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Graphical Abstract

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Highlights

Large-scale evaluation of the suitability of buildings for photovoltaic integration: Case study in Greater Geneva

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- Large-scale evaluation of the suitability of buildings to be equipped with photovoltaic systems (PV suitability)
- Simple labeling of PV suitability: A (very high), B (high), C (moderate)
- Multidisciplinary and multicriteria approaches considering social, economic, energetic, environmental, and technical criteria
- A cross-border territory (data from two countries, three administrative regions, 270 000 buildings)
- Decision support for massive urban deployment of PV systems

Large-scale evaluation of the suitability of buildings for photovoltaic integration: Case study in Greater Geneva

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Abstract

In the context of a rapid and massive deployment or renewable energy and in particular solar photovoltaic, it is necessary to develop methods and tools to guide this deployment. To this end, this work proposes a multicriteria approach for evaluating the suitability of a building to be equipped with photovoltaic (PV) systems (PV suitability). In the present case, technical (roof complexity), economic (payback period), environmental (CO_2 reduction), energetic (self-consumption), as well as social (heritage constraint) criteria are considered. These criteria are evaluated for each building of the Greater Geneva Agglomeration (GGA), a cross-border French-Swiss territory of nearly 270 000 buildings. A multicriteria method, ELECTRE TRI, makes it possible to sort these buildings into three categories, A, B, and C, that correspond to "very high," "high," and "moderate" PV suitabilities, respectively. Large differences are observed within the 210 municipalities of the GGA since some of them have almost no A-ranked buildings whereas others comprise more than 70% of these buildings. It is shown that, by prioritizing the A-ranked buildings, almost 50% of the annual electricity consumption of the Geneva Canton could be produced by PV systems. Finally, the method developed here offers a decision-aiding tool that could be used at a territory scale to achieve energy transition goals in terms of solar PV deployment.

Keywords: Multicriteria decision aiding, GIS, ELECTRE TRI, Photovoltaic, PV suitability, Urban solar, Energy planning

1. Introduction

Since the beginning of the 21st century, increasing concerns regarding the consequences of climate change have led to a reconsideration of the generation and the consumption of energy as well as the management of local resources. Based on the Paris Agreements adopted in 2015, most nations around the world made commitments to reduce their greenhouse gas (GHG) emissions. These set goals can only be met with the decrease in overall energy consumption and the substitution of carbon-emitting fossil energy by the production of renewable sources such as solar, wind, hydroelectric, and geothermal energy. Among the numerous sources of renewable energy, solar energy, which includes different technologies such as solar thermal, concentrated solar power, or photovoltaic (PV) panels, is particularly interesting because of its abundance and availability.

Urban environments offer an opportunity to deploy solar energy thanks to the presence of many unexploited surfaces that can be used, among other usage, to install PV systems [1]. In order to efficiently and massively deploy solar energy in urban environments, it is necessary to provide relevant information about PV potential – energy that would be produced by a PV system if it were installed on a surface element (roofs or facades)- at a large scale (city, territory, country) for all the decision-makers of the urban environment [2, 3, 4, 5].

To this end, tools and methods have been developed to estimate the PV potential at large scale in the urban environment. Most of these tools provide information as a geographical information system (GIS), and Gassar and Cha [6] reviewed the different GIS-based approaches and classified them into four classes: the sampling methods (see, e.g., [7]), the geostatistical approaches, the modeling approaches (see, e.g., [8]), or the machine-learning approaches (see, e.g., [9]). Most of these approaches focus on predicting or estimating the available space for PV integration as well as the expected PV energy production. This information is essential before assessing the suitability of a roof to be equipped with a PV system (PV suitability or PV feasibility). However, the PV suitability of a roof is complex and involves numerous parameters (economic, technical, social, etc.) that can play a determining role. In other words, the best roofs for PV systems are not necessarily those with the highest PV potential. It consequently appears that the answer to whether a roof is suitable for the installation of PV systems must consider several criteria and requires nuancing [10, 11, 12, 13, 14].

In the literature, there are several studies aimed at evaluating decision criteria for PV integration at different spatial scales. At the system and building scale Azzopardi et al. [15] used the ELECTRE III methodology in order to rank different PV systems for buildings considering qualitative, economic, environmental, and energetic criteria. Thebault et al. [16] used the same method to rank buildings in terms of their PV suitability. In this case they considered up to 11 decision criteria for a dozen of buildings. Kosorić et al. [11] put forward a methodological framework considering the different phases of the installation process and the inherent decision criteria. They apply their method to a high-rise building in Singapore and proposed an optimal integration scenario. At the district scale, Florio et al. [14] combined visual impact, building energy consumption, as well as power-grid constraints in order to propose an optimal deployment of PV systems. In a recent work, [12] developed a multicriteria sorting procedure to assess the PV suitability of a district in Geneva. These previous works were carried out at the district scale. However, in order to massively deploy solar energy, these approaches need to be developed at a larger spatial scale.

As the spatial scale increases, it becomes more difficult to consider a wide range of criteria. This is in part due to the availability of the data (e.g., Has the information been evaluated? Is it possible to evaluate it at such a scale?), the heterogeneity of the data (difference in the formats and evaluation methods within the study area), and data privacy (open-access, private, restricted) [5]. At the city scale, [17] considered the capacity of the power distribution grid to propose a strategy for the spatial deployment of PV energy with reduced costs. [18] assessed the visibility of roofs from the street in order to identify the section of the roof on which the installation of PV systems would have the least esthetic impact. Lee et al. [19] adopted a clustering approach to evaluate the PV suitability of buildings based on technical and economic criteria. However, these approaches consider one or two criteria, whereas it is clear that there is a need for a multicriteria evaluation of the PV suitability of roofs.

When several alternatives (here buildings that could be equipped with PV systems) are involved, it is necessary to provide clear information to decision-makers. For this, it is possible to implement a sorting procedure. Sorting consists in the assignation of the alternatives to predefined classes. When classes have no ordinal ranking, it is called "classification" whereas the term "sorting" is used when classes have an ordinal ranking (from the best to the worst class) [20]. The use of a sorting procedure coupled with

GIS is very common for solar maps ([21, 8, 19]). Nevertheless, these sortings are most often based on a single criterion, the PV potential.

This study is the continuity of work we proposed in [12], which consisted in developing a sorting procedure for the PV suitability of roofs. However, this previous work was carried out at a district scale (nearly 100 buildings). In the present work, the methodology is adapted and applied to a much larger scale (270 000 buildings). The present work therefore proposes a GIS-based sorting of the PV suitability of the roofs of a large urban area. To this end, different criteria related to the installation of PV systems are identified. The method is applied in the Greater Geneva Agglomeration (GGA), a cross-border territory of 2000 km^2. These criteria are evaluated using available data and GIS processing. To proceed with the multicriteria sorting, the ELECTRE TRI methodology is used. The methodology allows us to sort all the buildings of the GGA into three classes: A (very high PV suitability, to be prioritized), B (high PV suitability), and C (moderate PV suitability, to be confirmed).

The main contributions of the present paper are:

- Develop simple information labeling in order to rank the PV feasibility of buildings based of multicriteria decision-aiding methods.
- Demonstrate the feasibility of this approach for large urban scales with the use of GIS processing and the available layer of data.
- Apply this approach to a large spatial area (here the Greater Geneva Agglomeration) and highlight the heterogeneity, in terms of PV suitability, between the municipalities of a territory.
- Propose a tool for urban planners and local authorities to develop roadmaps and strategies to achieve the massive deployment of solar energy at large spatial scale.

2. Methodology

The aim of this work is to develop a sorting procedure that can be applied at large scale. For this, we use a methodology that combines multicriteria sorting (ELECTRI TRI methodology), GIS processing associated with various models (economic, physical, etc.), as well as expert knowledge. The overall methodology is presented as a workflow in Fig. 1, and explained in

detail in the following sections. The method is then applied to a case study (the GGA) for which most of the data are available through an online platform [22].

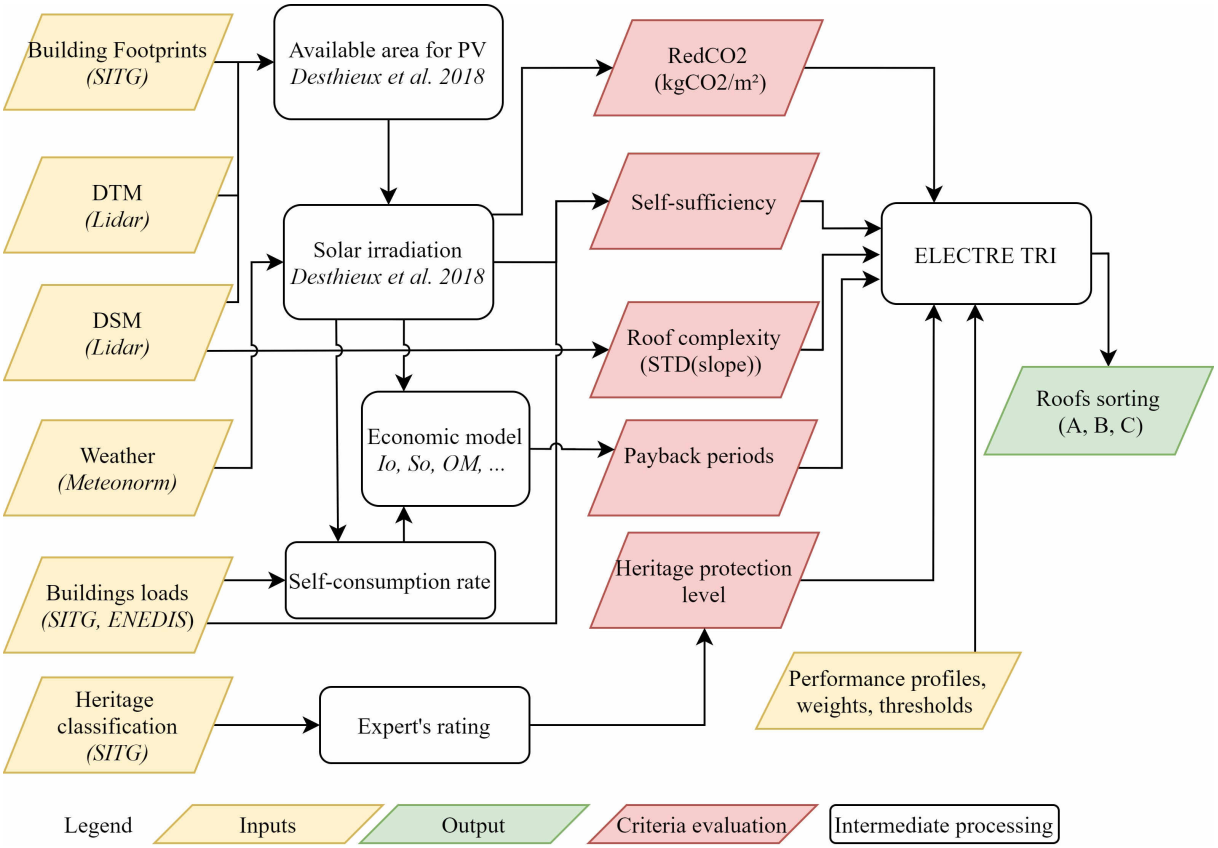

Figure 1: Workflow for the multicriteria sorting of the buildings of Greater Geneva

2.1. ELECTRE TRI

The ELECTRE TRI method was chosen as it has proven to be well adapted to site selection for PV systems [12, 23]. This method allows one to sort a large number of alternatives into a limited number of ordinarily ranked classes. Furthermore, it relies on fuzzy logic, which makes it possible to account for uncertainties and preferences of the decision-makers. This is particularly relevant for urban energy planning [24] in which technological solutions are in close relationship with human reasoning and well-being. The

basic aim of the ELECTRE TRI approaches is to assign a set of alternatives to predefined classes (also called categories or groups) [25, 26]. The assignation is made after alternatives are compared with the boundaries of the classes. The comparison is made using pairwise relation comparison using the concept of outranking. The detailed methodology is presented in Appendix B.

2.2. Description of the study area - Greater Geneva

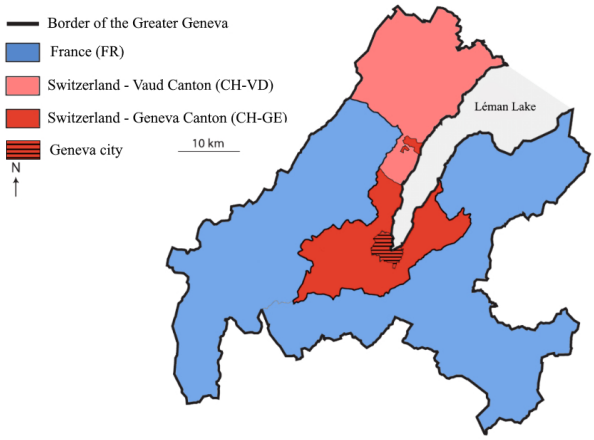

Figure 2: Illustration of the GGA. The blue area corresponds to the French (FR) part whereas the red areas are Swiss. The Swiss part is divided into two administrative parts, the light red area corresponds to the canton of Vaud (CH-VD) (a canton is the Swiss equivalent of a region) whereas the dark red area corresponds to the canton of Geneva (CH-GE). The city of Geneva itself (Lat. 46.207, Long. 6.142) corresponds to the striped part in the canton of Geneva

In this work, a case study is presented for the GGA. The GGA is a French–Swiss cross-border territory of 2000 km^2 and nearly 1 million inhabitants. The Swiss section is divided into two parts, one belonging to the Canton of Vaud (CH-VD) (a Canton being similar to a state in the federal system of Switzerland) the other to the Canton of Geneva (CH-GE). This distinction is important as these two cantons have different administrative systems, which results in different socioeconomic situations. Moreover, there is some heterogeneity in the quality of the data between these two parts of Switzerland despite the fact that they belong to the same country. More generally, the GGA can be seen as a territory composed of three administrative

regions, one French and two Swiss, with each of these regions having its own specificity in terms of data availability and legislation.

This work is carried in the context of a European INTERREG French–Swiss project called G2Solaire. This project brings together academics, experts, industry professionals, as well as associations and municipalities or their representatives, all of them being actors in the deployment of solar energy systems in the territory.

In total, the GGA consists of nearly 270 000 buildings, each of them being an alternative in the present case. The French part has 150 000 buildings while the Swiss part has the remaining 120 000 (80 000 for the Canton of Geneva, and 40 000 for the Canton of Vaud). For each of these buildings, we will use the data that are available in the various open-access databases or provided by partners of the project.

2.3. Definition and description of the criteria

For the present analysis, several influential criteria have been considered. These criteria were selected based on the literature as well as on discussions with different experts involved in the project. Five criteria were retained for the present study:

- self-sufficiency [27],
- economic benefit [28],
- environmental benefit [29],
- roof complexity [8, 30],
- heritage and esthetic qualities of buildings [18, 14].

These criteria and their definitions are presented in the following sections. The criteria are also non-redundant and the preferential independence is respected.

One notes that the PV potential (the amount of energy that a PV panel would produced if placed on a specific section of the roof) does not appear in the considered criteria. Indeed, the PV potential itself is barely used to make a decision. However, this information is crucial since it allows us to evaluate decision criteria such as the economic and environmental benefits as well as the self-sufficiency rate.

2.3.1. Evaluation of the PV potential

The evaluation of the PV potential relies on the 3D-GIS-based irradiation model, which has been developed at HEPIA [8]. The information is provided through a solar cadastre that covers the entire GGA area. This calculation takes into account the orientation and the slope of the roof, the local meteorological data, the distant shade (mountains, relief), and the near shade (shade from surrounding buildings or trees) and has been recently extended to the entire GGA [31]. Solar radiation on roofs is calculated at hourly resolution, for the whole GGA. More details on the calculation of the solar radiation on the roof are provided in Appendix A.

Due to the complexity of the urban environment (shade, reflections, etc.), roofs are often partly shaded. For this reason the optimal area for the integration of PV systems is often smaller than the entire roof.

In the present case, the optimal area for PV integration (A_{PV} in m^2) was defined as the area of the roof (location and size) that would provide the lowest economic payback periods (PP) if PV panels were placed on it. The PP corresponds to the number of years required to refund the initial investments, including local subsidies as well as operating and maintenance costs. The detailed calculation for the PP is described in section 2.3.3. In what follows, for each of the roofs of the GGA, calculations involving the solar potential were all conducted based on A_{PV} and a conversion efficiency of the PV system of 18%.

2.3.2. Criterion 1 (C1): Self-sufficiency

One of the main goals related to the use of solar energy is to increase the share of PV electricity production in the energy mix. One way to do so is to consume a part of the production locally [32]. This is referred to as self-consumption, and is particularly suitable in urban contexts where each building can produce and consume energy.

Self-consumption can have several co-benefits: It can limit the ramp rates and the reverse power flows and can increase economic benefits [13]. Finally, self-consumption allows each user to consume local and renewable energy fostering the feeling that they are directly contributing to the energy transition [32].

Two metrics of self-consumption are usually defined: the rate of self-consumption, τ_{sc}, and the rate of self-sufficiency τ_{ss}. The self-consumption rate τ_{sc} is defined as the share of the total PV production that is consumed by the building. The self-sufficiency rate τ_{ss} is defined as the share of the

total building energy demand that is being supplied by the PV systems *i.e.*:

$$\tau_{ss} = \int_y \frac{min(P(t), L(t))}{L(t)} dt \tag{1}$$

where P (kW) and L (kW) correspond, respectively, to the electrical power production and the electrical power consumption (load) of the building, y being the considered the time period, in this case a year.

In the present case, the self-sufficiency rate will be considered. Indeed, this indicator provides information on how much the installed PV panels could reduce the energy consumption of a building and therefore the energy stress that the building is creating on the power grid. Details on how L is evaluated based on the electrical energy consumption of the GGA buildings are presented in Appendix C.

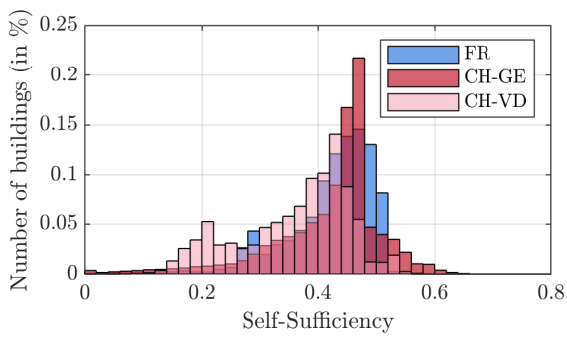

Figure 3: Histogram of the self-sufficiency rate of the buildings in the three administrative region of the GGA. Blue - French region (FR) ; dark red - canton of Geneva (CH-GE); light pink - canton of Vaud (CH-VD)

The self-sufficiency rates for the buildings of the GGA are plotted in Fig. 3.

2.3.3. Criterion 2 (C2): Economic benefit

Different economic indicators can be used in relation to photovoltaic energy [28]. Choosing one of these indicators is not necessarily an easy task as they can provide very different indications.

One of the most widely used indicators is the payback period (PP). The PP corresponds to the number of years required to refund the initial investments, including subsidies as well as operating and maintenance costs. There are two main ways to calculate the PP: simple payback calculated without

considering a discount rate, and discounted payback, which accounts for this [28]. Here, discounted payback is considered as it is better for taking into consideration the future money loss due to interest rates.

In order not to lose the thrust of the article, details about the pricing schemes used for the calculation of the PP (investment, discount rate, subsidies etc.) are detailed in Appendix D.

The distribution of the PP for each building of the GGA is plotted in Fig.4. It is very interesting to observe the differences in the distributions. These differences are due to the investment price, which is higher in Switzerland than in France (see Fig. D.17), as well as to the subsidies and pricing scheme, which are different for each of the administrative regions (see Table D.7).

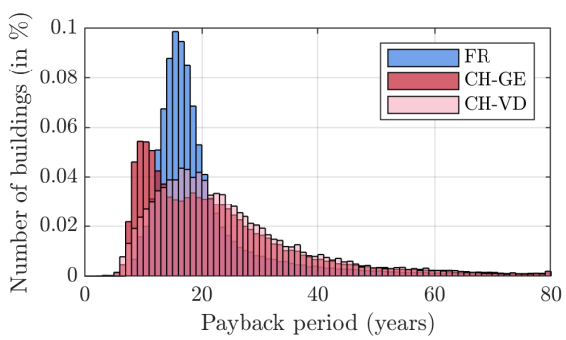

Figure 4: Histogram of the payback period (PP) (in years) of the buildings in the three administrative regions of the GGA. Gray–blue: French; red: Swiss (Geneva); pink: Swiss (Vaud)

2.3.4. Criterion 3 (C3): Environmental benefit

There are several ways to evaluate environmental benefits of an urban photovoltaic system. Here, it was decided to consider the reduction of CO2 emissions (e_{CO2}). Indeed, converting environmental benefits into e_{CO2} is widely used when assessing environmental impacts [33].

In this work, environmental efficiency is evaluated by estimating the reduction in CO2 emissions that the PV system would induce if it were installed on the considered roof. It is defined as:

$$Red_{CO2} = E(y) \times \frac{e_{CO2,grid} - e_{CO2,PV}}{A_{PV}}, \tag{2}$$

The subscript *grid* refers to CO2 emissions related to the energy provided by the grid, while the subscript *PV* indicates those of the PV systems.

Considering the European energy mix, the average emissions associated with electric energy production were $e_{CO2,grid} = 0.275$ kgCO2/kWh in 2019 [34]. Regarding PV panels, a life-cycle assessment of the National Renewable Energy Laboratory allowed us to estimates their emissions at approximately $e_{CO2,PV} = 0.050$ kgCO2/kWh [35].

The reduction in CO2 emissions per square meter is plotted in Fig. 5. Note that in eq. 2, the reduction in CO2 emissions is directly proportional to the annual energy that a PV system would produce per square meter, $E(y)/A_{PV}$, and therefore to the yearly irradiation received on the roof (under the present hypothesis of a constant conversion efficiency of the PV systems). Here, the buildings in all regions have relatively similar distributions of annual irradiation, with the buildings of the canton of Vaud having a slightly better irradiance. This may be due to the absence of long-distance shade in the south-eastern regions, because of the presence of the lake (see Fig. 2), and to the less frequent periods of fog particularly in the mountainous areas.

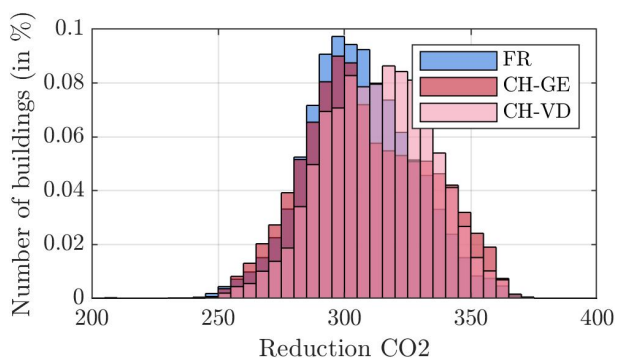

Figure 5: Histogram of the reduction in CO2 emissions (in kgCO2/(m².y)) for the buildings in the three administrative regions of the GGA. Gray–blue: French; red: Swiss (Geneva); pink: Swiss (Vaud)

2.3.5. Criterion 4 (C4): Roof complexity

In most of the current solar cadastres, the entire surface of the roof is considered as available for the installation of PV systems. However, in reality it is not this simple. Indeed, most of the roofs have superstructure elements such as chimneys, vertical windows, and HVAC (Heating, Ventilation and

Air-Conditioning). These elements reduce the available space for the integration of PV systems but also increase the constraints for this integration as the shadows cast by these elements weaken the PV suitability of the roof. In other words, a roof without superstructure elements is more suitable.

In the solar cadastre of Geneva, some of these superstructure elements (the largest) are already identified – based on the LiDAR data – therefore reducing the usable area for PV panel installation. However, as illustrated in Figure 6, not all the elements are detected. There are, to our knowledge, no databases available indicating the presence of these elements, and the manual identification of elements is time-consuming and therefore cannot be applied at a city scale.

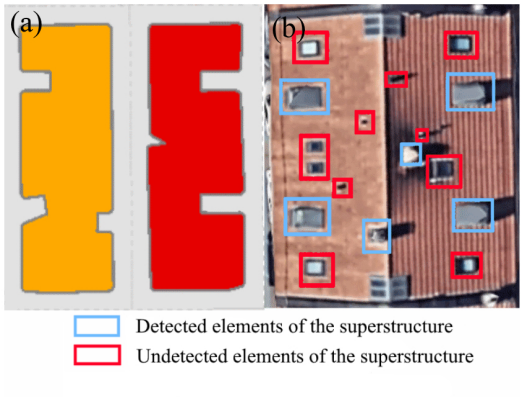

Figure 6: Detection of the superstructure elements of a roof. (a) Available area for PV systems according to the solar cadastre of GGA, the difference in colors indicates different solar irradiance; (b) aerial view of the same roof, with detected (surrounded by a blue rectangle) and undetected elements (surrounded by a red rectangle)

One way to quantify the number of superstructure elements on the roof is to evaluate the standard deviation of the roof slope. This is calculated here from the digital surface model (DSM), which is based on the raw LiDAR data measurements. LiDAR measurements of the GGA provide an evaluation of the height of each spatial point with an accuracy of 0.5 m. From these measurements it is possible to identify the presence of the roof and its mean inclination. However, when there are superstructure elements, the standard deviation (STD) of the roof slope increases. Note that this approach does not enable identification of in-plane superstructure elements such as in-plane windows or already installed solar systems.

An illustration of three buildings with a low (a), medium (b), and high (c) STD of the roof is provided in Fig. 7

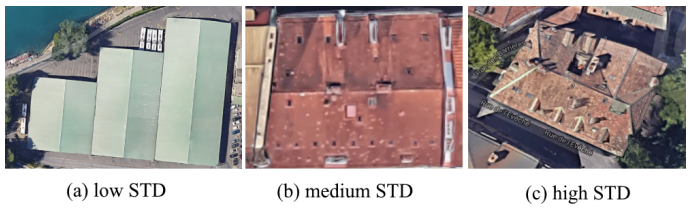

Figure 7: Representation of three buildings with a (a) low, (b) medium, and (c) high standard deviation (STD) of the roof slope

The distribution of the STD associated with the roofs of the buildings of the GGA is plotted in Fig. 8.

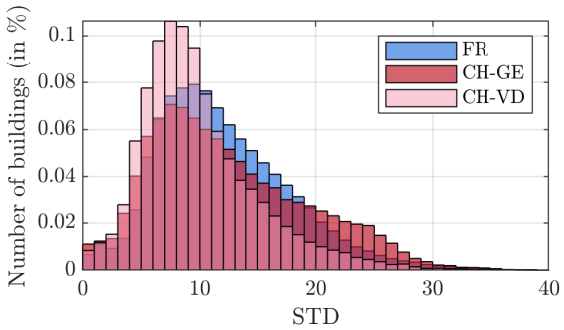

Figure 8: Histogram of the standard deviation (STD) of the roof slope of the buildings in the three administrative regions of the GGA. Gray–blue: French; red: Swiss (Geneva); pink: Swiss (Vaud)

2.3.6. Criterion 5 (C5): Heritage integration

In Europe, there are numerous heritage buildings and districts. The installation of PV systems near or on these buildings can by delicate since it can spoil their esthetic and cultural value [18, 36]. In general, the installation of PV systems onto or in areas close to heritage buildings and districts is either forbidden or must be carefully handled with the authorities and representatives in charge of local heritage. In some cases, the integration of solar panels in heritage areas may induce additional financial costs but it is also more time-consuming and requires additional efforts (administrative

process, discussion with local experts and urban planners, etc.). Therefore, it appears that this criterion is of utmost importance when considering the PV suitability of a roof.

The distribution of the heritage constraints in Greater Geneva is plotted in Fig. 9. Note that the vertical axis is plotted in log scale. As can be seen, the Swiss part has the highest share of highly protected buildings. This is due to the fact that a large part of the Swiss region is located on the lake shore. Municipalities on the shore are often built around old-town centers in which there are many heritage constraints. Another explanation could be that the list of heritage building is much more developed in Geneva than in the other two regions, as almost every building in the Canton is progressively referenced with different levels of protection.

However, in general, highly and moderately protected buildings represent, respectively, approximately 1% and 10% of the total share of buildings. This leaves nearly 90% of the buildings for which there are no heritage constraints regarding the esthetic integration of PV systems.

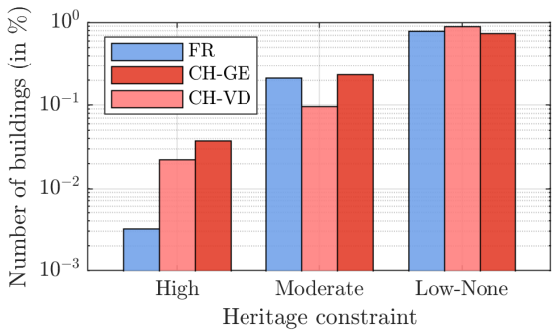

Figure 9: Histogram of the heritage constraints of the buildings in the three administrative regions of the GGA. Gray–blue: French; red: Swiss (Geneva); pink: Swiss (Vaud)

2.4. ELECTRE TRI parameters

In order to apply the ELECTRE TRI methodology, it is now necessary to define the weights of the criteria, the number of groups, and the performance profiles (the higher and lower limits of the groups). The ELECTRE method is a decision-aiding method intended to model the preferences of decision-makers using fuzzy logic. These preferences are modeled by a number of groups for the sorting, as well as the weights and thresholds associated with each criterion. These groups are usually defined based on discussions

with experts in the field. This was the case here since industries, local authorities, academics, and researchers belonging to the G2Solaire project were consulted.

From these meetings it was decided to sort the buildings into three groups of PV suitability referred to as A, B, and C, which corresponds to "very high," "high," and "moderate" PV suitability, respectively. The bounds for each of the group are presented in Table 1. There are no "low" groups since, as mentioned in section 2.3.1, for each alternative (piece of roof) there is a post-treatment that consists in finding the optimal areas of the roof for PV systems, based on the optimal PP. Furthermore, the aim of the present method is to enhance solar energy uses, and therefore the definition of a 'low' category may have been counter-productive.

Table 1: Performance profiles of the groups. *For heritage constraints, quantitative values are indicated in parentheses.

Suitability	C	B	A
C1 Self-sufficiency	<20%	[20%-30%[	≥30%
C2 Payback periods (years)	>15	[15-10[	≤10
C3 Reduction in CO2 ($kgCO2/m^2$)	<275	[275-325[	>325
C4 Roof complexity	>18	[9-18[	<9
C5 Heritage constraint*	High (0)	Medium (2)	Low (3)

After discussions with the experts, the economic criterion was considered as the dominant indicator and its weight was regarded as being twice that of the other indicators. The indifference, preference, and veto thresholds were also validated with experts and are reported in what can be considered as a fuzzy logic decision table in Table 2.

3. Results and discussion

3.1. Overview of the results at the territory scale

The methodology is applied for the entire GGA and allows us to sort all the buildings into three classes: 'A,' 'B,' and 'C.' The spatial distribution of the buildings and their classes are presented in Fig.10 (a).

Criteria	Weights	Indif.	Pref.	Veto	Obj.
C1	0.175	1%	3%	-	max
C2	0.3	1	2	10	min
C3	0.175				max
C4	0.175	2	4	-	min
C5	0.175	0	1	2	min

Table 2: Decision table presenting the set of weights and threshold. These parameters were determined based on discussions with experts in the field (academic, private companies, local authorities)

A summary of the sorting distribution is presented in Table 3. The A-ranked buildings account for 30% of the building stock, which represents a potential capacity of 33%.

Table 3: Summary of the distribution of the buildings of Great Geneva according to the different classes

Class	Building Share (%)	Potential Energy Production (GWh)	Potential Capacity (MWp)
A	30.1	1133	949
B	49.5	1722	1545
C	20.4	414	391

Details on the distribution of the buildings according to the different administrative regions is presented in Fig. 11 (see Fig. 2 for the location and description of the administrative regions). The French region appears to have the highest share of 'A' buildings (37 %) and the lowest share of 'C' buildings (13%), whereas the Vaud and Geneva cantons, respectively, have 18% and 19% of 'A'-ranked buildings. This difference can be explained by the investment price (lower in France), which allows most PV systems to have a PP lower than 20 years; moreover, as seen in Fig. 9, there are substantially fewer heritage constraints in France than in Switzerland.

In the magnified view of the results for the city center of Geneva presented in Fig.10 b it can be observed that there are numerous C-ranked buildings on the right-hand side. This is due to the presence of many highly protected buildings, as displayed in Fig. E.19, which constitute the old city center of Geneva. Furthermore, the city of Geneva has the highest density of buildings

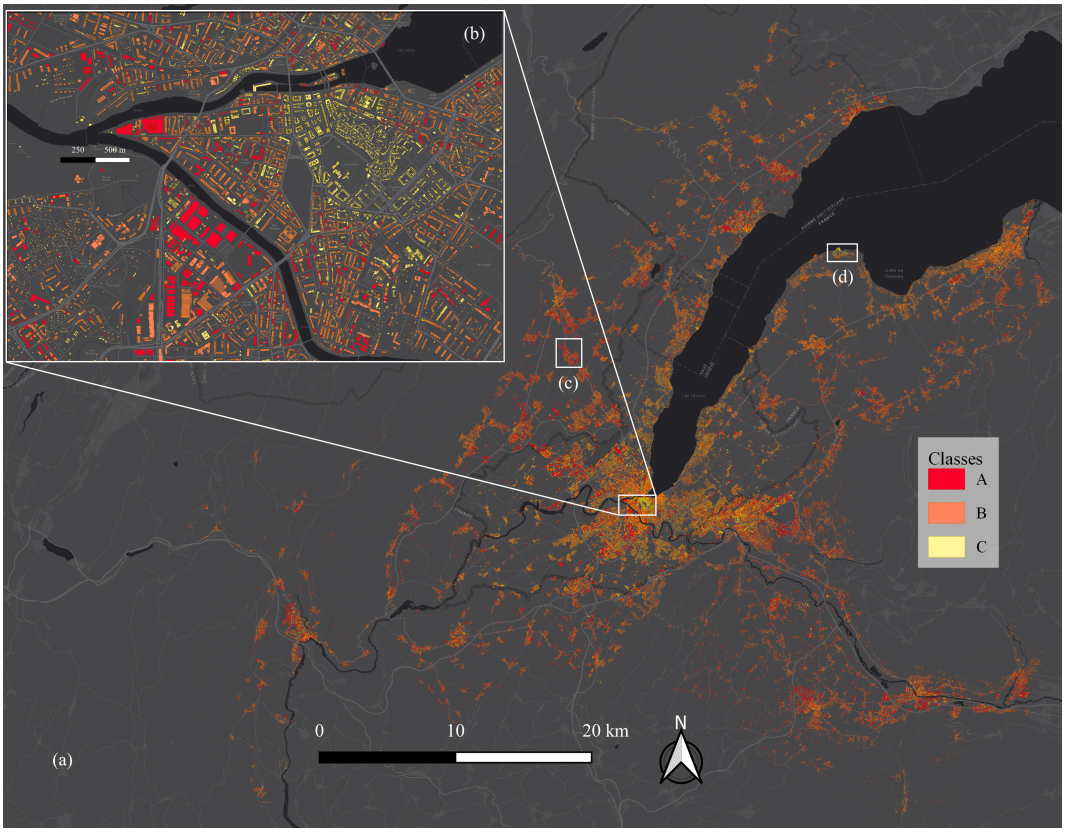

Figure 10: (a) Spatial distribution of the results of the sorting of GGA buildings. A magnified view of the center of Geneva is presented in the top left corner (b). Parts (c) and (d), respectively, correspond to the municipalities with the highest and lowest share of A buildings

in the GGA. This density can generate mutual shade between buildings, reducing the irradiance received and therefore the CO2 savings.

3.2. Comparison of the results with buildings already equipped with PV system

It is difficult to prove that the proposed sorting is 'exact' given that the methodology is a decision-aiding tool. Indeed, when a building is ranked in class 'C' it does not mean that this building is not suitable for PV systems. It only means that this building is less suitable than a building ranked in class 'A' or 'B.'

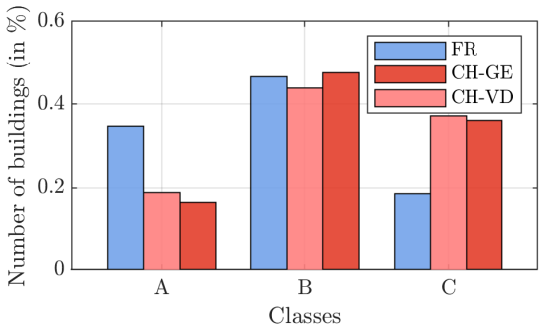

Figure 11: Distribution of the buildings into the three classes for each administrative region of Greater Geneva.

However, it is still possible to check whether there is a good correlation between the proposed sorting and the current distribution of the buildings that are already equipped with PV systems (this will be referred to as 'PV buildings').

To this end, the location of existing PV buildings in the Swiss part of the GGA will be used (i.e., the CH-GE and the CH-VD regions). These data were obtained using a machine learning (ML) model especially trained to identify PV systems on roofs in this area [37].

The model combines high-resolution images (0.25 m) collected during a multi-year aerial campaign by the Swiss Federal Office of Topography and a Convolutional Neural Network (CNN) U-Net architecture for pixel-wise semantic segmentation to locate and measure the size of rooftop solar installations in Switzerland. The false-positive rate (pixels classified as belonging to a rooftop PV, but that do not) resulting from application of the CNN is further reduced through a GIS-based post-processing step on a three-dimensional building database from the Swiss Building Registry. This approach allows us overcome the limitations of surveys and sparse databases in providing the mapping at a large scale of solar PV installations and it provides a basic tool to automatically monitor the temporal evolution of integrated renewable energy systems using open-access overhead imagery.

The distribution of the PV buildings in the CH-GE is presented in Table 4. In this table the first row presents the percentage of buildings in the CH-GE region belonging to each PV suitability class (same figures as those of the CH-GE histogram presented in Figure 11). The second row displays the percentage of PV buildings in the CH-GE region belonging to each PV

Table 4: Distribution of the PV buildings within each class in the CH-GE region.

Class	A	B	C	Total number of buildings
CH-GE buildings	16%	48%	36%	56608
CH-GE PV buildings	23%	56%	22%	5855

Table 5: Distribution of the PV buildings within each class in the CH-VD region.

Class	A	B	C	Total number of buildings
CH-VD buildings	19%	44%	37%	22054
CH-VD PV buildings	24%	49%	26%	1527

suitability class. Table 5 is similar to Table 4 except that it displays data for the CH-VD region.

In these tables the tendency shows that PV buildings are more likely to be ranked in A or B. This suggests that, until now, the A- and B-ranked buildings were preferred to C-ranked buildings for the installation of PV systems. These encouraging trends help to strengthen the idea that the present methodology is able to capture the preferences in terms of the PV suitability of the buildings.

3.3. Analysis by municipality

The GGA is composed of 210 municipalities; 45 in CH-GE, 47 in CH-VD, with the remaining being in France. There is a high heterogeneity between these municipalities, which can be due to different parameters such as their size, location, or history. These differences directly influence the PV suitability of their buildings. This is illustrated in Fig. 12, which displays the share of A-ranked buildings for all the municipalities of Greater Geneva. It can be seen that some municipalities have almost no A-ranked buildings, whereas in the best case, nearly 70% of the building are ranked as A. In the same figure $\tau_{c,A}$ is plotted, which is the share of the municipality's annual electric energy consumption that could be covered by the yearly production from A-ranked buildings if they were all equipped. It is defined as:

$$\tau_{c,A} = \frac{E_{PV,A}}{E_{Conso}}, \tag{3}$$

where $E_{PV,A}$ is the amount of energy that would be produced each year by the PV systems if all A-ranked buildings of the municipality were equipped, and E_{Conso} is the yearly electric energy consumption of the municipality. A

value of τ_c greater than 50% indicates that the A-ranked buildings could produce more electricity each year than half the needs of the municipality.

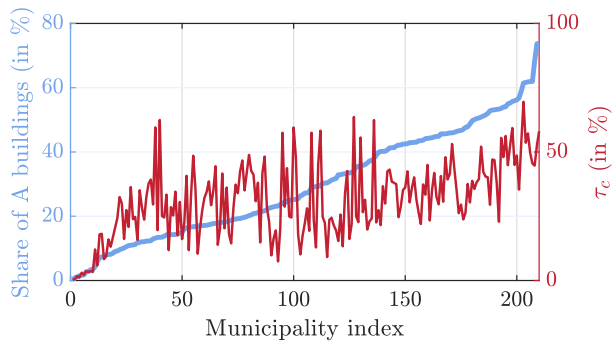

Figure 12: Share of ranked-A buildings in the 210 municipalities of Great Geneva (in blue). Municipalities are sorted by ascending order of the share of A buildings (left y axis). The right y axis represents the ratio of the potential PV production of A-buildings to the energy consumption of the municipality (as defined in eq. 15)

In general it appears that, except for the worst case (municipalities with few A-ranked buildings), the potential PV production of A-ranked buildings could represent between 10 and over 50 % of the municipality's electric energy consumption.

The distribution of the buildings into the three classes, for five municipalities (with the index numbers 1, 50, 100, 150, 210 according to Fig. 12) is plotted in Fig. 13. A visualization of the spatial distribution of the buildings and their rank is plotted for the municipality of Yvoire (located in Fig 10 d, lowest share of A buildings) in Fig. 14. The reason for this distribution is that Yvoire is a city near the Léman Lake with a very high level of heritage constraints. In this municipality it is therefore difficult to modify the building's appearance, and thus, the integration of PV systems is not easy. The best municipality according to the number of A-ranked buildings is the municipality of Segny (located in Fig 10 c), represented here in Fig. 15.

This analysis shows that it is crucial to adapt the solar strategy according to the municipality considered. Indeed, a similar goal, for example, producing the equivalent of 20% of the municipality's electric energy consumption with photovoltaic energy, could be difficult to reach by some municipalities whereas it would not be a problem for others.

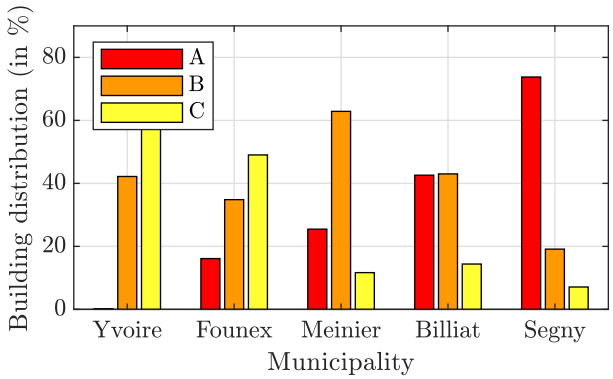

Figure 13: Sample of the building classes distributed evenly from the municipality with the lowest share of A-ranked building (Yvoire) to the city with the highest share of A-ranked buildings (Segny)

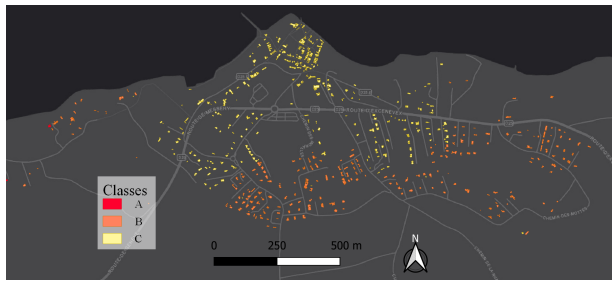

Figure 14: Municipality with the lowest share of A-ranked buildings

3.4. Multicriteria GIS sorting as a support tool for decision-makers

The proposed sorting can be used as a decision-aiding tool. This is illustrated in Fig. 16. The figure plots the cumulative capacity of the PV system that could be installed on the roofs of Greater Geneva (in MWp). To do so, the roofs are sorted first by their rank (A, B, C, shown by color rectangles) and then by their capacity (highest to lowest). Different stages have been indicated by dashed lines. These lines either represent real objectives in terms of PV deployment in the coming years, or are representative thresholds.

First, it can be observed that in total the cumulative capacity of all buildings considered here (A, B, and C) represents nearly 2800 MWp. The cumulative capacity that would be reached by only equipping A-ranked building is around 950 MWp and represents only 30% of the buildings. This is almost three times the objective of the Canton of Geneva for 2030 (objective of an installed capacity of 350 MWp). By equipping all the A-ranked buildings

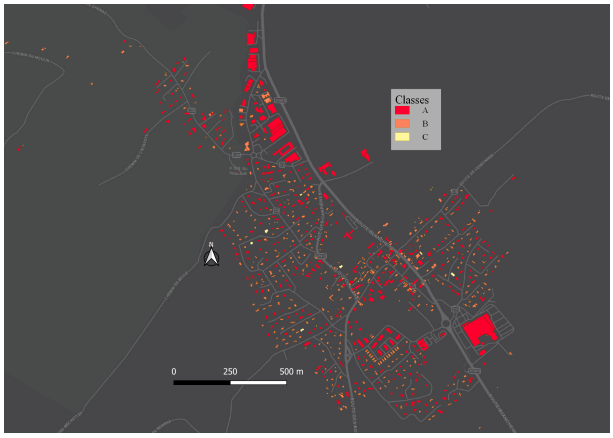

Figure 15: Municipality with the highest share of A-ranked buildings

and some of the B-ranked buildings, it would also be possible to match, on a yearly basis, the electric energy consumption of the CH-GE region. By adding a third of the B-ranked buildings, the energy produced would represent 50% of the energy consumed in 2019 by the households of the entire GGA.

We stress the fact that this is a theoretical installed capacity, which would be reached if all the buildings of Greater Geneva were equipped with PV systems. The actual installed capacity of the entire Greater Geneva is not known. However, in the Canton of Geneva (CH-GE) the capacity was 50 MWp in 2020.

It appears that, despite the large heterogeneity in A-ranked buildings (see Fig. 12), the present study demonstrates that prioritizing A-ranked buildings is largely sufficient to reach ambitious PV deployment goals and could be the basis for defining roadmaps for a realistic massive deployment of urban PV systems.

3.5. Limitations and perspectives

3.5.1. Uncertainties

In the present work, two types of uncertainties can be mentioned. The first uncertainty lies in the decision process itself. However, the proposed methodology was designed to account for this by the definition of weights and thresholds (see 2), which aim at reproducing a fuzzy logic decision.

However, although the purpose of these parameters is to account for uncertainty in the human decision-making process, the way these parameters

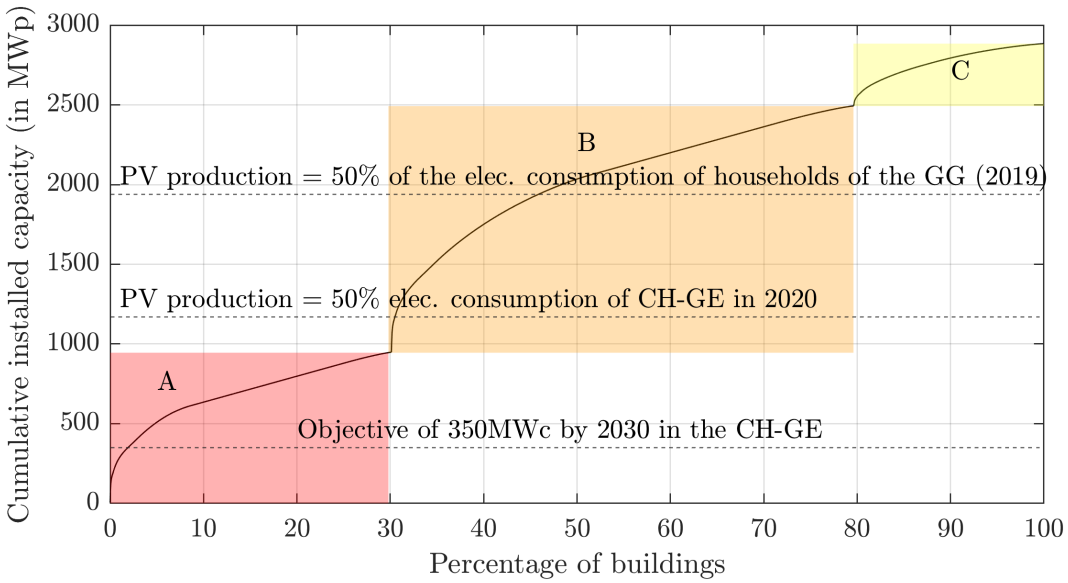

Figure 16: Cumulative installed capacity sorted by PV suitability. From left to right: A, B, and C buildings. Within one building class, the buildings are sorted by ascending capacity size. Different objectives in terms of PV deployment goals (known and calculated) are shown with dashed lines

are evaluated also generates some uncertainties. This represents an intrinsic limitation of this type of method especially in a multi-actor context. Indeed, different actors often have different expectations and constraints, which results in different sets of performance profiles (see, e.g., 1) weights and thresholds. Nevertheless, this represents only a minor limitation. Indeed, the present methodology can be applied for any type of actors, the only requirement would be to modify the set of weights and thresholds according to the respective actors. Furthermore, the ELECTRE TRI methodology has some subtle mechanisms that make it possible to represent human reasoning through the use of fuzzy logic (indifference, preference, and veto thresholds). This allows us to smoothen the impact of the thresholds.

Another uncertainty can stem from the choice of criteria. Indeed, in the present work, five influential criteria of PV suitability are used. However, this may not represent an exhaustive list of all influential criteria for roof-PV deployment.

The power grid or the structural robustness of the roof can also impact the decision regarding the installation of a PV system on a roof. The capacity

of the power grid is relevant at a high penetration level of PV electricity or for large PV installations [17]. In some cases it is necessary to modify or replace some part of the power distribution grid (by installing smartmeters or changing the transformer). This can induce major extra costs (economic as well as environmental or in terms of administrative time). However, in France and Switzerland, for privacy reason, it is not possible to access these data at large scale in open source. Regarding the structural robustness of the roof, it is also difficult to evaluate it at large scale. [12] proposed to estimate this based on the load induced by the roof-cover material and assuming that the roof frame was designed accordingly. However, this criterion was evaluated manually for a relatively small number of buildings (around 200). Such an approach cannot be followed in the present case where nearly 300 000 buildings are considered.

Nevertheless, if in the coming years information about these criteria becomes available, it will be easy to update the present methodology by adding one or more criteria, which will result in an updated map of the sorting of the roofs.

3.5.2. Universality

Finally, it should be stressed that the proposed methodology, in its general aspect, is largely scalable to other territories or cities. Indeed, as long as the required data are available, it is possible to apply this approach to any other territory. It is part of the strength of this approach, which allows it – by the definition of the decision criteria the performance profiles, of the weights and thresholds – to be adapted to many types of actors and preferences.

3.5.3. Policy recommendations

From the present work, two main policy suggestions can be formulated. Adapt PV deployment to local constraints: As demonstrated here, the irradiance received on the roof is not the primary concern when assessing the PV suitability of a building. Moreover, when considering a wider set of decision criteria, it can be seen that drastic difference appear – in terms of PV suitability – between the building stocks of municipalities. In order to allow for an efficient deployment of solar energy, it would be better to focus on the least problematic municipalities leaving aside the most problematic ones. This would save substantial time as well as financial and political efforts.

The open-database policy: As demonstrated in this work, being able to access open data at large scale, and for a wide range of information, allows one

to perform ambitious multidisciplinary research. The GGA agglomeration is one of the pioneering territories in this respect, and an acceleration of this open-data policy for other territories is, in our opinion, extremely beneficial.

4. Conclusion

The suitability of a building to be equipped with a PV system (PV suitability) depends on numerous factors. In this study, a multicriteria methodology is developed and applied to an urban territory, here Greater Geneva, a French–Swiss cross-border region of nearly 270 000 buildings. The PV suitability of all its buildings is calculated considering five decisional criteria, which are the self-sufficiency rate, the economic profitability (payback periods), the reduction in CO2 emissions, the roof complexity, and the heritage constraints.

Sorting of the alternatives (the buildings) is then performed using the ELECTRE TRI methodology. This method accounts for the preferences of all the actors through a fuzzy logic approach. Buildings are sorted into three classes, A, B, and C, which corresponds to a very high,a high, and a moderate suitability, respectively. Results are analyzed at a global scale (territory) as well as at a local scale (municipalities).

The main conclusions of this works are:

- The proposed sorting makes it possible to have simple information about the PV suitability based on an elaborate multicriteria methodology.
- Such sorting, coupled with GIS tools, can provide a decision-aiding tool for many actors (local authorities, citizens, associations), in order to guide them through the process of spatial deployment of PV systems. It can then help them to identify buildings that should be considered as priority for PV deployment in order to achieve energy transition goals.
- According to the proposed sorting, at the scale of the GGA, 30% of the buildings can be considered as highly suitable for PV integration. If equipped, these buildings would have a yearly production equivalent to 40% of the Greater Canton electricity consumption.
- There is a large heterogeneity in terms of PV suitability between municipalities of the same territory. In the least favorable case, there are

no A-ranked buildings, whereas in the most favorable there are nearly 75% of A-ranked buildings, which would represent a potential energy production of more than 50% of the municipality's consumption. This type of method could help prioritize district and municipalities with high PV suitability in order to efficiently and optimally deploy PV systems.

- This methodology allows us to identify districts/municipalities with low PV suitability. These districts should not be prioritized when deploying PV energy as they represent additional costs in terms of money and time.

- The proposed methodology is easily scalable and updatable as long as the relevant data are available.

Acknowledgments

The authors would like to thank the program INTERREG V Suisse-France for providing financial support to conduct this study in the framework of the project G2 Solar, which aims at extending the solar cadastre to Greater Geneva and to intensify energy solar production at this level. This work has been supported by the French National Research Agency, through the Investments for Future Program (ref. ANR-18-EURE-0016 – Solar Academy). The research units LOCIE and LISTIC are members of the INES Solar Academy Research Center.

Appendix A. Calculation of the solar radiation on roofs

As summarized by [21], the solar cadastre tool is a geographic information system (GIS) that provides information on the solar radiation that is received by roofs over a large territory.

In the present work, the data come from the solar cadastre in Greater Geneva. The calculation methods for the radiation are detailed in the work of [8] and were compared with other existing tools in the work of [38]. In what follows we will only provide the main hypothesis and models used in the solar cadastre of Geneva.

The total irradiance (I) received by an element of a surface at location x at a time t is given by:

$$I(x,t) = I_b(x,t) + I_d(x,t) + I_r(x,t), \tag{A.1}$$

where I_b is the contribution of the direct component (also called "the beam component"), I_d is the diffuse component and I_r is the reflected component.

The irradiance received from the direct component I_b is given by:

$$I_b(x,t) = BNI(t) \times r_b(x,t) \times S_b(x,t) \tag{A.2}$$

in which BNI corresponds to the direct normal component of the irradiance, r_b is the transposition factor, and S_b corresponds to the shadow cast from the neighborhood buildings ($S_b(x,t) = 0$ if, at time t, the surface located at x is shaded by another building, or $S_b(x,t) = 1$ otherwise). The transposition factor, r_b, depends on the solar elevation h and the slope of the considered surface β ($\beta = 0°$ corresponds to a horizontal surface and $\beta = 90°$ corresponds to a vertical surface). It is calculated as:

$$r_b(x,t) = sin(h(t))/cos(\beta(x)). \tag{A.3}$$

In order to model the contribution of the diffuse component to the received irradiance, the Hay model is used. This model considers two components: a circumsolar (anisotropic) and an isotropic component. Similarly to the direct component, the circumsolar component is calculated at each time step by considering the sun's position and the shadow. For the isotropic component, the sky-view factor is computed. In the solar cadastre, a sky model of 580 light sources is used.

The diffuse contribution, I_d, of the solar radiation is then calculated as follows:

$$I_d(x,t) = DHI(t) \times \left(\frac{GHI(t) - DHI(t)}{I_0} r_b(x,t) + SVF(x) \left(\frac{GHI(t) - DHI(t)}{I_0} \right) \right) \tag{A.4}$$

where GHI is the global irradiation received on a horizontal unshaded surface, DHI is the diffuse irradiation on a horizontal unshaded surface, I_0 is the hourly extraterrestrial irradiation, and SVF is the sky-view factor.

Finally, the reflected component is considered as isotropic and is estimated as follows:

$$I_r(x,t) = 0.5 \times GHI(t) \times \rho(1 - \cos\beta(x)) \tag{A.5}$$

where ρ is the coefficient of reflection of the surface, and β is the slope of the surface.

Finally, the weather data BNI, DHI, GHI are taken from the Meteonorm database [39], which are statistical solar radiation data, calculated from past observations.

Appendix B. ELECTRE TRI methodology

There are numerous types of ELECTRE methods (ELECTRE I, II, III, ELECTRE TRI etc). However, the common feature of these methods is the pairwise comparison relations. For a pair of alternatives (a, b), the comparison relations used are: the outranking relation, noted as aSb, meaning that alternative a is at least as good as alternative b; the strict preference relation, noted as aPb, which corresponds to aSb and not bSa; the indifference relation, noted as aIb, which corresponds to aSb and bSa; the incomparability relation, noted as aRb, which corresponds to not aSb and not bSa.

More specifically, the ELECTRE TRI method consists in assigning a set of alternatives to pre-defined classes (also called 'categories' or 'groups') [25, 26]. This is done by comparing in a pairwise way each alternative to the bounds of the groups and then deducing the sorting of these alternatives.

Let us consider N classes $C = C_1, \ldots, C_j, \ldots, C_N$, which are ordered and defined by a lower and a higher bound. The assignment of the alternative a to the category C_j is determined from the comparison of a to the bounds of C_j. Defining b_j as the higher bound of C_j (and therefore the lower bound of $C_{(j+1)}$), this comparison relies on the credibility of assertions aSb_j and b_jSa.

The credibility is evaluated using the credibility index, which is itself obtained by the calculation of concordance and discordance indexes. In ELECTRE TRI, the preference model that is necessary for the evaluation of the credibility index relies on:

- the definition of the thresholds for each criterion g_i
- the indifference threshold q_i
- the strict preference threshold p_i
- the veto threshold v_i
- the weights w_i, which represent the criterion's relative importance in the decision-aiding process.

For each criterion, the concordance index between an alternative a and the bound b_j is noted as $c_i(a, b_j)$ and ranges from 0 to 1. It reflects to which extent a is at least as good as the bound b_j. The discordance index is noted as $d_i(a, b_j)$ and also ranges from 0 to 1. It reflects to which extent a is different from b_j. Finally, the credibility index, ranging from 0 to 1, informs on the confidence of the pair-wise comparison (a, b_j). It is expressed from the reduction of the previous indexes and reinforces the outranking relation by using a predetermined threshold (of credibility) noted as λ.

From there, a "pessimistic" sorting is adopted, which consists in sorting the alternatives in the lowest category possible. It sorts the alternative a in the highest class for which it outranks the lower bound of this class *i.e.*, $aSb_j \Rightarrow a \in C_{(j+1)}$. It is also possible to consider an "optimistic" sorting process, which is slightly different and that would nuance the sorting of some alternatives to a higher category. There are no special specifications on whether the optimistic or pessimistic sorting should be selected. A 'pessimistic' sorting provides more conservative results and was adopted in many studies using ELECTRE TRI (see, e.g., [12, 23] for solar applications).

Finally, the method requires expert knowledge both for the identification of model parameters (thresholds, weights) and for understanding the information processing. Interested readers can find more information on computation of the indexes in [40].

Appendix C. (C1) Calculation of self-sufficiency for the GGA

For the calculation of P the electrical production of the systems, the hourly PV potential as calculated by the solar cadastre is used (see section 2.3.1). For the evaluation of the electric energy consumption of the building, L, three different calculation methods had to be used since the data quality and availability are heterogeneous between the three administrative regions (FR, CH-GE, CH-VD, see Fig.2).

In the Geneva Canton (CH-GE) the yearly electrical energy consumption is available from the unique energy company of the Canton, SIG (Industrial Service of Geneva), for most of the buildings. From there, different load profiles, based on more than 80 types of buildings (residential, single-house, apartment, restaurant, etc.), were used in order to disaggregate the annual energy consumption into an hourly energy consumption. The self-sufficiency rate is then calculated following Eq. 1.

In the canton of Vaud, data on electrical energy consumption are not available for each building. However, the building information system of the canton provides data on the categories (office, school, housing, etc.) and the floor area. Categories are regrouped into 12 building types that match those of the Swiss building code [41]. For each building class, the Swiss norm gives the electricity consumption index (in kWh/m^2). It is then possible to calculate an estimate of the yearly electricity consumption. Then, the same load profiles as those used for the canton of Geneva (for each matching building type) are used to build the hourly energy consumption profile.

In France, the main national energy company (ENEDIS) provides yearly consumption data for addresses that have more than 10 clients. Four load profiles provided by ENEDIS are then used (small residential, medium and large residential, tertiary activities, and industries). This represents about 5000 buildings (over 150 000 in total for the French region). For the remaining buildings, the same approach as that used for the canton of Vaud is followed.

Appendix D. (C2) Calculation of the economic benefits: Pricing schemes and subsidies in the GGA

The PP (in years) is defined, similarly to what is proposed by [28], as:

$$PP = L, C_L - B_L = 0 \tag{D.1}$$

where C_L and B_L are, respectively, the costs and benefits induced by the PV system from its installation to year L. L being the time period (in years) for the costs and benefits to be balanced.

Benefits are calculated as [28]:

$$B_L = S_0 + \sum_{t=1}^{L} \frac{E_{sc}(t)p_r + E_e(t)p_w}{(1+d)^t}, \tag{D.2}$$

where S_0 corresponds to subsidies, $E_{sc}(t)$ is the self-consumed energy at year t, and therefore $E_{sc}(t)p_r$ corresponds to savings made by deferring purchases to the grid at the retail price p_r, in year t. E_e corresponds to the excess production of energy, sold to the market at the wholesale price p_w. Finally d is the discount rate.

Costs are calculated as:

$$C_L = I_0 + \sum_{y=1}^{L} \frac{OM(y)}{(1+d)^y}. \tag{D.3}$$

where I_0 is the initial investment and OM_t are the yearly operations and maintenance costs in year t.

Table D.6: Discount rate as a function of the installed capacity

Capacity - C (in kWp)	≤ 9	]9-36]	>36
Discount rate - d	0.01	0.02	0.03

The yearly operating and maintenance costs in year t (OM_t) are evaluated at a fixed cost of 1% of the investment I_0 [28].

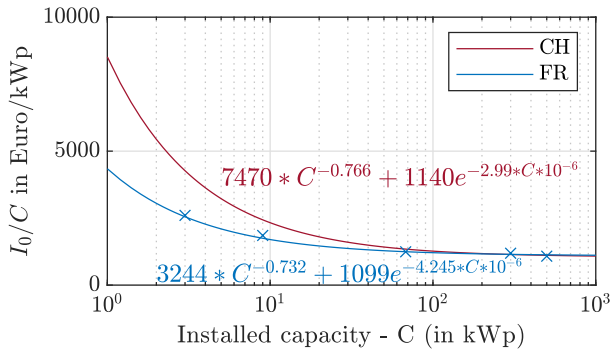

Figure D.17: Estimate of the investment price for a PV system as a function of its capacity. Data for Switzerland (CH) were obtained from [42] whereas those for France (FR) were interpolated from [43]).

Regarding the discount rate, different values were used depending on the installed capacity. This approach was proposed by the ADEME, the French Agency of Environmental Transition [43]. The idea is to consider that small PV systems will be installed mostly by individuals, for which the bank interests rate are rather low (around 1%). However, larger PV systems will be installed by investors or companies for which the PV system will be a financial product and for which a higher discount rate should be considered. The discount rates used in this study are summarized in Table D.6.

The investment price of a PV system depends on its capacity (in kWp (kilo Watt peak)). The market price for a classic roof-mounted PV installation was evaluated based on data from the SwissSolar [42] for Switzerland and from the French Environmental Transition Agency (ADEME) [43] for France. From these data, interpolations where made using power laws as reported in Figure D.17.

Table D.7: Retail and wholesale prices as well as subsidy schemes in the different administrative regions of the GGA - (date of July 1, 2021)

Region	p_w in €/kWh or CHF/kWh	C (Capacity in kWp)	p_r in €/kWh or CHF/kWh	S_0 in € or CHF
FR	0.155	<3	0.1	$380 \times C$
		[3 - 9]	0.1	$280 \times C$
		[9-36]	0.06	$160 \times C$
		[36-100]	0.06	$80 \times C$
		>100	0	0
CH-GE	0.1944	<30	0.1298	$700+380\times C$
		[30 - 100]		$700+290\times C$
		>100	0.1252	$700+290\times C$
CH-VD	0.2138	<30	0.0816	Similar to CH-GE
		>30	0.072	

Appendix E. (C5) Evaluation of the heritage constraints in the GGA

The different types of protection are referenced as a GIS layer in the GGA database [22]. An illustration of the heritage constraints in the center of Geneva is presented in Fig. E.18. The colors indicate different types of heritage classification.

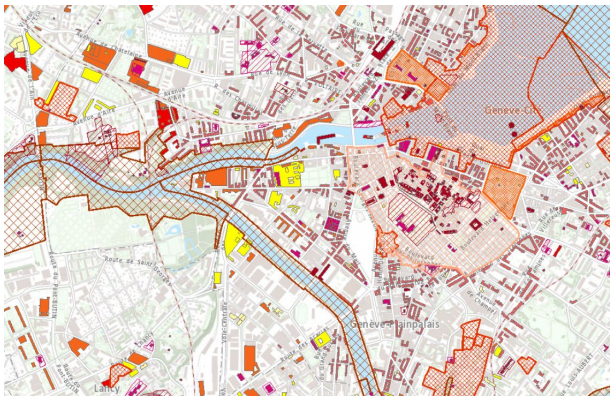

Figure E.18: Heritage constraints in the center of Geneva. The colors here are only for illustrative purposes and indicate different types of heritage protection.

The different types of heritage protection and the constraints they in-

duced regarding PV installation were discussed with experts of the Swiss and French heritage buildings. It was decided that they could be sorted into three levels: high heritage constraint, moderate heritage constraint, and no heritage constraint. A building with 'high' heritage constraint corresponds to a building on which it is very difficult to install PV systems, if not impossible. In the latter case it is mandatory to ask for additional authorization as well as to conduct extra studies regarding the esthetic impact of the PV installation. This is, for example, the case of heritage buildings such as old buildings with strong sociocultural value (religious and ancient buildings). A 'moderate constraint' corresponds to two main cases, either the building is of particular architectural interest, or the building belongs to an area in which urban modifications are submitted to validation from local heritage authorities. This is the case, for example, in France where, in a radius of 500 m around each highly protected building, special authorization must be given in order to modify the appearance of a building, which includes the installation of PV systems. Fig. E.19 shows the distribution of these three classes of protection in the center of Geneva.

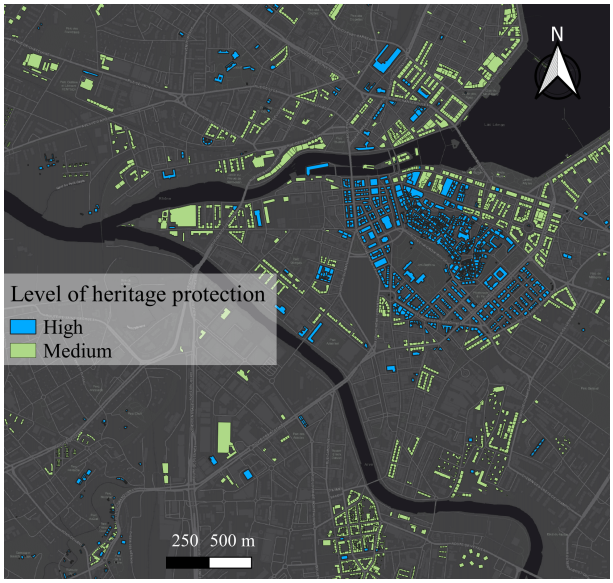

Figure E.19: Heritage constraints for buildings in the center of Geneva. Different colors indicate different types of heritage classification. Red indicates a high level of heritage protection; orange indicates a medium level, and the other colors were considered as low level of protection regarding solar integration.

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