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A toolkit for multi-scale mapping of the solar energy-generation potential of buildings in urban environments under uncertainty

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ABSTRACT

Many municipalities and public authorities have supported the creation of solar cadastres to map the solar energy-generation potential of existing buildings. Despite advancements in modelling solar potential, most of these tools provide simple evaluations based on benchmarks, neglecting the effect of uncertain environmental conditions and that of the spatial aggregation of multiple buildings. We argue that including such information in the evaluation process can lead to more robust planning decisions and a fairer allocation of public subsidies.

To this end, this paper presents a novel method to incorporate uncertainty in the evaluation of the solar electricity generation potential of existing buildings using a multi-scale approach. It also presents a technique to visualise the results through their integration in a 3D-mapping environment and the use of false-colour overlays at different scales.

Using multiple simulation scenarios, the method is able to provide information about confidence intervals of summary statistics of production due to variation in two typical uncertain factors: vegetation and weather. The uncertainty in production introduced by these factors is taken into account through pairwise comparisons of nominal values of indicators, calculating a comprehensive ranking of the energy potential of different spatial locations and a corresponding solar score. The analysis is run at different scales, using space- and time-aggregated results, to provide results relevant to decision-makers.

1. Introduction

The installation of photovoltaic (PV) systems in urban contexts is increasingly viable from both practical and commercial viewpoints. The simplest evaluation of the economic or environmental viability of a project is to examine the lifetime costs of installation, maintenance, and disposal versus the value of electricity produced. Given the multiplicity of potential sites in a city or on an estate, planners and large land owners are often tasked with prioritising the allocation of resources to sites based on their technical and commercial viability.

This paper presents approaches to making these decisions using simulations under uncertain environmental conditions. We have developed a method for comparing the potential of different urban sites to generate energy using photovoltaic systems. The method, embedded in a 3D mapping tool, provides an uncertainty-aware ranking of candidate locations for a multi-stage and multi-scale urban planning processes.

1.1. The problem

Simulating the behaviour of a physical system involves the consideration of fixed and random inputs, both of which might be known only with partial confidence. For any weather-dependent system, like buildings or solar power installations, the future weather is an uncertain boundary condition. The evaluation of solar installations in urban areas must also take into account the presence of obstructions, which are chiefly caused by urban vegetation and surrounding buildings or infrastructure. However, in the case of vegetation, the specific transparency and seasonal change of each tree are difficult to predict and are, therefore, also a source of uncertainty.

In order to provide robust planning decisions, we consider these uncertain factors in evaluating the suitability of different urban locations (hereinafter, plots) for photovoltaic installations. In a deterministic study, i.e., one in which all inputs are fixed to some nominal values, comparing and ranking different plots is straightforward. One

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could, for example, sort the plots by annual sum of production. However, the introduction of uncertain inputs complicates the comparison of options because different plots and systems respond differently to changes in those inputs. This creates an issue for planners and decision-makers, who have to make a definite decision but who cannot get a definite answer from a simulation study.

1.2. State of the art

The increasing availability of detailed geodata sets and improvements in computational models have made the assessment and visualization of solar potential at the urban scale a popular tool for planners. An extensive literature review can be found in Freitas et al. (2015). Recent implementations have extended the analysis to vertical surfaces (Catita et al., 2014; Bremer et al., 2016; Brito et al., 2017), but the evaluation is still commonly done in 2(.5) D, i.e., targeting only roof surfaces. These evaluations do not consider the varying effects of vegetation and weather on the evaluated surfaces.

Current methods are usually limited to the assessment of an installation itself, neglecting the subsequent use of the results of the assessment in the decision-making process. In fact, it is in this phase that uncertainty in the outputs could play an important role and should, therefore, be considered by risk-aware and risk-averse decision-makers. In this section, we review decision-making methods for assessing solar potential and their limits. We also investigate other methods that can be applied to this scope.

1.2.1. Decision-making for solar potential assessment

Solar cadastres (or solar maps) are tools to provide decision-makers with information about the suitability of a given surface for the installation of solar power systems (photovoltaic or thermal). They are usually conceived as web-based mapping tools in which the solar potential is displayed as false-colours overlays on 2D maps or orthophotos of an urban area. Dean et al. (2009) and Kanters et al. (2014) provide an extensive review of solar cadastres in Europe and United States. Although methods considering weather risk have been integrated in PV-array performance evaluation software (Dobos et al., 2012), to the best of our knowledge, evaluations included in solar cadastres are conducted using weather data from typical meteorological years (TMY), whose limitations have been described by Vignola et al. (2012).

As shown by Kanters et al. (2014), the suitability assessment of solar cadastres is generally based on minimum irradiation thresholds. In some cases, the choice of these thresholds is justified by financial assessments to guarantee the payback time of the installation (Nault et al., 2015; Jakubiec and Reinhart, 2013; Berlin et al., 2013). Surfaces are often classified with different levels of suitability depending on their solar irradiation, such as ‘reasonable’, ‘good’, ‘very good’ (Kanters et al., 2014).

Previous work (Nault et al., 2015; Peronato et al., 2015; Peronato et al., 2016a; Peronato et al., 2017a) has highlighted that error, risk, and uncertainty vary depending on the selected threshold. However, solar cadastres generally have a deterministic approach, which neglects the uncertainty of the result and the concomitant risk in the decision. Thresholds are also sensitive to the geometric regularity of the arrangement of solar modules (Peronato et al., 2015), an aspect that is also neglected in solar assessment tools.

In addition to thresholds, another method to provide information about solar potential is to attribute to each building a solar score. The solar score is usually calculated by reference to a best-case installation, as in the Mapdwell solar maps (Berlin et al., 2013), or by normalising the data to the best and worst values in a given location, as in the SunNumber website (Miller and Herrmann, 2016). This method facilitates comparisons between locations with non-homogeneous climate conditions as the score is relative to the specific conditions, allowing cross-country comparisons. However, the score still disregards other factors of uncertainty in the calculation which affect each building differently, such as vegetation modelling.

Solar cadastres focus on the potential of individual buildings, and in some cases differentiate the potential among the surfaces constituting the building envelope, while neglecting the aggregated potential of urban blocks or entire urban areas. They are targeted towards building owners, and often have an educational goal (Dean et al., 2009). They are sometimes used as back-end planning tools by municipalities, though mostly limited to the evaluation of their own real estate properties (Kanters et al., 2014).

Energy-planning tools focus more explicitly on a wider range of stakeholders, particularly utility companies and municipalities. In this sense, Ouhajjou et al. (2014, 2015, 2016) proposed an ontology-based urban energy planning providing a classification of the PV-suitability of buildings from each stakeholder’s perspective. However, this method then focuses on negotiation and consensus between the different stakeholders rather than the robustness of the single decision.

1.2.2. Ranking methods

In spatial planning, multi-criteria methods are used to define priorities among different locations, i.e., ranking options by priority of intervention. Recent sample applications include the definition of best locations for treated waste-water in-stream use (Kim et al., 2013). Ranking is a typical problem in multi-criteria decision-making, along with choice and sorting (Schärlig, 1985, Ch. 4c). The distinction between choice and ranking is not always clear, as ranking procedures can be adopted in decision problems that are more choice-like to give more options to the decision-maker (Schärlig, 1996, Ch. 10). Sorting can also be applied to ranked solutions by subsequent attribution to different categories. In this sense, ranking provides the simplest way to approach a decision problem, while allowing the decision-makers to introduce further choice- and/or sorting-based decisions.

Pairwise comparisons are often used in decision problems, as they are an effective method to subdivide a complex decision problem into binary preference questions. This is especially necessary when the criteria by which the alternatives are ranked or chosen are subjective and hence prone to inconsistency. The Analytical Hierarchical Process (AHP) (Saaty, 1980) and the outranking methods of the Electre (Roy and Vincke, 1984) and Prométhée (Brans, 1982) families make use of pairwise comparisons for decision problems involving both tangible and intangible (e.g., qualitative) criteria. Pairwise comparisons are also used when a preference model can only be applied to pairs of items at a time. This is the case, for example, in sport tournaments: only two teams can play each other at once, so a pool of n teams will require $(n^2-n)/2$ matches (or n^2-n matches if home- and away-games are considered) to obtain a final ranking of the teams.

Condorcet methods are some of the most popular pairwise ranking methods, with applications in both sport tournaments and elections. These methods calculate the score of each player/candidate as the number of victories by pairwise comparisons. The players are ranked based on the final score of each player, and ranking may include ties. An extension of the Condorcet method, the Copeland method (Pomerol and Barba-Romero, 2012, p. 122), also counts the defeats. It can be seen as a special case of the Borda count method (Shah et al., 2015), another popular method used in both elections and sports, which generally requires multiple matches between the same pair of opponents (or a ballot asking voters to rank the different candidates) to establish the final ranking. The Copeland method provides simple, robust and optimal ranking from pairwise comparisons (Shah et al., 2015). It is often criticised because it counts only the quantity of victories and defeats and ignores their magnitude. This limitation can be overcome by accepting fuzzy outcomes and introducing fractional scores, instead of the conventional boolean/crisp comparisons between alternatives, e.g., Naderi et al. (2012).