Combined Effect Of Window-To-Wall Ratio And Wall Composition On Energy Consumption:

Where Is The Turning Point?

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ABSTRACT: Passive architectural techniques have been always recommended in order to maintain comfort inside buildings. In air-conditioned buildings, they will be of benefit in reducing the energy consumed for heating, cooling and artificial lighting.

Windows are considered weak points in the building envelope due to their lower resistance to heat transfer than opaque parts. By minimizing the window-to-wall ratio (WWR), a higher potential of controlling heat flow is possible due to the presence of larger solid areas that can be thermally insulated, however, this can also lead to an increase in energy consumed by artificial lighting. By increasing WWR, the energy consumed for lighting decreases. However, the space, then, becomes more liable for heat transfer by conduction and for being penetrated by direct solar radiation, both that can cause an increase in energy consumed for cooling, while in the meantime, opaque parts of smaller area would be of a smaller mitigating effect.

This research aims at exploring the effect of WWR and wall composition on energy consumption, and at defining the appropriate wall compositions for different WWRs as well as at defining the turning point after which thermal treatments of opaque parts of the envelope becomes relatively of no significant benefit. Test rooms including WWR ranging from 0-100% and wall compositions with and without thermal insulation layers ranging from 1-10cm were modelled and simulated for energy performance under different climates. Energy consumption results of the different alternatives were compared, and recommendations were outlined.

Keywords: window-to-wall ratio, thermal insulation, energy consumption, performance simulation, desert buildings.

INTRODUCTION

Passive techniques have been always recommended in architectural design in order to maintain comfort in buildings. However, air-conditioned buildings are now rapidly increasing especially in desert cities. Passive techniques, then, will be of benefit in reducing the energy consumed for heating, cooling and artificial lighting. The design of the building envelope and its components including transparent and opaque parts play an important role in passive design.

Windows, representing the transparent part, are considered weak points in the building envelope due to their lower resistance to heat transfer compared to opaque parts. The latter can contain layers of thermal insulation which aims at minimizing heat transfer and at decreasing energy consumed for heating and cooling. By minimizing the window-to-wall ratio (WWR), a higher potential of controlling heat flow is possible due to the presence of larger solid areas that can be thermally treated. However, this can also lead to an increase in energy consumed by artificial lighting. By increasing WWR, the energy consumed for lighting will decrease, but the space becomes more liable for heat transfer by conduction and of higher liability to be penetrated by direct solar radiation that can cause an increase in energy consumed for cooling. In the meantime, solid parts of the envelope would be of smaller area, and thus, adding thermal insulation in this case would be of a smaller mitigating effect.

The evaluation of both parameters: WWR and Wall composition in terms of energy consumption create a platform for energy consumption-based decisions in architectural design. Literature showed that the effect of both parameters on energy consumption in buildings was addressed in numerous previous studies. In most cases the effect of only one of them was studied individually. Few studies addressed their combined effect especially in desert climates.

The effect of thermal insulation thickness on energy consumption was studied to define the optimum external wall insulation thickness in three Chinese cities based on the minimum consumption of cooling and heating energy in office buildings with WWR 40% [1]. The effect of insulation position on cooling energy loads of residential buildings at Hong Kong was investigated by simulating a wall model with various placement of 15 cm insulation thickness with alternatives of positioning on internal side, middle part and external side of the wall [2].

Other studies addressed WWR. The optimum WWR for Office buildings was explored in Germany in order to reach the lowest total energy demands for heating cooling and lighting for different orientations. The highest difference in energy demands between the optimal WWR and the worst one occurred in the North facade, while south facades showed the smallest difference [3]. The effect of using solar screens on different WWRs on energy consumption was studied in the desert climate of Khargah, Egypt. The research found out that with no shading device, WWR 4% was the optimum one, while by adding solar screen, the same performance of the latter can be achieved by a WWR 22%. [4].

Few studies dealt with the combined effect of insulation thickness and WWR on energy consumption [5,6], in which a study was performed on cities in Turkey for the effect of WWRs 10-50% and insulation on heating consumption only, and in Thailand, where effect of position of insulation with three thickness alternatives were examined at WWR 0-30-60% and the effect on cooling loads was detected. However, in both studies, the effect on artificial lighting energy consumption was not accounted for.

The definition of a turning point before which adding thermal insulation is of a significant impact on energy consumption and after which become insignificant needs a comprehensive approach that takes all of heating, cooling and lighting energy into consideration. A wide range of WWRs and insulation alternatives can help define the both the individual and combined effect of both parameters in each orientation of the façade.

Literature showed that this issue needs further investigation for air-conditioned residential buildings especially in desert climates

OBJECTIVES

This research aims at defining the range of WWRs in which adding a layer of thermal insulation in external walls has a significant effect, and the turning point after which this effect becomes insignificant. The study aims, also, to detect whether the turning point differs across cities of different climates and across different orientations.

METHODOLOGY

A test room with a single externally exposed wall was modelled. Alternatives of WWRs ranging from 0% (no window) to 100% (full window wall) were tested with a step of 10% (0%, 10%, 20%, 30%....100%), Figure 1. Each WWR was tested for alternatives of thermal insulation thickness ranging from 0-10cm with a step of 1cm (0,1,2,3,….10cm). In order to fine-tune results WWRs of 2,4,6,8% were also tested.

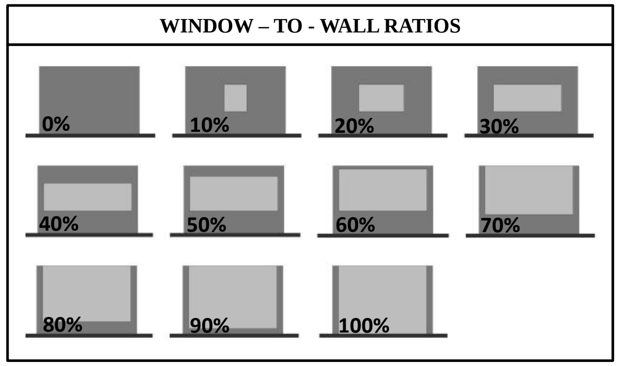

Figure 1: Tested window-to-wall ratios

The room was modelled using DesignBuilder software and simulated for energy performance using EnergyPlus. Heating, cooling and artificial lighting energy were accounted for. A light sensor was placed inside the room to dim the artificial lighting based on illuminance values. A residential occupancy schedule was assumed in which at least one occupant is always present. Simulation parameters are shown in Table 1.

Table 1: Simulation parameters of test rooms

SIMULATION PARAMETERS			
Test Room		**HVAC**	Setpoint
Dimensions	4X4m	Cooling	23
No. of people	2	Heating	21
Activity	Living	Type	Split
LIGHTING	Type	Fluorescent	Suspended
Daylighting control	Illuminance: 300 lux	Dimming: Linear/off	Sensor Height:
CONSTRUCTION			
Uninsulated wall	20cm concrete block + 2cm cement plaster each side		
Insulated wall	Two layers of 10cm concrete block + 2cm cement plaster on outermost and innermost sides with expanded polystyrene thermal insulation in between.		
Insulation thickness	Thickness :1, 2, 3, 4,……….10cm		
WWR	Range : 0, 10, 20, 30, ….. 100%		
Windows	Type	Double-glazed clear	
Roof	Insulated with 10 cm polystyrene foam		
CITIES	Alexandria, Cairo, Khargah, Berlin		

Simulations were performed for four cities: Alexandria, Cairo, and Khargah, located in Egypt, and classified as hot arid desert according to Köppen-Gieger climate classification [7], while the fourth was Berlin – was simulated for comparison – and classified as a temperate city with warm summer. Despite being classified as desert, the first three cities represent three different cases: Alexandria is a Mediterranean coastal city with a mild climate, Cairo is not coastal, and higher in daily maximum temperature, Khargah lies in the western desert of Egypt and is the highest in temperature. Berlin on the other hand has the lowest temperature, Figure 2.

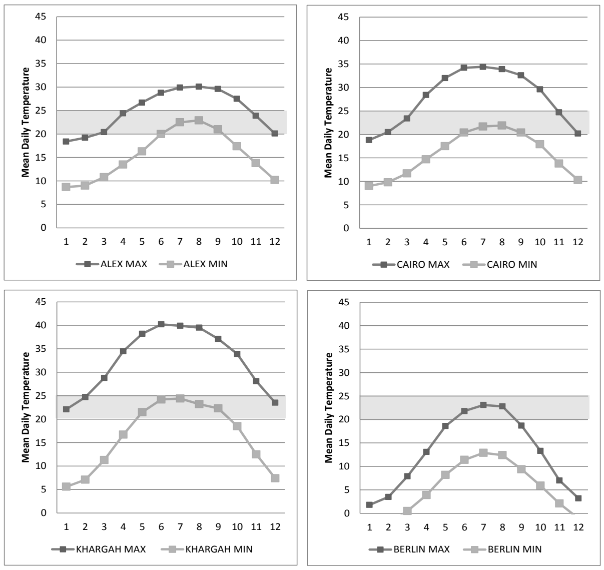

Figure 2: Mean daily maximum and minimum temperatures in tested cities for each month.

RESULTS AND DISCUSSION

Simulation results showed variations in energy consumption across the tested cases that can be explained as follows:

Window-to-Wall Ratio

To investigate the effect of WWR on energy consumption, the case of no wall insulation was tested for WWRs 0-100%. In the south direction results showed that energy consumption was highest at 100% WWR, while dropped down to the minimum consumption at WWR 8% in Alexandria and Kharga, and 10% in Cairo and Berlin. WWRs ranging from 6-10% were of very close consumption values.

Compared to a wall with WWR 0% (no window), the WWR of minimum consumption achieved 19% energy savings in Alexandria, 15% in Cairo, 8% in Khargah and 12% in Berlin, while WWR 100% increased energy consumption by 129%, 120%, 112% and 59% in these cities respectively. Figure 3 shows that despite the decrease that occurred in artificial lighting energy consumption at WWR 100%, the overall increase in all cities occurred due to the increase in cooling loads, even in Berlin. It also showed the magnitude of change in energy consumption in the desert cities was much more that in Berlin, which reflects the effect of desert climates and the high subjection to incident solar radiation.

In East and West directions, the WWR of minimum consumption ranged from 8 to 10% in all cities with minor differences in consumption between both cases in each city.

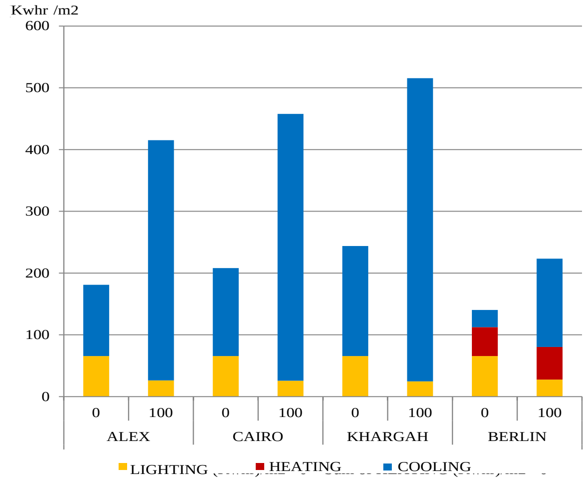

Figure 3: Energy consumption/m2 for WWR 0% and 100% in a south oriented façade with no insulation in tested cities.

In the North direction, the energy-efficient WWR was 20% in all cities, with differences between them in the amount of achieved energy savings that reached 27, 24, 19, 13% in Alexandria, Cairo, Khargah and Berlin respectively when compared to WWR 0%.

Orientation had an impact on the magnitude of effect of WWR on energy consumption. For example, by considering the case of no insulation and no window as a base case, in Alexandria, the WWR 100% - of the highest energy consumption – lead to an increase of 22, 90, 129 and 99% compared to the base case in North, East, South and West orientations respectively. Moreover, the range of WWRs that achieved savings was wider in the North orientation (up to WWR 60%) than in other ones in the same city (up to WWR 20% only), Figure 4.

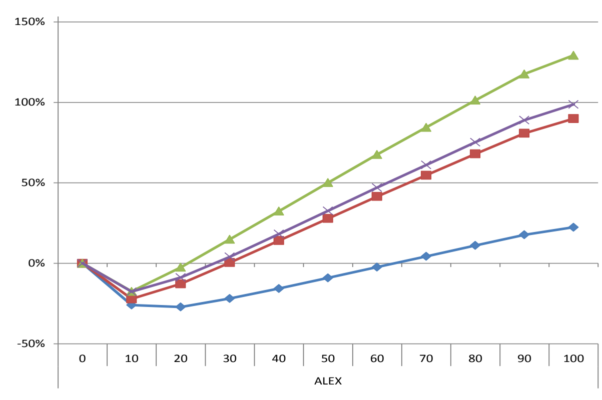

Figure 4: Percentage of energy consumption for WWRs 0% to 100% compared to a the base case (with no window and no insulation) in Alexandria.

In all cities, the energy consumption was always the lowest in the North orientation, followed by the East, while the South was always the highest. The West orientation was nearly the same as that of the South in Cairo and Khargah. In Berlin, The East, West and South directions were of close values with a range of only 5% difference in consumption.

Adding a layer of thermal insulation made significant changes in consumption values, however it did not alter the energy-efficient WWR across all tested cities.

Thermal Insulation

Thermal insulation changed the values of energy consumption in all cities compared to un-insulated cases. It resulted significant energy saving energy savings in some – but not all- tested cities.

By adding thermal insulation with thickness alternatives ranging from 1-10cm to the WWR 10% case facing North in Kharga city, for example, a gradual improvement in energy consumption occurred as the insulation thickness increased, Figure 5. At 10cm, savings reached 12% compared to the un-insulated case. Of this value, 4% savings were achieved only by a 1cm layer, 7% by a 2cm one and 10% at 5cm. This indicates that the additional 5cm of insulation was responsible for only 2% of energy savings. So, to select an appropriate insulation thickness for a certain WWR, it is recommended that this matter should be considered in terms of cost-efficiency in addition to energy consumption. A similar performance occurred in the other orientations.

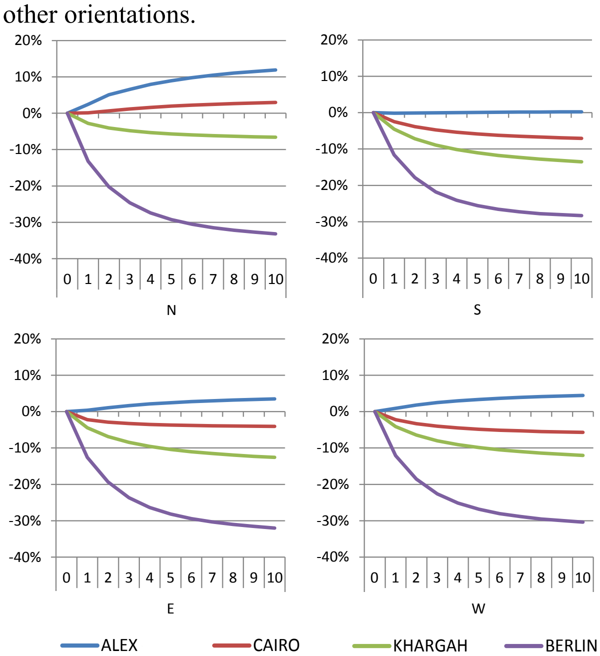

Figure 5: Percentage change in energy consumption for different insulation thicknesses compared to the un-insulated case at WWR 10% in all orientations.

In Alexandria, on the contrary, adding thermal insulation for WWR 10% did not result in any savings at all for different insulation thicknesses. Moreover, in the North direction it lead to an increase in consumption.

This can be explained by comparing the absolute values of consumption for both Alexandria and Khargah for that case in relation to the climatic conditions in both cities. In Khargah, where outdoor mean daily maximum air temperature reaches 40^{o}C, and is above thermal comfort level nearly all the year, there is a high potential for heat transfer through the building envelope by conduction, for which insulation proved efficient. While Alexandria, whose temperature is far below that of Kharga, with a much smaller difference between indoor and outdoor conditions, heat transfer by conduction becomes of much less potential. For that, insulation had a negative effect in the north direction as heat gained from outside or emitted from artificial lighting and internal loads become trapped indoors leading to an increase in cooling loads.

The combined Effect

The larger the opaque part of the façade, the larger potential impact of thermal insulation on energy consumption is. Also, The larger the transparent part of the envelope, the higher the liability of access of direct solar radiation and heat transfer though the window, and the lower the potential effect of thermal insulation, and consequently its thickness , on heat transfer and energy consumption. To detect the combined effect of both WWR and thermal insulation, the change in energy consumption between the insulated and un-insulated cases for each WWR was traced.

In Kharga, the difference in consumption between the un-insulated opaque wall (WWR 0%) and the case of 10cm insulation added in the middle of the wall was 14% energy savings in the South orientation. This value decreased to 10% at WWR 20%, and to 7% at WWR 30% and continued to decrease as WWR increased. A similar performance with a small difference in value occurred in the East and West directions, while savings in the North direction was much less and did not exceed 6% at WWR 0%.

A similar performance occurred in Cairo, with 10cm insulation. However, savings due to insulation started by 7% at WWR 0%, deceased to only 2% at WWR 30%.

In Berlin, thermal insulation achieved large savings in all orientations. This reached 24% at 10cm insulation in WWR 10% case oriented to South. This value decreased to 19% at WWR 20%, 14% at WWR 30%, and continued to decrease as WWR increased.

In Alexandria, a façade with WWRs 0% and 10% indicated no change in consumption due to insulation, a minor increase in consumption of about 1-3% was caused by increasing thickness of insulation in WWRs 20-80%.

The Turning Point

In order to define the turning point after which installing a layer of thermal insulation will be of no significant effect on decreasing energy consumption, the percentage of difference in consumption between both insulated and un-insulated cases in all WWRs in all orientations was calculated under all tested insulation thicknesses. The point at which this value was less than 5% savings was considered as a threshold to indicate that thermal insulation at a specified WWR was of no significant positive effect on energy saving, Table 2. Results, Table 2, showed that in Alexandria, thermal insulation was either of no significant effect on energy consumption, or of a significant effect but in a negative direction, leading to an increase in energy consumption. This indicated that using thermal insulation in walls of air-conditioned buildings in this city is not recommended in all orientations.

In Cairo, thermal insulation did not prove to be useful north and east facades. In the South and West, it proved useful only in case of WWR 0% (wall with no window) and WW10%. The threshold value was met at 4cm in the South and 5cm in the west directions. However, even at 10cm thickness, savings did not exceed 7%.

Table 2: Percentage of change in consumption due insulation thickness, compared to the case of "no insulation" in each WWR in all cities and orientations.

ALEXANDRIA — INSULATION THICKNESS

	WWR	1	2	3	4	5	6	7	8	9	10
NORTH	0	3.0	5.3	7.0	8.2	9.1	9.8	10.4	10.9	11.3	11.6
	10	2.5	5.1	6.6	7.9	9.0	9.8	10.5	11.0	11.5	11.9
	20	1.6	3.3	4.8	5.9	6.9	7.6	8.2	8.7	9.1	9.4
	30	1.5	3.0	4.2	5.1	5.9	6.5	6.9	7.3	7.7	8.0
	40	1.5	2.7	3.7	4.4	5.0	4.7	5.9	6.2	6.5	6.7
	50	1.3	2.3	3.1	3.7	4.1	4.5	4.8	5.0	4.3	4.5
	60	1.1	1.9	2.5	2.9	3.3	3.5	3.8	3.9	4.1	4.2
	70	0.9	1.5	1.9	2.2	2.4	2.6	2.8	2.9	3.0	3.1
	80	0.6	1.0	1.3	1.5	1.6	1.7	1.8	1.9	1.9	2.0
	90	0.3	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0
	100	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
EAST	0	0.7	1.3	1.9	2.3	2.6	2.8	3.0	3.2	3.3	3.4
	10	0.4	1.1	1.6	2.1	2.5	2.7	3.0	3.2	3.3	3.5
	20	0.9	1.7	2.3	2.8	3.1	3.4	3.6	3.8	4.0	4.1
	30	1.0	1.8	2.4	2.8	3.1	3.3	3.5	3.7	3.9	4.0
	40	1.0	1.7	2.1	2.5	2.8	3.0	3.2	3.3	3.4	3.5
	50	0.9	1.5	1.9	2.2	2.4	2.6	2.8	2.9	3.0	3.1
	60	0.8	1.3	1.6	1.8	2.0	2.2	2.3	2.4	2.5	2.5
	70	0.6	1.0	1.2	1.4	1.6	1.7	1.7	1.8	1.9	1.9
	80	0.4	0.7	0.8	1.0	1.0	1.1	1.2	1.2	1.3	1.3
	90	0.2	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.7
	100	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
SOUTH	0	-0.4	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
	10	-0.2	-0.1	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2
	20	0.4	0.7	0.9	1.0	1.2	1.3	1.3	1.4	1.5	1.5
	30	0.6	0.9	1.2	1.4	1.5	1.6	1.7	1.8	1.9	1.9
	40	0.6	1.0	1.2	1.4	1.6	1.7	1.7	1.8	1.9	1.9
	50	0.6	1.0	1.2	1.4	1.5	1.6	1.7	1.8	1.8	1.9
	60	0.5	0.9	1.1	1.2	1.4	1.4	1.5	1.6	1.6	1.7
	70	0.4	0.7	0.9	1.0	1.1	1.2	1.2	1.3	1.3	1.3
	80	0.3	0.5	0.6	0.7	0.8	0.8	0.8	0.9	0.9	0.9
	90	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
	100	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
WEST	0	0.9	1.6	2.2	2.6	3.0	3.2	3.4	3.6	3.8	3.9
	10	0.9	1.8	2.5	3.0	3.4	3.7	3.9	4.1	4.3	4.4
	20	0.5	1.4	2.1	2.6	3.0	3.3	3.5	3.7	3.9	4.0
	30	1.3	2.1	2.8	3.2	3.5	3.8	4.0	4.2	4.4	4.5
	40	1.2	1.9	2.5	2.8	3.1	3.4	3.5	3.7	3.8	3.9
	50	1.0	1.7	2.2	2.5	2.7	2.9	3.1	3.2	3.3	3.4
	60	0.9	1.4	1.8	2.0	2.2	2.4	2.5	2.6	2.7	2.8
	70	0.7	1.1	1.4	1.6	1.7	1.8	1.9	2.0	2.0	2.1
	80	0.5	0.7	0.9	1.0	1.1	1.2	1.3	1.3	1.4	1.4
	90	0.2	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7
	100	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2

CAIRO — INSULATION THICKNESS

	WWR	1	2	3	4	5	6	7	8	9	10
NORTH	0	0.7	1.4	1.9	2.3	2.7	2.9	3.1	3.3	3.5	3.6
	10	0.1	0.7	1.2	1.6	1.9	2.2	2.4	2.6	2.8	2.9
	20	-0.3	0.0	0.4	0.8	1.1	1.3	1.5	1.7	1.8	1.9
	30	-0.8	0.2	0.6	0.9	1.1	1.3	1.5	1.6	1.8	1.9
	40	0.1	0.4	0.7	0.9	1.1	1.3	1.4	1.6	1.7	1.7
	50	0.2	0.5	0.7	0.9	1.1	1.2	1.3	1.4	1.5	1.6
	60	0.2	0.5	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.3
	70	1.7	1.9	2.1	2.2	2.3	2.3	2.4	2.4	2.5	2.5
	80	0.2	0.3	0.4	0.5	0.6	0.6	0.6	0.7	0.7	0.7
	90	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4
	100	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
EAST	0	-1.3	-1.8	-2.2	-2.4	-2.5	-2.6	-2.7	-2.8	-2.8	-2.9
	10	-2.2	-2.9	-3.3	-3.5	-3.7	-3.8	-3.9	-4.0	-4.0	-4.1
	20	-1.0	-1.4	-1.6	-1.7	-1.8	-1.8	-1.9	-1.9	-1.9	-1.9
	30	-0.5	-0.6	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
	40	-0.2	-0.2	-0.2	-0.2	-0.1	-0.1	-0.1	-0.1	0.0	0.0
	50	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5
	60	0.2	0.3	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7
	70	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.6
	80	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
	90	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
	100	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SOUTH	0	-2.6	-4.0	-5.0	-5.6	-6.1	-6.5	-6.8	-7.0	-7.2	-7.4
	10	-2.5	-3.9	-4.8	-5.4	-5.8	-6.2	-6.5	-6.7	-6.9	-7.1
	20	-1.5	-2.3	-2.9	-3.2	-3.5	-3.7	-3.9	-4.1	-4.2	-4.3
	30	-0.9	-1.4	-1.7	-1.9	-2.1	-2.2	-2.3	-2.4	-2.4	-2.5
	40	-0.5	-0.8	-1.0	-1.1	-1.2	-1.3	-1.4	-1.4	-1.4	-1.5
	50	-0.3	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6	-0.6	-0.6	-0.6
	60	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
	70	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	80	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2
	90	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
WEST	0	-2.3	-3.5	-4.3	-4.8	-5.2	-5.5	-5.7	-5.9	-6.0	-6.2
	10	-2.2	-3.3	-4.0	-4.5	-4.8	-5.1	-5.3	-5.5	-5.6	-5.7
	20	-1.4	-2.0	-2.5	-2.7	-2.9	-3.1	-3.2	-3.3	-3.4	-3.4
	30	-0.8	-1.1	-1.3	-1.5	-1.6	-1.6	-1.7	-1.7	-1.8	-1.8
	40	-0.4	-0.6	-0.7	-0.8	-0.8	-0.8	-0.9	-0.9	-0.9	-0.9
	50	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	60	0.1	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
	70	0.1	0.2	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5
	80	0.1	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4
	90	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	100	0.0	0.0	2.9	0.1	0.1	0.1	0.1	0.1	0.1	0.1

KHARGAH — INSULATION THICKNESS

	WWR	1	2	3	4	5	6	7	8	9	10
NORTH	0	-2.1	-3.2	-3.8	-4.3	-4.6	-4.8	-5.0	-5.1	-5.2	-5.3
	10	-2.8	-4.1	-4.8	-5.3	-5.7	-6.0	-6.2	-6.3	-6.5	-6.6
	20	-2.8	-4.2	-4.9	-5.4	-5.7	-6.0	-6.2	-6.3	-6.4	-6.5
	30	-2.2	-3.3	-3.8	-4.2	-4.5	-4.7	-4.8	-4.9	-5.0	-5.1
	40	-1.6	-2.4	-2.8	-3.1	-3.3	-3.5	-3.6	-3.7	-3.7	-3.8
	50	-1.1	-1.6	-1.9	-2.1	-2.3	-2.4	-2.5	-2.5	-2.6	-2.6
	60	-0.7	-1.1	-1.3	-1.5	-1.6	-1.6	-1.7	-1.7	-1.8	-1.8
	70	-0.5	-0.7	-0.9	-1.0	-1.0	-1.1	-1.1	-1.2	-1.2	-1.2
	80	-0.3	-0.4	-0.5	-0.6	-0.6	-0.6	-0.7	-0.7	-0.7	-0.7
	90	-0.1	-0.2	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
	100	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
EAST	0	-4.4	-6.9	-8.5	-9.6	-10.5	-11.1	-11.6	-12.0	-12.4	-12.7
	10	-4.4	-6.9	-8.5	-9.6	-10.4	-11.0	-11.5	-11.9	-12.3	-12.6
	20	-3.1	-4.8	-5.8	-6.6	-7.1	-7.6	-7.9	-8.2	-8.4	-8.6
	30	-2.1	-3.3	-4.0	-4.4	-4.8	-5.1	-5.3	-5.5	-5.6	-5.7
	40	-1.5	-2.2	-2.7	-3.0	-3.2	-3.4	-3.6	-3.7	-3.8	-3.8
	50	-0.8	-1.1	-1.4	-1.5	-1.6	-1.7	-1.8	-1.9	-1.9	-2.0
	60	-0.4	-0.6	-0.7	-0.8	-0.9	-0.9	-1.0	-1.0	-1.0	-1.0
	70	-0.2	-0.3	-0.4	-0.4	-0.5	-0.5	-0.5	-0.5	-0.6	-0.6
	80	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3
	90	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOUTH	0	-4.7	-7.5	-9.3	-10.6	-11.5	-12.3	-12.9	-13.4	-13.8	-14.1
	10	-4.6	-7.2	-8.9	-10.1	-11.1	-11.8	-12.3	-12.8	-13.2	-13.5
	20	-3.3	-5.1	-6.4	-7.2	-7.9	-8.4	-8.8	-9.1	-9.4	-9.6
	30	-2.3	-3.6	-4.5	-5.1	-5.5	-5.9	-6.2	-6.4	-6.6	-6.7
	40	-1.6	-2.6	-3.2	-3.6	-4.0	-4.2	-4.4	-4.6	-4.7	-4.8
	50	-1.1	-1.6	-2.0	-2.3	-2.5	-2.6	-2.7	-2.8	-2.9	-3.0
	60	-0.6	-1.0	-1.2	-1.4	-1.5	-1.6	-1.7	-1.8	-1.8	-1.9
	70	-0.4	-0.6	-0.7	-0.8	-0.9	-1.0	-1.0	-1.1	-1.1	-1.1
	80	-0.2	-0.3	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6	-0.6	-0.6
	90	-0.1	-0.1	-0.1	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	-0.2
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.1
WEST	0	-4.6	-7.2	-8.9	-10.1	-11.0	-11.7	-12.2	-12.7	-13.0	-13.4
	10	-4.1	-6.5	-8.0	-9.1	-9.9	-10.5	-11.0	-11.4	-11.7	-12.0
	20	-2.9	-4.5	-5.5	-6.3	-6.8	-7.2	-7.5	-7.8	-8.0	-8.2
	30	-2.0	-3.1	-2.1	-4.2	-4.6	-4.8	-5.0	-5.2	-5.3	-5.4
	40	-1.4	-2.1	-2.5	-2.8	-3.0	-3.2	-3.3	-3.4	-3.5	-3.6
	50	-0.7	-1.0	-1.2	-1.3	-1.4	-1.5	-1.6	-1.7	-1.7	-1.7
	60	-0.3	-0.5	-0.6	-0.6	-0.7	-0.7	-0.8	-0.8	-0.8	-0.9
	70	-0.2	-0.2	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.4	-0.4
	80	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2
	90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

BERLIN — INSULATION THICKNESS

	WWR	1	2	3	4	5	6	7	8	9	10
NORTH	0	-11.3	-17.1	-20.1	-21.6	-22.4	-22.5	-22.4	-22.1	-21.7	-21.2
	10	-13.2	-20.2	-24.6	-27.4	-29.3	-30.5	-31.5	-32.2	-32.7	-33.2
	20	-11.9	-18.5	-22.5	-25.3	-27.5	-29.0	-30.1	-31.0	-31.7	-32.3
	30	-9.6	-15.0	-18.4	-20.7	-22.4	-23.7	-24.7	-25.5	-26.2	-26.7
	40	-7.6	-11.9	-14.6	-16.5	-17.9	-18.9	-19.7	-20.4	-21.0	-21.4
	50	-5.8	-9.1	-11.2	-12.7	-13.8	-14.6	-15.2	-15.8	-16.2	-16.5
	60	-4.3	-6.7	-8.3	-9.4	-10.2	-10.8	-11.3	-11.7	-12.0	-12.3
	70	-3.0	-4.7	-5.8	-6.5	-7.1	-7.5	-7.9	-8.2	-8.4	-8.6
	80	-1.8	-2.9	-3.6	-4.0	-4.4	-4.7	-4.9	-5.1	-5.2	-5.3
	90	-0.9	-1.4	-1.7	-1.9	-2.1	-2.2	-2.3	-2.4	-2.5	-2.5
	100	-0.2	-0.4	-0.5	-0.5	-0.6	-0.6	-0.6	-0.7	-0.7	-0.7
EAST	0	-10.9	-16.7	-19.6	-21.2	-22.1	-22.3	-22.3	-22.1	-21.8	-21.5
	10	-12.6	-19.3	-23.7	-26.4	-28.2	-29.4	-30.3	-31.0	-31.5	-32.0
	20	-10.1	-15.6	-18.9	-21.1	-22.8	-24.0	-24.8	-25.5	-26.0	-26.5
	30	-7.6	-11.7	-14.2	-15.8	-17.0	-17.8	-18.5	-19.1	-19.5	-20.3
	40	-5.5	-8.4	-10.3	-11.5	-12.4	-13.0	-13.6	-14.0	-14.3	-14.6
	50	-3.8	-5.9	-7.2	-8.1	-8.7	-9.2	-9.6	-9.9	-10.2	-10.4
	60	-2.6	-4.0	-4.9	-5.5	-6.0	-6.3	-6.6	-6.8	-7.0	-7.2
	70	-1.7	-2.6	-3.2	-3.6	-3.9	-4.2	-4.4	-4.5	-4.6	-4.7
	80	-1.0	-1.5	-1.9	-2.1	-2.3	-2.5	-2.6	-2.7	-2.7	-2.8
	90	-0.4	-0.7	-0.8	-1.0	-1.0	-1.1	-1.2	-1.2	-1.2	-1.3
	100	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SOUTH	0	-10.2	-15.5	-18.1	-19.4	-20.1	-20.2	-20.2	-19.9	-19.6	-19.2
	10	-11.6	-17.9	-21.8	-24.1	-25.6	-26.6	-27.2	-27.8	-28.0	-28.3
	20	-9.2	-14.0	-16.8	-18.6	-19.8	-20.6	-21.1	-21.5	-21.8	-22.0
	30	-6.7	-9.9	-11.8	-12.9	-13.6	-14.2	-14.5	-14.9	-15.0	-15.3
	40	-4.4	-6.6	-7.8	-8.5	-9.0	-9.3	-9.6	-9.8	-9.9	-10.1
	50	-2.8	-4.1	-4.8	-5.2	-5.5	-5.7	-5.9	-6.0	-6.1	-6.2
	60	-1.6	-2.4	-2.8	-3.1	-3.2	-3.4	-3.5	-3.5	-3.6	-3.6
	70	-0.9	-1.3	-1.5	-1.7	-1.8	-1.9	-1.9	-2.0	-2.0	-2.0
	80	-0.4	-0.6	-0.7	-0.8	-0.8	-0.9	-0.9	-0.9	-1.0	-1.0
	90	-0.1	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
	100	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
WEST	0	-11.0	-16.7	-19.7	-21.3	-22.1	-22.4	-22.4	-22.2	-21.8	-21.5
	10	-12.1	-18.5	-22.6	-25.2	-26.8	-28.0	-28.9	-29.6	-30.0	-30.4
	20	-10.0	-15.4	-18.8	-21.0	-22.8	-23.9	-24.8	-25.5	-26.0	-26.5
	30	-7.6	-11.8	-14.4	-16.1	-17.3	-18.2	-18.9	-19.5	-20.0	-20.3
	40	-5.7	-8.8	-10.7	-12.0	-12.9	-13.6	-14.1	-14.6	-14.9	-15.2
	50	-4.0	-6.3	-7.7	-8.6	-9.3	-9.8	-10.2	-10.5	-10.8	-11.0
	60	-2.8	-4.3	-5.3	-5.9	-6.4	-6.8	-7.1	-7.3	-7.5	-7.7
	70	-1.8	-2.8	-3.5	-3.9	-4.3	-4.5	-4.7	-4.9	-5.0	-5.1
	80	-1.1	-1.7	-2.0	-2.3	-2.5	-2.7	-2.8	-2.9	-2.9	-3.0
	90	-0.5	-0.7	-0.9	-1.0	-1.1	-1.2	-1.2	-1.3	-1.3	-1.4
	100	-0.1	-0.2	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.4	-0.4

Increase in Cosumption | 0 < Energy Savings< 3 | 3 ≤ Energy Savings< 5 | 5 ≤ Energy Savings< 10 | 10 ≤ Energy Savings | **TURNING POINTS BOUNDARY**

In Khargah, savings due to insulation were achieved in the four orientations. The threshold was met from WWRs 0%-30%. As shown in Table 2, the cases differed in the value of thermal insulation thickness needed to meet the threshold at each WWR case. More thickness was needed to meet the threshold at WWR 30% than in smaller WWRs. In all orientations, WWR of more than 30% did not meet the threshold as thermal insulation had a minor significance. In south orientations, near threshold values were achieved at WWR 40%. High savings (more than 10%) were achieved in WWR 0- 10% in the south, East and West directions.

In Berlin, thermal insulation showed a significant effect up to WWR 50% in South-oriented facades, WWR 60% in the East and West ones, and WWR 80% in the north direction. High savings were achieved by thickness starting from only 1cm. Savings increased as the insulation increased. They reached more than 30% in some cases. WWRs of larger than 80% in the north, 60% in the east and South, and 70% in the West did not meet the specified threshold.

CONCLUSIONS

The combined effect of window-to-wall ratio and thermal insulation thickness on energy consumed for heating, cooling and lighting in an air-conditioned residential building was explored in three desert cities: Alexandria, Cairo and Khargah, and in a city of a temperate climate; Berlin. The turning point after which thermal insulation proved to be of no significant effect was specified in the four orientations.

Results showed that in the moderate climate of **Alexandria**, thermal insulation was not useful, and moreover, it lead to increase energy consumption in many cases.

In **Cairo**, insulation proved useful only with the smallest tested window-to-wall ratios (WWRs 0% and 10%) in South and west orientations. Even with 10cm insulations, energy savings did not exceed 7%. It did not prove useful for WWRs above 30%

In **Khargah**, thermal insulation showed a significant effect in small WWRs, up to 30%. As thickness increased more savings were achieved. Savings exceeded 10% in small WWRs starting from 4cm insulation thickness. Insulation did not have a significant effect in WWRs larger than 40%.

In **Berlin**, insulation proved of a higher effect, and for a wider range of WWRs than all desert cities. Savings exceeded 30% in some cases. At WWRs higher than 80% in the north, 60% in the East and South, and 70% in the west, the effect of thermal insulation was insignificant.

Not in all desert climates did thermal insulation prove useful. It was of high significance in extreme hot and cold climate of Khargah, while in moderate climates, it did not prove useful in most of the cases in Cairo and all cases in Alexandria despite being classified as desert cities. It was of significant effect for a wide range of WWRs in Berlin.

FUTURE RESEARCH

As both the change in WWR and thermal insulation thickness have a direct impact on construction costs, as well as on the running consumed energy cost, it would be useful to address the combined effect and the turning point from a cost analysis perspective. This is to be done in future research.

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