The Impact of the Shape Factor on Final Energy Demand in Residential Buildings in Nordic Climates

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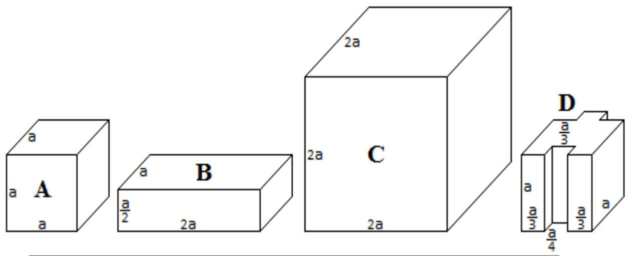
ABSTRACT

The shape factor of a building is the ratio between its envelope area and its volume. Buildings with a higher shape factor have a larger surface area in proportion to their volume, which results in larger heat losses in cold climates. This study analyzes the impact of the shape factor on the final energy demand by using five existing apartment buildings with different values of shape factor. Each building was simulated for twelve different scenarios: three thermal envelope scenarios and four climate zones. The differences in shape factor between the buildings were found to have a large impact and accounted for 10%-20% of their final energy demand. The impact of the shape factor was reduced with warmer climates and ceased with average outdoor temperature 11ºC-14ºC depending on the thermal envelope performance of the buildings.

1 INTRODUCTION

The shape factor of a building is a measure of the building's compactness and expresses the ratio between the building's thermal envelope area and its volume. The thermal envelope area is the area that separates between the conditioned and unconditioned areas or alternatively, the indoor and the outdoor environment. As a result, the heat losses through the thermal envelope account for large percentage of the total final energy use of a building in cold climates. Buildings with a higher shape factor are less compact and therefore have a larger thermal envelope area in proportion to their volume and therefore larger heat losses.

The value of the shape factor depends on the shape of the building for a given volume as illustrated by building A and B in Fig. 1. Both buildings have similar volume but different thermal envelope areas, which results in different shape factors. The size of the building also influences the shape. A larger building with similar shape will have lower shape factor as illustrated by building A and building C in Fig. 1. Irregular façades with trenches and bulges, e.g. heated balconies that extend beyond the façade, may also increase the shape factor as illustrated by buildings A and D in Fig. 1.



	A	B	C	D
Volume	a^3	a^3	$8a^3$	a^3
Thermal envelpe	$6a^2$	$7a^2$	$24a^2$	$7a^2$
Shape factor	6/a	7/a	3/a	7/a

Fig. 1: The shape factor of buildings with different sizes and shapes. The parameter 'a' symbolizes a unit of length.

Energy simulations done by Depecker et al.[1] showed that in colder climates the correlation between the final energy use and the shape factor is strong. Ourghi at el.[2] found strong correlations between the shape factor and final energy use in office buildings [2]. Ratti at el. [3]calculated a 10% difference in specific final energy use between Toulouse and Berlin due only to differences in their buildings' morphology. The study also suggested that cold climate may increase the impact of the results. As a measure to limit specific final energy use, China has integrated the shape factor of buildings into its design standard for energy efficiency of public buildings.

The standard applies strict values for new buildings in cold climates [4]. The aim of this study is to quantify the impact of the shape factor on the specific final energy use in residential buildings with different thermal envelope properties and different Nordic climate zones.

TABLE 1: DESCRIPTION OF THE CASE STUDIES BY SLECTED PARAMETERS

	Floor area	External walls[1]	Windows[1]	Ground floor	Roof	Shape factor[1]	Window-to-floor-area ratio[1]
Building A	2197 m^2	1088-1154 m^2	363-385 m^2	389 m^2	389 m^2	1.01-1.08	16.5%-17.5%
Building B	1711 m^2	909-970 m^2	303-323 m^2	401 m^2	401 m^2	1.18-1.25	17.7%-18.8%
Building C	975 m^2	530-564 m^2	177-188 m^2	289 m^2	289 m^2	1.32-1.41	18.1%-19.3%
Building D	1069 m^2	713-767 m^2	238-256 m^2	304 m^2	304 m^2	1.46-1.57	22.3%-23.9%
Building E	567 m^2	385-426 m^2	128-142 m^2	201 m^2	201 m^2	1.61-1.8	22.6%-25.0%

[1] The values vary because of the different thermal envelope scenarios as listed in Table 2.

2 METHEDOLOGY

The definition for the shape factor used hereinafter is the ratio of thermal-envelope-area-to-the-total-floor-area of the building. This definition differs from the definition mentioned in Section 1 by the size of the floor height. However, since all studied buildings have similar floor height the two definitions are equivalent.

2.1 The Impact Of The Shape Factor

Five newly built apartment buildings with different shape factors, ranging from 1 to 1.7, were used as case studies (Table 1). The specific heat demand of each building was calculated by the VIP-Energy simulation program under different scenarios. Three thermal envelope scenarios were used representing low energy efficiency thermal envelop scenario, common practice scenario and passive house standard scenario (Table 2). The buildings were simulated in four different cities: Malmö, Karlstad, Östersund and Kiruna, which represent four different Nordic climate conditions, covering most climate zones in Sweden and in other Nordic countries. The specific heat demand is the heat energy needed to be supplied in order to maintain an indoor temperature of 22°C.

The VIP-Energy simulation software [5] is a commercial dynamic energy balance simulation program that calculates the energy performance of buildings hour by hour. VIP-Energy has been validated by IEABESTEST, ASHRAE-BESTEST and CEN-15265. Monitored data for wind, solar radiation and humidity from the NOAA Earth System Research Laboratory was extracted by the VIP-Energy Climate data creator for year 2010 [6]. Monitored temperature data was imported from [7] for year 2010. Table 3 lists yearly climate values for each city.

This study analyses the energy efficiency of the buildings and therefore excludes the effects of tenants' activities, for example final energy use for domestic water heating and household electricity are not included. Final energy use from residents' behavior is difficult to predict [8] and may vary considerably between different households. In all simulations the area of the windows was set to be 25% of the total façade area and distributed evenly in all directions. Each building was simulated with the largest façade facing the south direction. The reason is to have similar conditions of solar energy gains for all the case studies. All the buildings are equipped with forced ventilation with air flow of 0.35 l/(s m^2).

TABLE 2: THERMAL ENVELOPE SCENARIOS

	Insulation thickness mm		
Thermal envelope scenario:	Low	Medium	High
External wall	120	180	420
Roof	120	190	400
Ground floor	100	160	350
	U-value W/(m^2 K)		
Thermal envelope scenario:	Low	Medium	High
External wall	0.331	0.229	0.103
Roof	0.304	0.202	0.1
Ground floor	0.318	0.208	0.099
Windows	1.7	1.2	0.7

2.2 Sensitivity Analysis: The Effect Of Different Relative Size Of Window Areas

The energy balance of a building is largely determined by the thermal properties of its different surfaces. Roof, ground floor and external walls have relatively similar thermal properties in comparison to the thermal properties of windows, in particular regarding thermal resistance and solar transmissions. Therefore it is important to study how the effect of the shape factor on the final energy demand will change for different shares of window areas.

The energy performance of building B (Table 1) was analyzed with different ratio of windows-to-floor-area that ranges from 0.2 to 0.25. The windows were distributed evenly around the building to have similar window area in each facade direction to reduce variations in energy performance because of differences in solar radiations from different directions. The effect of different windows-to-floor-area ratios was studied with the three thermal envelope scenarios in Table 2 and four different Nordic climate zones scenarios as described in Table 3. The specific heat demand was simulated by the VIP-Energy software.

TABLE 3: THE CLIMATE SCENARIOS

Location (city):	Malmö	Karlstad	Östersund	Kiruna
Latitude	55°36'N	59°23'N	63°10'N	67°52'N
Average outdoor temperature	7.7°C	4.8°C	1.8°C	-1.7°C
Yearly global solar radiation [kWh/m^2]	1,411	1,340	1,292	1,189
Average wind speed [m/s]	5.7	3.4	3.7	3.6

3 RESULTS

3.1 The Impact Of The Shape Factor

The impact of the shape factor on the specific heat demand is illustrated in Fig. 2-4 for buildings with different thermal envelope scenarios as listed in Table 2. In each of the figures, five building with different shape factors are compared in four different Nordic climate conditions resulting in 20 different scenarios. The results from the energy simulations show that the specific heat demand increases linearly with increasing shape factor irrespective of the climate conditions and thermal envelope properties. The slope of each linear line signifies the impact of the shape factor on the specific heat demand, that is to say the change in specific heat demand due to one unit change in the shape factor of the building.

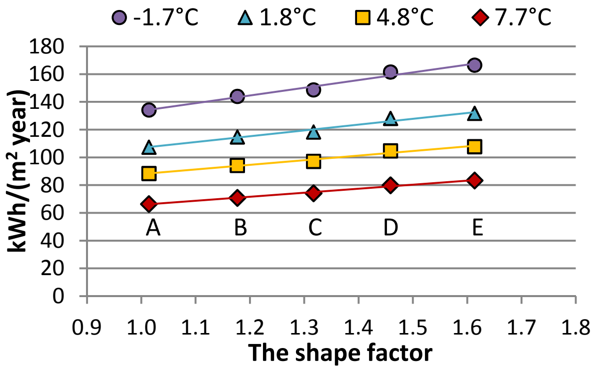


Fig. 2: The specific heat demand vs. the shape factor of the five buildings with thermal envelope scenario called Low in Table 2, and different annual average outdoor temperatures. The characters ‘A’ to ‘E’ signify the case study buildings listed in Table 1.

Fig.5 illustrates the values of the slopes of the different scenarios. The impact of the shape factor found to be higher in buildings with lower thermal envelope properties. The impact of the shape factor also reduces linearly with higher average outdoor temperatures. However the values in the Malmö climate scenario, with average outdoor temperature of 7.7°C, are higher than what can be expected by the trend-line. Malmö is the only coastline city among the four different cities listed in Table 3. It is subjected to stronger winds and has 60% higher average wind speed in comparison to the climates in the other three cities. The stronger winds were found to increase the impact of the shape factor on the specific heat demand by about 7 kWh/(m^2 year). This was confirmed by energy simulations with the wind speed as the only variable parameter.

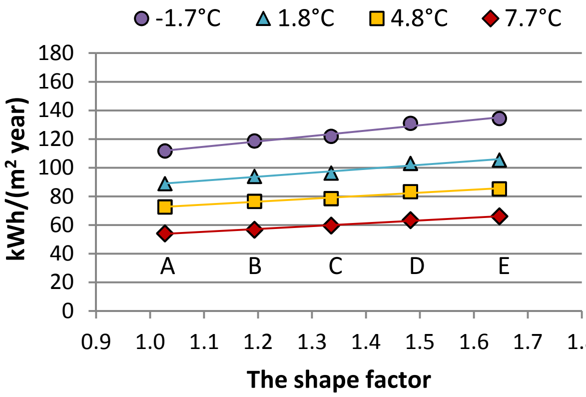


Fig. 3: The specific heat demand vs. the shape factor of the five buildings with thermal envelope scenario called Medium in Table 2, and different annual average outdoor temperatures. The characters ‘A’ to ‘E’ signify the case study buildings listed in Table 1.

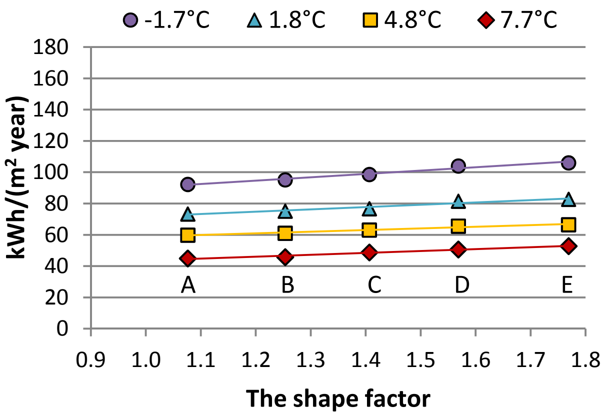


Fig. 4: The specific heat demand vs. the shape factor of the five buildings with thermal envelope scenario called High in Table 2, and different annual average outdoor temperatures. The characters ‘A’ to ‘E’ signify the case study buildings listed in Table 1.

By extending the trend-line in Fig.5, the impact of the shape factor is expected to be nullified with outdoor temperatures of 14.2ºC, 12.6ºC and 10.8ºC for the respective low medium and high thermal envelope properties. In climates with higher average wind speed, as in Malmö city, the nullification of the impact of the shape factor is expected to occur at higher temperatures.

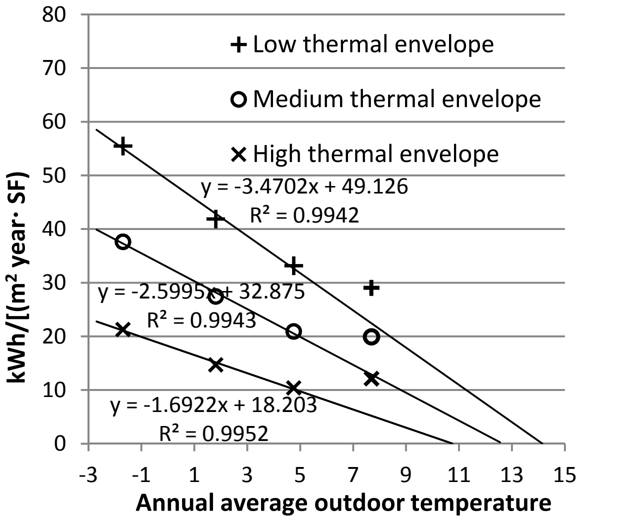


Fig. 5: The specific heat demand per unit difference in the shape factor (SF) for different scenarios of thermal envelope and outdoor temperatures. The calculation of the trend-line does not include buildings in the Malmö climate zone (7.7ºC).

Fig.6 illustrates the differences in yearly Energy demand, for each thermal envelope and climate scenarios, between the buildings with the highest and lowest shape factor. The highest differences in heat demand, 18%-20%, were found for buildings with lower thermal properties. 11%-14% differences in energy demand were found for buildings with high thermal properties. The lower values relate to climates scenarios with higher average outdoor temperature. The stronger winds in Malmö results with higher differences in heat demand among buildings with different shape factors. The shape factors of the different case studies ranged between 1 and 1.7; but buildings can be design with higher and lower shape factors that may results with larger differences.

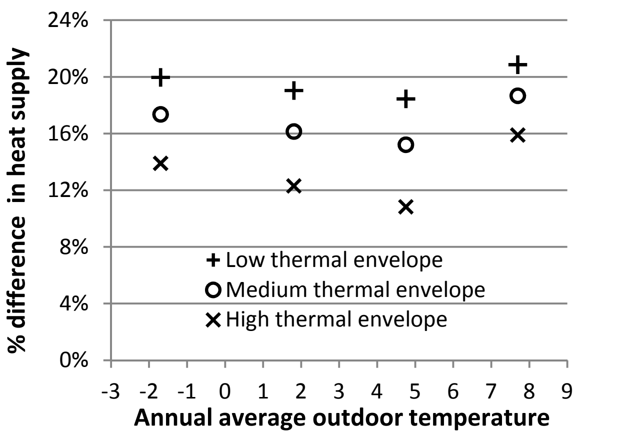


Fig. 6: The difference in heat demand between the buildings with the highest and lowest shape factor for the different scenarios of thermal envelope and climate conditions.

3.2 Sensitivity Analysis: The Effect Of Different Relative Size Of Window Areas

The specific heat demand was found to increase or decrease with higher relative window area depending on the climate conditions and the thermal envelope properties of the buildings as illustrated in Fig.7-9. Positive slopes indicate that the difference in conductive heat losses between windows and external wall is higher than the heat gains from solar radiations and v.v. Positive slopes will intensify the impact of the shape factor while negative slopes will decrease it.

The values of the slopes in Fig.7-9 ranges between 0-0.6 kWh/(m^2 year) per 1% change in window-to-floor-area ratio among buildings with different thermal envelope and climate conditions. The effect of the relative window size was calculated by multiplying the value of the slop by the percent difference in the window-to-floor-area ratio. That was done for each thermal envelope and climate scenario. Fig.10 illustrates the impact of the shape factor on the specific heat demand with correction to the differences in window-to-floor-area ratio.

Comparison between Fig.10 and Fig.5 reveal only minor changes to the specific heat demand caused by differences in window-to-floor-area ratio. Persson at el. [9] showed that the size of energy efficient windows does not have a major effect on the heating demand in the winter. This study expend Persson's conclusion to windows with lower energy efficiency. The conclusions apply to windows and walls with thermal properties according to Table 2.

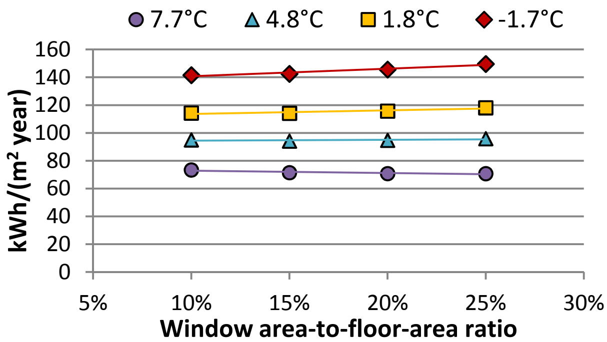


Fig. 7: The effect of the relative window size on the specific heat demand of buildings with Low thermal envelope scenarios and different climate scenarios.

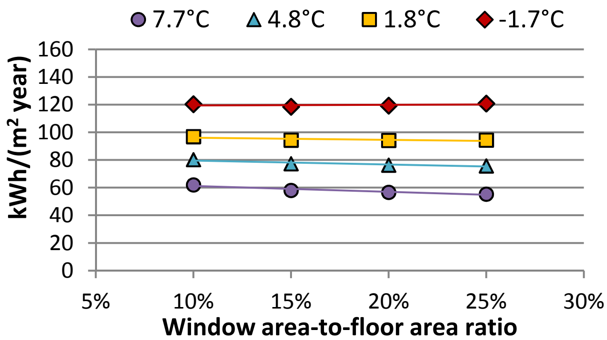


Fig. 8: The effect of the relative window size on the specific heat demand of buildings with Medium thermal envelope scenarios and different climate scenarios.

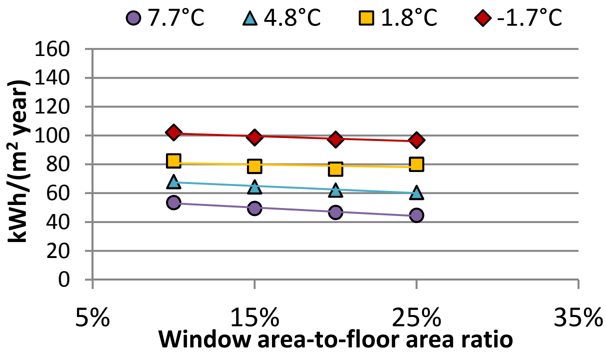


Fig. 9: The effect of the relative window size on the specific heat demand of buildings with <u>high</u> thermal envelope scenarios and different climate scenarios.

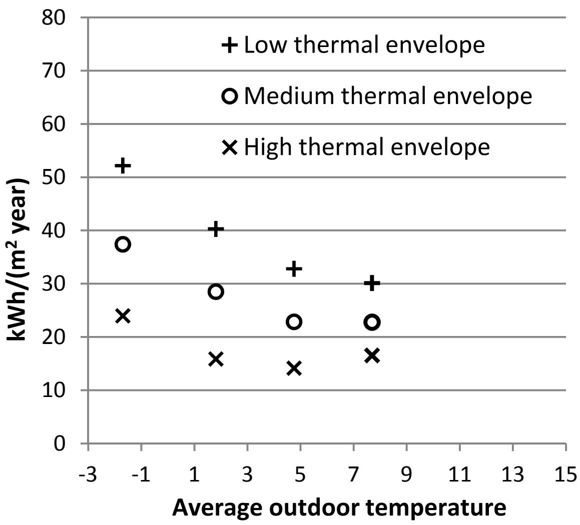


Fig. 10: The specific heat demand per unit difference in the shape factor (SF) of buildings with different scenarios of thermal envelope and climate conditions with correction to differences in window-to-floor-area ratio.

4 DISCUSSION AND CONCLUSIONS

This study investigates the impact of the shape factor on the specific heat demand in residential buildings located in different Nordic climates. Designing new residential buildings with lower shape factor will result in lower specific heat demand. However the impact of the shape factor varies considerably for buildings with different thermal envelope properties and for different climate conditions. For the scenarios used in this study the change in specific heat demand for a unit change of shape factor in the design of the building varied from 12 to 52 kWh/(m^2 year). The shape factor has higher impact on the specific heat demand in buildings with lower thermal envelope properties and buildings that are located in colder climates. The impact of the shape factor found to increase in regions with higher average wind speed as well. Sensitivity analysis found minor changes in specific heat demand caused by differences in window-to-floor-area ratio.

The span of shape factors among the investigated buildings in this study is 0.7. This difference was found to reduce the specific heat demand by 18%-21% for buildings with low thermal envelope properties, by 15%-19% for buildings with medium thermal envelope properties and by 11%-16% for buildings with high thermal envelope properties. The difference in shape factor between buildings could in other cases be even higher resulting in larger differences in specific heat demand. The impact of the shape factor on the specific heat demand was found to diminish in climates with annual average outdoor temperatures above 14°C for buildings with low thermal envelope properties and above 11ºC for buildings with high thermal envelope properties. The above temperatures are expected to be higher with higher average wind speed conditions.

The conclusion from this study is that the shape factor of buildings should be considered as an important energy efficiency measure in Nordic climates because of its large impact on final energy use in buildings. It would be advisable from an energy point of view to define limits for shape factors to reduce final energy use in new designed building, as was done in China [4].

5 ACKNOWLEDGMENTS

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