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Towards a digital workflow to assess visual impact of solar modules and their operation within energy-hubs

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Abstract. This study proposes an integrated methodology to assess the BIPV potential of existing urban neighborhoods, including social acceptance and grid infrastructure management issues; as a demonstration, a case study in Geneva, Switzerland is considered. In particular, the annual solar radiation on the outdoor exposed areas is calculated on an hourly basis and converted into electricity by considering standard monocrystalline PV modules. Social acceptability is evaluated on a discrete qualitative scale, based on the average visibility of the building envelope from the public space and assessed through a psychophysically reliable indicator. Three different envelope surface coverage ratios are assumed for BIPV, i.e. for low, medium and high visibility respectively. Renewable electricity generation is used to match the hourly electricity demand for lighting, appliances as well as an air-to-air heat pump that covers heating and cooling needs. Excess electricity is used within multi energy hubs featuring PV panels, a battery bank and an internal combustion generator; as a last resort, electricity is injected to the grid. As such, the levelized cost of energy and the grid integration level can be calculated at each time step. The financial outcome of the analysis may be used to explore novel business models for solar energy renovations in urban contexts.

1. Introduction

International organizations are fostering the renewable energy targets to meet more ambitious climate change mitigation goals. Beyond larger renewable production shares, the "Clean Energy for all-Europeans" legislative package aims at enhancing the role of citizens as "active consumers" [1] - [Art. 15], and "Renewables Self-Consumers" [2] - [Art. 21]. These concepts imply a more active engagement of local communities and contribute to make climate changes a social priority: citizens have the right to produce their own energy. Circa 83% of EU's households could potentially become "energy prosumers" by contributing to renewable energy production, demand response and energy storage: they may generate 45% of EU's electricity needs by 2050 [3].

In Switzerland, the Energy Strategy 2050 and the Energy Act [4] - [Art. 17] are encouraging communities to enter the energy market by interacting with the grid via a unique energy meter. Some interesting experiences of "solar" purchasing cooperatives have been attempted in this sense, allowing for a solar thermal cost reduction of up to 50% and for PV cost reduction of 15-20% [5].

Such a shift to decentralized renewable energy systems involves new technical and economic challenges. The grid is likely to be more solicited through a multiplication of interactions for energy buying and selling, leading potentially to power outages. Electric vehicles, smart e-boilers and batteries

could provide the necessary grid flexibility, complemented by a digital management system that distributes energy flows and their related financial transactions efficiently. This democratization of energy into a sort of "peer-to-peer" network requires new ways to account for renewed communities needs within a changing infrastructure. It is however essential to forecast social acceptability of decentralized renewable energy systems (DRES) and their components (i.e. Building Integrated Photovoltaic modules), while ensuring the necessary grid autonomy to keep a viable balance between energy intake and outtake.

This paper focuses on the complex integration of these systems into existing social and technical infrastructures. Visual impact is investigated as a driver for social acceptability and coupled with different solar coverage ratios affecting grid autonomy in order to find the optimal solution.

2. Methodology

This study is part of a strategy that aims at gathering different tools for the optimal design of BIPV modules. Research studies have been recently conducted in order to combine urban energy modeling with a local microclimate, by applying building energy simulations and adapting climatic data to the district scale [6].

The objective of this article is to assess more comprehensively the BIPV solar electricity production and optimize its use through an energy hub that combines different electricity production means a function of the hourly building energy demand, the PV energy supply, the grid electricity balance and the cost fluctuations [7]. A novelty of this approach is the use of an indicator to quantify the social acceptance of DRES within the current workflow thus refining the solar PV potential calculation (Figure 1). Such indicator focuses on an important aspect of social acceptance, which is the visibility of BIPV systems from the public space [8]. Visual impact is explicitly associated to social acceptability [9], especially in landscape or archaeological sites representing specific high sensitivity zones.
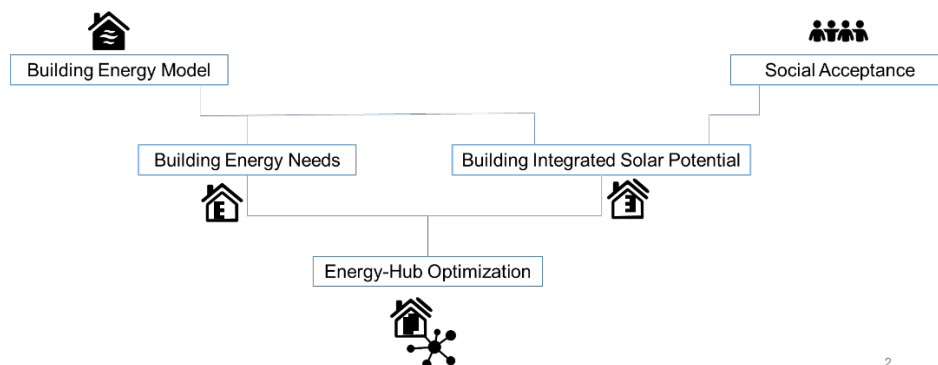

Figure 1. Proposed workflow for a comprehensive BIPV assessment, including a novel "social acceptance" indicator.

Overall, the visual impact of solar systems on building envelopes is assessed as a first step, and then categorized into three classes, i.e. a high, medium or low visibility. In a second stage, the BIPV coverage ratios of the envelope surfaces are tuned according to the visibility category. The last phase consists in the optimal design of an energy hub, which dynamically adjusts the supply energy mix to minimize its cost as well as its impact on the infrastructure.

The visibility of building envelopes from possible pedestrian positions in the public space constitutes the "visual impact", which is used in this article. A visual impact analysis is performed by projecting so-called 'visibility rays' from the pedestrian viewpoints to the mesh facets in which all buildings envelope surfaces are decomposed [10]. Any single mesh facet is visible, i.e. not obstructed by a physical obstacle, from a subset of viewpoints. The average view of any single mesh facet from all observer's viewpoints in the unobstructed subset constitutes the visual stimulus. It is quantified as a solid angle in a spherical field of view, then divided by the smallest perceptible stimulus for a human eye (i.e. the

threshold), equivalent to one square minute of arc for high luminance contrast conditions [11]. This ratio, called 'visual amplitude', represents a psychophysically reliable visibility index, which can be classified in three categories (i.e. high, medium and low visibility), based on the minimal visual acuity required for a standard observer to notice a single mesh facet [12, p. 120].

Energy demand of buildings and BIPV electricity production are determined on an hourly time step using the CitySim software [13]. All buildings are located in the "La Jonction" district located in Geneva; all the physical data relating to the site are retrieved from [14]. The site hosts circa 300 residential buildings, including an Eco-district of 312 apartments. In order to assess the solar potential of the site, the building geometry was complemented by including the roofs heights and orientations.

Three different envelope surface coverage ratios are assumed for BIPV, i.e. 70% for low visibility, 45% for medium visibility, and 20% for high visibility respectively. Standard PV modules featuring 143 W-peak/m^2 as peak power are combined with the location specific hourly solar radiation issued from a Test Reference Year (TRY). PV solar modules constitute the main electricity source on the supply side of multiple energy hubs located in the district; alternatively, electricity is issued from a battery bank acting as a renewable energy storage, from an internal combustion generator and, as a last resort, from the grid. On the demand side of the energy hubs, artificial lighting and electric appliances are responsible for the electricity demand; in addition, the heating and cooling loads of buildings are covered by air-to-air heat pumps featuring a 2.8 nominal Coefficient of Performance (COP). The Energy Management System driving in the energy-hub determines the cheapest energy mix by matching the hourly PV supply with the building demand. A Pareto optimization method is carried-out considering the life cycle cost and system autonomy level.

The visual impact assessment method has been tested first on different building block typologies [15], commonly used in environmental research [16]: the typological set is composed of six archetypes. As first, they are converted into three-dimensional building vector models in order to perform visual impact assessments from different viewpoints located on sidewalks along their perimeter. For an effective comparison in conditions of even visual prominence for roofs, all footprints are raised 4 m above ground, thus having the same elevation. A different roof type is associated with each archetype in order to create a range of possible urban configurations (Figure 3).
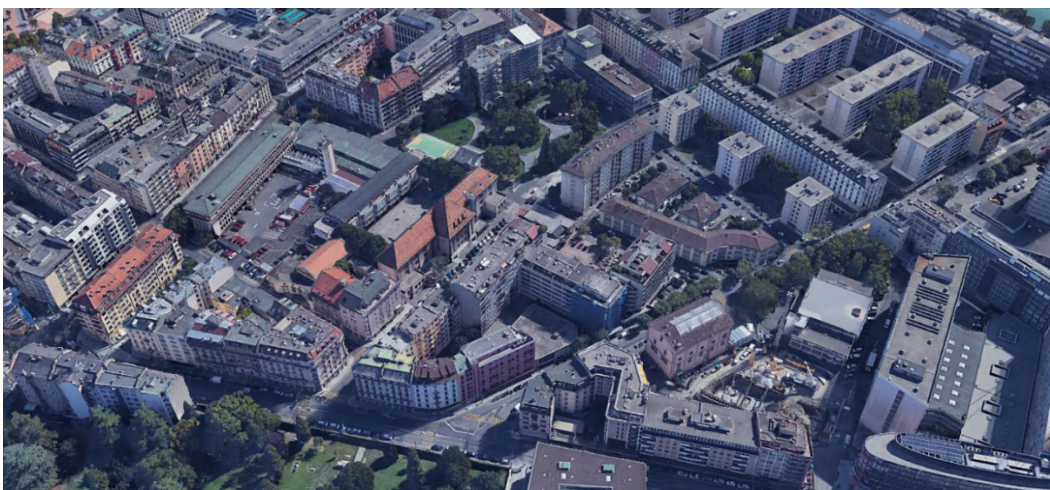

Figure 2. The neighborhood in the Jonction district, Geneva, Switzerland. Image from Google Earth ©

After assessing the visual impact on the typological set, the entire workflow was implemented on a real district in the city of Geneva, Switzerland. The district is situated in the neighborhood of "La Jonction" (Figure 2): it has been chosen due to the heterogeneity of building typologies as well as construction year ranges. Other interesting features are the multiple roof types and the complexity of the public space, which includes large roads, small streets, sidewalks, gardens, sport areas and parking areas.

The 3D vector model of the district was retrieved from online open data issued from the Service d'Information du Territoire de Genève (SITG). The city vegetation has been reconstructed from LiDAR points through an alpha-shape algorithm [17] and included in the model with a canopy permeability to 'visibility rays' of 50% for the visual impact assessment; trees have been neglected as for solar radiation analysis. Building envelope surfaces have been decomposed in rectangular mesh facets of 1.5 m x 1.5 m, corresponding to a pair of solar modules. Viewpoints have been sampled on the medial axis of pedestrian areas, such as sidewalks and pathways, with 2 m spacing and an elevation of 1.5 m above ground.

3. Results

The visual impact analysis of building archetypes is illustrated in Figure 3. The configurations corresponding to gabled and cross-hip roofs are the most visible, while flat and shed roofs are the least one. These outcomes cannot be extrapolated to other settings, because of the high variability in viewpoints sampling as well as possible building layouts. Nevertheless, they can be used as reference for comparisons with the real district.

Figure 4 shows the outcome of the visual impact analysis carried out in terms of visibility categories for the district in Geneva. Almost all façades are categorized by high visibility, as one would expect; flat roofs show a low visibility, except for some vertical surfaces belonging to on-top add-on and structures. Pitched roofs can be assigned to different categories: most sloped roof pitches, as well as those facing a garden or a large public space, are more likely to be highly visible. Depending on slope in combination with building height and road width, pitched roofs may be more or less visible, depending from the surrounding visual obstructions, such as trees and/or other buildings.

The integration of PV solar modules on building envelopes allows to generate 3.6 GWh of renewable electricity, which partially covers the annual electricity needs for lighting, appliance and heating/ cooling by heat pumps. As a result, the DRES can reach a fully autonomous operation without any external energy supply. However, the main challenge is matching the electricity demand and generation. Solar PV electricity is mostly produced during the summer period when the energy demand for heating is nil. In contrast, the energy generation during wintertime is useful when the heating demand is significant. As a result, the grid and the battery storage of the energy hub play a vital role when managing the mismatch between the demand and the generation. However, the battery bank is currently not cost competitive with the electric grid, its net present value increasing notably for the higher autonomy levels as illustrated by Figure 5: it overshoots when one minimizes the grid interactions below 25MWh.
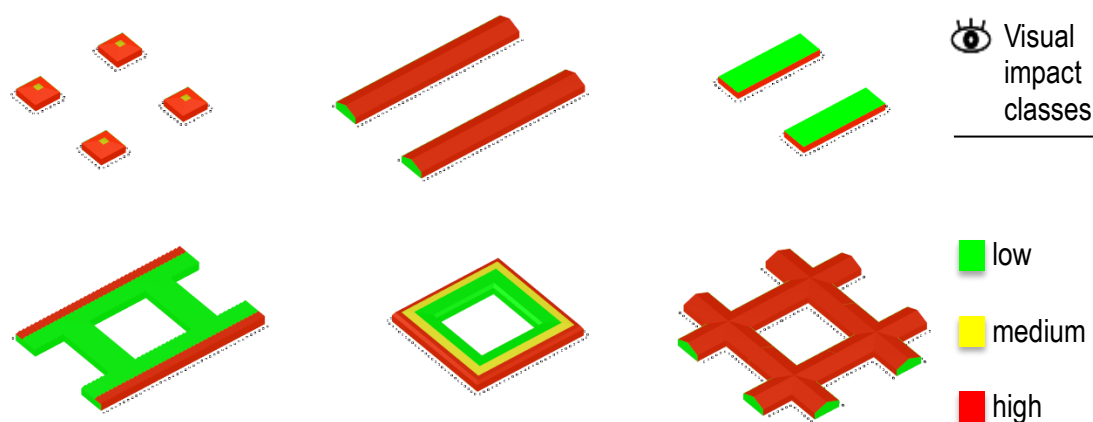

Figure 3. Visibility categories for the selected building archetypes. From left to right and top to bottom: pavilions with hipped roof, slabs with gabled roof, terraces with flat roof, terrace-courts with shed roof, pavilion-courts with mansard roof and courts with cross-hipped roof.
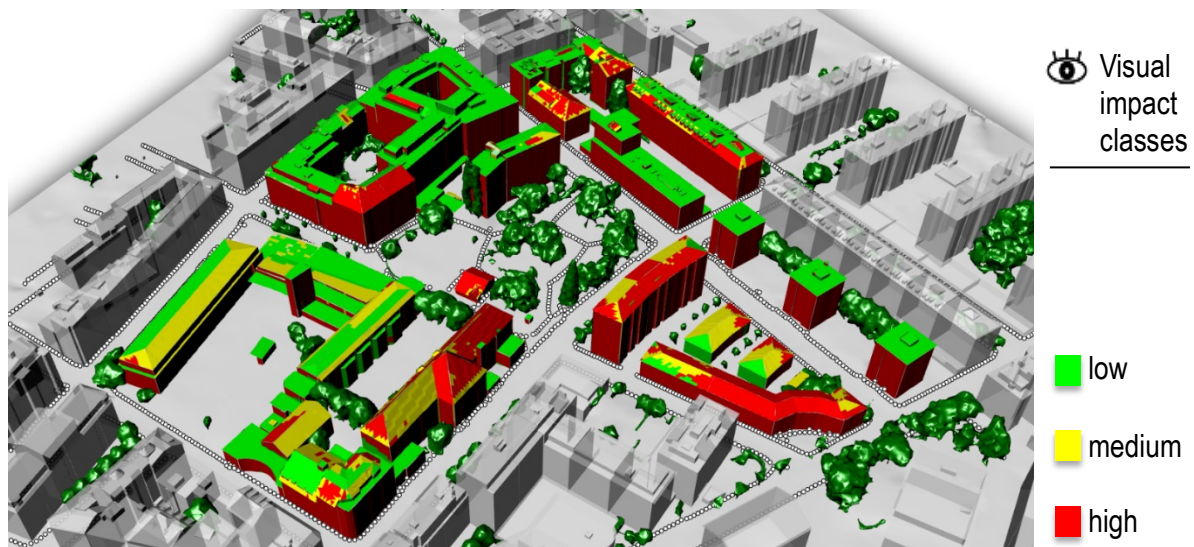
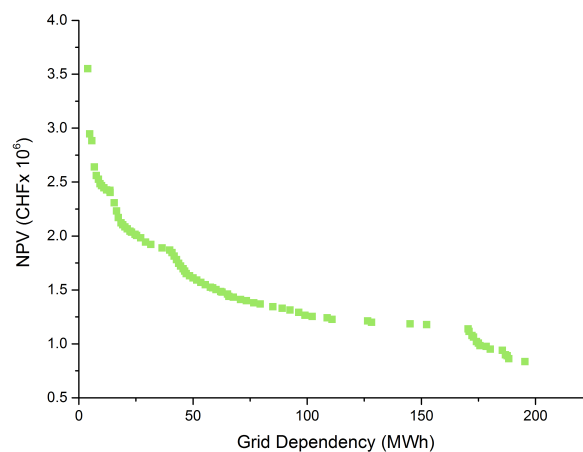**Figure 4**. Visibility categories for the selected neighborhood.

Figure 5. Pareto front showing the minimization alternatives for the actualized investment and operation cost in Swiss Francs (CHF) according to the Grid Dependency level.

4. Discussion and conclusion

The results presented hereby demonstrate that the considered 'Junction district' can be an energy autonomous urban site without impacting significantly on the visual perception of pedestrians.

The proposed methodology may be useful to estimate the viability of a large scale refurbishment of an existing neighborhood involving BIPV fostering Distributed Renewable Energy Systems. Overall, an entire neighborhood was analyzed providing information about the electricity load match with the solar electricity generation, the social acceptability and the technical feasibility of a solar PV installation by means of appropriate indicators. At the current stage, a few minutes were necessary to perform this visual impact analysis on a standard desktop PC (3.4 GHz CPU frequency, 16 GB of RAM) and half an hour for the DRES optimization: as such, the workflow can be easily replicable to the scale of a city.

The presence of trees being currently neglected in the building energy model, a further development will include the impact of the vegetation on the urban microclimate, on the thermal comfort of pedestrians, as well as on the energy demand of buildings and the solar potential of the urban site. However, the current methodology is promising for a more comprehensive solar energy planning as well as transdisciplinary issues, which could support decisions for stakeholders regarding urban energy hubs.

5. Acknowledgements

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