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Using Thermal Inertia of Buildings with Phase Change Material for Demand Response

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Abstract

In recent years, demand response programs have proved useful in managing peak demand and meeting sustainability goals, enabling an efficient use of the smart grid. Heating, ventilation, and air conditioning (HVAC) loads in buildings constitute a large proportion of the total energy consumption of households, and accordingly, a flexible and efficient operation of these devices can aid power utilities in meeting load management objectives while reducing consumer's electricity bills. With the emergence of promising new technologies, such as phase change materials (PCM), buildings can serve as a virtual thermal energy storage, which improves energy efficiency and also allows occupants to offer grid services like peak demand reduction. The objective of this paper is to establish the effectiveness of PCM as a demand response resource, demonstrating the extent to which it can be used for peak demand reduction. A wide range of scenarios are considered to investigate the impacts of geographical location, PCM melting point, duration of precooling and preheating, setting points of HVAC system, thickness and location of PCM, on the capability of the PCM in reducing or shifting the cooling and heating load. All simulations are performed using the EnergyPlus platform, examining typical residential buildings in five Australian cities: Brisbane, Sydney, Melbourne, Hobart and Perth. The simulation results showed a decrease in the HVAC demand in the buildings with PCM, in all cities, with the highest reductions observed in Hobart and Melbourne. The integration of a 20mm thick PCM in the roof, wall and floor of the building yielded a 21.8% and 16.7% reduction in annual HVAC demand in Hobart and Melbourne respectively, when compared to the building without PCM. However, this is with the assumption that the HVAC system is operating 24 hours a day for a whole year. The PCM-integrated building showed a shift in the HVAC demand in all cities except Perth. A shift by 9 minutes, 3 minutes, 60 minutes and 103 minutes was recorded in the cities of Brisbane, Sydney, Melbourne and Hobart respectively. The simulation results will be used in subsequent research to schedule the HVAC demand using a home energy management system.

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1. Introduction

In the US, currently about 40% of the total energy is consumed by residential and commercial buildings. Globally buildings consume more than 30% of the total primary energy of which approximately 50% is used for heating, ventilation and air conditioning (HVAC) [1,2], making it a major contributor to global greenhouse gas emissions. Australia's energy consumption follows same pattern with residential heating and cooling loads contributing significantly to the overall energy consumption of the country. This trend could change if the thermal capacity (or thermal inertia) of a buildings' envelope is utilized to provide some form of virtual energy storage, introducing flexibility in thermal energy use (e.g. by shifting consumption from peak periods to off-peak periods). This can be achieved using a *home energy management system* (HEMS), which automatically schedules the HVAC system to reduce energy consumption, while maintaining the desired thermal comfort level of the living space. In Australia, most residential buildings are lightweight, with low thermal inertia that needs to be improved to overcome the high fluctuation of the indoor building temperature. One immediate solution is the increased use of materials with high thermal inertia, like bricks. But this conflicts with Australia's carbon pollution mitigation targets due to high carbon-footprint of the brick structure. A novel technology that could be used to improve the thermal capacity of a lightweight building is the integration of phase change materials (PCM) into the building's envelope. PCM absorbs and releases thermal energy or heat due to changes in entropy within a certain temperature range, so called latent heat. In other words, latent heat is the energy that is absorbed or released when a material goes through a phase change from one physical state to another such as solid-liquid or vice versa.

The application of PCM for improving the energy efficiency of residential buildings has attracted much attention in the past two decades [3]. Christopher et. al [4] showed that using PCM in lightweight buildings is an effective way to reduce peak temperatures and discomfort hours, provided that the night ventilation is employed to solidify the PCM for use the next day. Fabrizio et. al [5] studied the effect of peak melting temperature and thickness of PCM in the reduction of cooling demand for five cities with Mediterranean climate. Cooling demand was observed to reduce with an increase in the thickness of the PCM and a strict correlation was seen between the chosen melting point and the thermal comfort level. It was concluded that PCM thickness and melting point are important factors to be considered in designing energy efficient building and PCM selection depends on climatic condition, building type, design parameters and internal loads. Castellón et. al [6] conducted several experiments on nine small cubicles to demonstrate the impact of PCM on improving thermal comfort and reducing energy consumption. PCM mitigated the fluctuation of the indoor temperature and the maximum temperature in the wall which had PCM appeared two hours later compared to the wall without PCM, and it was suggested that for better performance, free cooling at night could facilitate the discharging of PCM. Kosny et. al [7] conducted an experiment to evaluate the performance of the bio-based PCM and he observed a 10% reduction in annual cooling and heating load with the inclusion of PCM in the building's envelope. Becker [8] implemented some simulations in *EnergyPlus* for different building types: lightweight building, semi-light building and heavyweight building. In very heavy construction, PCM improved thermal comfort but had a marginal effect on energy saving; while for lightweight and semi-lightweight buildings, using PCM improved both the thermal comfort and energy performance. These studies show that the performance of the PCM is dependent on many factors such as the PCM melting point, building structure, climatic condition, operating hours of HVAC system, HVAC setting points etc. The application of PCM in Australia's residential buildings has been reviewed through only a few publications [9,10], and there is still no comprehensive investigation on a typical Australian building taking into consideration all the variables of PCM performance.

Within this context, this research evaluates the effectiveness of PCM on buildings in Australia's major cities based on the aforementioned PCM performance indices.

The remainder of the paper is arranged as follows: Section 2 explains the functionalities of HEMS in residential buildings, with a brief literature review. Section 3 details the method used in modelling the residential building in *EnergyPlus*. The simulated models along with some underlying assumptions are described in Section 4. The results of the case studies are discussed in Section 5, followed by the conclusions in Section 6.

2. Home Energy Management System in Residential Buildings

With the advent of advanced communication and metering devices and a massive growth of distributed energy resources, a *home energy management system* (HEMS) can be used to reduce residential energy consumption, and to modify the usage pattern of home devices in order to achieve a more efficient use of distribution networks and renewable electricity generation. In more detail, a HEMS is a device which monitors, controls and manages the operations of distributed energy resources and other controllable household appliances to modify patterns of electricity usage during peak periods in response to electricity price signals. It achieves this by means of a 2-way exchange of information with the grid through communication technologies and advanced control methods [11-13]. The HEMS essentially solves a mixed integer optimization problem with the objective of minimizing total cost subject to certain constraints (e.g. energy balance, battery state of charge, thermal comfort, etc). For a complete description of HEMS, please refer to [14].

HVAC systems are one of the largest schedulable home appliances that can be used to significantly reduce household electricity demand during peak periods. Many control schemes for HVAC systems have been introduced in the recent publications. For example, Krystian et. al [15] used a centralized model predictive control scheme to simultaneously control the operation of air conditioning systems and time shiftable appliances in the community of houses and concluded that on average their approach can reduce daily peak load of group of houses by 25.5%. Armin et. al [16] proposed a mechanism for scheduling home appliances to minimize peak load energy consumption and electricity cost. With an optimal scheduling of household appliances, a 7% saving in electricity cost was achieved. Authors in [17] presented an automated real time control strategy for thermal energy storage which resulted in 10% savings in cost of energy usage when compared to a case without energy storage systems.

In this work, PCM is used as a thermal storage resource which enables greater flexibility in the operation of the HVAC system. The HVAC can be managed through a central management module in HEMS which supports scheduling and setting of the HVAC system to reduce the cost of electricity by reducing energy demand and shifting the electricity consumption to off peak load hours.

3. Thermal Modelling of Residential Building in EnergyPlus

A number of modelling approaches are available to model residential buildings. These include the *finite difference method* (FDM), *finite volume method* (FVM), *lumped parameter method* (RC network) and computational fluid dynamics (CFD). These methods differ in their complexity, accuracy and computational speed. In particular, CFD is the most accurate of these but it's not computationally feasible; while the lumped parameter method is simple but accurate enough for short time horizon problems. Simulations in this research were implemented using the *EnergyPlus* software which uses the *conduction transfer function* (CTF) to estimate the heat transfer in buildings [18,19]. The CTF is essentially the lumped parameter method expressed as transfer functions using state-space method. CTFs are efficient in calculating surface heat fluxes since they eliminate the need to know temperatures and fluxes within the surface. However, CTF series gradually becomes unstable with decrease in the time step. This problem is overcome in *EnergyPlus* by using a master history with interpolation method. In this method, surface temperature and heat flux histories at intermediate instance of time are obtained by interpolation. One drawback of CTF is that it's a constant coefficient (being a time-invariant method), hence it cannot be used for modelling temperature-dependent thermal properties like PCM.

In order to model PCM, partial differential equations with a moving boundary need to be formulated. To solve the governing equations, either numerical or analytical methods can be used. In *EnergyPlus*, a one-dimensional *conduction finite difference* (CondFD) is method applied to solve this problem, which saves considerable time and computational cost. The CondFD algorithm is validated through some on-site experiments of PCM's performance and also through the standard evaluation of building software published by ASHRAE (the American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc.). To use this algorithm, there is an option to select either the Crank-Nicholson or fully implicit methods: The fully implicit method is used in this work. A detailed explanation of the CTF and CondFD is given in [20].

4. Models and Assumptions

In this section, the detailed models of the residential buildings considered are introduced, followed by some simplifying assumptions.

4.1 Models

In this work, three different building types are taken into account: lightweight, brick-wall and PCM-enhanced lightweight buildings; they are modelled in the *EnergyPlus* software. The physical dimensions of the buildings are kept unchanged in all building types. The only difference between lightweight building and brick-wall building is the wall composition. In the PCM-integrated building, PCM was added to three different locations in the building: the roof, wall and the floor of the lightweight building. In changing the thickness of the PCM, the thickness of the gypsum board was adjusted accordingly so as to result in same wall thermal resistance. Hence, in all three building types, the thermal resistance of the wall is same. The building is north facing with a total floor area of 150m^2. The house is modelled as a one zone, simple cube of dimension $15m \times 10m \times 2.7m$ .The details of the building's fenestration are presented in Table 1.

Table 1. Building components and its dimensions.

Building component	Dimension (Width(m)×(Height(m))
Door on north wall	0.85 × 2.1
Window on north wall	2.6 × 2.5
Windows on east wall	2.6 × 2.5 and 1.7 × 1.8

The wall composition and materials of the lightweight building, brick-wall building and PCM-integrated building are shown in Tables 2, 3 and 4 respectively. The PCM considered in this paper is BioPCM with the properties detailed in Table 4. The variation of its specific enthalpy with temperature is illustrated in Figure 1. Other material properties such as thermal conductivity, density and specific heat which are required inputs in *EnergyPlus* are extracted from ASHRAE handbook [21].

Table 2. Wall composition and its material properties in lightweight building [21].

Wall material from outside to inside	Thermal conductivity [W/(m.K)]	Density [kg.m^{-3}]	Specific Heat [J/(kg.K)]
Cement board	0.25	1150	840
Glass-fiber batts	0.043	14	840
Gypsum board	0.16	640	1150

Table 3. Wall composition and its material properties in brick-wall building [21].

Wall material from outside to inside	Thermal conductivity [W/(m.K)]	Density [kg.m^{-3}]	Specific Heat [J/(kg.K)]
Brick (fired clay) layer	0.84	1760	800
Glass-fiber batts	0.043	14	840
Brick (fired clay) layer	0.84	1760	800

Table 4. Wall composition and its material properties in PCM-integrated building [21,22].

Wall material from outside to inside	Thermal conductivity [W/(m.K)]	Density [kg.m^{-3}]	Specific Heat [J/(kg.K)]
Cement board	0.25	1150	840
Glass-fiber batts	0.043	14	840
BioPCM	0.2	860	1620
Gypsum board	0.16	640	1150

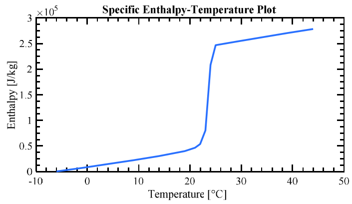

Fig. 1 Specific Enthalpy-Temperature plot for BioPCM with 23°C melting point [22].

4.2 Assumptions

Some simplifying assumptions made in this paper are given below:

- BioPCM is available in the form of a mat consisting of plastic blocks in which the PCM is encapsulated. In the simulations, we assumed PCM as a continuous layer.
- Same typical summer and winter days are supposed for all five cities as:
  Typical summer day: 1st February and typical winter day: 12th July.
  Typical summer week: 26th January to 1st February and typical winter week: 12th July to 18th July
- Two working durations are assumed for the HVAC system in the summer season. The first working period starts from 10pm to 8am of the next day and the second working duration is from 8am to 6pm. For winter, only the working duration of 8am to 6pm is considered. Precooling and preheating of buildings are scheduled to be in the HVAC working duration.
- According to ASHRAE standard [21], the comfort level for winter is considered 20-23°C and for summer 23-26°C. In this research discomfort level is calculated based on the percentage of the hours in a year that the temperature is less than 20°C or higher than 26°C.
- In our simulation a complete mixing model for room air is selected, so the room temperature is uniform without any thermal stratification.
- The HVAC system that used in this paper is a Packaged Terminal Heat Pump (PTHP). In the simulation, the HVAC setting in mostly at 20°C for heating in winter and 23°C for cooling in summer, otherwise its setting is stated.

5. Results and Discussion

As mentioned in the introduction, the melting point of a PCM is highly dependent on the geographical location of the building. In this paper three criteria were used for the selection of applicable melting temperature for each city: 1- discomfort level, 2- internal temperature fluctuation and 3- shifting time of demand. Based on the simulation results of the three mentioned criteria, the selected melting points of PCM for the five cities are: PCM25 for Brisbane, PCM23 for Sydney, PCM23 for Melbourne, PCM21 for Hobart and PCM25 for Perth. It is noticed that there is a correlation between the chosen PCM melting point and the average outdoor air dry bulb temperature (°C) of the city where PCM is used. PCM with lower melting point are more suitable for the cities with lower average temperature. After selection of the PCM type (melting point) for each city, different scenarios were implemented for each of the five cities and the five major findings are given below:

Firstly, the results showed that precooling from 10pm to 8am is more effective than precooling from 8am to 6pm in shifting the demand. In other words, changing the working hours of the HVAC system from 10pm-8am to 8am-6pm will result in a lower or no shift in the demand. The simulation results summarised in Table 5 shows that the highest shift in both cooling and heating demands occur when PCM21 is applied.

If the internal temperature of the buildings is plotted for summer and winter day in Hobart (as shown in Figure 2), it visualises the findings illustrated in Table 5. Figure 2a shows that precooling the building to 23°C from 10pm to 8 am (PCM21) causes a delay in exceeding the comfort level of 26°C, when compared to the case without PCM. This is approximately 51 minutes shift in cooling demand. But using PCM21 for precooling from 8 am - 6pm did not cause any shift in the demand (see Figure 2b). Figure 2c shows that for Hobart, using PCM21 yields the highest shift in the demand compared to other PCM types (as presented in Table 5).

Table 5. Demand shifting for 10mm PCM-integrated building with different melting point of PCM with various schedule of HVAC system (HVAC setting: 23℃ in Hobart).

PCM melting point	21 PCM	23 PCM	25 PCM	27 PCM	29 PCM
Summer day HVAC (10 pm to 8 am)	51 min	25 min	No shift	No shift	5 min
Summer day HVAC (8 am to 6 pm)	No shift	No shift	No shift	No shift	6 min
Winter day HVAC (8 am to 6 pm)	57 min	36 min	33 min	30 min	27 min

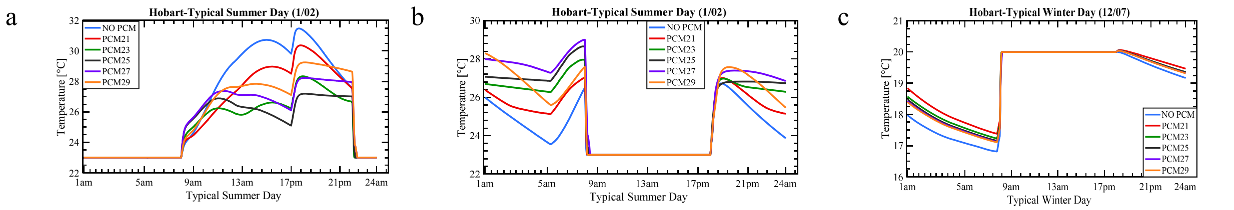

Fig. 2. (a) Internal temperature in the typical summer day of Hobart using different PCM types (with HVAC working duration: 10pm to 8am); (b) Internal temperature in the typical summer day of Hobart using different PCM types (with HVAC working duration: 8am to 6pm); (c) Internal temperature in the typical winter day of Hobart using different types of PCM (with HVAC working duration: 8am to 6pm).

Secondly, the effect of varying the setting point of the HVAC system was examined in this work. Results showed that changing the cooling system setting from 23℃ to 22℃, increased the demand shift time for all cities except Brisbane while increasing the setting point of the cooling system to 24℃ reduced the demand shift time in all cities. The maximum shift in demand observed in all cities with the adoption of PCM were: 9 minutes for Brisbane with HVAC setting point of 23℃; 3 minutes, 103 minutes and 60 minutes respectively for Sydney, Hobart and Melbourne with HVAC setting point of 22℃. In Perth no shift in the demand could be seen.

Thirdly, the inclusion of the PCM in the building resulted in the reduction in annual and weekly HVAC demand when compared to the building without PCM. Figures 3a and 4a illustrate this finding for Hobart city. Also, three different thicknesses (of 10mm, 15mm and 20mm) PCM were analysed in the simulations; the results showed that applying 20mm thick PCM resulted in the highest reduction in annual and weekly heating and cooling demand of the building for all cities (See Figure 3b and 4b).

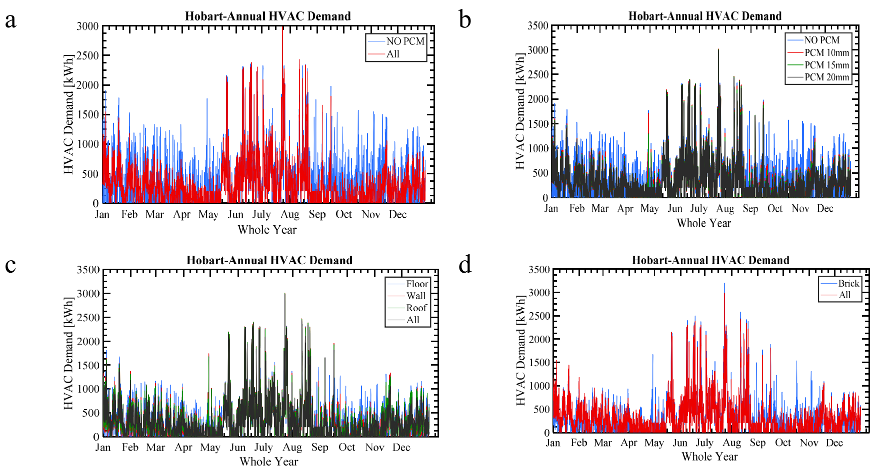

Fig. 3. (a) Annual HVAC demand (kWh) of building with 10mm thick PCM compared to building without PCM in Hobart; (b) Annual HVAC demand (kWh) of PCM-integrated building with PCM of different thicknesses compared to building without PCM in Hobart; (c) Annual HVAC demand (kWh) of PCM-integrated building with 20mm thick PCM in three different locations (roof, walls and floor) compared to building without PCM in Hobart; (d) Annual HVAC demand (kWh) of PCM-integrated building with 20mm thick PCM in all three locations compared to brick-wall building in Hobart.

Among all cities, increasing the thickness of PCM from 10mm to 15mm reduced the annual HVAC system demand by a maximum of 2.1% and a minimum of 0.6%; and increasing thickness of PCM from 15mm to 20mm reduced the annual HVAC system demand by a maximum of 2.4% and a minimum of 0.4%. Finally, changing the PCM thickness from 10mm to 20mm decreased the annual HVAC demand by a maximum of 4.5% and a minimum of 0.95%.

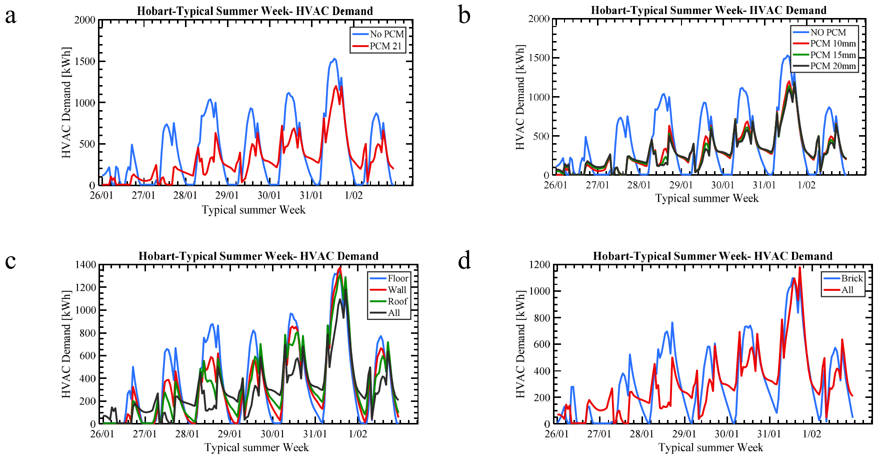

Fig. 4. (a) HVAC demand (kWh) of building with 10mm thick PCM compared to building without PCM for typical summer week (26/01 to 1/02) in Hobart; (b) HVAC demand (kWh) of PCM-integrated building with PCM of different thicknesses compared to building without PCM for typical summer week (26/01 to 1/02) in Hobart; (c) HVAC demand (kWh) of PCM-integrated building with 20mm thick PCM in three different locations (roof, walls and floor) compared to building without PCM for typical summer week (26/01 to 1/02) in Hobart; (d) HVAC demand (kWh) of PCM-integrated building with 20mm thick PCM in all three locations compared to brick-wall building for typical summer week (26/01 to 1/02) in Hobart.

Fourthly, the effects of using PCM at three different locations (roof, walls and floor) were examined separately and also with PCM in all three locations. For highest reduction in annual and weekly energy demand, it is best to use the 20mm thick PCM in all three locations due to increase in the overall thermal capacity of the envelope. When there is an economical constraint, using PCM in the roof is an optimal way of integrating PCM into the building. The second efficient option is installing the PCM in all the walls. This gives almost the same amount of reduction in heating and cooling demand with that of the roof. These findings are shown in Figures 3c and 4c.

And finally, we compared the results of the optimal PCM-integrated building (in this case the building with 20mm PCM in all roof, walls and floor) to that of the brick-wall building, for all cities. The inclusion of PCM resulted in an annual HVAC demand reduction of 7.3% and 1.4% in Hobart and Melbourne respectively. But, in the other three cities, brick-wall building had about 6.3% to 9.5% less HVAC (annual and weekly) demand compared to the PCM-enhanced building. The likely reason is that, compared to the other cities, Hobart and Melbourne have on average more frequent daily temperature fluctuations. Therefore, the PCM undergoes more frequent cycles of melting and freezing, which results in a lower HVAC demand. Figure 3d and 4d show the comparison between optimal PCM-integrated buildings with brick wall building for Hobart.

In all, simulation results confirm that the PCM-building is operating more efficiently in Hobart and Melbourne compared to the other three cities. Using precooling strategy in a typical summer day resulted in a maximum shifting of demand by 103 minutes and 60 minutes in Hobart and Melbourne respectively. And in a typical winter day, it resulted in a demand shifting of 57 minutes and 54 minutes for Hobart and Melbourne respectively. With a HEMS in place, it utilizes these shifts and schedules the HVAC system to move demand from peak periods to off-peak periods. In terms of HVAC demand reduction, the PCM-integrated building yielded 21.8% and 16.7% reduction in Hobart and Melbourne respectively with the assumption that HVAC system is operating 24 hours in a year with setting point of 20°C for winter and 23°C for summer.

6. Conclusions

Using PCM in lightweight buildings is highly beneficial in reducing the HVAC demand or shifting the demand to off-peak hours. Care should be taken in the selection of PCM based on the melting point as this has a high impact on both the demand shift time and demand reduction. Precooling and preheating duration and the HVAC temperature setting are also important factors that should be taken into consideration in the optimization problem included in HEMS. In this paper, it is shown that cities (in Australia) such as Hobart and Melbourne has a better incentive to adopt PCM technology in their buildings in contrast to high thermal inertia constructions. This work is an integral part of the smart home research and as a future work, these results will be used for the automation of the HVAC system in meeting the grid's demand reduction target.

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