

Article

A Cellular Approach to Net-Zero Energy Cities

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Abstract: Recent growth in the use of photovoltaic technology and a rapid reduction in its cost confirms the potential of solar power on a large scale. In this context, planning for the deployment of smart grids is among the most important challenges to support the increased penetration of solar energy in urban areas and to ensure the resilience of the electricity system. As part this effort, the present paper describes a cellular approach to a Net-Zero energy concept, based on the balance between the potential solar energy supply and the existing consumption patterns at the urban unit scale. To do that, the Geographical Urban Units Delimitation model (GUUD) has been developed and tested on a case study. By applying the GUUD model, which combines Geographic Information Systems (GIS), parametric modelling, and solar dynamic analysis, the whole area of the city was divided into urban cells, categorized as solar producers and energy consumers. The discussion around three theoretical scenarios permits us to explore how smart grids can be approached and promoted from an urban planning perspective. The paper provides insights into how urban planning can be a driver to optimize and manage energy balance across the city if the deployment of smart grids is correctly integrated in its operative process.

Keywords: Net-Zero; energy balance; solar energy; smart grid; urban cell; GIS

1. Introduction

Today, almost 80% of the global energy supply is consumed in cities [1], and, according to International Energy Agency (IEA) predictions, energy use will grow by 56% between 2010 and 2040 [2]. Considering factors like the urbanization processes, unsustainable lifestyles, and global consumption patterns followed by each society [3], the relationship between energy and city is one of the biggest challenges that urban planners have to face around the world. The aforementioned framework leads to a discussion on the growing interest in nearly-Zero Energy Buildings (nZEB) [4], which produce as much energy as they use, and the difficulties of their implementation [5]. In such pathway, reducing the energy load of cities, by means of renewable energies, is essential to achieve the nZEB goal and provide a significant contribution to a sustainable energy portfolio in the present and future world [6].

The recent growth in the use of photovoltaic technology and the rapid reduction in its cost confirms the potential of solar power on a large scale [7]. However, the share of energy supply in such a decentralized system requires an effective approach to energy flow management, making full use of smart grids and technologies [8,9].

Looking beyond the single building, the Net-Zero energy concept requires the elaboration of urban models with a widespread installation of photovoltaic systems and smart grid technologies [10].

It is important to note that developing synergies between several buildings, which are not necessarily nZEB as singles but as a whole, is useful to identify physical boundaries, which are called ‘on site’ generation systems [11].

Here, three important issues are involved in this more comprehensive approach to nZEB. The first is related to how solar potential in urban areas can be evaluated in order to be efficiently capitalized on by the installation of photovoltaic system in building [12]. The second is what kind of delimitation criteria can be considered to identify urban cells as independent systems in which the energy balance results from the differential between the solar energy supply and the building’s energy consumption [13]. The third is focused on the important role of smart grid technologies to manage the energy balance between power supply and demand in the system and from the microscale of the urban cells to the macroscale of the whole city [14]. In response to the aforementioned framework, this paper presents a cellular approach to Net-Zero, which aims to promote energy efficient cities, considering the different spatial scales, urban complexities, and technological challenges associated with sustainable energy planning.

2. Background

The scope of this study is to promote solar energy integration and smart grid deployment to support Net-Zero energy cities. In this way, the research framework addresses three main complementary domains:

- Physical-geographical approaches to urban form and land use analysis;
- Estimation of solar potential and energy consumption patterns in urban areas;
- Integration of smart grids in urban planning practice.

Physical-geographical approaches to the urban form and land use analysis are key to dealing with the complexity of cities [15]. Many of these approaches are used to analyse different aspects of urban development at a macro spatial scale such as urban shape [16], city size distribution [17], or population density [18], involving an array of interrelated methods and tools [19].

Increasingly, the widespread use of geographic information systems (GIS) has shifted the emphasis to new forms of analysis and planning at a fine spatial scale. One of the most effective methods is to employ urban models, based on the principles of Cellular Automata (CA) [16]. The concept of CA was introduced in the 60 s by Von Neumann as formal model of self-reproducing biological systems. Later, computer science, mathematics, and physics began to study CA for modelling their respective domains [20]. In 1979, Tobler introduced the concept of CA to geography and made the first application in the study of urban systems [21]. During the next two decades, these models continued to be developed, focusing on a wide range of phenomena related to urban studies [21]. For example, Clarke (1995) created a land use change model called SLEUTH (slope, land use map, excluded area, urban area, transportation map, and hillside area model) that simulates the urban growth process, showing the real value of planning and GIS application [22]. In this way, the SLEUTH model is capable of modelling complex urban growth dynamics and land use system changes, providing a set of spatial variables such as topographic slope, road networks, and land use maps [23].

Other CA-based models incorporating analyses of the linear dimension of urban infrastructures, the number of buildings, the density, and the possible uses with the number of years and population growth have also been proposed. The MURBANDY (Monitoring Urban Dynamics) model [24], is based on the concept of potential transition that takes into account factors such as suitability, accessibility, zoning, and neighbourhood effect.

Related to these issues, the MOLAND (Monitoring Land Use/Cover Dynamics) model [25] has been applied to European cities to assist spatial planners and policy makers to analyse a wide range of spatial policies and their associated spatial patterns. Nevertheless, this model does not have the capacity to simulate urban growth, and a new model called DUEM (Dynamic Urban Evolutionary

Model) has emerged to demonstrate how urban simulations can be developed to great effect using powerful methods of visualization built around GIS [26].

In this framework, the implementation of different CA models has shown several deficiencies, in part consequence of the difficulty in the delimitation of geographical areas through the rude expression of spatial divisions. On the other hand, the use of the cellular approach provides an opportunity to deal with the modelling requirements of the informatics tools in the aggregation and disaggregation of information, shifting urban model analysis from a large-scale perspective to micro-simulation [21].

In this regard, the cellular approach is the recognition of an alignment between the urban complexity and its study by means of spatial units that are conceived as the smallest urban units available: the cells [27]. Santé et al. (2010) relates that a formal CA can assume a cell space represented by a regular grid usually composed of square cells, although some authors have proposed using hexagonal cells in order to obtain a more homogeneous neighbourhood [28]. White (1997) reports that, at the latter scale, cells may represent cadastral units (i.e., actual land lots), which may have any shape [29]. In this frame, then, the application of CA models supports the transition from macro-scale to micro-scale and offers more and better data to understand the relationships between a range of key aspects such as urban form, built environment, land-uses, densities, and infrastructures across the city. However, while applying these analytical approaches to an urban system, the relationship between solar potential and energy consumption patterns can be effectively explored. Indeed, this is the lesson from the ample literature concerning the analysis of urban solar potential, with particular attention to GIS tools [30,31], parametric modelling [10,32,33] and new methodologies for solar urban planning [34] and design [35]. On the other hand, the relationships between the effect of urban geometry and energy consumption are illustrated by Ratti, Baker, and Steemers (2005) [36]. In that regard, Rode et al.'s (2014) work addresses in detail the relationship between morphological urban parameters and theoretical heat-energy efficiencies created by the spatial configuration of cities [37]. Indeed, the common theme running throughout global approaches to cities and energy revolves around the evidence that solar potential in urban areas is enormous [38] and that PV-generation and its penetration into the grid are central challenges to optimize energy savings, self-consumption, and costs [39]. In this context, smart grid technologies emerge as a solution to enhance every facet of the electric delivery system, including generation, transmission, distribution, and consumption [40]. In principle, smart grids promise a range of benefits but require domains of research that include the following conditions:

- Consider energy delivery solutions to the public network or their use in micro distribution networks at the scale of the neighbourhood [41];
- Assess the capacity of low-voltage networks to integrate additional and reverse power flows and prevent future impacts on their stability [42];
- Consider that data on energy flows require networks to be dynamic and have constant communication between supplier and consumer, which is the use of Information and Communications Technologies (ICTs) together with the decentralized production of energy, a fundamental and effective solution [43].

These three conditions are core in making the electrical system more reliable and efficient by means of intelligent devices that reduce electricity losses and detect and solve energy necessities more quickly.

At the building level, smart grid technologies can play a dual role: first, they support users that produce energy and sell it back to the grid, and, second, they help consumers to keep track of current electricity usage and/or predict future electricity demand [44]. These two functions deliver significant benefits to consumers, who can use electricity more efficiently and reduce their energy consumption and bill. Smart meters devices installed in buildings provide companies in the energy sector with the ability to monitor, for example, when a part of the city is using more electricity than expected or to detect problems on their systems and operate them more efficiently [40]. Moreover, with the

integration of electric vehicles within the grid, there is the need to meet the stationary load demand in parallel and its associated diurnal requirements [44,45]. Through a long-term vision, aspects such as locations for electric vehicle parking and charging and park-time length for a particular land use, will be essential urban planning parameters. Nonetheless, there is a need for the implementation of pilot projects to establish which smart grid models are more adequate to be adopted [46], supporting the vision of intelligent infrastructure and intelligent cities [47]. Indeed, smart grid deployment is a complex task [48], which interacts within a complex system, the city. In this sense, the large-scale approach and multidisciplinary nature of urban planning, coupled with solar energy smart grid integration, can lead to the more integrated and comprehensive energy management of cities. It is the closing of this presumption that this work aims to contribute by studying a single urban cell to shift, in a systematized way, at the macroscale within the ‘Net-Zero Energy’ balance scenarios developed at the city level.

3. Methodology

According to the literature, the Geographical Urban Units Delimitation (GUUD) model has been developed, dealing with a cellular approach to the urban form, land use analysis, and solar potential and energy consumption estimation. The present section of the paper describes the GUUD model and the methodology that supports its practical application to solar energy and smart grid integration in a case study: the city of Oeiras in Portugal. The GUUD is a model that operates at the city macroscale level by defining a simplest set of urban units that, like cells, can be considered negative, positive, or neutral in accordance with the differential between their respective potential of solar energy supply and existing energy consumption patterns (Figure 1).

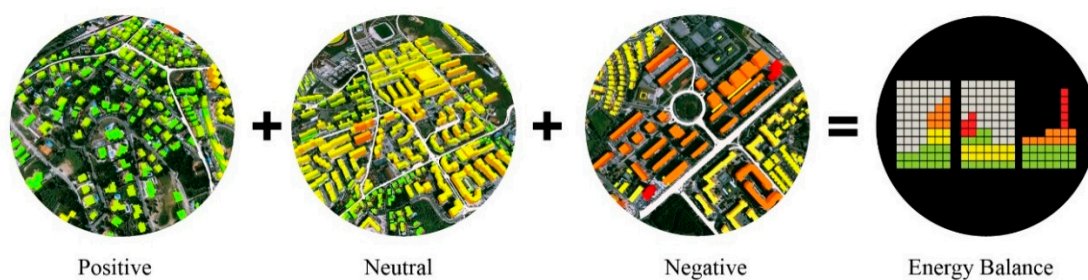
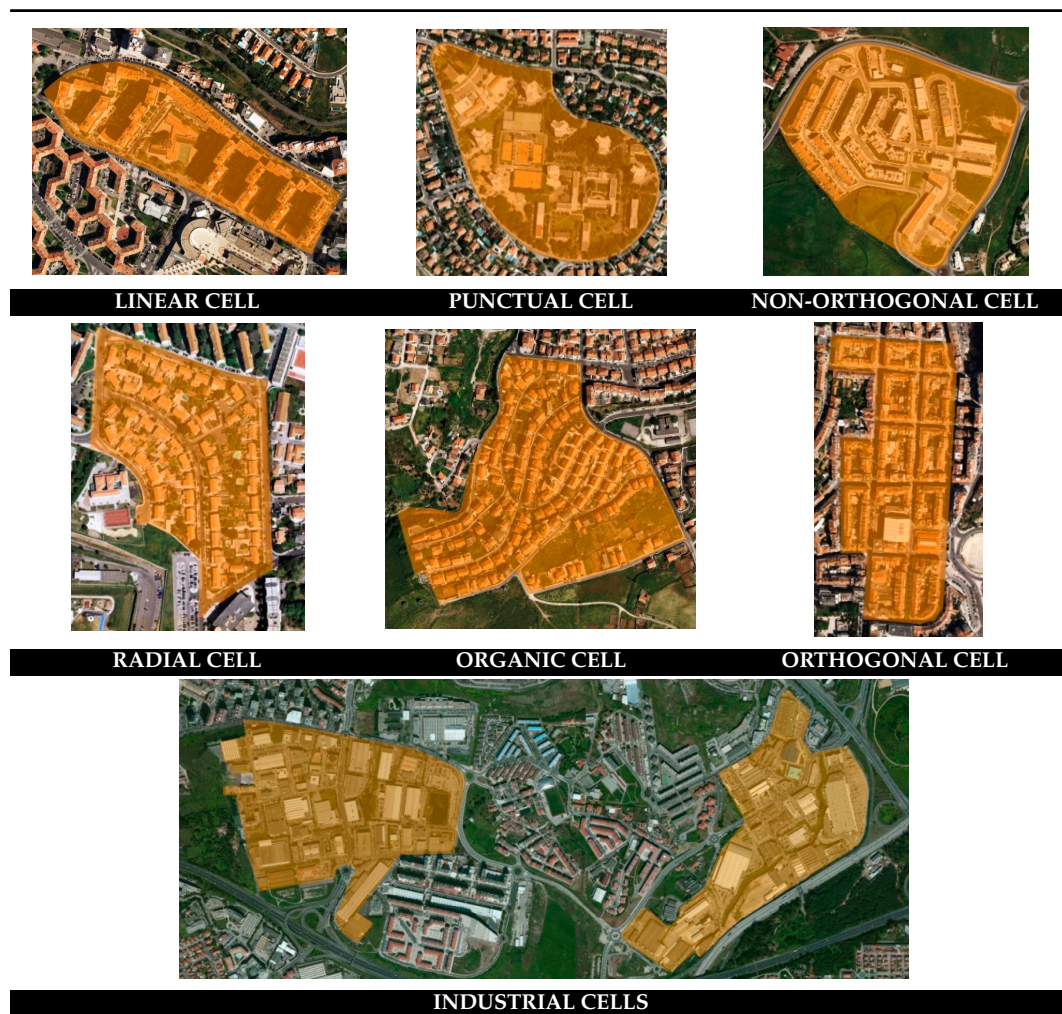


Figure 1. Geographical Urban Units Delimitation (GUUD) model: cellular approach concept.

This approach, inspired by cellular automata theory, permits us to interrelate within GIS a variety of determinants such as urban compactness [35], morphology [36], street patterns [49], buildings orientation [50], density [51], and land use [10], which have great influence on solar energy production and consumption. The statistical subsections joined to the ‘information reference geographical database’ released by the National Institute of Statistics (2011) [52] have been adopted as the starting point for the urban unit delimitation (Table 1).

Table 1. Examples of urban units based on statistical subsection delimitation across the city.

The identification of morphological cells assumes knowledge of the parts of the form and the way they structure themselves in the different identified sub statistical sections and makes sure that its implementation is replicable to other cities in European Union. Indeed, the use of such a statistical, geo-referenced grid allows urban planners to work with several levels of quantitative information, including official administrative boundaries, residential buildings, population census, households, and dwellings that can be interrelated to the physical components of the urban system; that is, buildings, streets, and infrastructure.

From within this geo-referenced grid, the GUUD model is calibrated by means of four delimitation criteria: construction timeline, population density, urban morphology, and land-use patterns. This framework permits us to filter the global database with specific parameters (Table 2).

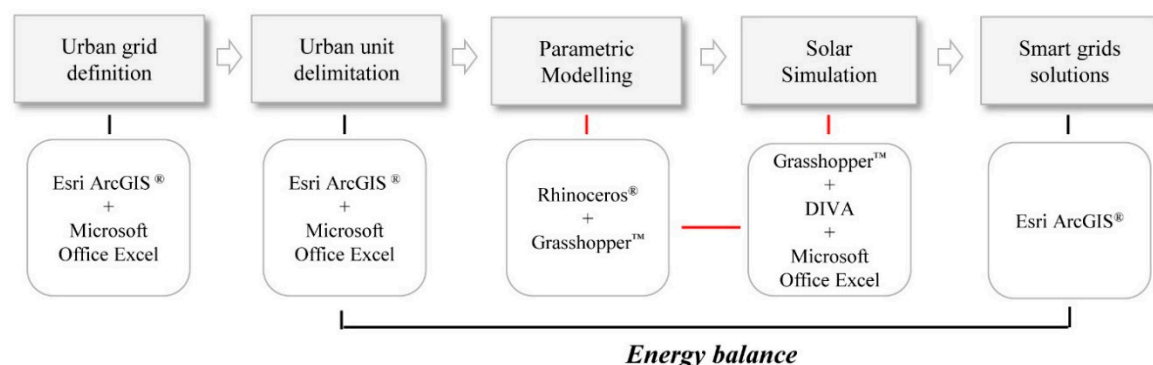
As result, the concept of the urban unit emerges as an operational element, which aggregates a set of statistical subsections, which are characterized by relations of proximity, neighbourhood, and common characteristics defined according to the spatial-time evolution of the urban model.

Table 2. Delimitation criteria of the urban unit.

A map of a city area with a red dashed line indicating the statistical subsections grid. The map shows various urban blocks and streets. A north arrow is located in the bottom right corner of the map.

	Period of Construction	years
	Resident Population	N°
Buildings Block and Street Pattern		Orthogonal
		Warped Parallel
		Organic
		Linear and Loops
Residential Building Types		Multifamily low-mid-high rise
		Single family attached—detached
Roof Typology		Pitched
		Flat
Zoning	Residential	Parks and Recreation
	Commercial	Service
	Industrial	Public facility
Land-Use Coverage System		Buildings covered area
		Open space area
		Street covered area

The Net-Zero energy concept is thus shifted from the building to the urban unit, developing synergies between several buildings, which are not necessarily nZEB but, by integrating photovoltaic systems and smart grid technologies, can be turned into energy balanced cells or solar energy exporter cells. At an operative level, the cellular approach is supported by an interactive workflow, which combines a large amount of vector data, satellite imagery, and tables, which are included in the GIS with parametric modelling and solar dynamic analysis (Figure 2).

**Figure 2.** Interactive workflow.

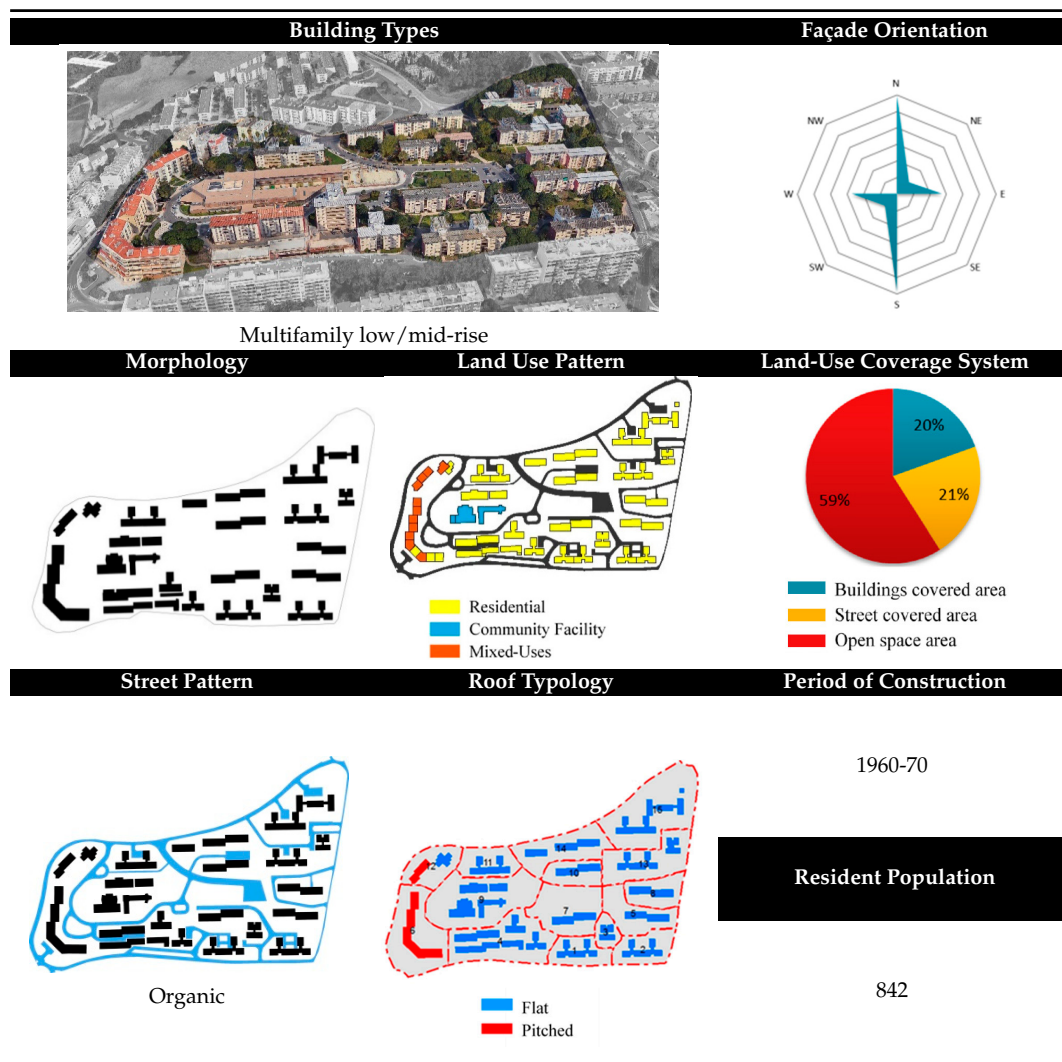
4. Case Study

This section describes the application of the methodology to Oeiras, a medium sized city located in the Lisbon Metropolitan Area in Portugal. The city covers 651 hectares and is delimited by a statistical grid with 1.916 subsections.

4.1. Urban Unit Delimitation

The cellular approach application at the city scale is obtained by analysing the large amount of vector data, satellite imagery, and tables, which describe the urban system within a GIS [13].

Table 3 shows an example of an urban unit that has been delimited, according to the four criteria of the GUUD model.

Table 3. Urban unit selected for validation. (Reproduced with permission of Elsevier).

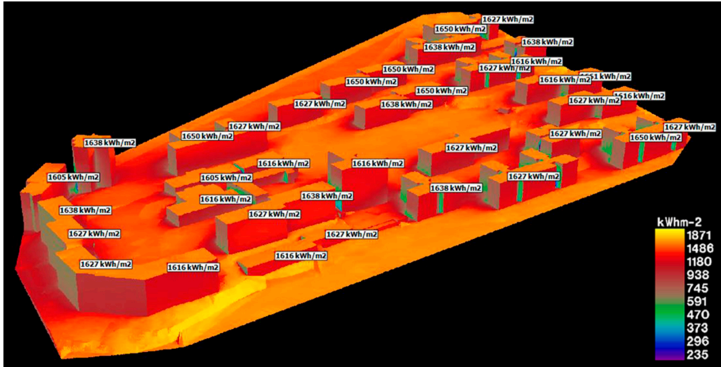
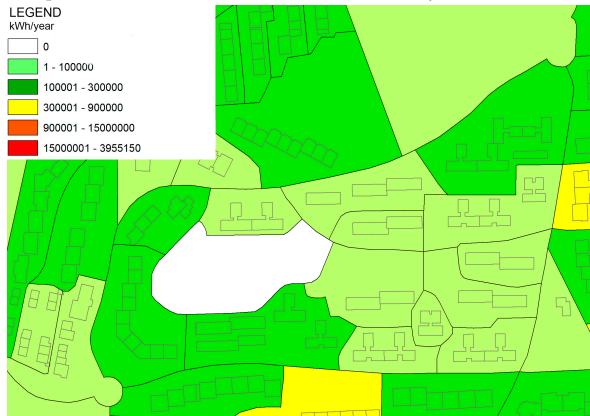
The urban unit is characterized by an area of 8.2 ha, a density of 102 inhab/ha, typical multifamily low/mid-rise buildings from the 60 s and 70 s, and an organic street pattern. The land use patterns show the prevalence of residential land uses, some existing mixed use buildings, and a primary school.

The urban form offers a great percent of open space area and, thus, fewer shading effects from the surrounding buildings. According to the geographic location and solar access conditions in Portugal, the best building roof and façade orientation for PV systems is south [53]. Considering this factor and the analysis of Table 3, it is possible to verify that the ratio between buildings with predominantly south facing orientations and with mixed flat and pitched roof typologies provides good conditions for solar potential implementation. On the other hand, the year of construction is determinant for understanding the quality of the materials, design, and state of preservation of the buildings, constituting an important parameter that affects the energy consumption.

All these aspects are confirmed by the results of the following table that shows how the energy supply from the potential installation of photovoltaic systems in the rooftop can reach theoretical penetration levels between 20% and 65%. The annual PV-generation has been calculated by adopting Amado and Poggi's methodology (2012), which permits an approximate estimation of solar potential for urban planning and design [53].

The energy consumption has been estimated by computing the relationship between the number of inhabitants and the statistical data about the annual electricity consumption per capita in the city of Oeiras, which accounts for 1.398 kWh (Table 4).

Table 4. Urban unit energy performances.

i. Solar Radiation Simulation Obtained from Diva		
		
ii. Predicted Annual Yield for PV Systems on Available Roof Area (kWh)	1.576.178	
iii. Average Annual Electricity Consumption for Each Subsection of the Urban Unit (kWh/year)		
		
iv. Average Annual Electricity Consumption of the Urban Unit (kWh/year)	984.192	
v. Differential between Energy Production and Consumption	62% Positive	38% Negative

4.2. Smart Grid Scenarios

Over the past few years, there has been an increased interest in pilot projects of the deployment of smart grids [46,54], smart meters and communication infrastructure [9,54], renewable energies [55], and alternative vehicle integration [56]. Planning for smart grids in cities is a task that must consider a large number of components in a system acting and interacting in time and space.

In this sense, the work of Niemi et al. shows the need to view the city simultaneously as a platform for local energy production and a sink of energy [43]. Nevertheless, this approach does not include important aspects such as urban morphology, land-use patterns, building typologies, or materials. Indeed, one must get behind the single technical aspects of smart grids in order to develop scenarios for the complex urban environment of the city and, thus, improve the coherent relationship between urban planning and energy management. Our simulation results for the selected urban unit show that the potential supply from a PV system on the roofs can satisfy 62% of the current electricity consumption. In this way, the urban unit provides a chance to explore and discuss a set of schematic scenarios of smart grids that can be developed by considering the spatial and temporal urban planning perspective.

4.2.1. 'Produces and Sells' Scenario

The first proposed scenario, is the 'Produces and Sells' scenario and promotes the installation of PV micro-generation systems on the suitable roof areas of all the buildings, in line with the new Portuguese legislation on PV generation for self-consumption [57]. For this purpose, the scenario enables small-scale PV system owners to consume the electricity produced or to sell the excess generated power to the grid at market prices.

Figure 3 shows the layout of the 'Produces and Sells' scenario, which is characterized by the existing low voltage network and a set of connection nodes for managing the solar supply from the PV micro generation systems across the urban unit.

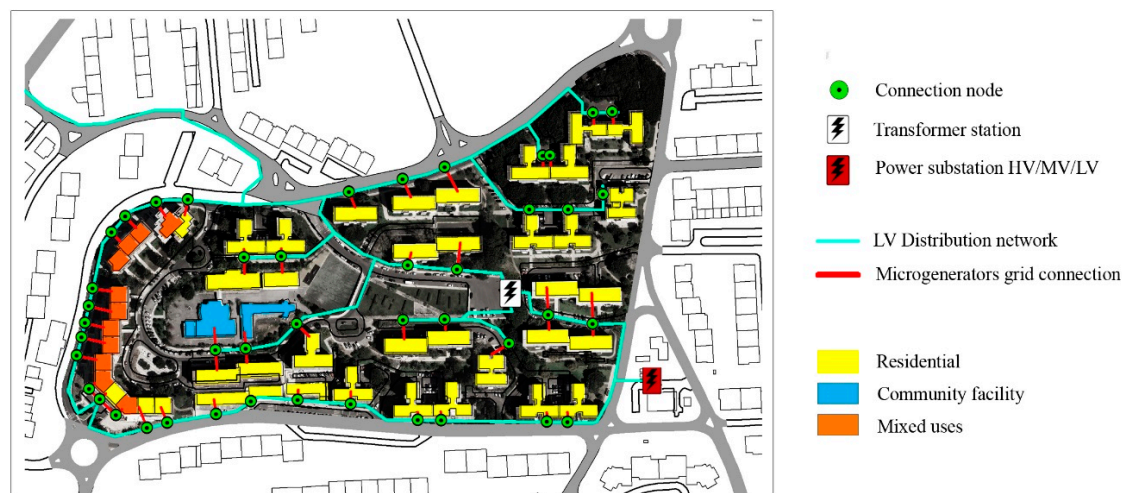


Figure 3. Layout of the 'Produces and Sells' scenario.

In line with Niemi (2012), the 'Produces and Sells' scenario assumes the adoption of a set of intelligent systems, namely [43]:

- Consumer smart meters that are installed in each dwelling to collect data on energy consumption and transmit this to the collective smart meter located in the building;
- A collective smart meter installed in each building constitutes the central server for the collection of data on energy consumption from all the consumer smart meters and data on energy production from PV micro generation systems. It manages the daily, monthly, and annual balance between production and consumption;
- A connection node is installed on the public distribution network and provides communication with the collective smart meter. It supports the management, monitoring, and optimization of energy flows produced on site and those supplied by the public distribution network.

From an urban planning perspective, the suggestions that emerge relate to energy efficiency, solar energy promotion, and regulation. In this sense, the hierarchy of smart meters, from buildings to the public distribution network, can allow a holistic enhancement of energy efficiency, covering three different levels: the consumer, the building, and the city. Furthermore, the consumer smart meter, controlling electricity costs, informs the consumer about how their energy is used, the efficiency of their electrical appliances, and how to improve it. On the other hand, the collective smart meter, controlling the energy performance of the building, allows the identification and evaluation of the global energy efficiency at the urban unit scale.

4.2.2. 'Produces and Shares' Scenario

The possibility of creating a system of interconnected networks is the basis of the 'Produces and Shares' scenario, in which the total PV supply from the urban unit is sold to the public network and the gains of this sale are shared between the producers in a weighted manner.

In this sense, the 'Produces and Shares' scenario differs from 'Produces and Sells', in terms of the economic mechanism, which is based on the differential between the costs and gains from the consumed energy and the produced energy.

The layout of the 'Produces and Shares' scenario is implemented on the principle of a microgrid in a grid-connected model [58], which collects the solar PV supply inside the limits of the urban unit and injects it to a public distribution network by means of an aggregation and control node (Figure 4). The aggregation and control node provides metering and management of profit rights that is processed according to the different energy consumption patterns of each consumer/producer.



Figure 4. Layout of 'Produces and Shares' scenario.

The 'Produces and Shares' scenario is based on the concept that solar energy is a common resource of the urban cell. As such, the economic factor is associated with the social responsibility of monitoring energy consumption and promoting energy efficiency behaviours. Here, the key-mechanism is that the tenant that improves their energy performance in the dwelling will have a higher economic return from the sale of the electricity, generated by the photovoltaics installed in all the buildings of the urban unit, than the tenant who shows consumption patterns higher than the average values.

In this way, the consumer smart meters and collective meters collect a large pool of data related to the energy performance of each building, which are made available to the policy makers and technicians responsible for planning and urban management, systematizing and standardizing information to model, and comparing and testing energy balance scenarios across the city.

However, this scenario also reflects another important issue: the lack of grid capacity associated with renewable energy supply. In fact, the increase in renewable energy will certainly have (if not already) deep consequences in terms of the structure of both the grids and the cities. Here, it is important to highlight the strategic scope of this scenario that promotes the concept of energy balance as way to create an efficient connection between urban cells, where energy production and consumption flows are balanced by smart grids according to the negative, positive, and neutral performances of each urban unit across the city.

4.2.3. 'Produces and Drives' Scenario

The 'Produces and Sells' and 'Produces and Shares' scenarios need always to work in a grid connected mode together with the public electric network to guarantee the stability of energy flows at the city scale. On the other hand, the 'Produces and Drives' scenario aims to evolve towards a final transition from the grid connect mode to a standalone mode, introducing storage systems [58,59]. In this effort, electric vehicles, as mobile storage systems, constitute a promising technology in the context of the smart grid being incorporated with the solar energy supply in urban areas [45,60].

In the 'Produces and Drives' scenario, the microgrid is coupled with smart charging points powered by PV systems, managing the mechanism of charging during off-peak periods or discharging at the peak of load consumption (Figure 5) [60].



Figure 5. Layout of the 'Produces and Drives' scenario.

The integration of electric vehicles into the micro grid is an important challenge, considering the urban planning perspective and the impact on transport modes. The question is directly related to the key domain of energy storage that helps overcome the problem of variable supply from renewable energy sources and allows electricity grids to operate more efficiently and cost effectively.

The contribution that this scenario gives to this strategic objective is associated with the fact that electric vehicles are becoming an economically viable solution to energy storage needs, and charging points will be expected to be planned across the city in a systematized way. Indeed, the determination of communities to support producers of electric vehicles will have, with this research, a basis of support that the whole system can be in balance and will thus reinforce the contribution of the article to the approach to Net-Zero energy cities.

In this context, the novel energy zoning of cities can be an important contribution to tackle the charge/discharge of batteries issue. In residential areas, energy demand is lower during the day, and the solar energy production can feed other parts of the city with economic activities such as services and industries. Here, the operational feasibility of renewable energy in cities has to be supported by a mix of complementary land uses that permit us to optimize how electric vehicles are charged in the night and in the daytime and to oversee the provision of charging points associated with PV installation onsite.

In this sense, zoning should consider mixed-used patterns and densities, relating them to optimize and manage solar energy supply and energy consumption patterns. This kind of adaptive zoning must also include other aspects such as the time of day or night, the day of the week, and the season of the year in relation to land-use patterns that are energetically compatible with the urban unit. Urban planning is therefore a key to successfully decrease transport-related energy use and reduce the need for excess energy, moving towards balanced urban units across the city.

5. Results and Discussion

The management and optimization of energy flows in cities is fully dependent on solar energy and smart grid integration. In this context, the present study aims to shift the Net-Zero energy concept from the building to the city scale. The overall hypothesis is to predict future deployment models of smart grids that connect urban cells with solar energy surpluses and urban cells in which energy consumption needs are not covered by the local supply.

A case study has been utilized to show the practical application of such a cellular approach, based on the delimitation of an urban unit, according to four specific criteria to simulate and quantify the existing and potential energy performances.

Three scenarios have been presented to pave theoretical ways to implement the upgrade of existing electric networks, together with solar energy and smart grid integration.

The first scenario is a short-term planning exercise that promotes energy self-consumption, selling the excess to the grid. Smart metering systems emerge as a key aspect to better integrate PV supply into the grid and provide useful information on real-time consumption to consumers, encouraging them to adopt more energy efficient behaviours.

The second scenario provides a novel economic mechanism to achieve higher outcomes in the promotion of PV supply and energy efficiency. The consumers that live in buildings with PV systems on the roof are, at the same time, producers, and all the energy produced by the urban unit is sold to the public network. The gains of the PV generation sale are shared between the producers based on their energy consumption behaviours so that investments in energy efficiency and energy saving lead to relevant economic benefits for consumers. In doing so, this scenario also supports the implementation of a platform to monitor and manage the energy production and consumption flows of urban units and across the whole city.

Finally, the third scenario explores the integration of storage systems in the city, with a focus on electric vehicles and PV generation. In this framework, zoning is a crucial issue to define mixed land-use patterns and densities that are energetically compatible with the charging needs of electric vehicle users.

The result of this approach is to move from a static urban planning process to a proactive approach, based on a scenario method to inform and integrate urban planners and policy makers in the design and monitoring of solutions that can make urban areas more energy efficient.

Tackling this affirmation, a comparison with other theoretical and practical approaches that are currently related to the task of integrating the deployment of smart grids in urban planning and promoting the concept of the Net-Zero Energy City has been developed. The review process was based on an analysis of peer-reviewed research published between 2003 and 2017 and indexed by the Scopus and ISI Web of Knowledge databases. According to an inductive approach, the selection of relevant research covered the following keywords: 'smart grids', 'urban planning', 'energy zoning', and 'Net-Zero Energy City'.

According to Zhang et al. (2017) [61], although studies on smart grids have been conducted from the perspectives of technologies, stakeholders, pilot projects, processes and outcomes, and risks and vulnerabilities, most work focused only on one aspect of smart grids. The work of these authors permits us to understand that smart grid deployment is not actually articulated with a territorial basis as cities are.

In their review article on Smart Grids, Ponce-Jara et al. (2017) [62] claim that the U.S. and Europe focus their efforts on energy efficiency, the deployment of renewable energies, and improving, strengthening, and expanding interconnections between countries and states. This review is proof of the importance and interest that the integration of the deployment of smart grids in urban planning raises at the fine-scale scales of the city, neighbourhood, and buildings.

The needs for a large, interconnected grid with strengthened local power transmission lines, the implementation of local or regional energy storage, and demand-side management, i.e., smart control of flexible, energy consuming devices, represent essential adjustments to the energy system

to solve unbalances between generation and demand [63]. In this study, the authors conclude that the choice of an approach requires a holistic analysis and vision of the future energy system of an urban region.

On the other hand, the concept of the Net-Zero Energy City is a novel vision that can be associated with the project of Masdar City [64]. Nevertheless, the case of Masdar City is a scenario-zero as it benefits from the lack of existing reality and consolidated dynamics, allowing for more radical interventions to be implemented. Indeed, existing cities call for different approaches. In this context, Li et al. (2017) [65] propose an approach based on the Net-Zero building cluster, within which smart grids, distributed power generation, and storage devices can freely share energy resources locally and globally, and the entire cluster will achieve maximum energy efficiency. However, this model limits its application to building clusters as autonomous and adaptive systems without any mutual interaction.

Overall, the integration of smart grids in urban planning and the concept of the Net-Zero Energy City emerge as topics that arouse the interest of planners and researchers but still lack proper frameworks and clearly defined methodologies to inform the territorial and city management and promote integrated decision-making. From this perspective, to predict solutions for smart grids and energy flow control systems in association with the design stages of the urban planning process is essential to coordinate the amount of infrastructural interventions that have to be processed together at the urban dimension. Indeed, energy planning is a real revolution for the cities of tomorrow, and the challenge we are launching in this research is the construction, today, of a proactive approach in the belief that cities can be moved toward a Net-Zero energy balance, which is a cross-cutting issue that involves solar energy, smart grids, and urban planning.

6. Conclusions

This study aims to understand the complexity that characterizes the relation between energy and city, developing a cellular approach based on the delimitation of urban units according to specific criteria that support a systematized comprehension of their physical components. Overall, the objective of the article is twofold. First, we discuss the novel concept of Net-Zero Energy Cities, supported by the balance between solar energy production and consumption. For this, it is considered that urban planning plays a key-role as it determines the evolutionary dynamics of cities and defines their structural components, including densities, land use, morphologies, building forms, and road patterns, which influence the energy performance at any spatial level. Second, we discuss that urban planning is a process that has to involve the deployment smart grids to guarantee that the energy flows and connectivity system support the balance at the city scale. As energy in cities asks for a transition toward solar energy and smart grid integration, urban planners, public administration/governance, and stakeholders need to better understand how to integrate these domains in the decision-making process and then effectively implement them into existing and new urban areas. In this way, the development of scenarios is an important step to test new models and support the elaboration of adequate policies and regulations.

To this purpose, the adoption of the proposed cellular approach provides a comprehensive view on energy performances at the scale of urban units, turning the whole city into a more workable framework for planning solar energy and smart grids. Through this, it is possible to guarantee that the grid, with its set of smart meters, is a viable solution that suits the efforts of the public and private sector in carrying out its activity and enables the energy and economic efficiency of energy production and consumption in urban areas.

The results of this study make clear that the deployment of smart grids is an essential step in the management of a city's energy, which has to be developed from an urban planning perspective.

This paper promotes the need to reformulate urban planning and update it with broader concerns such as solar energy and smart grid integration, which are essential to achieve the transition towards more sustainable cities. The integration of electric vehicles into the grids also emerges as an important

challenge from the perspective of urban planning that should consider charging areas and microgrids according to PV supply, economic activities, public facilities, or residential energy use.

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Abbreviations

CA	cellular automata
DUEM	dynamic urban evolutionary model
GIS	geographic information systems
GUUD	geographical urban unit's delimitation
MURBANDY	monitoring urban dynamics
MOLAND	monitoring land use/cover dynamics
nZEB	nearly zero energy buildings
PV	photovoltaic
SLEUTH	slope, land use map, excluded area, urban area, transportation map, and hillside area model

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