Incorporation of phase changing materials (PCMs) with solar cells

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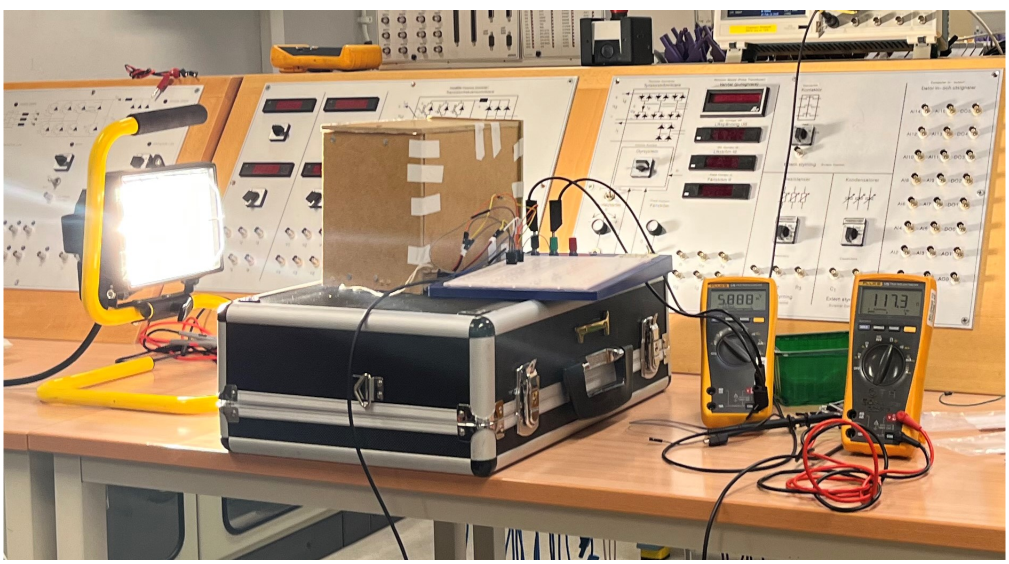
February 2022

Abstract

The increased use and scale of solar Photo-voltaic (PV) systems area increasing in the world and so are the global temperatures. As PV cells are heated, the cells lose efficiency due to a decrease in energy bandgap. Passive cooling using PCMs may counteract this effect and improve the PVs electrical power output. This report aims to investigate PV-PCM systems by performing an experimental labotary set-up and by reviewing existing theoretical models. The conducted experiment could not with any scientific certainty identify a difference although a 3.6 % increase using PCM would be observed in some instances. The theoretical model, using a day in Gothenburg with a simplified heat flux model, resulted in a 5.3 % increase in total power production during the day. While no part holds any real scientific value on its own, the results do indicate to some degree that a PV-PCM system can improve the output and further experiment and researched should be conducted to determine these effect. Finally, the report aims to reflect on the potential impact that PCMs have on the environment and the existing challenges that prevent the technology from reaching commercial scalability.



Contents

1 Introduction

There is today an increasing need for renewable energy sources in order to attend to a growing energy need while limiting the effect energy production has on the climate [1, 2]. Solar energy technology is constantly improving and it also uses space more effectively than most other renewable options [3]. Studies show that it is possible solar energy will account for up to 50 % of the total energy supply [4] and it is therefore important to get as much efficiency out of the system as possible.

Current commercial photo-voltaic (PV) cells have an approximate efficiency of between 15-20 % [5]. A reason for the seemingly low efficiency is that PV cells only efficiently absorb and transform light between 400 nm and 1100 nm [6]. With increasing temperature the efficiency of the solar cell reduces by approximately 0.4 % per degree Celsius due to a decrease of the band gap in the PV cells [7]. In theory the efficiency of a PV cell should increase if they could be cooled down and the heat transferred away or stored [6]. Phase Changing Materials (PCMs) are materials that change phase at certain temperatures and in that process absorbs energy without increasing in temperature [8]. Theoretically this could be used to absorb energy in form of heat from solar PVs and thereby help increase efficiency of the solar cell. The hypothesis for this paper is that by combining Solar PVs with Phase Changing Materials the heat created could be decreased and thereby give the solar cells a higher efficiency during high intensity hours.

The aim of this report is to, based on theory surrounding solar PVs and PCM, conduct an experiment to test the hypothesis of the PCMs ability to cool down a solar energy system and thereby increase the efficiency. In addition, a theoretical model for the total power output during one day will created. The report will also include a discussion of environmental and economical impact and scaleability as well as societal challenges together with an exploration of further applications of the PCM materials and the heat it stores from the PVs.

This paper will only focus on one type of PCM to initially test the theory and the type chosen is Climator C24 which is an inorganic salt. The tests will not be used to estimate the efficiency of PVs without and with PCM but rather to assess if adding PCMs has any noticeable effect analysing the difference between the two cases. Ultimately the paper will give a more general conclusion to where this kind of system could be beneficial. The cost of PVs will only be dicussed in relation to the cost of PCMs and the environmental impact of PVs will not be addressed. Furthermore, the applications discussed will be limited to a few types that were deemed relevant and could possibly be applicable in an early stage of this type of system. Further limitations and sources for errors will be addressed in the discussion part of this paper.

2 Theory

The theory chapter will address some basics around solar PV cells and how they work followed by some basic information about PCMs. After this some theory of the combination of PV cells and PCMs will be presented and then a brief account on a few applications for PCMs that could be relevant for an extended system including PVs and PCMs where the stored latent heat are used further.

2.1 Solar PV cells

Solar PV cells works by using the light energy, or particles called photons, to create electron-hole pairs in a semiconductor. A photon with sufficient energy to overcome the energy band gap can excite an electron in an atom and therefore create a free electron and a hole [9]. By incorporating a semiconductor, typically made from silicon, this free electron and hole can then be separated to two opposite sides, P and N. The N-side keeps the electrons while the P-side gathers the hole with the intrinsic electric field that exist in the junction between the P and N side [9]. This in turns create a voltage and if a load, for example a electric motor, is connected between the two sides, a current will be produced, see Figure 1 [10].

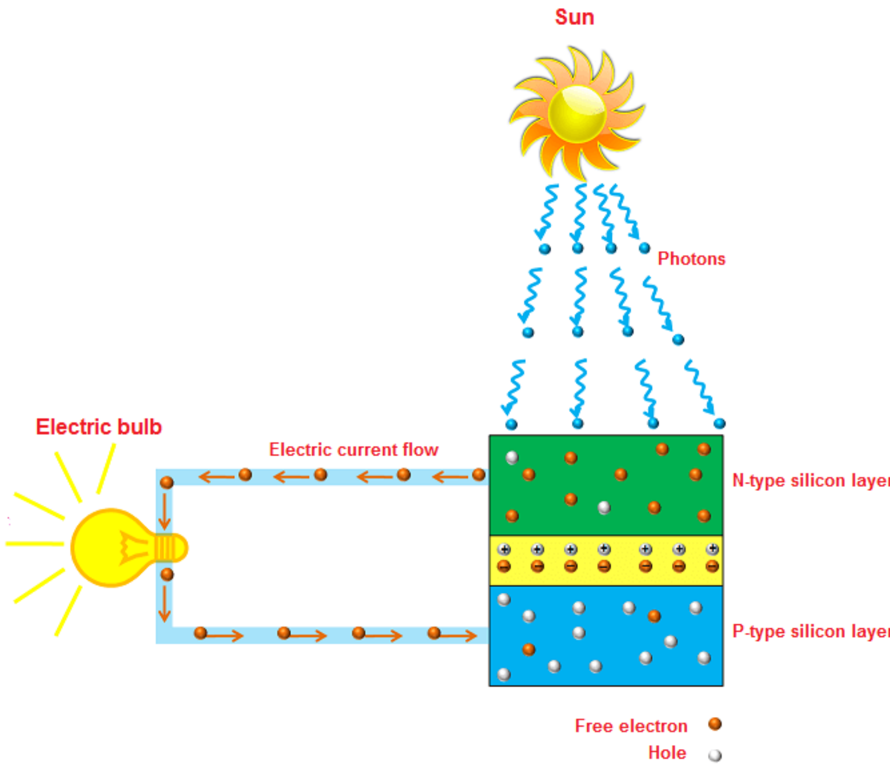


Figure 1: Working principle of a solar cell. Notice that the holes are not particles in them self but instead the polarized atom with it's opening. For modeling purposes this can though be thought of as a hole. Image from Physics and radio electronics [11].

This process is however temperature dependent. At higher temperatures, the gap decreases as the energy required to excite the electrons decreases [7]. By decreasing the required energy the open-circuit current, I_O increases. Equation (1) show the temperature dependencies in p-n junction semiconductor solar cells excluding potential minor temperature dependencies in the material.

$$I_O = qA\frac{D}{LN_D}BT^3e^{\frac{-E_{G0}}{kT}} \tag{1}$$

In the equation, D is the diffusion coefficient of the minority carrier and L the diffusion length of each carrier while N_D is the doping.B is a temperature independent constant that originates from the intrinsic carrier concentration but does not effect the temperature dependence [7]. Carriers are the name of the electron-hole pair, the rate of how the carriers spread, in the material is called diffusivity and the average life time between creation and recombination is called diffusion length [12, 13]. The result of this equation gives a heuristic rule for silicon solar cells that the current approximately doubles for every 10 °C increase in temperature. For I_{SC}, the short circuit current, the increase is small down to around 0.06 % per °C and does more depend on design and material.

From equation (1) the increase can be seen as temperature increase. However the total efficiency in higher temperatures is lowered due to the decrease in the short-circuit voltage, V_{OC} that can be described by equation (2).

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_O}\right) \tag{2}$$

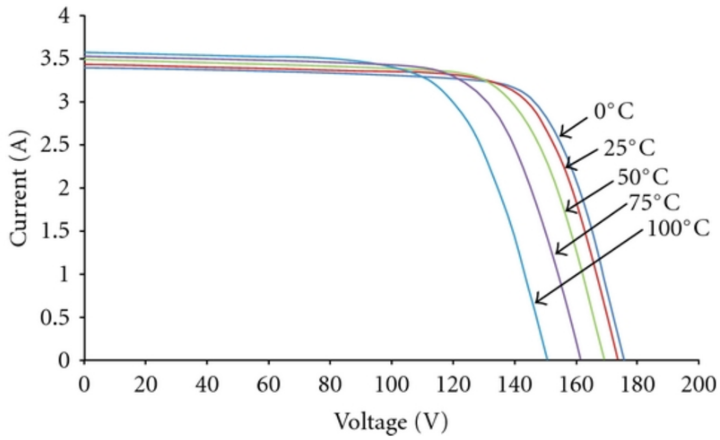


Figure 2: Temperature effect on solar cell open circuit voltage, V_{OC}. Notice that even if tests are done in 25 °C, the V_{OC} might be driven further in a cooled system with the same irradiation. Figure from Wang and Cheng [14].

From equation (2) and earlier statements regarding I_O and I_{SC}, V_{OC} can be seen to clearly decrease in Figure 2 and by taking the temperature derivative, assuming I_{SC} is roughly temperature independent and using the expression of I_O in equation (1). The decrease in voltage per °C can be found to be -2.2 mV for a silicon solar cell [7]. See Figure 2 for the total effect under different temperatures.

2.2 Phase changing materials, PCMs

Phase changing materials are an umbrella term for different types of materials that change phase, for example between solid and liquid. During this process the material itself does not change temperature but can instead absorb or release heat to it's surrounding, see Figure 3 [8].

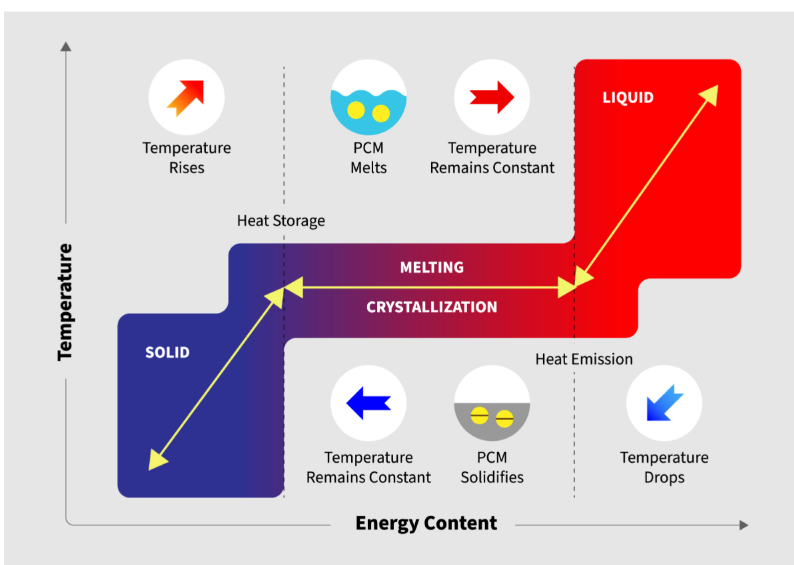


Figure 3: Typical idealized temperature curve for PCMs. Figure from Thermtest [8].

A common transition is for example between ice and water. The transition enthalpy, or latent heat, of ice is 333.5 kJ/kg [15]. While the ice-water phase transition occurs at around 0 °C, other PCMs have a transition point at room temperature and can therefore be used for cooling and heating in daily applications, for example buildings, cooling storage and potentially, solar cells [8].

2.2.1 PCM types

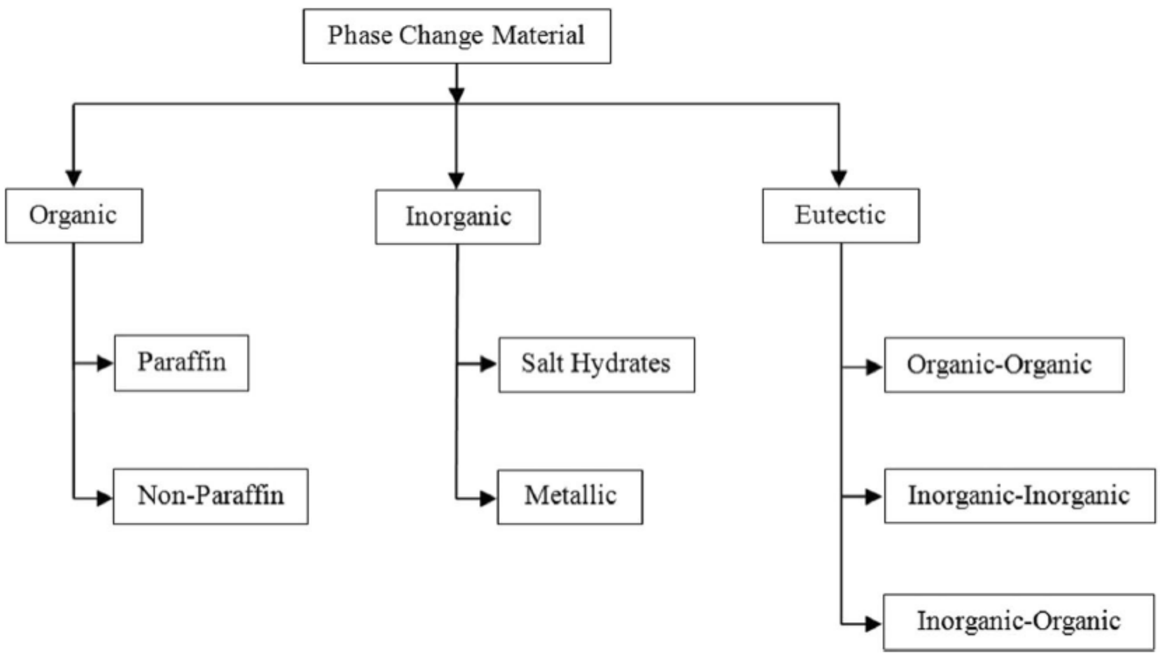


Figure 4: Classification of phase change material [16]

There are three main types of PCMs. Organic, inorganic and eutectic. These can then be divided into subgroups which can be seen in figure 4 [17, 16]. These all have different characteristics and properties that gives them different melting points and make them suitable for different types of use [16].

Organic PCMs are more chemically stable and non-corrosive when compared to their inorganic counterparts and their thermal conductivity is low. Organic PCMs can be further divided into paraffin and non-paraffin compound materials. Paraffin materials can be classified as oil products and belong to the family of saturated hydrocarbons. They are consistent, nontoxic, widely known and have a low vapor pressure in their melted condition. They do not exhibit a significant change in volume which makes the packaging process of these materials easier. Non-paraffin organic materials include a wide range of alcohols and fatty acids. They are flammable and have a generally high heat of fusion. They need careful handling and cannot be used with storage oxidizer agents [17, 16]. They have a very low thermal conductivity and are comparatively inexpensive. They also have a wide range of melting temperatures which facilitates the optimization of PCM design. They do have a high latent heat of fusion but due to their flammable properties, exposure to high temperature is not advisable. They are good thermal conductors, compared to the paraffins. However, they are also more expensive and pose the risk of decomposition when exposed to a high temperature. Inorganic PCMs boast of a higher latent heat of fusion, have a high thermal conductivity, and a sharp point for phase change. They are also non-flammable and less expensive than organic PCMs. Inorganic PCMs can be divided into salt hydrades and metallic. Salt hydrates have a higher volumetric latent heat capacity and also a higher thermal conductivity than the organic PCMs. They are characterized by a low environmental impact as they are generally non-reactive and thus compatible with most storage materials in nature [17, 16]. These are also the most extensively researched PCM due to their multifold applications.

The salt hydrates can be chemically considered as alloys of inorganic salt (AB) and water (H2O), resulting in a typical crystalline solid of the formula, AB.xH2O. During the phase change, the water released dissolves the formed nonhydrated salts, triggering a chain reaction sorts that is temperature dependent [17]. Metallics are PCMs with a very high volumetric heat of fusion and are therefor excellent thermal conductors. However, some of them are also toxic in nature which makes their storage options limited. They are also very expensive compared to their counterparts in this area which makes them undesirable for general public use [17, 16].

The third type of PCM available commercially are the eutectic PCMs. They are a combination of two types of PCMs, which helps to chemically retain the best qualities of both types. They belong to another highly researched area, owing to their multi-fold advanced qualities and application over a vast range of temperatures. They can be organic-organic, organic-inorganic or inorganic-inorganic types of compound. This improves their chemical stability while also providing a high heat capacity. The disadvantages of this type of PCM lies in the area of thermal conductivity. They are also more prone to leakage during the phase transition and could be commercially expensive when compared to their inorganic counterparts [18].

2.2.2 Super cooling

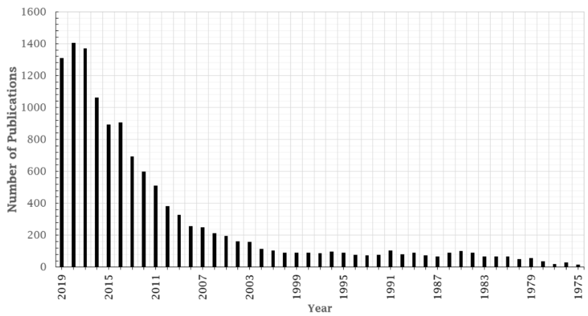
A common effect regarding PCM cycles are the change of transition points between the change from solid to liquid and back. During the crystallization, the temperature needed for the phase change might be below the melting temperature, this is phenomenon is called super cooling. It does occur as the activation energy needed to initiate the process is unavailable. In the case of solidification, this activation energy is the energy required to initiate the crystallization in order to activate the solidification. This is due to the needed surface energy that is required for crystals to solidify and to increase their surface area [19].

2.2.3 Applications of PCMs in solar energy

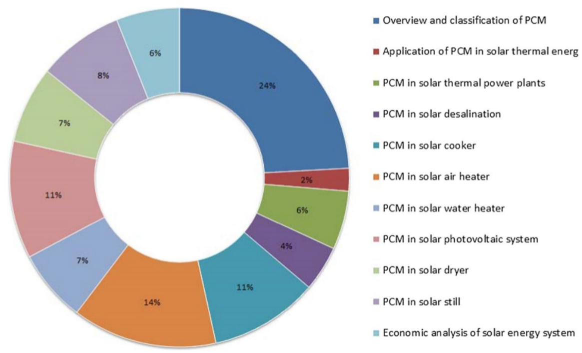
Phase changing materials have been used for many different solar energy applications. Here they are used to store or retain energy in order to be used for other applications and at other times [2]. Solar thermal energy (STE) storage is a method of storing thermal energy in substances such as PCMs to use for different applications such as space and water heating [2]. One method of desalinating sea water facilitates PCM by using it to heat up the water so it is distilled and separates fresh water from the salt [20]. Solar cooking systems can use PCMs to store heat and then use it to heat up the food during periods with lower solar radiation [21]. Solar air and water heating are two other application where PCM can be used [22]. Systems where PCM are used for STE can help places with no or limited access to electricity to cook through solar cookers and to warm up water [23].

2.2.4 Current research landscape on PCMs

During the 1970s, interest in PCM as an energy storage medium gained attention together with renewable energy due to the global oil crises. After the oil crises, research interest in the field of PCM as a Thermal Energy Storage (TES) gained traction as can be seen in Figure 5a. Although interest in PCM TES have gained steady traction, majority of existing commercial PCM products are typically used for small scale and/or in passive applications; example in wall-boards for indoor buildings, textiles and cold transportation boxes [24]. Furthermore, Tan [24] stated that a very low number of commercial PCM products are available and little experience with PCM TES installations have been reported. Figure 5b illustrates the breakdown of solar PCM related research, where Naveenkumar et al. [25] claim that less than 200 journal papers were published that focused on solar PCM research between 2016-2021. Of these, 11 % were specifically on the topic of PV-PCM systems. Therefore it can be concluded that there is opportunity for research development in the field of solar PCM and more especially PV-PCM.



(a)



(b)

Figure 5: (a) Number of Scopus indexed publications related to PCM TES [26]. (b) Breakdown of solar PCM related research [25].

2.3 Combining PV cells and PCMs

PV systems incorporated with PCM have been found to increase performance [22]. A study done by Hasan et al. [27] investigated PV system incorporated with paraffin based PCM under high temperature conditions in the United Arab Emirates. The paraffin based PCM with melting ranging between 38 - 43 °C was integrated at the back of the PV panel and its cooling effect was then monitored. The increased PV output (due to cooling produced by the PCM) was quantified. It was shown that the PCM produced less cooling in peak cool as well as peak hot months due to its incomplete melting and solidification respectively. The results from the study revealed that the PV annual electrical energy output increased by 6 % in the high temperature conditions [27]. To obtain this increase, an efficient heat transfer is essential in order to transfer the heat away from the PV to the PCM in order to cool the PV.

2.4 Heat transfer

The process of heat transfer can be divided into three mechanisms, convection, radiation and conduction [28]. In a PV, the main mechanisms of heat transfer is the radiation from the sun and the conduction of the PV cell with its surroundings [29]. This conduction will either help to increase the temperature of the PV or decrease it depending on the current temperature of the PV and the surroundings. The governing equation for this process is described in equation (3) where Q is the heat energy, t time, A area of transfer, d thickness of the receiving material and κ the thermal conductivity of the receiving material [28].

$$\frac{Q}{t} = \frac{\kappa A(T_1 - T_2)}{d}. \tag{3}$$

From equation (3) the heat transfer rate depends on the temperature difference where a greater difference gives a greater flux. It is also possible to get a negative flux which implies that heat are leaving the object. A PV cell might for example be approximated with a 5723 $\mathrm{J/kg \cdot K}$ and a thermal conductivity of around 0.8-1.2 $\mathrm{W/m \cdot K}$ depending on the design [30].

3 Method

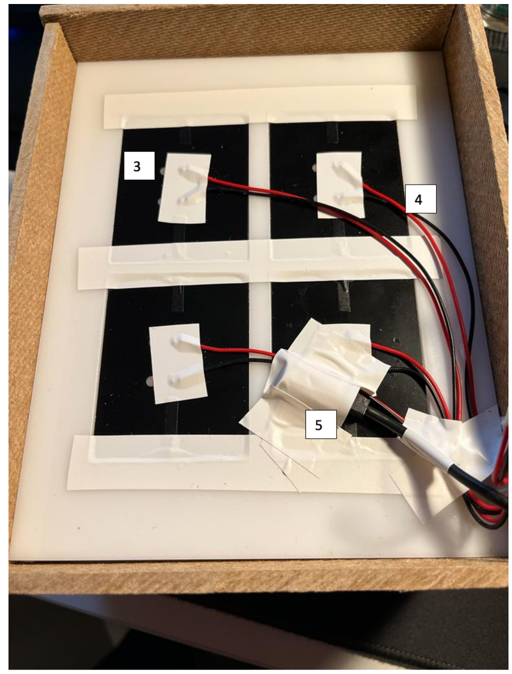
In the following method section, the experimental set-up and procedure are described. This includes a detailed explanation on the various components and tools used, and how the data generated were analysed.

3.1 Set-up

The setup consisted of a built model containing four 0.5 W, 5.5 Volt, 100 mA mono-crystalline silicon PV cells from Seeed Studio, each with surface areas of 70 mmx55 mm. The PV had a stated efficiency of 17 %. The PV panels were placed in a frame made of acrylic plastic using laser cutting placing the PV panels in the middle of the model with a 10 mm in between them. The PCM was an inorganic salt called Climator C24 based on sodium sulfate [31] which was encased in aluminium foil. The PCM was placed behind the frame with the PV cells and a lid was then placed on top of that to keep the PCM in close contact with the PVs for better heat transfer. There was also a few layers of aluminium foil placed between the PVs and the PCM to increase this as the backsides of the PVs were filled with wires and isolation tape, to prevent short circuiting the PV cells, that made direct contact hard. Taped to the back of one of the solar PVs was a surface temperature sensor to measure the temperature resistance. The sensor used in these labs were a PT100 sensor where the resistance at 0 °C is 100 ohms and equation (4), where $A = 3.9083 * 10^{-3}$ °C^{-1}, $B = -5.775 * 10^{-7}$ °C^{-2} and $R_0 = 100$ ohm, show the formula for converting resistance into temperatures above 0°C. The solar PVs were coupled in parallel and connected to a Fluke 175 true RMS multimeter using wiring through a breadboard. The surface temperature sensor was connected directly to another similar multimeter. The multimeter for the PVs was set up to show electrical potential and the one for the sensor to show resistance. A halogen floodlight lamp on 800W was placed around 400 mm away from the solar PVs who were placed, with the model. The model was built out of SI6mm think wooden fiberboard and had dimensions of 225 mmx180 mmx135 mm. See figure 6 and 7 for components and set-up.

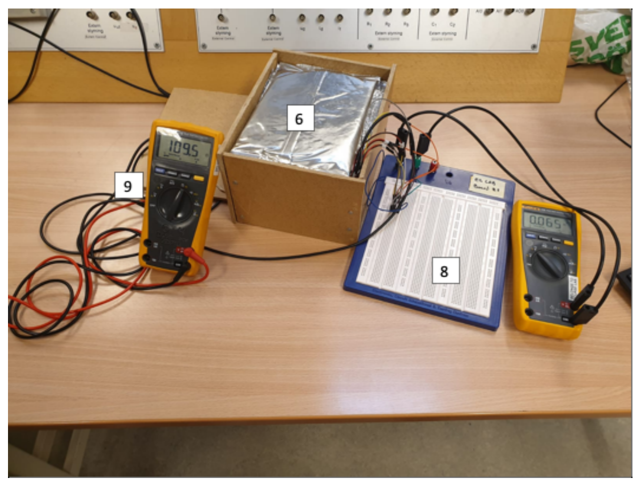
$$t = \frac{-R_0 A + \sqrt{(R_0 A)^2 - 4R_0 B(R_0 - R(t)}}{2R_0 B} \tag{4}$$

(a) Side view of solar PV-PCM model



(b) Top view of solar PV model (without PCM)

(c) Top view of solar PV-PCM with alumnium foil



(d) Multimeter, Solar PV-PCM model and breadboard showing the PCM

Figure 6: Set-up of model for experiment. 1 - Wooden frame, 2 - Solar PV panels, 3 - Acrylic plastic frame 4 - Electrical wiring, 5 - Temperature sensor, 6 - PCM (in aluminium container), 7 - Aluminium foil, 8 - Electrical breadboard, 9 - Multimeter.

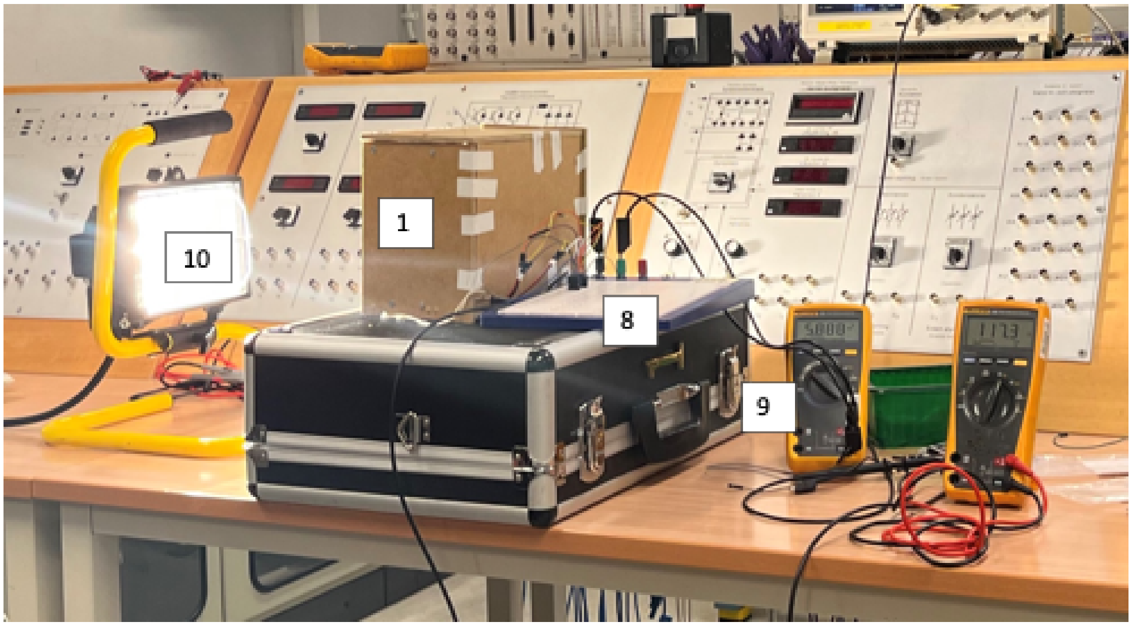


Figure 7: Overall lab experiment setup. 1 - Wooden frame, 8 - Electrical breadboard, 9 - Multimeter, 10 - Halogen floodlight lamp.

3.2 Procedure

When the execution started the resistance was marked down before lamp was turned on and then the electrical potential was marked down after 0 min. These values was then marked with two minute intervals. The experiments lasted for between 28 to 44 minutes and had start temperatures around 23 °C which was deemed to be the ambient air temperature in the lab. The decision to stop each experiment where based on when the resistance and electrical potential seemed to stabilise which would mean that the maximum temperature and electrical potential would have been reached. Due to time limitations these points where not fully reached but the experiments where stopped when the change of the values slowed down. Between the experiments the sPV panels where cooled down using encapsulated ice to speed up the process.

3.3 Theoretical model

By using data from SMHI for temperature and solar radiation for the 4/6-2021, a MATLAB code was constructed with a 100 % heat transfer efficiency and a simplified heat-flux equation with homogenized specific heat capacity for the PV cell and a heat flux depending only on the surrounding air and sun radiation. When the code was constructed, the effect of variable PCM-thickness and PV efficiency was investigated and the time in each degree calculated. The PV efficiency was initially assumed to 17 % at 15 °C. The two fundamental equations was equation (5) and (6). Equation (5) describes the total heat flux from the sun and the ambient temperature while equation (6) describes the power output for the system depending on the sun intensity and PV efficiency.

$$Q = Q_{Solar} - Q_{Ambient} \tag{5}$$

$$P = I_{sun} \cdot PV_{eff} \tag{6}$$

4 Results

The results from the physical experiments as well as the theoretical model is presented in the following part where the physical model yielded a maximum of 3.6 % increased in output for a specific time. For the theoretical model the total power output was instead analyzed for a whole day and yielded a 5.3 % increase in total power production.

4.1 Experiment

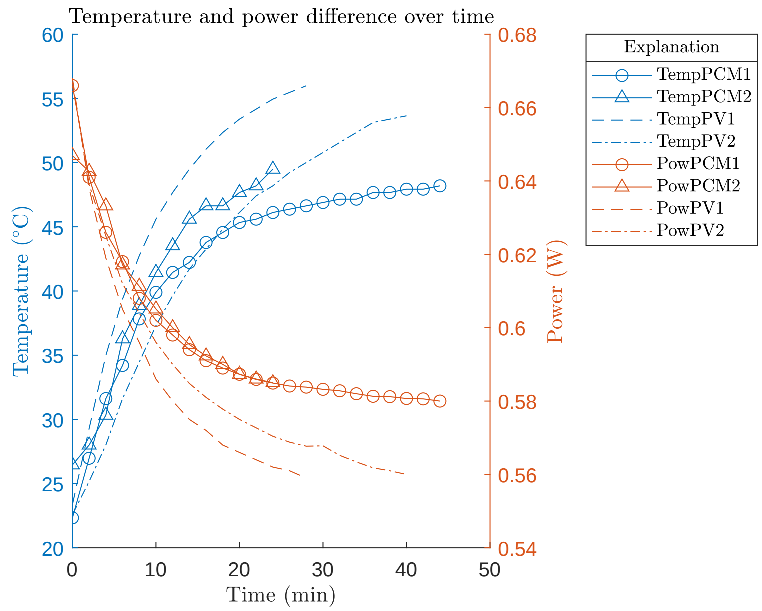


Figure 8: Temperature and estimated power for PCM-cooled PV cells and regular PV cells. Notice that the temperature and power differences does not match. This is suspected to be due to the use of a datasheet value of the current that might not match the real value.

As seen from Figure 8 a difference in both temperature and power output can be observed. PCM1 was the second to last measurement of the day and PCM2 the last of the day. PV1 was the first of the day and the PV2 the third of the day. The temperature was measured and the power estimated with a constant peak current value of 100 mA. The observed temperature for PV2 and PCM1 at the 40 min was 53.65 and 47.93 °C respectively. The difference equals a nominal temperature difference of 5.72 °C and a percentage decrease of 11.9 %. The power output at the 40 min mark, using the flat 100 mA current, was measured to 0.56 W and 0.58 W. This equals a 0.2 W nominal difference and a 3.6 % increase in output power.

4.2 Theoretical output potential

From the SMHI (Swedish Meteorological and Hydrological Institute) data and the stated PV efficiency the PCM thickness effect on the total power output was calculated, see Figure 9.

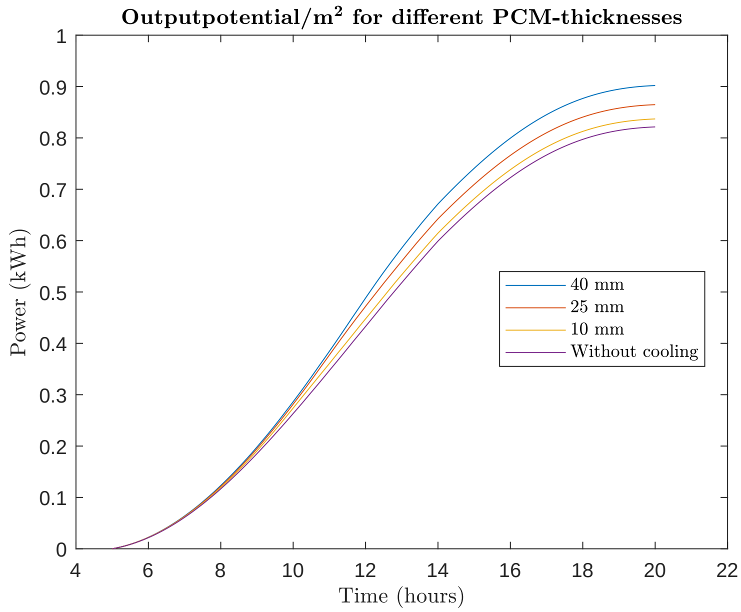
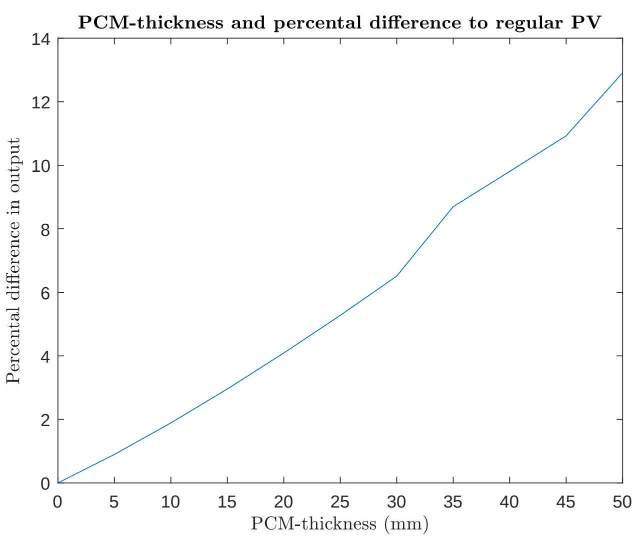
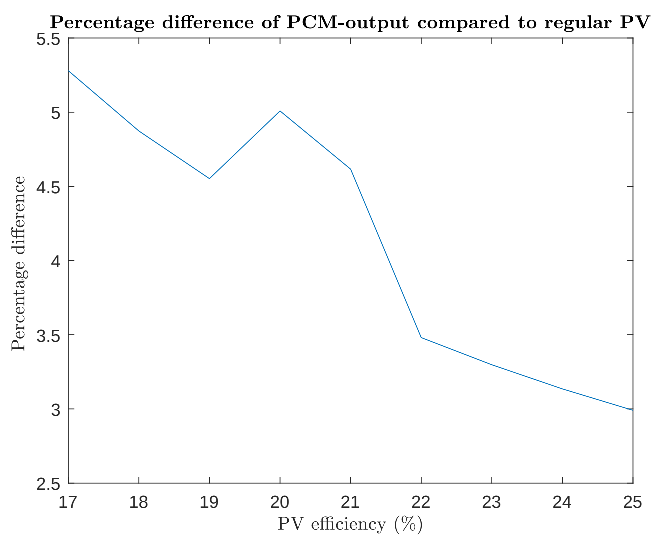


Figure 9: Total power output-potential for 1 sqm PV during 4/6-2021 in Gothenburg with an assumed 100 % heat transfer. Used data from SMHI ”Öppen data” [32].

From Figure 9 a clear increase in in power output can be observed. To reach the max temperature of the day the PCM system took 10.6 % longer and for a 25 mm system produced a 5.3 % increase in output power. With this two model were constructed. One showing percentage difference of output depending on the PCM-thickness, Figure 10a, aswell as depnding on the efficiency of the PV, Figure 10b. Figure 10a shows a clear increase as thickness increases assuming no difference in heat transfer while Figure 10b shows how the PCM efficiency declines as the PV efficiency increases.



(a) Power output potential as a function of PCM-thickness. Observe the overall exponential increase but as stated earlier, this is under a 100 % heat transfer assumption.



(b) Percentage difference between the PCM-PV and the regular PV as a function of the PV-efficiency. Notice the overall decline as the efficiency increases but also the rebound at 20 %.

5 Discussion

The following sections will discuss the results from the experiments, sources of error and the possible future of PCM- cooled PVs in terms of societal challenges, scalability and environmental impact.

5.1 Experiment

From the results a clear difference could be observed in both temperature difference and power output. In the sources found, a approximated 0.4 %/°C decrease in output efficiency was observed. With a nominal temperature difference of 5.72 °C this equals an estimated power output decrease of $0.4 \cdot 5.72 = 2.29\%$. The estimated power output for the experiment, using a flat 100 mA estimation of the current, gave a 3.6 % decrease between the two temperatures. These values are both broad and more of a general rule of thumb and sources of error will be discussed below. However, this experiment should be seen as a probe and test to try if it might be feasible to investigate and conduct further researched.

5.1.1 Sources of error

The experiment contained several sources of error that impacted the results to such a degree that a real error analysis could not be conducted. The experimental set-up, cut-off points and execution differed with each experiment and the total amount of experiments were too few. only two curves with approximately the same running time and initial temperature could be found and as such, no real conclusion can be drawn. This was primarily due to limited lab time and secondly due to new software that hindered the digital collection of the measurements. Except these overall sources the model and set-up contained several more factors of error.

The model itself was created without knowing the dimensions of the halogen floodlight lamp which presented challenges as the design was made for a smaller lamp. This meant that the model needed be be turned on the side and the closed environment that was meant to contain the air could not be replicated as intended and instead cooled the cell. The PV cells were connected in parallel which, with a low power output, resulted in a low power to noise ratio. In other words the signal and the natural noise were similar in amplitude. Also a multimeter was used as the oscilloscope software did not function properly and this presented several problems as the noise could not be measured and the measurements was hard to take in exact time intervals. The sensors were also connected in a way that only measured the backside of the PV cell and the fixture sometimes came loose which interfered with our measurements. An improved fixture and also a sensor on the front of the panel in order to get an approximation of the true temperature of the cell. In this case the cell was quite thin which might indicate that the difference should not be to great but it is still a source of error. Aluminium foil was used to create a heat transfer medium which was also a major source of error. This is due to the size of the sensor compared to the PV cell and a lack of heat transfer as the PCM was not in full contact with the PV cells. This created a delay where a significant voltage drop could be observed in the initial minutes before the PCM stabilized.

Overall these were the major sources of error that could be improved regarding both the design as well as the execution of the experiment. Suggestion for improvements for future experiments is discussed in the conclusion and future research.

5.2 Theoretical model

From the model several interesting aspects could be found. First of all, a clear increase of efficiency could be observed depending on the thickness of the PCM. The increase was exponential in nature but a major source of error in the model was the simplification of 100 % heat transfer. This is not true and an inclusion of a variable heat transfer dependent of thickness would probably decrease the output-potential.

The model also ignores the heat or cooling convention that depends on the surrounding air and winds. The data from SMHI was also interpolated which, even though the R-values of the fittings was ≈ 0.99, might vary in different ways. The heat equation used was also a simplification as only the radiation from the sun and the heat conduction of the PV was used. Radiation from the PV was for example ignored. the PV was also homogenized which is not true. The temperature that affects the power output might not be the same as the whole PV which has been assumed.

Although there are several sources of error, the model points towards a potential in PCM-cooling. As observed, the PCM-effectiveness increases as the heat generation from the ambient environment increases as well up to a certain point depending on the temperature range and PCM characteristic. For example, a temperature above the solidification point of the PCM decreases the total enthalpy of fusion and in turn it's cooling capabilities.

This means that climates with hotter temperatures are more suitable for PCMs up until a certain point. These points and ranges can be adjusted by using different PCMs suitable for the environment where the PV-PCM system are located.

The analysis was also for only one day day of data, Gothenburg 4/6-2021. To see the effect during a year, a total average per day and year in different regions would be needed to investigated to further develop understanding of ideal conditions and ranges.

5.3 Sustainability

There are three pillars of sustainability. Economical, environmental and societal. All these aspects are important in order to reach a sustainable world [33]. All three of these aspects are important to discuss when looking at solar PV cells. Solar energy is a renewable energy source but the technology used to generate the energy still requires resources and that also costs money. The economical and social aspects are important for the possibility to scale up a system and for the technology to reach all people. This section will discuss these aspects more in depth.

5.3.1 Environmental impact

Given the rapid increase in population growth and anthropological activities, concern over the levels of greenhouse gases (GHG) emitted in the earths atmosphere has increased. These GHG (primarily CO2, NOx etc.) are known to have adverse impacts on the earth - causing phenomena such as global warming. The ramifications of this are long-term extreme temperature conditions and high sea levels which will drastically impact a variety of wildlife and humankind as a whole. It is for this reason that interest in renewable energy sources such a solar PV and wind energy has become evermore important. It is however also important to understand the environment impacts associated with the various components that renewable energy technologies consist of - as they depend on extracting natural resources, and also require energy during production processes. The same too applies to PCM. Hence, the following section aims to describe typical sources of environmental impact of PCM by reflecting on existing Life Cycle Assessment and Life Cycle Inventory analysis on PCM.

A study conducted by Madeswaran et al. [34] aimed to provide an overview of recent Life Cycle Inventory (LCI) analysis of different PCM types. The study assessed PCMs used as thermal energy storage in concentrated solar thermal power plants, and further highlighted the environmental impact of several PCMs. LCI studies are a well-established method for identifying and quantifying all resources used to produce a product, as well as the substances that are released into the environment such as GHG emissions. The ecoinvent global database (version 3) was used in performing the LCI analysis in this study. Several PCMs were investigated on the basis of their physical and chemical properties, as well as their state and melting temperature (300 - 500 C) [34]. Figure 11 illustrates the scope of system boundary analysis, which is cradle-to-gate. In the study, the authors indicated that Eco-Indicator 99 was one of the methods used for calculating the environmental effects on energy consumption, biodiversity and human health. In understanding these effects, a life cycle assessment (LCA) was further employed to provide insight into the environmental impact of PCMs. Based on the melting point, enthalpy and required temperature range, sodium nitrate (NaNO3), potassium nitrate (KNO3) and potassium hydroxide (KOH) were salt based PCMs investigated.

As stated previously, the energy and emissions data used in the cradle-to-gate LCI and LCA study was calculated using the ecoinvent version three commercial database. The data catalogue used gives researches an approximation on the demand for energy usage and emissions generated during the production and usage of the different salt hydrates PCMs. Madeswaran et al. [34] further analysed the emissions to air and water caused by PCM production and usage, and the results of which are shown in Table 1. The emissions to the atmosphere are a key indicator in understanding the environmental impact, as these greenhouse gases contribute significantly to global warming. From the analysis done by Madeswaran et al. [34] was that each PCM investigated indeed had a different degree of resource consumption. For example, in a reference product of 1 kg, sodium nitrate consumed 0.33 kWh of electricity, while potassium hydroxide consumed 1.86 kWh. Data concerning electricity consumption for potassium nitrate was not included in the paper. Furthermore, heat energy is required in producing each PCM, where 2 MJ, 4.56 MJ and 7.34 MJ are required for sodium nitrate, potassium nitrate and potassium hydroxide respectively. Furthermore, PCM products such as sodium nitrate were reported to have carbon dioxide emissions, where 0.51 kg of CO2 are emitted per 1 kg of sodium nitrate. Surprisingly for Potassium nitrate and potassium hydroxide, there were no reported CO2 emissions. Finally, Sodium nitrate was reported to have carbonate, nitrate and sodium ion emissions in water amounting to 0.04 kg, 0.04 kg, and 0.03 kg respectively. Potassium hydroxide was reported have water emissions of chloride, potassium ion and water equavalent to 0.04 kg, 0.01 kg and 0.0031 m3 respectively.

From the above it is obvious that the production of PCMs indeed do have an environmental impact, as they require energy and resource materials in the production of each unit. Furthermore, other components such as the packaging of the PCM in containers and transportation from raw material extraction to factory production contribute to some degree to environmental impacts. Since there has been extensive research into solar-PV environmental impact assessments, this has been omitted in this report. Based on the findings of Madeswaran et al. [34], it can be concluded that there is value in performing LCI analysis to identify and assess the sustain- ability of phase change materials. As a future work, a comparative LCI and LCA study can be performed on a variety of different PCM types, and especially on PV-PCM systems as a whole. Furthermore, uncertainty and sensitivity analysis can be performed on some of the selected materials to test the robustness of the results reported in the paper. PCM indeed do have the potential to increase energy efficiencies of solar PV, which in turn may result in less solar-PV units being required and a result in a reduction in the environmental impact of solar-PV units. However, by reducing the environmental impact of PCM components and relying on carbon neutral energy sources, even the environmental impact of these sustainable sources may be further reduced.

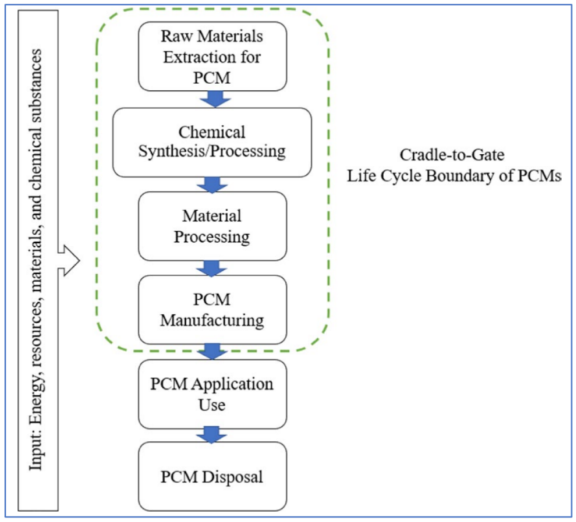


Figure 11: Crade-to-gate life cycle boundary of PCMs. Used figure from Madeswaran et al [34].

Table 1: LCI data of $NaNO_3$, KNO_3 and KOH [34].

Material	Inventory (Reference product = 1 kg)	Air Emissions	Water Emissions
Sodium nitrate (NaNO3)	Total annual production = 100,000,000 kg Electricity used in process = 0.3330 kWh Heat energy used in process = 2 MJ	Carbon dioxide = 0.5177 kg	Carbonate = 0.0372 kg Nitrate = 0.0384 kg Sodium ion = 0.0285 kg
Potassium nitrate (KNO3)	Total annual production = 500,000,000 kg Heat energy used in process = 4.5600 MJ	-	-
Potassium hydroxide (KOH)	Total annual production = 132,236,940,655,721 kg Salt tailing from potash mine = 0.023 kg Electricity used in process = 1.8601 kWh Heat energy used in process = 7.3420 MJ Potassium chloride used in process = 0.4930 kg	Water = 0.0013 m3	Chloride = 0.038 kg Potassium ion = 0.013 kg Water = 0.0031m3

5.3.2 Economical

The biggest problem involved with the application of solar PV cells is their coefficient of efficiency. Or more precisely, the decrease in the same value with continued operation. Even with the newest and/or best technologies available in the market, the efficiency remains around 20 percent and around 13-15 percent for older versions. This makes the current cost of solar panels expensive for household application and large-scale installations [35].

Addition of the PCM material to a standard solar model to improve the efficiency is the proposed solution in this report. On average, a solar farm costs around 12000 SEK per KW. It has a payback period of around 8 years, which is a rough estimate of how long it takes for the plant to regenerate or equal the initial investment costs [36].

A rapid growth was observed in the Swedish solar energy market as by the end of 2018 there were close to 25 500 grid connected installations. Nearly 10 200 installations were added in 2018 alone, taking the total installed power to a record 411 MW by the end of 2018. This data was nearly double than the previous year [37]. The average household electricity prices, in Sweden, for 1 kWh were 17.91 euro in the first half of 2021. Assuming the base value of the average price for installation and equipment to be roughly 15000 SEK per KW, with a production of 900 Wh per installed KW we can calculate the total expenditure and savings generated by the PV-PCM system.

The added cost each model can be given by the cost of the PCM + the cost of the solar panel (per KW of installation). This is roughly 45 SEK per Kg of material used [38]. Now the revenue generated from such a plant, simplified, is given by the electricity prices x the production of the energy (per kWh). The average increase in the output power of the PV cells as observed by our experiment was nearly 3.6 %. Thus the new total energy production with the improved efficiency is equivalent to the electricity prices x the improved production of the energy (per kWh). Using this logic, we observe the same percent increase in the revenue. This equals in a significant increase in the profit, which is also open to further scaling with the increase in plant capacity and higher end, cost effective equipment.

5.3.3 Societal and scalability challenges

As stated in Section 2.2.4, although research efforts on PCM TES are developing, there are limited large-scale commercial use of the technology. This is especially true for PCM TES being used in solar PV cells. The limited use of the technology indicates that PV-PCM is still in its infancy in terms of commercial use. Like with most technologies, they often develop in different growth stages that follow a S-curve pattern [39]. Typically the technology begins in an infancy stage where growth of the technology is relatively slow. As the technology becomes better by way of "learning by doing", the production cost per unit of product produced decreases. This triggers a positive feedback loop in which the technologies rate of improvement increases (due to decreasing production cost) and therefore diffuses in use more quickly. It can be assumed that PCM TES especially when combined with solar PV cells, lies within the early stage of technological growth. The assumption for this that since there is currently a low use of PV-PCM systems, low research publication output on the subject and potentially high production cost (this is not known for certain as there is no reported papers on this subject); are typically characteristics of emerging technologies in early growth phases. The aforementioned qualities too can trigger a negative-feedback loop which limits the technologies growth. Since commercial actors and researchers may not dedicate efforts into investing in PV-PCM systems as the technology may have not gathered legitimacy amongst key actors - as the promised rewards of the technology is yet to be proven in commercial use. A good example is within the construction industry, where many buildings and structures are used to placing solar PV cells on to make use of space and generate electricity locally. The construction industry is famous for its slow development and resistance to new technologies [40]. This means that there might be a need for clear proof of profitability and that these systems work before a PV-PCM system would be accepted and widely installed.

Spurring a new technology such as PV-PCM systems from infancy to a rapid growth phase, requires attention to a number of factors that may hinder a technology from developing. For example, theory on Technology Innovation Systems (TIS) aim to understand system weaknesses that limit an emerging technologies growth [41]. For example authors Bergek et al. [41], highlight eight key processes, or functions of concern which may influence diffusion of a technology. The eight functions are 1) Development of formal knowledge, 2) Entrepreneurial experimentation, 3) Materialisation, 4) Influence on the direction of search, 5) Market formation, 6) Resource mobilisation, 7) Legitimisation (acquiring social acceptance of the emerging technology), and 8) Development of positive externalities [41].

The goal of this paper is not to perform an exhaustive analysis of the aforementioned system of weakness for PV-PCM systems, but instead to highlight key areas that may be hindering its growth. As stated in Section 2.2.4, it is evident that the amount of research effort into PV-PCM systems is rather limited. This area of weakness ties closely to the function of development of formal knowledge which is evidently lacking for PV-PCM as a component. Furthermore, legitimisation may have not yet developed for the application of PV-PCM which may again be tied to the low research output in the field. This in turn limits market formation and entrepreneurial experimentation. To address these key system weaknesses, government can play a key role in incentivising research into the subject. This can be done by providing funding, or providing grants to private and entrepreneurs who invest in the technology. Furthermore, government may play a key role in facilitating partnership between traditional solar PV and PCM actors. Ultimately, government may consider using environmental policy instruments to further incentivise efficient solar PV systems. One possible idea would be to use a similar energy rating scale (as what is seen in many household equipment) to categorise the level of energy efficiency of a solar PV unit.

Finally, different PCMs have different melting and solidification points. This means that a PV-PCM system might need different types of PCMs in different climates and different parts of the world [27]. This might mean that if a highly functional system is developed it might not be applicable in the same way all over the planet and that can affect access to this technology for countries and groups of people.

6 Conclusion and future outlook

The overall conclusion of the experimental is that we could not by any scientific certainty identify a difference of output power and an improvement using a PV-PCM system. With this being said, the improvement and overall curves presented and discussed above appears to indicate that a difference do occur. For example could both a 3.6 % increase be observed at the 40 min mark for the experiments and a 5.3 % total output power increase for a day in June in Gothenburg using a theoretical model. Both of these approaches indicate some improvement and therefore further research, using improved methods and approaches, should be conducted to investigate the actual differences.

6.1 Experimental improvement

Several parts were identified during the experiments as sources of error and improvement and several suggestion for redesigns and execution were brought up. From a designing standpoint, one bigger PV cell instead of four smaller would give a more robust model as the sensor in this first iteration of design set-up was significant in comparison to the PV-cell and therefore the measurement and cooling was hard to measure. Furthermore, one big PV cell would maximize the area that could receive light as the frame now covered some part of the cells. As the lamp design was now know, a set-up that is created with the lamp's dimensions and vertical placement of cells and PCM could be created. The PCM could also be pre-melted and the formed around the temperature sensor in order to maximize surface contact between the PCM and PV cell and so the heat transfer. Aluminium foil or an improved system of heat transfer medium should be used as well but preformed PCM would minimize the vertical heat transportation. Then, by using two frames with duplicate cells, a system were one is cooled of while the other is running should be created in order to allow the inherited heat to disperse before the next experiment. The measurements should be also be automatized with an oscilloscope in order to reduce human error and increase precision. The oscilloscope in the lab was of a model that had not been used by any member of the project group and such an integral part of experimental measurements should be under control before starting the experiments. The measurements should also be standardized in time of of around 45 minutes for each measurement with at least six repetitions in order to be able to perform a proper comparison, error analysis and be able to give results with some level of confidence interval. With these changes in mind, the experiments would yield more accurate and precise results that could be analyzed and later on built upon depending of the results.

6.2 Future outlook and further research

An interesting area of research would be the inclusion of other PCM types in this project. The results obtained under the current setup were limited by the use of only the salt hydrate, inorganic kind, of PCM. Involvement of other kinds of PCM would open new doors for research in further improvement of the solar PV efficiency. Another way to build upon the finding of this report is to improve the laboratory conditions and minimising the sources of error. Testing the PCM under different environmental conditions would also be a good way to explore the possibilities of the proposed setup.

Large scale and extended applications, particularly involving building integration and ventilation and water systems, are further possible research areas. Using the energy stored in the PCM to other applications would mean an opportunity to use more of the energy from the sun and thereby increase the efficiency as it would reduce the need for direct electricity to power those applications.

Use of PCM to simply cool the PV cells resulting in an overall improved system efficiency, without any particular regard for reusing the latent energy is another application that could be scaled to fit the capacity of energy generating farms. This too, would require further testing and experimentation with different types of PCM and working environments.

Finally, although renewable energy sources such as solar PV provide a more sustainable alternative to fossil fuels, one can not down play the importance of improving the energy efficiencies of these units. PCM is an existing technology that may improve the efficiencies of solar PV. However, they too have an environmental impact. LCA and LCI studies of other PCM types would provide an interesting perspective. According to available research, PV-PCM systems are currently under studied, and more research into the field should be encouraged. This may lead to a snowball effect where more research into the field harnesses credibility of the technology, which in turn will attract entrepreneurial and commercial interest. Ultimately, this will decrease production cost and increase use, and perhaps - PCM too may benefit from increasing growth in solar PV globally.

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