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Storage systems for solar energy suitable for agriculture
Part one: thermal energy

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Summary. The solar energy reaching our planet is much greater than our civilisation needs. The main obstacle on the way to its wider use is high variability. This fact determines the need to provide a way to store the energy for the time when the Sun is not shining over particular region or the radiation is not sufficient. The paper presents various ways to accumulate the energy in the thermal form: sensible and latent heat, chemical/sorption, which are suitable for use in agriculture or rural areas. Along with the basic presentation, the most recent developments in each area are presented.

Key words: energy storage, solar, thermal, agriculture.

INTRODUCTION

The Sun is an enormous source of energy – the energy reaching the Earth in an hour is higher than all the energy used by its inhabitants over a year [35]. The following features encourage the use of solar energy in agriculture and rural areas: availability at the place of its use, conversion into other forms of energy involves no or little environmental impact (pollution, noise), the equipment for conversion is usually simple, involving no or little moving parts, which allows the use by a wide range of people and offers low maintenance needs. Also, many agricultural applications, like solar pumping or drying, are well correlated with solar energy availability.

The main disadvantage is the intermittency of radiation with three main components: yearly, daily alteration due to the change of the position of Earth in relation to the Sun and meteorological variation depending on the conditions on a particular day or year. The significance of the components depends on the location of the installation. Higher latitudes have greater seasonal variations whereas near the Equator the seasonal changes are smaller. Therefore various storage horizons are considered: daily (day-to-night), several days or seasonal.

The thermal energy is converted from the solar radiation by means of collectors. A typical flat-plate collector consists of the absorber plate, tubes which transport transfer fluid, glazing on top, thermal insulation and casing. Evacuated tube collectors use materials that change phase from liquid to vapour and vice versa to transfer heat within the collector tube. The condenser part is fitted into the manifold which carries the transfer fluid. Other types include parabolic trough collectors, compound parabolic collectors, linear Fresnel reflector, parabolic dish reflector. A detailed presentation of various technologies can be found in an article by Kalogirou [27] and Tian and Zhao [63].

There are multiple areas were solar thermal (ST) energy is already used in agriculture. One of the oldest applications is food products drying [3, 18, 28, 41, 70]. Animal farms have high hygiene requirements [12, 25], therefore water heating or preheating with ST systems can help to meet their high water heating needs. ST collectors decrease the use of conventional sources to heat farm buildings [29, 43, 62]. Modern designs of greenhouses improve solar energy utilization and extend the growing season of vegetables [17, 42, 69]. Solar-assisted refrigeration may also play an important role on future farms. The refrigeration can be achieved through a sorption phenomenon [22, 37] using thermal energy or with a motor-driven compression powered by PV [14].

Farmers can benefit by using PV on remote areas, where the electrical grid is not available or in places with access to the electrical energy to reduce cost and transform their farm to be more friendly to the environment. One of the first applications for PV in agriculture was water pumping for crop irrigation and livestock watering. A publication by Sontake and Kalamkar reviews its various aspects [59]. Greenhouses operated in hot climate need ventilation as one of the ways to reduce the inside temperature [38]. Ventilation is also needed on animal farms to reduce levels of harmful gases within the livestock buildings [66]. Other applications of PV in agriculture include: lighting of farm buildings [44], electric fences, pumps and compressors for aquaculture [46].

ENERGY STORAGE TECHNOLOGIES FOR SOLAR THERMAL

There are three main ways that of how the thermal energy can be stored: sensible heat, latent heat and chemical.

Sensible heat storage

Sensible heat systems accumulate energy as a temperature change of the material:

$$Q_{sensible} = m\, c\, \Delta T, \tag{1}$$

where:
m is the mass of the medium,
c – specific heat of the medium,
ΔT – change in the temperature.

The medium is thermally insulated in order to reduce energy exchange with the surrounding environment. The perfect material for thermal storage would have high energy density, good thermal conductivity, low environmental impact and corrosiveness. Water is the most commonly used storage medium in solar water heating systems on farms. Aquifers can accumulate heat or cold for long periods, however, environmental concerns limit the range of temperature change. Other materials include solids like metal, concrete, sand, brick and gravel. Mawire considers the application of edible sunflower oil which can be heated to high temperatures [39].

In most of the cases liquids are applied that are thermally layered structures [32]. Stratification plays a crucial role in minimizing energy loss and maximizing energy gain from the collector [53]. Various aspects of improving performance of a hot water storage tank are covered in [58].

A typical application of solar thermal energy is hot water production and storage in an insulated water tank for the farm and household needs.

An article by Li [36] has reviewed various aspects of sensible heat storage, including materials, stratification of fluids, heat transfer and performance comparison with latent thermal energy storage.

Kalaiarasi et al. [26] have presented a design of an air heater with integrated sensible heat storage in form of a copper tube filled with synthetic oil, which improves the efficiency of the process.

Kürklü et al. have studied a concept of a polyethylene tunnel type greenhouse with rock-bed solar energy storage [33]. The system proved to be useful in frost prevention in the Turkish environmental conditions.

Finding the best size of a storage tank is important for proper operation of a solar domestic hot water system and from economic viewpoint as too large tank increases overall system cost. Traditional approach includes f-chart calculations as described in [13] and [31]. Omu et al. used mixed integer linear programming model to find best area of the roof mounted flat plate collector and volume of the storage tank [48]. Rodríguez-Hidalgo et al. studied properties of a system providing hot water for 215 people in Spain [54]. The collector area was 50 m^2. The tank size was represented by a V/A ratio (tank volume to collector area). The analysis has proved that the V/A ratio should be between 0.005 m and 0.08 m in the presented system in order to achieve best plant efficiency.

The main disadvantages of heat storage in the form of sensible heat are low storage capacity per unit volume and non-isothermal behaviour during charging and discharging processes [5].

Latent heat

The latent heat can be expressed in the following form:

$$Q_{latent} = m\, \Delta h, \tag{2}$$

where:
m is the mass of the medium,
Δh – specific heat of fusion.

The medium accumulates heat when changing phase from solid to liquid or liquid to gas and returns it when the reverse phase change takes place.

There are a number of materials that can be used to store the energy in the form of latent heat: ice [55, 61], paraffin wax [11], Calcium chloride hegzahidrat [7], Stearic acid, Acetamide [57], organic prepared form fatty acids [16]. Pielichowska and Pielichowski and Zalba et al. have presented an extensive list of materials with potential application as a medium for energy storage in the latent heat form [50, 68].

It is desirable that a phase change material (PCM) had the following properties: high heat capacity and heat of fusion, stable composition, high heat conductivity and density. It should also be non-toxic [5]. Mehling et al. have proposed a combination of hot water storage tank and a phase change module to improve storage density, allow reheating of the transition layer after partial discharge and a compensation of heat loss in the top layer [40].

Except for the most commonly recognized solid-liquid phase change, other options can be used: gas-liquid, solid-gas, solid-solid [30].

Benli and Durmuş [6] have presented performance analysis of greenhouse heating system using latent heat storage. They used calcium chloride hexahydrate ($CaCl_26H_2O$) as a PCM. The air was used as a heat transfer medium. The installation provided 18 – 23 % of daily energy requirement as compared with conventional heating device. According to the study by Najjar and Hasan, application of PCM in the greenhouse can reduce maximum difference in the air temperature by 3 to 5 °C during 24 hours [45].

Ziapour and Hashtroudi have analysed an improved design of a solar greenhouse featuring a curved roof with a selective cover [71]. This cover modifies the light spectrally, allowing wavelengths between 400 and 750 nm to pass through and reflects near infrared radiation over 750 nm, which can be used for solar thermal energy generation. A thermal collector filled with water and a paraffin wax as PCM is placed in the focal line of the roof. The proposed design improves energy efficiency and economy in comparison to a conventional greenhouse.

Dashtban and Tabrizi have used paraffin wax as PCM to improve performance of a weir-type cascade solar still for water desalination in Iran [8]. Such modification increases productivity up to 31 %.

Islam and Morimoto have analysed the performance of a solar driven adsorption cooling system [22]. The energy is stored in the form of the latent heat of ice/water phase change.

Solar dryers can be divided into direct, indirect and mixed mode [56]. In the direct heater the product is heated directly by the Sun whereas in the indirect one the air is heated and blown into the drying chamber. Jain and Tewari have analysed the performance of solar crop dryer with PCM energy storage [23]. The accumulated energy allowed to keep the temperature between 40 and 45ºC after sunshine hours. The payback period of the dryer was prognosed to be 1.5 year. Kant et al. have given a review of energy storage based on solar dryers with a particular focus on setups with sensible and latent heat storage [28]. They have concluded that in order to improve thermal performance PCMs with large surface area and high heat of fusion are needed.

Ahmed et al. have reviewed improving properties of heat storage materials by addition of nanoparticles [2]. The main effect is increasing of the thermal conductivity of both sensible heat storage materials and PCMs.

An article by Islam et al. have extensively reviewed the technology with particular focus on using phase change materials in hybrid PV/ST systems [21]. According to their research such materials can improve the heat storage potential by 50 % as compared to water-storage systems.

Chemical storage

An interesting alternative to the already mentioned techniques is the thermochemical energy storage, which has a high gravimetric energy density (up to 1 KWh/kg), long (theoretically unlimited) storage period. However, the technology is complex and currently applied only on a laboratory scale [4]. It relies on a reversible reaction which can be written as [1]:

$$C + \text{heat} \leftrightarrows A + B. \quad (3)$$

The thermochemical material *C* absorbs heat and is transformed into reactants *A* and *B*. When *A* and *B* react with each other, the heat energy is released. *A* may be a hydroxide, hydrate, carbonate, ammoniate and *B* can be water, CO, ammonia, hydrogen. *A* and *B* can be any phase whereas *C* is usually liquid or solid [1]. Deutsch et al. [10] present an algorithm for systematic searching for potential thermochemical materials which results in nearly 1000 possible reaction systems. Rao and Dey [52] have described the process of solar thermochemical generation of hydrogen and carbon monoxide by means of splitting water and carbon dioxide by employing metal oxides. N'Tsoukpoe et al. have shown that internal condensation heat recovery using cascade thermochemical heat storage improves the efficiency of the process [47].

Sorption

Sorption heat storage is based on the principle of energy release during adsorption (sorbent in a solid form) or absorption (sorbent in a liquid form). In the process of physical adsorption, the absorbing molecule is bound by the Van der Waals forces, whereas in the chemical adsorption the molecules form covalent or ionic bonds. The chemical reactions are irreversible, so usually for storage purposes physical adsorption is employed [60]. During charging, the storage material is dehydrated consuming energy from a solar collector or waste heat from another process. Rehydration is an exothermic process, so the heat can be delivered when needed.

The materials used include: zeolites – both natural and synthetic [20, 24, 49, 65], silica gel [9, 51], aluminophosphates and silico-aluminophosphates [19] and metal-organic frameworks [15]. Water is used as a sorbate in most of the applications. If the environment temperature is below water freezing point, ammonia and methanol should be considered [67].

Table 1. Number of publications related to selected keywords

	Number of publications (fraction of publications in the previous year)					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
sensible heat	201 (1.04)	253 (1.26)	224 (0.89)	202 (0.90)	183 (0.91)	163 (0.89)
latent heat	177 (1.19)	192 (1.08)	180 (0.94)	241 (1.34)	292 (1.21)	299 (1.02)
sorption	126 (1.21)	101 (0.80)	118 (1.17)	89 (0.75)	88 (0.99)	92 (1.05)

Table 2. Number of patents related to selected keywords

	Number of patents (fraction of patents in the previous year)					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
sensible heat	445 (0.97)	533 (1.20)	591 (1.11)	601 (1.02)	642 (1.07)	560 (0.87)
latent heat	1239 (1.10)	1295 (1.05)	1249 (0.96)	1451 (1.16)	1515 (1.04)	1356 (0.90)
sorption	711 (1.15)	746 (1.05)	815 (1.09)	879 (1.08)	882 (1.00)	889 (1.01)

CONCLUSIONS

Application of novel technologies usually leaves potential users facing challenges resulting from high price and immature technology.

In order to evaluate the dynamics of the research carried out in the field of energy storage technologies two keyword searches have been performed in the Scopus database: publications and patents. The keywords used were: sensible heat, latent heat, sorption AND storage. Tables 1 and 2 present the result of the search.

The greatest number of publications and patents in the recent years have been related to latent heat. The greatest dynamics can be observed for publications on latent heat (especially in the years 2013-2014). In the last years the number of publications and patents has not been increasing significantly which may mean that the technologies have achieved maturity.

In this review paper various ways of solar energy storing have been presented with particular focus on recent developments.

In the agricultural sector, storing heat in ST applications is essential for the operation of the system and usually improves overall performance and usability in applications like greenhouses, where it can reduce peak temperatures [34], heat farm buildings [29], extend drying time and stabilize temperature of solar dryers [64].

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