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Relation between Energy Consumption and Window to Wall Ratio in High-Rise Office Buildings in Tehran

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Abstract

Development and expansion of high-rise buildings in Iran and the high energy consumption thereof have made adoption of energy consumption reduction strategies a necessity. Building shell and its various parts are the most effective elements in terms of energy consumption. Paying due attention to this fact, the authors of the present article investigate the relation between the window to wall ratio (W.W.R) and energy consumption in high-rise office buildings subjected to climatic conditions in Tehran. The eQUEST software was used to simulate the annual energy consumption of the considered base-case model. In this process, a 100% W.W.R was initially selected for the base-case model. Then, the research tests were conducted at W.W.R of 80%, 60%, 40%, and 20% both generally and individually (side-to-side test). The results showed that the window to wall ratio and annual energy consumption were directly related, i.e., a 20% reduction in the W.W.R could decrease the annual energy consumption in the research base-case model by 17%. Furthermore, the results indicated that the W.W.R affected the energy consumption differently at different sides of the base-case model and that in this respect, the building sides could be prioritized in the following order: south, east, west, and north.

Keywords: High-rise building, Energy consumption, Building energy simulation, Window to wall ratio

Introduction

High-rise buildings have, since the formation of human civilization, held a particular fascination for man. In the 20th century in particular, the following problems established the construction of high-rise buildings as a basic necessity in large cities the world over: population growth, the need for greater urban settlement as well as making more efficient use of the land in densely populated city centers, the necessity for reconstruction and renovation of urban areas, people's request for working and residing in cities, the necessity for reducing the costs associated with horizontal development of urban areas, and, last but not least, huge technological advances. However, development and spread of modern high-rise buildings throughout the past century have also been associated with multifarious problems including lack of attention to harmony between high-rise buildings and nature, serious environmental contamination, and excessive consumption of natural energy resources. In his research entitled "Designing Ecological Skyscrapers", Kean Yeang enumerates the following factors as causes of these negative aspects:

- Excessive energy and nonrenewable resources consumption during construction, utilization, and even demolition of tall buildings
- Deployment of more materials in structural systems for increasing resistance against lateral forces (bending, wind, etc.)
- More energy consumption for transporting people as well as pumping materials against gravity to the upper floors)Yeang, 2007, 411)

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Since high-rise buildings, due to the various requirements of human societies, are here to stay and their number is growing by the day, it is absolutely necessary to adopt appropriate strategies and models in an effort to reduce their hazardous environmental impacts to a minimum. As a considerable proportion of world energy consumption is allocated to the construction industry, and as fossil fuel resources are on the decline, it is essential for those active in the field of architecture to pay due attention to energy-efficiency as well as economizing aspects in the construction of high-rise buildings.

In Iran, this problem has come to the fore since the energy subsidies were removed and energy carrier prices followed the free market rates. The construction codes and regulations in Iran are basically in the form of general criteria on building location and features of urban landscape and are not inclusive of high-rise buildings or energy considerations. As such, these regulations do not recognize the energy consumption reducing/saving aspects of architecture. In particular, the energy consumption reduction strategies presented mostly in the construction phase are not architectural in nature and are merely amendments required for completion of construction phase. These elements can bring about the required effects only if the buildings are built in accordance with climatic models and rules, and this is what is currently lacking in the architectural filed in Iran.

The purpose of this study is to present models for designing high-rise office buildings in Tehran according to the City's climatic zone, as well as specific strategies for designing openings in geometrical high-rise buildings in an effort to reduce energy consumption.

Background

The previous research conducted on the envelope of buildings as well as on energy consumption in high-rise buildings, has mostly been specialized without paying due attention to the general aspects of the same. A quick look at the research in this field reveals that in most cases, only one or two features of a high-rise building envelope and their energy consumption effects are studied. For example, Bojic considers the effect on cooling loads in Hong Kong high-rise buildings of thermal insulation location as a building envelope component (Bojic, 2002, 347-355). In another study in 2002, the same author investigated the thermal function of windows in Hong Kong high-rise buildings (Bojic *et al.*, 2002, 71-82).

In their more detailed work, some researchers studied certain prevailing conditions in high-rise buildings and their envelopes, comparing the energy consumption in such buildings with the requirements of the existing standards and, at the same time, investigating the role of the envelope in energy consumption and making general suggestions in different cases. In their analysis titled "Energy Performance of Building Shells in various Chinese Climates", Yang *et al* (2008) first selected examples of high-rise buildings from various climates in China, and then compared the energy consumption of these buildings with those specified in Chinese as well as ASHRAE standards. They further described the role of the buildings envelope in reducing energy consumption in an effort to bring closer the buildings energy consumptions to the levels specified in the existing standards (Yang *et al.*, 2008, 800-817) while presenting general strategies in this regard. Other researchers tried to take a closer look at the envelope in high-rise buildings and its effect on energy consumption. Examples in this regard are Cheung *et al.* (2005, 37-48), Eskin *et al.* (2008, 763-773), and Yu *et al.* (2008, 1536-1546) which are considered in more detail in the following.

The common feature in these studies is their limitation in various fields, which renders them less reliable to a certain degree. The greater part of the research on envelope energy consumption effects of high-rise buildings regards hot and humid climatic conditions, particularly in Hong Kong. Examples include Lam (1993, 157-162), Higgs (1994, 91-95), and Leung *et al.* (2005, 147-156). Another feature of such research is that it is generally centered on high-rise residential buildings as the dominant application of this construction species. In his research in 2001, Bojic investigates the role of the envelope and location of thermal insulation on cooling loads in high-rise buildings under Hong Kong climatic conditions (Bojic *et al.*, 2001, 569-581). Yu *et al.* (2008, 1536-1548) studied the design of residential buildings envelope in China. Cheung (2005) also examined the energy work shell design for high-rise residential complexes in Hong Kong (Cheung *et al.*, 2005, 76-84).

As was mentioned before, the above research as a whole, basically considers specific rather than general aspects of energy consumption in high-rise buildings. This is in contrast with the purpose of the present study, namely, energy consumption relation to the W.W.R in high-rise office buildings. Another example of the previously conducted research is Bojic (2002) where cooling loads are considered as the sole effective element on energy consumption. Moreover, Eskin and Yu (2008) considered cooling and thermal loads, as well as their sum as the total energy consumption, in identifying the relation between the envelope elements and energy consumption (Eskin *et al.*, 2008, 763-773; Yu *et al.*, 2008, 1536-1546). Cheung also bases his energy consumption study on cooling loads. Another important aspect of the present research that is not considered in previous research is prioritizing the W.W.R based on envelope orientation as well as the effect of the same on energy consumption.

Materials and methods

By taking into consideration the proposed road map, the authors take different steps to obtain the desired results, following a certain strategy in each step. This is a quantitative research aimed at finding a relation between energy consumption and the W.W.R in high-rise office buildings. The descriptive and correlation approach was used in this study. In the literature review step, the authors use interpretive-historical strategies; in the variable test and logical deduction step, they use simulation; and finally, in the variable test analysis/conclusion step, they turn to descriptive statistics.

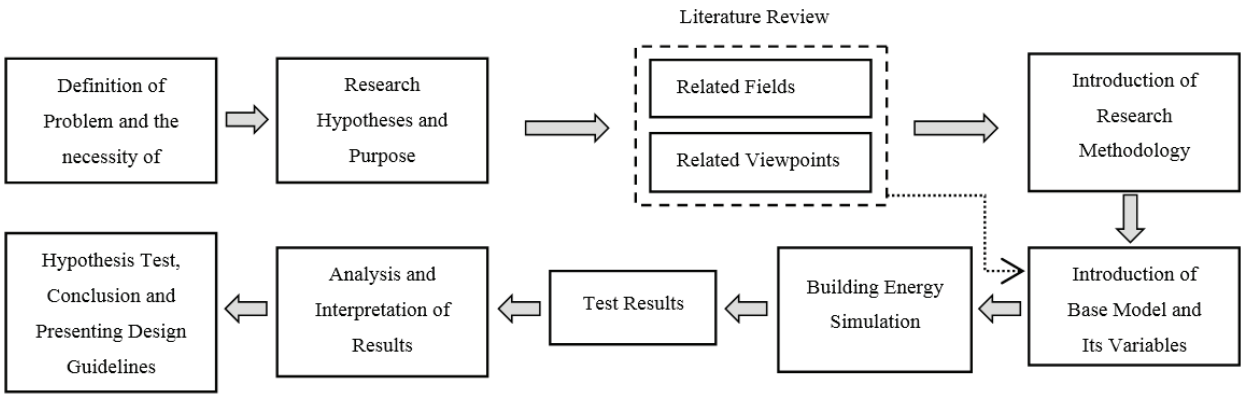

Figure 1: Proposed Research Procedure

Energy Consumption in High-Rise Buildings

Economic progress, population growth, globalization, and promotion of living standards in developed countries have all lead to greater utilization of energy resources. According to the International Energy Agency statistics, world energy consumption has increased by 50% in the past two decades and by approximately 70% since the 1970's. At the present rate, it is estimated that by 2020, the energy consumption in the developing countries, e.g., in the Middle East, will increase by 32% (Perez-Lombard *et al.*, 2008, 394).

Energy is consumed in various ways. The most important consumers of energy are the industries including transportation and construction industries. Statistics prove that a great share of the whole energy in the world is allocated to the construction industry: about 42% as compared with the 30 and 28% spent in the industrial and the transportation sectors respectively (Perez-Lombard *et al.*, 2008, 396). Building occupancy plays an important role in its energy consumption. For example, office occupancy consumes 20% of the total energy consumption of buildings. From a different point of view, energy consumption in the construction industry is a function of building occupancy.

In spite of the extensive research conducted on high-rise buildings various aspects including performance, architectural style, structural strategies, etc., few studies have investigated energy consumption in such buildings. Effective factors on energy consumption such as form, shape, natural light utilization, ventilation strategies, etc, have not so far been broadly studied. Among such studies, Oldfield *et al.* (2009, 591-613) followed a more targeted and comprehensive research. They divided high-rise buildings in terms of their energy consumption features and applications into five periods:

- First Period: From 1885 when the first high-rise buildings were constructed in 1916, during which dense constructional forms with minimum envelopes were designed for comfort in winter as well as natural light utilization.
- Second Period: From 1916 (legislation of New York Construction Code) to 1915 (development of glass facades). During this period, due to technological advances in installations and artificial light generation, as well as the development of pyramid shaped buildings, thermal energy consumption and, as a result, the total energy consumption in buildings increased.
- Third Period: From 1915 to the beginning of the Energy Crisis Era in 1973 when square block high-rise buildings with vast work spaces at various floors were developed. In these buildings, thermal energy absorption and dissipation through the outer building shells lead to increased overall energy consumption in the building.

• Fourth Period: From 1973 till now during which the energy crisis affected the deployment of vast glass facades in buildings, and new codes were introduced in the developed world for saving energy, including recommendations for using double-glass windows in building facades. Also, standards were compiled for office buildings which restricted utilization of artificial light.

• Fifth Period: From the introduction of environmental and sustainability perspectives in 1997 to the present, during which a new approach was adopted in the design of high-rise buildings. A great number of tall buildings were built aimed at reducing energy consumption through utilization of static solutions.

Energy Consumption Simulation in Buildings and Application Software

Among the tools available to architects, designers, and engineers in the study of energy-related behaviors, energy simulation software are the most efficient. Through creating a virtual building environment, these software packages provide for the expert the opportunity to predict the actual performance of the building as well as optimize and improve its design and make use of new energy-efficient technologies for it (Henseen, 2002, 1-14).

Like other technologies, simulation technology has also seen new advances, in both quality/capabilities and quantity/number of simulation software. There are more than 330 thousand simulation packages for energy consumption with extensive applications in various energy-efficiency measurement fields, renewable energy simulations, and sustainably efficient solutions. A brief summary of the capabilities of the introduced software is provided at the following website address: www.energytoolsdirectory.gov. In terms of suitability for architectural requirements, the best energy simulation packages are as follows (Ghiai *et al.*, 2013): Ecotect, ESP-r, TRNSYS, and eQUEST.

For selecting the most suitable packages for architectural simulations more exactly and reliably, we must compare their practical and theoretical features of the software. Thus, the final solution would offer itself in the form the interface of these features. Considering certain disadvantages associated with TRNSYS, namely, incomplete documentation, FORTRAN compiler requirement, and use of non-SI units, we ultimately end up with two choices: Ecotect and eQUEST. In the present research, the eQUEST was used for simulation purposes. The DOE-2.2 computational engine used in this software has been reliably used for more than two decades throughout the world. The eQUEST software is the result of putting together user graphics layer and design guiding tools (enhanced DOE-2 + Wizards + Graphics) which help the user through the step-by-step building design process. The software provides two different guiding processes for users. These user guides provide the user with various design options so that she can complete her step-by-step design. The software is designed in such a way that the user is prompted to provide the required information for the DOE-2 computational engine (Elahibakhsh and Shahmohammadi, 2007). The other capabilities of this software include structural design, equipment and mechanical installation design, building size and function (occupancy), floor layers arrangement, construction materials, and surface/space as well as lighting system utilization. Among the important features of the software are the multiple alternative simulation cases which enable the user to make comparisons regarding monthly and annual energy consumption of different buildings. This feature is utilized in the present study. To enable this capability, the software uses two methods (Hirsch and Associates, 2009):

1) Energy Efficiency Measures (EEM) which is used for simpler models restricted to specific changes.

2) Parametric Run which provides more change options in terms of both complexity and number.

Base-case model Introduction

To study and test the research variables, we must first introduce a model or sample as the main research basis so that the behavior/effects of the research variables can be compared with it (Ghiai, 2011). As the present research is about optimum features of high-rise office buildings envelope, the research base-case model also had to be a high-rise office building the physical properties of which were fully specified. For simplicity, these specifications are divided into two groups: "architectural-structural" specifications and "building services" (mechanical installations) specifications. Due to the architectural approach adopted in the present study, the former specifications are considered to be more important.

As the first step in determining the architectural-structural specifications for the base-case model, it is necessary to present the relevant information for the building skeleton, core type, number of storey, floor area, storey height, the elements, etc. This information is presented in Table 1.

Table 1. Base-case model specifications

Planl Geometry: Rectangle Plan Proportions: 1: 1/35 Plan Dimensions: 35m x 26m Plan Spatial Arrangement: Open Space Storeys: 15 storeys + 3 storeys underground Storey height: 4m (floor to floor) (floor height up to the false ceiling = 3m; False ceiling height = 60 cm) Storey Area: $745m^2$ (net) (82% of total storey area); Core and Service Areas for each Storey: 165m2 Direction of Rotation: 30 degrees south east (in Tabriz) and 15 degrees south east in Yazd Building Skeleton Type: Concrete Skeleton and Central Core (total area: 165 m2 equal to 18% of storey area)	General Specifications	Architectural-Structural Characteristics
Exterior wall Structure: Cement Plaster (2.5 cm), Concrete Wall (15 cm), Finished Plaster Cover as well as Paint (2.5 cm) Roof Structure: Mosaic Flooring (2.5 cm), Sand-Cement Mortar (2.5 cm), Roofing, light-Weight Concrete (5 cm), Structural Floor (25 cm) Storey Floor Structure: Stone Flooring (2.5 cm), Sand-Cement Mortar (2.5 cm), light-Weight Concrete (5 cm), Structural Floor (25 cm) Underground (Basement) Wall Structure: Concrete Wall (30 cm), Roofing Outer Wall Paint: Medium (Absorption Coefficient = 0.6) Opening Type and Material: 6 mm Double Glass (Double Clr/Tint) with the following Specifications: U: 0.54, SHGC: 0.7, VT: 0.79	Elements/Wythe Specifications	

The tools and mechanical installation (building services) features used in the base test model are selected based on proper assumptions made in the simulation tool (i.e., eQUEST software) for high-rise office buildings. Upon the introduction of the base-case model characteristics, it is necessary to introduce certain test conditions in the form of adjustment and control variables so that variable tests can be properly conducted. For example, climatic conditions, the number of hours and days the building is used, the degree of building occupancy by users, the tools used by users, etc. are among the factors and conditions the consideration of which would increase the reliability of the obtained results.

Research Variables

The variable used in this research as an element of high-rise office building envelope (base-case model) is the W.W.R. In the present study, the W.W.R is defined as the ratio of transparent (window) area to the opaque (envelope) area, where the opaque area is calculated as the product of the wythe length and the useful story height (from the floor elevation to the false ceiling elevation). In the W.W.R variable test, the purpose is to study the behaviors as well as the effect of the W.W.R on the total are duly analyzed. Energy consumption in the sample building introduced in the research where the W.W.R is assumed to be 100%. This means that at each outer building wythe front, the length of the transparent (window) is equal to the wythe length and the height of this area is equal to 3 meters.

The W.W.R variable test for determining its effect on total energy consumption is conducted in two main parts. In the first part, namely, the general part, the W.W.R of the base-case model is changed on all the wythes (northern, southern, eastern, and western sides) from 100% to 20%, 40%, 60%, and 80% respectively (Figs. 2, 3, 4 and 5). In the second part, the W.W.R variations are separately tested on each side. In other words, at each stage of the test, the W.W.R changes only for one side, and on all the other sides, the W.W.R retains its previous value of 100%. Ultimately, the results obtained from this test for Tehran Metropolis climatic conditions are expressed. The remarkable point in the W.W.R test is that, due to the limitations imposed by the software, and for simpler calculations, the opening (window) shape was considered as a strip. Moreover, to consider the occupancy of the building architecturally, the distance of the opening from the floor and the ceiling was reduced by an equal amount.

Figure 2: W.W.R= 20%

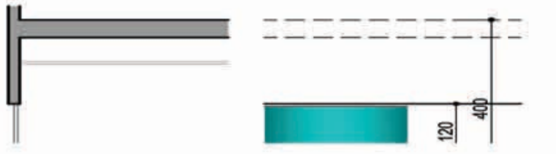

Figure 3: W.W.R= 40%

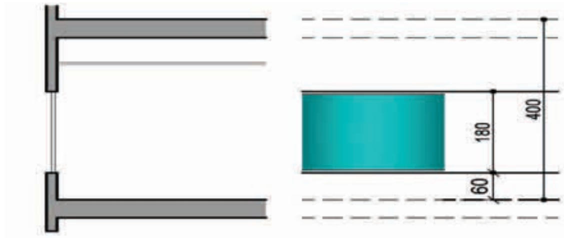

Figure 4: W.W.R= 60%

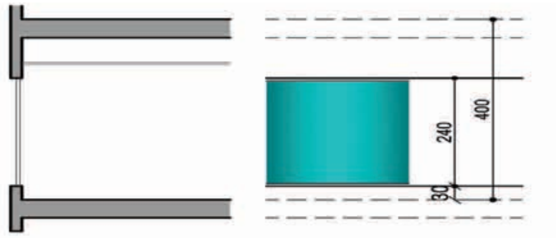

Figure 5: W.W.R= 80%

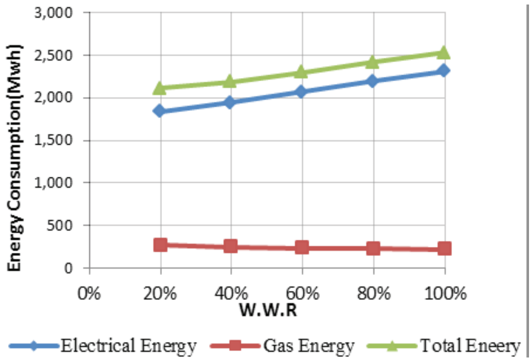

Diagram 2: Variations of electricity, gas, and total energy consumption with W.W.R

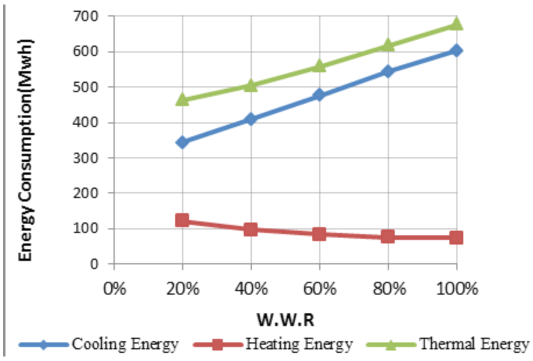

Diagram 3: Variations of heating energy, cooling energy, and thermal energy with W.W.R

The above diagrams indicate the results obtained from the W.W.R variable test for Tehran climatic conditions in the general case. The results of the same test were also obtained in the special case, i.e., for different sides of the building separately. Upon completion of research variable test results, it is necessary to analyze these results so that general conclusions can be derived from them. In this section, the results obtained from the W.W.R test conducted separately under Tehran climatic conditions.

The total energy consumption in the building was chosen as the criterion for investigation and classification of test results. However, studying the thermal behavior of the building can also greatly help in the correct classification of these results.

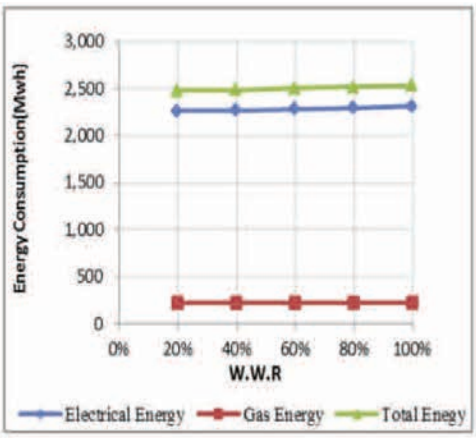

Diagram 4: Variations of electricity, gas, and total energy consumption with W.W.R on the northern orientation

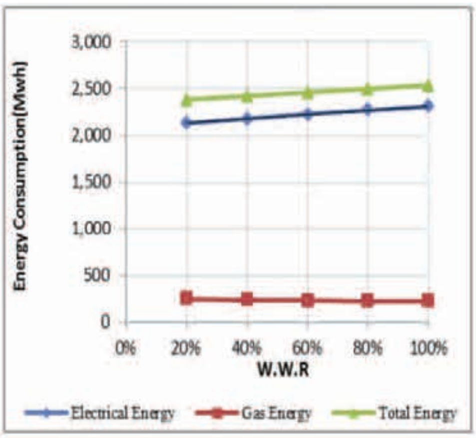

Diagram 5: Variations of electricity, gas, and total energy consumption with W.W.R on the southern orientation

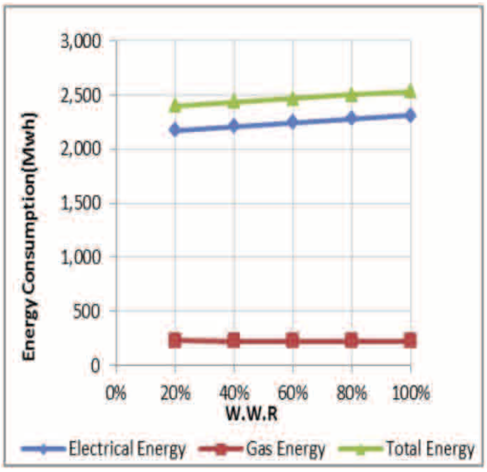

Diagram 6: Variations of electricity, gas, and total energy consumption with W.W.R on the eastern orientation

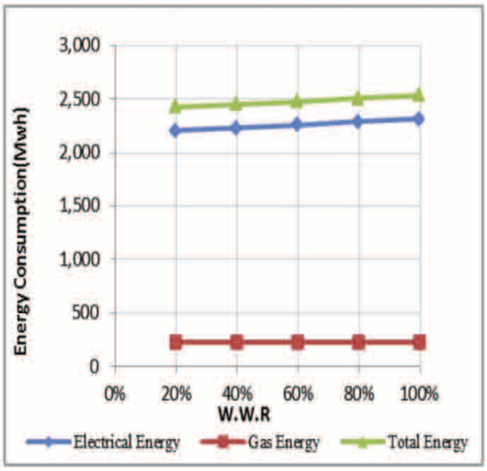

Diagram 7: Variations of power, gas, and total energy consumption with W.W.R on the western orientation

Results and Discussion

In the first part of the W.W.R test where this ratio varies equally in all directions, the results show that the total energy consumption in Tehran decreases as the W.W.R is reduced (Dia. 8). This reducing trend results in an overall 17% reduction in Tehran total energy consumption. The W.W.R has a similar effect on the base-case model thermal performance, i.e., a decrease in this ratio leads to a decrease in thermal energy consumption (Dia. 11). Considering that the correlation coefficient (R2) between the W.W.R and energy consumption is very close to 1, these two factors are directly correlated at a high level (Dia. 9). Moreover, the results from the above diagram indicate that the most reductions under Tehran climatic conditions occur at W.W.R between 20% and 40%.

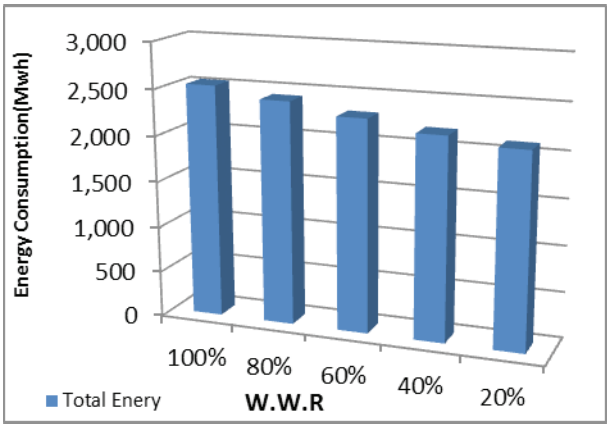

Diagram 8: Total energy consumption in Tehran in terms of various W.W.R

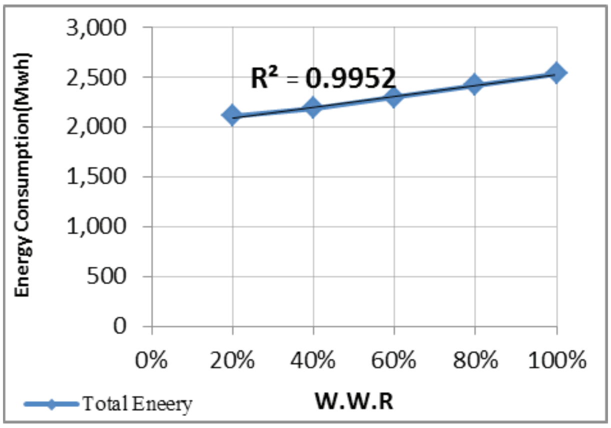

Diagram 9: Correlation between W.W.R and total energy consumption in Tehran

Study of thermal loads also points to a direct relation between them and the W.W.R variation. W.W.R variation in Tehran can reduce total thermal loads by 32%. The interesting point is that the cooling behavior is different from the heating behavior as the W.W.R changes, i.e., reducing the W.W.R leads to an increase in the heating loads (Dia. 11).

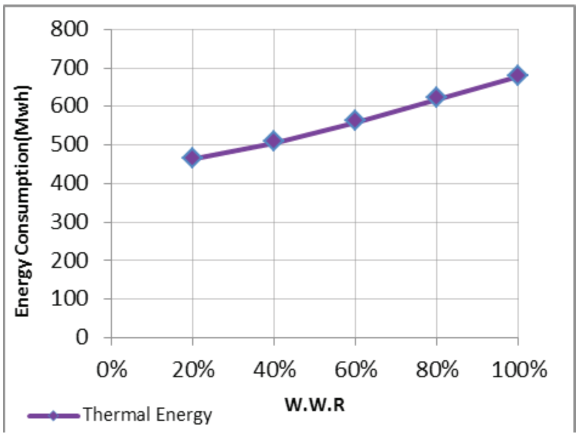

Diagram 10: Total thermal energy consumption variations with W.W.R in Tehran

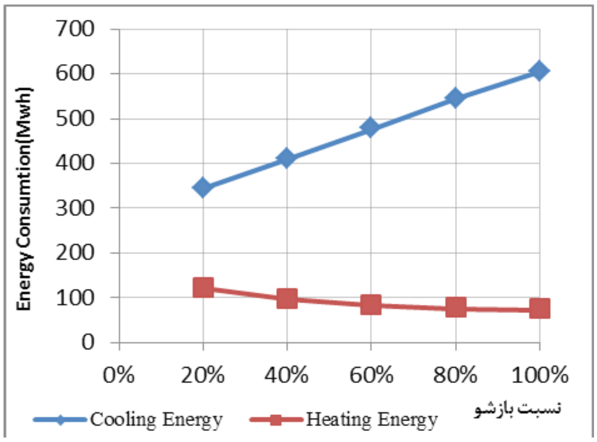

Diagram 11: Cooling and heating energy variations with W.W.R in Tehran

In the next step of the test, again the effect of the side-to-side (direction-to-direction) W.W.R on total energy consumption reduction can be observed. However, the crucial point here is whether this effect is uniform for different directions in the City of Tehran. The answer to this question can be found by analyzing the results obtained from the side-to-side W.W.R test.

At the northern orientaion of the envelope in Tehran buildings, reducing the W.W.R to 40% causes a reduction in total energy consumption, and this declining trend continues until an W.W.R of 20%, albeit with a reduced slope. These W.W.R variations in the northern front reduce total consumption by 2% at the most. In other words, up to an W.W.R of 40%, the effect on energy consumption is tangible and after that, it becomes intangible.

On the southern front, total energy consumption evidently reduces with the reduction of the W.W.R, and the slope of the curve remains constant. As compared with the northern front, this reduction is considerably greater, so that at a W.W.R of 20%, the total energy consumption decreases 7% as compared with the base-case model. Moreover, the most reduction in energy consumption occurs at a southern front W.W.R of between 40% and 20%. At the eastern and western fronts, the reduction of W.W.R also leads to energy consumption reduction and the minimum consumption occurs at an W.W.R of 20%. W.W.R variations at the eastern and western fronts cause energy reductions of 5% and 4% respectively. Examination of side-to-side W.W.R variations reveals that the W.W.R has varying effects on energy consumption at different fronts, and that this effect is less tangible at smaller W.W.Rs. Under Tehran climatic conditions, the W.W.R corresponding to the north, south, east, and west reduce energy consumption by 2%, 7%, 5%, and 4% respectively. By comparing the obtained results, one can deduct that the effect of W.W.R on the south is very pronounced, followed by that on the east, west, and north (Dia. 12).

Examination of the side-to-side W.W.R variations obtained for the base-case model in Tehran shows that thermal energy consumption is reduced with the reduction of the W.W.R. The results point to varying effects on energy consumption at various fronts. On the east and the west, the most reduction in energy consumption occurs, followed by the southern and the northern fronts (Dia. 13).

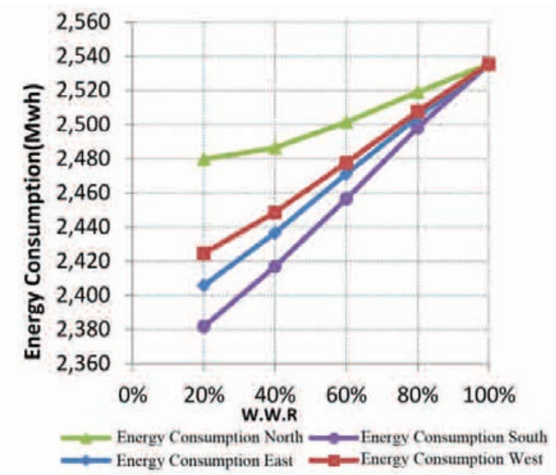

Diagram 12: Total energy consumption variation with W.W.R at different directions in Tehran

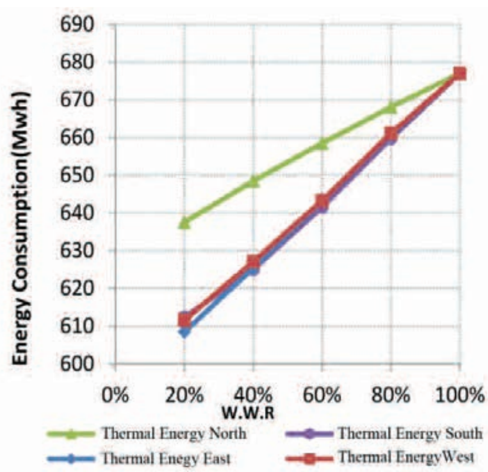

Diagram 13: Total thermal energy variation with W.W.R at different directions in Tehran

Conclusions

The obtained results and their analysis confirm the fact that the test variable, i.e., W.W.R, has a significant effect on total energy consumption as well as on thermal energy in high-rise office buildings under climatic conditions in the City of Tehran. As can be seen in the following table, reducing W.W.R also reduces energy consumption in the building. This reduction in consumption is also reflected in the total energy consumption and in the thermal energy.

Table 2. W.W.R effect on total energy consumption and thermal energy

Item	Window to Wall Ratio	Thermal Energy Variation	Total Energy Consumption Variation
1	W.W.R 80%	4%	9%
2	W.W.R 60%	9%	17%
3	W.W.R 40%	14%	25%
4	W.W.R 20%	17%	32%

The side-to-side examination of the test variables reveals the shell element priorities regarding their effect on total energy consumption. As can be seen in the following diagrams, these priorities are different for different directions (north, south, east, and west).

Considering the above points and the obtained variable test results, we can recommend the following design guidelines with regard to the W.W.R:

- The building W.W.R and total energy consumption are directly related, i.e., reducing the W.W.R leads to a reduction in total energy consumption. In both the studied cities, this is a direct relation with a high correlation coefficient ($R^2=1$). Also, reducing the W.W.R leads to a reduction in cooling consumption and an increase in heating consumption.
- The effects of the W.W.R on consumption is more tangible at lower values of this ratio, i.e., within the 20 to 40 percent range.
- In the case of uniform W.W.R variation in all directions, a 17% reduction is obtained for Tehran, indicating the significant role this ratio plays in the total energy consumption of the building.
- Side-to-side W.W.R test at various building fronts points out the fact that this ratio affects differently the energy consumption in different directions. In this regard, the following directions produce respectively the most reduction in energy consumption: south, east, west, and north.
- Comparison of the results obtained from diagrams and findings show that the appropriate W.W.R for the northern and southern fronts would be approximately 40%, and for the eastern and western sides between 20% and 40% (towards 30%).

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