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Multicriteria roof sorting for the integration of photovoltaic systems in urban environments

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Abstract

This work deals with the sorting of the suitability of the roofs for the integration of PV systems, implementable as a GIS (Geographical Information System). Such sorting can provide relevant information to help and guide urban actors further develop solar energy, and therefore contribute to the acceleration of the deployment of this source of energy in cities. Three scenarios of sorting are considered: the energetic, the economic and the multicriteria sorting.

The energetic and economic sorting scenarios are actually similar to the great majority of the currently proposed sorting in publicly available solar GIS tools (solar cadastre), which consider only one attribute such as the solar irradiation or the payback period. Knowing the limits of these sorting scenarios, a multicriteria approach is adopted and takes into account more impactful attributes in the urban actors' choices. The ELECTRE TRI methodology is used for this sorting problem. Different decisional criteria related to energy, economy, historic buildings and heritage, the structure and superstructure states of the roof are identified and detailed. The method is then applied to a set of alternatives (roofs) in a district of Geneva. The sorting results show that the proposed multicriteria scenario better integrates the complexity of the urban environment and provides a more relevant information regarding the suitability of the roofs for PV integration.

Keywords: Urban photovoltaic, ELECTRE TRI, Roofs sorting, Classification, Solar cities, suitability

1. Introduction

1.1. Solar energy in cities

Since the beginning of the 21st century, increasing concerns regarding the consequences of climate change have led to the rethinking of the generation and the consumption of energy as well as the management of local resources. During the COP 21, which was held in Paris in 2015, some nations of the world made commitments to reduce their Green-House Gas (GHG) emissions. These set goals can only be met thanks to the decrease of overall energy consumption and substitution of carbon-emitting fossil energy by the production of renewable energy (IPCC, 2019) 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 energy, concentrated solar power or PhotoVoltaic panels (PV), is particularly interesting because of its abundance and availability.

The production of energy thanks to PV technologies has undergone a sustained and accelerated expansion since its commercial development a few decades ago. In 2019, it represented about 2.6 % of the production of electricity in the world (PVPS, 2019) and should reach 25 % of the electricity needed globally by 2050 (IRENA, 2019a) for an expected installed capacity of 8500 GW. Some forecasts also suggest that 40 % of this capacity will be produced by distributed roof-mounted PV systems (IRENA, 2019a) and, as a result, cities are expected to play a crucial role in the achievement of the energy transition (Cajot et al., 2017; International Energy Agency, 2016). To meet this goal, a large-scale deployment of PV in built environment is needed. This will represent a large share of the available roofs. In Australia for instance, the large-scale deployment of PV resulted in the installation of such technology on 30% of roofs in certain regions (REN21, 2019a)

In order to efficiently deploy solar energy on a large scale in urban environments, it is necessary for all the actors of the urban environment – government, citizens, urban planners, energy utilities, … – to become involved (Kanters and Wall, 2016; Lobaccaro et al., 2019a; Mah et al., 2018; Ouhajjou et al., 2017; REN21, 2019b). Among them, one of the key actors is the end-user who both funds the PV system and takes benefits from its outputs. In the case of urban PV, the end-user is the private home-owner or large real estate owners (private or public) who often have the role of prosumers (consumers and producers of energy). The end-users can also be third parties, entrepreneurs or associations, that will go through leasing contracts with the owners for the exploitation of PV systems (Feige et al., 2011; Osseweijer et al., 2018; Wijeratne et al., 2019). The development of tools that provide easily accessed, reliable and relevant information to these actors about PV is considered as one of the prime movers of the energy transition in cities (Amado et al., 2016; Ballif et al., 2018; IRENA, 2019b; Mah et al., 2018; Wijeratne et al., 2019).

The end-users who are willing to install PV systems on their roofs are therefore eager to know whether they are suitable for this technology. In theory, the installation of a PV system on a roof is always possible. However, such equipment sometimes demands additional financial, aesthetic and structural efforts, not to mention the time needed for its putting in place. It consequently appears that the answer to whether a roof is suitable for the installation of PV systems is not binary but requires nuancing and taking into account different relevant criteria (Wijeratne et al., 2019). In other words, when a roof is suitable for PV integration, different degrees of suitability emerge, which is why sorting procedures have to be developed. Being able to create different groups of roofs with varying degrees of suitability could also be used by local authorities as an indicator to help prioritize PV deployment and meet the goals that have been set for 2050 (Cipriano et al., 2017). For example, roofs have high degree of suitability should be equipped first as they are cases when the integration of PV is highly beneficial. What's more, the group of roofs described as moderately suitable is one for which the PV integration should be further confirmed and studied while roofs classified as lowly suitable correspond to situations in which the PV integration will be the least easy.

1.2. The sorting of roofs for solar integration

Sorting consists in the assignation of alternatives, here roofs, to predefined groups. When groups have no ordinal ranking, it is called 'classification' whereas the term 'sorting' is used when groups have an ordinal ranking (Zopounidis and Doumpos, 2002).

The choice of using a sorting procedure is made as it provides information easy to read and understand for a large and non-expert audience. Such sorting must be accessible for every end-user and every possible roof of a certain area. To achieve this end, tools such as Geographical Information System (GIS) based on land-property registers (also called cadastres) can be used as they give information about the buildings of a given region. In our specific case, they could provide insights into the degree of suitability (Low, Moderate, High, Very High) of a roof to be equipped with PV systems.

Sorting processes have been widely used in cities. They take the form of GIS tools called solar cadastres (IRENA, 2019b; Kanters et al., 2014; Lobaccaro et al., 2019b).

The solar cadastre of a city is a geographical interface, which makes it possible to know how much sunlight a given roof, building, home or a part of them receives. The cadastres reviewed in (IRENA, 2019b; Kanters et al., 2014; Lobaccaro et al., 2019b) all sorted roofs by considering their solar irradiation *i.e.* the energy received yearly per square meter. The range and number of the resulting groups varies between the different cadastres. Some of them also detailed the building consumption or the economic outputs of solar energy, a piece of information that is, however, not included in the definition of the sorting. It remains monocriterion being based on the solar irradiation, as it is also the case for many of the proposed sortings in the literature (Jakubiec and Reinhart, 2013; Lukač et al., 2013; Santos et al., 2014). (Lee et al., 2018) defined a sorting method relying on both the solar irradiation and the economic potential of a roof. And yet, among the criteria that they selected, two economic criteria were the return on investment and the pay-back period, which are very similar criteria in the case of PV systems (Sommerfeldt and Madani, 2017a). This may induce a bias in the methodology as redundancy in the decisional criteria should be avoided in multicriteria decision analysis (Figueira et al., 2005).

Cities are complex environments and information about the solar or the economic potential is not sufficient when assessing the suitability of a roof to host a PV system (Wijeratne et al., 2019). Other key aspects must be considered such as, for instance, the presence of superstructure elements on the roof (Desthieux et al., 2018; Groppi et al., 2018; Mah et al., 2018; Walch et al., 2020), structural robustness (Wills et al., 2015), economic feasibility (Lee et al., 2018; Sommerfeldt and Madani, 2017a) or the heritage and aesthetic character of the given building (Florio et al., 2018; Groppi et al., 2018;

Probst and Roecker, 2015). Therefore, the sortings that have been proposed are limited as they do not address the multicriteria aspect of the suitability of a roof to host PV systems.

There is a wide range of multicriteria approaches that could be used for sorting and (Cajot et al., 2017; Kumar et al., 2017; Wang et al., 2009) provide a review of them in the context of the development of renewable energy. The use of MultiCriteria Decision Aiding (MCDA) methods is particularly interesting in the present case as these methods are transparent, easily understood and as they facilitate interdisciplinarity, promote public participation and, in some cases, can help glean quantitative and qualitative information (Cajot et al., 2017; Figueira et al., 2005). To our knowledge, no MCDA sorting approaches have been implemented to sort roofs according to their degrees of suitability to host PV systems.

The goal of the present work is to present a sorting method that helps evaluate the degree of suitability of a roof to host a PV panel by resting on several decisional criteria. Then, the multicriteria sorting is compared to two conventional monocriterion sortings, the first being economic and the second based on the solar irradiation. The different sorting methodologies used in the field are first listed and the motivation behind the choice of the ELECTRE TRI method is explained. The different criteria that need to be considered in the implementation of a PV system in urban environments are then introduced and evaluated for the considered alternatives. In the last part of this work, the results obtained with the multicriteria and monocriterion sortings are presented and compared in the case of urban districts in Geneva, Switzerland.

2. Methodology

The aim of the present section is to develop a methodology allowing the sorting of a wide range of roofs into different predefined groups. The sorting will be based on their degrees of suitability to host a PV system, itself measured thanks to its relevance for a targeted audience and specific criteria.

2.1. The choice of the sorting method

The use of MCDA is not new in the field of solar energy. Indeed, in an urban context, multi-criteria methods have been employed to deal with different problems. (Azzopardi et al., 2013; Huaylla et al., 2013) resorted to the ELECTRE III (ELimination Et Choix Traduisant la REalité) method to rank different PV technologies. (Matulaitis et al., 2016) used the ELECTRE III method to assess the financial policies of different countries considering mostly economic criteria. The authors (Thebault et al., 2019) also used ELECTRE III in order to consider different groups of decision makers and to rank a set of buildings according to their relevance to be equipped with PV panels. However, these methods are ranking methods for which the use makes sense with small amounts of alternatives. In the case of the deployment of PV technologies on a large scale, a great variety of alternatives must be considered, which is why sorting methods are more efficient.

There are various sorting methods that allow to address the problems raised by multicriteria sorting in cases when a large number of alternatives must be considered. MCDA sorting methods have been widely used in order to identify the optimal locations for PV power plants (also called PV farms) on a national scale. The Analytical Hierarchy Process (AHP) in Iran (Azizkhani et al., 2017), PROMETHEE in Turkey (Samanlioglu and Ayağ, 2017), TOPSIS in Iran and Spain (Nazari et al., 2018; Sánchez-Lozano et al., 2016) or ELECTRE TRI in Spain (Sánchez-Lozano et al., 2016, 2014) are good examples of such use. (Sánchez-Lozano et al., 2016) also compared TOPSIS and ELECTRE TRI concluding that both approaches were efficient tools in the identification of the optimal locations of PV farms. As to the assessment of optimal roofs for the integration of PV systems no MCDA methods were used, as far as we know, in urban contexts. What's more, the literature does not offer recommendations for the selection of a specific sorting method.

According to the review of (Cajot et al., 2017), weight sum methods, AHP, Multi-Objective Decision Method, TOPSIS and ELECTRE TRI are the most commonly used in the case of the planning of energy systems in cities. Among them, ELECTRE TRI (Figueira et al., 2005; Roy and Bouyssou, 1991; Yu, 1992) was tried and validated since it was devised to be as close as possible to human reasoning, resting on quantitative and qualitative evaluations of criteria, which is particularly interesting in an urban context as cities represent environments in which the human factor is prominent. The urban context is also source of numerous uncertainties as for example the impact of the vegetation on the evaluation of the solar potential. By considering these uncertainties, more robust assessing of the solar potential of the roofs can be achieved (Peronato et al., 2018). ELECTRE TRI, thanks to the preference model definition, allows to indirectly account for these uncertainties.

For these reasons, ELECTRE TRI seems to be a relevant method for the present problem, and will therefore be used. What's more, ELECTRE TRI is also very useful for the present problem as it is a highly scalable method which can be easily adapted to local specificities. This is particularly relevant for our study as the assessment of the degree of suitability of a roof sees variations when applied to different regions, countries or even decision makers.

2.2. ELECTRE TRI methodology

ELECTRE TRI is based on pairwise comparison relations. For a pair of alternatives (a, b), the used comparison relations are:

- the *outranking* relation noted aSb, meaning that alternative a is at least as good as alternative b,
- the *strict preference* relation, noted aPb, which corresponds to aSb and *not* bSa
- the *indifference* relation, noted aIb, which corresponds to aSb and bSa
- the *incomparability* relation, noted aRb, which corresponds to $not\ aSb$ and $not\ bSa$

The ELECTRE TRI method consists in assigning a set of alternatives to pre-defined groups (also called categories) (Figueira et al., 2005; Roy, 1981). This is done by comparing pairwise each alternative to the bounds of the groups and then deducing the sorting of these alternatives.

Let consider N groups $C = \{C_1, \dots, C_j, \dots, C_N\}$ 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 the 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 which is necessary for the evaluation of the credibility index relies on:

- the definition of the thresholds for each criterion g_j: the indifference threshold q_j, the strict preference threshold p_j and the veto threshold v_j,
- the weights w_j, which represent the criterion's relative importance in the decision-aiding process.

The concordance index between an alternative a and the bound b_j is noted $c(a, b_j)$ 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 $d(a, b_j)$ 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 λ.

From there, two types of sorting can be considered, which are the optimistic and the pessimistic sorting. These types of sorting are detailed in Table 1.

Table 1 Sorting processes of the ELECTRE TRI methodology

Sorting type	Pessimistic	Optimistic
Goal	Sort the alternatives in the lowest category possible	Sort the alternatives in the highest category possible
Process	Sort the alternative a in a category such as it outranks the lower bound of this category i.e. $aSb_j \Rightarrow a \in C_{j+1}$	Sort the alternative in a category such as the higher bound of the category is preferred to the alternative i.e. $b_jPa \Rightarrow a \in C_j$

As part of the ELECTRE TRI methodology, for the sake of clarity, in the remaining of the work only the pessimistic sorting will be considered. Considering the optimistic sorting would change nuanced the sorting of some alternatives to a higher category.

the remaining steps that must be followed are:

- definition of the alternatives
- definition of the criteria
- description of the alternatives
- Identification the ELECTRE TRI parameters
- sorting of the alternatives

The method requires experts' knowledge for both the models parameters identification (thresholds, weights) and the information processing understanding. Interested readers can find more information about the indexes computation in (Roy, 1990)

2.3. Definition of the alternatives

PV systems can be integrated on all type of building façades, including vertical façades. However, the integration of PV systems on roofs remains the most common practice due to lack of reliable energy and economic data regarding vertical facades.

Moreover, the great majority of the publicly available solar map, only gives information about the roofs. For these reason, only roof integration will be considered here.

In an urban environment the concept of roof must be clarified. Indeed, a large building can be divided into different owners, and therefore an entire roof can be split into different properties, belonged by different owners. Then the roof of a property is often composed of different roof sections, a roof section being a part of the roof's property with the same tilt and orientation. In the present paper, the alternatives will consist of the roof sections but will be referred to as 'roofs'. The distinction between a building, a property and the roofs is illustrated Figure 1 in which a building is divided into two properties, each of them being composed of two roof sections.

Figure 1: Illustration of the definition of a roof.

2.4. Definition of the criteria

In their recent work, (Wijeratne et al., 2019) reviewed more than fifty key factors involved in the designing and management of a PV project. These factors were scrutinised for all types of PV projects, in urban or rural terrains, and for all kinds of stakeholders. As was mentioned in the introduction, the focus of this paper will be on end-users and in the urban environment, which drastically reduces the number of key factors that need considering (Feige et al., 2011; Kanters and Wall, 2016).

The criteria that were identified as the most relevant to analyse the suitability of a roof to host a PV system in an urban area while taking into account the specificities of a given context were:

- the constraint induced by superstructure elements,

- solar irradiation,

- economic feasibility

-the structural robustness of the roof,

-the heritage and aesthetic qualities of buildings,

These criteria and their definitions will be presented in the following sections. Exhaustiveness of the criteria is guaranteed by the experts who were consulted for the present study and for whom the present criteria are representative of the decisional criteria in an urban context. The criteria are also non redundant and the preferential independence is respected.

As mentioned in sections 1 and 2.1, the conventional tools that already exist to sort roofs rely on only one criterion. In order to compare them with a multicriteria sorting method, two monocriterion sorting scenarios are investigated:

- One in which roofs are sorted by only considering solar irradiation (and therefore referred to as the “solar irradiation scenario” from now on)

- One in which roofs are sorted by taking into account the economic feasibility of the installation of solar panels only (a scenario hereafter mentioned as the “economic scenario”).

2.4.1. Superstructure constraints

In many of the current cadastres that have been reviewed, the entire surface of the roof is considered as available and therefore fails to be accurate as the superstructure elements often found on roofs like chimneys, vertical windows, HVAC, and so on, are not taken into account. An illustration of this problem is presented in **Figure *2*** for a solar cadastre of the city of Lyon. The red area on the left-hand side indicates a roof that the solar cadastre estimated to have a very high potential for PV integration but the aerial picture of this roof reveals that there is a large number of superstructure elements, namely two chimneys and three vertical windows. 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, which need to be estimated, lessen the degree of suitability of the roof. In other words, a roof without superstructure elements is more suitable.

Figure 2: Illustration of constraints induced by superstructure elements

2.4.2. Solar irradiation

It corresponds to the irradiation received yearly for each square meter.

Solar irradiation is used as a criterion in all the sortings proposed in existing solar maps (IRENA, 2019b; Lobaccaro et al., 2019a). This criterion provides relevant information about the efficiency of the PV system that would be installed. It also corresponds to an environmental indicator. Indeed, given that solar irradiation is expressed per square meter, it quantifies how much energy a square meter of PV system would produce each year. A square meter of PV system has a defined environmental cost, which depends on the resources that are required for its manufacturing, transportation, usage and recycling. Therefore, the environmental cost, for a given PV technology, is almost directly proportional to the solar irradiation of the roof on which it is installed. It is the case for CO2 savings or for the energetic return on investment.

2.4.3. The economic feasibility

There are different economic indicators that can be evaluated such as the Net Present Value, Levelized Cost of Energy (LCOE), the Return On Investment (ROI), or the Payback Period (PP) (Sommerfeldt and Madani, 2017a). In the case of PV systems, the LCOE corresponds to the ratio between the investment plus the Operation and Maintenance (OM) costs and the energy produced over the lifespan of the system. This indicator is more relevant to the industry or for macro scales (country).

However, when the decision maker is the end-user as it is the case in the present work, there are often additional economic parameters that must be considered. Indeed, in some countries, subsidies are available for the owners and/or installers of PV systems. These subsidies can either depend on the capacity of the PV system or on the amount of energy produced, which must therefore be appraised so as to provide a relevant economic criterion to the funders of the PV system. This is why indicators such as the ROI or the PP can be used.

In the case of PV system, the ROI corresponds to the ratio of the total benefits made from the PV system to the investment cost. The PP corresponds to the amount of time (in years) for the benefits (including subsidies) to equal the investment. In some cases, the ROI and the PP can provide very different and complementary information but when considering PV systems, the yearly benefits are almost constant during the lifetime of the PV system, with small changes due to the lessened efficiency of the PV system through time and to the potential variations in the price of electricity (Sommerfeldt and Madani, 2017a). For these reasons, the ROI and the PP period provide very similar kinds of information. In the present work, the PP will be used as it is the most comprehensive and user-friendly way of displaying economic feasibility.

2.4.4. The structural robustness of the roof

One of the factor that can significantly impact a PV project is the robustness of a roof (Lisell et al., 2009; Wills et al., 2015). Indeed, a square meter of PV systems can weigh between 10 to 20 kg. Depending on the type of the roof, the additional load, that a PV system represents, may be too heavy for the structure and therefore lead to additional work for the integration to be successful, either by finding lighter solutions or by reinforcing the actual structures. In any case, a defective structure results in the necessary re-thinking of the PV project and may sometimes lead to the abandonment of the project.

2.4.5. The heritage and aesthetic criteria

In some areas, such as Europe, there are a lot of heritage buildings for which the integration of PV systems can generate difficulties as it can spoil the aesthetic qualities of some areas (Florio et al., 2018; Probst and Roecker, 2015). In general, the integration of PV systems, onto or in areas close to heritage buildings and districts is either forbidden or must be carefully handled in concertation with the authorities or representatives in charge of local heritage (Groppi et al., 2018). In some cases, the integration of solar panels in heritage areas may induce additional financial costs but also be more time-consuming. It therefore appears that this criterion is of utmost importance when considering the degree of suitability of a roof.

3. Results for a case study in Geneva

3.1. Preliminary considerations

In the present work, the focus will be on already existing buildings which therefore are likely to be referenced in actual GIS cadastres. The case of roof-mounted PV panels will be considered as it corresponds to the simplest and cheapest method of integration for existing buildings (Wills et al., 2015). The polycrystalline PV technology will be the one under scrutiny as it corresponds to one of the most widely used technologies, because of its conversion efficiency of around 17%. However, the same problem could be addressed with another PV technology as long as it is considered for all the presented alternatives.

3.2. Selection of the alternatives

To illustrate the above-mentioned sorting procedure, districts of the city of Geneva will be looked at. The reasons why Geneva was chosen for this study are that the present work is carried out in the context of a French-Swiss project in Greater Geneva. What's more, Geneva offers many data in relation with the buildings, along with the solar cadaster, that can be used for the present work. However, despite the good availability of the data in the area of Geneva, some of the criteria cannot be automatically evaluated and must be manually measured, which, because it is time-consuming, is the reason why the present study is limited to the size of districts which offers reasonable balance between alternative sample size and time-consumption.

In what follows, the case of the Jonction district will be analysed. This district is relevant because it corresponds to a district in the heart of Geneva, with different types of buildings and architectures. Furthermore, this district is frequently used for studies on sustainable energy (see e.g. (Vázquez-Canteli and Kämpf, 2016)). An aerial view of the area of the Jonction district that is looked at in the present work is presented in Figure 3.

Figure 3: Aerial view of the considered part of the Jonction district. Credit: Google Earth

3.3. Available space on the roof

Being able to estimate the available space on a roof is crucial as it is the basis for the calculation of the solar potential of a roof as well as the economic indicators.

To that aim, the shaded areas which correspond in the present case to the parts of the roofs receiving less than 1000 kWh.y/m² are removed from the total surface area of the roof. There are no requirements for the lower limit, and but 1000 kWh.y/m² is a common value used in different solar cadastres (Lobaccaro et al., 2019b).

Secondly, the elements of the superstructures are considered. Ideally, all the superstructure elements and their projected shadows should be identified when evaluating the available space. However, to the best of our knowledge, this has never been achieved: only the largest of superstructure elements have been taken into account in past studies (Desthieux et al., 2018; Walch et al., 2020).

It is the case in the present work as the largest superstructure elements are detected by the LiDAR measurements, (carried with a precision of 0.5 m). The detected elements include some chimneys, air treatment units or vertical roof windows. These elements as well as the corresponding shaded areas (for which the cumulative yearly solar irradiation is less than 1000 kWh.y/m²) are removed from the total surface area of the roof when evaluating the available space for PV integration (Desthieux et al., 2018).

This is illustrated in **Figure *4***. In this figure, the elements of the superstructure that are detected by the LiDAR measurements are framed in green in **Figure *4*** (b) and are therefore removed from the available surface area represented in **Figure *4*** (a). The case of the undetected elements is addressed in section **A.1 Superstructure constraints**.

In the rest of this work, the available surface corresponds to the surfaces as presented in **Figure 4** (a), which takes into account a minimum threshold of 1000 kWh.y/m² and the presence of the large superstructure elements. This available surface is used for the calculation of solar irradiation and economic feasability.

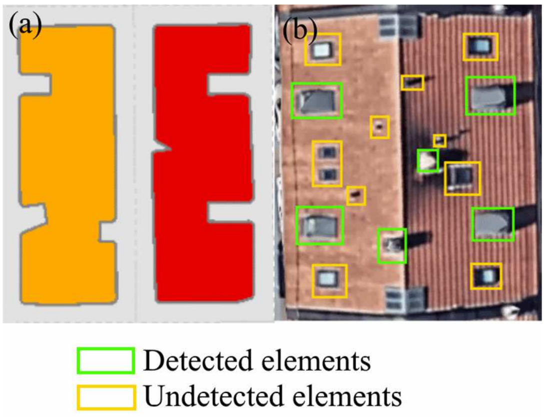

Figure 4: Detection of the superstructure elements of a roof. (a) available roof surface for PV integration according to Geneva solar cadastre, the difference in colors indicates different level of solar irradiation (b) aerial view of the same roof, with superstructure elements that are detected in the Geneva cadastre (surrounded by a green rectangle) and the elements not detected in the cadastre (surrounded by a yellow rectangle).

3.4. Description of the alternatives

The description of the alternatives highly depends on the available data. Here, the data used are mostly obtained from Geographical Information System layers that are available for the Geneva city (SITG, 2020). These layers of data have been made available by different experts. For the solar irradiation, the data used is provided by the solar cadastre of Geneva(SITG - Cadastre Solaire, 2020); for the other criteria, some post-processing of the data provided by the GIS layers is necessary.

For the sake of concision, it has been decided to only present a short summary of the evaluation metrics of each criteria in **Table 2**. However the detailed evaluation method for each criterion is presented in **Appendix: Description of the alternatives**.

Table 2: Summary of criteria evaluation metric and source

Criteria	Evaluation metrics	Source
Superstructure constraints	Density rate of undetected superstructure elements	Manual evaluation from aerial pictures (SITG, 2020)
Solar irradiation	Yearly solar energy received per m²	(SITG - Cadastre Solaire, 2020)
Economic Feasability	Payback Period	Method in Appendix
Structure Robustness	Roof covering material	Manual evaluation from aerial pictures (SITG, 2020)
Aesthetic and heritage integration	Visual criticity (Probst and Roecker, 2015)	Heritage database of Geneva Municipality (SITG, 2020)

3.5. Identification of the ELECTRE TRI parameters

It is now necessary to determine the weights of the criteria, the number of groups as well as the performance profiles *i.e.* the upper and lower bounds of the groups. This must be done by consulting experts in the fields of urban solar photovoltaic. In our case two experts were consulted. These experts are professional of installation and monitoring of PV systems in urban sectors with several years of practice in the fields of implementation of urban PV.

The experts came to the agreements that the economic feasibility was the most important criterion. It was then followed by the structural, aesthetic and superstructure constraints criteria, which were evaluated to have the same importance. Finally, the solar irradiation criterion was considered as of least importance. Indeed, despite that the solar irradiation is a necessary information to evaluate the economic feasibility, once the economic indicator has been calculated, the information about the solar irradiation in itself is only useful for energy or environmental consideration as mentioned in section 2.4.2.

By using the Simos methods (Figueira and Roy, 2002; Simos, 1990) it is then possible to attribute relative weight to each criterion as presented in Table 3.

Table 3: Experts' set of weights

Normalized weights	weights
Superstructure constraints	0.18
Economic feasibility	0.36
Structure Robustness	0.18
Aesthetic integration	0.18
Solar irradiation	0.11
Total	1

There are no recommendation regarding the number of groups that should be defined for the present sorting problem. Considering the case of solar cadastres currently available worldwide, the number of groups can vary between two and seven. In the work of (Lee et al., 2018), they used hierarchical clustering analysis method and claimed that four groups represented an optimal number of groups for their sorting problem that was considering economic and energetic criteria. (Sánchez-Lozano et al., 2016, 2014) also used four groups in their sorting of the locations for potential solar farms. For these reasons the use of four groups seems reasonable. Please note that the present methodology could be easily adapted if the numbers of groups were modified. The four groups considered here correspond to four degrees of suitability and will be referred to, Low, Moderate, High and Very High degree of suitability.

The category limits are presented in Table 4. Note that the structure and aesthetic criteria are qualitative. It is therefore necessary to convert them into numerical value, as displayed in brackets of Table 4. The limits between the low, moderate, high and very high groups for the aesthetic and structural criteria are then 3,5 and 7. Finally, for the structure robustness criterion, no alternatives were assigned to the moderate category as this group was considered as non-relevant by the experts. For that reason a "-" appears in the corresponding cell.

Table 4: Group definition, for the qualitative boundary, the numerical conversion is indicated in brackets.

Degree of suitability	Low	Moderate	High	Very High
Superstructure constraints - d (elements/m²)	≥0.125	[0.125-0.062[	[0.062-0.031[	≤ 0.031
Solar irradiation (kWh.y/m²)	[1000-1100[	[1100-1200[	[1200-1300[	≥1300
Economic (years)	[25-20[	[20-15[	[15-10[	≤10
Structure	Metal-Based (2)	-	Slate (6)	Tiles or Flat Roofs (8)
Aesthetic	Heritage buildings (2)	Noticeable architecture (4)	Neighbor to heritage buildings	Other buildings (8)

Finally, the indifference, preference and veto thresholds were also discussed with the experts and were reported in Table 5.

For the two monocriterion sorting scenarios, the same group bounds and thresholds than these discussed with the expert will be conserved.

Table 5: Indifference, preference and veto thresholds

Thresholds	Indifference threshold	Preference threshold	veto
Superstructure constraints	0.02	0.04	-
Solar irradiation (kWh.y/m²)	10	50	200
Economic	1	2	5
Structure	1	2	-
Aesthetic	1	2	5

3.6. Results of the sorting and discussions

A recent open-source webservice, diviz (Meyer and Bigaret, 2012), developed by the Decision Deck Consortium (Decision Deck Consortium, n.d.), allows the users to implement the ELECTRE TRI method as a workflow.

The main steps of the process are data recording, data conversion, concordance, discordance and credibility processing, and finally the displaying of order relation. Finally, it supplies the sorting of these alternatives. Then, the results are imported in ArcGIS to display the sorting as a GIS layer.

3.6.1. Expert sorting scenario

The results for the expert sorting are displayed in Figure 5 and summarized in

in Table 6. One of the alternatives corresponds to a particularly large roof the surface of which accounts for almost a third of the cumulative available surface of the considered alternatives. This alternative has a very high degree of suitability and occupies an important share of the total surface. For this reason, the results are presented with and without this large roof in Table 6.

Table 6: Results of the ELECTRE TRI sorting. * Numbers in bracket corresponds to the corrected number in the case the large roof is not considered.

Category	Number of alternatives	Share of the total number of alternative in %	Surface in m²	Share of the total roof surfaces in %
Low	57	33.5	927	4 (6)*
Moderate	61	25.5	3136	13 (20)*
High	57	28.5	5018	21 (32)*
Very high	15	7.5	15024 (6817)*	62 (43)*

The high and very high degrees of suitability are mainly reached by the largest roofs. This is expected as they usually have better economic feasibility, this criteria weighing for more than a third of the total weights. Naturally, smaller roofs are more likely to belonging to the low degree of suitability category. However, it should be noted that, in this case study, a self-consumption rate of 25 % was assumed for all buildings. If it was possible to estimate an individual self-consumption rate for each building, this sorting would be modified, especially for small buildings with high self-consumption rate.

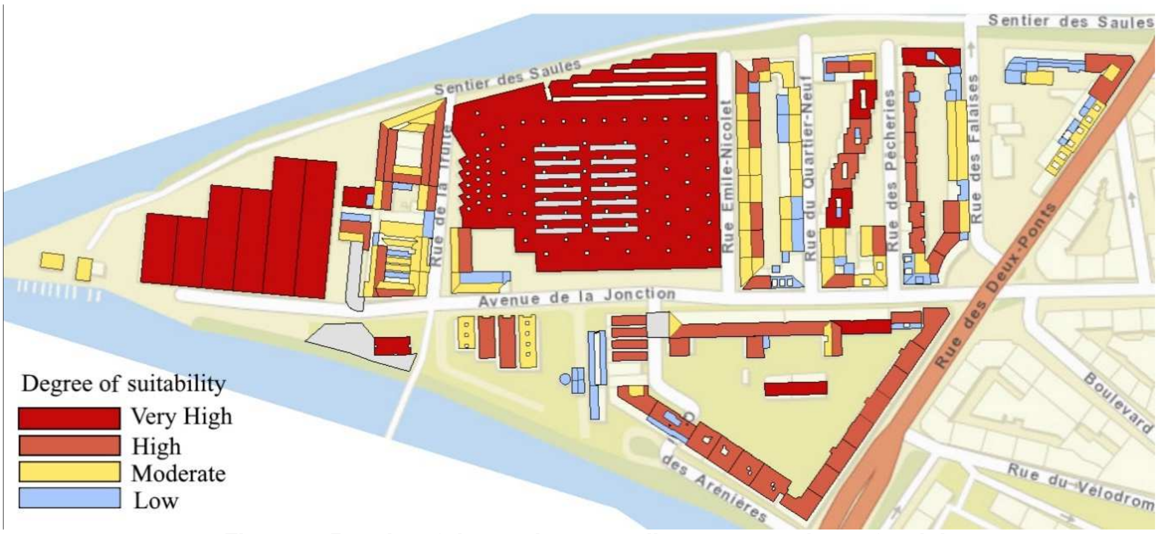

Figure 5: Results of the sorting according to experts' set of weights

3.6.2. Comparison with monocriterion sortings, discussions and perspectives

The results of the three different sorting scenarios are illustrated in Figure 6. Considering for example the roof framed by a dashed line, the expert sorting assigns the alternative to a high suitability, which is midway between the solar sorting (very high) and the economical sorting (moderate). This illustrates how this method takes into account the multicriteria aspects of the problem by nuancing the results that would have been obtained with monocriterion perspectives.

More generally, for the economic sorting, none of the represented alternatives reaches the category of very high suitability because none of the presented roofs is sufficiently large and receives enough irradiation to reach this category. One of the most important differences here is between expert and the solar sortings. In the solar scenario, eight of the represented alternatives are assigned to the very high group whereas only one roof reaches this category in the expert sorting. This is mainly due to poorer performances in the other criteria.

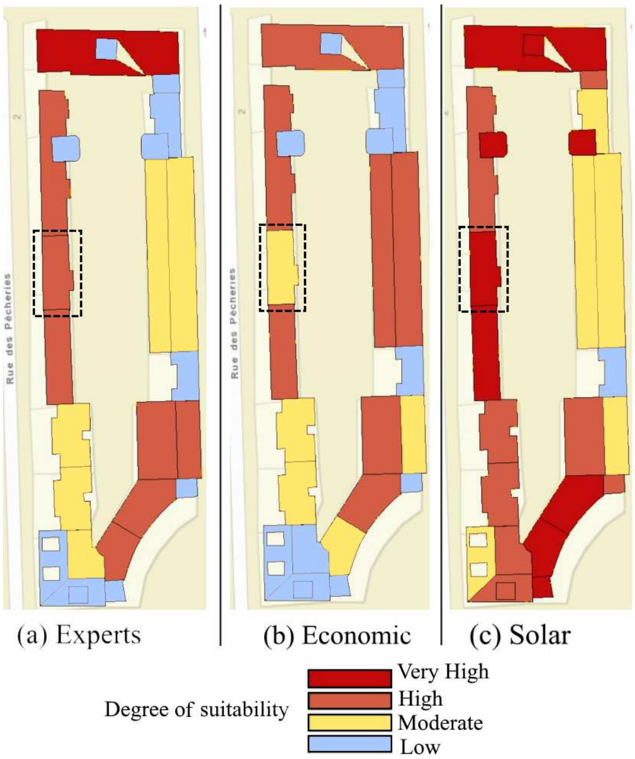

Figure 6: Results of the sorting process based on the different set of weights. (a) Expert sorting, (b) Economic sorting, (c) Solar sorting.

This difference is even more pronounced in heritage districts as illustrated in Figure 7. Even though some of these roofs have very high solar irradiation, the fact that they are located in a district regarded as urban heritage renders these roofs moderately or lowly suitable, which corresponds better to the reality of the urban environment.

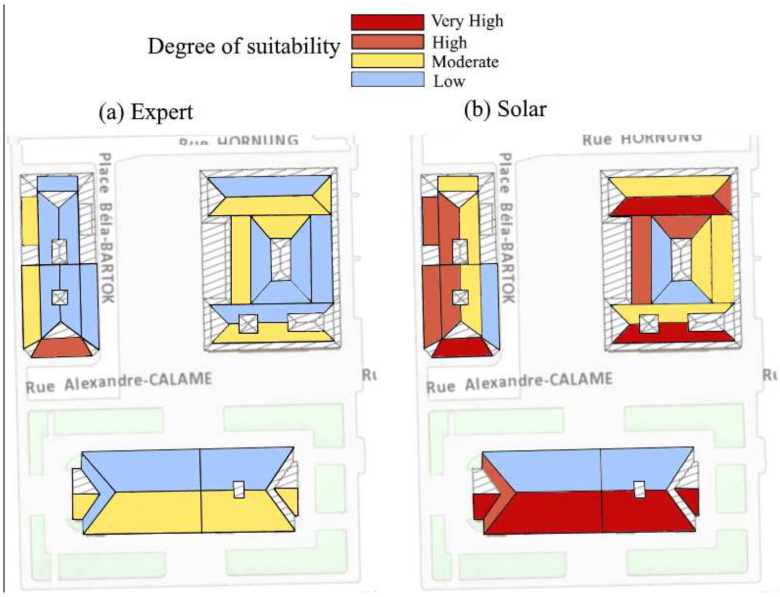

Figure 7 Sorting of the alternatives in heritage sensitive area according to (a) expert sorting, (b) solar sorting

Multicriteria sorting allows here the inclusion of the decisional criteria of the suitability of a roof for PV integration in an urban environment. It can be observed that the information provided by the multicriteria sorting is different and more realistic, from those that are provided by monocriterion approaches and in particular the solar cadastre approach that is only based on solar irradiation. Moreover, the proposed sorting can be easily adapted to the local context or to the concerned actors, which makes it highly scalable to other case studies in other urban areas.

This multicriteria sorting could be used in order to help decision makers achieve the 2050 PV deployment goals mentioned in the introduction. For example, municipalities or government could implement a similar sorting method in order to help and guide citizens in their decision to install PV systems on their roofs. On a larger scale, such sorting could be used by urban and energy planners to identify large amounts of highly suitable roofs, for example from the building categorized as high and very high, on top of which PV panels could be installed in priority (Amado et al., 2016; Cipriano et al., 2017).

The main perspective for this case study would be to collect data more efficiently. This could be done by on-site studies or polls. Another way would be to replace the manual evaluation of some criteria (here structure robustness and superstructure constraints) by an automated method. This could be achieved by using methods such as the convolutional neural network that would allow the deployment of the sorting on the level of an entire city and its easy application to other cities.

The evaluation of the available surface for PV integration could also be improved by using the geometric-regularity criterion defined by (Peronato, 2019). This approach consists in filling the available space on the roof by projecting virtual rectangles that have the size of a PV panel. Then, the rectangles for which irradiation is below a certain threshold are removed. This allows to have a more realistic estimation of the space available for PV panels as was for example done in (Walch et al., 2020).

Finally, individual evaluation of the self-consumption rate would allow to estimate more precisely the economic benefits and therefore improve the quality of the evaluation of the degree of suitability.

4. Conclusion

In the present work, a sorting procedure of roofs is proposed. It is based on their degrees of suitability to be equipped with PV systems. This sorting is devised for the actors of the deployment of such technology in urban contexts, be they real-estate owners, associations or entrepreneurs interested in the deployment of solar energy and willing to invest in it.

The ELECTRE TRI methodology is used here as it is a relevant and serious sorting method which has been successfully applied in past studies exploring the deployment of sustainable energy in urban contexts and of PV farms on larger scales. Moreover, this method can be easily adapted, which is crucial for the installation of PV systems since it highly depends on local policies and contexts.

Whereas the number of criteria that are considered for the suitability of a roof in actual solar cadastres and previous works rarely exceeds two, five decisional criteria are considered in the present work. These criteria are the solar irradiation, economic feasibility, structural robustness of the buildings, their aesthetic and historic qualities and the free space on the roofs. The historic, structural and free space criteria are of upmost importance when evaluating the suitability of a roof but were never considered before in a multicriteria study of the suitability of roods for the installation of PV systems.

Three different sorting scenarios are considered: the expert sorting, the economic sorting and the solar sorting. The expert sorting involves several criteria, whereas the economic and solar sortings are monocriterion approaches.

The results of the multicriteria sorting are displayed with a simple color-based representation and help understand and take into account the complexity of urban environments, which monocriterion approaches fail to achieve. Such sorting could be used by end-users in order to assess the degree of suitability of a roof for PV integration. If deployed on the scale of a whole city, this type of multicriteria sorting could also represent a powerful tool to help local authorities meet the PV deployment goals by 2050.

Appendix: Description of the alternatives

A.1 Superstructure constraints

Despite the detection of numerous superstructure elements, there are still some elements which cannot be identified by the LiDAR measurements as can be seen in **Figure *4*** (b). They are small superstructure elements on the roofs (small chimney, exhaust pipes, etc.), and elements which are integrated in the plane of the roof such as in-plane roof windows or glass elements of roofs. These elements must be considered for PV integration as they reduce the suitability of the roof. These elements can only be identified visually from aerial views.

To account for these elements, a density rate, noted d, will be calculated as the number of superstructure elements per square meters of available surface area. For d value of zero, there are no elements on the available surface. As d increases, the number of undetected elements per square meter increases. A high value of d consequently corresponds to more constraints from the superstructure elements inducing a more complex integration of PV *i.e.* a lower degree of suitability.

As an example the left and right roofs in in **Figure *4*** have the same available surface of 74m² and respectively six and five undetected elements. This leads to a density rate of respectively $d = 0.081$ elements/m² and $d = 0.067$ elements/m². In the present work, d is manually evaluated, from aerial images of the roofs, for each of the considered roofs.

A.2 Solar irradiation

The evaluation of the solar irradiation relies on the 3D-Geographical Information System (GIS) models developed at HEPIA Geneva. They used LiDAR data from 2016 to generate a Digital Surface Model (DSM), which represents the three-dimensional urban geometry of Geneva. Then, they applied solar radiation models which are detailed in (Desthieux et al., 2018). The calculated solar radiation for each roof section was then implemented as a GIS in the solar cadastre of Geneva (SITG - Cadastre Solaire, 2020).

The solar radiation calculation takes into account the orientation of the roof, its slope, the local meteorological data, distant shading (mountains, relief) and near shading (shade from surrounding large superstructure elements, buildings or trees). The solar irradiation of a roof is then defined as the space-average of the amount of solar energy received yearly on the available surface of a roof. It is therefore expressed in kWh.y/m²

A.3 Economic feasibility

To evaluate the economic feasibility of a roof, the discounted Payback Period, referred here as PP is considered. It is calculated similarly to what is proposed by (Sommerfeldt and Madani, 2017a) as follows:

$$PP = T, C_T + B_T = 0$$

Where T is the number of year to start earning money from the PV system, C_T and B_T are respectively the costs and benefits of the PV system from its installation to year T.

$$C_T = I_0 + \sum_{t=1}^{T} \frac{OM_t}{(1+r)^t}$$

Where I_0 stands for the initial investment cost, including taxes, OM_t stands for the operation and maintenance costs at year t and r is the discount rate.

$$B_T = S_0 + \sum_{t=1}^{T} \frac{Q_d P_r + Q_e P_w}{(1+r)^t}$$

In which S_0 stands for the subsidies granted by the government for the installation of a PV system. Q_d corresponds to the energy self-consumed which corresponds to savings from deferring purchases of the grid at the retail price P_r. Q_e corresponds to the excess production of energy, sold to the market at the wholesale price P_w.

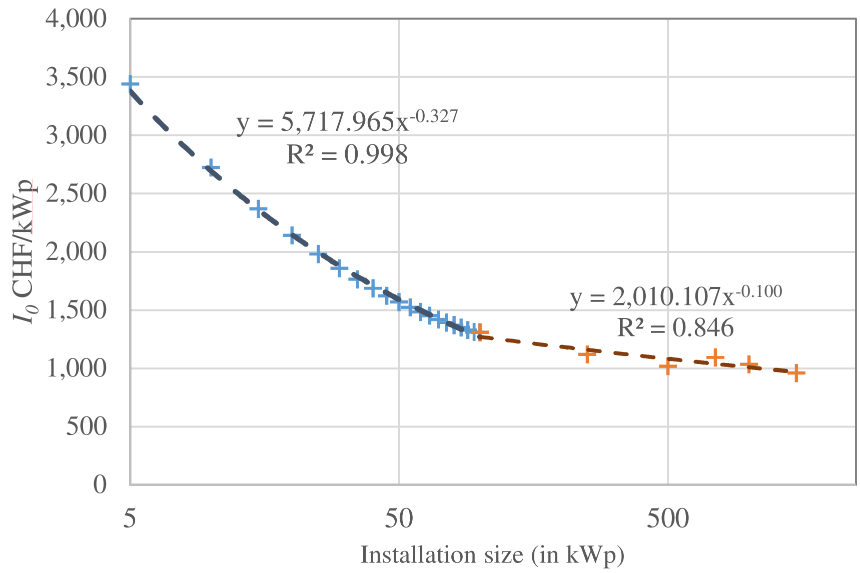

Figure 8: Estimate of the investment price for a PV system as a function of its capacity

The investment price of a PV system depends on its size. The size of a PV system is often expressed in kWp (kilo Watt peak) installed. The market price in Switzerland for a classic roof-mounted PV installation was evaluated thanks to a design tool developed by Swiss experts (SwissSolar, 2020) and reported in Figure 8. To approximate these data, two power-law interpolation curves were used between 5 and 100 kWp and between 100 and 800 kWp respectively. In what follows the investment price (I_0) for a PV system is calculated from these interpolation curves. The yearly operation and maintenance costs OM_t are evaluated at a fixed cost of 1% of the investment cost I_0 (Sommerfeldt and Madani, 2017b). A discount rate value of $r = 3\%$ is considered (Sommerfeldt and Madani, 2017b).

The values of Q_d and Q_e depend on the self-consumption rate of the building on which the PV system is installed. In order to precisely determine these values for each building, sub-hourly data of PV production and building electric power consumption are required (Luthander et al., 2015). If possible, it is highly recommended to follow this approach in order to accurately evaluate the ROI for each individual building.

However, such a high quality of data is difficult to obtain on a large scale. Indeed, the sub-hourly building energy consumption may not be recorded as it requires individual smart meters, and even when it is recorded it is often not available as it relates to the building inhabitant's privacy. Regarding the sub-hourly PV production, such information could be obtained on individual building scale by using simulation software. However, most of the time for larger scale estimation (city scale), only yearly or monthly PV energy production information is provided.

In the present case study, the PV energy production is provided on a monthly basis. Regarding the consumption of energy of the building, data is available. However, they only provide an annual value for the energy consumption. Furthermore, they do not provide information as to the total electrical energy consumption of the building. For these reasons, it is impossible to calculate the exact self-consumption rate for each individual building. In the present work, an average self-consumption rate of 25% was therefore considered. Note that this assumption may not favor small owners and households with high electric energy needs. Indeed, in these cases, a higher self-consumption rate can be reached, which could significantly improve the ROI and therefore the economic feasibility.

In the present case, it is considered that the PV systems are installed on the total available area of a roof for tilted roofs. In the case of flat roofs, it is considered that the PV systems are installed on 70% of the available area with a tilt angle of 30°, considered as optimal at these latitudes (Walch et al., 2020; Wills et al., 2015). The space left between each rows of PV avoid self-shadow casting. This type of installation is illustrated on a Geneva building in Figure 9.

Figure 9: Aerial view of a flat roof implementation of PV systems on a building in Geneva.

A.4 Structure Robustness

The best way to evaluate the robustness of the roof structure is to conduct an on-site study with a structural engineering office. However, this approach would be extremely difficult and costly on a large scale and therefore is not contemplated here.

Nevertheless, there are indirect ways to estimate whether the structure is likely to be sufficiently strong to host a PV system by analyzing the roof material. Indeed, roof materials have very different weights, and therefore impact differently on the structure. There are mostly two types of roofs: terrace roofs and tilted roofs. Terrace roofs are flat and are designed to support a heavy weight so that the implementation of PV system on them raises no issue. It is different for tilted roofs, the structural robustness of which is designed to support the covering material of the roof. The three most common roof materials in the Geneva agglomeration are clay tiles, slates and steel. The average weights per square meter for each of these materials are presented in **Table *7***. The average weight of PV systems is around 15 kg/m². It therefore appears that the additional load of PV system on a clay tile roof is small and therefore it is very likely that the actual structure is robust enough to support it. Regarding slate roofs, it is likely that the roof structure would be weaker than clay tiles and the additional load may consequently endanger the structure of the roof. Finally, aluminum or steel-based roofs are much lighter than PV system and therefore it is very likely that the roof structure needs reinforcing if equipped with PV systems.

Table 7 Common roof materials and their weights

Material	Average weight kg/m²
Aluminum/Steel/Copper	5
Slate	50
Clay tile	100

The identification of the roof types and roof materials is done manually from the aerial view of the building, for each of the considered roof.

A.5 Aesthetic and heritage integration

Information about heritage buildings and districts is available for the city of Geneva in the database of the Municipality of Geneva, in open-access as a GIS in the SITG website (SITG, 2020). In this database, an exhaustive list of the protected buildings and their level of protection is available.

Following a similar fashion as (Probst and Roecker, 2015), the aesthetic and heritage criteria will be graded following a visual criticity scale. In their work, they created a visual criticity indicator that was defined as the aggregation of both the heritage criticity of the building/district and the visibility of the roof. A building with a high level of heritage protection but for which the roof was almost not visible from the street was considered as less critical than a roof on a building with the same heritage protection level but that was more visible. However, whereas the heritage protection level is available for the whole Geneva, the map of the visibility of the roof is not. As a consequence, only the heritage aspect of the building will be considered in the visual criticity scale in this paper.

The highest visual criticity is reached with heritage buildings or heritage districts. Then, some building in Geneva are considered as “architecturally noticeable”. For these buildings, the criticity is high but not as high as for heritage buildings. Buildings which are neighbors to heritage building should also be considered with some care.

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