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Assessing the implementation potential of PCMs: The situation for residential buildings in the Netherlands

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Abstract

To be able to come to zero-energy buildings we need to apply multiple Energy Techniques and Measures (ETMs). Phase Change Materials (PCMs) can be considered as one of these ETMs and they seem to have a lot of potential. Due to their latent heat capacity, PCMs can help to store energy of our main renewable source, the sun, and to shave energy peaks. However, little is known about what barriers exactly exist in implementing ETMs —and PCMs in particular— in residential buildings. By assessing 1) the effects of PCMs on the energy performance of dwellings, 2) their financial effects and 3) the effects of implementing PCMs for stakeholders, the implementation potential of micro-encapsulated paraffin-based PCMs in Dutch residential buildings is determined and barriers are identified. The observation was made that the effects on the actual energy use cannot be easily estimated and that their impact on compelled EPIs is little. It was also observed that only the investment costs of the PCMs can be assessed and that uncertainty exists about how PCMs perform, when actually implemented in a dwelling and used by residents for several years. Although our experiments on PCMs integrated in concrete floors showed positive results, the implementation potential of micro-encapsulated paraffin based PCMs to support or replace heating systems in residential real estate is relatively low. The results could help developers of new ETMs to become aware of what advantages their innovation can offer and what shortcomings still need to be overcome.

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Keywords: Phase Change Materials; Energy Performance; Implementation potential; Barries

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1. Introduction

Many different Energy Techniques and Measures (ETMs) are available that enable principals in new building projects and owners of existing buildings to reduce the fossil energy use of a dwelling and its residents. Through ongoing research, existing ETMs are improved and new ETMs are introduced helping us to realize zero-energy buildings. Experimental research can demonstrate what effects a new ETM can have on the energy use of a building, but for successful implementation further characteristics need to be considered than the thermodynamic effects seen in experimental set-ups. One specific technique, the innovative application of Phase Change Materials (PCMs) in concrete floors, will in this paper be considered. PCMs have the ability to store latent heat at an engineered temperature. As such, they can act as a form of battery that stores thermal energy.

PCMs are not well known in the Dutch construction industry. They have only been applied in a very limited number of buildings. In 2011, interviews were taken by master students attending the Sustainable Building course at the University of Twente. The 31 interviewees were professionals working at construction departments of municipalities, architectural firms, installation companies, contractors and social housing associations. Offered a list of sixteen different energy techniques, PCMs was the least known technique to reduce fossil energy use. Given this situation and using Rogers' definition of an innovation being *an idea, practice, or object that is perceived as new by an individual or other unit of adoption* [1], PCMs can be seen as an innovation in the construction industry. According to the Organisation for Economic Cooperation and Development (OECD), an innovation is *an iterative process initiated by the perception of a new market and/or new service opportunity for a technology-based invention which leads to development, production and marketing tasks striving for the commercial success of the invention* (as cited in [2]). Although many other definitions are available [3], this extended definition of the OECD has the advantage that it addresses tasks and includes the element of commercial success. In this paper these tasks and striving for commercial success will play an important role, when considering the possibilities to implement PCMs in residential buildings.

Compared to many other innovative energy techniques, an advantage of PCMs is the possibility of using them in building elements as well as in installed systems. Therefore, a range of stakeholders could suggest their implementation and benefit from it, provided they are familiar with the technique and its benefits. Furthermore, PCMs can influence both natural gas use as well as electric energy use. When PCMs are used as part of the heating concept, they can reduce natural gas use. When PCMs are used as part of a cooling concept, they are likely to reduce electric energy use. In our aim to improve the implementation potential of PCMs for residential buildings, the following research question is addressed in this paper: how can PCMs align with the interests of stakeholders from an energy perspective, from a financial perspective and from the perspective of a building project? The stakeholders that will be taken into account are the government, principals, architects, advisors and residents[1].

Section 2 elaborates on a literature study on PCMs. Section 3 and 4 reflect on how PCMs effect the energy use of buildings and what their financial effects are, respectively. The effects of physically implementing PCMs in new and existing dwellings for stakeholders will be considered in Section 5. Furthermore, the relationships between stakeholders will be assessed, before we provide our conclusions and recommendations in Section 6.

2. Theoretical background on PCMs

2.1. General specifications of PCMs

PCMs have the ability to take in and to release thermal energy at a specific temperature when their state (solid, liquid, or gas) changes to another state under a steady pressure [4]. The thermal energy required or released by a material to make this transition from one state to another is called latent heat. Besides this latent heat, PCMs also store sensible heat in a similar way to all the other materials found in dwellings. The latent heat capacity of a material is generally much larger than the sensible heat capacity. Given that any material can exist in three different states at the right combinations of temperature and pressure, all materials can absorb and release latent energy and so could be

[1] An essential part of this paper has been published in the PhD-thesis of the first author [29]

regarded as a PCM. However, in general, the term PCM is reserved for those materials that have been designed or engineered to change state at a specific temperature under standard atmospheric pressure.

Three main groups of PCMs can be distinguished [5, 6]. The first group consists of organic PCMs, encompassing alkanes, waxes and paraffins. The second group are the inorganic PCMs consisting of hydrated salts. The final group are the so-called eutectics, which are mixtures of organic or inorganic chemical compounds or elements that have a single chemical composition. A eutectic system solidifies at a lower temperature than any other composition of the same ingredients [7]. Salts, hydrated or as part of a eutectic system, can offer a high latent heat capacity or melting enthalpy, but only at temperatures well above those required in dwellings. Further, the stability of their performance is debatable because, after some cycles of melting and solidification, the need for nucleating agents can become imperative [6], reducing the ability of the PCM to store latent heat. Paraffins melt at more appropriate temperatures, but have relatively low latent heat capacities compared to other PCMs. Furthermore, paraffins are flammable, although this risk can be reduced by proper encapsulation. For a specific purpose, the thermodynamic, kinetic, chemical and economic features of PCMs need to be considered in choosing or developing the right product [8]. In practice, melting occurs in a small temperature range where the transition from liquid to solid, or vice versa, takes place.

2.2. PCMs in buildings

In buildings, energy is used in many ways. In the Netherlands, thermal energy is needed to come to a comfortable indoor climate. Natural gas is often used to provide this thermal energy during the heating season. On the other hand, indoor temperatures can also rise beyond comfortable levels, especially during summer, and then a cooling system may be used to reduce the indoor temperature. In this case, electric energy is often used. Many variables play a role in what the users of a building perceive to be a comfortable temperature. As [9] noted, most people have an increasing tolerance of higher indoor temperatures as ambient temperatures exceed approximately 10 to 12 °C. Below these temperatures, the acceptable band is ≈2.5 °C and in a hot summer period this increases to ≈4.3 °C. During a winter's day with an ambient temperature of 3 °C, the indoor temperature preferably needs to be between 20.5 and 23 °C. With an ambient temperature of 9 °C in spring or autumn, the indoor temperature needs to be between 21.2 and 23.7 °C. However, when the average ambient temperature on a summer's day reaches 22 °C, the preferred indoor temperature can be between 22.7 and 27.0 °C. PCMs can potentially help to keep the indoor building temperatures in the ranges that are regarded as comfortable by most building users.

Many PCMs are available that have melting temperatures close to these favoured indoor temperatures [5, 10]. At the ambient temperature falls below these melting temperatures, the latent heat in the PCMs will be emitted to the surroundings. When the ambient temperature rises, the thermal energy necessary for liquefaction will be taken from the surroundings. The PCMs will thus act as a battery storing thermal energy. This makes it possible to increase the thermal capacity of buildings and to reduce extreme temperatures. Pasupathy et al. [6] distinguish three ways to use PCMs in buildings:

1. In walls, e.g. [11-13];
2. In other building components, e.g. [14, 15] and;
3. In separate heat or cold storages, e.g. [16-19].

These three ways of using PCMs cover two basic concepts. The PCMs can be applied *passively* in the construction, where they become a building characteristic, or they can be applied *actively* as part of the HVAC systems to heat or cool the building, when they become a system characteristic. This study focuses on the passive use of PCMs in concrete floors. Many scholars have conducted research on the use of PCMs in the building material concrete. Zhang et al. [20] noted that the "*combination of buildings materials and PCM is an effective way to enlarge the thermal energy storage capacity of building components for the purpose of direct thermal energy storage in buildings*". Furthermore they stated that *"porous building materials have advantages of low cost, ease of fabrication and widespread application in building industries*" (ibid, p. 654). Concrete is a commonly used material in buildings. The heat capacity and high density of concrete combined with the characteristic feature of PCMs of storing latent heat can result in new concrete mixes in which high temperatures can be avoided during hydration improving the compressive strength and durability. Further, this can result in new or better construction elements that, for example, could store thermal energy provided by solar irradiation [21]. Concrete incorporating PCMs can be used to store thermal energy, thus lowering the energy use of buildings and increasing thermal comfort [22-24].

Bentz and Turpin [23] specified potential applications of PCMs in concrete by analysing the calorimetry of PCMs embedded in porous lightweight aggregates. They addressed the need for further research and field testing. Hunger et al. [21] showed that micro-encapsulated PCMs can be applied in self-compacting concrete mixes reducing the peak temperatures during hydration. Cabeza et al. [12] offered valuable field data when using micro-encapsulated PCMs in concrete walls. Li et al. [25] used micro-encapsulated PCMs in composite floor elements made out of high density polyethylene and wood. However, the research at the University of Twente on the passive use of PCMs in concrete floors for heating purposes seems to have been the first in this area.

2.3. PCMs in concrete floors

There are several reasons to study the implementation of PCMs in concrete floors for heating purposes. First of all, as already noted, PCMs are not well-known in the Dutch construction industry. Secondly, stakeholders that opt to implement ETMs want them to be reliable and easily maintained. They also need to fit easily in current construction practices. Concrete floors containing PCMs do not need maintenance and are a passive part of the construction of a building. As such, this idea would seem to fit well with these stakeholder demands. Finally, solar irradiation provides possibilities to reduce the use of fossil fuels in buildings, even in the Netherlands, and so this development of a new energy technique that makes use of solar irradiation seems attractive.

Conceptually, in moderate climates, concrete floors incorporating PCMs could be used to store thermal energy provided by solar irradiation that directly enters dwellings through the windows during the day. This stored energy could then be released in the evening to reduce the energy demand for thermal comfort during the relatively cold night. An experimental set-up was developed together with colleagues from the Department of Construction Management and Engineering at the University of Twente to test the viability of using PCMs in concrete floors for this space heating purpose. In order to determine how much the energy use can be reduced by applying PCMs in concrete floors, experiments were conducted in the Dutch climate. For practical considerations, an experiment was developed that used boxes rather than real houses to test the effects that PCMs in concrete floors had on indoor temperatures. This experimental set-up (see Fig. 1), consisted of four insulated boxes with concrete floors, two with and two without PCMs. The effects of the PCMs on the indoor temperature were studied by monitoring weather conditions and indoor temperatures at different locations in the boxes. The results were disseminated by Hunger et al. [21] and by Entrop et al. [26].

In this experiment, Micronal DS 5008 X micro-encapsulated PCMs produced by BASF were used. According to the manufacturer's product specifications, the latent heat capacity is 110 J/g and the transition temperature is 23 °C [27]. However, product information that was released three years later, speaks of a latent heat capacity of 100 J/g [28]. Research by Hunger et al. [21] showed that the melting and solidification of the paraffin mix within the polymethyl methacrylate capsules occurs over a small temperature range. By using differential scanning calorimetry, they measured an exothermic enthalpy for solidification of 102.8 J/g with an onset temperature of 22.12 °C, and an endothermic enthalpy for melting of 99.7 J/g with an onset temperature of 25.20 °C. Although Micronal is offered for use as a support for or a replacement of cooling systems, there were no PCMs with lower melting temperatures available on the Dutch market at that time. Based on the melting temperature and considering different weather conditions, three situations can be distinguished regarding the thermal battery that PCMs form:

4. at low levels of irradiance and low ambient temperatures, the PCMs in the concrete have a temperature below 22.1 °C and are, therefore, not thermally charged;
5. with significant irradiance and ambient temperatures above 25.2 °C during the day, and falling below 22.1°C overnight, most or even all the PCMs are thermally charged during daytime and discharged during the night;

6. with high levels of irradiance and high ambient temperatures continuously above 22.1 °C, all the PCMs remain thermally charged throughout day and night.

Fig. 1. Four insulated boxes containing concrete floors, with and without PCMs, as part of our experimental set-up at the University of Twente [29].

Although the Netherlands are not known for their high temperatures or high levels of solar irradiance, the data collected in June 2010 showed that the PCMs in combination with an advanced glazing system helped to increase minimum temperatures by 7±3% in the boxes with light weight thin insulation. Furthermore, it helped to decrease maximum temperatures by 11±2% in the boxes with light weight thin insulation and 16±2% in boxes with heavy weight thick insulation. Analysing the experiments raised considerations which one should be aware of when applying PCMs in dwellings:

7. the sensible heat capacity of conventional building materials used in floors, walls and roofs of actual dwellings will be relatively large compared to the latent heat capacity of the amount of PCMs that can be applied in concrete floors without reducing their compressive strength significantly. In the experiments, 5% of the floor mass was made up of PCMs;
8. the ratio of the internal volume to the floor surface that is illuminated and heated by solar irradiation would be significantly larger in an actual house than in the experimental boxes;
9. the melting and solidification temperatures of the PCMs used are above the ideal for a heating technique that aims to reduce fossil fuel use by increasing the minimum indoor temperature through solar energy.

Although the latent heat capacity and the melting temperature of the used Micronal leave room for further improvement, investments can only be justified if there is a realistic chance that this energy technique will be implemented by actors in building projects. Encouraged by the positive results found in literature and demonstrated in these experiments, a further study on the possibilities for implementing micro-encapsulated PCMs in concrete floors is presented.

3. Assessing the effects of PCMs on the energy performance of dwellings

3.1. Characteristics of dwellings influencing the performance of PCMs

When PCMs are included in a dwelling, their impact on the energy use of the dwelling and its residents depends not only on the specifications of the PCM itself, but also on the environment. Fig. 2 illustrates how the solar irradiation enters a dwelling through the glazing to supply the floor containing PCMs with thermal energy. The dwelling, located in an external environment, provides an internal environment that needs to offer appropriate conditions if the PCMs are to be used effectively and efficiently. The overall effect of the PCMs on the fossil energy use of a dwelling and its residents will depend on the context in which they are applied. Five categories of characteristics can be distinguished when considering energy use in dwellings [29]: environmental characteristics, occupational characteristics, building characteristics, system characteristics and the appliances in the dwelling. PCMs can either be part of a construction or of an installed HVAC system. Considering the passive use of PCMs in concrete floors, Table 1 shows all the effects using the framework of characteristics.

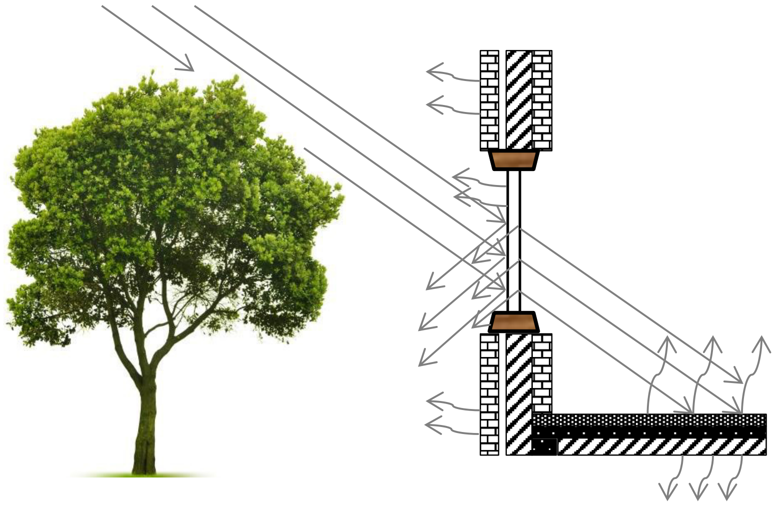

Fig. 2. Cross-section showing how solar energy can enter and indirectly leaves a dwelling [29].

Table 1. Characteristics that directly and indirectly influence the performance of PCMs in concrete floors in dwellings [29].

	Characteristics	Explanations
Environment	Solar irradiance	The available solar irradiance directly influences the indoor temperature of dwellings and, after passing through the glazing and warming the floor, the charging process of PCMs embedded in the concrete floor.
	Air temperature	The outdoor air temperature directly influences the temperature in the ventilated crawl space below the ground floor, and indirectly the indoor temperature of dwellings.
	Ground temperature	Depending on the type of floor and construction, the ground temperature can directly influence the floor temperature through conduction or indirectly by convection in the crawl space.
	Surrounding buildings	Other buildings near a dwelling can block solar irradiance at certain times and can therefore indirectly influence the performance of PCMs.
	Surrounding vegetation	Vegetation near a dwelling can block solar irradiance at certain times and can therefore indirectly influence the performance of PCMs.
Occupation	Residents' patterns of living	The presence of residents will result in a need for heating during the heating season (and maybe cooling during high summer). The particular use of the thermostat will influence what energy is stored in PCMs and whether this thermal energy is provided by solar irradiance or through the heating system by fossil fuels.
	Preferred internal climate	If residents prefer an indoor temperature above the transition temperature of the PCMs, the possibility exists that the PCMs will not discharge or be charged by solar irradiance. This means that the transition temperature of the PCMs needs to match the residents' preferences if they are to work effectively.
	Age of residents	In general, elderly residents prefer higher room temperatures than young people. Elderly people are usually more often at home, which means that the heating system will be on more often and solar irradiance will have little chance to charge PCMs in the floors. Thus, the age of the residents can indirectly influence the performance of the PCMs.
	Number of residents	The number of residents will indirectly influence the performance of PCMs. It can be anticipated that more residents will result in more furniture and belongings covering the floor. Also, having more occupants increases the likelihood of interference with indoor temperature controls.
Architecture	Floor surface	The more PCM that is in the concrete floor in range of solar irradiance entering the dwelling, the more free thermal energy that can be stored. Therefore, the floor area is of direct influence.
	Transmission surface	The transmission surface or thermal shell of a dwelling influences how much solar irradiance can enter and reach the floor. It also effects how quickly thermal energy can leave the dwelling. Therefore, the transmission surface has both direct and indirect influences.

	Internal space allocation	Internal walls obstruct solar irradiance. Floors on the north side of a Dutch dwelling see little sunlight. Further, not all rooms are heated (e.g. bedrooms). Therefore, internal space allocation has both direct and indirect influences.
Systems	Heating concept	Floors incorporating PCMs can be installed in a wide range of dwellings with heating systems that make use of solar collectors, heat pumps, natural gas combination boilers, radiators, wall heating and floor heating. The amount of fossil fuels saved will depend on the particular role of the PCMs in the total heating system.
Appliances	Presence of shades	Shades and awnings can prevent the PCMs from charging. However, if a room temperature significantly increases above the transition temperature of the PCMs, then shades or awnings can be (automatically) lowered to prevent overheating and the necessity of a cooling or air conditioning system.

All the categories of characteristics can have some influence on PCM use. This shows that many variables play a role when explaining how the performance of PCMs is affected by the context. Architects and advisors on building conditions could use the listed characteristics to stepwise explain to the principal, and maybe future owners and residents, which elements need to be taken into account if one wants to effectively and efficiently use PCMs in concrete floors.

If PCMs are implemented in a dwelling that is then used by its residents in a certain way, the PCMs become a part of a complex system where many different variables influence each other and the final energy performance of the whole. The overall effect of PCMs on the energy use of a dwelling and its residents can therefore probably only be accurately assessed through a real-life experiment where the energy use of several similar houses with and without concrete floors containing PCMs, with comparable residents and appliances and similar use, are carefully monitored over comparable weather conditions across all seasons. Such experiments are very difficult to organize. Therefore, when expressing views on the effects of PCMs in concrete floors, one needs to make clear what circumstances are assumed.

3.2. Including PCMs in energy assessment methods

It was explained in the previous section how many variables can play a role in determining how well PCMs function in dwellings. This section explains how PCMs can be included in the Dutch energy assessment methods. Like in many other countries, it is also in the Netherlands necessary for buildings to comply with a certain minimum energy performance. The use of PCMs in dwellings for cooling or heating, either passively in building materials or actively in installed systems cannot directly be taken into account in any of the three assessment and calculation methods available to come to Energy Performance Indicators (EPIs). Consequently, PCMs can only indirectly contribute to achieving a target EPI.

The effect of PCMs can theoretically be taken into account in certain forms of active use. The term active here refers to their incorporation in installed systems. If PCMs are for example integrated in a boiler system for space and/or tap water heating, or integrated in a heat exchanger of a ventilation system, they can contribute to the efficiency of that component of the system. If an official certificate, as provided by KOMO or Gastec, specifies the efficiency of a heat exchanger or boiler system incorporating PCMs, then the effects of the PCMs will indirectly be incorporated in calculating an EPI.

As with any passive use of PCMs, the use of PCMs in concrete floors for heating purposes cannot be taken into account in the assessment methods available for calculating EPIs. In calculating the Energy Performance Coefficient (EPC), a Dutch EPI for buildings that are newly built, the sensible heat capacity of a building is taken into account in determining the energy required for cooling to come to a comfortable indoor temperature during summer. This is the amount of energy needed to keep the indoor temperature below a maximum of 24 ^{0}C. The 'weight' of the construction is assessed by distinguishing three options [30]:

1. Traditional heavyweight dwellings with massive walls and floors. Such dwellings are assumed to have an average heat capacity of 450 kJ/m^{2}K related to the heated floor surface;
2. Lightweight dwellings with lightweight walls and construction design, but heavyweight floors. Such dwelling have an assumed average heat capacity of approximately 350 kJ/m^{2}K related to the heated floor surface;

3. Lightweight dwellings with a timber frame construction and lightweight floors. Here, the dwelling is assumed to have an average heat capacity of approximately 80 kJ/m^2K related to the heated floor surface.

The best, i.e. lowest, EPC is calculated if the first option is chosen. When the third option is chosen, this gives the highest EPC, with a value that is approximately 0.05 higher than the first. Although PCMs mainly offer a latent heat capacity, the negative thermal effects one can experience in lightweight constructions due to the low sensible heat capacities can be reduced or even be overcome by using PCMs. Based on an equivalence idea, a lightweight construction where PCMs were properly implemented, could be assessed as a traditional heavyweight one. However, in most cases, where a principal opts for a traditional dwelling constructed out of heavy materials, the implementation of PCMs will not result in a better EPI. In these cases, PCMs will have little added value for the principal in terms of complying with the Building Code. In such circumstances, a principal will first have to ensure that the design meets EPC requirements before considering any other ETMs, such as PCMs, if there is any budget left.

An inventor or organization aiming to get PCMs implemented in the construction industry is advised to ensure that the technique will be assessed in the prevalent energy assessment method employed in the specific country, when the efficiency and effectiveness of the ETM is clear and indisputable. The costs of experiments to scientifically determine the effects of a new ETM can act as a major bottleneck, especially for start-ups.

3.3. Reducing fossil energy use in dwellings

Residents generally want to increase their comfort and reduce their costs through a decrease in natural gas (m^3) and electric energy (kWh) use. When a principal wants to get a building permit for a new dwelling, the plans need to demonstrate compliance with the EPC requirements. One of the reasons why the Dutch national government aspires to lower energy use is to reduce greenhouse gas emissions. When attempting to introduce an energy technique based on PCMs, it is therefore necessary to explain or model how much the energy use and the use of fossil fuels can be reduced.

Unfortunately, the effects of incorporating PCMs in concrete floors are hard to model and to estimate. Shrestha et al. [31] have implemented an insulation system incorporating PCMs in Energy+, an energy simulation computer program available in the USA. Müthing [32] developed a model in COMSOL, a software package for multiphysics finite element analysis, and Prins [33] in VENSIM, a software package for dynamic simulations. Both of these latter two models were able to simulate the effects of PCMs in concrete floors on the indoor temperature of the boxes used in the experiments conducted at the University of Twente.

PCM Express is a software package developed at the request of BASF, the manufacturer of several PCMs that can be used in buildings. *PCM Express is a planning and simulation program for buildings PCMs. "It aims to support architects and planners in planning by facilitating reliable decision-making in dimensioning the system and by speeding up the market launch of PCMs"* [34]. Although the possibilities of incorporating a specific building design and accompanying HVAC systems in this software are limited, it can indicate how indoor temperatures will be influenced by the use of PCMs in different construction components. However, the program focuses only on the passive use of PCMs for cooling, not for heating.

The models of Müthing [32] and Prins [33], which reflect the experiment with the four boxes, excluded the use of heating systems, cooling systems, shading, internal heat loads, metabolism of occupants and any occupant interference. Despite this, the complex behaviour of the PCMs was already hard to model properly. PCMs provide a latent heat capacity that increases and decreases within a small temperature range, and that is different for the exothermic and the endothermic cycles. This behaviour is not compatible with the static values used to express the sensible heat capacity and thermal resistance of traditional materials used in dwellings. To make the situation even more complex, the ability of PCMs to store latent heat can reduce significantly as the number of usage cycles increases. The technical lifespans of PCMs have been categorised, and range from 50 cycles up to 10,000 cycles or more. In the Dutch climate, if PCMs are used from the first category and only last around 50 cycles, then the technical lifetime will only be around one year, if the transition temperature is roughly 21 to 23 ^0C. Further, at this moment the commonly used Dutch software (e.g. Bink and VABI) that has been developed to simulate the indoor climate in buildings does not offer the possibility to incorporate PCMs. If one wants to achieve wide scale implementation of PCMs in the

Netherlands, it will be necessary for their effects to be modelled not only in the software underlying the EPIs but also in software that can simulate the thermal behaviour of buildings.

In order to gain an impression of the effects of PCMs on the energy use of dwellings, one has to remember that the PCMs considered can store and release approximately 0.1 MJ/kg of latent heat. To place this value in perspective, 1 kWh of electric energy equals 3.6 MJ, and 1 m^3 of natural gas has a calorific lower heating value of 31.65 MJ, and a higher heating value of 35.17 MJ. This makes the latent heat capacity of the PCMs relatively low. In that it seems that 36 kg of Micronal is needed to 'store' 1 kWh of electric energy, or over 300 kg to 'store' the equivalent of 1 m^3 of natural gas. However, it should be emphasized that PCMs do not store electric energy or natural gas, but can only store thermal energy at a certain temperature. In the case of Micronal DS 5008 X, as used in the experiments at the University of Twente, the melting temperature is around 23 ^{0}C. When electric energy or natural gas is used to heat a living space, the transport of the energy and its conversion from fossil fuel, via electric energy in case of electric heating, to heat should be taken into account. Given the efficiencies of distribution and energy conversion, namely 39% when producing and transporting electric energy and 91% for the distribution of natural gas and 96% for the conversion of natural gas to heat, an additional 156.4% and 14.5% of primary energy can respectively be saved on top of the reductions in energy use as recorded by the energy meters in a dwelling.

Since 2012, the carbon dioxide emission resulting from electric energy use is set at 0.1569 kg CO_2/MJ (assuming $\eta_e = 39\%$) and from natural gas use it is 0.0506 kg CO_2/MJ (with $\eta_{ng} = 100\%$) [35]. Depending on the number of cycles that PCMs are charged and discharged, fossil energy can potentially be saved and carbon dioxide emissions reduced. For every cycle, one can save 0.016 kg CO_2 or 0.006 kg CO_2 per kg of Micronal respectively depending on whether electric energy or natural gas is being replaced. That is, from a CO_2 emission standpoint. It seems better to reduce electric energy use than natural gas use in a dwelling.

To finalize this section, it can be summarized that little insight exists into what extent the implementation of PCMs in concrete floors for heating purposes would reduce fossil energy use in a Dutch dwelling. However, it was possible to qualitatively outline which characteristics would be influenced. Furthermore, it can be stated that PCMs with a larger latent heat capacity would be advantageous and that, for heating purposes, a lower transition temperature than 23 ^{0}C would be beneficial. It is also necessary that simulation software becomes available in which different quantities of PCMs with various transition temperatures can be modelled. If such software was available, one could assess whether it is better to target a heating function and so reduce natural gas use or to target cooling and a reduction in electric energy use.

4. Assessing the financial effects of implementing PCMs

4.1. Investment costs of PCMs

The investment costs of PCMs can be expressed by a simple equation that takes into account the costs of implementing PCMs in the design of a dwelling and the costs of physically implementing the PCMs, including both product and installation costs, in a dwelling during the construction phase. The costs of incorporating PCMs in the design of a building can be related to the number of hours that architects and advisors will spend on providing the principal with information on the possible effects of the PCMs and on optimizing the location and quantity of PCMs in the dwelling that is being designed. Given that Dutch advisors do not have the appropriate software to simulate the effects of PCMs for heating purposes and architects do not have experience with PCMs for heating purposes, the first principals that consider applying PCMs for heating are likely to be confronted with relatively high investment costs for implementing PCMs in the design, if they want to know exactly what the effects on thermal comfort and energy use will be in advance. In this study, it is assumed that the initial applications of PCMs for heating purposes will receive direct support from the manufacturer of the product. Therefore, the investment costs associated with their implementation in the design are not taken into account.

The next component of the investment costs is the product costs. According to Mehling and Cabeza ([36], p. 43), product costs of commercial PCMs are in the range of € 0.50 to € 10 per kg. PCMs based on salt hydrates are relatively cheap, namely € 1 to € 3 per kg (ibid, p. 18). PCMs based on paraffins are generally more expensive. The Micronal that was used in the concrete floors of the experimental boxes had to be ordered from Germany at a price of € 8 per kg (including VAT, 2007 price). Although the prices of chemical products in a competitive market generally decrease over time, one has to recognize that the prices of many raw materials have been increasing in recent years. Therefore, in assessing the financial performance of PCMs the abovementioned product costs of € 8 per kg will be used.

Given the passive application of micro-encapsulated PCMs in concrete floors, it is possible to make them part of the concrete mix and, therefore, the installation costs should be low. The micro-encapsulated PCMs will replace or reduce the volume of one of the standard components of a standard concrete mix. A downside of this approach is that some of the capsules will inevitably break during the mixing process, which needs to be factored in when addressing the reliability of this energy technique. The investment costs for installing the PCMs for the application in this study are set at zero.

4.2. Financial benefits of PCMs

Given the relationships between several characteristics that influence the energy performance of a dwelling and the effects that PCMs can have on the energy use for space heating, the financial benefits of PCMs are explicitly interpreted as independent of a particular dwelling and household. By taking into account the price per kilogram, one can calculate how much the energy use in terms of kWh of electric energy or m^3 of natural gas needs to be reduced in order to cover the investment costs.

The 2013 Essent price for natural gas is € 0.6538 per m^3 and for electric energy € 0.2229 per kWh. On this basis and ignoring the impact of interest rates, a kilogram of Micronal needs to see a reduction of 12.2 m^3 of natural gas or 35.9 kWh of electric energy use within its technical lifespan. Given that 1 kg of PCM can store 0.1 MJ, and that the energy efficiency of a heating boiler is around 96% and the average calorific value of natural gas is 33.41 MJ/m^3, the PCMs will need to be fully charged and effectively discharged 3,913 times before breakeven. In the similar electric energy calculation, the PCMs need to complete 1,292 cycles to save the 35.9 kWh assuming the conversion of electric energy to heat in the room where the PCMs are applied is 100% efficient.

The number of days where the maximum temperature exceeds the melting temperature of 23 ^{0}C is unfortunately relatively low. Between 1981 and 2010, the maximum temperature reached or exceeded 20 ^{0}C on an average of 83 days per year, and 25 ^{0}C on 27 days per year [37]. This suggests that there will only be around fifty days a year when it is possible to properly load the PCMs. To achieve the number of cycles calculated in the previous paragraph, the life time of the PCMs needs to be at least 26 years (electric) or 78 years (gas). Furthermore, it needs to be taken into consideration that not after every warm day the PCMs will be able to completely discharge all latent heat. If PCMs with a lower melting temperature were available, the PCM could be charged on more days. However, the melting temperature needs to remain above the temperature the residents favour in order to ensure that the PCMs are not charged by the central heating systems rather than by solar irradiation. Although natural gas and electricity prices are expected to increase, the financial benefits from applying PCMs as a supporting heating system appear relatively low.

When PCMs are used (maybe in walls and ceilings) to avoid the need to install an air conditioning system, or as a replacement for a broken air conditioning system, the investment costs of the avoided system can be directly deducted from the investment costs of the PCMs. This will reduce the payback period significantly. Further, research shows that people residing and working in green buildings, e.g. which lack a cooling system, have a greater tolerance of high temperatures than people in non-green buildings with a cooling system [38, 39]. In summer, people in general also appreciate slightly higher indoor temperature than during winter [9]. As such, a building with PCMs can be experienced as more comfortable at slightly higher indoor temperatures than would be the case in buildings with a cooling system.

Independent of the envisaged situation, if PCMs are to be used to heat or cool a building, it is clear that reducing the costs of the PCMs and increasing their latent heat capacity need to be prioritized. Especially, when one considers that interest rates were not even taken into account yet to come to net present values of the positive cash flows. As such, salthydrates with their low costs and higher latent heat capacity seem to offer potential advantages over flammable paraffin-based PCMs, especially if they can offer the same reliability and technical lifespan.

5. Assessing the effects for stakeholders of implementing PCMs

PCMs have only been applied in a few Dutch office buildings to reduce the use of cooling systems or to make cooling systems redundant. As far as in known, PCMs have not yet been used in concrete floors to specifically support or replace heating systems in dwellings. Hence, few stakeholders have experience of the effects of using PCMs. This section considers what the effects would be for stakeholders involved in developing, designing and using dwellings.

5.1. Implementing PCMs in floors of new and existing dwellings

When developing a new product, a target group is often identified. Those wanting to implement PCMs in the concrete floors of residential buildings could focus on two target groups: principals that are developing new dwellings, and owners that want to improve or renovate existing dwellings. The Dutch housing stock consists of more than seven million dwellings, but only a relatively small number of new dwellings are added to this stock each year. Therefore, a developer of an ETM has a much larger group of potential clients if the product can be implemented not only in new but also in existing dwellings.

In *new dwellings,* the floor is part of the structure and is often finished with a layer of concrete that is ≈50 mm deep to cover the pipes and tubes of the installed systems. As in the experiments with the boxes discussed earlier [26], the micro-encapsulated PCMs could be added as the final ingredient during mixing, just before the final cement layer is poured onto the floor construction. PCMs will reduce the strength of the concrete, but up to 5% of the mass can safely consist of PCMs [21]. A major advantage of applying PCMs in new dwellings is that future residents will not experience any inconvenience. The concrete layer will take approximately the same time to dry out whether or not PCMs are added.

In *existing dwellings,* the implementation of PCMs in concrete floors for heating purposes is only likely to take place if extensive renovation is planned, such as if an old wooden floor is to be replaced by a new insulated concrete floor. Here, as in a new build, a layer of concrete containing PCMs could be poured on top of the new floor construction. Adding a layer containing PCMs to floors of existing dwellings would demand quite some effort from the residents, who would need to temporarily move and store their furniture in a different location. Further, they will not be able to use the rooms in which the floors are being modified for a few days. If the kitchen or bathroom were to be re-floored, it is likely that the residents would need to be temporarily accommodated elsewhere.

It is worth mentioning that incorporating PCMs in concrete could mean that activities in the domain of building physics would be allocated to a group of contractors that have not been intensively involved with thermal comfort before. A heating system would still be necessary, so system installation contractors will probably not experience any less involvement in these building projects. For those involved in designing the concrete mix and in preparing and pouring the concrete, attention would have to be paid to the quantity and quality of the micro-encapsulated PCMs.

In designing the dwelling, there would be a task for consulting engineers with expertise in building physics regarding the quantity and quality of PCMs. Their knowledge on the thermal behaviour of buildings, plus use of simulation software and the correct product information from PCM manufacturers, would create an appropriate platform for determining how much PCM, with what melting temperature, should be included to reduce the need for using fossil fuels to heat the dwelling. In collaboration with the architect, specifications of the dwelling would be taken into account when simulating the thermal behaviour. Given that the behaviour of the future residents will influence the effectiveness of the PCMs, it would be advantageous if the principal (A) is the future resident, (B) knows the future residents, or (C) can select future residents such that they match the occupational behaviour assumed when designing the dwelling. Why residents might want to implement PCMs will now be explained.

5.2. Motives for stakeholders to implement PCMs in building projects

In the phases preceding the construction phase, many decisions have to be taken in finalizing the design and construction plans of the future dwelling. Many ETM investments can and will be considered, and some will be implemented and some rejected. Although the developer of PCMs will need to explain to the contractor how to apply them correctly in the construction phase, actual implementation will not take place unless stakeholders are convinced in the pre-project and pre-construction phases that PCMs are a worthwhile investment. Another reason why PCMs might be implemented in concrete floors for heating purposes would be if it was to become compulsory, but this seems unlikely.

If PCMs were to be made compulsory, or were useful in achieving a compulsory energy performance, the financial benefits would be less critical than if they are merely regarded as an optional extra investment on top of other ETMs that are necessary to comply with the law. The national government could, through the Building Code and the standards assigned therein, influence the relative advantage of PCMs in meeting compulsory energy levels. Municipalities that check applications for building permits for their compliance with the Building Code would then have the task of checking if the impact of the PCMs on the energy performance was correctly calculated.

Given the current situation, in which PCMs do not have a role in the theoretical energy performance of a dwelling, stakeholders need to be persuaded by other means. A sound investment needs to see energy use reduced, maintenance costs dropped, reliability increased, user comfort improved and the value of dwelling increased. From the perspective of the owner of the dwelling and its residents, the costs of an ETM could discourage investment while the benefits could encourage it. Arguments that consider the reductions in energy use and accompanying environmental emissions, and the reduced energy costs, have already been addressed. Consequently, only considerations related to reliability and maintenance, to user comfort, possible negative rebound effects and the value of the dwelling are addressed in this section.

Compared to a situation where PCMs are not used, maintenance costs are not expected to increase for the resident. A decrease in maintenance costs for the conventional system could be possible, if the number of evenings in which the heating system is required to heat water for the radiators and the pump employed to pump this heated water around the radiators is reduced. Maintenance costs are also unlikely to increase, given the passive use of PCMs with no moving parts and no mass being transferred.

In terms of reliability, large differences in quality can exist between the PCMs of different producers. The manufacturer of the PCMs used in the experiments, BASF, has committed itself to German quality standards for PCMs as specified in RAL-GZ 896 [40]. The Micronal DS 5000 X and Micronal DS 5001 X products have been certified with an A-label that guarantees more than 10,000 cycles of use [41]. The product used in the experiments was DC 5008 X which is based on almost the same paraffin mix as DS 5001 X, but with a 3 ^{0}C lower melting temperature [28]. Comparing the PCMs with a cooling or heating system in which the technical life expectancy will be fifteen to twenty years at most, this means that the PCM could be charged 500 times per year for the same lifespan. However, given that only roughly fifty days a year are expected to provide the proper ambient conditions to cycle the PCMs, their working life is hypothetically estimated at 200 years.

However, reliability remains an issue. Although the product information provided by the manufacturer is positive about the ability of the micro-capsules to withstand drilling [28], the process of mixing the concrete puts severe strains on the capsules. In the experiments conducted by Hunger et al. [21], a significant proportion of the capsules were found to be broken once mixing and hydration of the concrete had taken place. Given this information, it seems likely that some of the paraffin wax will leak away and may in the long run partially evaporate. If this occurs, the amount of PCMs in the mix will provide a smaller latent heat capacity than anticipated based on the original product information. If this occurs, residents of a dwelling with a floor containing PCMs might notice that the reductions in energy use are less than expected and that these reduce further over time.

Although PCMs implemented for heating purposes will not always discharge during high summer, and therefore overheating can still occur, user comfort is nevertheless expected to rise. The inclusion of the PCMs provides a latent heat capacity that will reduce the use of the sensible heat capacity of the dwelling’s materials. Therefore, the number of days that a living room, or even the whole dwelling, becomes uncomfortably warm should be reduced.

A rebound effect can occur if an ETM is not used by the residents as the developer, manufacturer, architect or advising engineer thought it would be. In such situations, an ETM may reduce the energy use less than expected or even increase the energy use. In installing PCMs in concrete floors, one needs to avoid natural gas being used to charge them rather than solar irradiation. For this to be avoided, the melting temperature needs to be close to the temperature that is regarded as comfortable by the residents, and preferably by unknown future residents. Further, it will need to be clearly communicated to current and future residents how they can make effective and efficient use of the PCMs. If residents experience an added value of PCMs, it is likely, provided that this is properly marketed, that the value of dwellings with floors containing PCMs for heating purposes will see a premium over dwellings without this technique. A well-known example of such an effect was with the introduction double glazing in the 1970s, which quickly became and remains valued as a means of increasing property value.

5.3. 5.3. Relating the stakeholders in implementing PCMs

Among the stakeholders in a residential building project we can identify four implementation relationships, which are shown in Fig. 3. In a building project where the designed dwelling already complies with the Building Code, the principle is free to decide whether to implement additional ETMs, such as PCMs. This decision will be taken based on various factors including information to hand on the considered ETMs. In general, such information does not take into account the context in which a specific project takes place. As such, time and money need to be invested in order to gain reliable information on the effects of the PCM in the context of a specific environment, building and residents, all with their unique characteristics. This information could be provided by the organization that offers the PCM, by the architect or through advisors. This element of the implementation is referred to here as the *design implementation* by the architect, principal and advisors.

Before approving the actual physical implementation, the principal has to be able to finance the investment costs and have confidence that the PCM will sufficiently reduce the energy use of the dwelling over a period long enough to see the investment as financially sound. Only if these considerations are made, and positively assessed by the stakeholders, will the principal give an order enabling a contractor or installer to apply or install the PCM. This element of the implementation process is referred to as the *physical implementation* by the contractor and principal.

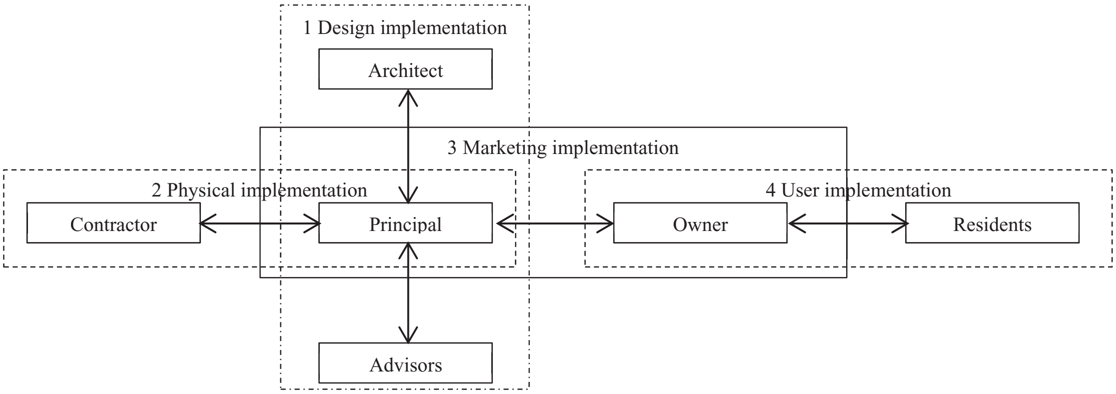

Fig. 3. Visualization of the relationships among internal stakeholders in building projects as related to the implementation of ETMs [29].

Where the principal is both the owner of the dwelling and its resident, not many stakeholders need to be persuaded. However, when the principal, the owner and the residents are different organizations or persons, their perceptions are likely to differ and alternative aspects of the implementation might be carefully weighed by these various stakeholders. Here, the principal not only needs to be convinced of the advantages of the considered PCM, they also have to be able to sell the building to the future owner. This element of the implementation process is referred to as the *marketing implementation* by the principal and owner.

The future owner needs to explain to the future residents how they can ensure the implemented ETM functions properly, producing the greatest benefits for them. If the PCM is not used correctly, then the implementation should not be regarded as successful. This last element of the implementation process is referred to as the *user implementation* by the owner and residents.

6. Conclusions and recommendations

This paper started with a research question on how PCMs can align with the interests of the stakeholders from an energy perspective, a financial perspective and the perspective of a building project? Although the conducted experiments showed positive results, the implementation potential of micro-encapsulated paraffin based PCMs in concrete floors to support or replace heating systems is expected to be relatively low in the Netherlands. It can be concluded that the implementation of PCMs requires various efforts from stakeholders involved both before and during a building project. Table 2 shows which perceived shortcomings were identified. This table is expected to be helpful for *developers* and *manufacturers* of PCMs, as a first group of stakeholders.

Table 2. Shortcomings of PCMs integrated in concrete floors in Dutch residential buildings as identified in this research.

Energy perspective	Financial perspective	Building project perspective
The relatively low latent heat capacity of paraffin-based PCMs compared to the relatively high sensible heat capacity of materials used in Dutch residential buildings;	The relatively high investment costs in terms of PCM material costs;	Stakeholders' low familiarity with PCMs;
The climate offers only a few days each year to passively charge and discharge PCMs set in concrete floors;	The relatively low price of natural gas compared to the price of electric energy;	The relatively limited availability of PCMs compared to other ETMs such as insulation materials, high efficiency boiler systems, photovoltaic systems and thermal solar collectors;
The limited availability of computer programs to simulate the effects of PCMs in a building, specifically of incorporating PCMs in the floors of dwellings for heating purposes;	The reliability of PCMs which still need to demonstrate their technical life when applied in concrete floors.	The required user pattern for residents to make full use of the ability to passively charge and discharge PCMs;
The inability to incorporate PCMs in the calculation method for EPIs;		

Based on information provided by the manufacturer, the architects or the advisors on HVAC systems, the *principal*, the stakeholder that invests in this ETM, has certain expectations about its performance after implementation. When a principal considers implementing PCMs, it is important to ask the developer, manufacturer or sales person to specify what reduction in kWh of electric energy, m^3 of natural gas or GJ of thermal energy can be anticipated for dwellings and residents in what circumstances. The effects of implementation, in terms of energy use, user comfort, maintenance, reliability, rebound effects and the value of the dwelling should be made as explicit as possible for the specific context in which the PCMs are to operate.

The *architect* would seem to be the appropriate stakeholder to specify and to explain this context. In some cases, advisors on HVAC systems can assist the architect or even take on this role of explaining the context in which the PCMs are to be implemented. However, one should recognize that in many small residential building projects advisors are not contracted to design the installed systems. *Architects or advisors* may, on the basis of their experience, have some views on an ETM. If simulation tools are available, it is also possible to try and simulate the effects of the ETM. Simulating the effects within several implementation scenarios may offer insight into how the reduction of the energy use can be maximized in relation to the financial costs. The actual physical implementation during construction will be carried out by a different stakeholder. This contractor or installer needs to be well informed about the assumptions made during the design phase in order to understand the implications for their activities.

When the *government* considers the effects of an ETM, the focus may be on environmental considerations regarding emissions and the depletion of fossil fuels. If so, it is important to consider the origins of the energy forms whose use is being reduced. Natural gas needs to be extracted and transported through a vast network of pipelines. Fossil fuels are converted into electric energy that is then transported through the power grid. Every element in this production and transport process results in a loss of exergy: the potential of the energy flow to perform mechanical work. This means that the reduction in energy use is greater than that recorded by the final consumer on their domestic meters.

In order to make implementation possible, more insights are needed into the behaviour of PCMs in concrete floors in the context of specific building projects with their stakeholders and actors, and after completion the *residents* of the specific building. Such insights could be obtained by conducting a pilot study in which PCMs are actually applied in concrete floors of several dwellings, either in already occupied renovation actions or in new projects. Anyone offering PCMs, or for that matter any other new ETM, can use the model presented in Fig. 3 to consider what information and tools will be required to persuade stakeholders in each of the four implementation relationships. As outlined in this paper each relationship needs its own specific kind of information and tools in order to persuade the stakeholders that an ETM can be implemented and that it is worth implementing. If any of the stakeholders surrounding the principal convinces the principal that the ETM cannot be implemented, does not offer additional value, or seems to be unreliable, then rejection is likely. In the case of PCMs in concrete floors for heating purposes, there are inadequate insights, a lack of detailed information, and no appropriate simulation tools available. Here, the *government* in its various roles as a principal, legislator, enforcer of the Building Code and a champion of reducing fossil fuel use could take on the important role of initiating and stimulating pilot projects.

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