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# Potential and Risk for Zero-Energy-Buildings under Defined Urban Densities

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## Summary

The aim of this paper is to develop a method to evaluate the potential and risk of renewable energy development by examining the land-use requirement of zero energy building (ZEB). To date there is still a lack of knowledge about which kind of building and which kind of building arrangement would be optimal to save as much as possible land for compensating measures of ZEB. How does the compensating area change with number of floors or plot ratio? Does the compensating area required by one unit of area of use increase or decrease with the number of floors and plot ratio? We intend to develop a method to address these questions and draw the attention to further explore the relationship among the variables. Some of the suggestions about the planning of land-use requirement of energy production could be derived from our preliminary results: 1) to save land for compensating measure, small number of floors should be used; 2) to save land in general, high plot ratio should be used. And, within the high plot ratio, small number of floors should be used. With the results of this research, we hope to contribute to the discussion about urban sprawl and compact city. We also hope to further advance the investigation about the relationship between urban density and energy production. It may also encourage land-use policy makers to include land-use requirement of renewable energy production into consideration.

**Keywords**: Zero Energy Building, compensating measure, urban densities, energy demand, land-use requirement

## 1. Introduction

In order to bring primary energy consumption and CO2 emission to zero, one of the contributions is to optimize buildings to become zero energy buildings (ZEB). Primary energy consumption includes thermal energy for heating, cooling, and hot water as well as power for mechanical ventilation and artificial light. This energy demand can be minimized by architectural techniques but it is not possible to bring it to zero (e.g. time of use during dark hour's leads to the use of artificial light). To reach zero, the remaining energy demand has to be covered by building services using renewable energies.

The purist definition of a ZEB claims that this energy is to be gained on-site (from the building envelope or the ground under or near the building) or off-site [8]. This leads to the competition between the area of use to be served, which creates energy demand, and the size of building envelope or the size of the estate to cover this demand with renewable energies. A wider definition would allow producing a part of the energy off-site (outside of town) on compensating areas, which could be covered with wind turbines, PV modules, sustainable agriculture, etc. We will call that a zero energy building with compensating measures (ZEB_CM). From an ecological point of view both versions of a ZEB have the same zero contribution to CO2 emission and they are adequate options.

In a city with very high urban density, the purist ZEBs are often not possible. Or, vice versa, the trial to derive a city with purist ZEB’s would lead to a limited urban density which would be below urban densities known as optimal for public transport systems (and minimized transportation energy) and a liveable urban situation. A ZEB_CM opens a way for an ecological development respecting these other criteria.

But even if we assume such an “optimal” urban density as a precondition we do still not know which kind of building and which kind of building arrangement would be optimal to save as much as possible land for compensating measures. The comparison of land-use requirement of ZEB and ZEB_CM respectively will deal with some interesting questions: How does the compensating area change with number of floors or plot ratio, which is the ratio of ‘area of use’ and ‘estate area’? Does the compensating area required by one unit of area of use increase or decrease with the number of floors and plot ratio?

The aim of this paper is to develop a preliminary method to evaluate the potential and risk of renewable energy development by examining the land-use requirement of ZEB and ZEB_CM. We intend to develop a method to address these questions and draw the attention to further explore the relationship among the variables. It may also encourage land-use policy makers to include land-use requirement of renewable energy production into consideration.

## 2. Methodology

The method used for this paper was developed for a master course “Climate Responsive Architecture and Planning”. Here the potential of ZEB and ZEB_CM was explored for fifteen big cities in all main climate zones around the world. The target of the course is to derive design rules for ZEB and ZEB_CM, to carry out design of building types and type facades, to develop rules for building distance and urban density, and to investigate the required space for compensating area.

For this paper we choose Singapore as the case study for the following reasons. Firstly, the Singapore Master Plan (MP) [10] provides very detailed land-use plan, which includes very specific regulation about building height and plot ratio. It shows the permissible land-use and density for developments in this highly densified city. The plan offers us a good starting point to explore the relationship between building height, urban density, and compensating area by examining the existing plan. Secondly, Singapore government has been very encouraging in the development of ZEB [2]. However, there is also a huge demand for additional area of use and high-rise building [10]. If the ZEB_CM requires additional land, it would be a critical issue for Singapore government to balance the need of land for energy production and other land-use needs. Finally, the consideration of land-use needs has been clearly stated in the MP: “Given the constraints of the small land area, the Master Plan and the Concept Plan have played a vital role in helping to balance many land-use needs in the following six key focus: Housing, Transport, Economy, Recreation, Identity, and Public Spaces”[10]. To date, we have not found any indication that energy production is included as one of the needs for land-use in the MP. In this paper, we intend to offer some information as reference for the future planning of Singapore to integrate ZEB into the land-use requirement.

Before we start the investigating there are several preconditions with regard to the definition of building types, comfort models for summer, and regenerative building services. The analysis focuses on office buildings.

### 2.1 Definition of standard office room, building type and building mode

A standard office room for 12 users (area of usage 168 m²) was predetermined to gain comparable result. It was assumed that this room could be one of a series of rooms, situated in the middle of an office building so that the building can be thought as continued horizontally and vertically.

The target of the university course was the optimization of this room to local climate and conditions by architectural technologies to bring energy demand to its minimum. For the different climates different types of building mode are possible: Adaptive, air-conditioned or, as a combination of both, hybrid.

An adaptive building is understood as a building with natural ventilation where the users can adapt their surrounding according to their preferences: Operable windows, personal switches for artificial light, thermostats, etc. Besides heating with standard systems, cooling is also possible with thermally activated ceilings. In adaptive buildings, the expected comfort temperature is assumed as in accordance with adaptive comfort models [1, 3], where above 20°C indoor comfort temperature varies slightly with the mean value of outdoor temperature. This assumption avoids waste of energy or saves energy for cooling.

In air-conditioned buildings temperature is controlled by building services (mostly to 26°C). The use of mechanical ventilation systems is standard.

Singapore has a hot and humid climate where outdoor temperatures are predominantly above comfort limits during daytime. For this reason we assume in this paper that the building is run in air-conditioned mode. Nevertheless there are also chances to run the building partly in adaptive mode, saving power demand for mechanical ventilation and cooling and thus leading to still better results.

To retain chances of a partly adaptive use the optimized standard office room for Singapore has a building depth of only 8.75 m to allow natural ventilation. The geometry of the optimized room is presented in figure 1.

The energy demand of this optimized room is determined with energy plus based transient simulation software (Primero-Comfort [9]). The effect of buildings shadowing each other and influence on power demand for artificial light is included.

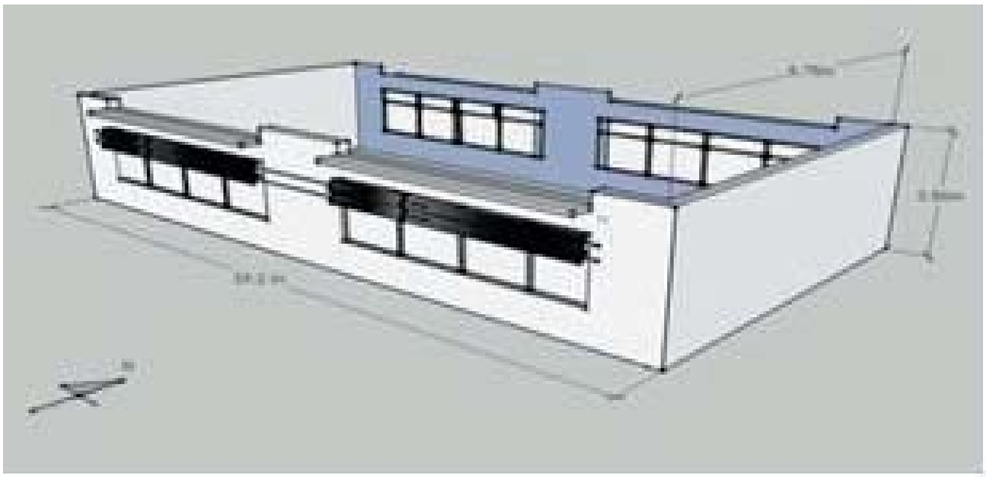

Fig. 1 The design of the optimized room with the design of overhang (width: 19.2m, depth: 8.75m, height: 3.5m).

### 2.2 Building services and renewable energy production on-site (ZEB)

The renewable energy concept is based on a combination of two systems for thermal and electrical energy. A geothermal system uses thermal energy from the ground (heat exchangers up to 100 m depth are assumed) which is transferred to the right temperature for heating and cooling with a power driven heat pump. The power production is delivered from PV modules mounted on the building's roof.

A purist ZEB produces all energy on site. Thus, the peak in heating or cooling power determines the necessary size of the geothermal system. Because the ground between two buildings can be used only once for geothermal systems this determines finally the minimal size of the estate and thus the building distance. For power it is assumed that the grid can serve as storage. The necessary size of PV modules is thus determined by the yearly power demand of the building. Because we assume only the roof as possible area for PV this determines finally the maximal number of floors producing this power demand. Thus, number of floors and building distances are not free of choice but determined by the target to reach a ZEB.

In Singapore there is no heating demand; table 1 shows the strategy for cooling and the assumed coefficients of performance (COP).

Table 1: Cooling strategies, resulting COP for power demand

| Priority | Cooling system | Power demand |
|---|---|---|
| 1st | Geothermal and thermally activated ceiling, natural ventilation | Heat pump COP 2.5 |
| 2nd | Geothermal and mechanical ventilation. Standard air change 2 1/h | Heat pump COP 2.5 plus power demand for ventilation |
| 3rd | Standard chiller, mechanical ventilation. Standard air change 2 1/h | Chiller COP 1.5 plus power demand for ventilation |

### 2.3 Building services and renewable energy production on-site and off-site (ZEB_CM)

For a ZEB with compensating measures (ZEB_CM) the number of floors and building distances are free of choice and defined by other principles like minimal urban density, liveability, etc. From the predefined building distance the maximal power of the geothermal system can be calculated backwards as well as the maximal yearly power generation from the building's roof. Both are compared with the real energy demand for thermal and electrical energy. If a part of these energies is not covered it has to be covered by compensating measures off-site to reach a ZEB_CM.

In Singapore we have only cooling and no heating. That leads finally to only power demand to serve all systems. Thus, compensating measures means power production off-site. To be fair the same PV modules like on the building's roof were assumed to determine the necessary compensating area.

Of course, renewable power production off-site could be replaced by other systems like wind turbines on- or off-shore, power plants, etc. Based on data for the energy density of these systems [5], it can be estimated that PV modules gives the best values. Thus, for all other systems the compensating area will be larger than the one we used in this paper. On the one hand, we assume that PV modules cover the whole land and no other use is possible. On the other hand, wind turbines have a smaller energy density for power production but cover land only point by point, leaving space for other uses like agriculture. Thus, regarding energy density, it is not the end of the story, further investigation would be necessary here to clear up the interdependencies.

### 2.4 Singapore government's urban plan

Singapore government's urban plan (see figure 2) controls the plot ratios for further city development. Supplementary the building heights are limited by a given maximal number of floors depending on the plot ratio (5 floors up to pr 1.4, 12 for 1.6, 24 for 2.1, and 36 for 2.8) [10].


Fig. 2 Example of Plot Ratio Plan developed by Singapore's Urban Redevelopment Authority showing city center [10]. The indicated numbers are the given plot ratios.

Table 2: Different investigated variants according to Singapore government's urban plan

| Variant | Description |
|---|---|
| Purist ZEB without compensating measures | |
| 1 | • 3.4 floors as a result of PV power production on building's roof<br>• Building distance according to peak cooling demand and geothermal system. But the resulting distance is less then prescribed by Singapore standard. Thus Singapore standard is assumed with building distance 12 m and plot ratio 1.4 |
| ZEB_CM with PV modules off-site, pr 1.4, 2, 2.5, 3, 3.5, and 4.2 | |
| 2 | • 8 floors<br>• Building distance according to respective pr |
| 3 | • 12 floors<br>• Building distance according to respective pr |
| 4 | • 24 floors<br>• Building distance according to respective pr |
| 5 | • 36 floors<br>• Building distance according to respective pr |

Exemplarily we chose plot ratios of 1.4, 2, 2.5, 3, 3.5, and 4.2 for our investigation. Because we want to investigate if the given combinations of pr and floor number are optimal, we do not follow Singapore's rules and assume for all pr a variety of 8, 12, 24, and 36 floors. From this, building distances can be calculated accordingly based on the pr. The results lead to the 5 investigated variants described in table 2.

# 3 Results

In this paper we aim to explore the relationship between urban density and required compensating area in order to meet the target of land-use efficiency. We propose that urban density could be evaluated in several ways. Firstly, it can be evaluated by how much total space is required and how the total space requirement varies with number of floors and plot ratio. Secondly, urban density can also be evaluated by land-use efficiency, which is measured by the size of the compensation area that is required for each unit of area of use. Finally, we would like to address the issue about energy sprawl, defined as the product of the total quantity of energy produced annually (e.g., TW hr/yr) and the land-use intensity of production (e.g. $km^2$of habitat per TW hr/yr) [12]. In order to examine the energy sprawl created by the requirement of compensating area, we compare the changes before and after compensating area are included into the calculation of urban density.

## 3.1 Measuring the level of space-saving

The measurement of space-saving consists of two indicators. Firstly, the level of space-saving can be measured by compensating area. Compensating areas of buildings with different heights and plot ratio are then compared. Secondly, the sum of estate area and compensating area is compared among buildings with different heights and plot ratio.

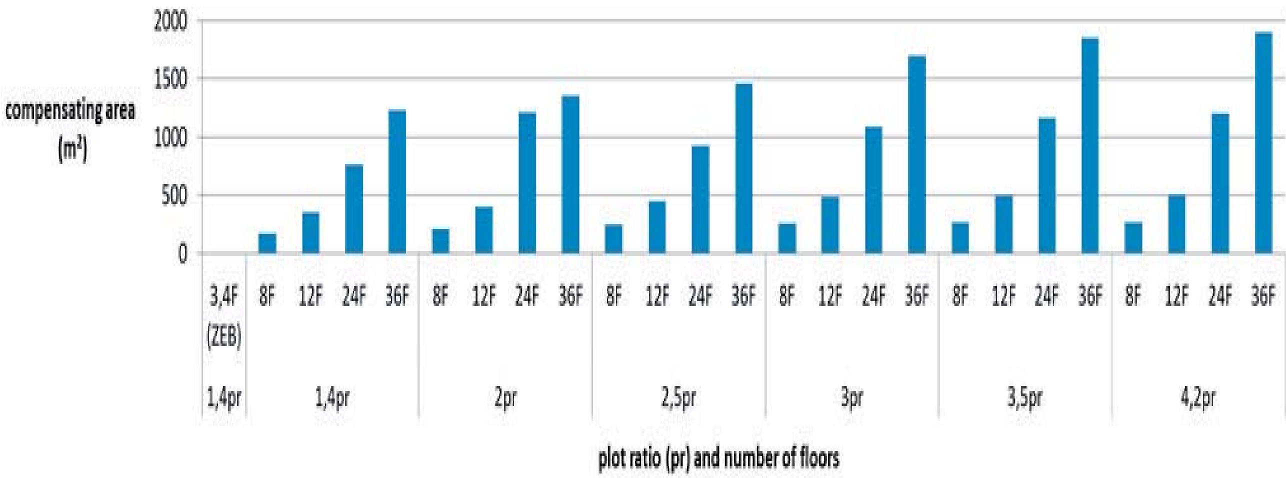


Fig. 3 Required compensating area by building height and plot ratio.

The results presented in figure 3 show that, comparing with a low-rise building, a high-rise building requires more compensating area. And the compensating area increases with plot ratio.

But we propose another indicator which highlights the interdependencies in a clearer way: Space-saving should also be measured by the total required area, including both estate area and compensating area. The results in figure 4 show that, the higher the building, the larger total area is required. However, the total required area decreases as the plot ratio increases.


Fig. 4 Total required area by number of floors and plot ratio.

### 3.2 Evaluating the land-use efficiency of energy production

Land-use efficiency of energy production is measured by the ratio of compensating area and area of use, which represents the need of compensating area for each unit of area of use. This standardized compensating area makes it easier to carry out comparison of land-use efficiency among different types of buildings.

$$\textit{Land-use efficiency} = (\textit{compensating area}) / \textit{area of use} \qquad (1)$$

The results in figure 5 show that, for each unit of area of use, a higher building needs more compensation area than a low-rise building. The results also show that, the larger the plot ratio, the more compensating area is required for each unit of area of use. This means low-rise buildings and small plot ratio are in fact more efficient in land-use in terms of energy production.

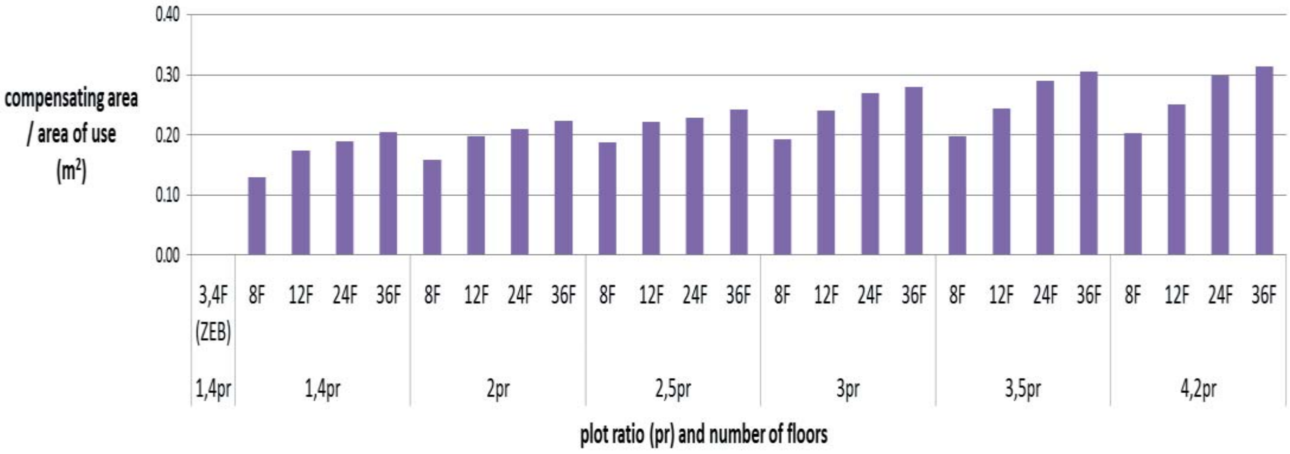


Fig. 5 Ratio of compensating area and the area of use by number of floors and plot ratio.

Furthermore, it would also be interesting to examine the ratio of the total area, i.e. the sum of estate area and compensating area, and area of use.

$$\textit{Land-use efficiency (2)} = (\textit{estate area} + \textit{compensating area}) / \textit{area of use} \qquad (2)$$

The results in figure 6 show that, the total required area per unit of area of use increases with number of floors and decreases with plot ratio. This means that, when estate area is included, low-rise buildings and larger plot ratio are in fact more efficient in land-use in terms of energy production.

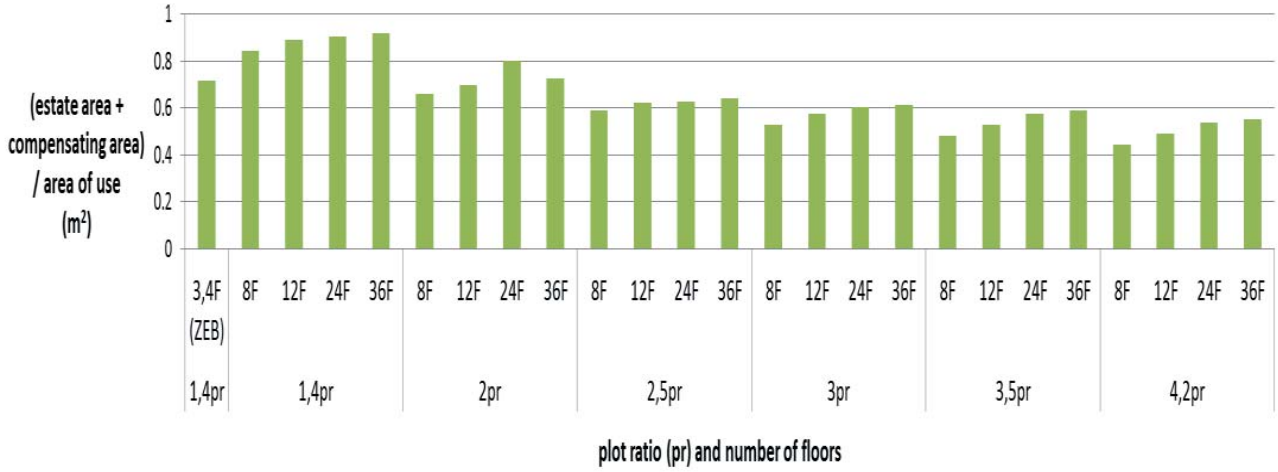


Fig. 6 Ratio of total area and the area of use by number of floors and plot ratio

### 3.3 Effect of compensating area on urban density

A measure for urban density is the plot ratio, which is:

$$(urban\ density=)\ plot\ ratio = (area\ of\ use) / (estate\ area) \qquad (3)$$

Due to the requirement of compensating area to supply renewable energy, we are also interested to examine the changes in the urban density when compensating area is included in the calculation. We define the extended urban density as:

$$extended\ urban\ density=area\ of\ use / [(estate\ area)\ )+(compensating\ area)] \qquad (4)$$

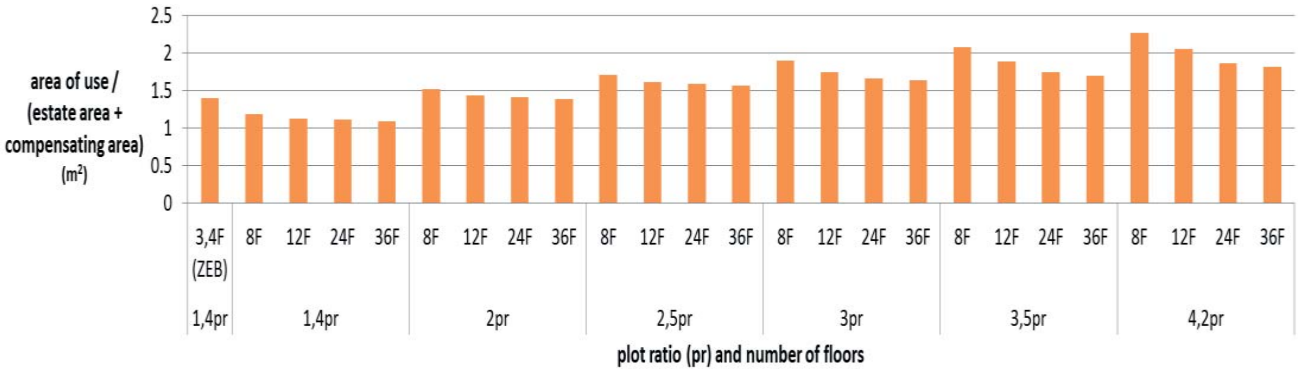


Fig. 7 Extended urban density by number of floors and plot ratio

Comparing the urban density (plot ratio) and the extended urban density with different building heights, the results in figure 7 show that extended urban density decreases with number of floors but increases with plot ratio. This means that, the taller the building, the larger the difference between original density and the extended density. And the differences is even greater in large plot ratio than the small one.

# 4 Discussion

Based on the results in previous section, we derive some general suggestions with regard to the planning of land-use requirement of energy production:

- If the priority of land-use planning is to save land inside the town, use high plot ratio.
- If the priority of land-use planning is to save land for CM, use a small number of storeys.
- If the priority of land-use planning is to save land in general, use high plot ratio. And, within high plot ratio, use small number of floors.

Supplementary we give some comments to the physical aspects which lead to the results. The detailed noted figures for pr, COP, etc. are special for the location and will be different for others. But the discussion shows also the general tendencies:

- Up to pr 2.5 the building distance is big enough to cover the whole cooling demand with basic cooling (geothermal, heat pump, thermally activated ceiling)
- For higher pr, the estate is fully used for geothermal but a part of cooling demand is still not covered, we need standard chiller with worse COP and thus higher power demand.
- Up to pr 2.5 there is remarkable influence of shadowing and the resulting power demand for artificial light. The lowest power demand (best daylight access) here is with the higher number of floors and bigger distances. For plot ratio 3.5 and higher, the shadowing is so strong that artificial light has to be used the whole time, independent of number of floors.

Our results in section 3.4 show that the inclusion of compensating area changes the urban density. This variation increases with number of floors and plot ratio. If Singapore government takes compensating area into the consideration of the future plan without changing the plot ratio in the current plan (5 floors up to pr 1.4, 12 for 1.6, 24 for 2.1, and 36 for 2.8), the number of floors will need to be reduced. As the results in figure 7 shows, the differences between urban density and extended urban density is smaller when the number of floor is smaller.

Our results lead us to the questions in the next step: is it possible to include compensating area in the land-use planning in Singapore? At first glance, high-rise and high-density developments seem to be simple ways to circumvent the limited land. However, high-rise building increases the demand for larger compensating area. On the other hand, there are a little bit more than 50 percent of the areas that are reserved for airports, ports, sewage treatment plants, and water catchments [11]. For the future planning, we propose that areas with the potential for multi-usage, such as compensating area for renewable energy production, should be identified and calculated. Then the regulation of building height can be derived by using the methods proposed in this paper. Meanwhile, we suggest that methods for the estimation of compensating area, the variables that contribute to variation in energy consumption, and the comparison among districts should also be further refined and developed in the future research.

# 5 Conclusion

We hope that this paper can contribute to the discussion about urban sprawl and compact city by including building energy consumption and renewable energy production on-site and off-site into the considerations. Also, the discussion about urban density and energy production is often focusing on population density. It is our attempt to propose a supplementary measure by exploring the relationship between building density and energy production. Finally, this paper intends to fill the gap between building design and energy density, which is about the relationship between different types of energy production technologies and land-use requirement. We propose that the land-use planning of renewable energies does not only need to measure energy density, but it should also consider how much land is required with different building design. The possible further development of this paper would be to include more cases in different climate zones and to carry out comparative studies. Alternatively, it may also be interesting to look further into other aspects of land-use policy in the selected city and discuss about the balance among various land-use needs with a more holistic view by including land-use requirement of energy production into consideration.

## 6 Acknowledgements

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