Large-scale multicriteria sorting for the integration of photovoltaic systems in the urban environment

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Abstract

This work proposes a multicriteria approach in order to evaluate the suitability of a building to be equipped with Photovoltaic (PV) systems. In the present case, technical (roof complexity), economic (payback period), environmental (CO2 reduction), energetic (self-consumption) as well as social (heritage constraint) are considered. These criteria are evaluated for each building of the Great Geneva agglomeration, then a multicriteria methods, ELECTRE TRI, allows to sort these roofs in three categories that corresponds to "Very High", "High", "Moderate" suitability.

Key Innovations

- Multi-criteria classification including heritage, economic, energetic and technical criteria
- Large scale GIS evaluation of criteria for building PV installation
- Multi-criteria sorting at a territory scale

Practical Implications

This work presents a method to evaluate the relevance of a building to be equipped with PV systems, based on a multicriteria approach. It allows to provide a ranking of the roofs at a wide scale (here a territory), and provides a simple information based on more complex layer of information. Such approach can be used by the different decision makers related to solar energy deployment in cities.

Introduction

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 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.

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 et Wall 2016; REN21 2019). 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 (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 (IRENA 2019; 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 requires additional financial, or aesthetic efforts. It consequently appears that the answer to whether a roof is suitable for the installation of PV systems (PV-suitability) is not binary but requires nuancing and taking into account different relevant criteria (Thebault, Cliville, et al. 2020; Thebault et Gaillard 2021). 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. 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.

To deal with this aspect we have already proposed to develop a multicriteria sorting to assess the suitability of the roofs to be equipped with PV system (Thebault, Clivillé, et al. 2020). However, this work was carried at a district scale (nearly 100 buildings). In order to provide a relevant information to the majority of the actors of solar energy, it is, necessary to develop method which can be applied at larger scale, which in this case, represents the city scale. The present communication is therefore in the continuity of (Thebault, Clivillé, et al. 2020) and proposes a Geographical Information System (GIS)-based sorting of the PV-suitability of the roofs of the Geneva agglomeration. To that aim, different criteria related to the installation of PV systems are identified. These criteria are evaluated using data that are available at large scale, usually in GIS format. To proceed with the multictriteria sorting, the ELECTRE TRI methodology is used. Finally, the results are presented and discussed for the case of the Great Geneva agglomeration.

Methods

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, Greco, et Ehrgott 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 $C = \{C_1, \ldots, C_j, \ldots, C_N\}$ 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 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, a 'pessimistic' sorting is adopted which consists sorting the alternatives in the lowest category possible. Sort the alternative a in a category such as it outranks the lower bound of this category i.e. $aSb_j \Rightarrow a \in C_{j+1}$. It is also possible to consider an 'optimistic' sorting which process is slightly different and that would nuance the sorting of some alternatives to a higher category.

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)

Definition and evaluation of the criteria

For the present analysis, several criteria have been considered. These criteria relate to:

- the self-sufficiency,
- the economic benefit,
- the environmental benefit,
- the roof complexity,
-the heritage and aesthetic qualities of buildings,

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

Criteria 1 (C1): The self-sufficiency

One of the main goals related to the use of solar energy is to increase the share of PV electricity production. One way to do so is to consume a part of it locally (Luthander et al. 2015). This is referred to as self-consumption, and is particularly suitable in urban context where each building can produce and consume energy.

The two most usual cases of self-consumption are the on-grid and the off-grid configurations. The off-grid configuration consists in a building equipped with PV systems which is not connected to the grid. In this case, all the produced energy from the PV systems must be consumed by the building itself. In Europe, the off-grid configuration corresponds to a small minority of the cases which often corresponds to isolated buildings, which, by definition, have no impact on the electrical grid. The on-grid configuration corresponds to a building, equipped with PV systems, which injects whole or a part of its PV production in the grid. This configuration represents the large majority of the cases, especially in urban environments.

Self-consumption can have several co-benefits: it limits the ramp-rates and the reverse power flows. It also, in some cases, can increase economic benefits. Finally, self-consumption has also a 'social impact' in the way that it allows the PV system owner to develop the feeling that he is directly contributing to the energy transition by consuming local and renewable energy (Luthander et al. 2015).

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 $\tau_{ss}$is defined as the share of total building energy demand that is being supplied by the PV systems.

In the present case the self-sufficiency rate will be considered. Indeed, this indicator gives an information on how much the presence of PV panels, can reduce the energy consumption of a building.

In order to evaluate the self-sufficiency, two information have been used: the monthly solar irradiance and the energy consumption. The evaluation of the solar irradiance relies on the 3D-Geographical Information System (GIS) based irradiation model, that has been developed at HEPIA (Desthieux et al., 2018) (An illustration of the solar irradiance as displayed by the solar cadastre is presented in Figure 1). The information is provided through a solar cadastre information system that covers the entire Great Geneva agglomeration area. This cadastre takes into accounts the roof orientation, the roof slope, the local meteorological data, the distant shading (mountains, relief) and the near shading (shades from surrounding buildings or trees) and has been recently extended to the entire Great Geneva region (Stendardo et al. 2020).

Figure 1: Solar irradiation as displayed by the solar cadastre of Geneva. Orange colour indicates a roof that receive between 1000 and 1200 kWh/m²/y. Red colour indicates roofs that receive more than 1200kWh/m²/y

Criteria 2 (C2): The economic benefit

Different economic indicators can be used when related to photovoltaic energy (Sommerfeldt et Madani 2017). Among them the Payback-Periods (PP) is probably one of the most meaningful to non-experts. The PP corresponds to the number of year which are necessary to refund the initial investments, including local subsidies and operation and maintenance cost.

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.

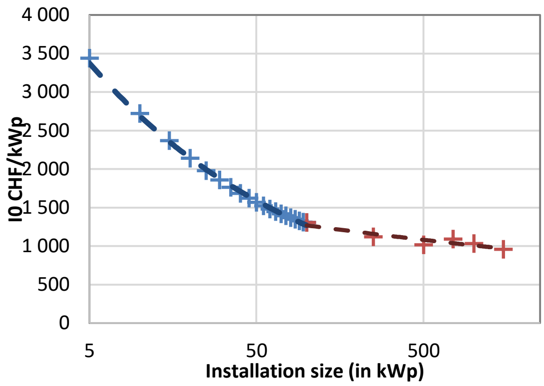

Figure 2: Estimate of the investment price for a PV system as a function of its capacity. Two correlations were deduced from these data, one obtained for small-medium installation the blue part (exponential) and one for the large installation, the red part (linear).

The investment price of a PV system depends on its capacity (in kWp (kilo Watt peak)). The market price in Switzerland for a classic roof-mounted PV installation was evaluated based on data from (SwissSolar, 2020) as reported in Figure 2.

Criteria 3 (C3): The environmental benefit,

There are several ways to evaluate environmental benefits of an urban photovoltaic system. Here it has been decided to consider the reduction of CO2 emissions. Indeed, in most of the European countries, the CO2 emissions associated with the production of 1kWh of energy are more than these from 1 kWh of Photovoltaic energy.

Considering the European mix, the average emissions associated with the energy production was of $e_{CO2,UE}$ =0.275 kgCO_2/kWh in 2019 (European Environment Agency 2021). Regarding PV panels, a life-cycle assessment of the NREL allowed to estimates their emissions around $e_{CO2,PV}$ =0.050 kgCO$_2$/kWh (NREL 2012).

Therefore, here, the reduction in CO2 emissions of a photovoltaic system was calculated as

$$Red_{CO2} = Q \times (e_{CO2,UE} - e_{CO2,PV})/A_{PV}$$

Where Q is the total energy production of the PV system and A_{PV} the area of the PV system (in m²).

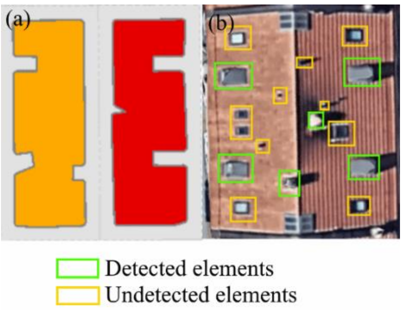

Figure 3: Detection of the superstructure elements of a roof. (a) Geneva solar cadastre available roof surface, the difference in colors indicate different solar irradiance (b) aerial view of the same roof, with detected (surrounded by a green rectangle) and undetected elements (surrounded by a yellow rectangle).

Criteria 4 (C4): The 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 as simple. Indeed, most of the roofs have superstructure elements such as chimneys, vertical windows, HVAC. These elements reduce the available space for the integration of PV systems but also increase the constraints for this integration as the shadows casted by these elements, lessen the degree of 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 therefore reducing the suitable are for PV panels installation. However as illustrated in Figure 3, 1 - not all the elements are detected. There are, to our knowledge, no available databases for the presence of these elements, and the manual identification of elements is timely and therefore cannot be applied at a city scale.

One way to quantify the number of superstructure elements on the roof is to evaluate the standard deviation of the roof slope from the LiDar data. Indeed, slope of the roofs are calculated from the LiDar measurements. These measurements consist in an evaluation of the height of each spatial point with an accuracy of 0.5m. From these measurements it is possible to identify the presence of the roof and its inclination. However, when there are superstructure elements, the standard deviation (SD) of the roof slope increases. Note that this approach does not enable to identify 'in plane' superstructure elements such as in plane windows or already installed solar systems.

Criteria 5 (C5): The heritage integration

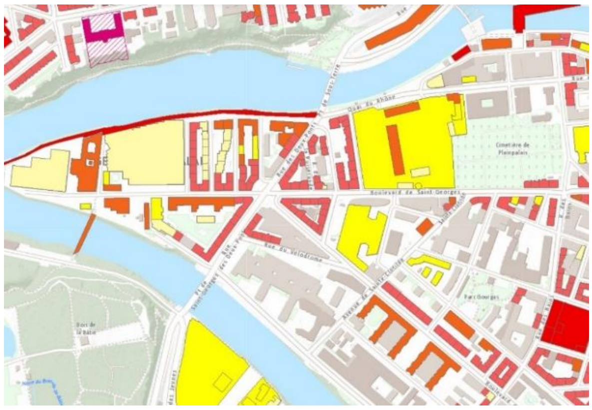

Figure 4: Heritage constraint on building in the centre of Geneva. Different colours indicate different type of heritage classification. Red colour indicates high level of heritage protection. Orange indicates medium level and other colours were considered as low level of protections regarding solar integration.

In some areas, such as Europe, there are a lot of heritage buildings for which the integration of PV systems can by difficult as it can spoil the aesthetic qualities of some areas (Florio et al. 2018; Probst et 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.

Table 1: Summary of criteria evaluation metric and source

Criteria	Evaluation metrics	Source
C1 Self-sufficiency	Share of total building energy demand that is being supplied by the PV systems (in %)	Solar irradiance (SITG - Cadastre Solaire 2020) and building consumption (SITG 2020)
C2 Economic benefits	Payback period (in years)	Solar irradiance, building consumption, investment prices (SwissSolar 2020)
C3 Environmental benefits	Reduction of CO2 emission (in CO2/m²)	Solar energy production and CO2 emissions of the UE mix.
C4 Roof complexity	Standard deviation of the slope of the roof	Numerical model of the surface (SITG 2020)
C5 Heritage integration	Experts rating	Heritage database of Geneva Municipality (SITG 2020)

In the present case there are different classes of protection

Table 2: Set of weights and threshold. These parameters are determined based on discussion with experts of the fields (academic, private companies, local authorities)

Criteria	weights	Indif.	Pref.	Veto	Obj..
C1	0.15	1%	3%	-	max
C2	0.40	1	3	12	max
C3	0.15				max
C4	0.15	2	4	-	min
C5	0.15	0	1	2	min

related to heritage buildings. These classes are referenced in a SIG layer (SITG 2020) as displayed in Figure 4. These level of constraints have been discussed with experts of the Swiss and French heritage buildings. It was decided that these heritage constraints could be sorted in three level: High heritage constraint, Moderate heritage constraint, and no heritage constraint.

A summary of the criteria, the associated indicators and there sources is presented in Table 1.

Results and discussion

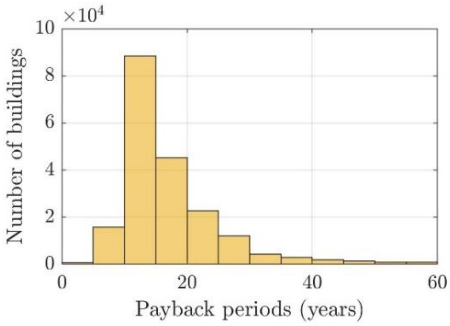

Figure 5 Histogram of the payback period of the buildings of the Great Geneva

In the present work the focus will be on already existing buildings which are likely to be referenced in the actual GIS database. The case of roof-mounted PV panels will be considered as it corresponds to the simplest and cheapest integration method for existing buildings. The polycrystalline PV technology will be considered as it corresponds to one of the most widely used technology, essentially mature. Its conversion efficiency is around 17%.

Description of the alternatives

In total the Great Geneva consists of nearly 270 000 buildings, each of them being an alternative for the present case. The French part has 150 000 buildings whereas the Swiss part has the remaining 120 000.

Figure 5 and Figure 6 shows the evaluation of the criteria 2 (Economic) and 5 (Heritage) at the Great Geneva scale. The Payback periods of a PV system for the buildings of the Great Geneva mostly ranges between 5 and 30 years. It can also be seen that the vast majority of the buildings have low or no level of constraints.

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 sorting group).

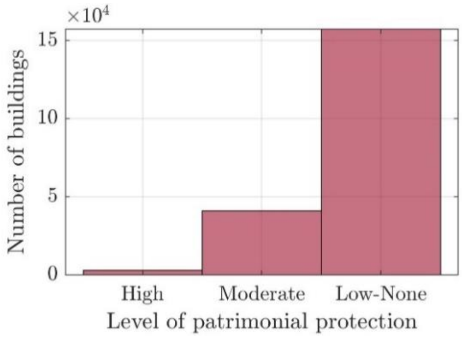

Figure 6: Histogram of the heritage constraints of the buildings of the Great Geneva

In the present case it was decided to create 3 groups of suitability referred to as 'Very High', 'High' and 'Moderate' suitability. The reason is that in the present case there is already a preliminary selection during which, all roofs which receive less than an average of 1000 kWh/m²/year are disregarded. Therefore, we only consider roofs that already receive a decent level of irradiation. The bounds for each of the group are presented in Table 3. These bounds were discussed with experts in the fields and local decision makers.

Table 3: Group definition

Suitability	Moderate	High	Very High
C1 Self-sufficiency	<20%	[20%-30%[	≤ 30%
C2 Economic benefits (years)	>18	[18-12[	≤12
C3 Environmental ($kgCO_2/m^2$)	<20	[20-40[	>40
C4* Roof complexity	<9	[9-18[	>18
C5 Heritage constraint**	High (1)	Medium (2)	Low (3)

* these values can be read as: <9 Few superstructures elements, [9-18[moderate number of superstructure elements, >18 many superstructure elements.

** The qualitative value is converted into a quantitative value presented in brackets.

After discussing with experts of the field (academics, industrials, start-ups in urban solar energy field) it appeared that the economic feasibility was the most important criterion. Using the Simos methodology (Figueira et Roy 2002), we came to the following set of weights Table 2. The indifference, preference and veto thresholds were also validated against experts and are reported in Table 2.

Results of the sorting

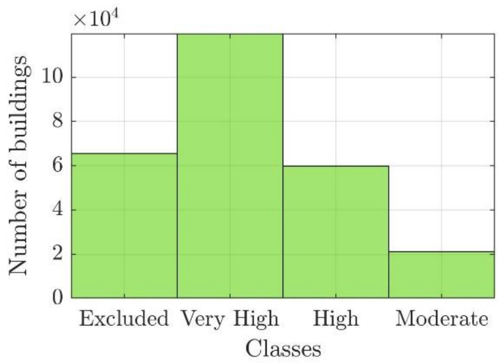

Figure 7 Repartition of the buildings into the three classes, the amount of buildings that have been excluded is also displayed.

The methodology is applied for the entire Geneva agglomeration and allows to sort all the building into three classes. The repartition is presented in Figure 7. According to the irradiance excluding threshold, nearly ¼ of the Geneva building were excluded. Considering now the building that have been sorted, 60% of them were sorted as 'Very High', 30% as 'High' and 10% as 'Moderate'. Note that, this repartition depends on the parameters presented above (weights, bounds of the limits, thresholds etc).

An overview of the results for the city centre of Geneva is presented in Figure 8. As it can be noted, most of the biggest roofs are coloured in Green meaning that they have a very high suitability. This result is expected here as the largest surfaces are usually the most profitable due to the economy of scale in the investments needed for the PV system. It can also be observed that, in the right part of Figure 8 there are very few building with a 'Very High' suitability. The reason is that this area corresponds to the old town of Geneva and most of the building there have heritage constraints.

This type of methodology has many interests:

- It allows to have simple information based on an elaborate multicriteria methodology,
- It can provide a decision aiding tool for many actors (local authorities, citizens, association), in order to guide them through the process of installing PV system,
- At a district scale, it allows to identify districts with high suitability. These districts could then be prioritized in urban energy plan.
- This methodology also allows to identify districts with low suitability. These district should not be prioritized when deploying PV energy.

Limitations and perspectives

As for any multicriteria decision aiding approaches, it is necessary to consider weights and thresholds. This represents a 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 set of weights. However, 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 considered actors. Furthermore, the ELECTRE TRI methodology has some subtle mechanisms that allow to represent the human reasoning through the use of fuzzy logic (indifference, preference and veto thresholds). This allows to smoothen the impact of the thresholds.

In order to validate the present study, it could be possible to consider the buildings that are already equipped with PV systems, and check if the majority of them belongs to the very high class. However today this validation is impossible as there are no public database of the roofs that are equipped in France or in Geneva.

Another limitation of this work is the access to certain data. Indeed, other criteria have an influence on the suitability of a roof to be equipped with PV panels. It is for example the case of the local grid capacity. This information is, to our knowledge, not available in open-access in the Great Geneva agglomeration and therefore was not considered here. However, if in coming years this information become available, it will be very easy to

Figure 8 Overview of the sorting results for the buildings in the center of Geneva. A Grey building corresponds to an excluded building. Then Green, Yellow and Blue respectively corresponds to the Very High, High and Moderate classes.

update the present methodology by adding one more criteria, which will result in an updated map of the sorting of the roofs.

Conclusion

This paper presents a sorting methodology of the buildings according to their suitability to be equipped with PV systems. This sorting is based on a multicriteria approach performed using the ELECTRE TRI method. The different criteria considered are, the self-sufficiency, the payback periods, the roof complexity, the reduction in CO_2 emissions and the heritage constraints. Three classes of suitability are defined which are 'Very high', 'High' and 'Moderate' suitability.

The method is then applied to the case of the Geneva Agglomeration (Grand Genève). This French-Swiss region is composed of nearly 260000 buildings. The different parameters of the ELECTRE TRI models are defined based on discussion with experts (thresholds, weights, limits of the classes, …).

The methodology successfully allows to evaluate the suitability of the roofs and provide a relevant tool to help decision makers into identifying the right building for PV system installation.

Acknowledgement

Authors would like to thanks 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 cadaster to the Greater Geneva and intensify energy solar production at this level. This work has been supported by the French National Research Agency, through Investments for Future Program (Ref. ANR-18-EURE-0016 - Solar Academy). The research units LOCIE and FRESBE are members of the INES Solar Academy Research Center

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