Establishing an Optimal Range of Density for Sustainable Urban Form

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Introduction

After the 2010 earthquake, Chile requires the rebuilding of more than 100,000 houses including entire neighbourhoods. Besides the destruction, this event also evidenced the necessity of neighbourhoods to prepare for natural disasters, lack of energy supply and future adverse consequences of climate change. The reconstruction process provides a unique opportunity to plan and build the highly discussed sustainable and resilient cities. A recurring theme of discussion for the planning of sustainable cities lies in the level of density for the urban form. So far, compact cities and urban sprawl are two main outcomes of urban growth which have been at the centre of debate when addressing sustainability. While urban concentration has been claimed as a sustainable way during the last few decades (Beatly 1995; Dantzing and Saaty 1973; Willis 2008), urban sprawl has been the most common form of urban growth during the same period of time. Even though most of these sustainable proposals aim to reduce energy consumption, they continue to depend largely on fossil fuels. Now, as oil runs out and the increasing population leads to more global energy consumption, sustainability in terms of urban communities should and possibly will be understood as the ability to be energy self-sufficient and resilient against an adverse insecure energy future. This paper focuses on finding the best range of density for sustainable urban form when establishing energy self-sufficient and resilient neighbourhoods by establishing a comparison between neighbourhoods' annual energy consumption and their annual on-site energy generation potential. Four consumer parameters have been selected: space heating demand; other domestic energy needs, transport fuel and food energy consumption. On the other hand, four others parameters have been selected to achieve this energy self-sufficiency and resilience: efficiency measures at the buildings' envelope, the use of solar energy (PVs and Solar Water Heater) to provide the basic household's energy needs, electric cars charged by electricity from PVs as a method of transport and food production at home. This study will be based on the revision of four real neighbourhoods in the Chilean city of Talca. Determining which case study, with its corresponding density, achieves a balance between its annual energy consumption and on-site energy generation potential, will serve as a basis to establish the best range of sustainable density.

1. Methodology

The paper firstly describes the four selected case studies highlighting those features relating density and energy at the residential level. Then, it does a diagnosis of current patterns of energy consumption by each selected parameter. This diagnosis considers current and common behavioural of energy consumption of Chilean households trying to be accurate with the collected information. After that, achievable measures to reduce the energy consumption specifically for the annual space heating and domestic energy demand are analyzed and implemented because only after this step, does adopting on-site renewable energies become attractive (Garbutt 2006). Subsequently, a detailed analysis about on-site energy generation potential by using solar energy systems will be carried out. Both analyses, potential and energy consumption will be summarized and expressed in kWh/ha/year for each case study. Finally, a balance between demand and on-site energy generation potential is described to establish the physical density which becomes self-sufficient and resilient by generating all energy needs for the four selected consumer parameters. It is important to consider that the study has been based on consumption and generation potential only no detailing in associated costs with the implementation of solar systems which may be part of further research.

2. Case Studies

Four representative case studies in terms of density, current urban development, typology and materiality, among others, have been selected to give a general idea of the entire Chilean city of Talca. In turn, the city is itself a representative case of medium-sized cities in developing countries. While all information is strictly related to the mentioned city, the proposed methodology could be useful to perform the same study in cities with different features if all data were accessible. Specifically, Talca characterizes by the recurring use of peripheral areas to develop new urban configurations with low density. City centres, in turn are developed by projects with high density addressing the compact city idea. Because city centres still work as the main activities attractor, the selected case studies have different location regarding the city centre in order to obtain a general idea concerning transport energy consumption.

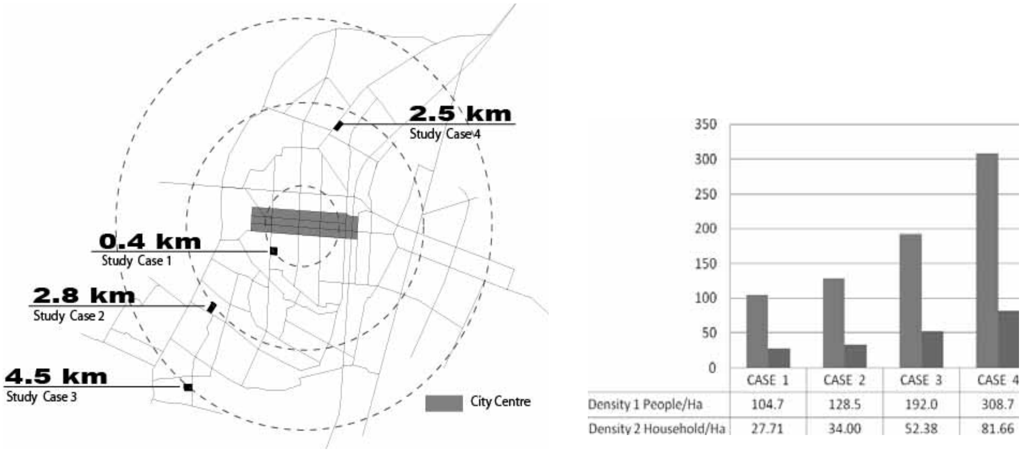


Figure 1. Four Case Studies and their Range of Densities
The average Chilean household size is 3.78 people

Figure 1 gives a summary of the range of densities for the four case studies. Although these density ranges may be interpreted as low, principally in terms of household/ha, these ranges are mostly common in Talca, being representative of neighbourhoods not only in this city but also for all those medium-sized cities in Chile. In terms of surface density per hectare, common areas, such as streets, sidewalks and green zones have been discounted, considering only households within their own boundaries.

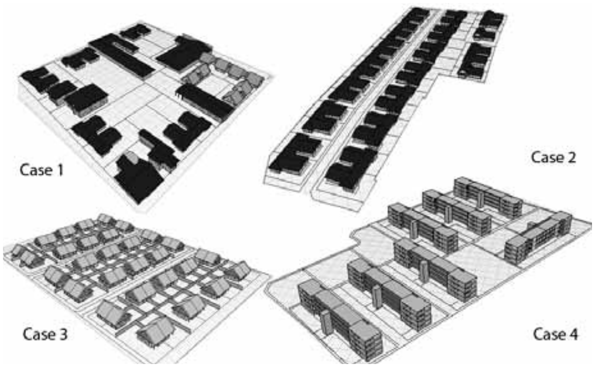


Figure 2. Four Cases Studies' Spatial Distribution

Possibly a fifth higher density range could have been analyzed, for instance a 10 stories or higher apartment building. However, this has been mainly ruled out due to these cases are unable in generating their own energy consumption because their very small roof size and available land. In addition, they consume more energy in common areas so that all the energy reductions they may save are offset (Myors, O'Leary and Helstroom 2005).

Table 1 highlights m^2 built per ha, including data about land occupation ratio, and states the available m^2 per ha after adding an additional m^2 for each house.

Table 1. Total m^2 and Available Land Surfaces

Case Studies	Average m^2 built/ house	Total m^2 Built/ha	m^2 First Story/ha	Available m^2/ha*
Case 1	115.3	3,195	2,455	6,990
Case 2	98.0	3,332	3,332	5,990
Case 3	70.0	3,667	2,442	6,425
Case 4	70.0	5,782	2,415	6,150

*After having added 20 m^2 to for parking, legal restrictions and pathway.

The highest percentage of land occupation corresponds to case 2. It seems strange that this does not correspond to case 3 or 4 which have a higher density, however this is because case 3 includes two story homes and case 4 includes four story apartments thereby releasing available land surface.

3. Annual Energy Consumption Diagnosis

(1) Space Heating Demand

To obtain the annual space heating demand in each study case, ECOTECT software has been used. In order to operate properly, relevant input data has been established concerning the location and climate. Furthermore, the same data have been used for all cases to have uniformity in the outcomes. These data are shown below:

- Heating under 18.5°C between 7:00 AM-23:59 PM and under 12°C between 0:00 AM-06:59 AM
- 3.78 people/house with 80W for each
- 25W/m^2 sensible heat as Internal Gain
- Air Change Rate: 1.0

It has been careful to specify the material and levels of insulation in each case. For blocks containing mainly the same type of housing but with different orientations, calculations were performed to obtain an average. Thus, for example, in the case 3, the same house was calculated in all four directions, obtaining an average that represents the whole.

(2) Domestic Energy Consumption

Electricity and gas consumption have been denominated as domestic energy. To obtain information related to, national databases as well as some on-site surveys have been carried out. Wood is main mean of heating resource so electricity and gas are used only to run electrical appliances, cooking and hot water. Any electricity consumption for heating has been allocated to heating diagnosis. It is important to note that 10% electricity consumption for common areas has been added in case four only as this is the only case which contemplates it.

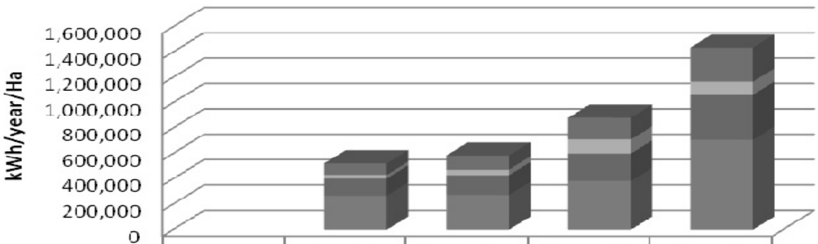
(3) Transport Energy

To obtain data regarding transport fuel consumption at residential level, information concerning the number of daily trip as well as destination has been used from SECTRA (2003). However, data on distance travelled daily has been difficult to be established. Thus, an in-situ survey per each case study was carried out to determine the household average daily distance travelled. Data concerning using public transport has also been included. Once this data is obtained and expressed in annual travelled Km, a rate conversion proposed by BERR (2008) has been used in order to state the results in kWh posing a 0.16 kWh/km travelled.

(4) Food Energy

Although at rest, our body needs energy to stay alive. The recommendations from WHO (World Health Organization) established a caloric intake between 2,000 and 2,500 Kcal/day for an adult male and 1,500 and 2,000 kcal/day for women. In order to be accurate to achieve feasible data and outcomes in this research, an average of 2,050 calories per person was considered, assuming an average Chilean family consists of a man, a woman, a teenager and a child.

Now, if 1 kWh = 860 kcal, a daily intake of 2.38 kWh per person will be used to determine total food consumption. As 3.78 person/household has been used in this research, 8.99 kWh would be the daily consumption per household. Figure 3 summaries the information obtained for the four consumer parameters:



	Case 1, Historic Centre	Case 2, La Florida	Case 3, El Culenar	Case 4, Apartments
Food Consumption	90,926	111,565	171,877	267,955
Transport Fuel Consumption	28,320	44,339	110,611	103,537
Domestic Energy Consumption	135,778	154,904	217,847	354,883
Heating Space Demand	269,178	274,856	383,856	709,723

Figure 3. Total Annual Energy Consumption Four Case Studies

As expected, an ascendant curve is obtained due to an increase in households per hectare. It might be thought there is no significant difference between cases 1 and 2, but it should be considered that these have different floor areas, 115 and 98 m^2 respectively. Thus, if all case studies were standardized in 70 m^2, as the floor areas for cases 3 and 4, the difference in the curve would be more noticeable. Figure 4 gives a summary in percentage terms of the total households' annual consumption. This is useful to understand the consumption distribution for the four selected consumer parameters.

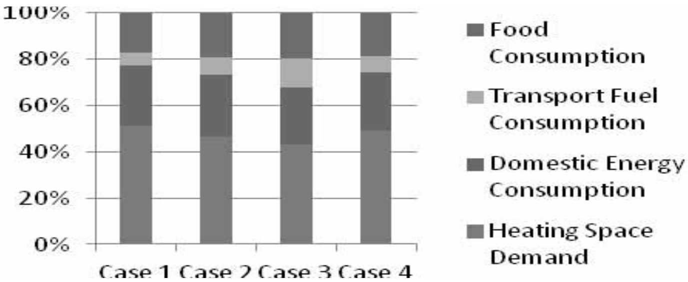


Figure 4. Consumption Distribution Ratio by Parameter

Space heating demand accounts for almost 50% of total annual energy consumption considering the current buildings' thermal characteristics. The second larger consumer is domestic energy which is almost similar in each case. It is interesting to highlight the low incidence transport fuel energy has in the total consumption where case 3 has the higher demand due to the greater distance from the city centre compared with the other cases.

4. Energy Generation Potential on Site

Energy generation on-site has become a good alternative to deal with energy shortages. It could significantly reduce the current dependence on imported energy creating resilient and sustainable neighbourhoods to cope with an uncertain energy future. However, before that, it is necessary to establish reductions of space heating demand and domestic energy consumption.

(1) Space Heating Demand Reductions

ECOTECT software has been carried out to simulate space heating reductions by using different standards for the building envelope and air change rate. Apart from the current scenario, two others have been analyzed. Firstly, the fulfillment of the new Current Chilean legislation regarding insulation standards, and subsequently, using an international city's standard reflecting similar climate conditions but higher efficiency standards. Figure 5 shows the space heating demand in accordance with the three proposed scenarios. The following U-value data were used for the two proposed scenarios. A 0.5 air change rate is now used. Materiality, occupancy patterns and heating times were kept constant.

Table 2. Thermal Regulations and Degree Days by Analyzed Cities

	Wal	Roof	Window	Floor	Degree Days 18.5°C Base*
	U-value	U-value	U-value	U-value	
Talca	1.70	0.38	-------	0.60	1,846
Wellington*	1.00	0.28	3.60	0.66	1,794

*NZS 4218:2009 Thermal Insulation-Housings and Small Buildings. Wellington: New Zealand.

It is noteworthy that these technical conditions can still be improved by using higher standards. In turn, the construction and implementation of strategies in the state of design will be crucial in compliance with such projections.

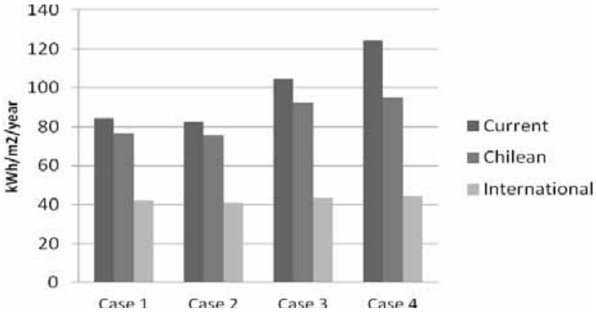


Figure 5. Space Heating Demand kWh/m^2/year by the 3 Scenarios

An average reduction of 50% for the first three cases when comparing the current state with international scenario is achieved. Even more noteworthy is the reduction of 65% for case 4 when comparing it with the same scenarios. The information obtained is useful to highlight the potential energy reductions available, and their importance, before adopting on-site generation renewable energies. After having reduced the energy consumption to a minimum, strategies to produce on-site energy are now suitable to be posed.

(2) Energy from Solar Systems

Although opportunities to take advantage of solar energy are found in many ways, this study has focused on photovoltaic and solar water heater systems only. Features such as silent operation, ease of installation in existing roofs and the constant increase of production with a corresponding fall in prices are the main reasons for choosing solar energy to set up self-sufficient neighborhoods.

By using 3D models and software able to simulate orientations and efficiency range, roof sections of the four neighborhoods' houses were analyzed to obtain the electricity generation potential per hectare. In order to standardize results, only roof sections have been used and any other element where PVs could be mounted, such as parking garage roofs have not. An efficiency ratio for each roof section with respect to the optimum has been calculated. Sections with over 90% efficiency have been identified and selected to continue the performance. Then, the exercise of installing a selected 1.58 x 0.80 size 180 Pmax(W) PV module on that selected roof sections was subsequently carried out. For every single house, 4 m^2 has been reserved in order to place a solar water heater. Each PV module area has been multiplied for the 1,649 kWh annual incident radiation received (UTSFT 2008). At the end, a simple calculation has been made using the 14.1% module efficiency. As this represents optimal conditions, certain loss percentage was also calculated: 5% for dust and other obstructions, 5% due to wiring and another 5% of DC conversion losses have been considered. Figure 6 summarizes the information obtained. Two different situations have been posed in order to optimize the on-site electricity generation potential. Situation A represents the current orientation of roof surfaces in the four case studies. In turn, situation B represents a proposed case where the roof surfaces, specifically in cases 1 and 3, have been reoriented to obtain more electricity. This assumption only affects the roof orientation without disturbing either the house's inner distribution or its total energy consumption.

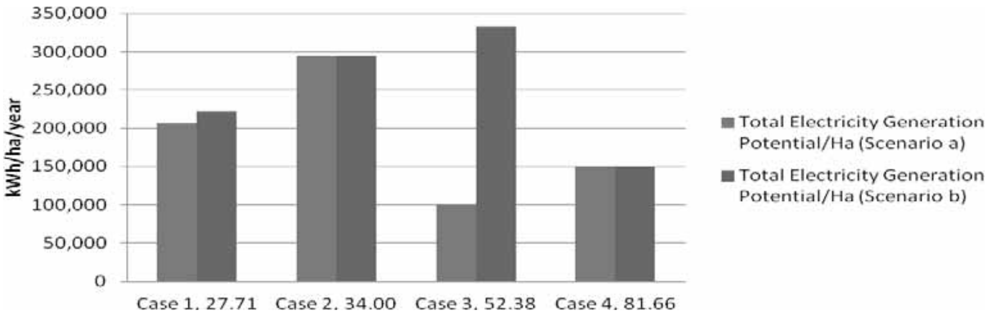


Figure 6. Total on-site Electricity Generation Potential (kWh/ha/year). Situation A and B

As observed, cases 1 and 2 have the higher potential (situation A) as these cases have a higher roof surface/m^2 built. Case 3 has also a higher roof surface/m^2 ratio but this has not a great potential due specifically to its orientation which most of their roof section are west-east orientation reaching only 87% so that they have not been considered. But when changing the slopes orientation maintaining all other features intact, the potential for electricity generation is increased by over 300% (situation B). Also, the exercise has been useful to highlight the influence of sloping roofs over flat ones, since in the last case; distances between rows of modules must be respected to not create shadows. This separation reduces the capacity of generation. Specifically, in case 4, 50% fewer panels have been mounted because of their flat roofs.

In terms of hot water by using Solar Hot Water Collector, the Chilean Ministry of Energy, for example, has provided a useful spreadsheet to calculate solar fraction. According to this spreadsheet and, after having made a study of most solar thermal systems legally registered in the Thermal Solar Systems Record, a 75% solar fraction has been determined for the Talca's case so that energy consumption related to domestic energy as mentioned before will be now lower.

(3) Electric Vehicles

Electric vehicles have been considered an important mean to reduce CO_2 emissions, above all if charging them by using renewable energies only such as hydro, wind or PVs. In the last case, 100% of CO_2 emissions could be reduce. Apart from this benefit, electric vehicles may also play a fundamental role when dealing with energy shortages and adverse consequences after natural disasters. This is mainly for the opportunity to use the electric vehicle's batteries as a source of storage of the electricity produced by PVs in time when the grid fails causing blackouts.

The capacity of the battery charge is a major disadvantage compared to conventional cars. Current ranges of BEV autonomy average around 160 km for mass production models. However, this is still sufficient to cover daily travel needs. The average Km travelled per household/day was found to be 32.59 km/day in all four cases by including a ratio of km travelled by using public transport. This range would equate to nearly four days of use in the case of the vehicle with least autonomy. In relation to the battery efficiency, the average range for all the models currently at the market reaches 0.129 kWh/km. Meanwhile, BERR (2008) gave the range of efficiency separated for cycles of years, suggesting efficiency improvements through time. It was established values of 0.16 kWh/km by 2010, 0.13 kWh/km by 2020 and 0.11 kWh/km by 2030. With the information obtained by setting three possible scenarios: current, 2020 and 2030, it is now possible to determine the kWh demand to cover the annual travelled distance in all case studies. Table 3 shows such a result.

Table 3. kWh Demand Required for Annual Transport Distances

	Km/Ha/year	Scenario 1*	Scenario 2**	Scenario 3***
Case 1	176,998	28,320	23,010	19,470
Case 2	277,115	44,338	36,025	30,483
Case 3	691,332	110,613	89,873	76,047
Case 4	647,086	103,534	84,121	71,179

* kWh Consumption/ha at rate 0.16 kWh/km; **At rate 0.13 kWh/km; ** At rate 0.11 kWh/km

A suitable incorporation of renewable energies, mainly photovoltaic, coupled to the use of batteries as a storage alternative in an emergency can cause a fully sustainable and resilient scenario.

(4) Food Energy

As essential as oil is for vehicles, food is essential for the functioning of human beings. However, shortages in fossil fuel reserves, rise in energy prices and a significant rise in the population will lead to a significant increase in obtaining this vital element for survival.

Growing food at home is a real option to achieve resilient and self-sufficient neighbourhoods and can help to approach the sustainable optimum density range.

Table 1 has already detailed the availability of land in each case including an average of 20 m^2 for parking and walking trails per single site. Other elements such as trees, concrete driveways and playground areas have not been included. However, shadows from fixed obstructions have been considered as these are irremovable and also because growing food is subject mainly to the amount of daily sunshine received. Six hours of daily sunshine have been estimated as a general factor calculation to grow up good crops. To obtain cumulative data of daily sunshine hours, solar access simulations for each case study were carried out using software ECOTECT. Table 4 shows the percentage and final available m^2/ha to calculate on-site food generation potential.

Table 4. Available m^2/ha to Cultivate Domestic Food

	Available m^2/ha	% Sunshine under 6 hr/day	Total Available ^{2}/ha*
Case 1	6,990	7.40	6,473
Case 2	5,990	39.60	3,618
Case 3	6,425	56.80	2,776
Case 4	6,150	14.65	5,249

According to the information obtained simple comments can be made. The predominant shade percentage becomes greater for smaller sites, especially in areas with higher density in terms of building floor area in the first story/ha. In turn, considerable influence is exerted by fences and their shadows. Once the available area for food growing is known, loads of energy potential for those areas can be estimated. Only vegetable consumption which represents 10% of a person's diet has been considered for their ability to be generated entirely in home gardens. Allen (1999) cultivated a familiar garden with the most common vegetables getting a 1.98 kWh/m^2/year as a result. With this data as a reference, Table 5 states the final diagnosis for each case study. Neither energy embodied nor footprint calculations have been included, only a tangible and real production potential instead. In relation to nutrients and compost, these may also be provided by residents using composting techniques. Water should not be an obstacle for the reduced irrigation by using some artisanal techniques. Also there would be enough water if the 749 mm rainfall per year was considered.

Table 5. Total on-site Vegetable Production Potential (kWh/ha/year)

	Total m^2 available/ ha	Total kWh/ m^2/year	Total on-site Vegetables Production Pot. kWh/ha/year*
Case 1	6,473	1.98	12,817
Case 2	3,618	1.98	7,164
Case 3	2,776	1.98	5,496
Case 4	5,249	1.98	10,393

*Total m^2 available/ha x Total kWh/m^2/year

As expected, cases with more available land get more production potential, such as case 1. This information will be useful to summarize results in next section.

5. Definitions of Optimal Range of Sustainable Densities

With both data, the annual energy consumption and potential generation, a balance is presented to find which case achieves that energy self-sufficiency and also to analyze the relation between energy and density in the city under study. In order to have a more detailed analysis focusing on achievable measures in energy consumption reductions through time, three different proposed scenarios have been established. In turn, two different situations have been posed by each scenario. The three different scenarios contain specific characteristics related to increasing the housing's thermal envelope efficiency, increasing technologies and reducing energy consumption due to governmental programs. On the other hand, situations A and B represent the two cases in order to optimize the on-site energy generation potential which already was mentioned in section 5.2. As food cannot be provided by electricity, the analysis has been divided in two parts. Firstly, Figure 7 summarizes the information concerning space heating demand, domestic needs and transport fuel energy.

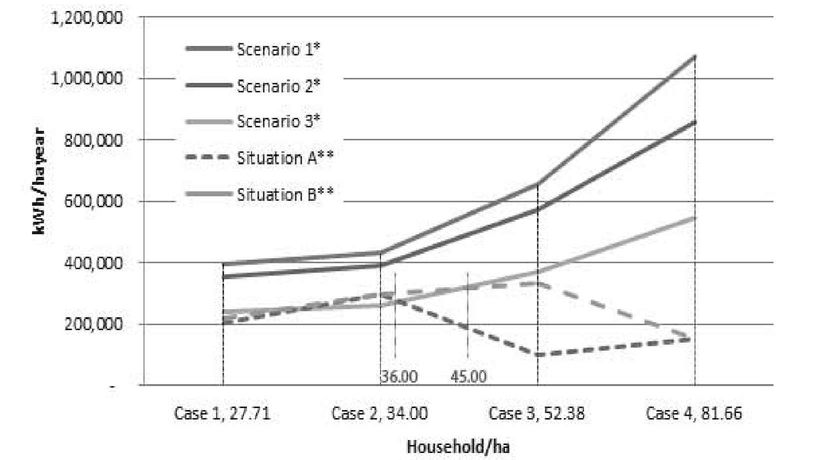


Figure 7. Summary between Energy Demand and on-site Generation Potential in all Proposed Scenarios

The information presented shows, on the one hand, the significant reductions in energy consumption which may be achieved by using energy efficiency measures and better technology in the analysed parameters. On the other hand, it shows the relation between density in the urban form and energy use when trying to establish a balance linking energy consumption and on-site energy generation potential by using renewable energies. This relation shows, as expected, a higher density higher consumption as there are more household/ ha. However, in terms of on-site generation potential the information shows the reverse: a higher density, lower potential. The information has also determined a range which reaches a balance between demand and potential. While the current orientation of roof surfaces creates a range up to 36 household/ha approximately, the case which optimized roof surfaces established a range up to 45 household/ha. These measures, to reduced energy consumption, seem to be, therefore, a significant strategy to pursue in order to reach a self-sufficiency in energy consumption.

Now, if food consumption is incorporated as the fourh parameter to define the optimal sustainable density, a range of up to 30 household/ha would be optimal. This is achieved after having done the same balance between annual food consumption and annual on-site food generation potential on the available areas, as shown in Figure 8 with information from section 5.4. Case 1 is the unique case which would reach its annual vegetable demand annual vegetable demand.

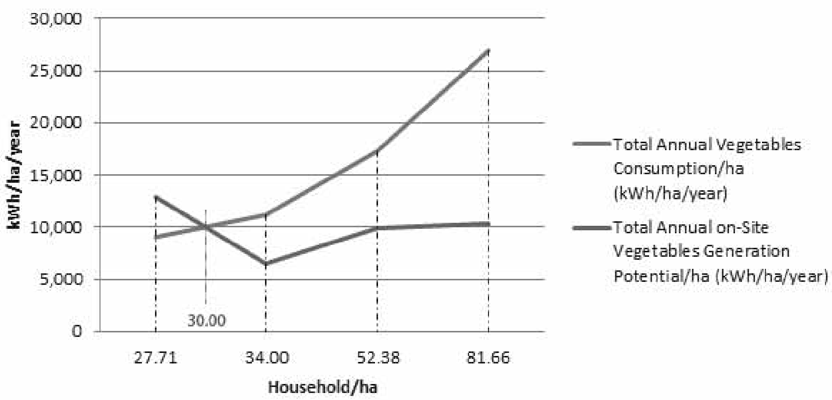


Figure 8. Summary between Annual Vegetable Consumption and on-site Vegetable Generation Potential

Conclusions

The research has determined the current possibility in generating self-sufficient and resilience neighbourhoods by using energy efficiency measures and solar energy as the main energy source. In this way, when establishing an urban residential model able to generate their own energy to satisfy its energy consumption related to transport, household use and food, a non-compact model is more efficient in terms of providing all energy needs generated on-site. In this specific city case, a range up to 30 household per hectare is able to match its consumption with its energy generation potential. For this more efficient sustainable density model, a holistic understanding of design and the construction process, as well as the use and proposal of renewable energies, is necessary to establish energy self-sufficiency able to cope with an unstable and vulnerable future concerning energy use. As Hirsch (2005) pointed out, it should take at least 20 years in the adoption of new policies and plans to change the current system of reliance on fossil fuels. The scheme presented in this thesis is part of one of those ideas in the planning of new neighbourhoods.

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