published online: 11 October 2016

Abstract Various heating systems are used to meet the heating requirements of the greenhouses. The conventional solution for this problem is the burning of some fossil fuel inside the greenhouse during cold days. The use of latent heat energy for greenhouse heating in winter days is a significant development. The storage of the excess heat in greenhouses for sunny days in a cold season is advantageous, in view of increasing concerns over usage of fossil fuel. Thermal storage plays a vital role in solar devices particularly in greenhouses to improve its performance because of the intermittent nature of solar energy. Therefore, a storage system constitutes an important component of the solar energy utilisation system. Thermal energy can be stored as sensible heat, latent heat or chemical energy. The present study is carried out to present a review of the solar greenhouse based on latent and sensible heat energy storage. The various designs and application methods are reviewed considering different thermal energy storage materials employed for building a solar greenhouse and future prospects of the same have been discussed.

Keywords Greenhouse · Thermal energy storage · Solar energy

This article is part of the Topical Collection on *Regional Renewable Energy*

✉ Amritanshu Shukla
ashukla@rgipt.ac.in

Atul Sharma
asharma@rgipt.ac.in

Karunesh Kant
k1091kant@gmail.com

1 Non-Conventional Energy Laboratory, Rajiv Gandhi Institute of Petroleum Technology, Raebareli, UP 229316, India

Introduction

Sustainability has been at the centre of attention for many decades and is key to human growth and mankind. One of the most challenging areas of sustainability is the food production. The growth of population requires higher production yield while the high cultivation output requires a substantial capital investment cost, as well as direct and indirect energy inputs. *Considering the continuous cost of energy, particularly fossil fuels, and the external energy demand must be reduced in order to cut down the total annual operating cost.*

Solar energy, an abundantly available, clean and safe energy source, is an attractive alternative for many of the fossil fuel-based passive and active heating applications. During the day, excess solar thermal energy can be collected and stored, to be utilised at night for the heating needs of greenhouses. Proficient and cost-effective heat storing is the main factor in the utilisation of solar energy for agricultural purposes. Solar energy can be stored as sensible heat, latent heat and the heat of reaction or a combination of these. In most energy storage systems the energy is stored by means of sensible heat in materials such as water and rocks. In latent heat storage (LHS) systems, the thermal energy is stored at the time of phase change of a material. The phase change materials (PCMs) can store great amounts of heat in the phase changing from solid to liquid. LHS systems using PCM, in general, provide much higher energy storage density as compared to sensible heat storage. To store solar energy, the use of LHS systems for thermal energy storage has turned out to be an attractive design option in terms of manufacturing cost and storage efficiency. The productivity of seasonal storage, as well as that of daily storage, depends on climate conditions system configurations and various set points for environmental control.

Currently, greenhouse cultivation is a growing industry in many states due to rising needs for agricultural products with an increase of population. Due to that reason, greenhouse requirement for food cultivation is an additional substitute for meeting increased food demand year around. The plant growth factors can be organised and maintained at optimum level year around in the greenhouses [1, 2].

Greenhouse is an expensive way to produce greenhouse crops and there are many factors to consider before the farmer chooses to cultivate food by this way. The greenhouse may be used for drying also [3]. The energy demand for agriculture use has increased significantly with the introduction of high-yielding varieties and systematic crop production practices. The greater cost of heating a greenhouse using conventional fuels such as natural gas or oil has resulted in many cultivators switching to alternate fuels. Greenhouse production is carried out by taking advantage of favourable climatic conditions while keeping the operational cost at a minimum level. Conventional greenhouses typically depend on the sun to supply their lighting needs, although these are not planned to use the sun for heating purposes. For the heating purpose, they utilise direct combustion of natural gas, liquefied petroleum gas, water heaters and unit heaters for maintaining the temperatures necessary to grow plants in the colder months. However, solar greenhouses are designed to utilise solar energy for both heating and lighting. It reduces the need for fossil fuels for heating.

In the present study, the authors have reviewed the use of thermal energy storage to store the solar thermal energy for maintaining the internal temperature of the greenhouse at a level consistent with the crop production. Before discussing the thermal energy storage systems, a brief introduction to greenhouse has been given in the following subsection.

Basis for Classification of Greenhouse

There have been number of classification schemes for greenhouse discussed in the literature; however, the main classification schemes are based on needs and budget, specialist usage and the shape of construction, which are discussed in brief.

Needs and Budget [4]

Three categories of greenhouse depending on needs and budget have been defined to assist people in selecting the most appropriate investment.

i. *Low technology greenhouses*: These types of greenhouses have a total height less than 3 m. It does not have vertical walls and has poor ventilation. Such type of greenhouse structures is cost effective and easy to erect.
ii. *Medium technology greenhouses*: Medium technology greenhouses have vertical walls more than 2 m and less than 4 m and total height is less than about 5.5 m. It may have roof or side wall ventilation or both.
iii. *High technology greenhouses*: High technology greenhouses have minimum 4 m wall height with the roof peak being up to 8 m above ground level. High technology greenhouses have roof ventilation and may also have side wall vents and offer superior crop and environmental performance.

Conventional and Specialist Use

Greenhouses types as per usage can be divided into two main groups: conventional greenhouses and specialist greenhouses. *Conventional greenhouses* include *Dutch light*, *traditional span*, *three-quarter span*, *lean-to and mansard or curvilinear greenhouses. Specialist greenhouses* include *dome-shaped*, *conservation*, *alpine house*, *mini*, *polygonal and polytunnel greenhouses* which are described as follows:

i. *Traditional span*: Traditional span greenhouse is practical in terms of growing space and headroom by its vertical sides and even span roof. This type of greenhouse provides the best use of space for the minimum cost for raising seedlings and growing border crops.
ii. *Dutch light*: These types of greenhouses are designed in order to allow in full light through the sloping sides and suitable to grow border crops, preferably low-growing ones.
iii. *Three-quarter span*: These types of greenhouses are positioned with one of its sides against a wall, rather beside a sunny wall because the light is a little more restricted than in a free-standing greenhouse; however, this also means that it will need some extra shading in the summer time.
iv. *Lean-to Lean*: These types of the greenhouse can be used in a garden with insufficient space for a free-standing structure. Similar to the three-quarter span, this kind of greenhouse will benefit from the warmth and insulation of the house wall.
v. *Mansard or curvilinear*: These kinds of greenhouses have slanting sides and roof panels intend to allow in maximum light obtainable so a best place for this type of greenhouse is an open site with no shade from the surrounding trees or buildings.
vi. *Dome-shaped*: These types of greenhouse offer an elegant design that is mostly useful in exposed positions. These are stable and offer less wind resistance than traditional greenhouses.
vii. *Polygonal*: For a focal point in the garden or for gardens where the look is important, polygonal greenhouses are

the most hand-me-down. Several octagonal or polygonal greenhouses are a good choice; however, they may be more expensive than traditional greenhouses of similar sizes.

viii. *Alpine house*: Usually those greenhouses have timber-frame with louvre vents all along the sides, which help for most effective ventilation. Usually, these types of greenhouses are not heated and they are not closed except the winter is too cold; therefore, the insulation is not needed. They are used mostly aimed at plants that just need some safeguard from dampness and rain and require a bright and well-ventilated place.

ix. *Conservation*: These types of the greenhouse are designed to save as much energy as possible using special features. The roof panels are angled to permit optimum light penetration and mirrored surfaces are also used to reflect light within the greenhouse itself.

x. *Mini*: Aimed at a limited space for a garden, or it can be used for a small number of plants to grow, useful, low-cost greenhouses are available in different sizes and also as free-standing or wheeled versions.

xi. *Poly-tunnel*: For a low-cost protection, plastic polytunnel greenhouses are a good choice. It covers a large area, is covered with heavy-duty transparent plastic sheets, which offers protection from cold and the wind, and easy to move where needed.

Shape, Utility and Material of Construction

The different types of greenhouses classified based on shape, utility, material and construction are shown in Fig. 1.

Phase Change Materials for Thermal Energy Storage

Latent heat thermal energy storage commonly known as PCMs are particularly more attractive in comparison to other thermal energy storage due to its ability to provide high-energy storage density per unit mass and per unit volume in the almost isothermal process, i.e. storing heat at a constant temperature corresponding to the phase-transition temperature of PCM. Thus, PCMs release large amounts of energy upon freezing in the form of latent heat and absorb equal amounts of energy from the immediate environment upon melting. A number of PCMs have been investigated by different researchers for different applications [5–7, 8•, 9, 10]. A classification of PCMs is shown in Fig. 2 [11]. Various types of PCMs, which can be used for integrating PCM with a solar greenhouse in the appropriate temperature range, are tabulated in Table 1. During sunshine hours, the maximum temperature within the greenhouse varies from 30 to 40 °C [12].

Greenhouse With Thermal Energy Storage

The concept of stored excess energy inside the greenhouse, such as the use of the rock beds [13], has been developed due to the need of developing heating systems for greenhouse based on renewable energy sources. Bouadila et al. [14••] carried out an experimental study of two insulated solar greenhouses. One greenhouse was attached with latent heat energy storage solar air heater. Figure 3 represents the external and internal view of the solar greenhouse. The experimental setup consisted of the small chapel-shaped greenhouse with floor area equal to 14.8 m^2 (3.7 m × 4 m) and 3 m of height. The galvanised steel structure is fixed to the ground with stones and concrete. The wall and roof oriented to the south were covered by plexiglass having 3 mm thickness. Sidewalls and the northern roof were built by sandwich panels with 0.4 and 0.6 m of thickness, respectively. The southern wall and roof were having a slope of 30° and 33°, respectively. The greenhouse was equipped with a centrifugal fan controlled by a differential thermostat. The heating system of the insulated greenhouse with latent heat storage (IGLHS) was a new Solar Air Heater with Latent Heat Storage Collector (SAHLSC) by means of a packed bed of spherical capsules as a latent heat storage system [15•]. The study was conducted to estimate night-time recovered heat of the SAHLSC in the greenhouse. The solar energy stored in collector during the daytime was supplied at night. As a consequence of this system, on 23rd of February 2013, the amount of the heat recovered at night-time of this system attains 30 % of the total heating desires. The energy stored was equivalent to 56 % of the daytime total excess heat inside the greenhouse.

Vadiee and Martin [16••] developed a theoretical model using *TRNSYS* to carry out the energy analysis of greenhouse. From the economic feasibility assessment, the results indicate that the concept has the potential of becoming low cost. The key investment for the closed greenhouse concept could be paid within 7–8 years with the savings in auxiliary fossil fuel bearing in mind the seasonal thermal energy storage systems. Though, the payback time may be reduced to 5 years, if the base load is chosen as the design load instead of the peak load. In this case, a short-term thermal energy storage systems need to be added in order to cover the hourly peak loads.

Benli et al. [17] carried out a study to analyse the thermal performance of a PCM-based thermal storage unit. Solar air collectors heating system were developed for space heating of a greenhouse and charging of PCM as shown in Fig. 4. $CaCl_2.6H_2O$ was used as PCM in thermal energy storage with a melting temperature of 29 °C. Hot air charged the PCM storage unit during day time which is delivered by ten pieced solar air collector. The stored heat is utilised to heat ambient air earlier being admitted to a greenhouse. The present study is based on experimental results of the PCM employed to analyse the transient thermal performance of the storage unit

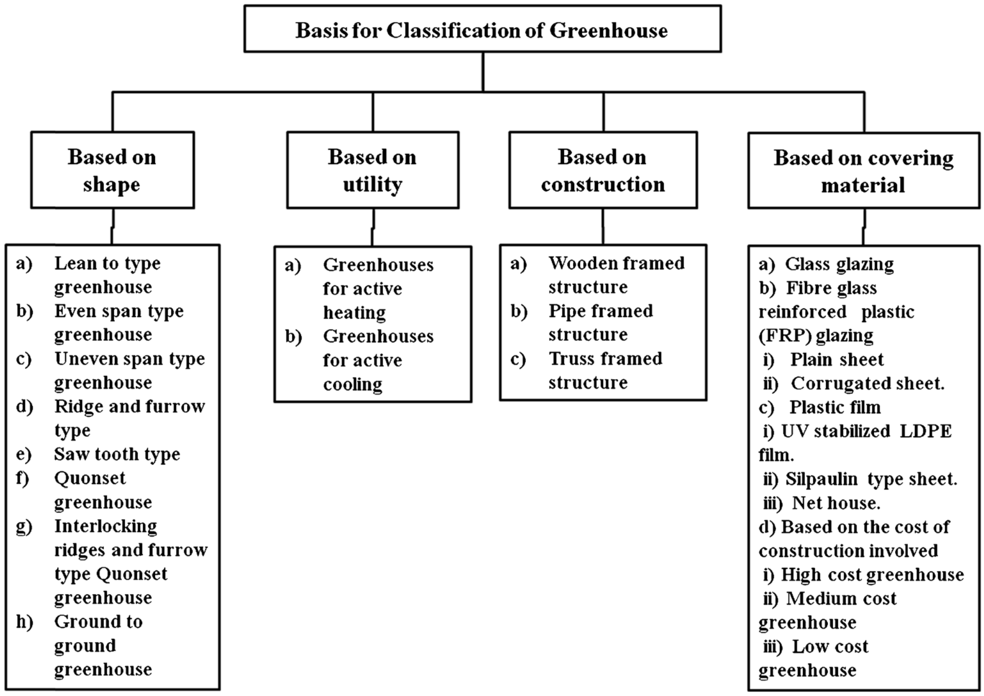

Fig. 1 Classification of based on shape, utility, material and construction

during the charge and discharge periods. The planned size of collectors integrated with PCM provided about 18–23 % of total daily thermal energy requirements of the greenhouse for 3 to 4 h, as a comparison to the conventional heating device.

Öztürk [18] attempted to heat the greenhouse of 180 m^2 floor using paraffin wax as a PCM with the latent heat storage technique. The system consists mainly of five units: (i) flat plate solar air collectors (as heat collection unit), (ii) latent heat storage (LHS) unit, (iii) experimental greenhouse, (iv) heat transfer unit and the (v) data acquisition unit as shown in Fig. 5. The LHS system for greenhouse heating was analysed and its energy and exergy efficiencies were obtained. The effects of various factors on the net energy and exergy efficiencies were examined and conclusions are drawn which are independent of location and weather on the following basi: (i) greenhouse heating with solar energy, (ii) heat storage material for greenhouse heating and (iii) evaluation of the system efficiency.

Willits et al. [13] developed and validated a computer model to describe a greenhouse with a thermally attached energy storage. The system was modelled having for a 6.7 × 12.2 m greenhouse with a 3.0 × 10.0 × 1.8 m rock bed attached via insulated ducts. Provisions were made to circulate air from the greenhouse by the rock bed and back whenever heating or cooling was required. When the capacity of the bed was reached, heating and cooling were accomplished in the normal fashion. The computer model was based upon two existing models, one for the greenhouse and one for the rock bed. Modifications were made to each to increase their efficiency and to account for the single aspects of this system. The justification was accomplished for three separate days comparing observed data with predicted results.

Chou et al. [19] established an analytical thermal model for a greenhouse on the basis of heat transfer processes to study the performance of heat pump to obtain the heating and dehumidification requirements. Specific energy consumption (SEC) and coefficient of performance (COP) of the heat pump were calculated, along with the condenser and evaporator capacity ratings needs to offer the essential thermal conditioning to a modelled greenhouse. The heat transfer process between

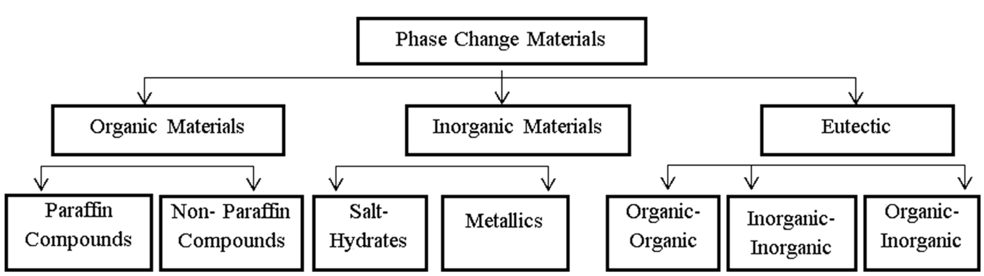

Fig. 2 Classification of phase change materials [11]

Table 1 PCMs and their properties, which can be used for greenhouse

Compound	T_m (°C)	H_f (kJ/kg)	Ref.
Propyl palmitate	16–19	186	[21, 22]
Glycerin	17.9	198.7	[5]
Hexadecane	18.1	236	[23–25]
Butyl stearate	19	140	[25–28]
Propyl palmitate	19	186	[25, 26, 28]
Dimethyl sabacate	21		[25–28]
Octadecyl3-mencaptopropylate	21		[25, 26]
PolyglycolE600	22		[25, 27–29]
Octadecylthioglyate	26		[25, 27–29]
Vinyl stearate	27–29		[25, 27–29]
Paraffin C18–C21	28–40	200–244	[9, 30]
1-Tetradecanol	38	205	[30, 31]
D-Lattic acid	26	184	[5]
Methyl palmitate	29	205	[5]
Polyethylene glycol 600	20–25	146	[5, 30]
$FeBr_3.6H_2O$	21.0	105	[5, 30]
$Mn(NO_3)_2.6H_2O$	25.5	148	[5, 30]
$CaCl_2.12H_2O$	29.8	174	[5, 30]
$LiNO_3.2H_2O$	30.0	296	[5, 30]
$LiNO_3 \cdot 3H_2O$	30	189	[5, 30]
$Na_2CO_3 \cdot 10H_2O$	32	267	[5, 30]
$Na_2SO_4 \cdot 10H_2O$	32.4	241	[5, 30]
$KFe(SO_4)_2 \cdot 12H_2O$	33	173	[5]
$CaBr_2 \cdot 6H_2O$	34	138	[5]
$LiBr_2 \cdot 2H_2O$	34	124	[5]
$Zn(NO3)_2 \cdot 6H_2O$	36.1	134	[5]
$FeCl_3 \cdot 6H_2O$	37	223	[5]
$Mn(NO_3)_2 \cdot 4H_2O$	37.1	115	[5]
$Na_2HPO_4 \cdot 12H_2O$	40	279	[5]
$CoSO_4 \cdot 7H_2O$	40.7	170	[5]

the various components within a greenhouse is shown in Fig. 6. Numbers of assumptions were made before modelling the greenhouse which was as follows: (i) the air inside the greenhouse was well mixed; (ii) no stratification of temperature of plant, covers and other constituents; (iii) the analysis was based on the quasi-steady-state conditions inside the greenhouse and transient behaviour for short time-intervals was not considered and (iv) the ground heat loss from the floor top to the ground was assumed to be in a steady-state. The performance of the heat pump to keep the greenhouse air at a day temperature of 27 °C and night temperature of 18 °C with a relative humidity of 40 % spans 1.2–4.0 and 1000–16,000 kJ/kg for COP and SEC, respectively.

Başçetinçelik et al. [20] applied energy and exergy analysis to evaluate the efficiency of the greenhouse with latent heat storage. Solar energy was stored using the paraffin with the latent heat technique for heating the greenhouse of 180 m^2. The thermal exergy stored were 1740 and 60 W for the charging periods and the average values of the net energy and exergy efficiencies of the system were found to be 41.9 and 3.3 %, respectively.

Future Outlook and Summary

Studies discussed above clearly suggest that greenhouse based on latent thermal energy storage have great potential. The summary of research work carried out by the different researchers on the different types of the greenhouse is represented in Table 2. Although efforts have been put on the design and performance of solar greenhouse, a greenhouse with thermal energy storage still needs the further research and development, research in the field of the greenhouse with thermal energy storage is required at a much faster pace to fill the gap in the market. The greenhouses have important economic potential in cold and arid agricultural area. In order to establish optimum growth conditions in greenhouses, renewable energy sources should be utilised as much as possible. Effective uses of energy storage medium with suitable technology in the modern greenhouses will play an important role on the performance of greenhouse. Some of the potential future research prospects are presented below.

Design of Heat Exchanger for Energy Storage

Solar greenhouse with thermal energy storage is an early stage of development. Further work must focus on poisoning the

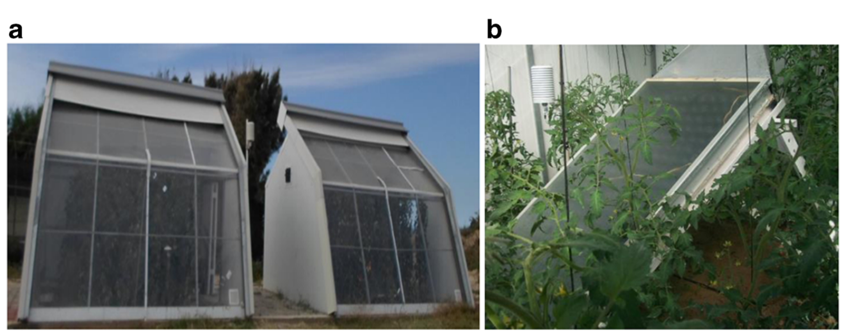

Fig. 3 Experimental setup. **a** Two insulated greenhouse external view. **b** Internal view with latent heat storage solar air heater [14••]

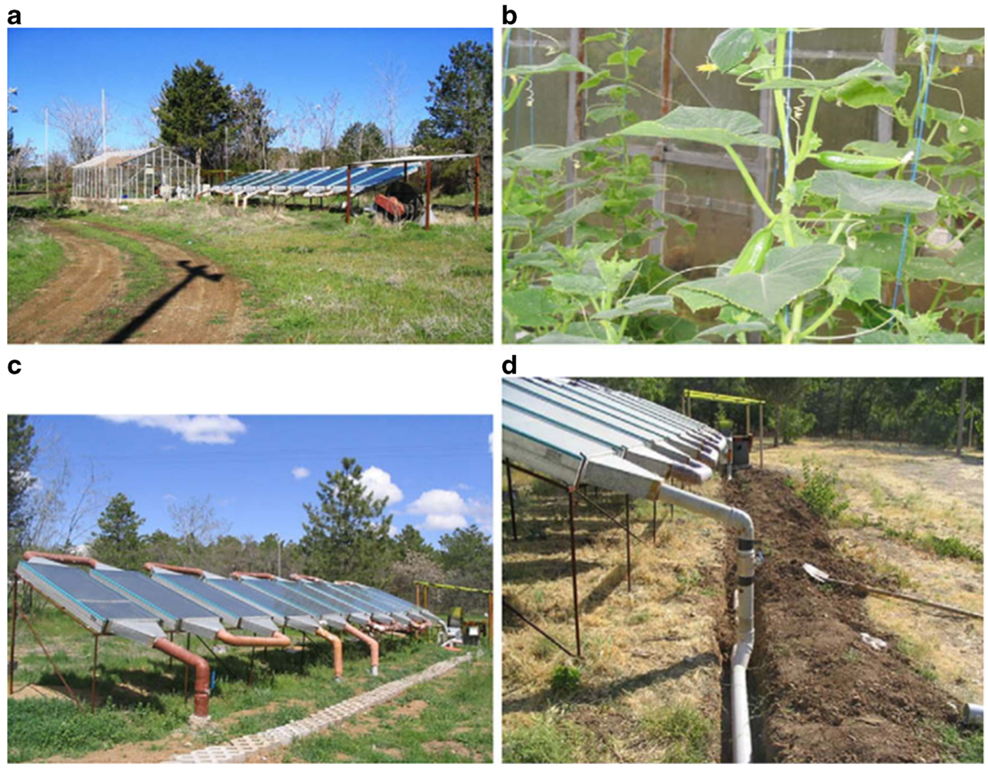

Fig. 4 The view of solar collectors unit and experimental greenhouse (**a**, **b**). Air circulation lines and solar collectors(**c**, **d**) [17]

complications of the existing systems and developing better quality or novel optimised system prototypes. Furthermore, any newly designed system, to have any chance of succeeding, must be both cost-effective and energy efficient when in operation.

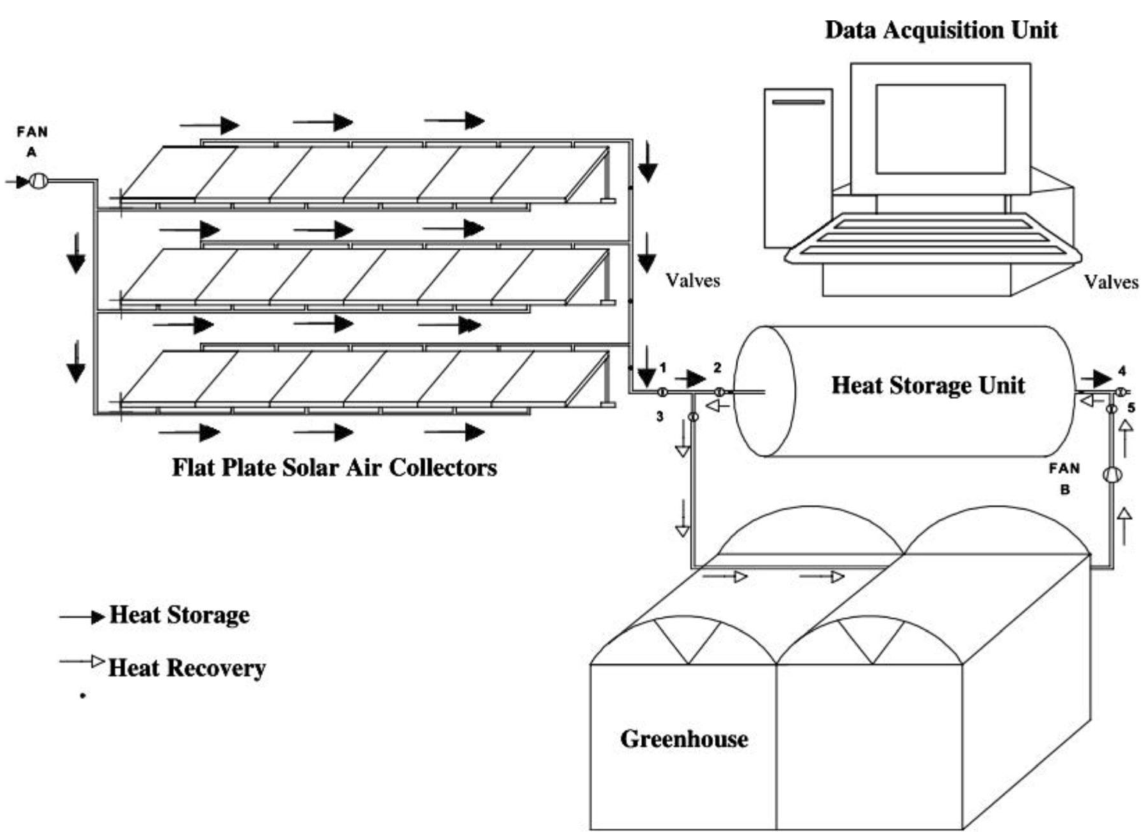

Fig. 5 The arrangement of the heat storage and greenhouse heating system [18]

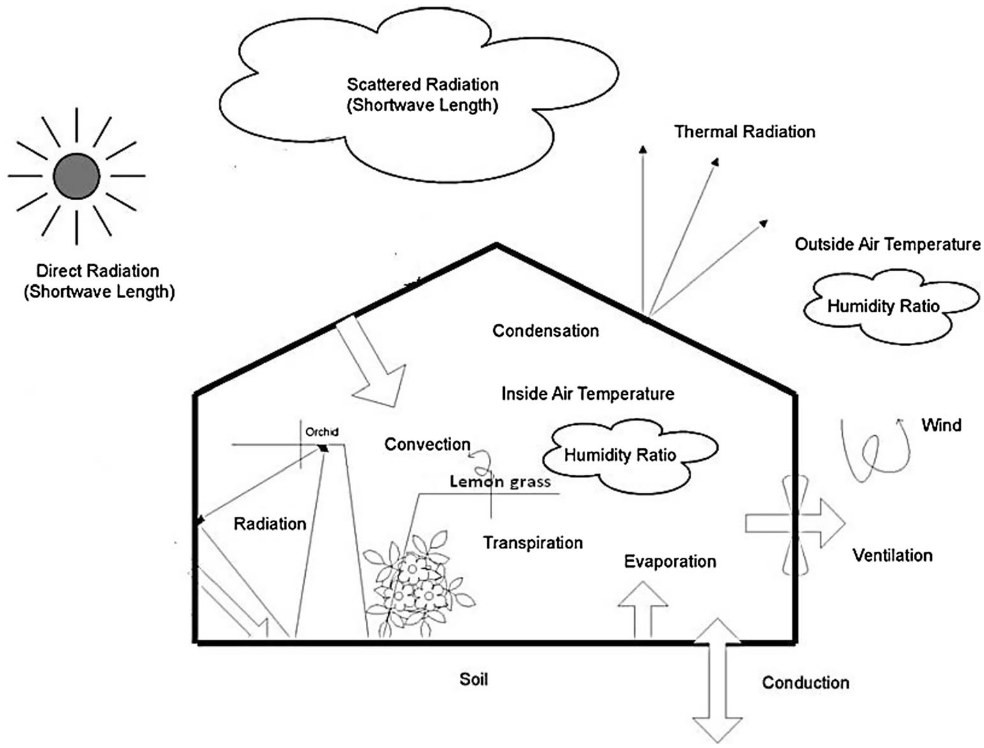

Fig. 6 Heat exchanges between the various components within a greenhouse [19]

Mathematical Analysis

After developing a system's physical structure, a comprehensive understanding of the fundamental characteristics of heat and mass transfer in the integrated system is important. The existing studies indicate that there are still opportunities for investigators to improve the modelling of transient heat and the mass transfer process taking place throughout the system. Furthermore, the modelling technique, such as finite difference model and non-linear transient two-dimensional or three-dimensional numerical models, can be used and selected as the appropriate one. The numerical model developed should be validated by analytical solution, if probable, and then by experimental results.

Performance Evaluation and Demonstration

Experimental studies should be conducted to study system thermal performance and verify reliability. Moreover, the yearly overall performance of the system should be examined in relation to various climate zones. System performance monitoring and evaluation of practical projects must be undertaken to find out the potential profits resulting from specific levels of market penetration.

Table 2 Summary of research work carried out by the different researchers

S. No.	Author	Concluding remarks on previous research	Reference
1	Bouadila et al.	The amount of the heat recovered at night time by system attains 30 % of the total heating desires. The energy stored was equivalent to 56 % of the daytime total excess heat inside the greenhouse.	[14••]
2	Vadiee and Martin	The payback time may be reduced to 5 years if the base load is chosen as the design load instead of the peak load.	[16••]
3	Benli et al.	The collectors integrated with *PCM* provided about 18–23 % of total daily thermal energy requirements of the greenhouse for 3 to 4 h, as a comparison to the conventional heating device.	[17]
4	Öztürk	The effects of various factors on the net energy and exergy efficiencies were examined.	[18]
5	Willits et al.	The computer model was based upon two existing models, one for the greenhouse and one for the rock bed.	[13]
6	Chou et al.	The performance of the heat pump to keep the greenhouse air at a day temperature of 27 °C and night temperature of 18 °C with a relative humidity of 40 % spans 1.2–4.0 and 1000–16,000 kJ/kg for COP and SEC, respectively.	[19]
7	Başçetinçelik et al.	The thermal exergy stored were 1740 and 60 W for the charging periods and the average values of the net energy and exergy efficiencies of the system were 41.9 and 3.3 %, respectively.	[20]

Life Cycles Assessment of Economic Feasibility and Environmental Benefits

An economic evaluation is necessary for the greenhouse with thermal energy storage systems, to determine if the extra capital cost of additional infrastructure is definitely outweighed by additional energy conserving. Then, the applicability, suitability and impacts generated by the systems must be addressed at the ecological and social levels. It may be expected that these systems will have a comparatively high payback period taking into account the initial cost of solar stills and the additional cost of the PCM. Further effort should be conducted from the perspectives of life cycle assessment and economic evaluation.

Conclusion

There are a substantial research and field level performance of the greenhouse with thermal energy storage in all over the world. The greenhouse with thermal energy storage was found suitable for regulating the temperature of controlled environment for the crop production in cold and arid areas. For intermediate temperature range, sensible heat storage (SHS) is the available viable option for thermal energy storage purpose. The liquid SHS materials are expensive; however, the research is also directed toward the improvement in their life, which could be useful in such type of thermal applications. Solid SHS materials are economically more attractive for high-temperature range than the liquids and their volume necessity is nearly same. Thermal energy storage using PCMs in general offers much higher energy storage density as compared to liquids or solids SHS. High-energy storage densities over a narrow temperature range make PCM attractive for greenhouse heating. The PCMs have problems with repeatability, heat transfer rate and containment that need to be solved before its implementation into any kind of latent heat storage systems; therefore, the systems can become commercially and economically feasible for intermediate temperature ranges. In this addition, future studies should be focused on latent heat storage concept for greenhouse heating and improvement in the efficiency of the systems. Such theoretical and experimental studies will be very useful to optimise the management of the heat storage systems for the solar greenhouse system.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance
•• Of major importance

1. Sethi VP, Sharma SK. Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. Sol Energy. 2008;82:832–59.
2. Sethi VP, Sharma SK. Survey of cooling technologies for worldwide agricultural greenhouse applications. Sol Energy. 2007;81:1447–59.
3. Prakash O, Kumar A. Solar greenhouse drying: a review. Renew Sust Energ Rev. 2014;29:905–10.
4. Micro Irrigation Systems Design_ Lesson 29 [Internet]. Available from: http://ecoursesonline.iasri.res.in/mod/page/view.php?id=124931
5. Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renew Sust Energ Rev. 2009;13:318–45.
6. Sharma A, Dong L, Buddhi D, Un J. Numerical heat transfer studies of the fatty acids for different heat exchanger materials on the performance of a latent heat storage system. Renew Energy. 2005;30:2179–87.
7. Sharma A, Shukla A, Chen CR, Dwivedi S. Development of phase change materials for building applications. Energ Buildings. 2013;64:403–7.
8.• Sharma A, Shukla A, Chen CR, Wu T-N. Development of phase change materials (PCMs) for low temperature energy storage applications. Sustainable Energy Technol Assess. 2014;7:17–21. **The publication gives the details of developing novel phase change materials which could be used as thermal energy storage for solar green house.**
9. Abhat A. Low temperature latent heat thermal energy storage: heat storage materials. Sol Energy. 1983;30:313–32.
10. Baetens R, Jelle BP, Gustavsen A. Phase change materials for building applications: a state-of-the-art review. Energ Buildings. 2010;42:1361–8.
11. Kant K, Shukla A, Sharma A, Kumar A, Jain A. Thermal energy storage based solar drying systems: a review. Innovative Food Sci Emerg Technol. 2016;34:86–99.
12. Bouadila S, Skouri S, Kooli S, Lazaar M. Experimental study of two insulated solar greenhouses one of them use a solar air heater with latent heat. Tunis: 6th International Renewable Energy Congress (IREC), Tunisia. 2015. p. 6–9.
13. Willits DH, Chandra P, Peet MM. Modelling solar energy storage systems for greenhouses. J Agric Eng Res. 1985;32:73–93. Available from: http://linkinghub.elsevier.com/retrieve/pii/0021863485901209 .
14.•• Bouadila S, Kooli S, Skouri S, Lazaar M, Farhat A. Improvement of the greenhouse climate using a solar air heater with latent storage energy. Energy. 2014;64:663–672. **Paper carries detail experimental study taken up for analyzing the performance of solar greenhouse with latent heat storage.**
15.• Bouadila S, Skouri S, Kooli S, Lazaar M, Farhat A. Performance of a new solar air heater with packed-bed latent storage energy for nocturnal use. Appl Energy. 2013;16:1–5. **Contains experimental and numerical study to analyze the performance of solar air heater with latent heat storage.**

16.•• Vadiee A, Martin V. Thermal energy storage strategies for effective closed greenhouse design. Appl Energy. 2013;109:337–43. **Paper gives detailed Energy analysis done using TRNSYS.**
17. Benli H, Durmus A. Performance analysis of a latent heat storage system with phase change material for new designed solar collectors in greenhouse heating. Solar Energy. 2009;83:2109–19.
18. Öztürk HH. Experimental evaluation of energy and exergy efficiency of a seasonal latent heat storage system for greenhouse heating. Energ Conver Manage. 2005;46:1523–42.
19. Chou SK, Chua KJ, Ho JC, Ooi CL. On the study of an energy-efficient greenhouse for heating, cooling and dehumidification applications. Appl Energy. 2004;77:355–73.
20. Başçetinçelik A, öztürk HH, Paksoy HÖ, Demirel Y. Energetic and exergetic efficiency of latent heat storage system for greenhouse heating. Renew Energy. 1999;16:691–4.
21. Cabeza LF, Castell A, Barreneche C, de Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. Renew Sustain Energy Rev. 2011;15:1675–95.
22. Khudhair AM, Farid MM. A review on energy conservation in building applications with thermal storage by latent heat using phase change materials. Energy Convers Manag. 2004;45:263–75.
23. Kenisarin M, Mahkamov K. Solar energy storage using phase change materials. Renew Sust Energ Rev. 2007;11:1913–65.
24. Bo H, Gustafsson EM, Setterwall F. Tetradecane and hexadecane binary mixtures as phase change materials (PCMs) for cool storage in district cooling systems. Energy. 1999;24:1015–28.
25. Mehling H, Cabeza LF. Heat and cold storage with PCM: An up to date introduction into basics and applications. 1st ed. Mehling H, Cabeza LF, editors. Springer; 2008.
26. Zhou D, Zhao CY, Tian Y. Review on thermal energy storage with phase change materials (PCMs) in building applications. Appl Energy. 2012;92:593–605.
27. Zalba B, Marín JM, Cabeza LF, Mehling H, Marin JM, Cabeza LF, et al. Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. Appl Therm Eng. 2003;23:251–283.
28. Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renew Sust Energ Rev. 2007;11:1146–66.
29. Cabeza LF, Castell A, Barreneche C, De Gracia A, Fernández AI. Materials used as PCM in thermal energy storage in buildings: a review. Renew Sust Energ Rev. 2011;15:1675–95.
30. Memon SA. Phase change materials integrated in building walls: a state of the art review. Renew Sust Energ Rev. 2014;31:870–906.
31. Hawes DW, Feldman D, Banu D. Latent heat storage in building materials. Energ Buildings. 1993;20:77–86.