Solar energy integration in urban planning: GUUD model

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Abstract

With more than half of the world’s people living in cities and about 75\% of the population that will live in urban areas by 2050, meeting energy demands sustainably is one of the most important challenges for the future of society. This paper presents the solar energy integration in urban planning by using the GUUD - Geographical Urban Units Delimitation model. The concept behind this is that city districts and neighborhoods can be turned into solar power stations that behave like atoms. Appealing to the cellular automata (CA) concepts, the GUUD model assumes the division of the city into “cellular units” according to four delimitation criteria: construction timeline, population density, urban morphologies and land-use patterns. To do this, the model is calibrated to collect a selection of data inputs which are the bases of a workflow that combines GIS with parametric modeling and solar dynamic analysis. Its application to a case study shows how is extremely important to understand the existing urban models to relate them effectively with energy aspects at the whole city scale. Furthermore, the results of solar dynamic analysis suggest how the energy supply from the widespread installation of photovoltaic systems in the urban context can provide a sustainable contribution to energy demands but at the same time has to be supported by smart grids for its correct management and completed by more energy efficient buildings and other renewable resources towards the city energy balance.

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1. Introduction

With more than half of the world’s people living in cities and about 75% of the population that will live in urban areas by 2050, meeting energy demands sustainably is one of the most important challenges for the future of society [1]. The implications of urban population growth on global issues of energy consumption, energy security and climate change, address for effective solutions, to support the indispensable change towards more energy efficient cities. In this context, enhancing the use of solar energy in urban areas may play a fundamental role to reduce energy loads and greenhouse gases emissions (GHG) and other pollutants. During the last decade, this necessity has stimulated the interest of researchers to develop suitable approaches for solar energy integration in urban planning [2]. The concept to turn city districts and neighborhoods themselves into solar power stations,[3] is a complex challenge that requires comprehensive and interrelated approaches. The elaboration of future scenarios which simulate the widespread installation of photovoltaic systems and potential spatial changes in the urban context is particularly well suited to support this assumption. The literature with an explicit focus on scenario development using 3d models and advanced daylight simulation, shows operational outcomes about methods and tools for the calculation and visualization of the solar energy potential of buildings roofs and facades [2,4,5,6,7,8]. But an effective scenario has to include a comprehensive description of the existing urban model and its development patterns and dynamics in order to understand the factors and parameters which determine the solar potential and support its concretization and management [9]. In this framework, cellular urban models are excellent vehicles for exploring the spatial complexity of cities [10] and if predominantly based upon areas of local interactions, such as city districts and neighborhoods, they can be modeled as cellular automata (CA) [11]. This paper presents the solar energy integration in urban planning by using the GUUD - Geographical Urban Units Delimitation – a model based on the CA concepts of urban cellular subdivision.

Indeed, the issue has come to look for and implement concepts and practices for urban planning and design which relate with solar potential and other fields including land use and street pattern, buildings and open spaces conception and smart grids. Furthermore, urban planning has to take into account results from relating economic, social, and environmental and governance factors with solar energy integration [9]. In this sense, once electricity generation from solar energy grows, its costs decline, making always more economical its development in the future. Moreover reducing energy load of cities by means of solar energy integration is essential to achieve the mitigation of GHG emissions and provide a significant contribution to a mixed renewable energy portfolio in the present and future European Union [12].

2. Background

In the present context of society dependence on energy, a more sustainable model of urban planning is required, one that is able to provide different solutions for urban development taking into account the solar energy potential. In this framework, an inclusive urban planning process which focuses on solar energy and its integration in urban areas, has emerged with the name of Solar Urban Planning [9,13]. This approach is supported by different planning methodologies which consider the use of solar potential as a key issue of urban design to improve energy supply and efficiency in existing urban areas and promote Building Integrated Photovoltaic (BIPV) in new ones. To do this, predicting the suitable locations for photovoltaic systems on buildings and their potential energy supply is a fundamental step to support solar urban planning practices [2]. The aforementioned framework leads to the discussion on the simulation of the incident solar radiation over the large geographical scale of the city [2,4,6,8]. The use of real data to support simulations requires the calibration of models that can be built, based on historical and statistical data where the factors are considered inside its geographic limits – cells [14]. In this sense, the application of models from macro-scale to micro-scale offers more and better data to address the challenges created at the city scale and understand the relationships of a range of key issues such as: demography, urban form, built environment, land-uses and densities. Urban cells behave like atoms and can be compared with cellular automata introduced in the 60’s by Von Neumann, and its implementation into urban systems realized by Tobler in the 70’s [15]. The study and simulation of periods of time can be used in two different types of cases: 1 – analysis between urban and rural land extensions and its relation with the level of infrastructures developed including topography modification; 2 – analysis of land-use, linear dimension of urban infrastructures, number of buildings, densities and
uses with the number of years and population growth. This model is different from the SLEUTH model developed by Clarke, [16] who does not introduce population and land-use. The MURBANDY model, [17] is based on a vector of potential transition that takes into account the factors of suitability, accessibility, zoning and neighborhood effect. Related with this model, the MOLAND model [18] that has the capacity to simulate future scenarios for cities, has been applied to European cities was also considered. This model does not have the capacity to simulate capacity to urban growth and a new model appears named DUEM created by Batty and Xie (1999) and Centre of Advance Spatial Analysis [19]. In this context, the entrance of Geographic Information Systems (GIS) with its fine scale of analysis in the available tools of the urban planning process should result in the vanishing of abstraction or analogies in its morphological models.

Nevertheless, the implementation of different studies with the cellular automata model 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 cellular automata provides an opportunity to deal with the modeling requirements of the informatics tools in the aggregation and disaggregation of information, shifting models from a large-scale perspective to micro-simulation, [20]. With the recent necessity to provide urban solutions with more efficiency in the energy area, the simulation models can be used and calibrated using real-world data [15], to analyze urban areas and explore future scenarios of land-use and urban expansion integrating aiming to the solar energy integration in urban planning [14].

3. The GUUD model

3.1. Description of the model

The GUUD is a model for Geographical Urban Units Delimitation that provides an operational support for the definition and implementation of urban planning practices for solar energy integration at the city scale. It supports two concepts:

1. energy supply from widespread installation of photovoltaic systems and its management by using smart grids has to take into account the spatial and functional features of the urban model;

2. energy flows through the whole city have dynamics linked to production and consumption patterns which have to be analyzed and controlled.

In this context, the GUUD model emerges from the necessity to relate urban planning fields and solar energy in order to meet a range of requirements which directly affect the energy efficiency of cities (figure 1).

![GUUD model framework](image)

Fig. 1. GUUD model framework
To give an operational link between the aforementioned framework and the complexity of the city scale, the concept of cellular automata (CA) has been adopted. According to White (1997), the cellular automata approach for urban modeling means “the definition of discrete cell space, together with a set of possible cell states and a set of transition rules that determine the state of each cell as a function of the states of all cells within a defined cell-space neighborhood of the cell; time is discrete and all cell states are updated simultaneously at each iteration” [21].

3.2. Cellular unit and grid

The geometric configuration of the cell used to represent spatial data and the criteria for its delimitation can have profound effects upon subsequent analysis and interpretation [19].

In this sense, the GUUD model assumes the division of the city into “cellular units” according to four delimitation criteria: construction timeline, population density, urban morphologies and land-use patterns. These criteria are extremely important to understand the urban model and its relationship with energy aspects [22,23,24,25,26] and thus define, in a coherent manner, the cellular unit (table 1).

Table 1. Cellular unit’s delimitation

| City detail | Statistical subdivision | Delimitation criteria |
|-------------|-------------------------|-----------------------|
| Oeiras 38°44'-9°24' | [Diagram of statistical subdivision] | Period of construction: 1945-60 |
|             |                         | Resident population: 1354 |
|             |                         | Buildings block and street pattern: Orthogonal |
|             |                         | Building types: Multifamily low-rise |
|             |                         | Roof Typology: Pitched |
|             |                         | Land-Use Coverage System: 41% Buildings covered area, 40% Street covered area, 19% Open space area |

Taking into account that CA models need not be spatial per se or spatial in the two-dimensional sense either, most models appeal to the idea of representing the spatial system on a regular lattice such as a grid [19]. In the GUUD model, the grid is structured on the statistical subsections released by the National Institute of Statistics (INE, Portugal) [27] which divide the urban areas according to the smallest homogenous area, whether built-up or not, existing in the statistical section (table 1). This statistical grid-based system enables the associations between cellular units and the geo-referenced information based on population and housing census.

3.3. Cellular unit state and transition rules

In most urban modeling applications, cell states depend on the focus of the model [21]. In the GUUD model, the state of any cellular unit depends upon the potential of solar energy supply and the energy consumption patterns which are related to what is already in that cell.

The differential between the energy production and consumption defines the set of the possible cellular unit states which can be: (1) positive or (2) negative.

The transition rules of the GUUD model are inspired by the structure of the atom where protons, electrons and neutrons are the cellular units that behave as particles with positive, negative or no electrical charge according to
their energy performances. In this sense, the transition rules relate the cellular units to what is happening in their immediate neighborhoods in order to implement the energy balance of the whole cellular system: the city.

3.4. Scenarios elaboration workflow

The scenarios are elaborated by modeling the current state of each cellular unit at time t, to an outcome state at time (t+1) which predicts the solar energy potential of the cellular unit if photovoltaic systems would be integrated in the existing suitable roof and façade areas.

To do this, the GUUD model is calibrated to collect a selection of data inputs which are the bases of a workflow that combines GIS with parametric modeling and solar dynamic analysis (figure 2).

4. Case study

In this section, the GUUD model is explained in more detail through its application to a case study of a medium-sized city, Oeiras in Portugal.

At an operative level, the cellular approach at the city scale is obtained by analyzing the large number of vector data, satellite imagery and tables which define the urban model in a Geographical Information System (GIS).

The city total area of 651 ha, has been delimited by mean of a grid based on 1.916 statistical subsections (INE, Portugal) [27].
The evolution of the buildings block and street patterns has been classified according to the models studied by Southworth and Ben-Josep (1997) [22]. Table 2 shows three cellular units (CU) which synthetize the most common urban forms resulting from the analysis of the city.

Table 2. Cellular units for validation

| Buildings block and street pattern | CU 1. Warped Parallel | CU 2. Linear and Loops | CU 3. Organic |
|-----------------------------------|-----------------------|------------------------|---------------|
| Period of construction            | 1960-70               | 1970-80                | 1960-70       |
| Resident population               | 2615                  | 1848                   | 842           |
| Building types                    | Multifamily mid-rise  | Multifamily mid-rise   | Multifamily low/mid-rise |
| Roof typology                     | Pitched and flat      | Pitched                | Pitched and flat |
| Land-Use coverage system          |                       |                        |               |
| Buildings covered area            | 27%                   | 56%                    | 50%           |
| Street covered area               | 30%                   | 28%                    | 20%           |
| Open space area                   | 23%                   | 16%                    | 21%           |
| Façade orientation                |                       |                        |               |

Comparing the resident population and the year of construction emerges how the higher densities tend to be in the CU1 and CU2 corresponding to the rapid growth of the city that occurred from 1960 to 1980 [27].

Another important correlation regards the street patterns which influence the façades orientation and consequently the solar energy potential on them and on the roofs of the buildings [24].

According to the geographic location and solar access conditions in Portugal, the best building roof and façade orientation for PV systems installation, is south [9].

Taking into account this factor, a clear heterogeneity can be observed among all the three CUs.

The CU1, associated to high density, multifamily mid-rise buildings and a mix between flat and pitched roof typologies, is the cellular unit that presents the more complex characteristics for solar potential implementation.

In the CU2 e CU3, the buildings block and street patterns offer a greater percent of open space area and thus, less shading effects of the surrounding buildings.

The CU3, with low population density, adequate space between the buildings and predominant south façade orientations presents the best solution in order to reach the balance between solar energy production and consumption.

All these aspects are confirmed by the results of the solar energy potential and consumption estimations (table 3).
### Table 3. Cellular units states

| Solar radiation simulation obtained from Ecotect® | CU 1       | CU 2       | CU 3       |
|------------------------------------------------|------------|------------|------------|
| Predicted annual yield for PV systems on available roof area (kWh) | 2,280,441  | 742,816    | 1,576,178  |
| Average annual electricity consumption by residential use (kWh) | 3,655,770  | 2,583,504  | 984,192    |
| Differential and cellular unit state | 38% Positive (1) | 62% Negative (2) | 22% Positive (1) | 78% Negative (2) | 62% Positive (1) | 38% Negative (2) |

The annual energy production by PV systems has been calculated by adopting the methodology elaborated by Amado & Poggi (2012) [9]. Likewise energy consumption is strictly related to urban form but also to other variable factors such as constructive and geometrical aspects of buildings or user behavior, is quite complex to obtain an exact estimation [23,25]. To date, the study presents only the electricity consumption of residential buildings based on the statistical information which consider the annual electricity consumption per capita of 1,398 kWh/inhab and the resident population of each CU. It is important to refer as this statistical approach entails a considerable approximation and thus the ongoing targets will be focused on the integration of dynamic simulation for energy consumption analysis in order to reaching better results.

### 5. Results and Discussion

The scenarios in table 3 show the state of each cellular unit at time (t+1) simulating the solar energy implementation by means of PV system installation on building roof areas. In this case the façades don’t present the sufficient conditions for an efficient PV production and thus they haven’t been counted. Comparing the results of CU1, CU2 and CU3 it’s possible to realize that the urban morphology and housing typology of CU3 are the most efficient to reach the goal to develop and transform a city into an example of nearly zero energy city. However, the consumption needs to decrease and this depends by the build solutions and the typology and shape of roofs. The CU1 and CU2 present more necessities of electricity because of the huge number of population concentrated in the CU, a fact which permits to understand as tall buildings and high densities are a real problem in urban areas. Furthermore, the results of solar dynamic analysis suggest how the energy supply from the widespread installation of photovoltaic systems in the urban context can provide a sustainable contribution to energy demands but at the same time has to be supported by smart grids for its correct management and completed by other renewable resources towards the city energy balance.

### 6. Conclusions

In this paper, the GUUD model has been proposed in order to describe its structure and application in the field of solar energy integration in urban planning. Appealing to the cellular automata concepts, the GUUD permits the simulation of the state of each cellular unit and thus predict its energy performance in a coherent and synthetic way. Thanks to the use of a GIS platform, this cellular approach also allows to visualize how and where energy is used and where can be generated by photovoltaic panels installed on buildings roofs and façades. This framework aims to facilitate the implementation of smart grids that can connect and manage the cellular units relating their energy...
states with urban densities and mixed land-use parameters. Further research will reflect the GUUD capacity to simulate urban planning interventions on the cellular units and understand how to efficiently change their energetic state and improve the energy balance of the city.

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