LAND-USE PLANNING FOR ZERO-ENERGY-BUILDINGS: COMPARISON OF FOUR HIGH-DENSITY CITIES

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ABSTRACT

A net approach to Zero-Energy-Building (Net ZEB) requires all energy demand to be met by on-site generation of renewable energy. An off-site ZEB with compensating measure (off-site ZEB_CM) allows off-site land to be used if the energy demand cannot be met due to the urban arrangement of buildings. A method is developed for evaluating the potential and risk of Net ZEB and off-site ZEB_CM in densified urban situations by examining their land-use requirement on- or off-site. Four cities with different climates are modelled: Singapore, Cairo, Beijing and Hamburg. The preliminary results indicate that (1) the rate of change in CM per unit of area of use is not a constant number and varies with numbers of storeys, urban density and climate zone; (2) to save land for the compensating measure, a small number of storeys should be used; (3) to save land in general, high plot ratio should be used. Within a high-density situation, a small number of storeys should be used. This research contributes to the discussion about urban sprawl and compact city by investigating the relationship between urban fabric and energy harvesting. It may encourage the land-use policy makers to include land-use requirement of renewable energy harvesting.

Keywords: zero energy building, compensating areas, urban density, energy demand, land-use planning, low-carbon society

1 INTRODUCTION

The main interest of this paper is to examine the relationship between urban fabric and land-use requirements for achieving enough renewable energy to cover urban energy demand. Even though it is known that there is the discrepancy between demand and supply by the renewables, this problem is often overlooked. The importance of this problem has been further emphasized by recent studies reporting that energy sprawl, which is defined by the development of new land area required for energy production, is now one of the largest driver of land use change for the foreseeable future with increasing proportion of renewable energy harvesting. For example, Trainor et al. [1], quantify projected energy sprawl in the United States through 2040. Their results show that when land-use requirements of compensating measures (CM) are included, more than 800,000 km2 of the additional land area will be affected by energy development. Not only is this number higher than projections for future land use change from residential development or agriculture, but also that the pace of development is more than double the historic rate of urban and residential development. “The possibility of widespread energy sprawl further increases the need for energy conservation, appropriate siting, sustainable production practices, and compensatory mitigation offsets” [2]. The need for reducing energy sprawl, therefore, further enhances the importance of research that investigate the density, the geometrical and morphological characteristics of buildings that minimize the energy consumption.

In order to bring primary energy consumption and CO_2 emission to zero, one significant contribution is the optimization of buildings to a new standard of Net Zero-Energy-Building (Net ZEB). The most common definition of a ZEB is the Net ZEB that calculates primary energy consumption, including thermal energy for heating, cooling and hot water as well as

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power for mechanical ventilation and artificial light. It contains all sorts of energy in buildings that can be directly influenced by building design.

It should be mentioned that power for appliances and energy for traffic are not included in this paper. For some locations with low heating or cooling demand, power for appliances may be dominant. To create a real carbon-free city, power for appliances and energy for traffic have to be covered by renewables. Nevertheless, this paper concentrates on energy consumption that is influenced by building design and arrangement. The power for appliances and energy for traffic are not included in this paper and the standard definition of a ZEB is used here.

A ZEB balances the energy of demand and supply sides. Energy demand can be minimized by architectural techniques, but it is not possible to bring it to zero. For example, the use of buildings during the dark hours leads to the demand for artificial light. To reach zero, the remaining energy demand has to be covered by building services using renewable energies.

The Net ZEB definition framework developed by Satori et al. [3], describes and analyses different aspects of Net ZEB in a series of five criteria and sub-criteria. One of the criteria, the physical boundary of the building system, is used in this paper to identify the so-called “on-site” and “off-site” generation systems. Defining the building system boundary is necessary for identifying whether energy flows cross the boundary. The physical boundary of the building system may encompass a single building or a group of buildings. If all energy flows are within the boundary it is considered on-site, otherwise, it is off-site. Detailed definitions of Net ZEB and off-site ZEB_CM used in this paper are in the following.

1.1 On-site Net Zero-Energy-Building (Net ZEB)

The Net definition of a ZEB requires that this energy is to be gained on-site from the building envelope or the ground under or near the building [4]. This requirement leads to the competition between the area of use to be served, which creates energy demand, and size of building envelope and size of the estate to cover this demand with renewable energies. This requirement also limits number of possible storeys and minimal building distance. In this paper, this type of ZEB is called an on-site ZEB.

1.2 Off-site Zero-Energy-Building with Compensating Measures (off-site ZEB_CM)

A wider definition of ZEB allows producing a part of energy off-site on compensating areas outside of town. A compensating area could be covered with wind turbines, PV modules, sustainable agriculture, and etc. In this paper, this type of ZEB is called an off-site Zero-Energy-Building with compensating measures (off-site ZEB_CM). From an ecological point of view, both versions of ZEBs have the same zero contribution to CO_2 emission and they are adequate options.

The first challenge faced by land-use planners is that, in a city with very high urban density, a Net ZEB is often not possible because it is usually limited by height and volume due to the requirement to produce energy on-site. Or, vice versa, the attempt to derive a city with a Net ZEB would lead to a limited urban density. The limited urban density would not be optimal for public transport systems, which minimized transportation energy [5], and a liveable urban situation.

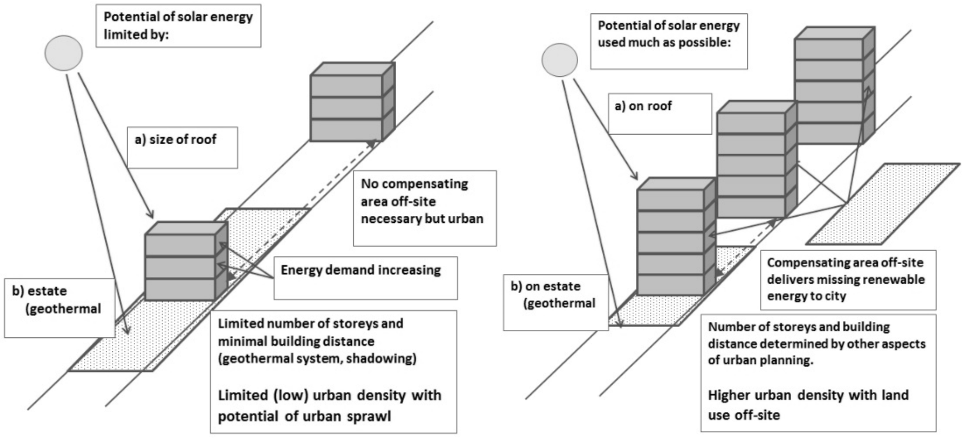


Figure 1: Main characteristics of Net ZEB (left) and off-site ZEB_CM (right).

Although an off-site ZEB_CM represents an alternative solution, land-use planners still face the challenge that an off-site ZEB_CM requires compensating areas outside of town and this requirement creates competition among the land uses, such as forestry protection or agricultural activities. “To create a sustainable energy future for their own people, countries (or cities) with both dense and high-consumption, should expect renewable facilities to occupy a significant fraction of their land, if they ever want to live on their own renewables” [6].

1.3 Aim of this paper

The aim of this paper is to develop a preliminary method to derive general tendencies of renewable energy development in different climates by examining the land-use requirement of Net ZEB and off-site ZEB_CM and by offering a simplified model with general and identical assumptions for all locations to obtain comparable results. The intention is to address these questions and draw broader attention to further explore the relationship between the variables. It may also encourage land-use policy makers to include land-use requirement of renewable energy harvesting into consideration.

The existing tools, such as CitySim or Umi (MIT), are not used in the current research because they are more tailored for detailed simulations for one specific location. The objective of this paper is to derive general tendencies and rules for different climates without regarding detailed situations of a special location.

The following questions are investigated:

- For the land-use for energy demand: How can energy consumption and energy sprawl be reduced without affecting urban density?
- For the land-use for renewable energy supply: How does compensating area per unit of area of use change with numbers of storey, urban density and energy harvesting technologies?

2 METHODS

The method used is this paper has been developed for a master course. Here the students explore the potential of Net ZEB and off-site ZEB_CM for big cities in all main climate zones around the world. The target is to derive design rules for Net ZEB and off-site ZEB_CM, to carry out the design of building types and type facades, to develop rules for building distance and urban density and to investigate the required space for the compensating area for all these locations.

The analysis focuses on office buildings instead of a real urban land use, which includes residences, offices, retail, industries etc. The reasons for this simplification is that, firstly, it is not possible to find a distribution of land uses which is really representative for all climates, locations, or cultures. The target of this paper is to derive general tendencies and comparable results for different climate zones. Therefore, a general and identical assumption for all chosen cases is necessary. Secondly, although residential buildings have the highest percentage in area of use in all locations, the energy demand of office buildings is higher than that of residential buildings. Thus, if the derived design proposal can cover the demand for office buildings, it can also cover the demand for residential buildings.

Before the investigation starts, there are several preconditions with regard to the definition of building types, comfort models for summer and winter, and regenerative building services.

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

A standard office room with 168 m^2 of area of usage (12 m width and 14 m depth) for 12 users was predetermined to gain comparable results. 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 development of the optimized room, which is adapted to local climate and conditions, is based on several tools and sources: 1) Climate analysis was carried out by Climate Consultant [7] and its rules; 2) Best practice examples, vernacular or traditional architecture; 3) Experiences of students coming from these locations. Finally, the construction, window size, shading system of the office room are also carefully selected to adapt to the local climate and condition.

The remaining energy demand has to be covered by renewable building services on-site for Net ZEB and on- and off-site for off-site ZEB_CM. Three types of corresponding building mode can be distinguished: adaptive, air-conditioned and hybrid.

An adaptive building is understood as a building with natural ventilation where the users can adapt their surrounding according to their preferences: no dress code, operable windows, personal switches for artificial light, thermostats, and etc. Besides heating with standard systems, cooling is also possible with thermally activated ceilings. In adaptive buildings, the expected comfort temperature is assumed in accordance with adaptive comfort models [8], [9], where above 20°C indoor comfort temperature varies slightly with the mean value of outdoor temperature. This assumption delivers comfort and also saves energy for cooling.

At locations with outdoor temperatures far from comfort range, mechanical ventilation (with heat recovery) is used to control air change and thus thermal losses. This may happen for cold periods for heating as well as for hot periods for air-conditioning, which controls the temperature to be mostly at 26°C. Singapore is a typical example of a hot and humid climate, where air-conditioning is used 12 months a year.

A hybrid building is the one which can be adaptive for some months when outdoor temperature is not too far from comfort range and also be run with mechanical ventilation and heating or air-conditioning for other months.

Four cities representing different types of weather will be investigated in detail: Hamburg (cold winter with mechanical ventilation), Beijing (cold winter and hot summer with adaptive months in between), Singapore (hot winter and hot summer) and Cairo (adaptive period in winter and hot summer).

The energy demand of this optimized room is determined by Energy Plus (U.S. Department of Energy, n.d.) based transient simulation software, PRIMERO-COMFORT [10]. The effect of buildings shadowing each other and its influence on power demand for artificial light are included.

2.2 Building services and renewable energy harvesting on-site (Net 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 (Coefficient of power (COP) heating 3.5; Energy Efficiency Ratio (EER) cooling 2.5). The power harvesting is delivered from PV modules with an efficiency of 14% including system losses mounted on the building’s roof. The Net ZEB produces all energy on site. The numbers of storey and building distances are not free of choice but determined by the target to reach a ZEB. Thus, the peak of heating or cooling energy demand determines the necessary size of the geothermal system. Because the ground between two buildings can be used only once for geothermal systems, this demand also determines the minimal size of the estate and thus the building distance. For power, it is assumed that the grid can serve as storage. Effects of time shift between production and consumption are neglected here. The necessary size of PV modules is thus determined by the yearly power demand of the building. Because it is assumed that only the roof as the possible area for PV, this determines the maximal numbers of storey producing this power demand.

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

For an off-site ZEB_CM, the numbers of storey and building distances are set by other criteria of urban planning. From this predefined building distance, the maximal power of the geothermal system can be calculated backward. If the geothermal system is too small to cover the demand, it is necessary to add standard air-to-air heat pumps (split device, EER 1.5) for further cooling.

The maximal yearly power generation from the building’s roof can also be calculated. If the real thermal and electrical energy is not covered by the systems on-site, the remaining part has to be covered by renewable compensating measures off-site to reach an off-site ZEB_CM. For the investigations presented here, PV-modules horizontal for power are chosen. For thermal energy, the problem of transporting from compensating land to the city was already mentioned. Thus, the thermal energy has to be transported as raw material in form of any energy plant. To be comparable the same wood pellets are chosen for all locations regardless of whether they are available there.

For the selected cities, the energy demand, the coverage potential on-site and the need of compensating land off-site are investigated for a set of different urban arrangements

Table 1: Different investigated variants for urban density (plot ration pr) and number of storeys.

Storeys	4 8 12 24 36	4 8 12 24 36	4 8 12 24 36	4 8 12 24 36	4 8 12 24 36	4 8 12 24 36
pr	1.5	2	3.5	3	3.5	4

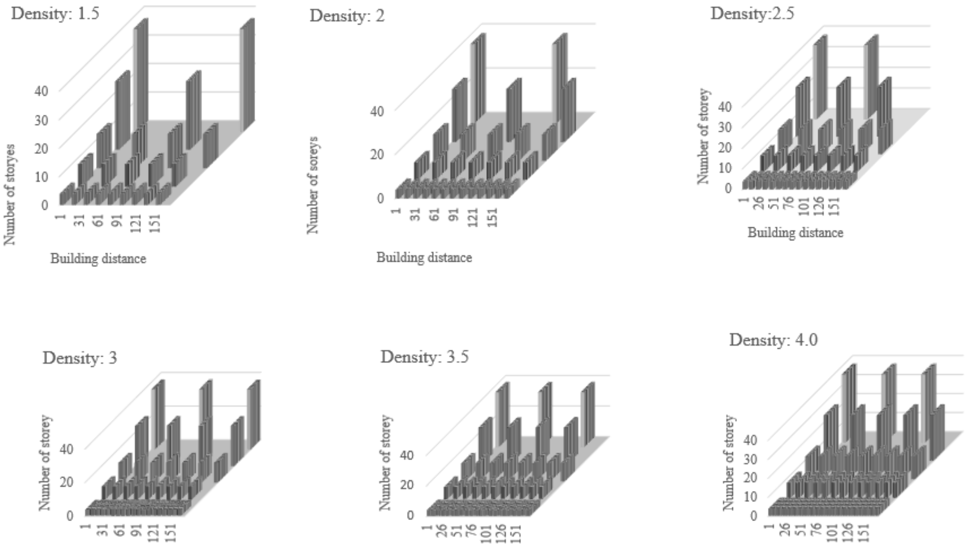


Figure 2: Relationship between urban density, the number of storeys and building distance.

covering different densities (plot ratio) which are realized by different numbers of storey and building distances (Table 1 and Fig. 2). The plot ratio of medium-high to high densities, which are also the plot ratios prescribed in Singapore's development plan (Singapore Urban Redevelopment Authority, 2014), are chosen the investigation. The numbers of storey ranges from low to multi-storey buildings in order to cover all styles.

3 RESULTS FOR LAND-USE EFFICIENCY OF OFF-SITE ZEB_CM

The land-use efficiency of different urban densities and numbers of storey can be described by the following indicators that take both of estate and compensating area into consideration.

3.1 Indicators for evaluating the land-use efficiency of energy harvesting

The land-use efficiency of energy harvesting is measured by ratio of compensating area to area of use (CM ratio (1)). It represents the need of compensating area for each unit of area of use. This standardized compensating area makes it easier to carry out the comparison of land-use efficiency among different types of buildings. The smaller the CM ratio (1), the less CM is required and the higher the land-use efficiency it is. Therefore, a smaller CM ratio (1) is preferred.

$$\text{CM ratio (1)} = \text{compensating area} / \text{area of use}. \tag{1}$$

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

$$\begin{aligned}\text{CM ratio (2)} &= (\text{estate area} + \text{compensating area}) / \text{area of use} \\ &= \text{total area} / \text{area of use}.\end{aligned} \tag{2}$$

3.2 Indicators for effect of compensating area on urban density

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

$$\text{Original urban density} = \text{plot ratio} = (\text{area of use}) / (\text{estate area}). \tag{3}$$

Due to the requirement of the compensating area to supply renewable energy, urban density is changed after including compensating area in the calculation. The modified urban density is defined as the following:

$$\text{Extended urban density} = \text{area of use} / [(\text{estate area})) + (\text{compensating area})]. \tag{4}$$

3.3 Results for CM ratio (1)

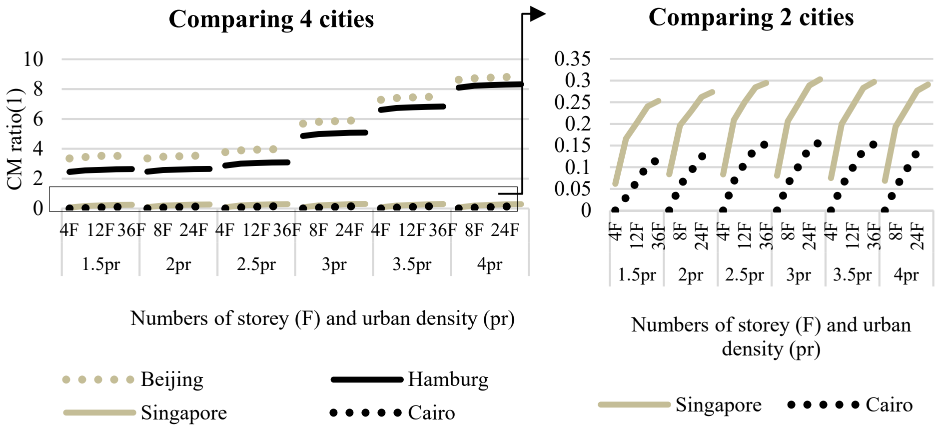
The analysis of results focuses the relationship between climate zones, land-use efficiency and urban fabric. The results in Fig. 3 present the relationship between CM ratio (1) and urban fabric. The first pattern to be observed is the relationship between CM ratio (1) and numbers of storey. Because the CM ratio (1) is a standardized indicator, if the number of storey does not affect the CM requirement, CM ratio should be the same among different number of storeys. However, the results show that CM ratio (1) increases with numbers of storey. This means that the larger the numbers of storey, the more compensating area is required for each unit of area of use. In other words, for each unit of area of use, a higher building needs more compensation area than a low-rise building. Land-use efficiency decreases with numbers of storey and there is a negative relationship between numbers of storey and land-use efficiency.

Another result that can be observed in Fig. 3 is the relationship between urban density and CM ratio (1). The results show that the larger the urban density, the more compensating area is required for each unit of area of use. In other words, for each unit of area of use, a larger urban density needs more compensation area than a small one. Land-use efficiency decreases with urban density and there is a negative relationship between urban density and land-use efficiency.

3.4 Results for CM ratio (2)

The results in Fig. 4 compare the relationship between CM ratio (2) and urban fabric at city level within each climate zone. The first pattern to be observed is the relationship between CM ratio (2) and numbers of storey. Fig. 4 shows that, the larger the numbers of storey, the more estate and compensating area is required for each unit of area of use. In other words, for each unit of area of use, a higher building needs more estate and compensating area than a low-rise building. Land-use efficiency decreases with numbers of storey and there is a negative relationship between numbers of storey and land-use efficiency.

Another result that can be observed in Fig. 4 is the relationship between urban density and CM ratio (2). The results show that the larger the urban density, the more estate and compensating area is required for each unit of area of use. In other words, for each unit of area of use, a larger urban density needs more estate and compensating area than a small one. Land-use efficiency decreases with urban density and there is a negative relationship between urban density and land-use efficiency.


Comparing 4 cities

Comparing 2 cities

Figure 3: CM ratio (1) by the numbers of storey and urban density in Beijing, Hamburg, Singapore and Cairo.

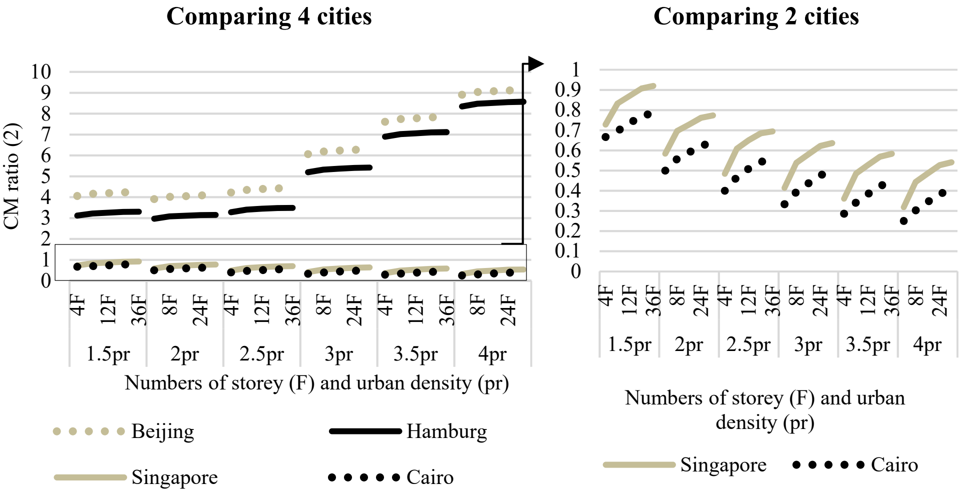

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Figure 4: CM ratio (2) by the numbers of storey and urban density in Beijing, Hamburg, Singapore and Cairo.

3.5 Results for effect of compensating area on extended urban density

The results in Fig. 5 presents the relationship between numbers of storey and extended urban density. The results show that the higher the building, the smaller the extended urban density and the larger the difference between original density and extended urban density. And the difference is even greater for higher buildings. The important implication here is that, on the one hand, higher buildings increase the area of use and, therefore, increases the extended urban density. On the other hand, it also increases the requirement for CM and reduces the extended urban density. There is a diluting effect of CM on the extended urban density.

Another result that can be observed in Fig. 5 is the relationship between original and extended urban density. The results show that the larger the original urban density, the smaller the extended urban density and the larger the difference between original and extended urban density. This also means that, on the one hand, extended urban density can be increased by reducing the building distance and, on the other hand, it also increases the requirement for CM and reduces the extended urban density.

4 DISCUSSION

This paper is motivated by anticipation that the development of new land area required for energy production is becoming the main driving force of land use change. The immediate challenge faced by urban planners is to reduce the energy consumption and energy sprawl without affecting urban density. In the high-density area, the CM becomes an important factor to land use change. There is the pressing need to understand how compensating area changes with the numbers of storey, urban density and energy harvesting technologies. More specifically, the core of the question is to explore the relationship between urban fabric and the CM.

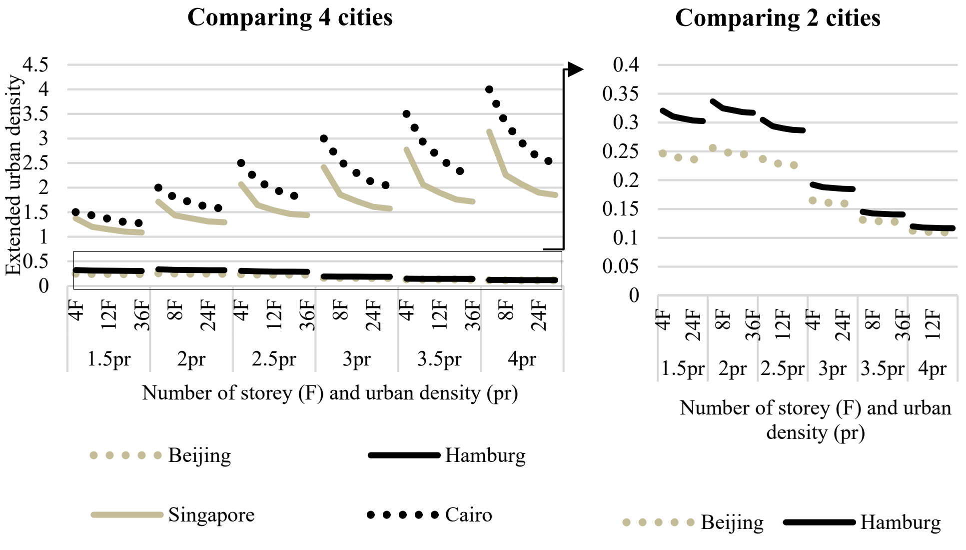
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Figure 5: Extended urban density by the numbers of storey and urban density in Beijing, Hamburg, Singapore and Cairo.

To answer these questions, this paper develops an experimental method with regard to how to find the best solution for land use planning of ZEB and which parameters may be taken into consideration. As the planning targets vary among different cities, planners can now apply this tool to explore the effect of CM on their own proposal.

4.1 Physical aspects

The detailed noted figures, such as plot ratio, EER or COP, are specific for each location and will be different from each other. But they represent the typical behaviour for corresponding climates. The results depend strongly on the efficiency (EER and COP for machines, energy density for harvesting of solar radiation) of renewable energy harvesting for thermal energy, including heating and cooling, and power on-site and off-site. Changes in the kind of energy harvesting technology may completely inverse tendencies.

In Singapore, there is only demand for cooling and the need for heating does not exist. In Cairo, cooling demand is much higher than heating demand and becomes the dominant source of energy demand. The cooling demand can be easily covered by the geothermal system and heat pump. Thus, compensating measure means power harvesting by PV off-site. In order to determine the necessary compensating area, the PV modules of off-site ZEB_CM and those on the building roof inside the city are assumed with the same efficiency, same arrangement, and same harvest per m^2. The energy density of PV modules is relatively high (see Fig. 2) and the high cooling demand would lead to a moderate compensating area.

While Beijing has both cooling and heating demand, Hamburg has only heating demand. That leads to both power and heating demand to serve all systems. Thus, compensating measure means power harvesting by PV and wood pellets off-site. The energy density of wood pellets is very week (see Fig. 2). Therefore, a high heating demand would lead to a huge requirement of compensating area dominated by PV. This pattern can be observed in all of the graphs, which show that the difference between Beijing and Hamburg as well as the difference between Singapore and Cairo becomes smaller as the numbers of storey and urban density increase.

For all locations, there is a different threshold where the capacity of the geothermal system is fully used and less efficient technologies for cooling (split device) has to be used or compensating measures for heating have to be used respectively.

4.2 General recommendations

The main target of this paper is to develop a tool for planners to include CM in the planning process, therefore, the values of the results in this paper are not intended to be not representative. Instead, the results serve as an example to demonstrate how to use the method. Based on the results, general suggestions are derived with regard to the planning of land-use requirement of energy harvesting:

- 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 small numbers of storey.
- If the priority of land-use planning is to save land in general, use high plot ratio with small numbers of storey and low-rise building.

- Try to use other possibilities for renewable heat production inside the city, such as district heating based renewables. Try to avoid using the compensating area for energy plants that competes with food production. For wood pellet production, sustainable forestation should be given the priority.
- The smallest plot ratio has the lowest need in compensating area for heating. Under these constellations with low plot ratio, low-rise building with small numbers of storey are the optimal option because compensating area is minimised, and the priority is given to daylight access.
- Up to urban density 2.5, there is a remarkable influence of shadowing and the resulting power demand for artificial light. Buildings with higher numbers of storey and bigger distances have the lowest power demand with the best daylight access. For buildings with the urban density greater than 3.5, the shadowing is so strong that artificial light has to be used at all time, regardless of the numbers of storey.

5 CONCLUSIONS

In this paper, supplementary measures were created to explore the relationship between building density and energy harvesting. This research fills the gap between researches about energy density and building design by revealing the relationships between different types of energy harvesting technologies and land-use requirement of different urban densities. The results show that the optimisation of zero-energy buildings with on-site energy generation will reduce urban densities in several different climatic zones and that low-rise buildings with high density may be an optimal option. It is suggested that the land-use planning for renewable energy must measure energy density and also consider the amount of land required by different building designs. This research highlights the importance of land-use policy and the need for urban policy to create a more holistic view by including a land-use requirement for energy harvesting.

The target of the current paper is to generalize tendencies and dependencies between area of use, estate area and compensating land for different climates. Future studies focussing on the detailed investigations for one special location would benefit from the more detailed description of urban fabric and mix-use of land between studied cities. Also, more precise assumptions about time displacement of production versus consumption and whether the grid absorbs differences between onsite production or consumption should be included in the subsequent studies. Detailed solutions, which optimizes the supply side in terms of land requirements, for special cities in different climate zones requires more precise tools. However, such results would be specific and only valid for the chosen city, instead of the general tendencies provided in this paper. These issues deserve to be further discussed in future studies.

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