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ABSTRACT

Nowadays, retail stores are highly interested in the application of strategies such as demand response (DR) in refrigerated display cabinets (turning off the cold machine during a certain time) to increase their flexibility in energy management and to facilitate the integration of renewable energy sources. One of the main concerns related to DR deployment is the product and air temperature increase inside the cabinets when the refrigeration machine is turned off. Thermal energy storage TES by phase change materials (PCM) has been demonstrated to be a solution to replace for a limited time the refrigeration unit and maintain the product at low temperature. However, the presence of PCM heat exchanger altered the air curtain performance as well as the thermal behaviour of the display cabinet. Successful integration of PCM needs implementing new cabinet design and operating conditions. Moreover, if this technology is applied for many display cabinets, management strategies need to be considered so that the PCM can be charged and discharged in suitable conditions. If renewable energy sources are available, energy management scenarios combining electrical sources (grid and renewable) and thermal energy storage (PCM) can be planned. The main objectives of the present work are, first, to identify improvement options and optimized parameter ranges that can request the PCM integration in the display cabinet; and second, to test different energy management scenarios at the scale of a supermarket. The study shows that by improving the perforation pattern of the rear duct channel and increasing the fan power, a more homogeneous product temperature distribution and better thermal behaviour of the cabinet are obtained. The effects of the operating conditions (ambient and setpoint temperatures) on thermal behavior, energy consumption and PCM charging/discharging time are analyzed by experimental

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investigations. A simulation tool was developed to evaluate the global efficiency of a supermarket equipped with PCM display cabinets. For different energy management scenarios, it evaluates the potential of this technology to support DR applications, reduce the electricity contract power of the retail and facilitate the utilization of renewable energy sources, photovoltaic (PV) solar panels in particular. PCM integration allows a reduction of maximal power demand by 8 % in the scenario without PV panels and by 13 % in the scenario with PV panels.

KEYWORDS

PCM, heat exchanger, display cabinet, energy management, demand response, photovoltaic (PV)

ABBREVIATION

DAG	Discharge air grid
DR	Demand response
GHG	Greenhouse Gases Emissions
PCM	Phase change material
PV	Photovoltaic
SR	Reference scenario
TES	Thermal energy storage
VBC	Vertical beverage cooler

1. INTRODUCTION

Issues related to the refrigeration industry are becoming more and more important given climate change and the increasing demand for cold applications (food preservation, air-conditioning, etc.). Currently, it accounts for 8 % of Greenhouse Gases Emissions and 17 % of the worldwide electricity consumption in industrialized countries [1]. With the growing concerns on global warming, it is urgent to replace conventional ways of energy use and management in refrigeration applications by more sustainable solutions such as the development of renewable energy. For this transition, more flexibility is required to deal with the intermittency and the unpredictability of renewable energy sources [2, 3]. Demand response (DR), as one of the flexibility tools, consists in reducing or even stopping the energy consumption in an industrial site during a certain time. Because of the need for cold energy and lighting, food retailers (supermarkets, hypermarkets and stores) are in the lead on the scale of electrical consumptions and GHG emissions per surface area (food retailer: 548 kWh/m^2/y and 266 kg CO_{2eq}/m^2/y; non-food retailers: 238 kWh/m^2/y and 132 kg CO_{2eq}/m^2/y [4]). Refrigerated display cabinets are widely used in retails and account for 70 % of the total refrigerated energy [5, 6]. In this context, retail stores are interested in the application of DR in refrigerated display cabinets (by turning off the cold machine) to increase energy management flexibility and to facilitate the integration of renewable energy sources.

The major issue to the application of DR in display cabinets is the fast increase of the product and air temperature during these periods. Thermal energy storage TES technology by phase change materials (PCM) that has been developed and used for heat preservation in building [7-9] could be used in display cabinets to limit the temperature rise during DR. Indeed, the energy stored in the PCM can replace the cold production machine during a DR period. Up to now, this technology was considered by a few published works. Alzuwaid *et al.* [10, 11] placed 1.8 L of water gel PCM into two single-panel radiators at the back channel of an open vertical display cabinet. Lower air and product temperatures during defrosting (12 min) and 5 % reduction of the energy consumption were observed. Adding PCM has an effect on the airflow rate and cold machine behaviour of a vertical beverage cooler (VBC) which was investigated numerically by Ezan *et al.* [12]. The PCM (a slab) was inserted in the rear duct of the VBC. Its presence reduced the airflow rate and increased the pressure drop. The PCM integration enhances the cooling performance of the VBC by extending the compressor off duration and limiting the sudden temperature rises. Recently, Ben-Abdallah *et al.* [13] have investigated experimentally the integration of PCM in an open display cabinet. The product temperature rise was limited to 1 °C during 2 h compressor stop, while 2 °C was measured for the display cabinet without PCM, with similar ventilation. However, the PCM addition has also modified the airflow and thermal behaviour inside the display cabinet: a 28 % reduction of the air curtain flow rate was observed, resulting in higher product temperatures at the higher shelves and the front of the display cabinet, and colder product temperature at the lowest shelf because of the increase of the air flow rate through back panel perforations at this position. The main results of this study related to the changes in thermal and airflow behaviours due to PCM integration were summarized in Table 1.

As highlighted in those studies, while the potential of adding PCM in display cabinets to maintain product and air temperatures during compressor off (DR, defrost…) periods was confirmed, the thermal and energy performances of this technology depend on various parameters such as:

- the design of the display cabinet (fan power, perforations...) and the design of the PCM container device (heat exchanger choice and dimensioning, PCM mass and properties ...)
- operating conditions (ambient and cabinet temperature set point…)

The impact of some of those parameters on the performance of a display cabinet *without PCM* can be found in the literature. Gray *et al.* [14] studied the effect of perforation patterns of the rear duct in a display cabinet and found that while 70 % of the air in circulation needs to be delivered through the air curtain, the remaining 30 % which exits through the back panel perforations needs to be judiciously distributed between the shelves to meet the standards. The configuration of the supply air fans and the cooling coil needs to be considered when designing the perforation patterns. Navaz *et al.* [15] noticed a significant temperature increase in the display cabinet without perforation. Wu *et al.* [16] tested various porosities of the back panel and found a decrease of the product temperature at the rear with the increase of the perforation density. Chen and Yuan [17] tested 3 perforation densities and found that the cabinet temperature decreased as the perforation density increases. Important effects of ambient condition on the display cabinet performance were observed in the same study. Influence of operating conditions on the display cabinet performance has been analysed by Chaomuang *et al.* [18] and Ben-abdallah *et al.* [19]. While higher product temperature was found with higher ambient temperature, the increase depends on the position of the products inside the cabinet. The influence of control parameter on product temperature and quality was studied by Kou *et al.* [20]. In this work, the measurements were performed with two setpoint temperatures (-0.5 °C and -2.2 °C): freezing damage was noted in bags located at the back for lower setpoint temperature (-2.2 °C); for the other case (-0.5 °C), the temperature at the front of the display cabinet can exceed the temperature standard.

From the previous literature review, several research gaps/scientific questions were identified:

- For display cabinets with PCM, how design parameters and operating conditions can impact their performances (preventing the rise of air and product and air temperatures during off periods and minimizing energy consumption) from the perspective of DR application?
- For supermarkets equipped with those modified display cabinets, which management strategies with regards to PCM charging and discharging should be applied?

- If renewable energy sources are available, what energy management scenarios combining electrical sources (grid and renewable) and thermal energy storage (PCM) can be planned?

To respond to these questions, the present work is organized into two parts: parametric and scenario studies. In the parametric study section, the effects of design parameters (perforation rate, fan power) and operating conditions (ambient and setpoint temperature) on thermal behaviour, energy consumption and PCM charging/discharging time, are analyzed by experimental investigation. This section aims to identify improvement options and "optimized" parameter ranges that can support the PCM integration in the display cabinet. The second part of this work simulates three scenarios of PCM integration in several display cabinets to explore the potential of this technology at the scale of a supermarket. Different objectives are targeted in each scenario: 1 – to perform a maximal number of DR periods; 2 - to reduce the electricity contract power (power capacity contract between food retail and an electricity provider) and 3 – to facilitate the use of renewable energy sources.

2. MATERIALS AND METHODS

2.1. Display cabinet with PCM integration

The experimental set-up consists mainly in a vertical open display cabinet with PCM (water). The choice of water as PCM was based here on the adapted melting temperature for chilled product conservation (0 - 6°C), high latent heat, safety and cost. Other PCMs in the same melting temperature range (mainly paraffin) have lower latent heat and higher price, and could also be used in other configurations. PCM (7 kg) was inserted inside a finned tube heat exchanger as it provides a large exchange area. It was placed at the rear duct of the display cabinet. This location provides a sufficient volume and suitable conditions of heat transfer between airflow and heat exchanger during PCM charging and discharging cycles. More information on the choice of PCM type, the PCM heat exchanger dimensions and position can be found in the previous study [13]. The display cabinet was placed in a test room with control ambient temperature.

T-type thermocouples were used to measure the temperature of product (back and front positions at 1^{st}, 3^{rd} and 5^{th} shelves, blue points in Fig. 1a), air (inside the rear duct and at discharge air grid DAG, green points in Fig. 1a) and PCM (black points in Fig. 1b). Hot-wire anemometer (Testo 435 – 4) was used to measure air velocities in the display cabinet. A wattmeter (Digiwatt) measured the electrical power demand of the display cabinet and the compressor alone. The compressor energy consumption was calculated by the time integration of the measured power. The sensors and their uncertainty are shown in Table 2.

2.2. PCM charging/discharging process and charging ratio

A PCM charging/discharging cycle is presented in Fig. 1c. During charging process (AD), the PCM, initially in liquid phase was cooled to about 0 °C (AB), changes to solid (BC) and continues to be cooled (CD). During discharging process by compressor stop (DA), the PCM temperature increases in the solid phase (DE), changes to liquid (EF) and its temperature continues to increase till the beginning of a new cooling step (FA). A charging ratio is defined according to the temperature of PCM at 5 positions inside the heat exchanger (Fig.1b). A charging ratio of 25 % will be reached when the PCM at position 2 is fully solid with a temperature lower than 0 °C (point C, Fig. 1c), and so on for position 3 (50 %), position 4 (75 %), and 5 (100 %).

2.3. Overview of the studied parameters

4 parameters were investigated for the display cabinet with PCM integration: the perforation rate of the 1st shelf, fan power, setpoint and ambient temperatures. While perforation rate and fan power are design parameters, setpoint and ambient temperatures are operating parameters.

Effect of the design parameters

3 studied configurations are presented in Fig. 2:

- Configuration 1, reference: design parameters are not modified.
- Configuration 2: 80 % of the perforations of the first shelf is obstructed, same fan power as the reference.
- Configuration 3: 80 % of the perforations of the first shelf is obstructed, higher fan power.

2.3.1. Perforation rate of the rear duct panel

Due to PCM integration, a lower product temperature than in the display cabinet without PCM heat exchanger was observed at the first shelf. Indeed the PCM heat exchanger in the rear duct increased the airflow rate through the perforations at this level. Besides, PCM heat exchanger narrowed the air cross-section and led to temperature increase for packages located in the upper shelves. The reduction of perforation density at the first shelf is a possible solution to homogenize the product temperature inside the display cabinet by increasing the product temperature at the first shelf and decreasing the product temperature in the upper shelves. In configuration 2 (Fig. 2), the perforation of the first shelf is obstructed of 80 %.

2.3.2. Fan power

Adding PCM in the rear duct decreases of the air curtain flow rate by 28 % at the discharged air grid compared to a display cabinet without PCM heat exchanger. In configuration 3 (Fig.2), a more powerful fan (70 W) was tested whereas the fan power of the reference configuration is 25 W.

Effect of the operating parameters

2.3.3. Setpoint temperature

The setpoint temperature defines the evaporator outlet air temperature. A lower air temperature increases the temperature gradient between the air in the rear duct and the PCM, which might enhance the heat transfer in the PCM heat exchanger and reduce the PCM charging time. The charging time for 3 setpoint temperatures of -1 °C, -3 °C and -5 °C was evaluated in this study.

2.3.4. Ambient temperature

The infiltration of warm and moist air from ambient through the air curtain contributes 70-75 % to the total cooling load of an unmodified open display cabinet [15, 21-23]. It is thus important to observe the operation of a display cabinet with PCM at different ambient temperatures, the charging and discharging time in particular. In this study, three ambient temperatures were tested: 16 °C, 21 °C and 26 °C, the air humidity was not measured in this study.

The four studied parameters and their range are summarized in Table 3.

2.4. Overview of the studied scenarios

Scenarios of PCM integration in a medium-sized supermarket (1200 m^2, annual electricity consumption 605 MWh [24]) are considered. During a day, the supermarket's total power demand varies between 44 and 124 kW, mean value 79 kW as shown in Fig. 6b (SR curve). This power demand includes: positive display cabinets (26 kW), negative display cabinets (mean value 13 kW), lighting (21 kW) and others. The PCM integration is only used for positive display cabinets. Practical scenarios (S1, S2 and S3) were investigated and compared to the reference scenario without PCM (SR):

- S1: PCM integration for DR application
- S2: PCM integration for the reduction of electricity contract power capacity - system downsizing
- S3: PCM integration for the use of renewable energy sources
- SR (reference, measured data [24]), without PCM: DR is not applied in this scenario

For each scenario, daily planning of DR applications and setpoint temperature variation for one or two groups of positive display cabinets is proposed. Then the daily variations of the supermarket power demand and PCM charging ratio are calculated from this planning. The following assumptions and constraints are used:

- When the PCM is fully charged, the display cabinet power supply can be cut off for a maximal duration of 2 h. In this study, the *DR duration is then fixed at 2 h*.
- After DR, the refrigeration unit is restarted; the product temperature is back to its reference state after 4 h (experimental data, not shown in this article). Thus, there is *at least 4 h between 2 DR applications*.
- The set-point temperature of the display cabinets without PCM is T=-1 °C
- PCM can be fully charged within 4 h at the setpoint temperature T = -5 °C (Cf. 3.1.2.1)
- PCM can be fully charged within 6 h at the setpoint temperature T = -3 °C (Cf. 3.1.2.1)
- When the PCM is charged at 100 %, this charging level can be maintained at the setpoint temperature T = -1 °C.
- The produced solar energy by PV is only used for positive display cabinets (scenario S3) and not for other usages.
- The ambient temperature is 16 °C.
- The ventilation by the fan inside the display cabinets is always maintained.

3. RESULTS AND DISCUSSION

3.1. Parametric study of PCM integration in display cabinets

3.1.1. Influence of design parameters on product and air temperature distribution inside the cabinet

Fig.3 presents the thermal cartographies inside the display cabinet for the three configurations; the values correspond to the time-average air and product temperatures during 2 cycles of PCM charging/discharging (Fig.1c). These results were obtained with the set-point temperature of -5 °C and the ambient temperature of 16 °C.

3.1.1.1. Perforation

The comparison between the two configurations 1 and 2 (Fig.3) shows that the perforation obstructions at the first shelf increase the temperature of the packages on the first shelf and lower the packages and air temperature on the third and fifth shelves. This result can be explained by a lower air flow rate through the perforations at the first shelf, a higher airflow rate inside the rear duct and a lower air temperature at DAG for the configuration 2 (0.9 °C instead of 1.6 °C). This result highlights that by improving the perforation pattern of the rear duct, better thermal behaviour and a more homogeneous product temperature distribution can be obtained.

3.1.1.2.Fan power

A higher fan power (70 W - configuration 3; 25 W – configurations 1 & 2) increases the airflow rate inside the rear duct as well as air velocity at DAG (1.75 m s^{-1} instead of 0.58 m s^{-1}). It is noted that the air velocity at DAG of a display cabinet without PCM heat exchanger was only 0.80 m s^{-1}. The comparison between the configurations 2 and 3 (Fig.3) shows that for configuration 3, a lower product temperature was observed and especially for the front packages. Indeed, a stronger air curtain was generated in this case with higher airflow rate and lower air temperature (-0.2 °C at DAG for configuration 3 instead of 0.9 °C in configuration 2) providing better protection of the product from external infiltration. However, as more ambient air is driven by the air curtain into the return air grid, the daily compressor energy consumption is higher in configuration 3 than in the reference configuration (Table 4). It should be noted that 70 W is not the optimal value for fan power, lower power (35 W) might be sufficient to overcome the airflow rate reduction. In this study, a high fan power (70 W) was chosen so that the impact of this design parameter could be analysed in a larger range.

3.1.2. Influence of design and operating parameters on PCM charging/discharging time

This section analyses the impact of design parameter (fan power) and operating parameters (setpoint and ambient temperatures) on the PCM charging/discharging processes to identify suitable parameter ranges for the control of PCM charging/discharging times.

3.1.2.1.Setpoint temperature

Fig.4 presents the time evolution of charging ratio obtained at different setpoint temperatures: -1 °C, -3 °C and -5 °C. The charging process was quicker for the lowest setpoint temperature (-5 °C) because this condition provides the highest temperature difference between PCM and air inside the rear duct: PCM charging time reduces of 36 % when setpoint temperature reduces from -3 to -5 °C. For the set point temperature of -1 °C, the air temperature wasn't low enough to freeze completely the PCM. However, a lower set point requires more energy: daily consumption of 3.6×10^4 kJ at the setpoint temperature of -5 °C compared to 3.2×10^4 kJ at the setpoint temperature of -3 °C and 3.0×10^4 kJ at the setpoint temperature of -1 °C.

The optimal choice of set point temperature is not a fixed value because it depends on the instant cooling power required for PCM charging. For example, if the objective is to charge the PCM quickly, a lower set point is required. If the PCM is charged at 100 % and it is only necessary to maintain this charging level, a higher set point temperature (-1°C) can be selected.

3.1.2.2.Ambient conditions

Fig.5 illustrates the time evolution of PCM charging and discharging ratio for different ambient temperatures: 16 °C, 21 °C and 26 °C. During the charging process, the refrigerating system has to freeze the PCM while maintaining air and product temperature inside the display cabinet. The charging time is longer for higher ambient temperature because of a higher thermal load due to ambient air infiltration. During the discharging process, the cold machine is turned off and the PCM provides cold energy to maintain a low temperature inside the cabinet. As the fan is kept running during the discharging process, the ambient air infiltration comes through the return air grid to the PCM heat exchanger. A higher ambient temperature (26 °C) increases the thermal load and shortens the PCM discharging time.

When the ambient temperature rises from 16 °C to 26 °C, the charging time (for 100 % charging ratio) increases by 20 % while the discharging time decreased by 50 %. It can be noted that discharging time is more impacted by ambient conditions than the charging time. Indeed, during the discharging process, the cold machine of the display cabinet is turned off, so the temperature rise is highly influenced by the ambient temperature and greatly impact the heat transfer between the PCM and its surrounding air which depends on their temperature gradient. During the charging process, PCM exchanges heat with cold air coming out of the evaporator. As the air temperature is controlled by the machine, it is much less influenced by the ambient condition than during the discharging process.

3.1.2.3.Ventilation flow rate

The ventilation effect on PCM charging and discharging time was shown in Table 4, the setpoint and ambient temperatures were set at -5 °C and 16 °C respectively. Compared to the configuration 1-reference, a higher fan power (configuration 3) reduced both charging (-16 %) and discharging times (-45 %). Indeed, higher air velocity in the rear duct enhanced the heat transfer between air and PCM and reduces the charging / discharging times. The ventilation effect is stronger during the discharging period when the compressor is off and the system is driven by external air infiltration.

3.2. Scenarios study of PCM integration in display cabinets

This section presents three simulation scenarios of PCM integration in a supermarket. In scenario 1, the PCM is used so that a maximal number of DR periods could be performed in a day. The objective of the scenario 2 is to reduce the electricity contract power of the supermarket: a smart organization of DR periods and PCM charging periods is proposed. In scenario 3, renewable energy sources are available and could be used to charge the PCM during the daytime.

3.2.1. SCENARIO 1 - PCM integration for DR applications

This scenario aims to perform a maximal number of DR applications in one day. All positive display cabinets are supposed to be equipped with PCM heat exchangers. To charge rapidly the PCM after each DR period, the setpoint temperature is fixed at -5 °C for those positive display cabinets with PCM (Fig. 6a). For the scenario without PCM (SR), the setpoint temperature is -1 °C. As there is a time gap of at least 4 h between two DR applications and the DR duration is 2 h, the maximal number of DR per day is 4. Fig. 6b presents the comparison of the daily power demands of the reference scenario SR – without PCM (dash line) and scenario S1 in which 4 DR periods are applied (continuous line). A reduction of power demand at each DR can be observed which corresponds to the turning off of positive display cabinets (-26 kW). However, because of a lower setpoint temperature, higher power demand is needed in S1 scenario in “normal” time (apart from DR periods). As shown in Fig. 6c, the PCM discharges completely at each DR and then is completely recharged after 4 h before the next DR.

This result shows how PCM increases supermarket flexibility in energy management. In this scenario, PCM can provide extra autonomy which allows shifting the energy consumption to avoid on-peak periods. Moreover, depending on the energy provider, DR applications can bring additional income to the supermarket. It is highlighted that the 2h autonomy in this study corresponds to the addition of 7 kg of PCM in each display cabinet. Depending on the display cabinet and PCM integration design, a higher quantity of PCM can bring even higher autonomy.

3.2.2. SCENARIO 2 - PCM integration for the reduction of contract power - system downsizing

The flexibility in energy management from PCM might be used to “reshape” the power demand curve to reduce its maximal level. As in the scenario 1, demand response is only applied to positive display cabinets with a total demand power of 26 kW (Cf. 2.4.Overview of the studied scenarios).

In order to obtain more flexibility, the positive display cabinets are divided into 2 groups: the first group (G1) representing 70 % of 26 kW (=18.2 kW), the second group (G2) representing 30 % of 26 kW (=7.8 kW). Different evolutions of setpoint temperature and demand response periods are applied for these two groups: blue solid line for G1 and red dashed line for G2 (Fig. 7a). The lowest setpoint (T=-5 °C) is for quick PCM charging, the medium (-3 °C) is for slow charging while the highest set point (-1 °C) is to maintain PCM charging level (at 100 %) after being completely charged (Fig. 7c). 4 DR (2 per group, blue highlights for G1 and pink highlights for G2) are applied to allow the reduction of power demand during peaks: 8-12 h and 14-16 h. For the scenario S2, the maximal power demand is reduced from 124 kW (reference value - SR) to 114 kW (-8 %). This result shows how PCM integration reduces the supermarket contract power and thus its electricity bill. Moreover, if PCM is integrated in display cabinets at the design phase of the supermarket, smaller cold machine (smaller power and cheaper) – refrigeration system downsizing can be considered. It can be observed that power demand is lower in scenario 2 than in scenario 1. Indeed, these scenarios represent two different energy management strategies: maximal DR applications (scenario 1) and system downsizing (scenario 2). The difference in their results can be explained by two reasons: the use of lower setpoint temperature in scenario 1 for quick PCM charging and the use of two display cabinet groups in scenario 2 for more flexibility.

3.2.3. SCENARIO 3 - PCM integration for the use of renewable energy sources (PV panels)

For this scenario (Fig.8), it is considered that positive display cabinets are powered by solar energy between 10 h and 16 h. The needed capacity of PV can be supposed to be the same as the total demand power of the positive display cabinets: 26 kW. During the period of PV utilization (10h-16h), the grid demand power is reduced and the PCM is charged completely from 0 to 100%. The energy stored by PCM can replace the cold machine during 2 h and represents 52 kWh. While it is a known fact that free energy will offset the requirement, this scenario highlights the possibility to use renewable energy for TES charging in the supermarket in daytime. Another charging phase is programmed at night when the electricity is available and less expensive (from 0 to 6 a.m.). As it is not necessary to charge the PCM quickly, the setpoint temperature is fixed at -3 °C during charging. Similarly to the previous scenario, the display cabinets are divided into 2 groups for DR applications: 70 % (G1, blue solid line) and 30 % (G2, red dashed line). For each group, 2 DR periods are applied (G2: 6-8 h and 16-18 h with pink highlights; G1: 8-10 h and 18-20 h with blue highlights).

The use of PV panels coupled with PCM storage allows a reduction of maximal electricity power demand to the grid from 124 kW to 108 kW (-13%). As shown in this scenario, PCM integration and DR applications can be a solution for more flexibility in renewable energy management: excess produced energy can be stored in PCM and released during DR periods.

4. CONCLUSIONS

This work presents original parametric and scenario studies of PCM integration in display cabinets. The aim is to evaluate how this technology can offer more flexibility in retail's energy management, by applying demand response (DR, by turning off cold machines) and the use of renewable energy sources (PV panels). Two design parameters (perforation rate of the rear duct panel and fan power) and two operating parameters (setpoint and ambient temperatures) were investigated in the parametric study. An adequate design of the perforation pattern regarding the PCM heat exchanger and display cabinet configuration is essential to obtain homogeneous product temperature distribution in the display cabinet. A higher fan power (70W, initial power: 25W) generated a stronger air curtain providing better protection of products from external air infiltration. This solution can also balance the reduction of the airflow rate in the rear duct due to the PCM heat exchanger; however, it increased the energy consumption of both fan and compressor due to a more important thermal load. The operating parameters have important impacts on PCM charging and discharging processes. For a display cabinet with 7 kg PCM, the charging time (from 0 to 100 %) can be reduced from 6 hours to 4 hours if the set point temperature is reduced from -3 °C to -5 °C; higher energy consumption is needed for lower setpoint temperature. The ambient temperature has more impact in PCM discharging than in charging periods: an increase of ambient temperature from 16 °C to 26 °C generates 20 % charging time more and 50 % discharging time less. In the second section, three scenarios of PCM integration in the supermarket were simulated. These scenarios have demonstrated many potentials of this technology for the supermarket's energy management. PCM integration can facilitate DR applications (up to 4 DR periods of 2 h per day). Moreover, PCM integration and DR applications can support the use of renewable energy sources as excess energy can be stored in PCM and released during DR periods. The cost associated with the deployment of this technology is mainly due to the integration of PCM heat exchanger inside display cabinets. New designs of display cabinet taking into account various impacts of a new heat exchanger on the thermal and airflow behaviours might be guided by the results of the present study. The investment cost for new display cabinets can be counterbalanced by multiple benefits: financial incentive related to DR applications; reduction of the supermarket's contract power;

reduction of investment and operational costs related to refrigeration system downsizing. While a deeper cost-benefit analysis may be necessary, it is important to note that the economic performance might vary from one country to another as it depends on the local electricity market and economic incentives related to energy management strategies.

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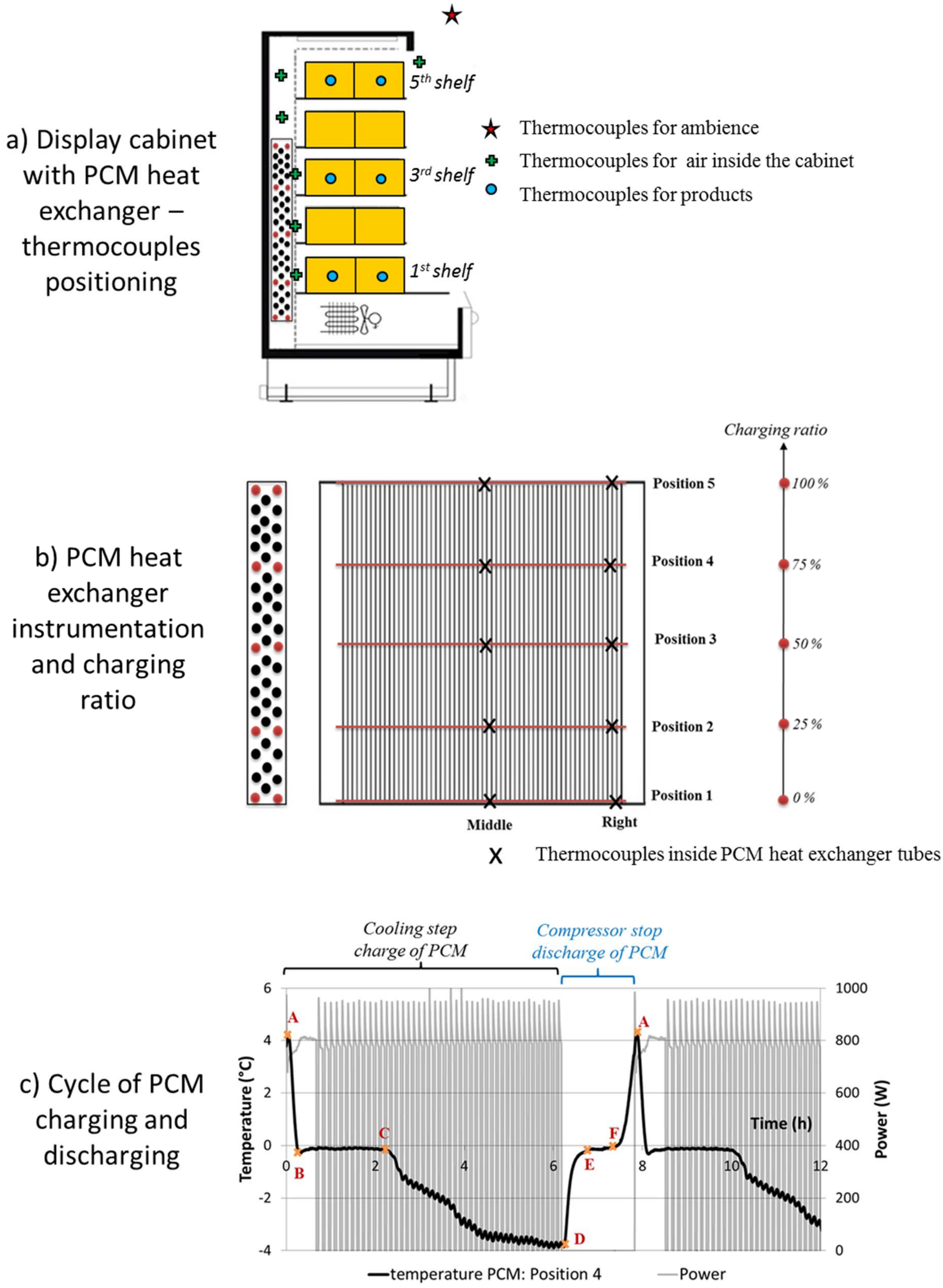

Figure 1: Instrumentation of display cabinet with PCM heat exchanger – charging/discharging cycle

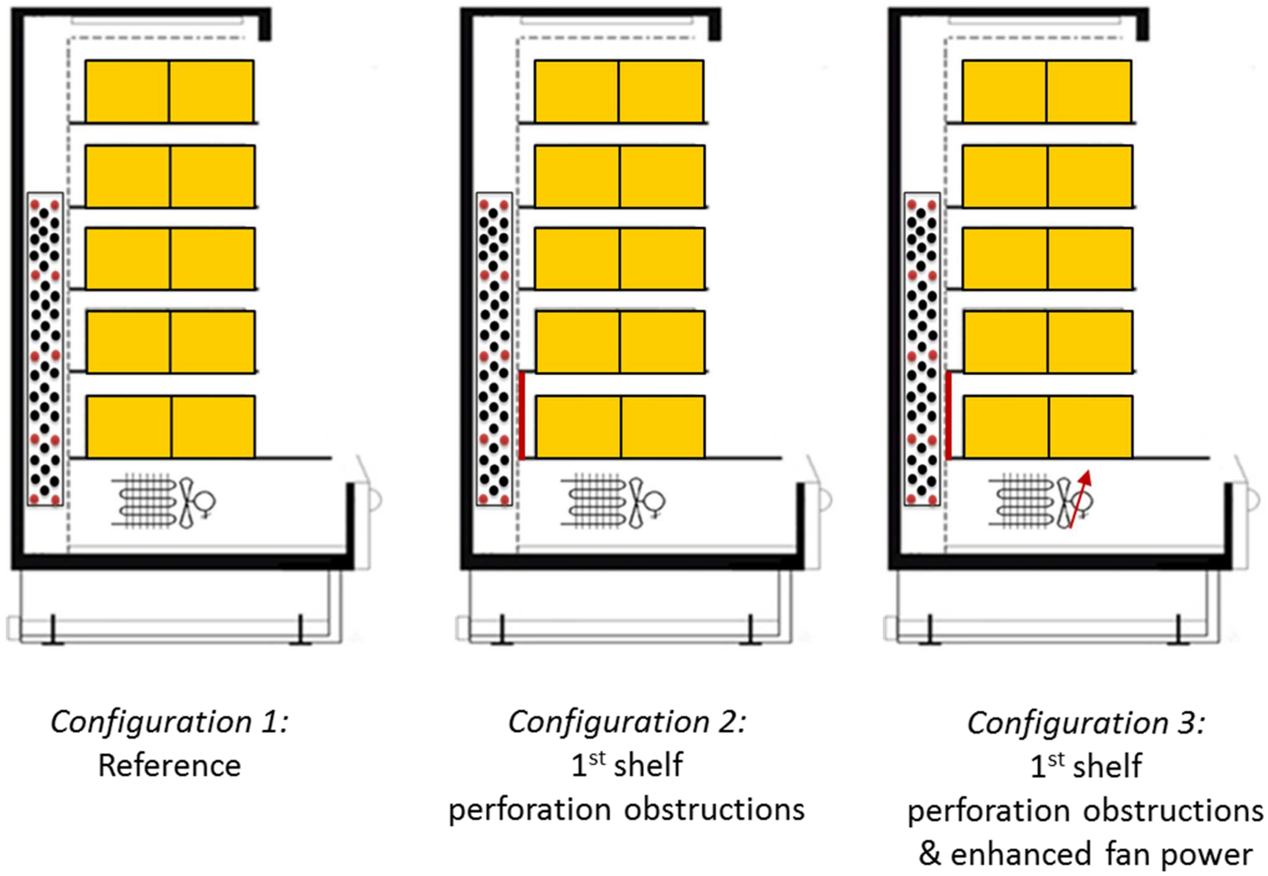

Figure 2: Studied configurations of display cabinet with PCM heat exchanger

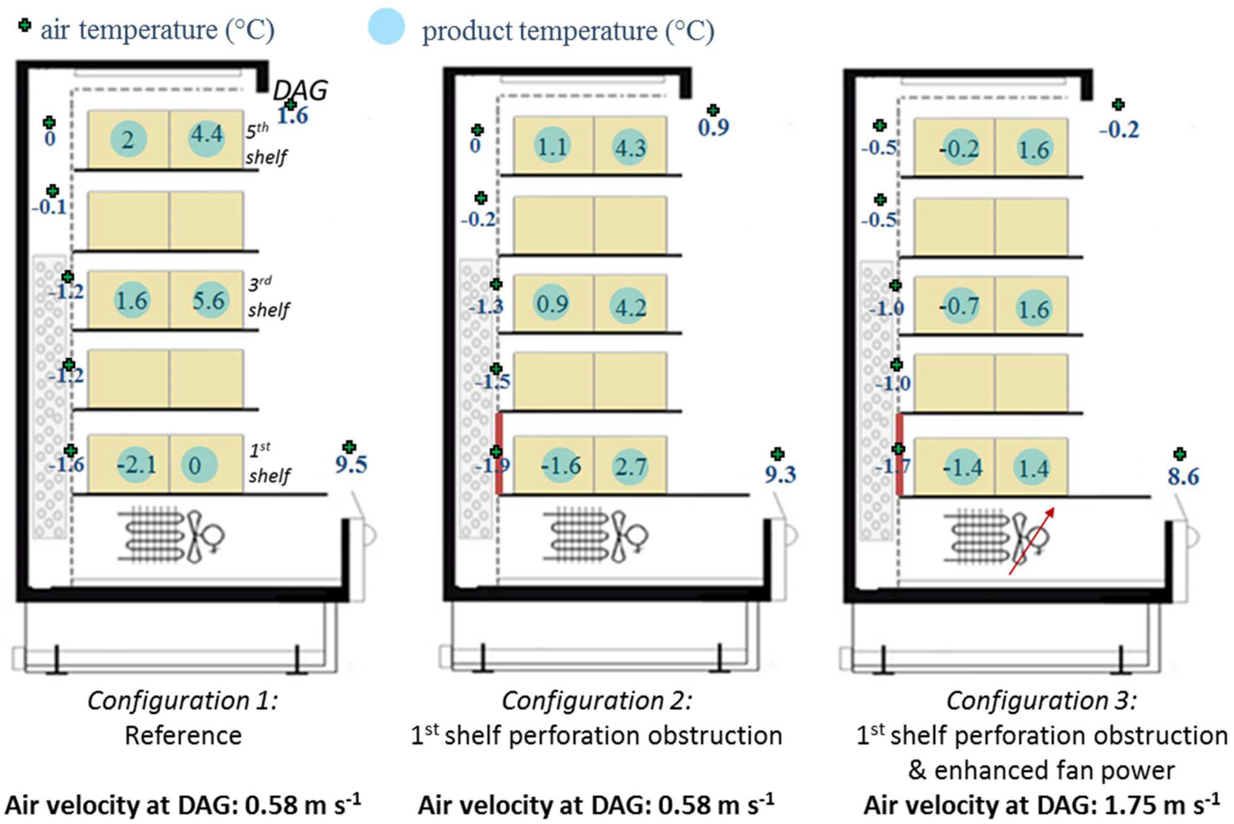

Figure 3: Thermal cartography comparison of three configurations

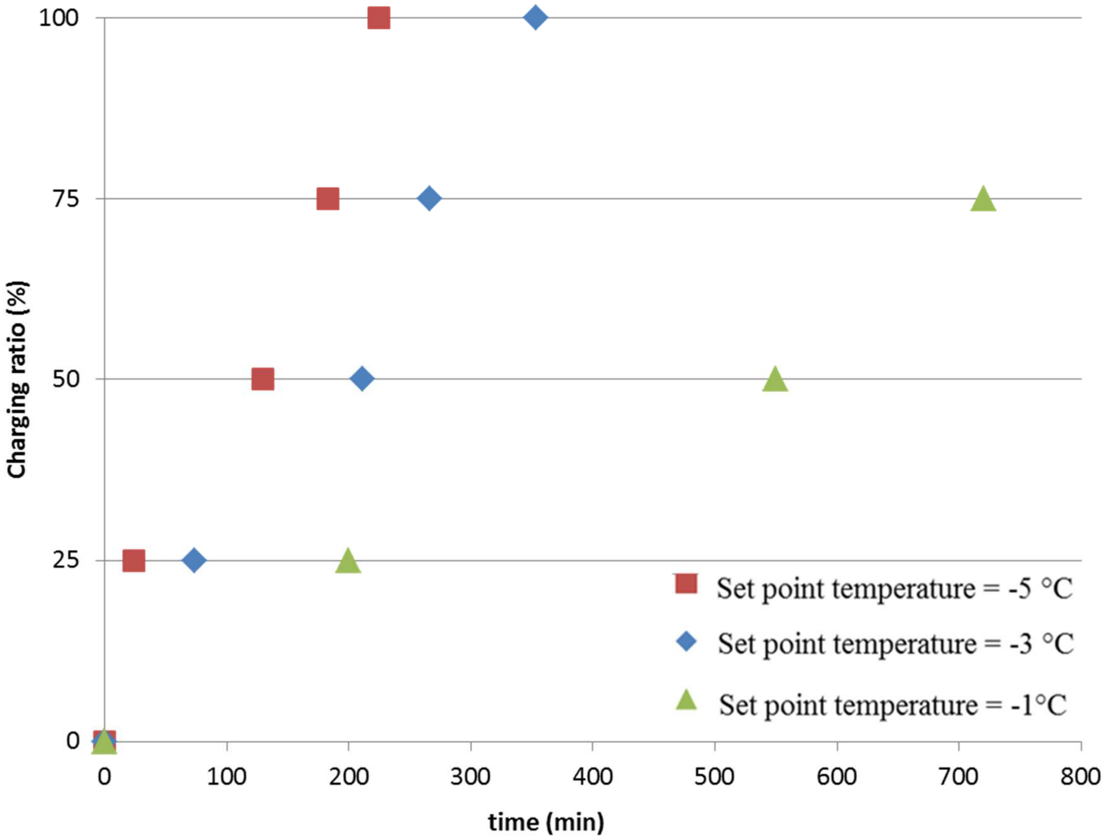

Figure 4: Influence of set point temperature on charging time

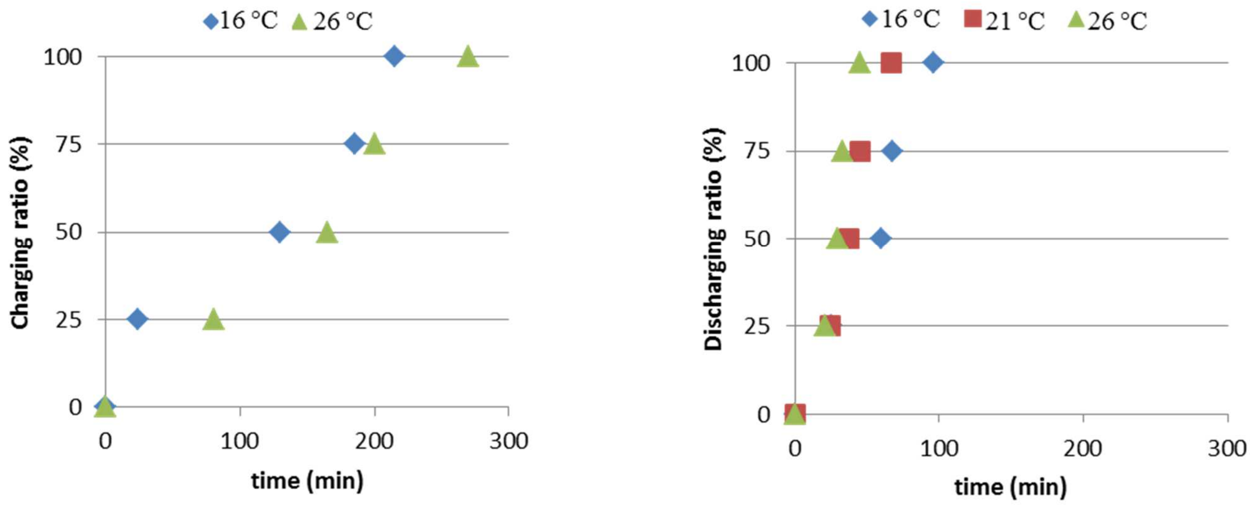

Figure 5: Influence of ambient temperature on charging/discharging time

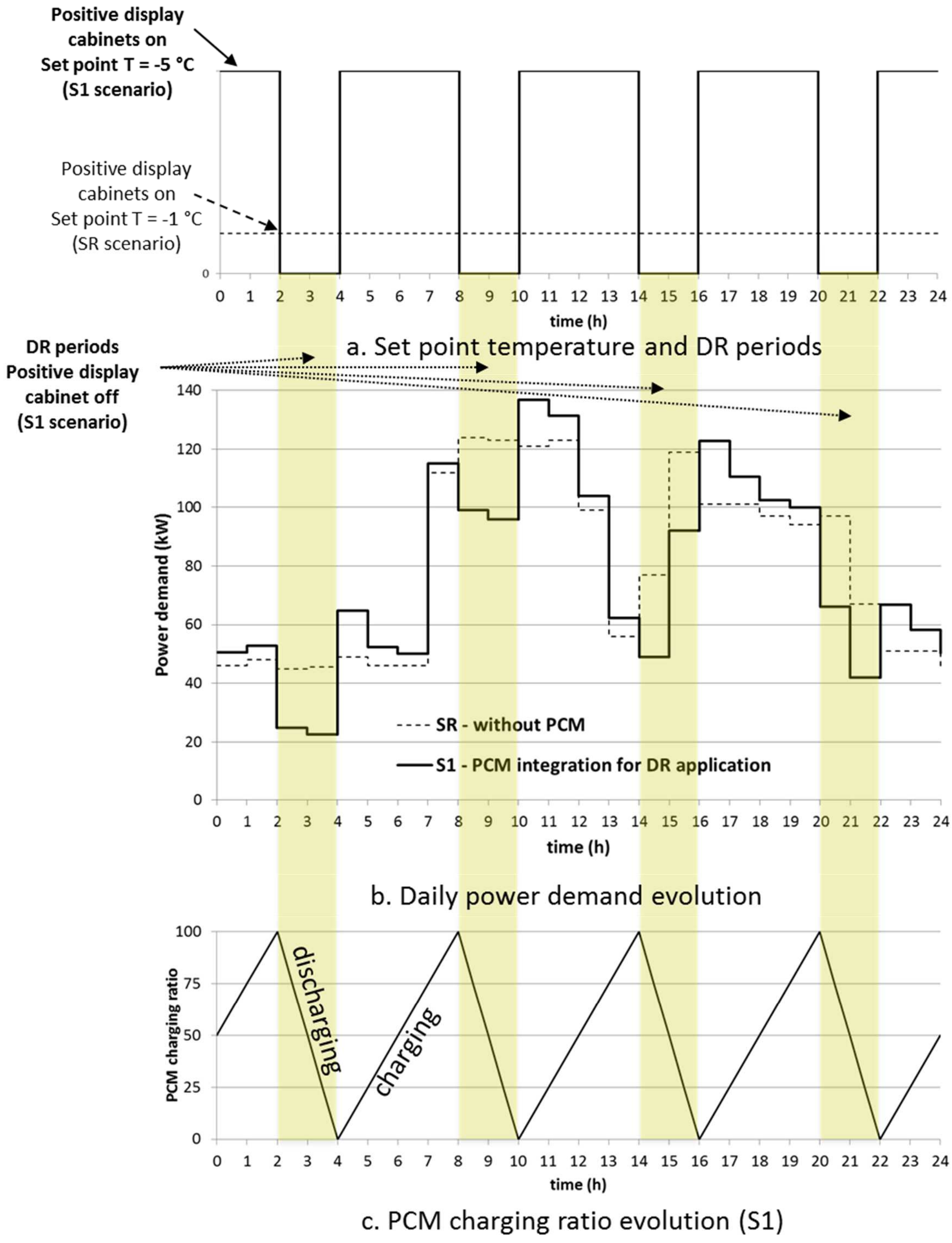

Figure 6: Daily evolution of set point temperature, power demand and charging ratio – comparison between scenarios SR and S1

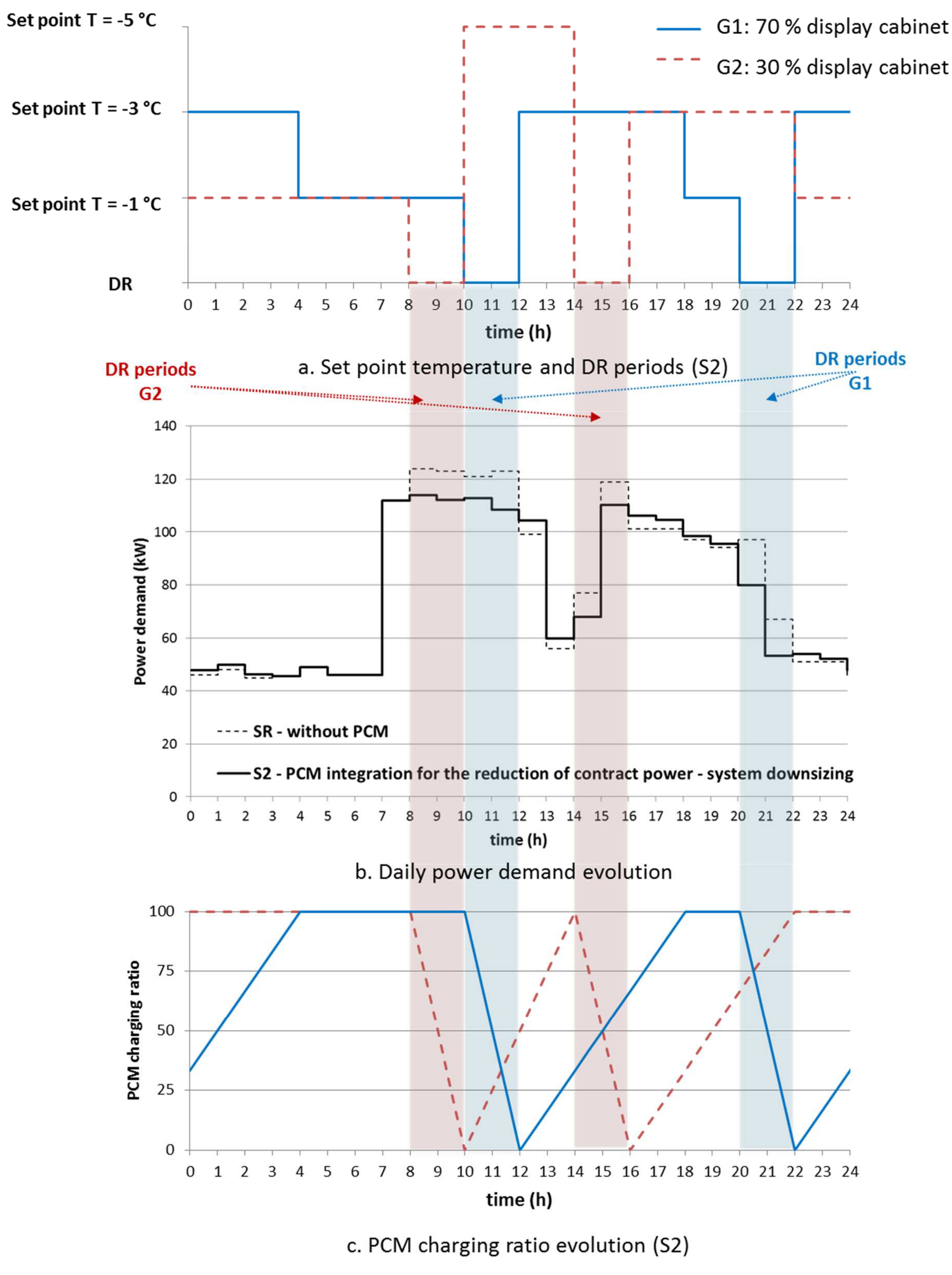

Figure 7: Daily evolution of set point temperature, power demand and charging ratio – comparison between scenarios SR and S2

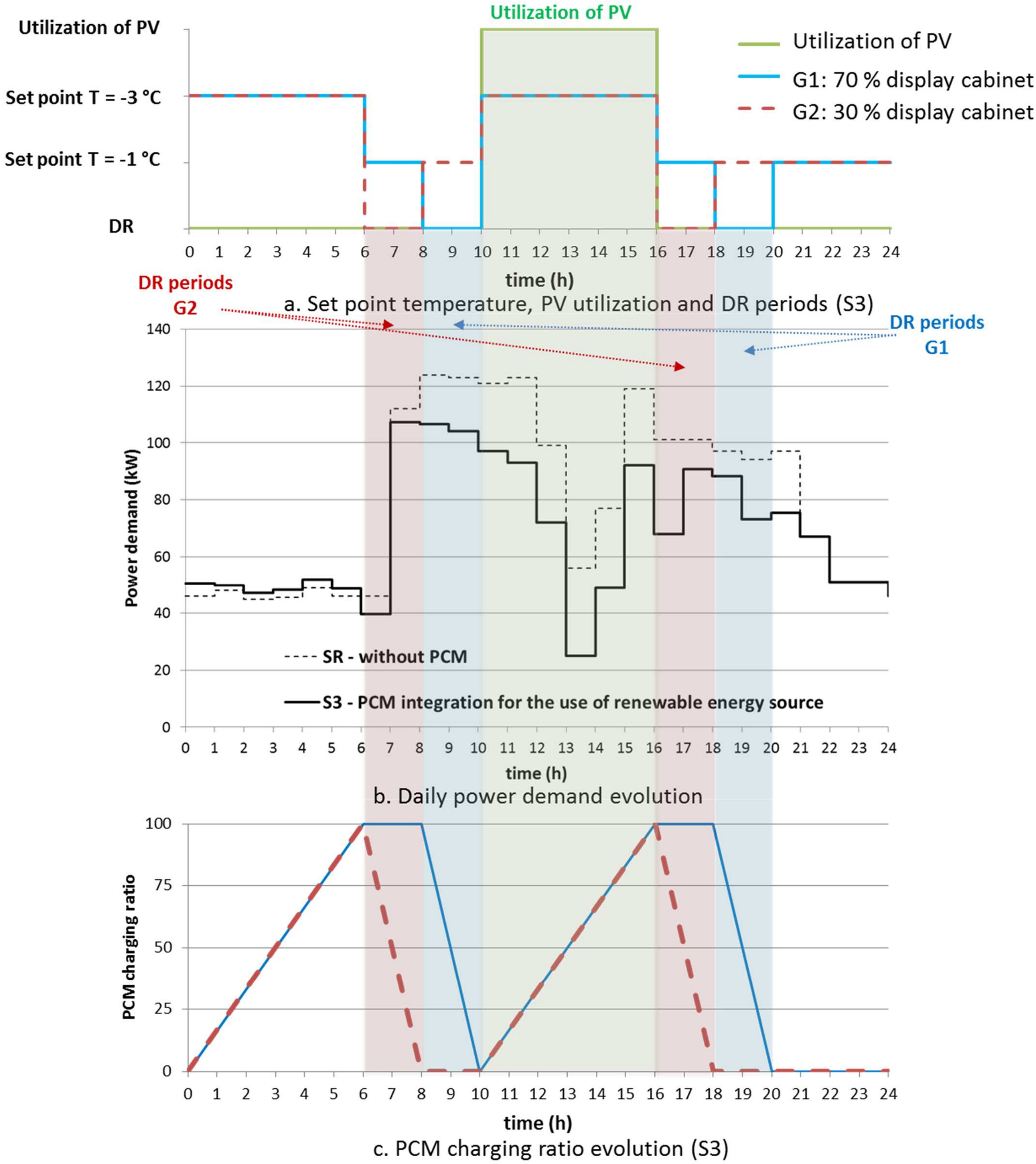

Figure 8: Daily evolution of set point temperature, PV utilization, power demand and charging ratio – comparison between scenarios SR and S3

Table 1: Impact of PCM heat exchanger on thermal and airflow behaviors of the display cabinet from previous study [13]

Parameter / phenomenon	Observations
Product temperature rise during 2 h compressor stop	2°C in display cabinet without PCM 1°C in display cabinet with PCM
Air velocity at the discharge air grid (DAG)	0.80 m s^{-1} in display cabinet without PCM 0.58 m s^{-1} in display cabinet with PCM (same ventilator)
Air curtain flow rate	Reduction of 28 % of air curtain flow rate in display cabinet with PCM
Product temperature	For display cabinet with PCM: higher product temperatures at higher shelves and at the front of the display cabinet, colder product temperature at the lowest shelf

Table 2: Sensors and measurement uncertainty

Sensor/Type	Measurement	Uncertainty (manufacturer data)
Thermocouple/T-type	Air, product and PCM temperature	0.3 °C
Hot-wire anemometer /Testo 435 – 4	Air velocity	0.02 - 0.06 m s^{-1} in the range of 0 - 2 m s^{-1}
Wattmeter/Digiwatt	electrical power demand	2% of measured value

Table 3: Studied parameters

Parameter	Range	Objective of the modification
Perforation rate (1st shelf)	100 % / 20 %	homogenize product temperature inside the cabinet
Fan power	25 W / 75W	enhance air curtain
Set point temperature	-1°C/-3°C/-5°C	modify charging time
Ambient temperature	16°C/21°C/26°C	modify charging/discharging time

Table 4: Ventilation effect on energy consumption and PCM charging/discharging time

Configuration	Air velocity at DAG ($m\ s^{-1}$)	Daily power consumption (kJ)	Charging time (min)	Discharging time (min)
1-reference	0.56	$3.6\ 10^4$	225	96
3- Perforation obstructions and enhanced fan power	1.75	$5.3\ 10^4$	190	53