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Hybrid PCM and Transparent Solar Cells in Zero Energy Buildings

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Abstract: Zero energy building design could be realized by passive design. Having energy conservation concepts and active mechanical renewable energy generation systems could be considered as passive technique. This concept becomes a very interesting technique in countries that consume a lot of energy for their domestic sector. The purpose of the recent paper is to investigate the effect of hybrid construction material that merges phase change material, PCM walls for heat load minimization and transparent solar cells, and TSC in the windows for electricity generation for the purpose of illumination in such typical design. PCMs could be used for storing thermal energy and utilizing this energy during different annual seasons by absorption or release mechanisms to keep the building's inside temperature at thermal comfort state. While TSC,s are substances that allow partial Sun light penetration for illumination during day and use the other part for electricity generation at night. The paper introduce a typical architectural design for residential building that utilizes such type of constructional material for energy saving and analyzes thermal effectiveness of using PCM and power production effectiveness of using TSC as passive technique integrated with the zero-energy building envelope. Proper modeling tool has been used to investigate the impact of these materials on the thermal comfort perceived by the occupants. Results show that using such type of hybrid materials reduces annual energy consumption. It has been concluded that the passive structural heat isolation and power production material is a very effective manner in countries like Iraq which has severe temperature differences between summer and winter seasons.

Keywords: *Phase change material, transparent solar cells, zero energy building, architectural design*

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I. INTRODUCTION

The comfortable residential environment is realized at average temperature of 21^{o}C and moderate humidity [1]. During cold season, the air inside building is heated using adequate heat source. While during hot season, the heat added to the building is controlled by either adding special isolation material or by proper air cooling packages. In both cases the building materials affect the comfortable temperature inside. During hot climate, typical constructional material ensures sufficient cool during day and sufficient warm during night. Using thin wood blanks could be improved by adding other material to them. The material with high thermal resistances affects energy flow inside and outside of the buildings, as the energy flow is inversely proportional to thermal resistance. Insulation process normally controls wall thermal resistance, R to heat flow. The second important factor which is taken under consideration is the heat capacity of the material used in building construction. Heat capacity is defined as materials capability for heat energy storage. Using material with low heat capacity is preferred to reduce stored heat energy. During the heat flow process material temperature is changed sensibly. For example, comparing stone and cement with other struc-

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tural material shows higher heat capacity. When heat energy flows into such type of material it changes temperature very slowly while it stores the heat energy. Residential buildings based on passive solar energy are normally constructed from stone or rock that occupies high heat capacity. The privilege of utilizing material with sufficient thermal mass is effective during sunny days, while this energy could be drawn at night [2, 3, 4]. In terms of building construction, the addition of PCMs to the walls of the building acts as storage and regulates the internal thermal balance and performance of the building [5].

One of the most efficient ways to store thermal energy is through the utilization of PCMs in passive cooling/heating of buildings [6, 7]. Different research projects have been developed since the last decade including [6, 8, 9, 10, 11]: direct incorporation or impregnation of the construction material, incorporation of PCM capsules in building components, manufacturing new panels with PCMs to replace classic wallboards or integrate with traditional wall, and incorporation in a plate heat exchanger to improve the performance of a HVAC system.

II. LITERATURE REVIEW

[12], studied the effect of using phase change material on building thermal performance. The author took under consideration the cold season in his research. The researcher proved that PCM which occupies melting temperature equivalent to room temeprature is capable to reduce extra thermal load at temperatures (above 26^{o}C) and ensure comfortable environment houses with lower cost required for cooling purposes. Therefore, the potential for energy savings of different combinations is required to be evaluated. The author concluded that future work should concentrate on investigating comparison between PCM integrated material effect and other conventional systems for cooling application.

[13], investigated the effect of PCM melting temperature on design criteria of zero energy buildings. In their research, the utilization of PCM was in typical heat storing layer walls. PCM melts at temperatures that exceed its melting temperature. The phase changing process is proportional to the latent heat extractd from the conditioned premises, which will then cool building interior with less energy. This process is applicable in the day period of summer seasons. At night, heat exchange process is reveresed as the heat stored in PCM walls will be rejected to building interior. During the winter, PCM is capable to store more energy in comparison to other constructional material, with the latent heat of PCM being 286 kJ/kg. The simulation process is conducted using TRNSYS in on hourly basis. Type204 material is used as main component in the program which is used to model a PCM-wall within structural element of a dwelling. Type204 is assumed to interact with building model, Type56. The calculated energy did not depend on the additional heating or cooling systems, and the ventilation air supply temperature was assumed to be equal to the indoor air temperature. The comparison is conducted between a room integrated with PCM panel at different melting temperatures and a traditional one. The results showed that the optimum melting temperature was 22.5^{o}C for both hot and cold seasons. [14], conducted an experimental study to investigate PCM thermal energy stored in buildings. The objective of the study was to analyze the performance of Phase Change Materials (PCMs) in residential housing for different range of climates. The paper shows the main outcomes of the experiments performed in the Concordia University Solar Simulator and Environmental Chamber research facility (SSEC, Montreal, Canada). PCM boards were fixed on the rear surface of tested wall located in the temperature conditioned room. The postulated analysis which considered the verification process for the purpose of model calibrations is ensured using several experiments. Results prove that the apparent thermal inertia of the room is increased which reduces on daily basis temperature variations in the test hut. Calibrated Energy Plus model is used to simulate and broaden the analysis in a Mediterranean temperate climate and in cold Canadian climate. Setup environment is used to simulate hot summers in Mediterranean climate. The results for both locations are analyzed and showed that maximum storage for solar gains in PCM wall with a multiple layer which occupies high density is the better configuration when cold climate is considered, while its performance is non optimal when hot climates are considered as the PCM panels that occupy high thermal mass walls should be fixed at different positions in lightweight structures. [15], studied PCM and buildings thermal energy storage. The author showed that thermal energy storage, TES has very big effect on reducing the energy demand of residential buildings and/or to increase the energy related system efficiency. Different parties intended to achieve this potential by focusing on the studied point. Part of these studies concentrated on cost reduction and increasing the compactness of the systems for the purpose of increasing materials energy density. Other objective was to increase the thermal conductivity of the materials by developing new material. The study concentrated on special fluids that can realize both material storage and heat transfer purpose.

On other hand the feasibility of solar energy could be taken under consideration with high priority as the earth is exposed to an energy in one hour which is equal to that consumed by humans during one year [16]. Extraction part of this energy may resolve problems governed with global environment and energy, Nansen, 1995. Accordingly, so many research activities are concentrated on solar cells of different organic and inorganic glasses. Wafer based silicon is considered as the most applicable technology, however the interest to use amorphous thin-film and Cadmium Telluride (CdTe) technologies is less. Michael Gratzel and coworkers produced "Gratzel Cell" or the DSSC to simulate photosynthesis -the natural processes through which plants convert sunlight into energy- by sensitizing a Nanocrystalline TiO_2 film using novel Ru BIPYRIDL complex. In dye sensitized solar cell DSSC the initiation of charge separation is taken place by kinetic competition like in photosynthesis which leads to photovoltaic action. The recent researches proved that DSSC are reliable material class when both low cost and moderate solar cell efficiency are considered. [17], published a paper studied the transparent, Dye-Sensitized solar cells of high performance for See-Through photovoltaic windows. The research proved that Dye-Sensitized Solar Cells (DSSCs) are part of interesting photovoltaic technologies, and transparent DSCs are utilized as photovoltaic windows. However, the performance of transparent DSCs is limited due to the counter effect of photocurrent generation phenomena actuated by light absorption property with the light transmittance property reuired to ensure high transparency. The authors proved that transparent DSCs that occupy could acheive (3.66%) effeciency with light transmittance of 60.3%. The research is concentrated on the generation of a system which is composed of ultraviolet and near-infrared dye sensitizers that collect invisible or low-eye-sensitivity region light with high performance while transmit high-eye-sensitivity regions light. The novel design showed reliable results to be implemented for dual purposes due to its reasonable transparency property and its capability to be utlized as photovoltaic windows. [18], used concentrated light to increase transparent DSSC efficiency. They proved that transparent DSSCs are utilized for construction in modern architectural design building's to ensure reliable electrical power and day lighting. In this research, TiO_2 electrode thickness is changed to show the effect of transparency on performance of DSSCs. The 10 m thickness device shows 5.93% power conversion efficiency and 12.75 mA/cm^2 current generation that ensures transparency of 37% in the visible range. However, the main drawback that has been shown in the results is concerned with performance decrease in DSSCs during scale increase. This conclusion is realized using a DSSC optical concentrator to use small sized devices for more power generation. In addition, the results discuss the effect of operating temperature on the performance of bare and concentrator-coupled devices. Power conversion efficiency is increased by 67% under 1000 W/m^2 illumination at 36 ^{o}C for the concentrator-coupled device. Maximum current which is registered at 40 ^{o}C is 25.55mA/cm^2 in the concentrated coupled device, while current at the same temperature for the bare cell is 13.06mA/cm^2.

III. PHASE CHANGE MATERIALS (PCMS)

PCMs are defined as those whose phase is changed due to heat loss and gain. The phase change usually takes place at certain temperature which is recalled melting temperature at which the energy that is absorbed to change its phase. The exchanged energy is nominated as latent heat of fusion. The design criteria for using such type of material within structural material require that they change its phase at operating temperature close from building space temperature, 20 ^{o}C to 32 ^{o}C [12, 17]. PCM should also pose relatively high latent heat and high thermal conductivity per unit volume of the structural material; and they should also be safe environment wise.

A. *Classification of PCMs*

Figure 1 illustrates the main classified types of PCMs which are manufactured for proper work within the desired temperature range. Paraffin and salt hydrides could be considered as the most applicable PCMs for buildings application.

B. *PCM Integration Methods*

PCMs are usually used in lightweight indoor surfaces (walls, ceilings or floors) structures which could be considered effective to increase their thermal capacity. PCM could also be used in different ways in thermal envelopes of building (external walls/roof, windows/shutters, ventilation system). PCM in such types normally loses heat to the environment during night. Proper study is required for integration method taking under consideration all the physical properties and design limitations under consideration. The most applicable techniques that could be used for PCM integration into building structure are immersion, direct incorporation and encapsulation.

- Immersion means using melted PCM for building material immersion; capillary action is implemented for material absorption of the PCM.

- The PCM could be added directly during the production phase to the construction material.

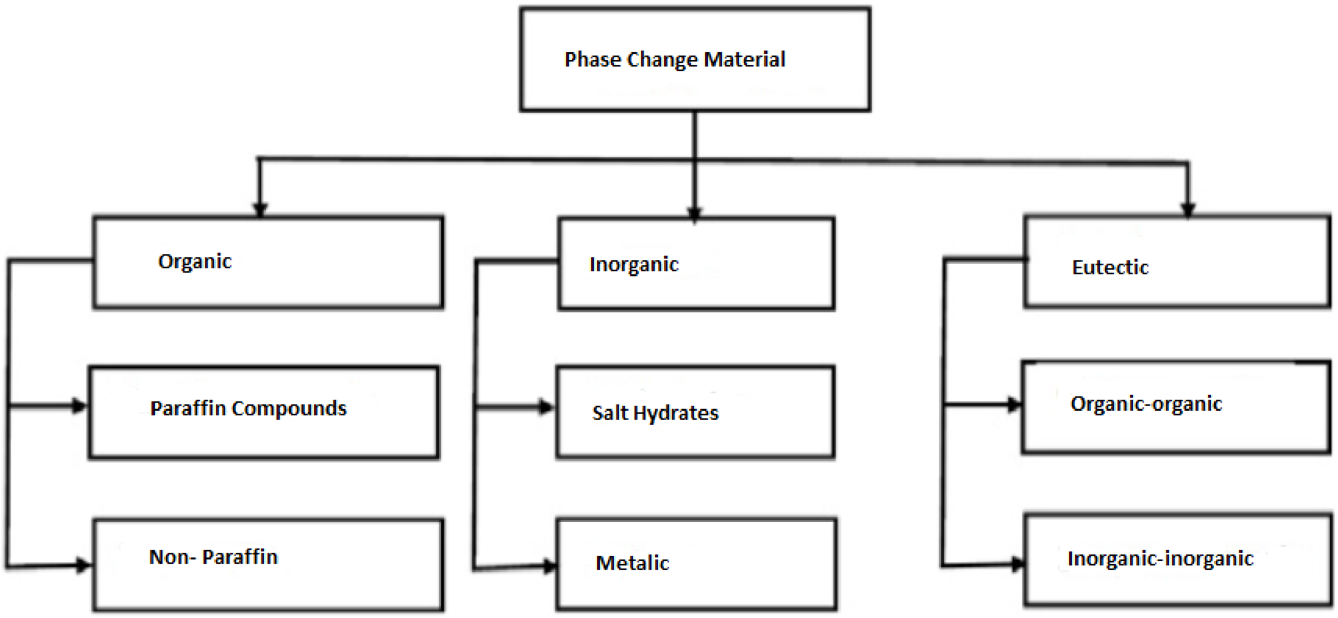

Fig. 1. Claasification of PCM's

C. *Transparent Solar Cells, TSC for Windows*

The low energy density of solar illumination necessitates deployment of solar technologies over large surface areas in order to capture enough of the suns energy. The obstacle of large-area deployment could be overcome with the development of a low cost transparent, photovoltaic PV technology that can be integrated onto window panes in homes, [19, 20]. Figure 2 illustrates the main effective components that are used in the transparent Photovoltaic (PV), which capturesing Ultraviolet (UV) and Near-Infrared (NIR) light and transmits visible light. The thin layers at the right used for PV coating could be precipitated on glass, plastic, or other transparent substrate. UV and NIR lights are absorbed in the core of the coating, accordingly the generated current will be capable to flow via the transparent layers when these electrodes are connected by external circuit. These type of lights are reflected back into the active layer, while (AR) layer which is considered as anti-reflecting layer reduces reflection and then increases the incoming light. TiO_2 electrode thickness and the incident light temperature have an effective role in describing the efficiency of such solar cells as proved by the recent scientific works. The design criteria in the recent work for usage of such type of solar cells are based on the production of 6 mw electricity per cm^2.

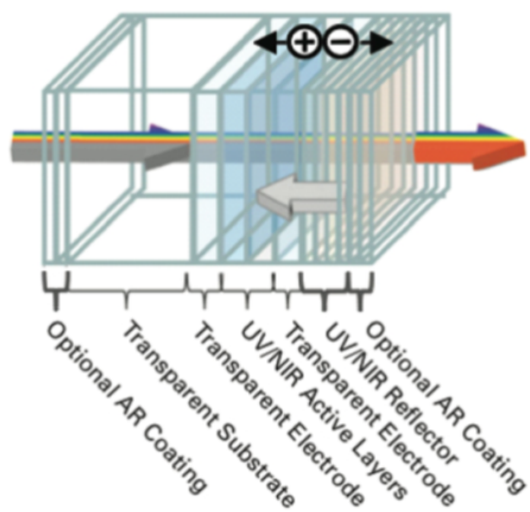

Fig. 2. Multi layer transparent solar cell windows, [19]

IV. POWER SAVING CALCULATIONS

A. *Power Saving Based on PCM Utilization*

The recent research estimates the effect of the structural material selection on power saving based on heat load calculations for typical residential house in Baghdad. Outside ambient temperature is estimated based on the average annual temperature records in Baghdad for several years. This approach takes under consideration that the design temperature inside the building according to the national standards is 21^0C [1]. The average values of the maximum and minimum temperatures and the estimated day and night hours per each month are estimated based on the annual temperature records in Baghdad according to the Iraqi Meteorological Directorate, IMD reference, see Table 1, [21]. The annual power consumption saving due to implementation of the PCM material in comparison to that based on classical structural material is estimated according to several assumptions. The calculations are based on the proportionality of the difference between the design temperature of building interior and exterior which is dependent on the day and night periods in addition to the nominated season, [22]. The architectural design of the residential house is shown in Figure 3. The total area of both floors is 300m^2, while the volume of the house is almost 900m3, see Figure 4. The total surface area of the walls and roof is 478 m^2. The wall and roof are designed with integrated PCM material of 0.25m thickness as the whole thickness of the wall. The PCM material selected for such type of building is n-Heptadecane whose thermal properties are listed in Table 2. For simplicity of calculation of thermal conductivity of the other structural material rather than PCM, it is assumed to be equal to PCM thermal conductivity, *k*, 0.2 W/m.oK. Table 3 and Table 4 highlights in yellow color the effective differences between the desired internal temperature of the house, 21^oC and the outside temperature per day or night per month during which PCM material melts during day and solidifies during night. While the difference highlighted in light blue color shows the period during which the PCM material continues its melting for 30 days during day period. Using very simplified assumptions the following approximate formulae could be used to express the relations between PCM thickness and its phase change temperature:

$$T_{m,opt} = T_r + 3Q/ht_{stor} \tag{1}$$

$$D_{opt} = (tn.h/.\Delta H).(Tom,opts - TN) \tag{2}$$

$$T_r = (tdTd + tnTn)/(td + tn) \tag{3}$$

Where;
$T_{m,opt}$: Optimal point of the PCM phase change, [^{0}C],
T_r: Average room temperature, [^{0}C],
Q: Heat absorbed by room surface unit area, [J/m^2],
H: Average heat transfer coefficient between the surrounded air and wall surface, [W/m^2.^{0}C],
Td: Room temperature during daytime, [^{0}C],

Based on the above formalized equations and substituting the assumed values related to the material properties including PCM heat capacity, Cp and the exposure of the typical residential house to the estimated temperature differences during day hours of May between house interior and exterior spaces, the thickness of the PCM in the designed integrated wall is calculated as follows:

$$q(w/m^2) = k.(\Delta T/\Delta x) \tag{4}$$

(a) Front view

(b) View at 45° angle

(c) Rear view

Fig. 3. Trypical architectural design of residential house with different views

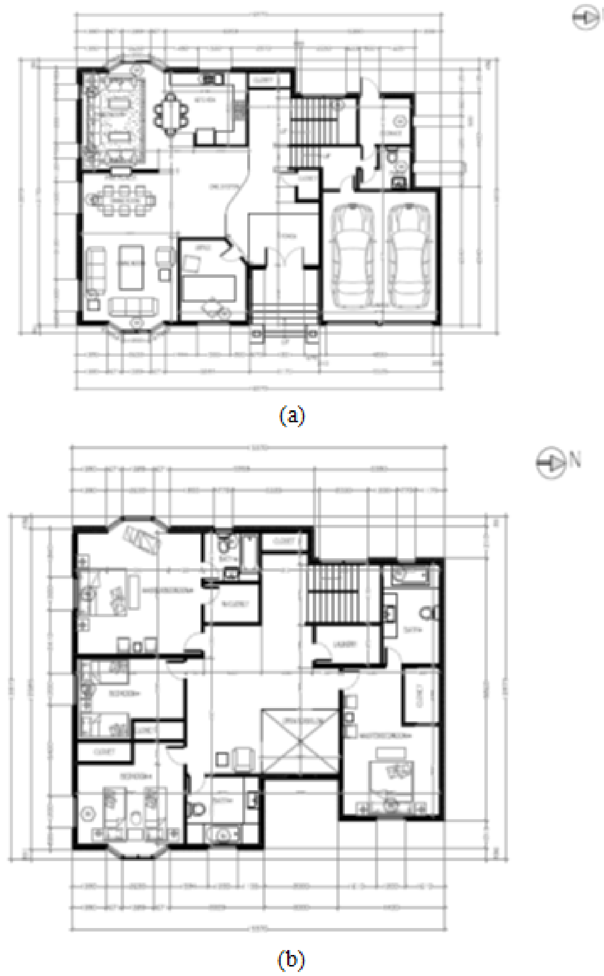

Fig. 4. House layout: (a) First floor (b) Second floor

$$h_m.M_{PCM} = q(w/m^2).t \quad (5)$$

$$th_{PCM}(m) = M_{PCM}/\rho_{PCM} \quad (6)$$

Where:
$q(w/m^2)$: heat from from outside to building inside per square meter
k:thermal conductivity of the integrated material, 0.3 w/m^2.^oC
Δx: thickness of the integrated wall,
h_m: heat of fusion of PCM, 215kJ/kg
M_{PCM}: Specific mass of PCM, kg/m^2
$th_{PCM}(m)$: Thickness of PCM inside integrated wall, m
ρ_{PCM}: PCM density, kg/m^3

The following shows the sample of calculations for the two categorized intervals which are based to cover the annual power saving based on PCM utilization:

1. The amount of power saving during March, April, October and November based on PCM melting and solidification energy exchange during day and night periods:

$E1/A = t.k.(\Delta T/\Delta x)$
$E1/A = 30d.(12hr/d).(0.2w/m.^oC).(3^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(11^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(9^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(6^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(12^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(5^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(3^oC/0.25m) + 30d.(12hr/d).(0.2w/m.^oC).(12^oC/0.25m)$
$E1/A = 17.9kw.hr/m^2$
$E1 = 17.9kw.hr/m^2 x478m^2$
$E1 = 8.56x103kw.hr$

2. The amount of power saving during May based on PCM melting only during whole month. $E2/A = t.k.(\Delta T/\Delta x)$
$E2/A = 30d.(14hr/d).(0.2w/m.^oC).(17^oC/0.25m) = 5.6kw.hr/m^2$
$E2 = 5.6kw.hr/m^2 x478m^2$
$E2 = 2.68x10^3 kw.hr$

The total power saving per year, E could be calculated by summation both *E1* and *E2*

$E_{PCM} = E1 + E2$
$= 8.56x10^3 kw.hr + 2.68x10^3 kw.hr$
$= 11.24x10^3 kw.hr$
Where:
A: The unit area of the wall, m^2
E1: The energy absorbed and released by PCM within four months, (March, April, September and October) that undergoes heating and cooling process during day and night.
E2: The energy absorbed by PCM during May (day and night) as the temperatures are in both intervals higher then the desired room temperature, Tr =21^{o}C.

TABLE 1
ANNUAL TEMPERATURE RECORDS IN BAGHDAD BASED ON IMT REFERENCES

Month	Minimum Temperature During Day °Hours Per Day	Maximum Temperature During Night °C	Hours Per Night	
January	4	10	16	14
February	9	10	19	14
March	10	12	24	12
April	15	12	30	12
May	20	14	36	10
June	24	14	41	10
July	26	14	44	10
August	25	14	44	10
September	21	12	40	12
October	16	12	33	12
November	9	10	24	14
December	5	10	17	14

TABLE 2
TEMPERATURE DIFFERENCES BETWEEN THE BUILDING

Month	Temperature difference at night, °C	Temperature difference at day, °C
January	(21-4)	(21-16)
February	(21-9)	(21-19)
March	(21-10)*	(24-21)*
April	(21-15)*	(30-21)*
May	(21-20)	(36-21)**
June	(24-21)	(41-21)
July	(26-21)	(44-21)
August	(25-21)	(44-21)
September	(21-21)	(40-21)
October	(21-16)*	(33-21)*
November	(21-9)*	(24-21)*
December	(21-5)	(21-17)

TABLE 3
THERMAL PROPERTIES OF THE PCM USED IN THE TYPICAL HOUSE

Melting point, ^{o}C	Density, kg/m^3	Thermal conductivity, w/m.^{o}C	Latent heat of fusion, kJ/kg
22	778	0.21	215

B. Power Saving Based on Transparent Solar cell, TSC Utilization

The classified windows which are selected to utilize transparent solar cells are shown in Table 4. The table shows the directions of these windows and their total effective areas, Aw,eff. The contribution of TSC,s in these windows to electrical power saving during night could be calculated as shown below:

The assumptions are made based on the metrological date related to Iraq climate. These assumptions covered the percentage of sunny days per month and the day light hours per month as shown in Tables 2 and 4.
$E_{TSC} = A_{w,eff}.t_{exp}.S\%.PTSC$
$= 66.55m^2.[122d.12hr/d.0.75]_1 + [123d.14hr/d.0.8]_2 + [120d.10hr/d.0.66]_3.60w/m^2 = 13x10^3 kw.hr$ Where:
E_{TSC}: Energy saved by the transparent solar cells used in the windows for night illumination purposes, kw.hrs.
$A_{w,eff}$: Total effective areas of the windows,m^2.
t_{exp} : The exposure time of the transparent solar cell windows to sun light, hrs.
S%: The percent of sunny days per each time interval. Suffix 1, 2 and 3: the time intervals 1, (March April, September, and October), 2, (May, June, July, and August), 3, (January , February, November, and December). If the electricity power produced from such type of cells is specified for illumination purpose only then these windows will substitute the general power consumption which could be estimated according to residential house are of 300m^2 as 0.5kw per hour.

Then total electrical power, Es could be calculated as shown below:
$E_s = 365d.10hrs/d.0.5kw$
$E_s = 1.825x10^{10}kw.hrs$

TABLE 4
POWER PRODUCTION RATE

Window Designation Number	Direction	Windows Total Effective Area*, $A_{w,eff}, m^2$
W1	2(south), 1(East) and (1) west	35.1
W2	2(south)	2.18
W4	1(east) and 1(west)	15.52
W5	3(south) and 2(east)	7.47
W7	1(west)	6.28

*Total effective area is the sum up of the windows areas of same sizes taking under consideration the expourse time percentage of such window to sun light per day interval hours.

V. RESULTS AND DISCUSSION

The yearly energy consumption is divided into two seasons; heating and cooling seasons. The heating season starts in October and ends in March while the cooling season extends from April till September. The heating and cooling energy demands for the selected model versus different PCM melting temperatures which were simulated through a simple mathematical model as shown in paragraph, 4.1. The consumed energy to compensate for temperature flactuation and maintain constant space temperature was calculated. The calculated energy excluded the effect of any air conditioning facility, and the ventilation supply air temperature was considered equal to indoor air temperature. Power saving results related to thermal load effect using PCM as wall integrated material showed 11.24x10^{3}kw.hrs per year, while that related to power saving allocated for illumination purposes by using tranparent solar cells showed 1.825x10^3 kw.hrs.

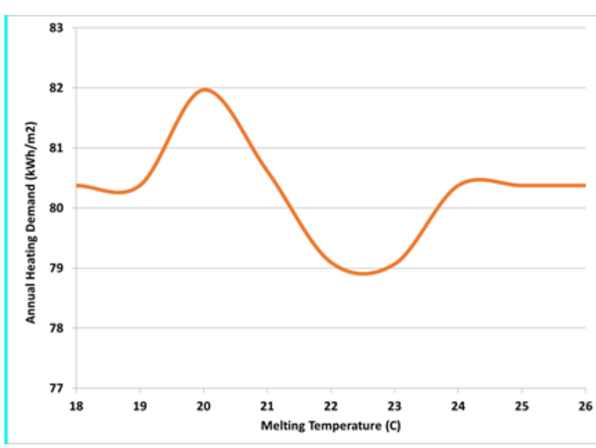

Fig. 5. Effect of PCM melting temperature on the annual heating demand, [13]

Based on the electricity power consumption price in Iraq, 0.25 USD/ kw.hr the amount of saving will be 3266USD per year which could be considered as an effective figure by the occupants and the governmental authorities. It is noted that the optimum melting temperature in winter and summer is 22C. Figure 5 represents heating load versus PCM melting temperature. Figure 6 shows the effect of cooling load on PCM melting temperature.

At the optimum PCM melting temperature, the heating energy reduces by 13.09% as compared to the base case, while the cooling energy reduction due to PCM jumps to 20.32% as compared to the the base case, [13].

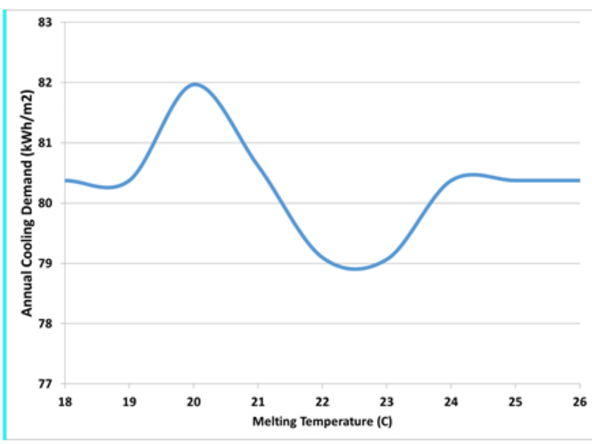

Fig. 6. Effect of PCM melting temperature on the annual cooling demand, [13]

The results prove that utilization of such type of constructional material is economic during residential building life, and the amount of power saving depends both on the architectural and civil design of it in addition to the type of these materials. The results show fluctuation in power saving percentge along year seasons and this fluctuation could be normalized by implementing more auxiliary power saving systems that are capable to flatten the production and consumption simultaneously.

VI. CONCLUSION

The recent work aims to estimate the feasibility of using structural mterial in modern residential buildings that simultaneously save and generate power and keep the same comfort of standard houses. The design criteria of the architectural design are to orient the building in such direction that optimize the utilization of tranparent solar cell windows for effective power generation during day light, while the design criteria of the civil design are based on embadding the PCM in the walls and ceilings for thermal power saving during the selected seasons. PCM affect energy reduction as follows: This ranges (18-22% lower cooling and 10-15% lower heating) based on maximum and minimum annual temperatures in Baghdad city. It is concluded from the research that the cost benefit from the utilization of phase change and transparent solar cells material in the buildings have an effective impact on the total heating and cooling cost required in the these buildings specially in countries that have a big difference in the summer and winter temperature differences in addition to saving the elecrical power required for illumination. Using the identified structural material did not have any additional cost impact when it is compared to the ordinary structural material. Another benefits from using such type of material summarized in low weight reasonable strength which adds some structural privileges in addition to its excellent thermal properties. Such type of material is recommended in special usage building that require an optimum design specification between strength, architectural and thermal properties. As future work the authors recommend to investigate a comparitive study among several PCM types and explore the economic effect of their utilization on power saving. This work could be backed up by experimental data that could be collected from tests on trypical building using climate simulation room. The other future work that could be recommended is to conduct an experimental study about the effect of building orientation of electrical power generation based on using transparent solar cells in the windows. Further work could be added to study the effect of utilization PCM material as emaded structural material and its effect on the indoor environment to comply with the ventilation requiremnts for acceptable indoor air quality [23].

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