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Evaluation of the effect of building orientation on achieved solar radiation - a NE-SW orientated case of urban residence in semi-arid climate

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Abstract

Nowadays, with the development of the economy, the demand for energy is increasing rapidly while the energy supply is growing shorter and shorter. Researches indicate that energy consumption in the residential sector counts for the main parts of the total energy consumption. This paper evaluates the effect of building orientation on exposure to the solar radiation in a NE-SW orientated case of urban residence in semi-arid climate. SW envelope, with an annual exposure of 13.52 percent, only improves the thermal comfort of the house because of its annual climatic radiation trend. For vertical NE surface with insufficient winter radiation exposure of (0 %) and cool summer radiation exposure of (3.38 %), it could be concluded that the NE elevation is suitable and in demand in the summer but not in the winter. Total annual horizontal solar radiation exposure percentage of (83.04%) indicates that huge non- climatic roof radiation is inappropriate and should be omitted. Finally, the effects of solar radiation envelopes on electricity and natural gas consumption were thoroughly discussed.

Keywords: *Building orientation, Energy consumption, Residential sector, Solar radiation.*

1. Introduction

Energy is a vital input for social and economic development of any country. Residential sector is a significant consumer of energy, and thus a focal point when planning any energy consumption efforts. Considering the limited resources of energy, low energy buildings have attracted lots of attention in recent years. Like many other countries in the world, energy consumption of the residential sector in Iran makes up the main part of the total consumption. Therefore, a focus on energy consumption efforts with regard to the residential sector is of great importance.

The residential energy consumption depends strongly on the climate of a region [1]. Arid climate is identified by two substantial characteristics: high temperature and low humidity [2]. In these regions, direct exposure to solar radiation on horizontal surfaces is between 700 to 800 kcal/h/m² [3]. Tabari and Hosseinzadeh Talaee investigated the trends in maximum (T_{max}) and minimum (T_{min}) air temperatures for 19 synoptic stations in arid and semi-arid regions of Iran during 1966-2005 [4]. Results indicate that the majority of the trends in T max and T min time series show increasing tendency throughout the last decades. The T max and T min warming trends were more obvious in summer and winter than autumn and spring. Therefore it is essential to harness the mentioned climate's solar radiation.

Shiraz (Fars province's capital), located on 29° 33′ latitude and 52° 33′ longitude, is an outstanding example of a city in an arid climatic in Iran. With an increasing population, Shiraz has high amount of energy consumption in the residential sector [5]. This city gets an abundance of sunshine [6], and as the result, has a

Abbreviations	unit	description
NE-SW	-	North East- South West
E_{vr-SW}	(BTU/m²)	the received solar radiation on SW vertical envelope
E_{vr-NE}	(BTU/m²)	thereceived solar radiation on NE vertical envelope
E_{hr}	(BTU/m²)	The annual amount of solar radiation received by the horizontal roof
E_r	(BTU/m²)	The total received solar radiation on surfaces
$E_{Electricity}$	kwh	The electricity consumption
E_{Gas}	m³	The natural gas consumption

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high potential of solar energy utilization which can provide some part of the required energy in the residential sector. The average cumulative annual irradiation, the average daily irradiation, and the percentage of frequency of days with clear sky are 7250 MJ/m2, 19.9 MJ/m2, and 59%, respectively. Yaghoubi et.al showed that there was a decrease in solar radiation on horizontal surfaces in the 1960s and 1970s in Shiraz [7]. The statistics reveals the accuracy of high potential for solar energy utilization in Shiraz. Furthermore, to provide greater thermal comfort and to decrease energy consumption, due to its growing cost in Iran (omitting energy subsides), the need to harness and control radiant energy is evident. By understanding the climatic profile of Shiraz, architects created the works that the primary design criteria focused on thermal comfort. Ghavam's historic Naranjestan home is a prime example [8].

This study evaluates the effect of building orientation on exposure to solar radiation in a NE-SW orientated case of urban residence in a semi-arid climate. The remainder of the paper is organized as follows: Section two, presents background of the energy consumption in the residential sector as well as the orientation effects on energy consumption in the buildings. In Section three, the methodology is presented, and in section four the detailed description of the houses is explained. Results and discussion are presented in Section five. Finally, the last Section includes the concluding remarks.

2. Backgrounds

An up-to-date review of various modeling techniques presented by Swan and Ugursal was used for modeling residential sector energy consumption [9]. A critical review of each technique, focusing on the strengths, shortcomings and purposes were provided along with a report on review of the models. In their paper, Lee and Kung proposed an adjustment to the traditional approach by using climate classification and data envelopment analysis (DEA) [10]. The study first adopted group analysis to classify the evaluated buildings into different climate groups. Secondly, scale factors (temperature and number of the rainy hours) were identified by regression analysis. DEA was then employed to assess the energy management efficiency of the evaluated buildings. In another research, Michalik et al. used fuzzy inference system approach in order to forecast the energy demand in the residential sector [11]. By using residential energy consumption survey data, obtained from the Energy Information Administration, instead of focusing on the conditional average, Kaza used quintile regression analysis to tease out the effects of various factors on entire distribution of the energy consumption spectrum [12]. Results showed that while the housing size matters for space conditioning, housing type had a more pronounced impact. Dong et.al used support vector machines (SVM), a neural network algorithm, to forecast building energy consumption in the tropical region [13]. The objective of the paper was to examine the feasibility and applicability of SVM in the building load forecasting area. Four buildings in Singapore were selected randomly as case studies. All prediction results were found to have coefficients of variance less than 3% and percentage error within 4%.

The amount of available researches which have been conducted on the effect of building orientation on received solar radiation is not sufficient. Jaber and Ajib discussed an assessment conducted on the best orientation of the building, the windows size, and the thermal insulation thickness from energy, economic and environmental point of view for the typical residential buildings located in the Mediterranean region [14]. The results showed that about 27.59% of annual energy consumption can be saved by choosing the best orientation, optimum size of the windows, the shading device, and the optimum insulation thickness. Yu et.al employed EQUEST software to analyze the effects of energy saving strategies on air conditioning's electric consumption of differently orientated rooms in a hot summer and cold winter zone in China [15].

2.1. Building's solar radiation gain

Different architectural characteristics' influences on energy consumption in a building; for instance, envelope construction, roof material, building's shape, number of stories in the building, windows, infiltrations and relationship to ground. As the result of building's envelope having a major effect on reducing cooling and heating need, case study parameters are investigated in one orientation (NE-SW). Other influential characters involve consumer behavior, envelope's thermal transfer value, occupants, window to wall ratio, number of steps, equipment, lighting, length to width ratio, longevity and etc.

To avoid solar radiation in hot summers, shading and thermal insulation are important considerations in vernacular house design [16]. Moreover, to absorb solar radiation in a cold winter, window ratio and thermal mass get much attention in vernacular house construction method. Significantly, in modern design, attention has not been given to the climatic characteristics of solar radiation on envelopes. Parker et.al monitored six homes in Florida, before and after coatings the roofs. Reduction in air-conditioning electricity consumption was reported between 11% and 43% [17]. Jafarpour and Yaghoubi estimated monthly and annual radiation for only one location in Shiraz (Iran) [6]. In another research, Yaghoubi and Sabzevari calculated the monthly clearness index for Shiraz, Iran [18]. Partridge and Proctor employed a model to predict solar radiation on the earth's surface [19]. Although the suggested models can easily be used for any location in Iran, the solar radiation on vertical surfaces with different angles, which is more beneficial in architecture, have not yet been considered in the researches.

3. Methodology

Selected houses were chosen from among all the houses which were built 40 years prior to the research. This was done because of Shiraz's development in different periods. The basic characteristic of this period's architecture is entering modernism. In this time, imported house parts were common and type of energy used changed from oil to gas, and electricity. Initial one hundred random selection by kh Bonyan marsos co (2011) leads to choosing only one high percent house orientations; North East- South West (NE-SW). Therefore, the study can provide new model and improve residential building energy situation by offering positive or negative criticism. A variety of factors are associated with energy consumption. In this research, two major ones, i.e. building characteristics, and energy consuming part were investigated.

For obtaining horizontal and vertical surface radiation in the computational method, many soft wares such as Energy plus, Eco tech, Transys , Radiation on solar collectors, Ret screen, etc. have been employed, but Shiraz's climate characteristics leakage is the main problem in the mentioned softwares (due to not calculating the detailed climatic parameters by shiraz's Meteorological Bureau (2011)). For achieving the research aim, Victor Olgyay method (Victor Olgyay, 1963) is applied to calculating solar radiation on both horizontal and vertical surfaces and their parts (window, door, terrace and wall).

This study involved experimental and analytical activities which could be divided into these phases: selecting the data; investigating the sample characteristics and calculating E_r (Solar radiation on horizontal (E_{hr}) and vertical (E_{vr}) building envelopes); Calculating cooling and heating energy consumption ($E_{cooling}$, $E_{heating}$) of the buildings; extracting positive and negative points of a typical house in energy consumption. For the process, different statistical and experimental methods are used.

Some points should be mentioned with regard to measuring procedures :

- There are four different energy consumptions for both electricity and natural gas, including:

$E_{Cooling} + E_{Heating} + E_{Lighting} + E_{Equip.} = E_{Total} = E_{Primary}$

- Cooling energy consumption ($E_{Cooling}$) of the proposed case study is derived only from electricity, as the sample house was not equipped with gas-cooling devices.
- Heating energy consumption ($E_{Heating}$) of the proposed case study is derived only from natural gas because of not using any electrical thermal equipment.
- in this survey, $E_{Lighting}$ and $E_{Equip.}$ have been considered to be constant, and $E_{Heating}$ and $E_{Cooling}$ would be measured as follows:

$E_{Electricity}$:

Summer: $E_{Electricity}=E_{Cooling}+Cons.$ Then: $E_{C.E}=E_{Cooling}$

Winter: $E_{Electricity}=E_{Heating}+Cons.=0+Cons.$ Then: $E_{C.E}=0$

$E_{Natural\ gas}$:

Summer: $E_{Natural\ gas}=E_{Cooling}+Cons.=0+Cons.=Cons.$ Then: $E_{C.G}=0$

Winter: $E_{Natural\ gas}=E_{Heating}+Cons.$ Then: $E_{C.G}=E_{Heating}$

- months of space heating in winter (low temperature months), and space cooling in summer (warm and hot; high temperature months) depend on the sample house behavior in different periods for heating or cooling need.

3.1. Energy consuming parts of the building

There is a close connection between energy use in buildings and the resulted environmental damage. This is because of the energy intensive solutions that are employed in buildings to attain comfort conditions in terms of mechanical cooling, forced ventilation and artificial lighting. In order to achieve thermal comfort, utilization of passive methods and techniques in modern buildings are required [20]. Due to the amount of used energy in Shiraz (electricity and gas), for calculating energy consumption, electricity consumption is divided into 4 sectors including cooling, lighting, heating, and equipment. Cooling energy consumption in hot season is the main electricity consumption in Shiraz. In mid-life and the selected house, the primary and common cooling system is water cooler, and the additional system used is fan. The same as electricity, gas energy consumption is classified into heating and equipment,. The main heating energy consumed in cold season is gas. In mid-life houses and the selected ones, the primary and common heating system is gas heater.

4. Detailed description of the house

Described in details, case study has NE-SW orientation with 30° rotation from N (Fig. 1). This house's plan typology is the most famous one among the one hundred randomly selected houses in residential sector of Shiraz. Some of the important effective parameters on solar gain are: total occupants 4; Land

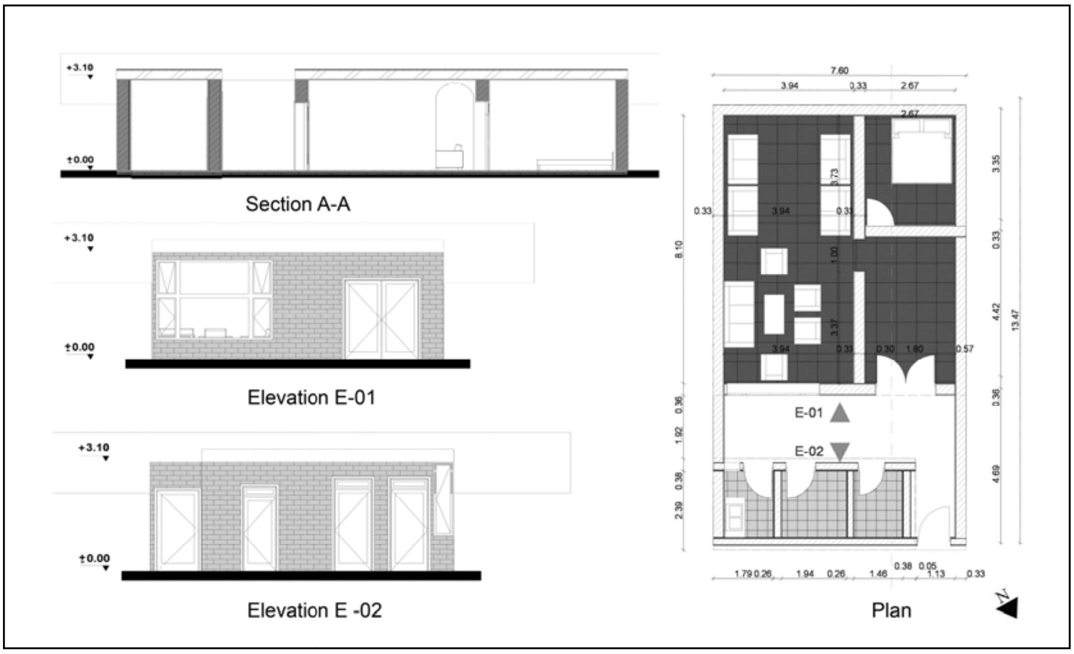

Fig. 1 Plan, elevation and section of case study, Kh Bonyan Marsoos co., 2011

area and built area 102 and 78.2 m²; 2 side; 1 step; Length to width ratio1.07; Proximity degree 52.5 and Window to wall ratio 0.061 SW and 0.21 NE. This house is 40 years old and receives solar radiation on SW envelope, NE envelope and roof (Table 1). Energy consuming equipment types (natural gas and electricity sectors) are explained in Table 2.

5. Results and discussion

The received solar radiation depends on the direction. The tilt angle has a major impact on the solar radiation incident on a surface. If the angle between the surface and the radiation is orthogonal, then the highest radiation is received (Bhandari, 2010). For the case study direction in this paper, the hourly and daily radiation on vertical (NE 30°, SW 30°) and horizontal (roof) surfaces for square per meter are calculated (table 3). As illustrated in Fig. 2:

• Vertical NE 30° surface has minimum amount radiation and its volatility, to some extent, is the same as the horizontal one, but the amount is opposite. In warm months, only a little radiation is absorbed and in cold ones no direct radiation exists. This cold direction is not suitable for the cold season. In addition, throughout the winter, the buildings against the principle one produce shadow on this facade bringing the received solar radiation to zero.

Table 1 Solar radiated envelopes and theirs parts in case study

Row	Orientation of Radiated envelope	Total m²
1	SW envelope	25.84
2	NE envelope	24.32
3	Roof	68.74

Table 2 main energy consuming parts in case study (cooling and heating characteristics)

Main energy consuming parts	System	Number
Cooling	Water cooler	1
	fan	2
Heating	Gas heater	2

Table 3 Solar radiation on case study direction for square per meter (BTU/m²)

Month	Horizontal envelop	Vertical envelope	
	Roof	NE 30°	SW 30°
1st April	158.859	9.0113	87.093
1st May	188.1225	22.3889	60.62
1st June	214.83125	41.1547	32.98
1st July	225.05025	48.44735	27.22
1st August	214.83125	41.1547	32.98
1st September	188.1225	22.3889	65.96
1st October	158.859	9.0113	87.093
1st November	126.344	0.6503	103.58
1st December	106.835	0	112.69
1st January	87.6047	0	114.96
1st February	106.835	0	112.69
1st March	126.344	0.6503	103.58

• Due to its climatic solar radiation absorption, the vertical SW 30° surface is the strongest climatic direction. This high quality direction gains the most radiation in the coldest month (January) and the lowest one in the warmest month (July). Therefore it is cool in the summer and warm in the winter. This makes the SW 30° surface more appropriate than the other orientations as far as the energy behavior is concerned.

• Horizontal envelope has the highest amount and it's volatility for square per meter and day implies the maximum received radiation in the warm months (June, July, August), and the minimum ones in the cold month (January). This indicates that the roof direction is non-climatic. In peak summer cooling demand, maximum solar energy is received and in peak winter heating demand, minimum solar energy is obtained.

5.1. Solar radiation in case study envelopes

Due to the calculated radiation for square per meter and the surfaces area of the SW-NE case study using the evaluation of E_{vr-SW}, E_{vr-NE}, E_{hr}, E_r, it is concluded that (Table 4):

• Vertical building envelopes are one of the most proper envelopes for receiving climatic solar radiations. Absorption of solar radiation by the mentioned surfaces, energy demands of lighting, cooling and heating are fulfilled and building energy efficiency is improved, provided that a proper building orientation (BO) exists. Vertical envelopes in the house are including SW and NE, therefore the radiation received to both envelopes. In SW envelope, the annual E_{vr-SW} trend on the SW

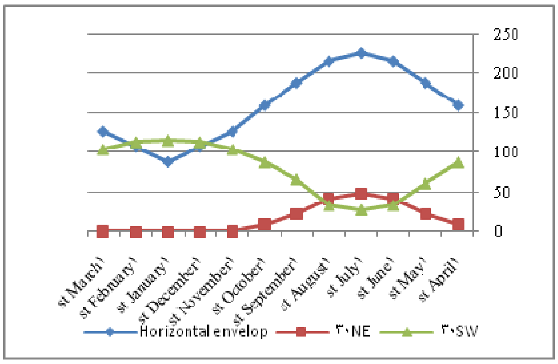

Fig. 2 Solar radiation on case study direction for square per meter (BTU/m²)

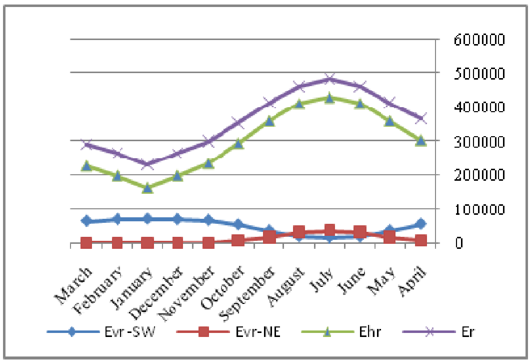

Fig. 3 Comparison of received solar radiation on building envelopes

vertical envelope is contrary to the horizontal one, which in cold seasons is the maximum amount and in warm ones is the minimum value. Therefore, it can be stated that if the radiation from roof is omitted, the climatic and low energy consuming house is the one that has more climatic radiation on its vertical envelopes. Finally, south vertical building envelopes are the best envelope for receiving the climatic solar radiation. Despite the annual E_{vr-SW} trend, annual E_{vr-NE} trend is the same as roof one. In addition, low received radiation at the present elevation leads to a high heating need in the winter (Fig. 3).

•The annual amount of solar radiation received by the horizontal roof (E_{hr}) is relevant to that of atmospheric solar radiation; so it's high in the warm season and low in the cold one. Due to the mismatch of this received energy between the seasonal heating and cooling energy demands, houses that receive more energy via the roof, have a higher level of energy consumption. The highest level of received energy through the envelopes is related to the roof; by its' non-climatic radiation, and it would be effective in reducing the energy efficiency of the buildings.

•The total received radiation on the surfaces (E_r) is not suitable; due to high energy received in the summer. The opposite is true in the winter.

The case study window to wall ratio in NE elevation is inappropriately high (0.21), thus in the cold season the heat transfer from the windows is undesirable. Similarly, the NE and the SW elevation windows are not perfect, because the window to wall ratio is insufficient. Therefore, the windows that being exposed to climatic solar radiation is small. The window condition is not perfect due to energy consumption. Although in a 2- sided house energy behavior in the summer is efficient, the extra elevation of the NE side in the winter affecting energy consumption depends on their window areas. Length to width ratio (1.07) in this house is almost 1 and, consequently, the square plan leads to non-climatic surfaces both the vertical and the horizontal one.

6. Conclusion

The received solar radiation could be divided into three main parts; the horizontal envelope (roof), the main vertical envelope (SW elevation) and the NE envelope. Each of the mentioned envelopes plays an effective role in the annual and monthly energy consumption behavior. The percentage of each envelope's solar radiation shows its effect on energy consumption. Total annual E_{hr} percentage (83.04%) indicates that the inappropriately huge non- climatic roof radiation should be omitted. The external and the internal devices may be used to reduce this radiation. Shading devices and insulation materials are examples of the available solutions (Table 6).

For vertical NE surface with an insufficient winter radiation (0 %) and cool summer radiation (3.38 %), it could be pointed out that the NE elevation is sought after in the summer; whereas, this is not the case in the winter. Therefore, shading devices should be avoided in this part and the window area should be low enough to decrease heat loss in the winter. Double windows and insulation improve the surface thermal resistant in the winter.

In addition, SW envelope with annual 13.52 percent exposure improves the thermal comfort of the house because of its annual climatic radiation trend. Vertical building envelopes are the ones that receive climatic solar radiations. By absorbing the solar radiation in the mentioned surfaces, energy demands of lighting, cooling and heating are fulfilled and the building's energy efficiency is improved, provided that a proper building orientation (BO) exists. Although the SW envelope is not a more perfect direction than the SE one, it has many beneficial points (i.e. high winter solar gain and low summer one). The only advantage of the SE direction is morning radiation exposure which is better than the hot evening radiation in the SW direction. Vertical shading devices and insulation complete this elevation climatically (Fig. 4).

6.1. Annual energy consumption

By considering the energy consumption bills for electricity and natural gas, it becomes clear that energy consumption is related to the solar radiation. Due to the SW's summer afternoon radiation gain, cooling load increases. Moreover, due to the NE's big windows heat loss and SW small window gain, the heating load increases (Table 6 and Fig. 5)

Table 4 Solar radiation on vertical and horizontal building envelopes in case study (BTU/m^2)

Month	E_{vr-SW}	E_{vr-NE}	E_{hr}	E_r
April	56158.77	6785.28	304637.62	367581.67
May	37779.54	16858.42	360755.06	415393.02
June	20713.1	30988.84	411973.26	463675.2
July	17095.61	36480.49	431569.6	485145.7
August	20713.1	30988.84	411973.26	463675.2
September	37779.54	16858.42	360755.06	415393.02
October	54347.2	6566.4	294810.6	355724.2
November	66910.57	474	234469.2	301853.77
December	69338.55	0	198264.3	267602.85
January	70439.64	0	162576.9	233016.54
February	69338.55	0	198264.3	267602.85
March	64680.22	458.2	226653.56	291791.98

Table 5 Solar radiation percentage on vertical and horizontal building envelopes in case study (BTU/m^2)

Main energy consuming parts	System	Number
Cooling	Water cooler	1
	fan	2
Heating	Gas heater	2

Table 6 Monthly and annual energy consumption by sector in case study

Month	Horizontal envelop	Vertical envelope	
	Roof	NE 30°	SW 30°
1st April	158.859	9.0113	87.093
1st May	188.1225	22.3889	60.62
1st June	214.83125	41.1547	32.98
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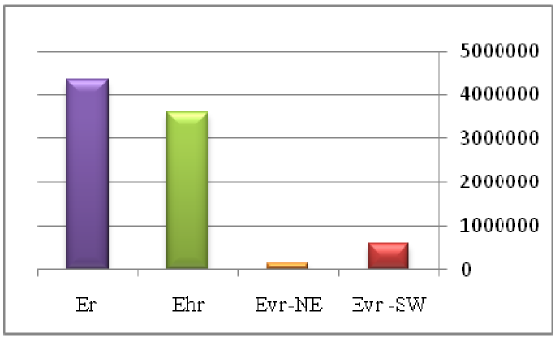

Fig. 4 Comparison of annual received solar radiation on building envelopes

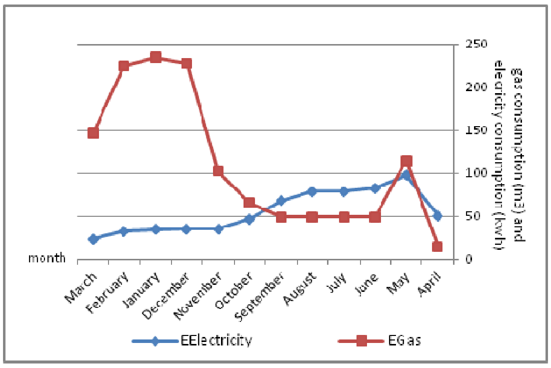

Fig. 5 Monthly energy consumption by sector in case study

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