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Cost-Optimal Net Zero Energy Communities

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Abstract: The objective of this research is to study the cost of Net Zero Energy (NZE) communities of different urban scales and densities, while taking into consideration the local climate and the type of buildings in the community. A comprehensive model was developed for this purpose, with which the cost-optimal configuration of renewable energy-related technologies for an NZE community can be identified. To validate the model, data from two case studies that differed in their climate and building types were used. The results of this study contribute to a better understanding of the implications of NZE requirements for urban planning. An increase in the scale of a community was found to reduce energy costs, up to a certain point. Urban density, on the other hand, was found to have a more complex impact on costs, which depends on the local climate of the community and the subsequent energy demand. This underlines the importance of addressing the technological design of energy systems at the initial stage of the urban planning of energy-efficient communities, before the urban density, the unbuilt areas and the building types are set.

Keywords: life cycle cost (LCC); net zero energy; neighborhood planning; renewable energy

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1. Introduction and Literature Review

Previous authors have explored the possibility of expanding the Net Zero Energy (NZE) concept from a building scale to a neighborhood or district scale [1]. Such a strategy could be beneficial since it allows the sharing of needs, costs and resources among multiple buildings. It also underlines the importance of addressing energy aspects in urban planning at an early stage, by integrating the spatial and energy planning processes [2]. Spatial and energy system planning should be closely linked together early in the urban planning process, since both the energy demand in buildings and transport, as well as the exploitation of potential local energy resources, are determined by the urban form [3]. This is of great importance since nowadays there is an increase in the amount of distributed energy generation [4].

In order to appropriately address energy and resource issues, urban planning will have to change, and planners will be expected to simultaneously handle both qualitative aspects of urban planning along with the more quantitative concerns of energy system design and engineering [5]. However, urban planners currently lack sufficient knowledge on how their decisions may affect the potential energy performance of future buildings, for example, regarding solar energy generation [6]. In particular, it is currently not clear how the implications of urban planning on the energy and economic performance of energy systems should be evaluated [7].

Thus, there is a clear need to establish an appropriate framework and well-defined methodologies that will allow energy to be considered as a central aspect of urban planning [5]. In particular, there is a lack of knowledge on how to account for the impact of the scale and density of urban development on energy performance, despite the fact that these are important available operating parameters. Thus, Cajot et al. [5] note that the intermediate community or neighborhood scale appears to be an ideal compromise between the advantages of either the urban scale or building scale in energy planning. These include the advantages of a limited complexity and of a reduced number of stakeholders on the one hand, and the opportunities of energy and cost efficiencies at a larger scale on the other hand. However, it is still unclear how to set the exact boundaries of an urban project, given the influence of local conditions on the optimal scale of relevance for energy planning. The question of identifying this optimal scale is therefore regarded as an open one, requiring further research to provide researchers and practitioners with rigorous and systematic tools that can quantify the gains and losses of considering different scales [1,5]. Density too has been identified as a particularly important parameter, which is defined at the urban planning stage and significantly affects energy performance [7].

In practice, the density and scale of urban development are the result of complex urban planning processes, which involve various policies and mechanisms, including zoning regulations and local subsidy schemes [8]. While urban planning is carried out through a large number of different processes and at different levels in each country, one can generally distinguish between two stages [9]:

1. The initial strategic urban planning stage, in which policies and zones are defined through master plans that determine the scale and density of the development.
2. The later urban design stage, in which specific features of a city such as its energy systems, individual building types and public facilities are determined in detailed plans, after the definition of master plans.

When energy aspects are ignored in the initial stage, in which a neighborhood's density and scale are determined, this will inevitably constrain the design of a neighborhood's energy system in the second stage and may lead to sub-optimal solutions.

The cost of the energy systems is obviously another crucial variable, since it is a basic consideration that will determine their actual development [7]. Yet the relationship between the scale and density of NZE communities and their costs remains unexplored. Previous studies that dealt with energy planning at an urban scale have typically excluded the evaluation of costs [2,5]. The objective of this study is therefore to analyze how the costs of NZE communities are affected by changes in their density and scale.

1.1. Life Cycle Cost Analysis of NZE Communities

While many papers have discussed energy systems in NZE communities (e.g., [10]), they have not analyzed how the costs of these communities can be minimized. Multiple studies have included the use of Life Cycle Cost (LCC) analysis to optimize the design of NZE buildings, in different countries and climate zones (e.g., [11–15]). However, the Life Cycle Costs of NZE communities have been addressed much less. Bucking and Cotton [16] describe a reproducible methodology to help modelers identify energy and economic saving opportunities in the early community design stages. The methodology is applied in the design of a Net Zero Energy community under development in Southwestern Ontario, and the LCC is analyzed. There is however no comparison between the LCC of a single NZE building and its cost in an NZE neighborhood, and no discussion on the implications of scale/density. Odonkor et al. [17] proposed an approach that significantly reduces the total energy cost in clusters of NZE buildings by the generation of optimal operational strategies and the implementation of adaptive decisions in response to changing operation conditions. The focus in their paper is however on the cost of energy purchased and sold to the grid only, and not on the LCC of the incorporated technologies. Zhivov et al. [18] describe an optimization process for clusters of NZE buildings and implement part of the process on a cluster of buildings in Fort Bliss. One of the results from the analysis of the central cooling and heating system in the given study showed how a centralized system is more Life Cycle Cost-effective than decentralized systems, and how the optimal design can be easily expanded for future needs. The study however did not examine the impact of scale/density on the optimal design of the cluster and its LCC.

Several studies examined the economic and energy aspects of an implementation of a specific technology in the design of NZE communities. Shareefdeen et al. [19] analyzed the implementation of a biogas digester in an NZE community in Ontario. The achieved design resulted in a gas production cost that was very close to nonrenewable gas market cost. Burch et al. [20] examined a new central district solar system, which resulted in a reduced distribution piping size and consequently in a reduced cost. These studies however focused on one specific technology and did not consider the wide variety of technologies that should be applied in NZE communities.

1.2. The Impact of Scale and Density on Costs

Several studies discuss the implications of urban density and scale on the integration of energy technologies. Coleman et al. [21] discuss the advantages of community-scale solar, which was defined in the paper as community-shared solar systems or other mid-size arrays that are owned by utilities or by third-parties that sell energy to a utility, in the range of 0.5–5 Megawatt peak (MWp). One of the main conclusions in the study is that community-scale solar has the potential to utilize the advantages of both behind-the-meter and utility-scale installations by enjoying utility-scale economies while leveraging distributed benefits. Nussbaumer and Thalmann [22] studied the influence of system design on heat distribution costs in district heating. District heating networks with a connection load of between 0.5 MW and 4 MW were analyzed under certain conditions. A higher heat density of the system, which usually has a direct relation with a higher urban density of the community, might decrease heat distribution costs under certain conditions. Heat distribution costs, however, may not necessarily decrease with an increase in the scale of the system. This is not the case in the cost of the heat-producing boilers themselves, as described in the *Technology Data for Energy Plants* report of the Danish Energy Agency [23], which shows a significant cost reduction due to the enlargement of scale in a majority of boilers, including boilers that use bio-fuels.

Resch et al. [24] studied the impact of urban density and building height on energy use per capita in cities, considering energy use for both domestic and mobility needs. The results of the study show that denser cities have a lower energy use per capita due to transportation benefits, reduced heat exchange of taller buildings and reduced floor area per capita. The increased urban density, however, has a negative effect as well. The available area for energy-producing technologies at a community level obviously decreases as density increases, since these technologies are installed on commercial rooftops, parking lots and unbuilt areas. This is a major issue since these technologies are crucial to achieve NZE goals in a way that is efficient in terms of cost and energy, as shown by Scognamiglio and Garde [25] for Photovoltaic (PV) technologies. Another negative impact is that the solar irradiation availability is poor in high-density urban fabric with high site coverage, due to the shadows cast by neighboring buildings, as shown in Cheng et al. [26].

1.3. Summary

It is widely agreed that the enlargement of the NZE concept to a community scale could provide several advantages, in terms of both energy management and the reduction of costs. However, it is not clear how the scale or the density of the community should be determined to reduce its costs to a minimum. Unlike a single NZE building, whose design is largely defined according to a predetermined urban environment, the urban form of an NZE community is determined in the urban planning phase. A specific urban form of the NZE community may have a huge impact on its energy and cost performance. It could thus help reduce costs and achieve a higher energy performance, which in turn could lead to a wider adoption of this concept.

To date, studies focusing on the LCC analysis of NZE communities have been rare. The few studies that were found focused on the analysis of a specific case study, with a given number of buildings that are laid out in a given density. Studies that analyzed the effects of urban density or scale on technologies implemented in communities generally focused on the energy performance aspects, assuming that a specific type of technology is used, or analyzed non-NZE communities.

Therefore, the goal of this research is to analyze the impact of the density and scale of new NZE communities on their Life Cycle Costs. The results of this study could improve our understanding of the implications of the NZE approach for urban planning. To achieve this goal, the research addresses, for combinations of various renewable energy technologies, the following specific objectives:

1. To determine if the enlargement of the NZE concept from a single building to a community changes its optimal technological design.
2. To determine how the scale of an NZE community, i.e., the number of buildings, affects its LCC.
3. To determine how the LCC is affected by the density of the community and by the area allocated for community-level energy systems.

These questions were answered by developing a model, with which the cost-optimal technological design of a community is identified for specific scales and urban designs, while considering the local climate and the types of buildings in the community. To test the model, it was applied with data from two case studies that differed in their climate and types of buildings.

2. Optimization Model

The proposed optimization model is a Life Cycle Cost (LCC) configuration selection model. The configuration here relates to energy production (e.g., PV), savings (e.g., insulation) and utilization (e.g., AC), defining the size of each unit and the number of units in each type of system. Using this model, the optimal configuration of energy-related technologies is identified for each specific community type, scale and density, while taking into consideration building types and local climate (Figure 1). The model's principle structure can be defined as follows.

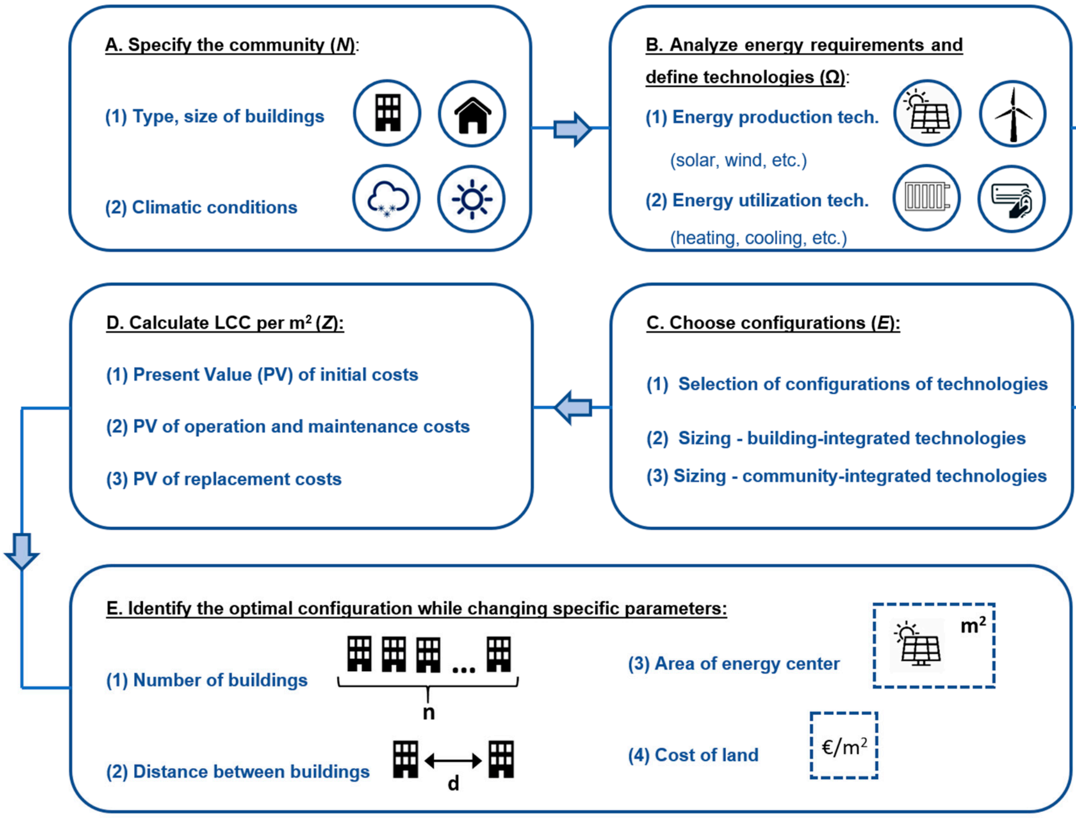

Figure 1. Implementation of the Life Cycle Cost (LCC) optimization model.

The energy-related LCC per unit of building area is minimized by choosing an energy technological configuration, while satisfying three types of constraints: (1) the chosen configuration is constructed from a domain of optional choices for the specified neighborhood; (2) the chosen configuration saves at least a defined portion of the neighborhood annual energy consumption; and (3) the chosen configuration occupies installation areas within the available areas for this purpose in the specified neighborhood. The various types of area are, for example, rooftop areas or energy center areas.

A generic formulation of this model (1) can be defined as follows:

$$Minimize\ Z = LCC(E;N),\ s.t.\ E \in \Omega(N); G(E;N) \geq \alpha C(E;N); A(E;N) \leq AA(N). \tag{1}$$

where $LCC(E;N)$ is the LCC of energy configuration E in neighborhood N; $\Omega(N)$ is the domain of feasible energy technology configurations in neighborhood N; $G(E;N)$ is the annual grid-sourced energy saved through local generation of energy from renewable sources; α is the portion of $C(E;N)$—the annual energy consumption—which should be saved; $A(E;N)$ is the vector of needed areas of various types; and $AA(N)$ is the vector of available areas for these various types of systems in neighborhood N. Figure 1 exhibits the model's construction and use steps, indicating in parentheses for each step, the main relevant model notation.

For demonstrating and validating this model, it was employed for two different types of neighborhoods (scenarios). Computer application of the model has been developed for this purpose, with the following more specific definitions, identified for the two scenarios.

The decision vector E consisted of three types of decision variables: (1) the selection of technologies for each purpose (producing energy or reducing energy consumption), (2) the determination of the number of units per house in the chosen building-integrated renewable energy production technologies, and (3) the determination of the number of units in the chosen community-integrated technologies for renewable energy production. The domain $\Omega(N)$ specifies the interrelated optional choices for these dimensions of E (the details of which are omitted for being technically involved and of limited value).

The community N specifies its total area; the type, sizes and number n of buildings (assuming for simplicity they are all of the same design and evenly spread in the neighborhood); as well as the seasonal climate pattern. The community specifies in addition the available types of areas $AA(N)$ between buildings (e.g., parking lots), on rooftops of buildings, and the portion of the community area that may be used for energy centers.

The LCC per unit of area functions consist, for each type of system, of three types of components: (1) the present value of initial cost, including design, planning, construction, acquisition, supply and assembly costs; (2) the present value of operational and maintenance costs of the system after it is put into operation, including energy costs, replacement parts and labor required for maintenance; and (3) the present value of replacement and demolition costs of the system. The present values were calculated for 50 years, while considering the local interest rate and inflation rate of each examined community.

Information on costs was collected and cross-checked from a number of sources including technology suppliers, building owners, public databases (e.g., [27,28], etc.) and scientific publications (e.g., [22,29], etc.).

Some simplifying assumptions were included in this initial study. The optimization model assumed that the buildings in the community are similar in shape and energy demands, and are distributed uniformly across the community. Community-level energy centers were assumed to have the same potential of renewable energy production and to be located at the edges of the neighborhoods they serve. These assumptions are not expected to significantly affect the conclusions that can be derived from the results of the model's implementation, since individual fluctuations are likely to cancel each other out in the aggregate. However, the model can be easily adjusted to consider a larger variation of buildings and energy centers.

In addition, buildings in the communities are assumed to be connected to the electrical grid, and when the energy produced from local renewable sources is higher than the demand, the surplus electricity is fed into the grid. Specifically, according to the Net Metering regulation, which is common in many countries, supplied energy is credited in kWh when the production is higher than consumption, and offset at other times when the consumption is higher than production. Positive credit is annulled at the end of each year, and negative credit is charged according to the local energy price. This regulation deters over-production as well as local storage of energy by making these economically disadvantageous.

3. Implementation and Validation of the Model

The model was implemented by the Solver of Microsoft Excel software. The Generalized Reduced Gradient (GRG) Nonlinear Programming optimization method was employed, considering that all the decision variables are Integers and Booleans and that the objective and constraint functions are partially nonlinear, yet smooth. To reduce the probability that a local optimum solution is identified instead of the global optimum, the solution is repeated for a set of random initial values.

In order to implement the model using real-life input, data were used from two case studies built in the framework of an EU-funded project called "Zero Plus". The goal of Zero Plus is to develop a comprehensive and cost-effective system for NZE communities, and to implement this system in a number of case studies across the EU. One of the case studies is located in Cyprus, in a Mediterranean climate with very mild winters and hot summers. It includes individual houses with two stories and an area of about 500 m^2, on plots of approximately 1700 m^2 each, within a larger settlement of 255,000 m^2. The other case study is located near Grenoble in France, in a colder climate that is defined as 'Oceanic' according to the Koppen–Geiger climate classification. It includes five-story high rectangular apartment buildings with 18 dwellings for social renting (around 1100 m^2 inhabited area), within a larger complex that also includes dwellings for social selling.

Since these case studies included the construction of only a small number of buildings, they were used in this study as a source of reliable data to examine the implications of an implementation of the NZE approach at larger scale. They are further described in [30].

The assessment of energy demand in the case studies was based on simulations. These addressed hourly schedules and regulated energy consumption, covering the end uses of space heating, cooling, ventilation, domestic hot water, fans and pumps, while unregulated loads such as lighting, computers, televisions and cooking were not included.

The analysis of the Cyprus case study was based on simulations carried out in free-running and thermostatically controlled conditions by means of the "Design Builder" software program. Design Builder was chosen as it is a dynamic simulation software, which provides advanced tools for modelling heating, ventilation and air conditioning (HVAC), daylighting, airflow, cost, energy and carbon content. The analysis in the French case study was based on simulations carried out with the "Pleiades" software program. This program combines a calculation module for energy needs and comfort indicators, a module for checking fulfillment of the French Thermal Regulation (RT2012) requirements and a module for dimensioning heating and cooling equipment.

The design of the Cyprus case study included composite cool thermal insulating materials based on a new generation of extruded polystyrene (XPS). Forty millimeters of insulation was added to the exterior of each building. The design of the French case study included 16 cm polyurethane exterior insulation of the roofs in addition to 10 cm of mineral wool interior insulation, and 20 cm of rock wool insulation under the cladding of the exterior walls.

In addition, microclimate simulation was performed to incorporate the impact of the local microclimate on the building's thermal-energy performance and on renewable energy production. For further details on these simulations, the reader is referred to Gupta and Gregg [31] and to Castaldo et al. [32].

To answer the questions that were defined in Section 1.3 (Summary), the optimal configuration of energy-related technologies and their LCC were identified in each case study, while changing specific parameters (Figure 1). In this way, the impact of variations in each parameter on the LCC could be identified, while taking into consideration the location, the climate and the types of buildings in the case studies.

The actual design of the case studies ensured that the Zero Plus project's target of a net regulated energy consumption of less than 20 kWh/m^2/year was met, with a consumption of 16 kWh/m^2/year in the French case study, and of 14.8 kWh/m^2/year in the Cyprus case study.

3.1. Configurations of Technologies

In each case study, a number of configurations of technologies were examined, both for heating, ventilation and air conditioning (HVAC) and water heating, as well as for the generation of electricity. Additional relevant technologies were analyzed in this study, apart from those that were included in practice in the Zero Plus project. Relevant data were collected from the literature and official reports, to support an assessment of the impact of changes in density and scale on the cost and performance of these technologies. Naturally, the study could be further expanded to include additional technologies, such as possible future innovative technologies.

Cyprus case study: The building considered in the Cyprus case study is a high-end single-dwelling villa. Three different configurations of HVAC and water heating technologies were examined. The warm Cypriot climate requires mostly air conditioning and cooling in buildings, and hot water for sanitary needs. Each configuration supports the thermal needs of the building as was simulated:

- Configuration A includes three technologies: an innovative solar HVAC system fed by low-grade solar thermal energy, designed to provide cooling, dehumidification, heating and ventilation for the shared spaces of the house, such as the kitchen and the living room; three built-in unitary split AC units for the other rooms; and a solar water heating system for sanitary hot water production that is installed on the roof of the building.
- Configuration B is similar to configuration A, except that the conventional solar water heating system is replaced by a system containing high-concentrating photovoltaic collectors with an active cooling system, which combines water heating and power generation. This system is also installed on the roof of the building.
- Configuration C includes five conventional unitary split AC units, and the solar water heating system described in configuration A.

For renewable energy generation, two types of technology were examined in the Cypriot case study:

- A PV system.
- A hybrid system of wind turbines and PV panels.

Each of these technologies was examined while implemented at a building level (i.e., on the rooftop) or a community level (i.e., rooftops of parking lots, commercial buildings or ground mounted in the available area in the communities).

French case study: The building in the French case study is an apartment building for social housing, with a total net area of 1005 m^2. The apartments in the building are heated with low-temperature radiators in each room, which are fed by hot water, supplied by one of the following configurations:

- A wood pellet boiler, which provides hot water for space heating and for sanitary needs, either building-integrated or integrated in a community district heating center from which the heat is distributed through a heat distribution system.
- A wood chip boiler integrated in a community district heating center.

Two types of technology were examined in the French case study for renewable electricity generation: a PV system and a hybrid of PV modules and wind turbines. Each of the technologies was examined while implemented at a building or a community level.

3.2. The Impact of a Community's Scale on Its LCC

The impact of community scale on the optimal energy-related LCC (per m^2) of small- to medium-sized communities was studied. To this end, the scale of the community in the Cypriot case study was varied from 1 to 50 single-dwelling buildings, and the optimal configuration of technologies identified for each community size. The building considered in this case study was duplicated as many times as needed to increase the scale, and the impact on the costs of the technologies was determined as these were affected by changes in scale.

In all the variations of scale that were examined, the optimal combination of technologies included built-in air conditioning units, a solar water heating system on the roof of the building, and a PV system implemented at a building and/or community level with an average capacity of 12.75 kWp per building. However, the size of the community-level centers at which energy is produced was affected by changes in scale and had a significant impact on the costs of the technologies. The size of community-level energy centers rises when the scale of the community is increased. The increase in scale consequently decreases the LCC/m^2 of the technologies by up to 15% (Figure 2). These results stem from the fact that community-integrated technologies are more cost-efficient than building-integrated technologies, since they share system components such as the inverter. The results concur with those of Fu et al. [29], who found that in general, the cost of PV systems is 27% lower in larger installations (of 10 kW–2 MW) as opposed to residential systems (of 3–10 kW).

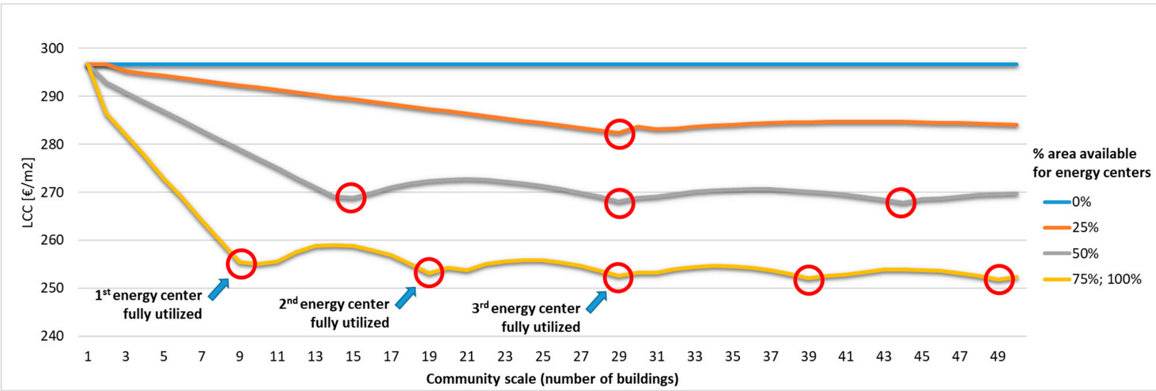

Figure 2. Change in the cost of the Cypriot case study, as a function of community scale and of the area available for community energy centers.

As can be seen in Figure 2, a significant cost reduction is achieved at a scale at which the first energy center reaches its full possible capacity, as defined in the model. In light of this constraint on the capacity, a further increase in community scale requires the establishment of a new energy center. Since the renewable energy systems installed in the new energy center will not benefit from the reduced costs achieved in the existing energy center, its establishment causes a slight increase in the overall cost. This cost eventually decreases again to a similar level when the new center in turn reaches its full capacity. This cyclic pattern will continue indefinitely as the scale of the community is further increased, unless the maximum size of a single energy center is changed.

The optimal combination of technologies in the French case study included low-temperature radiators fed by hot water from a boiler based on bio-fuel (wood pellets). This boiler was integrated at either a building or community level, and included a community heat distribution system when district heating was considered. An additional technology that was identified was a building- and/or community-level PV system.

The scale of the community in the French case study was varied from 1 to 28 buildings, each containing 18 dwellings (i.e., a range of 18–504 dwellings). The number of buildings examined in the French case study was lower than in the Cypriot case study due to the bigger size of the buildings themselves, both in their area and the possible number of tenants. The level of implementation of the heating boiler(s) and of the PV systems (building or community) changed according to the community's scale. The size of the boiler increased as a function of the increase in the scale of the community, and consequently its cost was reduced (Figure 3).

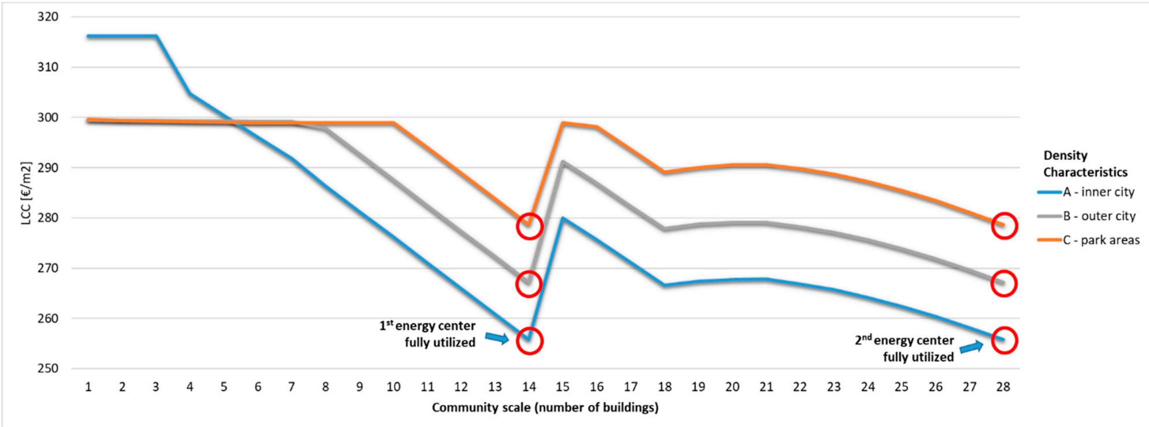

Figure 3. Change in the cost of the French case study, as a function of community scale and density.

The results in Figure 3 stem from the fact that when the community is of small scale, its optimal design includes only building-integrated boilers, which are less cost-efficient than district heating, since a district heating system is only relevant once the threshold of a capacity of 0.5 MW and higher is crossed (corresponding to the energy consumed by least four of the buildings considered in this study). However, once the scale of the community is larger than five buildings and as more buildings are connected to the district heating system, the relative cost (in LCC/m^2) of a heating boiler is lower when its capacity is increased.

As is the case for community-level PV centers in the Cypriot case study, the maximal cost reduction is constrained by the size of the energy center. The minimum cost is reached at the scale of 14 buildings, which requires the establishment of a heating center with a wood pellet boiler at a nearly full capacity of 2 MWp. For a community at the scale of 14 buildings, and with a high "inner-city" density, a minimum cost of 255.8 €/m^2 is achieved. In comparison, when the alternative technology of a district heating system based on a wood chip boiler is included under the same circumstances, the minimum LCC for an optimal configuration is 11% higher (284 €/m^2). A further increase in the scale of the community, beyond 14 buildings, requires the establishment of a new heating center, which first increases the cost since the new heating center does not benefit from the cost reduction achieved with the existing heating center. Eventually, at a larger scale, the costs reach the same or a slightly lower level when the new center reaches its full capacity as well.

It is noteworthy, however, that a heating center with a wood pellet boiler was found to be more cost-efficient than a wood chip boiler due to the constraint on the maximum size of the community (28 buildings), which required a maximum heat capacity of 4 MWp. A further increase in the community's scale above the level examined in this study can be expected to lead eventually to the integration of a high-capacity wood chip heating boiler in the district heating center. Such a boiler, with a typical capacity of 1–12 MW, has the highest initial and operations and maintenance costs (fuel excluded), but the lowest fuel cost. At larger scales, the low fuel cost could thus override the high initial costs and operations and maintenance costs, resulting in a further reduction of total costs. However, the phenomenon of cyclically increasing and then decreasing costs would inevitably occur at this scale as well, just as in the smaller scales examined in this study, as the technological design would be duplicated.

3.3. The Impact of a Community's Density on Its LCC

The original settlement on which the Cypriot case study is based is very spacious and has only low-height buildings. Therefore, in this case study it was assumed that there is no significant mutual shading between the buildings in any examined scale or density, and that 90% of a building's rooftop is available for the installation of building-integrated systems. For each of the 50 selected community scales, the optimal configurations of technologies were identified at four levels of community density, reflecting the area available for energy centers (calculated as a percentage of the buildings' rooftop area in the community). In other words, the optimization method was executed for 200 cases in total.

The main results in Figure 2 show that when the area available for community-level energy centers is larger, additional community-integrated systems can be installed instead of building-integrated systems. The increase in the share of energy produced in community-level energy centers in turn corresponds to a lower cost. In this study, this effect was limited to a minimum cost achieved when the value of the "available area" parameter is 75% (i.e., 75% of the buildings' rooftops area in the community). An increase in the value of this parameter to 100% had no further impact, since the share of energy produced by the community-level energy systems had already reached a maximal value of 95% (with the remaining 5% produced by building-integrated solar water heating systems).

The French case study has a denser urban layout than the spacious Cypriot village. Therefore, to account for the impact of mutual shading between the buildings in such an urban layout, the available area for building-integrated renewable energy systems on the rooftop was assumed to be 50% in all density variations. Three types of urban density, described in Table 1, were examined for each of the 28 selected community scales. In other words, the optimization method was executed for 84 cases in total.

Table 1. Density variations in the French case study.

Examined Density	Plot Ratio (e)
Inner city	$0.5 \leq e < 2$
Outer city	$0.3 \leq e < 0.5$
Park areas	$0 \leq e < 0.3$

The plot ratio (e) describes the relation between the building space area and the corresponding unbuilt land area, and reflects different urban categories relevant to district heating systems, as defined in Persson and Werner [33] (Table 1).

The level of implementation of the heating boiler(s) and of the PV systems (building or community) changed according to the community's density. The results in Figure 3 show that up to a scale of five buildings, the cost of the technologies is significantly higher in a high inner-city density scenario. This stems from the fact that in a high-density community the area available for community-level PV systems is limited, and this causes an increase in the costs of the PV systems compared with their costs in the two other densities that were studied. However, once the scale of the community is larger than five buildings, its cost is higher in low-density scenarios, while the high inner-city density entails the lowest costs out of the three examined. This is due to the following factors:

- In the French case study, all the regulated energy (~71% out of the total energy consumption) is generated by the heating system, while the PV systems produce only ~29% of the total energy. Consequently, the heating system has a larger impact on the cost of the technologies than do the PV systems.
- The heat distribution system is more cost-efficient in a denser environment, due to lower capital and heat distribution costs.

A district heating system that includes a heat distribution system is therefore more cost-efficient in higher densities, and is therefore included in the optimal design at smaller community scales. This cost efficiency more than compensates for the limited area available for community-level PV centers in a high-density community.

3.4. Sensitivity Analysis

In addition to affecting the area available for community-level energy centers, urban density is also assumed to have an impact on the following variables:

- The maximal area of a single energy center (in m^2).
- The cost of the land required for energy centers (in €/m^2).

A sensitivity analysis was carried out to examine the implications of variations in those variables.

When the impact of an increase in the maximal area of a single energy center was examined in the Cyprus case study, it was found that such an increase reduces the LCC/m^2 of the technologies by up to 14.6% (Figure 4). This is due to the fact that the physically bigger centers enable a bigger capacity of installations, which results in a lower cost of community-integrated renewable energy systems, and consequently a lower overall LCC/m^2 of the technologies. The community scale at which the first energy center reaches full capacity ranges from 7 buildings (when the maximal area of a single energy center is set at 500 m^2) to 22 buildings (when the maximal area is set at 1500 m^2).

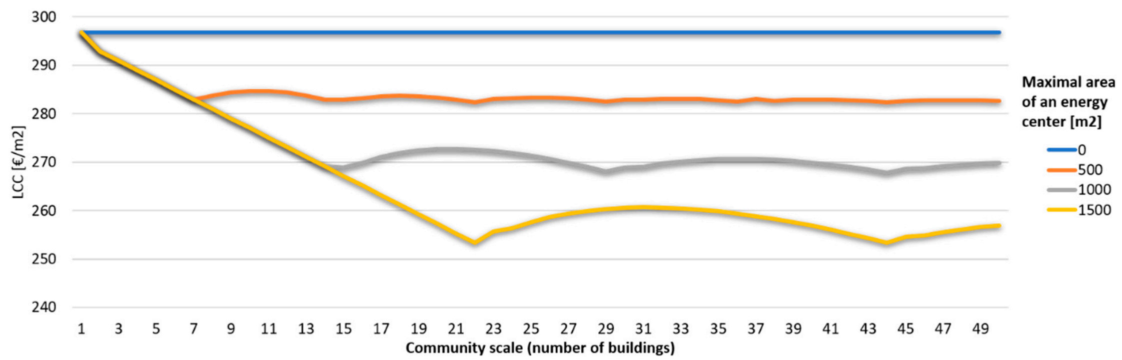

Figure 4. Change in the cost as a function of the maximal area of a single community energy center.

When the impact of an increase in the cost of land for establishment of energy centers was examined, it was found that such an increase raises the LCC/m^2, up to the point where it becomes economically undesirable to install renewable energy systems at a community level and all the systems are building-integrated (Figure 5). This is due to the fact that the cost of land increases the initial costs of the energy centers, up to the level where these costs exceed the costs of building-integrated alternatives. Consequently, at a certain cost level, the initially less efficient building-integrated alternatives become preferable. In this case study, this point was reached when the land cost was between 50 €/m^2 and 75 €/m^2.

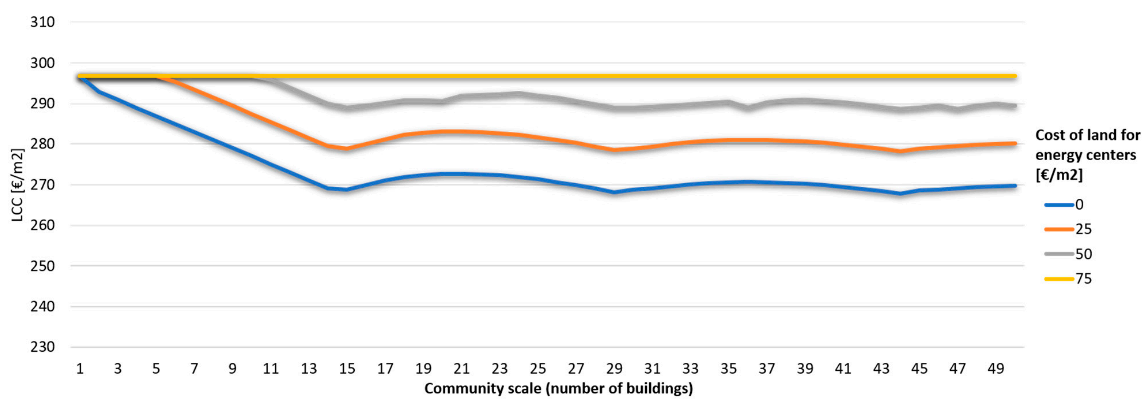

Figure 5. Change in the cost as a function of the cost of land.

4. Analysis of the Results

The results reveal how urban type, density and scale impact the LCC-based selection of energy technologies for NZE communities (Table 2). A significant reduction of LCC was achieved through proper configuration, sizing and location of renewable energy systems both on buildings and in community energy centers.

Table 2. Comparison of results in each case study.

	Cypriot Case Study	French Case Study
Climate	Mediterranean	Oceanic
Main energy demand	Electricity-based	Heat-based
Renewable energy source	Solar	Mostly bio-fuel, and some solar
Optimal community size	7–22 buildings	14 buildings, with 252 dwellings
Impact of higher density	Increases LCC	Decreases LCC

As observed in both case studies, an increase in the scale of a community opens opportunities for economies of scale through community energy centers, but only up to a certain point. Identifying this certain point depends on the interaction among various parameters, which the proposed model resolves. The most significant reduction in LCC (per m^2) is achieved when the scale of the community exploits the full capacity of the first energy center. A further increase in the community scale requires additional energy center(s), realizing an oscillating pattern of the LCC versus community scale, reaching again and again the lowest LCC, whenever the community scale exploits the full capacity of the installed energy centers. The larger the community scale, the smaller the LCC oscillation amplitude and the steadier the LCC near its lowest level. In practice, various reasons might limit the relevance of this phenomenon, such as limited allowed capacity of, or area for energy centers, or reaching a scale that justifies much larger and more economical energy center(s).

Urban density, on the other hand, has a more complex impact on energy LCC (per m^2), with opposite behaviors in the two examined case studies. Urban density determined the optimal share of energy produced at either a building level or community level, having a significant impact on the LCC. However, whereas in the Cyprus case study a lower density reduced the LCC, in the French case study LCC was higher in lower urban densities. This difference stems from the local climate of the communities, and the type of energy consequently required to supply the HVAC and water heating demand (Table 2). Here again, the subtle interaction among various parameters of the problem provides nontrivial yet understandable results through the proposed model.

The Cyprus case study is in a location with a mild climate, and all of its energy requirements are supplied by electricity. Therefore, 95% of the energy in this case study can be produced by PV systems that require space. In low-density communities, larger PV plants can be installed, which results in lower costs. The area available for community-level renewable energy systems not only affects the absolute cost reduction, but also the rate at which this reduction is obtained. It should be noted that the impact of density was limited in this study by Net Metering energy regulations, which prevent over-production from being worthwhile.

In the French case study, which is located in a colder climate, most of the energy is required for a heating system. Consequently, the cost of heat distribution has a significant impact on the overall costs and decreases as urban density increases. While the high density reduces the availability of areas for PV systems, their reduced importance means that density becomes an advantage at a scale at which a district heating system becomes efficient.

These results indicate that the impact of urban density on the cost of NZE communities depends on the local climate and the consequent energy types required to meet the energy demand. Whereas a low urban density (and low land cost) will reduce the cost for communities with electricity-based demand, a high urban density will have a positive impact in communities with heat-based demand. Naturally, the proposed model can also identify optimal solutions for communities that combine both electricity-based and heat-based energy demand to differing degrees, which could possibly lead to additional types of solutions and LCC patterns.

5. Conclusions

Until now, it was widely agreed that the enlargement of the NZE concept to a community scale brings multiple advantages, which could result in a reduction of costs. However, it was unclear how exactly the scale and density of the community affect those costs. Moreover, urban planners lacked sufficient knowledge on how their decisions may affect the potential energy performance of such communities. The model that was developed in this research supports an analysis of the implications of the density and scale of communities on the LCC of the technologies required to reach NZE performance.

The results of this study also underline the importance of considering the design of energy systems at the initial stage of the urban planning of energy-efficient communities, in order to reduce their costs. The design of energy systems is usually defined only once the urban density, the unbuilt areas and the types of the buildings have already been set in the urban plan. This limits the types of technology that can be implemented, and consequently their efficiency, in terms of both energy and costs. By considering the design of energy systems before the initial urban plan has been completed, the energy efficiency and costs of Net or Nearly Zero Energy communities could be improved.

This research confirmed the hypothesis that under certain circumstances, community-level solutions are indeed superior to building-level solutions from a cost perspective. However, it also identified circumstances when this is not so (for example, when the cost of land exceeds a certain level, or when the building density of the community is too low for a district heating system to be economically superior to a building-integrated system). Furthermore, it identified the actual extent of energy cost savings that can be achieved through the community-level approach, which was found to be up to 15% of the Life Cycle Costs in the case studies that were analyzed. Finally, this research also identified the settlement scales that were optimal under specific circumstances and predefined constraints. In the case studies that were included, this scale was found to be quite modest and within the scope of a development that can be relatively easily initiated by a local authority or development company. Naturally, an urban development can be composed of a number of adjacent neighborhoods of such a scale and still achieve the optimal level of LCC. These aspects can be particularly relevant in light of the recent debate concerning positive energy districts—urban areas that not only generate more energy than they consume, but also include systems to actively manage this energy and minimize the impact on the grid.

This is an initial study of the economic implications of an implementation of the NZE approach at a community level. The model presented here can support further research to gain a better understanding of this topic. Such research could include changes in the assumptions that were made in this research regarding the type and distribution of buildings and energy centers. Additional building types, locations and climates, as well as energy-related technologies, could also be considered in future research based on the model proposed in this research. This could lead to better insights regarding the way in which buildings with different energy consumption profiles and requirements should be connected within a single "energy community" [34], and how local PV electricity and thermal energy production and sharing can be optimally combined in such communities [35]. It is our hope that this paper will contribute to extending and enriching these ongoing discussions by ensuring that the cost-related aspects of NZE communities are included in future research.

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