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Review

Use of Phase Change Materials for Food Applications—State of the Art in 2022

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Abstract: The availability of food to a growing world population is a matter of concern for decades. Despite that, post-harvest losses are large in many countries, due to insufficient food preservation. And recently rising prices for fossil energies additionally increase food cost, thus increase the demand for energy efficiency. Probably the first application of phase change materials (PCM) ever was the use of ice for food storage, for preservation. Related to that is the use of ice for transport, and for fast cool down in food processing. The result of a desktop study shows the range of food applications of PCM, the advantages using PCM, and the state-of-the-art, meaning past and ongoing R&D, also including existing commercial products. The overview covers food processing, e.g., industrial process cooling and heating, local pre-cooling of harvested food, solar drying and cooking, for storage and transport e.g., solar cold rooms, fridges, display coolers, trucks and containers, and for food production specifically greenhouses and water purification. PCM are used in many real applications as commercial products, and in many other applications their advantages are proven. Regarding future R&D, the overview also identifies potential for improvement, possibly even of commercial products.

Keywords: energy storage; phase change material; food; processing; storage; transport; production; preservation; application

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1. Introduction

1.1. Phase Change Materials (PCM)

Heat and cold storage, depending on an application, are scientifically called thermal energy storage TES. Three basic effects can be used: just changing the temperature of a material as it is, changing its phase, or changing its composition. Just raising the temperature of a material is the effect most frequently used, even in everyday life. The associated heat is also called sensible heat, because the temperature change can be sensed easily. If using a phase change, commonly used is phase change between solid and liquid, also called melting and solidification. Typically, this allows the storage of considerable amounts of heat, in comparatively small volume, in a narrow temperature range where the phase change occurs (Figure 1). Materials that are able to store a significant amount of heat by changing phase are commonly also called Phase Change Material (PCM). It is also common to call them latent heat storage material, expressing that heat is stored without a change of temperature; however, the term is often even used in cases where some temperature change is involved when changing phase.

Ideally, PCM undergo the phase change at a single phase change temperature T_{pc}, as shown in Figure 1.

At T_{pc} the value of the specific heat capacity c_p is then infinite, due to the related step in the enthalpy. The enthalpy change during phase change $\Delta_{pc}h$, commonly also called phase change enthalpy, is then often called latent heat, meaning “hidden” heat, as the temperature T ideally remains unchanged at T_{pc} while heat is stored and released during the phase change. Most PCM however show some non-ideal phase change behavior; this means, for example, that phase change occurs in a temperature range instead at a single temperature, that a PCM needs to be cooled below the phase change temperature before the phase change starts (called subcooling or supercooling), or in general that phase change on heating and on cooling follows different temperature behavior (called hysteresis).

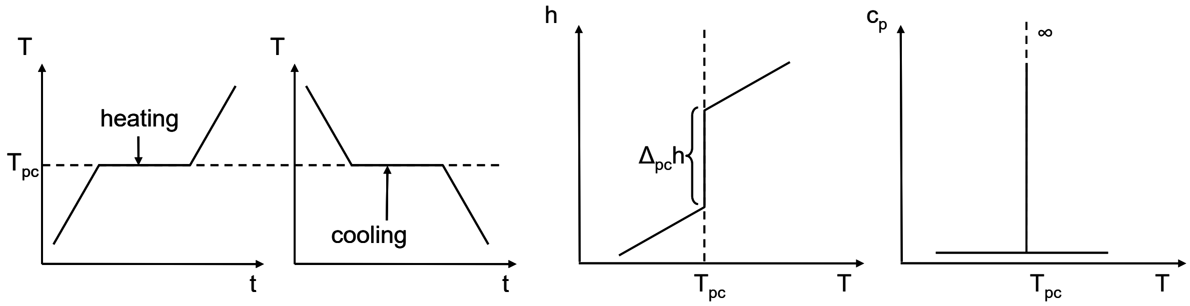

Figure 1. Ideal phase change: heating and cooling T(t), as well as h(T) and c_p(T).

The ability to store a significant amount of heat by changing phase in a small temperature range results in two main fields of use [1]: heat storage (also called thermal energy storage) with high storage density (per unit mass or volume) in a small temperature interval, and passive temperature stabilization (temperature control). Because of these advantages, PCM are used today in a wide range of applications [2]: in buildings for space heating and cooling as well as to prepare domestic hot water, in logistics, specifically the cold chain, for heating or cooling of the human body, even including medical applications, in mobility, in electronics, as well as industrial processes.

Common PCM are for example water, paraffins, fatty acids, sugar alcohols, salt hydrates, and salts. PCM as bulk material are commercially available in a temperature range from about −50 °C to about +90 °C. For application, the PCM is often encapsulated, sometimes combined with another material to a composite material to modify one or several of its properties, or to add a completely new property.

The most common PCM is water, if solid called ice. Ice has been used for cooling food and beverages already in ancient times, and this is still the most common application of water as PCM. It is directly added to food or beverages (if the water quality is good enough), e.g., as ice cubes, or encapsulated, e.g., in plastic containers, to prevent contact or even mixing with other things as well as preventing the water from flowing away such that it can be used over and over again. Encapsulated water, often just called ice packs, are e.g., used to cool picnic boxes. With a volume of up to thousands of m^3, ice storages are common, for cooling industrial processes, buildings, even parts of towns [3].

1.2. Food Applications—Overview

"Food" can be defined differently. The United Nations Environment Program, UNEP, defines "food" as "Any substance—whether processed, semi-processed or raw—that is intended for human consumption. Food includes drink . . . ", "It does not include cosmetics . . . " [4]. This definition is used here.

Availability of food is essential, and if insufficient it is a main cause of poverty, even political instability. Food loss [4], e.g., by spoilage, and the cost of energy related to food, are a growing concern. Thus, this paper reviews the state-of-the-art of the use of PCM in food applications, and its potentials.

Early humans hunted and gathered food in the natural environment, and consumed it as is, immediately. With the use of fire, food could be cooked, thus modified in a way that it often can be digested better, also that harmful bacteria are killed. For later use, e.g., during winter, with food surplus even for trade, storage and transport required food preservation. This was done by drying food using the sun, wind, the fireplace, by salting food etc. Nowadays, practically all food is produced, in a non-natural environment, typically on a scale larger than for personal consumption, and most food is modified also in some way. Further on, applications like cooking serve for preservation as well as modifying food for consumption. The purpose, and so what is done, as well as by whom it is done, has a big effect how something is done, and so the technical solution for an application. Consequently, an overview to structure the applications, specifically regarding food processing, preservation, and cold chain, is needed. It is shown in Figure 2.

Nowadays, only few people consume food that is self-produced, meaning grown, gathered, or hunted. Consequently, nowadays food is practically never consumed directly, e.g., directly after food harvest. Even food that is consumed unmodified usually requires transport, and also storage, on the way from its production to its final consumption. Consequently, food needs to be preserved, to remain fresh, to keep its nutritional value, and to avoid spoilage (meaning it becomes unconsumable e.g., for health reasons). The straightforward way of food preservation, thus without modifying the food, is by keeping food cold, (in case of warm meals, which are modified food, directly before consumption by keeping them hot).

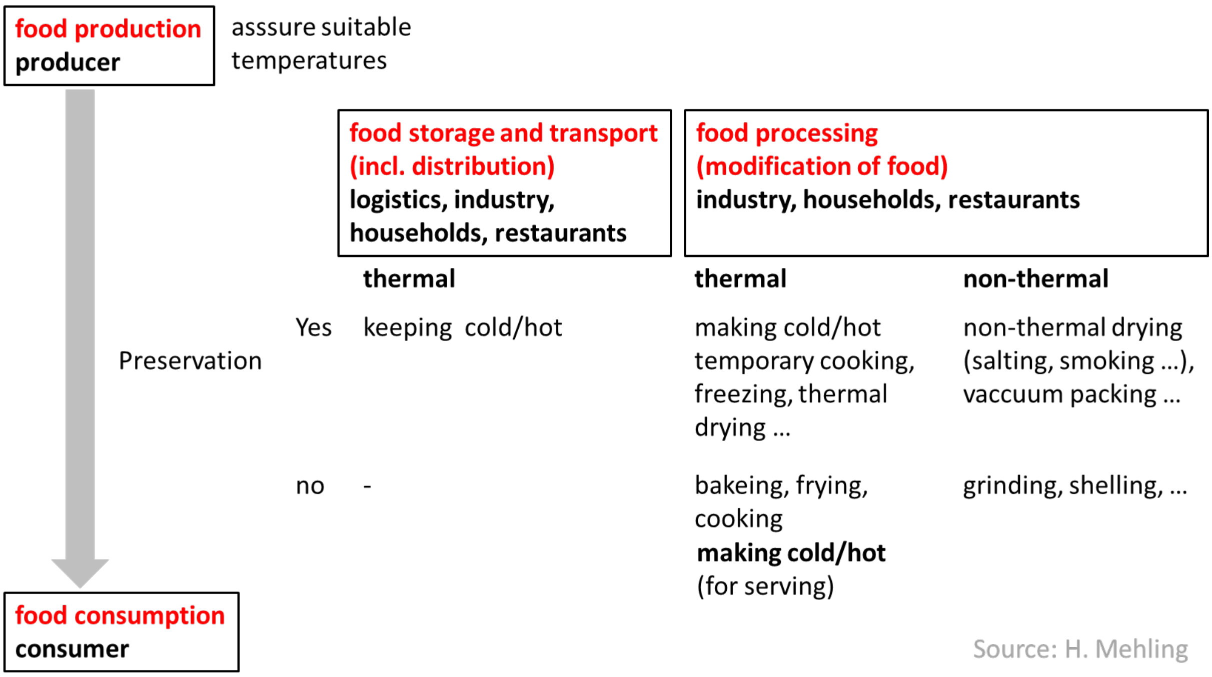

Figure 2. Overview on food applications, specifically thermal ones.

Most food however is not consumed unmodified. Food modification, meaning the transformation of natural products into food, or of one form of food into other forms, is commonly called food processing. Food processing is nowadays done by the food industry, in addition to the households and restaurants. Due to its importance, it is not surprising that many food processing methods are for food preservation. Food processing includes food preservation by thermal treatment like refrigeration and even freezing, by boiling, sterilization, pasteurization, and also by drying in case it is done by temperature and heat. Besides, non-thermal methods of food preservation are drying methods like salting, vacuum packing to keep humidity and even air out, addition of preservatives, irradiation, or also high hydrostatic pressure. Food processing, defined as transformation of natural products to food, or of one form of food to others, however does not just include food preservation; thus, this field of applications is separated in Figure 2. Food processing also includes a wide range of processes which are not for preservation, e.g., processes for making natural products edible, turning ingredients into familiar food, or for modifying food with respect to its content of calories etc. thus dietary needs. Some of these processes are thermal, like baking bread, frying sausages, cooking meals or pre-cooking them for ready-to-eat or heat-and-serve foods. Others are without thermal treatment, like making wine, grinding grain, extracting and filtering oils, ... And, at least in a strict sense, food processing does not include cooling for the preparation of cold drinks, so this kind of thermal treatment is separated from food processing somewhat at the bottom of Figure 2.

Nowadays, even food production is optimized, not so surprising at least if done on an industrial scale. Therefore, heating greenhouses for food production in agriculture during winter is not uncommon, and even shelters for pigs are sometimes heated. Also, because of the scarcity of drinking water in many areas of the world, desalination of seawater is becoming increasing attention.

The overview on food applications, in Figure 2, shows a very wide range of food applications. They are located at the producer, within logistics, at the food industry, the households, and restaurants. And they serve different purposes. While in food storage and transport, and often in food production, keeping the temperature within a well-defined and narrow temperature range is usually the primary goal, in food processing thermal treatment is often less strict on temperature while the amount of heat supplied/rejected and time gains importance. This has a huge effect on the technical solution for an application. Therefore, applications for food processing are discussed first, including also applications for making food cold/hot for serving, then applications for food storage and transport, and finally food production. In each of these groups of applications the specific examples of applications build own subsections. Often even the same goal, e.g., cold storage, is approached by technically different ways depending on the specific application, e.g., cold storage in logistics, in supermarkets, or in households, are all solved by technically different approaches.

2. Food Applications of PCM

2.1. Food Processing

2.1.1. Background

Food modification, meaning the transformation of natural products into food, or of one form of food into other forms, is commonly called food processing. In addition to households and restaurants, food processing is nowadays done on a large scale by the food industry. Food processing includes non-thermal processing like grinding grain to make raw flour, as well as thermal processing like cooking.

Thermal food processing methods comprise those for preservation of food and not for preservation. Those food processing methods for food preservation can again be split up into making food hot/cold, specifically refrigerating and freezing, where the food is then kept at the temperature during the following storage and transport, and only temporary heat/cold treatment, like boiling, sterilization, pasteurization, and drying, if done by temperature and heat. Those food processing methods which are not for food preservation focus on modifying food for making natural products edible, for turning ingredients into familiar food, … like baking bread, frying sausages, cooking meals or pre-cooking them. Thermal food processing methods play a crucial role in making natural products edible, in food preservation, and thereby reducing food loss. Heating has two main purposes. Heating can prevent many foodborne illnesses, as heating can kill or inactivate harmful organisms (bacteria, viruses, …), and heating can increase the digestibility of many foods which are inedible or poisonous when raw, like cereal grains, beans … Heating methods comprise methods to prepare food for consumption, like baking, roasting, frying, grilling, barbecuing, smoking, boiling, steaming and braising, as well as methods for food preservation, like boiling, sterilization, pasteurization, and also drying in case it is done by temperature and heat. Cooling, in contrast, is mostly used for food preservation, for food to remain fresh, to keep its nutritional value, and to avoid spoilage (meaning it becomes unconsumable e.g., for health reasons). Besides for food preservation, cooling is also used to prepare foods like ice cream.

The type of food and the purpose of thermal processing determine the temperature and time of a process. Like any living organism, bacteria need temperatures not too cold and not too hot to grow etc., and well outside this temperature range they die. Therefore, for food preservation, it is recommended to keep food not within a temperature range between about 10 °C and 60 °C to avoid rapid growth of bacteria. Keeping food at lower temperatures limits their growth. Just keeping food cold is called refrigeration, and typically done at temperatures of 4 °C to 8 °C and useful for shorter periods. Keeping food below 0 °C it is called freezing, typical is at −18 °C, and useful for longer periods. Keeping food at higher temperature can significantly reduce the presence of bacteria, even kill all bacteria if the temperature is high enough and if given sufficient time. According to [5], "Since none of the bacteria related to foodborne illness can survive, let alone reproduce, at moderate temperatures, holding food above 140 °F/60 °C indefinitely is safe. This is why the soup at your local lunch counter can be kept hot all day long in a heat-controlled container and why hot buffets use steam baths to keep the foods warm." Processes at higher temperature but for limited time can reduce the presence of bacteria to "safe" levels for near-term consumption or for an extended shelf life. Cooking food even kills most bacteria, however a minor (yet safe) number can survive, and if given the right temperature and time they can reproduce again to unsafe quantities. Thus, after cooking fast cooling is advisable if later food storage is intended. Not for food preservation are methods that via chemical and physical reactions improve flavor and increase nutritional value. Such reactions start at 50–60 °C with protein denaturation [5]. Related cooking methods can be split up into those with "moist heat", in water (blanching, boiling) and thus typically below or at 100 °C, and those with "dry heat" (baking etc.) at temperatures up to 300 °C.

The temperature and time requirements of a heating or cooling process characterize the demand side in a technical solution for heating and cooling. Also relevant is the supply side of energy. Heating can be done conveniently without heat storage if heating can be done by burning fossil fuels or electric heating from the electricity grid. Only if done otherwise, like when using a heat pump or solar heat, heat storage becomes important, and then using PCM can become a consideration. But PCM compete here with other technologies, like hot-water storage. Cooling, specifically when requiring temperatures below ambient, is usually done by an electrically driven cooling machine. For technical as well as economic reasons a cold storage is often integrated, and because of its advantages, PCM are often the prime choice.

2.1.2. Multi-Purpose Cold Storages for Various Cooling Applications

In the food industry, cooling is e.g., needed in slaughterhouses, generally meat industry, dairy industry, central kitchens, breweries, and bottling plants. Cooling is to a large degree used for food preservation, by refrigeration and even freezing, but also otherwise in food processing, for example to make ice cream. Cooling in general refers to any type of cooling, independent of temperature. For cooling to temperatures below ambient temperature electrically driven compression coolers, called chillers, are commonly used. If the demand for cold by the production process is fluctuating, it is often more economic to size the cooler/chiller not to the maximum demand, but just to the average demand and cover the peak demand by cold stored in a cold storage. Cold storage also allows producing cold at higher energetic efficiency, usually at night when due to the lower ambient temperatures, maybe also at lower cost, when cold production is shifted to electricity price off-peak times. And a cold storage also can serve as a backup. The same situation exists in process cooling e.g., in the pharmaceutical and chemical industry, and air-conditioning of buildings. Consequently, the same technical solution of combining a cold storage with an electrically driven cold production unit (cooler/chiller) is used in many places for different purposes. The technologies for cold storage use mainly cold-water storage as sensible heat storage, and ice storage using the phase change of water. While cold-water storage is useful only for cooling well above 0 °C, cooling at temperatures just a few degrees above 0 °C is done by ice storage using water/ice as PCM, while at temperatures below 0 °C usually eutectic water-salt solutions are used. For high cooling powers, mixtures of water and ice (called ice slurry) that can be pumped are used, sometimes ice is even added directly to a process. Generally, PCM compete with other technologies, primarily cold-water storage. The low price of water makes the economics of ice storage comparatively easy. It is therefore not surprising that the use of ice storage is widespread, not only in building applications like air conditioning and district cooling, but also for industrial applications. A variety of technologies exist which can basically be split up in two groups, one where the ice is produced and used in a storage compartment, and heat exchange is by a heat transfer fluid via a heat exchanger or by direct contact with the ice, and a second group where ice is produced as small or larger particles which can be used for cooling directly.

The market for the first is occupied by many companies, ranging from big to medium and small ones. Some of them are already active for several decades. A brief description of the technologies used, estimation of the worldwide installed capacity of cold storage with ice, and its effect in the electricity grid has [3]. Well-known companies producing ice storages are for example BAC, Calmac, and Cristopia (subsidiary of CIAT), EVAPCO, or FAFCO. Installation examples can be found on the websites of BAC [6], mentioning specifically dairies, breweries, meat processing, wet air pre-cooling for storage of fruit and vegetables, Calmac [7], and Cristopia [8], mentioning specifically slaughterhouses and meat industries, central kitchens, bottling plants, dairy industries, breweries. In recent years, the company Sunamp (https://sunamp.com, accessed on 1 December 2022) has developed, and now markets PCM TES. Starting the business with storages for space heating and domestic hot water, using PCM of phase change temperature at 58 °C, now also storges to freeze (−30 °C), refrigerate (5 °C), and even sterilize (118 °C) are available, with storage capacities ranging from 3 kWh to 12 kWh for domestic applications, and 80 kWh for industrial applications. However, no cold storage application in the food area was found. The market for the second group of technologies seems to be more diverse. Companies offering ice harvesters or so-called flake ice or slurry ice makers seem to be in large number. Slurry ice makers for example produce ice that has the consistency of slush or snow, being pumpable, thus applicable directly at the cold demand and with high cooling power, even directly used to cool food. Ref. [9] describes the use of ice slurry thermal energy storage for cheese process cooling, specifically a specialized application for a cheese plant in Hanford, California. Raw milk is purchased at local dairies and processed into cheddar cheese. There are several processes requiring product cooling, some are cooled over several hours of a day, others require nearly instantaneous product cooling. Because the cooling load profile varies significantly throughout a day, various types of ice TES systems were considered for load-leveling and electricity cost reduction, and also for offering backup cooling. Finally, in this case the slurry ice system was chosen because of its high ice-making efficiency, the expandability of the system to meet long-term loads, layout flexibility of the components, and the cost relative to the other options. Ref. [10] describe the use of heat storage for dairy, in Bergen, Norway. The system consists of several heat pumps connected to several thermal energy storages, for different purposes of cooling and heating, like pasteurizing and hot water; here the thermal energy storages chosen are all water tanks.

Despite the commercial availability of a wide variety of cold storages using different technologies with distinct advantages, there is still need for R&D in several areas: storage materials, storage design, and system design. Ref. [11] present the design and performance of a TES consisting of a pillow plate heat exchanger immersed into a low-temperature phase change material (PCM) with phase change temperature of −9.6 °C as the storage medium. According to the authors, it is one of the first experimental investigations featuring a large-scale technical solution that allows for coupling the evaporation and condensation processes of the refrigeration system with the melting and solidification of a low-temperature PCM in the same heat exchanger.

For many applications, specific storage solutions are developed, often integrated in the whole system. Such applications are discussed now.

2.1.3. Milk Cool-Down

Milk spoils quickly in a warm climate. If not cooled and then stored cold, milk spoils within a few hours. In remote areas of developing countries, where grid electricity is often unreliable or even non-existent, this can be a serious problem, leading to huge losses of quality of milk, even spoilage and complete loss. Off-grid solutions are to cool milk by absorption chillers powered by biogas or solar thermal collectors, or compression coolers running on PV-electricity. If in-grid as backup, or generally to buffer the load, ice storage is an option, being cheap, reliable, and environmentally friendly, as compared to batteries. Generally, cooling allows more flexibility in the time when milk is sold, and the distance to customers. E.g. organized in a cooperative, milk can be collected from nearby farmer members of the cooperative, cooled, and later marketed to generate an income. Ref. [12] discuss this application in detail, including solutions and economics. But the approach is not only interesting for developing countries. According to [13], recently introduced new legislation in New Zealand requires farmers to cool down milk more quickly. This would require higher investment cost, and higher energy costs. In New Zealand, most electricity suppliers provide night tariffs which are significantly lower. With a cold storage energy demand can be shifted from morning to night time, reducing energy costs. But more important, cold storage will allow farmers to continue using existing chillers, instead of increasing their capacity. Ref. [13] discuss the state-of-the-art of cooling milk on farm, for the situation in New Zealand, commercially available cooling technologies there, and approaches developed at the University of Auckland with an ice storage allowing to cool milk via a heat exchanger. For developing countries, approaches to cool milk also just in small to medium quantities are studied. One approach is making ice, and then inserting it into the milk-can that contains the milk to be cooled. This approach has been studied by [14], who investigated the performance of a small on-farm milk cooling system for PV applications experimentally as well as by a computer model. The study was later continued [15]. Ref. [16] describe a system, being similar, and a successful field test performed in Tunisia. But there are also commercial systems.

The company Inficold sells milk coolers for medium to large quantities [17]. The coolers have different size suitable for small dairy farms, milk collection centers, or central milk chilling centers. They have an ice storage integrated (Figure 3) to allow fast cool down and operation 24 h, with only 6 to 8 h grid or solar PV electricity to charge, and no diesel generator, electric battery etc. as backup. For more, [12] discuss more solutions in detail, including economics.

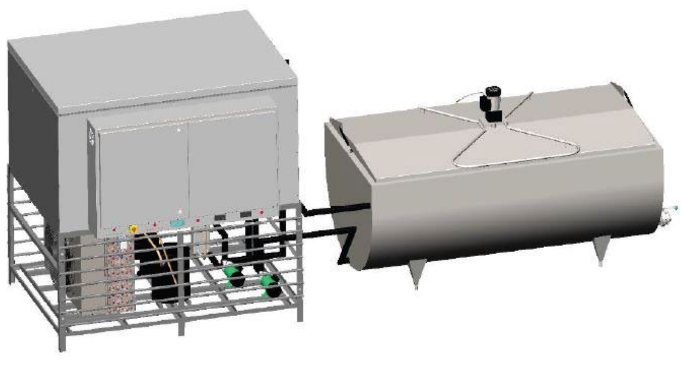

Figure 3. 1000 L bulk milk cooler with ice storage (source: Inficold).

2.1.4. Solar Freezer/Pre-Cooler

Cooling of harvested food, as fast as possible, including dropping core temperatures, increases the shelf life significantly and minimizes food wastage. This is especially critical for foods which have a high heat capacity, and spoil comparatively fast, such that technical solutions should be designed accordingly.

A possible solution is a mobile solar-driven freezer/pre-cooler [18], shown in Figure 4, which runs totally off-grid, and is on wheels to be taken directly to the harvesting location. It allows cooling down the harvested products right after harvest, and also cooling them during the following transport (first mile transport).

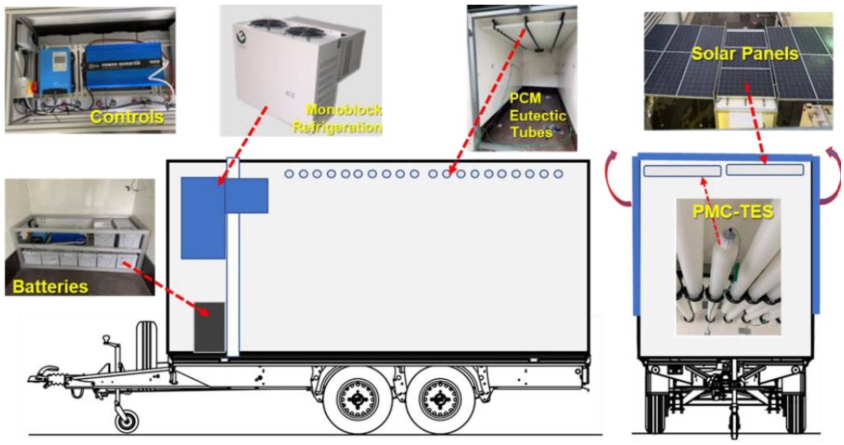

Figure 4. Mobile solar-driven freezer/pre-cooler (source: Phase Change Material Products Ltd.).

Another example is a solar powered cold storage facility, developed for fishermen, as stand-alone, off-grid, 100% solar-powered system. Two units with 20 m^3 are installed on remote islands in Indonesia [18]. They are designed to keep 1000 kg of fish at −2 °C, in ambient temperatures of up to 40 °C, and have the capacity to cool down 200 kg of new, 'un-iced' fish per day (total cooling load of 30 kWh per day). A 6.4 kW solar array, backed up by a relatively small 10 kWh battery, runs the whole system. The system is equipped with PCM TES in the ceiling, capable to store 15 kWh cooling capacity at −4°C, which allows the compressor to do most of its 'work' during the day, when solar power is available.

2.1.5. Multi-Purpose Heat Storages for Various Heating Applications

The situation of multi-purpose heat storages for various heating applications is quite different compared to cold storages for cooling. While for cooling water/ice is a technically and economically suitable storage material, and experience with it exists for thousands of years, for heating no such material exists. Technically and economically suitable PCM for heating still had to be developed in the past decades. The focus was here on space heating and domestic hot water, as well as TES for solar-thermal power. PCM in a suitable temperature range for food processes, and related suitable storage concepts, therefore are mainly a spinoff of developments made for completely different application areas. And not to forget, the general options to choose from for heating applications are quite different from those for cooling. PCM compete here with other technologies, like hot-water storage, but moreover heating can be done conveniently without heat storage if heating is done by burning fossil fuels or if done by electric heating. Only if using a heat pump, if using solar-thermal collectors, and more recently if using intermittent, surplus energy from solar PV or wind, heat storage becomes important, and using PCM is one option. For supply of heat to a production process in general there is no significant market share of PCM yet, because of the competition with hot water storage, which is cheap and allows easy power regulation. However, there are several market niches. One market niche is when space is limited and/or the allowed temperature range to store heat is small. Another is when the temperature is generally far above 100 °C where the pressure in water storage can become critical. This also applies if steam is finally required.

In recent years, the company Sunamp (https://sunamp.com, accessed on 1 December 2022) has developed, and now markets PCM TES. Starting the business with storages for space heating and domestic hot water, using PCM of phase change temperature at 58 °C, now also storages to freeze (−30 °C), refrigerate (5 °C), and even sterilize (118 °C) are available, with storage capacities ranging from 3 kWh to 12 kWh for domestic applications, and 80 kWh for industrial applications. And the first use in the food area is now investigated.

2.1.6. Distilleries for Whiskey

In a feasibility study, performed as part of Phase 1 of the BEIS Green Distilleries competition, the company Sunamp and Heriot-Watt University investigated if a high temperature, large-scale PCM TES could be used by distilleries to enable fuel switching to low carbon or even zero emission technology. The results are published in a report [19].

According to the report, the Scotch whiskey industry is one of the most energy intensive subsectors of the national “food and drink” industry, and is working towards net zero emissions by 2040, including all operations from maltings production to distillation, maturation, blending, bottling and warehousing. Generation of heat for malting and distillation is the main source of emissions in the distilling industry. Heat demand is met by steam, in most cases today produced by the combustion of fossil fuels or biomass.

The feasibility study investigated if large scale PCM TES could allow to size distillery heat generating technology to an average load instead peak demand, and if then a smaller generating unit could encourage the use of zero or low carbon technology and/or enable the use of more renewable options. Using energy and process modelling from Heriot-Watt University, with data from their on-campus distillery as well as industry input (e.g., distilleries peak demands, duration, temperature, ...) the size of storage was determined, required to peak shave and enable renewable energy derived thermal energy. The result is that a large-scale (MWh) PCM TES can be used, which could be available e.g., in 10, 20 and 40 ft shipping container modules. Currently Sunamp manufactures PCM TES with storage capacities ranging from 3 kWh to 12 kWh for the domestic market and 80 kWh for industrial applications. Throughout, the same basic technologies and construction, a container which contains PCM and heat exchanger, are used, so can be scaled to a required size. For the case studied, requiring steam production, the existing PCM TES technology for 118 °C can be used. The report shows how scaling can be done. According to the report, in a system with 5 kW PV coupled and a 20 kWh storage, the storage will have a rapid payback time from savings on electricity, which could pave the way to net zero carbon distillery. They plan, in Phase 2, to proof the finding by real scale testing at several demonstration sites.

2.1.7. Beer Brewing

The Birmingham Centre for Energy Storage, at the University of Birmingham (UK), and the company Estrella de Levante (Spain), work on the development of a heat storage [20], which aims to reduce the use of fossil fuels in the brewing industry. The storage is for waste heat recovery, by increasing the storage capacity of the production plant, for efficient management of energy resources. The storage is constructed with a heat exchanger concept, filled with the PCM. The base of the PCM is $Mg(NO_3)_2 \cdot 6H_2O$, and it melts around 88 °C. The storage was tested successfully in a lab scale system. A larger storage has been constructed and integrated into the brewing plant for further testing.

2.1.8. Solar Food Drying

Food drying is a way to preserve food, e.g., fruits, vegetables, herbs, grains, fish, and meat. Dried fruits and vegetables have shelf lives of 1 to 2 years. Especially in developing countries with lack of other means of food preservation, like cold storage, food drying can significantly reduce postharvest losses. The farmers can sell more, and usually at higher price since they can choose when selling their produce. And not to forget, also consumers can take advantage of carrying dried fruits without needing any other means of preservation, for example when traveling or working. Dried fruits and vegetables may be eaten plain as a wholesome snack, incorporated into baked goods or sweets, or seasoned to make pickles. Additionally, they can be reconstituted by soaking in water.

Drying of food means the removal of water from the food via its surface, and connected the transport of water from within the food to the surface. The driving forces can be an increase of the vapor pressure at the food surface to a level above that of the ambient air by heating the food, or the reduction of the vapor pressure in the ambient air to a level below that at the food surface. Heating of food can be by radiation, by conduction, or by convection. The reduction of the vapor pressure in the ambient air is usually by heating the air, which increases its ability to absorb water; another option is applying vacuum. Generally, temperature affects the removal of water but also the resulting food quality (e.g., proteins start to denaturate at 50–60 °C). Thus, the optimum temperature range for thermal drying depends strongly on the type of food to be dried; it is typically in a range between 40 °C and 80 °C. Compared to common thermal methods of food drying using heat from burning fossil fuels, drying using solar heat has the big advantage that the large amount of heat needed for drying is from a free, renewable source.

Introductions to solar dryers for food drying can be found in [21,22]. Desirable properties of the dried food are low and uniform moisture content, minimal portion of damage to the produce, high nutritive value, visual appearance and taste . . . The drying process itself does not only lead to the intended removal of water, but might have other effects on the food quality, e.g., negative effects due to improper drying conditions or equipment. For example, too high temperature or excessive direct exposure to sunlight might reduce food quality. Thus, classification of solar dryers is by various criteria: their temperature as high or low temperature solar dryers, their heat source as fossil fuel dryers (conventional dryers) or solar dryers, by their construction principles, or by their operation principles. For the background discussion it is not necessary to discuss any of them specifically, or in any detail.

Solar heating means heating is only possible in daytime, and in addition only if the weather is suitable. This leads to two issues of economic importance. First, the dryer dries only in a fraction of the time, often less than 50%, and is thus operated well below its potential output. Second, the time needed until the desired low moisture content is finally reached is unnecessarily long and this significantly increases the risk of spoilage. Thus, besides having a lower output than possible, part of the output produced might even be spoiled and thus useless. For both reasons a backup heat source can be installed to bridge times of no or little solar heat input. Thus, at least for large-scale solar dryers, a backup source is recommended to bridge bad weather. Besides thermal issues, some further issues related to food quality are relevant. Commonly used open sun drying is low cost and easy, however it is unhygienic, and besides inefficient temperature control, direct exposure to the sun results in a poor quality of the product, e.g., loss in nutritional value of the food, loss in taste, as well as negative changes of the visual appearance. Thus, good systems also should be rather closed, and the food should not be exposed to direct sunlight.

Several reviews on solar drying using PCM for thermal energy storage exist: [21,23,24]. They show that research on this topic is quite widespread. In summary, they mention the option of using a thermal energy storage (TES) as backup heat source, the TES being charged by solar heat in daytime, and specifically using Phase Change materials (PCM). The use of PCM in a food drying process is here not just for heat storage in general, the phase change of the PCM additionally allows stabilizing the temperature in the range that gives the best food quality. Further on, if heat from a solar collector is used, thus solar process heat, the high storage density in a small temperature range limits the rise of the temperature of the storage and therefore leads to an increase in the efficiency of the solar collector. While the reviews cover many aspects, like different dryer types, ways to integrate PCM, and PCM choice, [25] report on the development of PCM specifically for solar drying systems. Ref. [26] report on the experimental investigation of a PCM Assisted Greenhouse Solar Dryer explicitly for Hibiscus Leaves and improvements in drying by PCM.

For a few years now, there is also a commercial solar food dryer using PCM, which was developed by PLUSS Advanced Technologies Ltd., Mumbai, India. The dryer, with the name Aagun® (Figure 5), allows drying of food after sunset, even during night, by heat stored in PCM. In addition, the PCM buffers the drying temperature such that too high drying temperatures are avoided and the resulting food quality is optimized. Details are published in [27] and the product website [28].

Figure 5. Solar dryer with PCM, for drying agriculture produce (source: PLUSS Advanced Technologies Ltd.).

2.1.9. Solar Cooking

Cooking is a type of food processing, specifically using heat to prepare food for consumption. Generally, cooking has two main purposes. First, cooking can prevent many illnesses possible if food is eaten raw. Cooking can kill or inactivate harmful organisms (bacteria, viruses, . . .). Second, cooking can increase the digestibility of many foods which are inedible or poisonous when raw, like cereal grains, beans . . . For both purposes, the achieved effect depends on temperature, cooking time, and cooking method used. There is a large set of methods for cooking, like baking, roasting, frying, grilling, barbecuing, smoking, boiling, steaming and braising, which vary widely in the applied temperature (about 60 °C to 300 °C), the required time, and the method of heat transfer.

In many developing countries, cooking in households is still mainly based on fossil fuels or biomass, which is a significant source of air pollution, CO_2 emissions, and recently also causing increasing cost. These problems can be avoided using solar energy for cooking, available in many developing countries. Thus, it is not surprising that research on solar cooking is plenty, and commercial cookers available.

Basically, solar energy can be used as solar thermal as well as solar electric, both useful for cooking. However, solar electric, using PV modules to generate electricity which it is then used for cooking, is rarely discussed, an exception is [29]. Reasons are probably that solar thermal collectors are available for many decades, can be self-built, and have comparatively high conversion efficiencies. Nevertheless, electric systems have also distinct advantages; e.g., for indoor cooking when the energy from the sun has to be transported to the cooking site indoors, or for serving a wide temperature range.

Solar thermal cookers are primarily classified based on their design regarding collecting solar energy as box-type, panel-type, and concentrating solar cookers. Moreover, they can be classified depending on how solar thermal energy is transported to the cooking vessel, thus by direct or by indirect heat transfer. Important is if cooking is outdoors at the solar thermal collector or indoors some distance away from it. Further on, as solar energy is not always available at the right time for cooking, or with sufficient power, integration of an energy storage is desired; typically, this is a thermal energy storage, even for solar electric cooking as discussed in [29]. The different issues regarding solar thermal cookers are discussed in many publications, e.g., [30–32]. Refs. [31,32] also give extensive overviews of publications and results.

Specifically with regard to thermal energy storage, TES, this can be done as sensible heat or latent heat, and can be integrated into the cooking pot, where the cooking pot is placed, or between cooking pot and solar thermal collector. For example, [31] describe a cooking pot with PCM integrated, which can be heated via the solar thermal collector in daytime, and can later be used for cooking separate from the solar collector. Ref. [32] describe a solar cooking system for baking, where PCM is integrated into the plate where the food is placed for baking; the PCM is a $NaNO_3$—$KaNO_3$ mixture. Ref. [32] also describe a similar system that is not for baking but to cook with a cooking pot; the PCM is erythritol. Ref. [33] report on a solar thermal cooking system for 6000 meals per day, with a separate thermal energy storage; the system uses water/steam for heat transfer at 150 °C to 170 °C from the solar thermal collectors to the kitchen, and stores heat in a pressurized hot water tank. Ref. [34] give a review of parabolic solar cookers with thermal energy storage, specifically parabolic solar cookers as they achieve high temperatures in short times, so allow most types of cooking. An extensive overview is given on the research, results, and publications where they are presented, for sensible as well as latent heat storage. Their results show that most research is on latent heat, that most work is experimental, few is modeling. Important is that most of the research is technical, while only very few studies considered the techno-economic and socio-economic analysis of solar cookers as compared to conventional cooking methods. Economic and social aspects are however crucial to ensure economic competitiveness of developments as well as their social acceptance by the intended users.

Summarizing, while solar thermal cookers of a wide range of types are commercially available, and while also integration of a thermal energy storage, specifically using PCM, is advantageous, there is yet no commercially available solar cooker or system with a PCM storage integrated. The research is highly fragmented, which is not surprising keeping in mind the wide range of temperatures and additionally cooking situations that are often hard to combine with solar thermal energy as energy source.

2.1.10. Beverage Cooling etc.

As already discussed in the introduction, just changing the temperature to a temperature desired for consumption does not fit to the definition of food processing, referring to a transformation of natural products into food, or of one form of food into other forms, in a strict sense. But since these processes are even less belonging to storage or transport, they actually fit best to food processing and are therefore discussed here after those processes that fit in a strict sense.

Beverage cooling is undoubtedly the most common and also most frequent application of PCM by far. And it is done by a variety of approaches, which gives a good overview on how PCM can be applied.

Direct cooling of beverages by adding ice in form of ice cubes is today standard, especially in summer. To speed up the cooling, the ice is crushed (large surface) or the beverage stirred (forced convection). Actually, there is probably no type of beverage which is not cooled this way today. In the extreme case, small ice particles are used, and a type of beverage made of such ice and a drink is called a "slushy". Preparation is by mixing the ingredients including ice cubes in a blender, thereby crushing the ice, or by a commercial slush machine which uses cold water and then cools the ingredients down to form ice.

Having ice directly added to a beverage leads to dilution with water, which is not desired in many cases. Indirect cooling, meaning cooling the beverage via heat exchange, avoids the dilution of the beverage. The easiest approach is a bucket with cold water, better ice, where the beverage is placed for cool down. This is standard for bottled wine or soft drinks in cans, thus small amounts. For big beverage containers, this can be done by a pipe heat exchanger, with the beverage flowing in the pipe and ice on the outside. To tap cold beer, so-called "ice bank coolers" are commercially available from several companies. They have a cold storage where water is frozen to ice by a refrigeration unit, and to tap cold beer the beer flows through coils immersed in the storage. One of the manufacturers [35] mentions that it is also useful for wine, water, and cocktails. Ref. [36] performed an experimental investigation of the energy efficiency of such a beverage cooler with ice storage. They concluded, that by modifying the control of the ice storage a reduction of 15% in energy consumption and a significant decrease of refrigeration system startups could be achieved. Further energy savings are possible by other measures.

While cooling of beverages is standard, and commercial solutions exist and are widely used, the analysis of [36] is a clear reminder that there can be still significant demand for

R&D. The higher energy costs which are experienced nowadays, compared to previous years, might initiate further R&D to optimize even already commercial products towards saving more energy.

2.2. Food Storage and Transport

2.2.1. Background

Nowadays, food is practically never consumed directly, e.g., directly after its harvest. Even food that is consumed unmodified is usually transported and also stored on its way from production to consumption. Storage and transport on the way from production of raw food to consumption takes place many times, between industry, distribution centers, supermarkets, households and restaurants, and the consumer.

During the time of storage and transport, food needs to be preserved, to remain fresh, to keep its nutritional value, and to avoid spoilage. The straightforward way of food preservation, thus without modifying the food, is thermal: by keeping food cold, or for warm meals directly before consumption by keeping them hot. As already discussed before, in the background on food processing (Section 2.2.1), for food preservation it is recommended to keep food not within a range between about 10 °C and 60 °C. Keeping food at lower temperatures distinguishes between keeping food cold and keeping food frozen. Keeping food cold, called refrigeration, is typically done at 4 to 8 °C (useful for shorter periods), and keeping food frozen, below 0 °C it is called freezing, is typical done at −18 °C (useful for longer periods). Keeping food above 60 °C is just for distributing and keeping ready meals for consumption.

Keeping food in a narrow temperature range for preservation is typically done in a well-insulated space. Thus, food preservation during storage or transport typically needs less heating or cooling power than making food hot or cold in food processing, including bringing it to the temperature for preservation. Technical solutions for storage and transport, compared to processing, focus thus more on keeping the temperature in the desired temperature range, which makes PCM very suitable for these applications.

Storage solutions keep food in the required temperature range while being stored at a given location. For this, the storage space is well insulated to reduce heat exchange with the ambient, and remaining heat exchange is compensated by a heating or cooling device, a pre-charged PCM, or by a combination. Because food storage and transport happen on many different levels, it is not surprising that there is a wide range of technical solutions. An approach for cold storage of food is to combine cold production with cold storage, typically an electrical driven compression cooler with an ice storage, and to supply cold if needed to the space where food is stored. Another approach is to place the cold storage into the space where food is stored, and which is well insulated, while having the cold production unit outside. Then the cold production unit can even be detached during transport, or storage at different locations. Independent transport containers usually use pre-charged PCM instead of a heating or cooling device, because in transport a power connection is usually missing. However, they can also be used for storage.

The focus now is on storage solutions with a fixed location where a source of electricity is available or can be made available. The advantage of using PCM to shift or buffer heating or cooling loads is typically an increase in energy efficiency, reduction of cost, and having backup in case of power failure.

2.2.2. Cooling in Supermarkets

Supermarkets need cooling in different ways: space cooling to avoid that food stored in shelfs is exposed to high temperatures in summer, and cooling to lower temperatures in fridges and display coolers. Ref. [37] analyze the performance of an ice storage integrated into the air-conditioning system of the hypermarket in Ankara, Turkey, thermodynamically and economically. According to their analysis, the ice storage stores 47% of the 8332 kWh daily total cooling load, which coincides with the duration of the peak tariff for electricity. Therefore, the ice storage allows to turn off the chillers during peak tariff hours. Based on the analysis of the data collected over the four years of operation, they found that the ice storage reduces the energy cost for air conditioning by about half, and has paid back its initial cost within the first 3 years of operation. Integration of an ice storage in an air-conditioning system should be an application which is state-of-the-art, however it is not clear how widespread its use is. According [38], there was only limited application in supermarkets at that time, assuming that one reason is the in supermarkets often required lower temperature. Therefore, different integration approaches were suggested [38]: one approach is to integrate the ice storage at the condenser, another is to integrate the ice storage to subcool the condensed refrigerant. A third suggestion is the use of storage materials with phase change temperature significantly below 0 °C. No information was found as to how far these technologies have been adapted in supermarkets by now.

2.2.3. Cooling Large Food Production, Storage, and Distribution Facilities

As just discussed for supermarkets, connecting a cold storage to a cooler, and supply the produced cold to the space for storing food cold is possible. If the whole space has to be cooled to freezing temperatures, a possible approach becomes integrating the storage into that space. It has several advantages. Generally, it has practically no losses, because all the heat exchange between storage and its environment leads to cooling of the space and the contained food. Also, cooling still continues even in electricity blackouts.

The company Viking Cold Solutions™ Inc., Houston, TX, USA (https://www.vikingcold.com, accessed on 18 October 2022) focuses on such a system, for frozen food production, storage, and distribution facilities. For this, macro-encapsulated PCM is placed above the food (Figure 6), and stores cold supplied by the cold production unit via cold air into the space where the food is stored. The cold stored in the PCM cools the food, maintaining stable temperatures, even if cold production outside is turned off. The effect can last for many hours, thus allows to run cold production at maximum design efficiency which saves energy, reduces equipment wear down, and also allows use of electricity during times of low electricity prices, thus saving cost. According to information on their website, the efficiency of cold production is increased by up to 26%, while electricity cost can be reduced even up to 50% by shifting electricity demand to times of lower electricity prices. In addition, this approach can serve as a backup in case of failure of electricity supply of the cold production unit. Besides these advantages for the user, the option to shift electricity demand to off-peak demand hours also allows better flexibility for the utility, meaning the electricity supplier. The technology was tested in a customer installation and validated by an external consulting company in a two-year study [39]; the report is available for everybody at the company's website. Mentioned on their website is also that the approach is useful for solar-PV driven systems. In developing countries, where grid electricity is often not available or not reliable, solar PV is often the first option.

Figure 6. Approach to cool frozen food production, storage, and distribution facilities (source: Viking Cold Solutions™ Inc.).

2.2.4. Small, Solar Cold Rooms/Houses

While in developed countries fast collection of newly produced food like milk, fish etc. is quite efficient, or immediate cooling at the production site using grid electricity is available, this is often not the case in developing countries. The previously discussed milk cooler and the solar freezer/pre-cooler are already applications in this context. Consequently, local, and thus smaller cold rooms/houses that allow cooling close to sites of food production are also needed. Actually, the solar freezer/pre-cooler solutions, previously discussed in Section 2.1. Food Processing, mobile (Figure 4) or stationary, are already for cold storage, but specifically also with a significant capability of cool-down power and thus were discussed earlier.

In many parts of India, there is a lack of cold storage facilities, because electric power is not available, or because the use of diesel generators as electric power source is too expensive. As a consequence, a significant part of the fresh food produced must be sold immediately, often at times of peak supply, or it loses quality during storage, in the worst case is even completely lost. All this leads to a low income for farmers. The same situation exists in many developing countries around the world. Many of them have lots of sunshine, so a solution to make cold storage space available are solar powered cold rooms. Ref. [12], in their analysis of costs and benefits of clean energy technologies in the milk, vegetable and rice value chains, also analyze different options for solar cold storage. These are PV driven cooling with electric storage (batteries), the same with thermal storage using PCM (ice) or with a chemical process, cooling by thermal sorption refrigeration, and cooling by passive and sorption combined systems. According the report, PV driven cooling with batteries is the most common solution and largely available on the market; solutions typically allow storage between 0 °C and 15 °C for up to seven days without sun. Systems with an ice bank typically allow storage in the same temperature range for up to three days, and similar those using a chemical process. The other two options are usually not recommended for the vegetable chain due to limits in performance and volume to cool, or are still in the R&D phase. In their analysis of costs, specifically of commercial products, from all PV driven cooling options the examples with ice storage have the lowest cost with one exception. For systems using batteries they also mention that a major expense is replacing the batteries every 6 to 7 years.

The commercial solutions analyzed in [12] however cover few products on the market. Figure 7 shows a solar cold room from PLUSS Advanced Technologies, also called Himacool ™. The solar cold room allows storage of fresh fruits, vegetables, etc., in the temperature range 2 °C to 8 °C, or −25 °C to −15 °C, cooled by a compression cooler driven by solar PV panels mounted on the rooftop, and buffered at a temperature depending on the PCM used, thus not only ice. More detailed information has [40], as well as the corresponding Himacool ™ brochure [41]. Ref. [42] has an interview with a representative of the company Inficold, describing many technical details of their solar cold storage houses, the market size, significant reductions of food loss achieved, and decision to scale the technology for larger applications. Ref. [43] specifically discusses the business case for solar PV cooling with ice storage in Africa, stresses that compared to electrical energy storage it is less complicated, requires less maintenance, and has no limited lifespan, and that the investment payback period is less than three years. The advantages of ice storages compared to batteries in solar cooling applications are also discussed at several applications in [12].

Figure 7. Solar cold room (source: PLUSS Advanced Technologies Ltd.).

2.2.5. Small Coolers and Freezers

The idea to integrate PCM into small coolers and freezers was already investigated in the early 1990s. Latest around the year 2000, the first commercial application was brought to the market: the company Kissmann has coolers and freezers e.g., for small boats, with PCM as thermal buffer [44]. Somewhat bigger storages for food, chest coolers and freezers, e.g., used in households, are for 2 to 8 °C (cooling) and −24 to −18 °C (freezing). Here, the company PLUSS Advanced Technologies has developed a commercial product; Figure 8 shows how PCM pouches are integrated into the compartment walls. The advantage of the PCM is as backup for the case of power failure, common in countries with no stable grid, like India, and to increase the efficiency of the electric cooler. According tests under the supervision of UNIDO (United Nations Industrial Development Organisation) and CII (Confederation of Indian Industries) described in [45], the freezers and coolers with PCM provide thermal backup up to 16 h at an ambient temperature of 35 °C to 40 °C, and the electrical energy consumption is reduced by 20–25%. The return on investment is achieved in 9 months. According to [45] over 50,000 freezers and coolers have already been integrated and deployed with PCM technology in India, equivalent to a market penetration of 2%. Several large- and small-scale manufacturers and a major OEM are commercially adopting the technology on a large scale. More and up-to-date information can be found on the company website (https://pluss.co.in/logistic/, accessed on 27 September 2021).

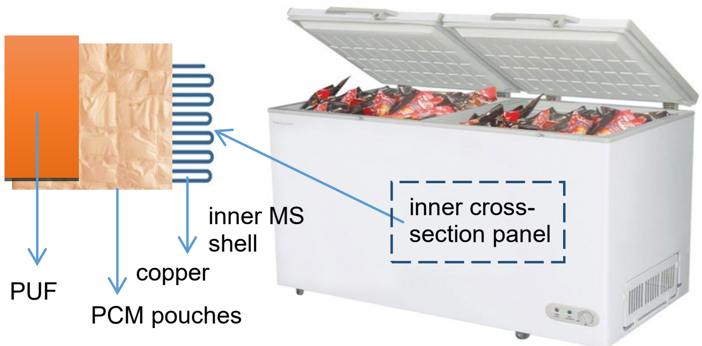

Figure 8. Freezer/cooler (source: PLUSS Advanced Technologies Ltd.).

While it seems as if there was little R&D in the past on Section 2.2.4, the situation is quite different for Section 2.2.5. Even several reviews on the topic are for example available. Ref. [46] made a literature review concerning different aspects of the use of PCM in conventional refrigeration systems. It covers different aspects like the amount of PCM, its phase change temperature, and position of its integration, investigated by modeling as well as by experimental testing. The PCM can be attached to the evaporator or condenser of the compression cooler, or placed somewhere inside the food storage compartment; each option has distinct advantages and disadvantages being discussed. Ref. [47] has a similar scope, and specifically lists references with respect to the PCM position. Further on, it includes a table with the results of experimental works, specifically the change of COP, and the same for simulations. Ref. [48] reviewed cold storage techniques in food preservation appliances such as refrigerators, freezers, as well as others. With respect to domestic refrigerators and freezers they specifically summarize experimental and numerical results including the PCM used, its placement, the focus of the investigation, and the outcome.

Besides the technical and economic advantages for the user, the option to shift electricity demand to off-peak demand hours by energy storage could allow more flexibility for the utility, the electricity supplier. Specifically, the reduction of the peak demand on an electric grid that is based on renewables by shifting demand to non-peak hours, increasing grid stability, is of increasing interest in many parts of the world. Compared to the discussion of "2.2.3. Cooling Large Food Production, Storage, and Distribution Facilities", here are many small ones. Ref. [49] investigated the potential for load shifting by domestic refrigerators in smart grids. They argue that these appliances are available for the most advanced strategies of demand-side load management (DSLM), and that by combining smart grid technologies and thermal energy storage by using PCM the full potential of the approach can be realized. Further on, they say that thermal energy storage by PCM has many advantages compared to the other option, electrical energy storage with batteries. After a review of studies on load shifting with domestic refrigerators and freezers, with and without PCM, they conclude however that refrigerators and freezers equipped with PCMs and the technology for DSLM are still absent in the market and research works focusing on the synergy of these technologies are still rare. They conclude that further public sector intervention is important to motivate consumers and energy providers to make the required investment.

2.2.6. Display/Retail Coolers and Freezers

Like with any other application for storage of food, display/retail coolers and freezers are a storage compartment which is more or less well insulated, and has for temperature stabilization a cooling device, However, being for display/retail of food products they have different, quite specific conditions of use. First, to display the food the compartment is sometimes left completely open, in most cases however closed by a transparent window, thus not at all or at least not well insulated. Second, to allow a customer to take food out, even if there is a window it can be opened and is so for each product taken out. Finally, regularly a large amount of new product is brought in to fill the gaps, and often has to be cooled down. Consequently, compared to other applications for storage of food, the cooling power needs to be larger, and the frequency and magnitude of variations in the required cooling power also tends to be larger. Display/retail coolers and freezers are constructed in two ways, either to present products vertically, with food placed on shelves and display and food takeout to the front, typical for bottles and cans, or to present products horizontally, with display and food takeout to the top, typical for seafood like fish. These construction types have a large impact on options to integrate PCM and resulting advantages. Generally, like with any other application for storage of food, the use of PCM to store cold promises certain advantages. PCM could reduce temperature variations due to cooler on/off, including power outages and defrost cycles, and specific to display/retail coolers and freezers also during opening to take food out, and loading of new food including its cool down. Related is a reduction of the frequency and magnitude of variations in the required cooling power, and related wear down, sizing of the cooler, and energy consumption. If the amount of PCM is large enough, load shifting to off-peak electricity rates is possible. Altogether, the use of PCM promises significant advantages with regard to food quality, maybe equipment design and maintenance costs, and increasingly important regarding electricity cost.

Ref. [50] made a review on R&D on cold TES by PCM in refrigeration systems, including PCM available as well as applications in food transport and packaging, commercial refrigeration, and various other refrigeration systems. Regarding equipment like small plug-in vending machines, display cabinets etc., the paper lists theoretical and experimental R&D, which comprises the PCM used, how the PCM is integrated, and the main results on the effect the PCM has. The PCM used was mainly water/ice, and additionally some commercial paraffins for transition temperatures only a few °C above 0 °C. Integration of the PCM itself was in shelfs where products are placed, in air flow channels, into the cooler circuit or on its evaporator (where the cold produced is delivered). Typical results are that the use of PCM leads to a reduction in energy consumption, reduced compressor on-off, and a reduction in temperature fluctuations, specifically during defrost (even power failure), and peak compressor power reduction. The latter two should be specific to applications where openings to take food out are frequent, and also when new product is supplied uncooled and has to be cool down (for example bottled drinks). Ref. [51] lists several studies on open and closed display cabinets, experimental and numerical, the PCM, and the main observations. The PCM in those studies was water/ice as well as some commercial products, probably water-salt eutectics. The PCM was integrated in the air flow, shelf, or at the evaporator of the cooler, and observations were mainly on maintaining the temperature at times when the cooler is off. Ref. [48] also has a short passage covering R&D in this area. Ref. [52] describe specific experimental investigations on a display cabinet (empty), with water/ice as PCM, and integration in the evaporator of the cooler. The investigations comprise comparison of the case with PCM and the reference case without. The results show the potential of PCM to keep cabinet air temperatures low, specifically to provide cooling for several hours. However, they also identified problems, for example if the PCM supercools and low heat transfer between PCM and air.

Interesting is that all the literature sources showed R&D only on applications with a vertical display. Here, no commercial solution seems to exist yet, probably due to the complexity of PCM integration. The reason to focus on vertical display might be that horizontal display at a first glance is less interesting, because in horizontal display cooling with ice is a simple and still common solution, e.g., for seafood. However, ice does not work for cooling at temperatures below 0 °C. And here commercial solutions exist for display/retail coolers and freezers, not being mentioned and discussed in previous publications. First, the commercial solution from PLUSS Advanced Technologies Ltd., previously discussed in the section on Section 2.2.5, is not only available for households but also for retail. Descriptions are available e.g., in [53–55]. Figure 9 shows the commercial solution again, now for display/retail with transparent lid on top.

Figure 9. Display/retail freezer/cooler (source: PLUSS Advanced Technologies Ltd.) and PCM-based cold battery as thermal backup for retail freezers (source: RGEES, Arden, NC, USA).

Further on, there is another commercial solution for horizontal display. Ref. [56] describes the commercial use of PCM as thermal backup for retail freezers (Figure 9). According to the source, the problem in this application is that when cooling ice cream, during the warm season there is an increased cooling demand that can cause compression coolers to fail. Consequences are cost for replacement of the cooler, and the risk of losing the ice cream if it cannot be stored cold elsewhere. The solution offered are plates filled with PCM changing phase at −26 °C, which are cooled in a separate freezer, and then placed horizontally within the air circulation chamber under the ice cream pans. The plates with PCM provide thermal backup to maintain ice cream frozen even on cooler failure, and during normal operation reduce the load on the cooler which reduces energy consumption, maintenance, and the risk of failure, all related to cost savings. Ref. [56] also has some interesting customer testimonials, mentioning that otherwise, meaning without the PCM solution, dry ice is commonly used.

2.2.7. Buffet Cooling

Technically somewhat similar to the application by RGEES, plates with PCM are also commercially available to keep food cold on buffets [57]. For this application the use of "just" ice, commonly as crushed ice, is also common.

2.2.8. "Just" Ice

At the transition of the discussion of storage and transport of food it is necessary to discuss also just ice.

Historically [58,59], natural ice, harvested in winter from the surface of lakes and rivers, has been stored and transported to places where it was used for many cooling applications, specifically for cooling foods like meat, fish, vegetables, and fruits. Natural ice allowed to keep food refrigerated or frozen, by keeping it together with the food for example for storage in rooms, cellars, cupboards (predecessors of today's household refrigerators), boxes, which are also useful for transport, as well as for transport in compartments on trucks, trains, ships etc. The use of natural ice was replaced starting with the 20th century by mechanically driven cooling, allowing cooling where and when needed, including also the production of artificial ice in industrial plants for applications where ice is still used.

Because of its simplicity, using just water/ice without an encapsulation and maybe heat exchanger, its application is often forgotten. However, despite that natural ice is practically completely replaced, the use of artificial ice is still widespread, and a big market. Actually, the technology of using artificial ice for cooling has even significantly developed: today, ice is not only used in blocks of different sizes. Today smaller ones vary in shape, like cube or flake ice, are mixed with some water to be able to flow, even pumped, called slush ice and ice slurries. According [60], the amount of manufactured can or block ice in the US in 1997 was 345,000 t, that of cube, crushed, or other processed ice about 2,211,000 t. This was 25 years ago; numbers should have been rising a lot since. Nevertheless, these numbers are for any application. Artificial ice to cool food is still seen on buffets, display/retail coolers in marketplaces and supermarkets, specifically for fish, used on fishing boats etc. Specifically regarding food, the fish industry is interesting, has data available, and is active also in R&D. Ref. [61] has some interesting information on the use of ice for fish handling: advantages of ice, compared to other cooling methods, as its large cooling capacity and self-contained temperature control by melting (characteristic of PCM), its convenience regarding its storage, transport, and even production from water (mentioning even the use of clean seawater), that it is a safe food-grade substance if produced properly and utilizing drinking water, and depending on the type of ice can be distributed around fish. And specific to the application, cooling is very critical to produce safe fresh fish of acceptable quality. The Norwegian fish industry, to take as example, is dominated by fish farming and the export of salmon. Every week between some 10,000 and 25,000 t of salmon (fresh, chilled, or frozen) are exported [62]. For export, these are put on ice for transport. Ice accounts for about 30% of the weight of a shipment while 70% is fish (according personal communication), roughly a ratio of 1:2. This means, every week some 5000 to 12,000 t of ice; and this only for the export of salmon.

According [63], storing fish in ice boxes, as was done historically, causes complex handling at today's common large catch volumes. It is today only applicable for smaller boats. In larger ones, harvested fish caught far away from the shore is stored in tanks until delivery for onshore processing. Tanks equipped with mechanical refrigeration are called refrigerated sea water (RSW) systems. If ice is added they are called chilled seawater (CSW) systems. It is crucial to prepare the tanks for the fish input in a way to have a minimum temperature. The paper numerically investigates four different scenarios: ice added in various amounts, and the use of a PCM with 4 °C phase change temperature in the tank's outer shell, within tank's tubes, and in a separate tank integrated in the return line of the RSW system. The objective of the investigation was to reduce the chilling time for bigger catch and better use of the refrigeration system at low loads. The results showed that the addition of ice in the chilling tank and the use of a 4 °C PCM in a separate tank are most promising and should be investigated further.

Using "just" ice is in many ways convenient. Ice has a phase change temperature which is very suitable to keep food cold, at temperatures as low as possible while at the same time avoiding freezing which could harm the quality of some foods. Being frozen water, ice can be used in direct contact with food to be cooled if the water used to produce ice is of food quality; otherwise, direct contact should be avoided. Also, as water is practically available everywhere, ice can be produced easily in any place, even homes. And last, but not least, it is environmentally friendly and practically at no cost, such that especially for transport it is not necessary to bring the "PCM" back from the destinations of transport to the origin. These issues are important in applications of storage of food, and even more for the transport of food.

Another issue is the concept for cold (or heat) production and the use of PCM for cold (or heat) storage. For storage, in the previously described large cold storage and distribution facilities, smaller cold rooms, even smaller coolers and freezers, the cold production and the cold storage by the PCM was combined, meaning both were part of the application. But for transport this is often not feasible for various reasons. The most obvious is that cold production by electrically driven compression cooling requires electricity. During transportation, a connection to the electricity grid is not available, production of electricity by other means, like a combustion engine, is not very efficient, and storage of electricity, e.g., in batteries, is costly and adds weight. Nevertheless, the different options are always in competition with each other. Typically, the solution is to charge the PCM in an external facility, or if the PCM is fixed to connect it temporarily to an external facility for charging. The following discussions highlight this.

Transport, not just of food but practically of anything, is done in mobile units ranging in size from small and medium sized bags and boxes to medium and larger containers. The largest ones can be an integral part of trucks or train wagons, while smaller ones are commonly independent and also used for storage.

2.2.9. Bags, Boxes, and Smaller Containers for Independent Transport

Commercial solutions to transport temperature sensitive goods, including also food, are common today. To keep the temperature in the required temperature range, good insulation is always the first approach. Active cooling of small boxes can be done by a Peltier element if electricity is available, e.g., in a car. For independent, passive cooling, ice or other PCM can be added to the temperature sensitive goods to stabilize their temperature to the temperature required. The temperature stabilizing effect of the PCM lasts typically from a few hours to several days. In situations where a heat source or a cooling machine cannot be used, for example in the cargo bay of a plane, using PCM or dry ice etc. is the only option. The most common example is an insulated bag or box, used together with ice packs, e.g., for a picnic. Commonly, the PCM is macroencapsulated, e.g., water in the ice packs, and charged (cooled) externally.

Figure 10 shows some examples. The bag shown (left) can for example be used to transport ice cream. Similar commercial solutions exist for the transport including also storage of breast milk [64]. Another, a coffee mug with PCM, is to get hot coffee to a suitable drinking temperature quickly and then keep it there for a long time [65]. Robust boxes are also available, for any kind of use (Figure 10, center; details, including performance, are available at [66]), or for specific use like storage and transport of hot food for catering (e.g., [67]). Small containers for plane transport are commercially available with temperature stabilization by PCM (Figure 10, right), electrically driven heating or compression cooling, or cooling by dry ice, but typically not used for food.

Figure 10. PronGO® bag and box (source: both PLUSS Advanced Technologies Ltd.) and va-Q-tainer for large volumes (source: va-Q-tec AG, Würzburg, Germany).

The decision to choose a specific solution depends largely on the value of a product, if handling of small amounts of the product is economic and feasible, and the means of transport. As mentioned above, storing fish in ice boxes, typically used on small boats, would cause excessive handling at large catch volumes on large boats, such that on large boats fish caught far away from the shore is stored in tanks until delivery for onshore processing. The same applies also to other food products, not just fish. Transport of temperature sensitive goods in smaller units with own means for temperature stabilization is only one of several options. No matter if a product is packaged in smaller amounts or not, transport of large amounts on a truck, train, or ship can be done in large compartments fixed on these, or by independent containers of a standardized size, which can be transported and easily switch between them.

2.2.10. Compartments That Are Fixed on a Van, Truck, or Trailer

Compartments for the transport of temperature sensitive goods fixed on a truck, train etc. are common. Historically, ice as ice blocks, which melted and was then flowing away, was first used for their cooling. With the invention of heating and cooling devices like electrical heaters and compression coolers these became the new standard. Their advantages are significant: wide range and variable service temperature, as well as unlimited service time as long as energy for running them is available.

Common on trucks and vans today is a diesel-driven compression cooler, installed outside the refrigerated space, typically on the front side somewhat above the driver compartment, with cold release inside the refrigerated space where e.g., food is transported by a heat exchanger and a fan for air motion. R&D on the use of PCM in that application area is already going on for more than a decade, as literature reviews in [48,50,51,68]. Overall, several different approaches are discussed in R&D to modify cooling on trucks, differing in where and how the PCM is integrated, and also how it is charged.

The smallest modification is just adding PCM to the overall system. Ref. [69] looked at PCM integrated into the walls, and found that it reduces heat input from the outside to the interior between 11 and 43%. Further R&D on integrating PCM into the walls are [70] (numerical). Ref. [71] make a detailed investigation for Malaysia. They compare the integration of PCM with that in buildings, specifically walls, to cut down average and peak heat transfer from the outside environment to the refrigerated space. According to their simulations, already 80 kg of PCM yield substantial load reductions and energy savings. Generally, because of the different thermal resistances, it can be expected that PCM in the walls buffers mainly heat input from outside, while PCM installed in the refrigerated space buffers the load in the refrigerated space in general thus also including door openings but not only. Ref. [72] (see [48]) investigated the configuration where a van with a regular cooling unit was additionally equipped with PCMs slabs installed under the ceiling of the refrigerated space. Investigation was by numerical modeling, looking at the general performance and performance upon door openings. The investigations looked at the use of paraffins with melting points a few °C above freezing, and showed significant performance improvements during door openings.

While just adding PCM to the overall system is a rather small modification of the overall system, larger modifications involve the change of the means of cold production or even its complete shift off the van or truck to external facilities and non-driving times. Ref. [73] experimentally studied cooling of the refrigerated space by a plate installed inside the refrigerated space, on the ceiling, filled with water as PCM, and a fan to improve convection between the surface of the plate and the refrigerated space. Refrigeration was achieved by a tank with Liquefied Natural Gas to (LNG) to run the car engine, however before getting there, the evaporated cold gas flowing through tubes immersed in the plate that contain the PCM. Ref. [74] investigated cooling the refrigerated space by PCM installed inside the refrigerated space, at its front. Experimental investigations were performed in tropical climate, on a stationary prototype, with the refrigeration unit outside attached to the refrigerated space. Initial cool down to −40 °C was done using off-peak electricity at night when the vehicle is stationary. Afterwards, independent cooling by the PCM was tested. The PCM used changes phase at −30 °C, has a latent heat of 175 kJ/kg, and was used in an amount of 275 kg. The results showed an improved temperature control performance, and also significantly lower energy costs compared with the conventional refrigeration. Ref. [75] (see [50]), presents another modification, where the external part for cold production, diesel driven, is replaced by a cold storage using PCM which can be charged by connecting to an external refrigeration system through valves once the truck is for example in a warehouse or depot. The PCM tested was a water-salt solution with melting point of −26.8 °C, macro-encapsulated in flat plastic capsules in the storage. Prototype testing revealed the need of some 360 kg of PCM, having a weight comparable to that of an onboard conventional refrigeration system, and that if an external refrigeration system with a COP between 1.0 and 1.5 is used, the new PCM system would cut down cost by more than 50% at Australian ambient conditions. In a follow-up work [76] a numerical model was used to simulate the performance of the entire system.

Each of the approaches in R&D, just adding PCM to the overall system, changing the means of cold production, or even its complete shift off the van or truck to external facilities and non-driving times, has individual advantages. Installing PCM inside the refrigerated compartment combined with cooling by an external facility brings many of these advantages together. The approach is commercially used, and successful for several years. An example is a system for PCM cooled vans etc., which uses PCM encapsulated in metallic plates, developed by PLUSS Advanced Technologies Ltd. As described in [45], the plates are mounted inside the transport compartment (Figure 11), and are charged by an external electrically driven compression cooler during non-operational hours, e.g., at night.

Figure 11. PCM filled metallic plates mounted in a van for cooling (source: both PLUSS Advanced Technologies Ltd.).

During transport of products the PCM assures that the required temperature is maintained, for up to 16 h, thereby enabling the transportation of goods like food, while minimizing the dependency on diesel/petrol for continuously running cooling units, and reducing operational costs [40] as well as emissions. According to [45], the payback period is estimated to be about 4 to 6 months, and there were more than 200 trucks running on roads at the time of publication. To develop the application of the plates in more kinds of trucks, PLUSS is partnering with other companies. More information is available at the company's website (https://pluss.co.in/logistic/, accessed on 27 September 2021). Similar commercial solutions are also available from other manufacturers in India (Ice Make), Turkey (Eutectic car), Lithuania (Carlsen Baltic), and the USA (Cold Car USA), according to their websites.

2.2.11. Compartments That Are Fixed on a Train

A very informative article on transportation of food by train is [77]. To transport perishable freight at specific temperatures so-called refrigerator cars (also called reefer car, refrigerated boxcar . . .) were developed, which do not just rely on ventilation, but instead have their own way of cold supply. As early as 1851, butter was transported in the US by purpose-built freight cars, using ice for cooling. A few years later transport of beef started, then fruits . . . To avoid direct contact between food and ice, the ice was placed in separate bins. After about 400–600 km, new ice had to be supplied. By 1920, thousands of ice-cooled rail cars were in operation. In the second half of the 20th century, mechanical refrigeration started to replace the use of ice. Similarly to the US, in Japan refrigerated transport of fish in cars equipped with ice bunkers started in the early 1900s, in parallel to fish in smaller boxes with ice. By the 1960s, refrigerated trucks began to displace rail transport, in the late 1980s also reefer containers. Mechanically cooled cars never became widespread in Japan. In the UK, the needs to refrigerate food during transport on trains was minimized by using nonstop express trains, and the generally shorter distances in the UK. Nevertheless, some ice cooling as well as mechanical cooling on cars was used. Summarizing, cooling by ice and mechanical refrigeration were used on a large scale, while however dry ice (frozen carbon dioxide) was tested but not economic. In any case, nowadays many railways around the world transport in specialized refrigerated containers, the trains now taking back the role of long-distance transport by trucks between transport hubs to reduce CO_2 emissions.

2.2.12. Independent Containers for Transport by Truck and Train

A refrigerated container or reefer container is a container used for transport and capable of refrigeration, for example for transport of fruits, vegetables, or meat [78]. According [78], commonly, the containers have an integrated mechanical refrigeration unit running on electricity, which is directly available at a harbor or on a container ship, while on trucks and trains (or just as backup) electricity can be supplied by diesel-powered generators attached to the container. Sometimes dry ice is used for cooling, allowing cooling even for many days independent of electricity. Common on ships is also cooling by cold air from ship-based cooling units.

Using electricity supplied by diesel-powered generators on trucks and trains is however not efficient. According news releases by the University of Birmingham [79,80], University of Birmingham researchers together with CRRC Shijiazhuang (China's largest railway truck maintenance company and rail vehicle air-conditioning equipment manufacturer) developed the world's first-of-a-kind "refrigerated" road/rail container with cold storage using PCM. Once charged, the PCM can keep the interior temperature of the container for over 100 h, while a full charge can be achieved in less than 2 h. According to the news release published in 2018, the technology had completed commercial trials carrying real goods for 35,000 km of road and 1000 km of rail transport across different climate zones. Compared to diesel powered refrigeration, cooling with PCM has the advantage of energy saving and environmental benefits, constant temperature, and the passive cooling allows an easy transfer of the containers between trains and trucks which offers better flexibility across the supply chain. In 2019, CRRC Shijiazhuang started to deliver the first order of 49 containers to Yunnan Su Lida Agricultural Products Supply Chain Co., Ltd.

Some details of the test results are reported in [81]. According to the paper, the tested 40 ft ISO standard container was equipped with 10 plates containing a total of 1260 kg of PCM (commercial Rubitherm RT5). The plates were charged by a separate charging facility. Discharge took almost 95 h. Results showed that the new container had significantly improved performance compared to diesel-powered reefers, with the system COP as high as 1.84, a reduction of the energy consumption by 86%, a reduction of the operational cost by 91%, and a reduction of emissions by 78%. Ref. [82], from CRRC Shijiazhuang, describe and discuss the tests in detail.

2.3. Food Production

2.3.1. Background

Nowadays, even food production is optimized, which is not surprising at least if done at industrial scale. However, it is not only on an industrial scale. Even in private production for self-consumption people try to optimize the production of food. Applications for PCM are the heating or cooling of greenhouses for food production in agriculture, and, because of the scarcity of water in many areas of the world, purification of water, mainly desalination of seawater, for drinking, irrigation, and for other uses. Similar to processing, temperature and amounts of heat play a role; otherwise, no common background exists.

2.3.2. Greenhouses

Large parts of the world have distinct seasons. Often, for a part of the year growing plants for food production in the natural ambient is not possible, or limited to a selection of plants. This limitation can be avoided by growing plants in an artificial environment, e.g., in a house. This way, sometimes even plants are grown which have no suitable season in a region at all. Early forms of an artificial environment were ordinary brick or wooden houses with a larger area of glass windows for solar irradiation of the plants, and some additional means of heating. Nowadays, common is the use of simple metal frames, and transparent plastic sheets are often used instead of glass windows. Sometimes even the sunlight is replaced by lamps. Thus, the term "greenhouse" nowadays generally refers to a constructed enclosing which creates an artificial environment, designed for growing of out-of-season or out-of-region plants. It assures the right climatic or better growing conditions (temperature, humidity, solar irradiation, . . .), artificially, for growing the plants in an otherwise unsuitable or at least not optimum environment. Common is the use of greenhouses in cold, or in dry climates. Their size ranges from small private ones for self-consumption to large ones for industrial production. To get an idea of the scale of the use of greenhouse constructions, in the Netherlands, in 2017 greenhouses occupied nearly 5000 ha = 50 km^2 [83], and in 2018 their surface area in Andalucía, a region of Spain, covered even 35.489 hectáreas [84].

To assure optimum conditions, besides temperature, humidity, and irradiation, also ventilation is needed. Ventilation supplies fresh air for photosynthesis, can remove plant pathogens, and allows the access of pollinators like bees to the plants. Means for supplying heat or cold, keeping humidity, for solar irradiation, and for ventilation, in many ways affect each other. For example, solar irradiation also supplies heat, ventilation can supply heat or cold depending on the outside air conditions . . . And plants vary a lot in their optimum growing conditions. This makes the design and operation of greenhouses a complex topic, with obviously no single solution. This is also reflected in the R&D publications.

Already in 1978, a book described the technology of solar greenhouses in detail [85], including the storage of heat by sensible heat in the ground, walls, or barrels filled with water, and as an upcoming technology paraffins and salthydrates as PCM. They can be used completely passive, or with some active air motion, and just buffer temperature swings. Especially in cold climates, heating is often crucial and commonly done actively by burning fossil fuels which causes considerable operation costs. Thus, heating by free solar heat is desirable, which requires thermal energy storage to shift excess heat from days with sunshine to days without as well as nights (instead of ventilating excess heat away). Also, if using waste heat from elsewhere, or if using a heat pump, thermal energy storage can help.

Ref. [86] reviewed the use of PCM in greenhouses, specifically their choice and way of application. They reviewed a large list of R&D publications, regarding the PCMs used, their properties and stability, and how the PCMs are applied in greenhouses, the performance and parametric sensitivity, from experiments as well as numerical models. The types of PCMs are mainly paraffins and fatty acids, and the salthydrates $CaCl_2{\cdot}6H_2O$ and $Na_2SO_4{\cdot}10H_2O$, which cover melting points between 2 °C and 70 °C. They found several types of applications: heating/cooling with the PCM integrated into the north wall, integrated in a heat exchanger, or directly in the solar thermal system. Generally, the performance in completely passive systems is with regard to temperature swings, while in active heating systems there is usually a setpoint and performance is as energy savings. They report reductions in temperature swing by up to 6 °C, fuel savings up to 48%, and payback periods reported are between 3 months and 6 years. Another recent review [87] discusses the integration of PCM in passive systems, by integration of PCM in wallboards on greenhouse walls or storage containers, and active heating systems, by combining PCM with heaters, heat pumps, and solar thermal collectors. Commonly, TES is by sensible heat, using rock beds, water reservoirs, or underground pipes. The paper has an extensive literature on TES with PCM used in greenhouses reviewed. It lists a few publications dealing with the combination with heaters and heat pumps, showing significant reductions in energy consumption, and payback period between 4 months and 8 years. For the integration with solar thermal collectors, the analyzed publications show a significant increase in nighttime greenhouse temperature by the use of solar energy stored in the PCM during daytime, by up to 6 °C. Regarding the use of PCM wallboards, increased storage capacity and a wide range of nighttime temperature increase from 0.8 °C up to 12 °C was found. If there is no wall, PCM can be stored in containers distributed in the greenhouse, even in the root zone of the plants. For the use of PCM in storage containers, temperature reduction in daytime and increase in nighttime were up to 7 °C. The authors conclude that selection of the PCM, its melting temperature, quantity, encapsulation, and type of integration, and that appropriate design parameters (like greenhouse size, shape, orientation, heat transfer coefficient of the envelope ...) should be selected, taking into account climatic conditions and control, to achieve significant saving of energy and cost. Ref. [88] performed such a study, with eight different locations which have dry climate and mainly a cooling load for most time of the year, using an HVAC system which is solar driven absorption refrigeration system, and varying the PCM temperature between 21 °C and 27 °C.

While there is a large number of R&D publications, there seems to be yet rather little economic activity. Ref. [89] describes experimental testing in small greenhouse in Asheville, North Carolina, USA. Initially, the greenhouse was experiencing very high wall temperatures, much higher than the ambient. To reduce the excessively high wall temperature, a 22 °C PCM was installed at the walls, which resulted in a reduction of the afternoon peak temperature from 47 °C to 35.5 °C. It is interesting that the second test of commercial products also was in an attempt for limiting/reducing extreme temperatures, but instead for overheating it was with respect to the opposite of overheating, meaning protection from frost. Frost damage by freezing in plant tissues at temperatures below 0 °C can be severe as a single occurrence can destroy a harvest, or plants in general. But it is not only a problem in unprotected agricultural areas, but generally a problem in nature. It is therefore not surprising that nature throughout evolution has found countermeasures. Basically, these are lowering the freezing point as well as avoiding nucleation of water in plant tissues, or more straightforward, avoiding cooling to subzero temperatures. And here, some plants are using the latent heat of water outside the plant tissue which when freezing releases its latent heat and thereby protects the plant itself from freezing [90,91]. Among many other methods, the use of the latent heat of water when freezing is also an effect used by humans. As described by [92] (CHAPTER 7—ACTIVE PROTECTION METHODS) in detail. Its commercial use by sprinklers is e.g., described in [93]. The use of commercial, encapsulated PCM from RGEES, for frost prevention, describes [94]. Experiments were done on a farm, using pouches hung in a tree and also flat containers on the ground. With PCM, all of the citrus, as well as the avocado tree, made it through the winter.

2.3.3. Solar Water Purification

Water is crucial for us. We need some 2 L or more per day of water at high purity, just for drinking. And we need much more water for many other things, in the food area for cooking, dish washing, and of course for animals to drink, and for the irrigation of plants, the latter not requiring too high purity. Water is found in nature in different sources, directly from precipitation as rain, collected in rivers, temporarily stored in lakes and reservoirs, or for longer as groundwater, and last but not least the oceans. Depending on the source, the water can contain solid particles, dissolved chemicals like salts or gases, and biological matter like bacteria etc. Removing undesired substances from water to get water for consumption, safe to drink or for other purposes, is called water purification. Today, safe drinking water is still not sufficiently available in many developing countries, and during severe droughts can even be rare in developed countries. Thus, water purification is a topic of great and even increasing importance. A wide range of methods for water purification is available [95], for example physical methods like sedimentation, filtration through sand or membranes, and distillation, the addition of chemicals like in flocculation and chlorination, or the use of electromagnetic radiation, specifically UV. In a particular case, the best method depends on the purity required, impurities in the available water, then the suitability of purification methods for that case, and finally the availability and the economics.

Important on a large scale is regarding impurities removing salts, specifically for water from the oceans, called desalination, and for drinking water removing harmful bacteria etc., called disinfection. Currently two technologies dominate: thermal desalination, where evaporation and later condensation are used for desalination, and reverse osmosis, where saltwater is pressed under high pressure through membranes which keep the salt back. The most common method of thermal desalination is using waste heat from power plants that run on fossil fuels. Because of that, there is a strong trend to use the reverse osmosis, preferably with electricity from solar or wind. However, reverse osmosis has problems with additional waste from chemicals needed to keep the installations working. Therefore, thermal desalination using solar heat comes in focus. According [96], in fossil driven thermal power plants the waste heat used is typically at temperatures between 65 °C and 115 °C. Solar thermal technologies could thus use cheap and efficient thermal energy storage, compared to electrical energy storage. Thus, water desalination plants working on the principle of solar thermal evaporation and later condensation are discussed and investigated, but still at a rather low level. Fossil fuel prices just increased recently. Literature research gave just one existing plant and a few research activities, and nothing on refurbishing fossil driven thermal desalination with a solar thermal heat source, as is discussed for coal power plants. Aalborg CSP [97] together with Alfa Laval developed a solar desalination system, combining their experience in solar power and desalination. A concentrated solar power (CSP) field produces hot water, which by a hot water storage tank allows to run the desalination unit 24 h a day. In the desalination unit, the hot water is used to evaporate seawater and then condensate the vapor, thereby producing freshwater. A system was installed in Australia in 2016, by Sundrop Farms, and produces according the website of Aalborg CSP 250,000 m^3 of fresh water per year. According an article published on the SolarPACES website [98], the US company Katz Water Technologies, founded 2016, developed an efficient thermal desalination unit, which won the first two stages of the DOE's stepped series of awards to develop a concentrated solar thermal (CST) technology.

According information on the DOE website [99], the intention of the funding program is to develop solar thermal desalination technology, including addressing storage technology.

The situation for very small installations, just one to several m^2 in size, is different, so discussed separate. Their design can be extremely simple, in a single setup and operating completely passively. A container is covered by a transparent window where the sunlight enters. The sunlight is absorbed at a dark surface, which gets heated thereby, and gives the heat to the water to be evaporated; often this is simply a basin. The water evaporated, which is then clean water, fills the container and is then condensed at the window, which is typically the coldest surface of the container interior. An inclination of the window makes the droplets of condensed clean water move along the window downward, to a spot where it is collected. The design can be varied with regard to the materials used, the shape and dimensions, and other things. Solar stills with the simplest possible design are commercially available from several manufacturers. Regarding R&D, to improve their efficiency and reduce the cost, a number of reviews are available. Refs. [100–102] give water yields up to 10 L/m^2 per day; reasonable, as the heat of evaporation of water is about 0.7 kWh/kg and for solar input of 1kW for 12h. This shows a main weakness of the simple designs: recovery of the condensation heat to use it again. Multiple evaporator/condenser surfaces and heat regain, as in commercial plants, reach better yields. Ref. [103] developed a simple, yet multistage configuration, and reached in a small prototype with 10 stages a solar-to-vapor conversion efficiency of 385% with a production rate of 5.78 L/m^2 per hour. Another crucial weakness of solar thermal desalination is that solar heat is only available at sunshine. However, storage of solar heat to drive desalination at night can be done by thermal energy storage. Ref. [104] reviewed R&D on the use of PCM to improve the daily productivity of solar stills. They collected dozens of publications, tabulated the type of solar still, the PCM used, and main results. These comprise passive (all in one) as well as active (external source/collector ...) solar stills, with the PCM improving the yield in a wide range, varying with PCM used, integration approach, and still type. Ref. [105] made another review, covering an even bigger variety of systems. For simple stills, the maximum yield found was 8.1 L/m^2 per day. For active solar stills, yields up to 11 L/m^2 were found, in systems using evacuated tube collectors and external condensers. These values are still below or around the expected maximum of 10 L/m^2 per day, not surprising as the limiting factor is the solar energy absorbed per day. Except for one, all systems discussed had no multiple stages, were without heat regain, which seems to be crucial for further, significant yield gains. Worth mentioning is that already with the existing systems, estimated cost for freshwater were found to be in the order of 0.02$ per liter.

3. Summary and Conclusions

"Food", essentially meaning what we eat and drink, is the basis of human life besides the air we breathe. Insufficient availability, including too high prices, is a main cause of poverty, even political instability. Nowadays, energy consumption for supply of food is significant in many stages, so rising energy prices consequently lead to rising food prices. Even more, large parts of food produced are lost by spoilage. Spoilage is related to further problems: production of more food than finally consumed causes avoidable energy consumption, greenhouse gas emissions, pollution with fertilizers, pesticides, and also land-use. The reduction of food loss, as well as of food related energy consumption, is thus of great importance.

In this work, an overview on the state-of-the-art of the wide use of PCM for food applications was given. The applications were grouped as belonging to food processing, storage and transport, or production. Food processing means transformation of natural products into food, or of one form of food into another. This comprises modifying food to make natural products edible or turning ingredients into familiar food, for example by various cooking methods. It also comprises modifying food for food preservation, crucial to use food later, also at different places, thus after food storage and transport. Therefore, processing also includes the thermal treatment by boiling, drying, as well as cooling food down to avoid spoilage. With respect to energy, the amount of energy required for food transformation is often a crucial issue. State-of-the-art are multi-purpose cold storages, mainly ice storage, for various cooling applications. Multi-purpose heat storages just have become commercially available in recent years. Specific use is, for small farms, in small milk pre-coolers, pre-coolers for freshly harvested food, and also solar drying. Still in the R&D stage is the use of storages for distilleries and beer brewing, and the use in solar cookers. Beverage cooling, by adding ice cubes or by using ice storages to tap cold beer, is also state-of-the-art. Food storage and transport is, regarding thermal energy, dominated by the need for food preservation. Therefore, keeping food at the right temperature, and minimizing heat exchange, is in the foreground. Most common is storage of food cold, called refrigerated, typically at 4–8 °C for shorter periods, and freezing it, typically at −18 °C, for longer periods. Since water/ice and eutectic mixtures of water and salts are cheap PCM, their use is widespread. And other PCM are entering the commercial use. Commercial storage applications are cooling of supermarkets, larger as well as smaller storage rooms, small coolers and freezers, buffet cooling, and of course the use of ice directly on marketplaces etc. Directly using ice is also used to transport fish. For transport however widespread use is today also in bags, boxes, and small containers. The use of PCM for cold storage to cool the compartments on vans, trucks, or trailers, to avoid inefficient use of gasoline to run a cooler, has successfully entered the market. Use for cooled containers, for flexible transport by truck and train, just started commercial application. Food production has not yet received the same attention as food processing, storage, and transport. Heating of greenhouses and thermal water desalination have until recently in large-scale facilities been done using fossil fuels. Only for small-scale applications the application of PCM for better use of solar thermal energy has been investigated intensively. However, with rising energy prices, interest increases. Finally, one field of application not mentioned earlier should be mentioned now. It just came up recently, and fits not to any of the application groups discussed before. According a recent article [106], PCM can also be used for management of food waste, and at the same time to supply renewable energy. This is by the use of PCM in biodigesters, which can digest food waste and produce biogas in turn. Prototype testing of a biodigester with PCM for temperature control resulted in significant improvement. Therefore, summarizing, PCM have already reached real application on commercial scale in some areas. For many other applications improvements using PCM have been proven, but more research is needed. PCM already play a significant role in food applications, and their contribution will increase even more.

The overview also shows some general things. The state-of-the-art of a technology is not always covered by what is found in R&D papers; the technical solutions in products are a part of the state-of-the-art. Also, the existence of a product does not mean the end of R&D. Often, energetic optimization is missing. Further on, for new products field testing and demonstration might be needed, also to create awareness. And were R&D is done already for a long time, it might be necessary to rethink R&D strategies again. What is the lesson learnt from past R&D? A solution, finally to be used on larger scale in real application, necessarily requires the manufacturing of standardized products. Basically, three options are available. The first is encapsulated PCM as individual storage module. The second is a whole individual storage. The use of ice packs and the use of ice storages in many areas is not only due to the low price of water; it is also standardized production on large scale, reducing the cost relating to anything besides the PCM. In addition, guidelines exist for their use in transport boxes, or integration in systems for process cooling. That these are crucial, not just the low price of water as PCM, is clear from the large-scale success of other PCM, encapsulated, in storage and transport applications, and the starting use in individual storages e.g., for heating applications. The third option is the integration of PCM into a larger product, such that its function is automatically assured; no guidelines or design tools are further required then. Successful examples are the use of PCM in small coolers, freezers, reefer trucks, or transport containers. Looking at solar cooking, greenhouses, and solar water stills, which have been investigated intensively, and for a long time, it seems that a good approach, finally to be used on larger scale in real application, is still missing. This is not surprising; all three are highly dependent on the local climatic conditions, greenhouses and cooking have a wide range of conditions in their use, and ways of integration are plenty. To move forward it seems necessary to select relevant application cases which promise large-scale use, and then trying to find out which of the above mentioned three options is most promising. For example, to heat greenhouses growing similar plants and under similar climatic conditions an approach might be to use a solar air collector connected to a PCM-TES, sized by guidelines for each individual greenhouse. Further on, for the third option, the integration of PCM into a larger product, modification or combination of existing products should be tested. For example, for solar water desalination, solar stills as well as encapsulated PCM are commercially available, however not a single publication testing the combination was found. Even if not fully satisfactory, such tests can show the potential for real applications, and might encourage producers to modify their PCM products in the necessary way. In any case, this is just an example. However, it shows that taking into account the importance of food and the role that PCM play already, R&D should, besides investigating basic questions, also focus on the real application.

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