economically benefit the local population. In addition, the installation of solar panels (photovoltaic and solar collectors) on building envelopes will be the norm if the current trend of more efficient and less expensive panels is prolonged. Therefore, the integration of farming areas and the potential installation of solar panels should be considered as some of the design parameters for new residential districts in Singapore and SEA.

Numerous studies have tackled the problem of the insertion of productive gardens in urban areas from the point of view of land use planning (Indraprahasta, 2012), of the use of roof top (Astee & Kishnani, 2010) and of vertical farming and high-tech methods (Despommier, 2013). In addition, several studies have been conducted on the potential of the urban form to harvest solar energy (Kanters & Horvat, 2012) and on the calculation methods of solar distribution on urban environments and solar access (Ibarra & Reinhart, 2011). In the context of Singapore, several studies have dealt with the impact of urban form on several environmental indicators like daylight and natural ventilation (Zhang el al. 2012; Lee et al. 2013)

However, no study was found in literature about the impact of urban form on sunlight availability for food production. There is also a need to conduct a comprehensive study dealing with both food and energy harvesting in tropical high density areas. Therefore, the objective of this study is to verify, through the use of computational tools, the impact of a series of densities and urban forms on sunlight availability for one of the three identified typical public housing typologies in Singapore: point block. This is translated into coefficients of self-sufficiency in terms of food (vegetables and fruits) and energy. The study provides the basis for future environmental and energy assessments including the potential of each variant for natural ventilation and carbon footprint reduction.

METHOD

The study is divided into three main stages: (1) calculation of solar availability on the point-block cases, (2) calculation of the potential of food harvesting on ground and facades and, (3) calculation of the potential of energy harvesting by Photovoltaic (PV) panels on facade and roof surfaces.

Building typology and simulation cases

Three typical public housing typologies from Singapore (Housing Development Board (HDB)) and, to some extent, from other SEA new urban areas will be assessed: point block, slab block and contemporary block. However, in this paper only the analysis of the point block typology is presented. **Table 1 shows** a summary of the twenty five point block cases that are assessed in terms of solar access by using density and geometry parameters: plot ratio (PR), site coverage (C_s) and building height (H_b). PR is defined as the ratio of the gross floor area of all buildings to the area of the analysed plot where all buildings are located. C_s is defined as the ratio of the ground floor area of all buildings to the area of the analysed plot. H_b may vary from case to case but all buildings in the same case has equal H_b.

The plot area is the same for every case: 520 x 520m^2 (27 ha). This represents the equivalent area of a typical large precinct in Singapore or several small ones including the area for car circulation. A similar plot area was used in a natural ventilation study for typical residential district in Singapore (Lee et al. 2013). **Figure 1 shows** the different C_s and building arrangements for the point-block typology. The different densities were defined departing from the typical PR of the most recent HDB developments in Singapore (PR = 3.0). Then a matrix was developed considering PR, C_s and building height. The height varies in order to keep the same -or very similar- PR on the cases coinciding with the diagonal of the matrix **as shown in Figure 1.** That means a case (2-4) having site coverage 13% with 27 floors has the same PR = 3.0 than a case (4-2) with C_s of 21% and 17 floors. For the sunlight availability simulations, every case is partially replicated in order to take into account the effect of neighbouring buildings. **Figure 2 shows** the extended models for three C_s: 10%, 16% and 27%.

Singapore's weather conditions (1.3°N) are considered for the analysis. The sky conditions are considered as intermediate sky which is typical for Singapore along the year. However, the actual values of solar radiation are taken into account from the ASHRAE International Weather for Energy Calculations (IWEC) Data (US Department of Energy, 2013). The sunlight availability of three cases is contrasted with the conditions of Hanoi, Vietnam (21°N) to assess the influence of latitude.

series of solar irradiances and illuminance levels. This version of Daysim can be integrated into Autodesk Ecotect which facilitates the modelling of the geometries while allows more accurate calculations in comparison with the Ecotect Solar access model (Ibarra & Reinhart, 2011).

Radiance simulation parameters were defined according to ‘scene complexity 1’. This means 5 ambient bounces, 1000 ambient divisions and 300 ambient accuracy among other parameters. The simulation accuracy is increased by using the DDS model which more precisely accounts for the effect of obstructions (neighbouring buildings) on the incident radiation and illuminance values.

Daysim calculates both the Daylight Autonomy (DA) and the average illuminance levels per point for the analysed period (whole year). The DA is a climatic-based index which denotes the percentage in which a minimum –defined by user- illuminance level is achieved by daylight alone for a specific time interval (Reinhart and Walkenhorst, 2001). In this study, DA is used to determine the percentage along the whole year in which each analysed point receive more than 10 000 lux from 8:00 till 18:00. The optimal illuminance level for certain vegetables and fruits is considered to be 10 000 lux for about 8 hours (Conover and Flohr, 1996). When the DA is below 80% (less than 8 hours with 10 000 lux), a reduction coefficient is applied for the calculation of the annual yield.

A grid of points (lighting sensors) was generated in every case to obtain the illuminance levels. For the ground a grid of 5 m by 5 m was generated among the buildings. For the facades grids of 5 m (X or Y axes according to orientation) by 12 m (Z axis) were generated adapted to the building height. In the case of the roof, a single point was defined due to the lack of obstructions from other buildings. No distinction is made about the different solar availability per facade orientation and height. The average of all facade points will be considered for the calculation of both the farming and solar energy potential.

The effect of shading devices (30 cm overhang along all facades on every floor) on ground and facade illuminance levels (lux) is considerable: 4% lees sunlight on ground surface and 12% less on facades. However, modelling all shading devices increase the calculation time several times, therefore, an equivalent reflectance coefficient (-20%) on the facade was applied to account for the ground illuminance reduction due to the shading devices. But since the facade reflectance values have little impact on the facade illuminance levels, another coefficient is applied directly on the final illuminance levels to account for the presence of horizontal shading devices. For overhangs of 30cm, a coefficient of 0.9 will be applied accounting for a 10% reduction.

Population and area for farming and PV panels. The amount of population per case is calculated considering that 70% of GFA is residential, 20% institutions and 10% commercial. The total amount of residents per case were calculated according to the average area per capita in the HDB of the last decade equal to 25m^2 and considering a floor plan efficiency (rental flat area out of GFA of residential building) equal to 85%. For the farming activity we consider part of the ground area and part of the facade while for the solar energy harvesting we consider part of the roof surface and part of the facade. The farming area on the ground was derived from the actual land use at Punggol New Town in the northeast of Singapore. From the total plot area, 15% is considered to be for roads and 35% for open space and recreation. The 50% remaining area is distributed between buildings and farming areas according to the different C_s. The area for car parks is considered to be underground or above ground. In the latter case, the roof of the car park is considered to be covered by playgrounds, circulation, green and farming areas. The farming area on the facade considers 50 cm of planters along 30% of the perimeter of the facade. Three fifths of the planter’s thickness (30cm) is projected outside of the building facade acting as a shading device. The remaining is considered to be inside the facade perimeter as part of a balcony or external common corridor. The other 70% of the facade perimeter is considered to be used for the installation of Building Integrated Photovoltaic (BIPV) panels. Eighty percent of the roof area is considered to be covered by solar panels.

Selection of crops and food self-sufficiency. A selection of crops was done in order to calculate the yield potential of the farming areas and the potential of food (vegetables and fruits) self-sufficiency of the total population in each case. The criteria to select the type of crops were (1) suitability for local context, (2) preference among local residents and, (3) productivity. A reduced variety of vegetables and fruits were chosen with different productivity indices. The vegetables are Kang Kong (30%), Water Mimosa (20%), Chinese Celery (20%), Water Cress (10%) and Pumpkin (20%); the fruits are Dragon Fruit (80%) and Banana (20%). The yield from the crops ranges from 5 to 30 tonnes per hectare for the Pumpkin and the Dragon Fruit respectively. The food cycle per year is from 1 to 18 for Banana and Kang Kong respectively.

Two scenarios are considered regarding the technology used for farming. The first one, termed as ‘conventional’, refers to urban ground farming methods. This method considers both the traditional ground soil gardening and the use of soil planters or containers. The second scenario is termed as ‘hybrid’ and it is a combination of the ‘conventional’ and the ‘vertical’ methods (50% ground surface each). The ‘vertical’ method refers to hydroponics, aeroponics and vertical soil-based structures like the A-shaped SkyGreen system introduced in Singapore. The vertical methods are considered to be around 4 times more productive than the conventional ones (Mugundhan, 2011). Only vegetables are considered to grow using the ‘vertical’ method. **Table 2 shows** the area needed for vegetables and fruits in order to achieve self-sufficiency per capita for the two scenarios.

Table 2. Area needed in order to achieve food self-sufficiency per capita (2 scenarios)

	Yield needed per year per capita (t)	Area needed per year per capita (conventional) (m^2)	Area needed per year per capita (hybrid) (m^2)
Vegetables	109	9.4	3.7
Fruits	55	14.8	14.8
Total	164	24.2	18.5

PV panels and energy self-sufficiency. Polycrystalline Silicon (pc-Si) and Thin-film Amorphous Silicon Copper Indium Selenide (a-Si CIS) on a horizontal position were considered for the roof and facade respectively. Typical efficiencies and temperature factors were considered: 13% and 8% for pc-Si and a-Si CIS respectively. The energy use per capita of 1287 kWh from April 2013 till March 2014 is considered for the calculation of energy self-sufficiency corresponding to a typical HDB apartment (Singapore Power Group, 2014). Solar collectors for water heating are not considered at this stage.

RESULTS

The results corresponding to the solar availability analysis and the potential of food and energy harvesting for 25 cases of point block typology are presented in this paper.

Sunlight availability

The results of the illuminance levels (luxh) per point are averaged for the ground and facade respectively. **Figure 3a shows** the average illuminance levels for the 25 cases on ground and facade points. As expected, when density (PR) increases, sunlight availability (illuminance levels) decreases. The decrease of illuminance levels is less evident on the facade points (15%) than on the ground (45%) because all facades, disregarding its orientation and the plot density, have a limited (≤ 0.5) sky view factor in comparison with less obstructed horizontal surfaces (≤ 1.0). **Figure 3b shows** the average percentage of time in which illuminance levels are above 10 000 lux. Here the differences between the lowest and highest densities are lower both for the ground points (around 12%) and facade points (6%).

Farming potential and food self-sufficiency

Figure 4a shows the ratio of food self-sufficiency for the conventional and hybrid cultivation methods. The differences between the two methods are more evident on lower densities in which larger ground area is available for the installation of the vertical farming systems.

The impact of the different urban density indicators was analysed. The H_b alone has a minor influence on the ratio of self-sufficiency (R^2=0.2). The increase of H_b results on a counterbalance effect: first it allows larger building facades with a higher potential for the installation of planters, but it also means a larger amount of residents. The second factor is more influential and make that, in general, the higher the building the less potential for self-sufficiency. C_s has a higher impact on food self-sufficiency because the amount of land available for farming is directly proportional to C_s. Therefore, there is a stronger correlation between food self-sufficiency and C_s (R^2=0.65). PR, **shown in Figure 4b,** and population density have the strongest correlation: R^2=0.96 and R^2=0.95 respectively. This is expected because the building and population density take into account both the horizontal (C_s) and vertical (H_b) densities factors.

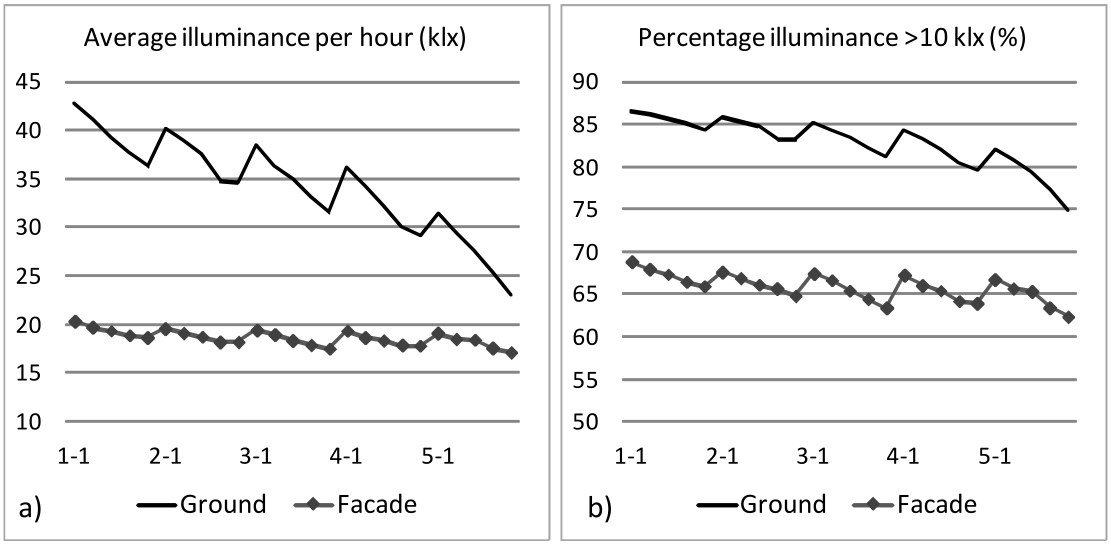

Figure 3 (a) Average illuminance levels per hour for the ground and facade points and (b) average percentage of time in which illuminance levels are higher than 10 000 lux.

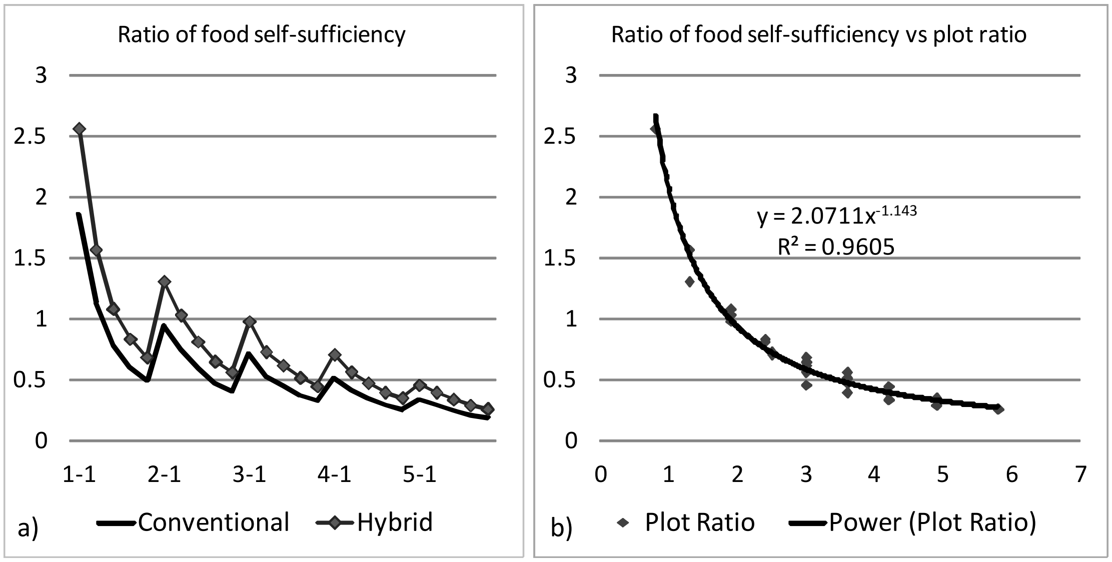

Figure 4 (a) Ratio of food self-sufficiency for the conventional and hybrid cultivation methods (ratio ≥ 1 self-sufficient) and (b) Correlation of the ratio of food self-sufficiency to plot ratio.

Solar energy potential and energy self-sufficiency

Based on the assumption of having 80% of the roof surface covered by PV panels and by considering BIPV as shading devices (30cm) on 70% of the facade perimeter on each floor the following results **shown in Figure 5** were obtained in terms of energy self-sufficiency. As expected, the highest energy output was obtained on the densest case (5-5 with PR = 5.8) due to the larger total roof surface and facade perimeter (more and higher buildings). However, when calculating the energy output relative to the amount of residents the cases with the lowest H_b (<42 m, cases 1-1, 2-1, 3-1, 4-1 and 5-1) are the only ones achieving energy self-sufficiency (> 98%) **as shown in Figure 5a**. This is also evident **in Figure 5b** which shows a strong negative correlation (R^2=0.98) between energy self-sufficiency and H_b. The taller the building the lower the energy self-sufficiency due to the fact that the increase of PV panels does not counteract the effect of the larger amount of population on energy demand. Different from food self-sufficiency, PR has a much lower correlation with the energy self-sufficiency (R^2=0.43). This may be explained by the fact that even with the same plot ratio, two cases may have different roof area for PV panels. I.e. cases 1-5 and 5-1 (PR = 3) have 37% and 77% of energy self-sufficiency respectively.

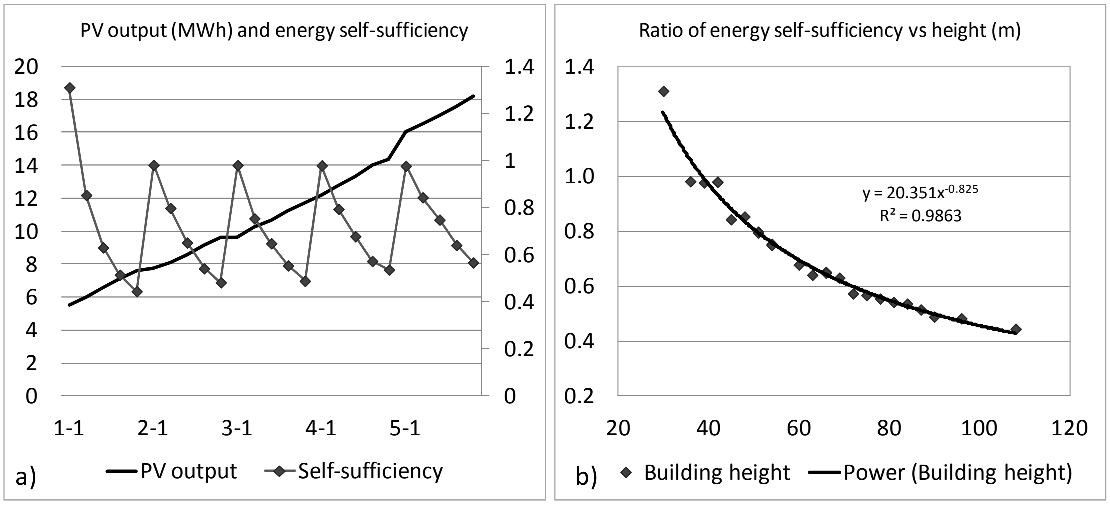

Figure 5 (a) Energy output from PV panels (roof + facade) and energy self-sufficiency and (b) correlation of the ratio of energy self-sufficiency to building height.

Sunlight availability on higher latitudes

A comparison was made between Singapore and Hanoi in terms of DA (%) **as shown in Table 3.** The reduction of the DA in Hanoi is significant for the ground if PR is higher than 3. For the facade sunlight availability, this reduction is significant for all PR. Therefore, the impact of higher densities on the reduction of sunlight for farming and energy harvesting becomes larger with higher latitudes.

Table 3. Comparison between Singapore and Hanoi, DA (%)

		DA [%] Ground average		Ratio [-]	DA [%] Facade average		Ratio [-]
Cases	Plot Ratio	Singapore	Hanoi	Hanoi / Sing	Singapore	Hanoi	Hanoi / Sing
1-1	0.8	87	81	**0.93**	73	52	**0.71**
3-3	3	83	73	**0.88**	70	46	**0.66**
5-5	5.7	75	55	**0.73**	66	42	**0.64**

CONCLUSION

This paper describes the process and results of the first stage of a study on solar availability on three typical public housing typologies. Twenty five cases corresponding to the point block typology were analysed in this paper. Sunlight availability was calculated in order to predict the potential of food (fruits and vegetables) and energy harvesting and the degree of self-sufficiency on each of the 25 cases. Ground and facade surfaces were considered for the farming activities while facade and roof surfaces were considered for the installation of PV panels. The results show that food self-sufficiency is achieved in 6 of the 25 cases corresponding to the cases with the lowest PR (0.8 ≤ PR ≤ 1.9) if a hybrid farming method is applied (conventional + vertical). If conventional method of ground-based farming is used, only two cases achieve self-sufficiency. Regarding energy harvesting, the cases with the lowest building height (< 42 m, < 14 storeys) achieve energy self-sufficiency due to the maximum exposed area with PV per amount of residents. Therefore, the indicators having the highest impact on the food and energy self-sufficiency are the plot ratio and building height respectively. However, this may not be fully applicable on other typologies and urban forms. Site coverage is still a crucial factor in providing food autonomy in urban areas due to the higher importance of ground than facade surfaces for the total food production.

From this study we can conclude that in tropical regions the reduction of food and energy self-sufficiency due to denser urban environments is more a consequence of the reduction of the farming and PV area in relation to the total population than to the reduction of the sunlight availability. However, as shown in the case of Hanoi, with higher latitudes and a lower frequency of the sun near the zenith, the impact of the surrounding obstructions on reducing the sunlight availability increases.

The other two typical housing typologies in Singapore, ‘slab’ and ‘contemporary’, will be the continuation of this study. In addition, the influence of the facade and plot orientations and of the sunlight availability at different facade heights will also be analysed together with the integration of other types of energy harvesting and conservation technologies like solar thermal and algae bioreactors. These studies will provide the basis for further environmental and energy assessments as well as a framework for a more comprehensive discussion about the impact of food and energy self-sufficiency strategies on several urban indicators in pursuit of a drastic carbon footprint reduction.

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REFERENCES

Astee, L.Y., and Kishnani, N. T. 2010. Building integrated agriculture: Utilising rooftops for sustainable food crop cultivation in Singapore. Journal of Green Building, 5 (2): 105-113.

Cheng, V., Steemers, K., Montavon, M., and Compagnon, R. 2006. Urban form, density and solar potential. The 23rd Conference on Passive and Low Energy Architecture, Geneva, Switzerland.

Conover, C. and Flohr, R. 1996. Light, fertilizer and cultivar selection affect growth and yield of containerized patio tomatoes. Commercial Foliage Research Reports, 96 (1).

Despommier, D. 2013. Farming up the city: The rise of urban vertical farms. Trends in Biotechnology, 31 (7): 388-389.

Ibarra, D., and Reinhart, C.F. 2011. Solar availability: A comparison study of six irradiation distribution methods, Proceedings of Building Simulation 2011, Sydney: 2627-2634.

Indraprahasta, G.S. 2013. The potential of urban agriculture development in Jakarta. Procedia Environmental Sciences, 17: 11-19.

Kanters, J., and Horvat, M. 2012. Solar energy as a design parameter in urban planning. Energy Procedia 30: 1143 – 1152.

Levinson, R., Akbari, H., Pomerantz, M., and Gupta, S. 2009. Solar access of residential rooftops in four California cities. Solar Energy, 83 (12): 2120-2135.

Reinhart, C.F., and Walkenhorst, O. 2001. Validation of dynamic radiance-based daylight simulations for a full-scale test office with outer venetian blinds. Energy & Buildings, 33 (7):683-697.

Lee, R.X., Jusuf, S.K., and Wong, N.H. 2013. The study of height variation on outdoor ventilation for Singapore’s high-rise residential housing estates. International Journal of Low-Carbon Technologies, 0:1-19.

Singapore Power Group Ltd. 2014. http://www.singaporepower.com.sg/

US Department of Energy. EnergyPlus weather data. (accessed on September 2013) http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=5_southwest_pacific_wmo_region_5/country=SGP/cname=Singapore

Ward, G., and Shakespeare, R. 1998. Rendering with radiance. The Art and Science of Lighting Visualization. Morgan Kaufmann Publishers.

Zhang, J., Heng, C.K., Malone-Lee, L.C., Jun, D.C.H., Janssen, P., Kam, S.L., and Tan, B.K. 2012. Evaluating environmental implications of density: A comparative case study on the relationship between density, urban block typology and sky exposure. Automation in Construction, 22: 90–101.