A new framework to evaluate the adequation between the solar potential and energy demand of an urban-rural territory in a mountainous area

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Abstract

The development of renewable energy is urgent given the current climate change and Europe energy supply contexts. Among the renewable sources, solar energy is promising and solar technologies spread quickly in the last years. The local production matching with the local energy demand is possible with these technologies and needs to be promoted in the next years to limit the loss induced by the transportation and storage of energy. However, solar potential (irradiation received on a surface) as well as demand are complex to model with accuracy, as many phenomena impact it (shading…). This study proposes a methodology to map solar potential in a rural area, considering several aspects such as the local climate, topography and global climate change. A first overview of the workflow developed is presented, combining several software in order to study the solar potential and its influence on the energy mix at the scale of a village located in a rural area. In particular, the focus is made on mountainous regions which are isolated areas with strong environmental constraints. This work will present a short state of the art, a first overview of the workflow developed which presents the tools that will be used to investigate the solar potential and the territory that will be studied.

Keywords: solar potential, renewable energy, energy mix, rural territory, energy modelling, software

1. Introduction

The world is currently facing an increase in global energy demand, partly caused by population growth. This leads to negative impacts on the environment through air and water pollution, gas emissions (with CO_2 emissions that are expected to rise). Therefore, there is a need to act to limit CO_2 emissions associated with energy consumption and production. Targets have been set by many states in this sense and achieve carbon neutrality by 2050. The overall population increase is mainly related to an increase of the population in urban areas, which results in the energy demand being located in cities, in addition to the fact that buildings consume a large proportion of the energy (75% of the energy demand in 2050).

In order to reduce global energy demand and achieve the carbon neutrality goal, one possibility is to decarbonize energy production through the development of renewable energies and the increase of sustainable energy sources sharing in the energy mix. However, these renewable energies face many challenges, which are intermittency, difficulty of forecasting and variability in time and space, which could induce a mismatch between demand and production, which will lead to the need to resort to fossil fuels/national grid or storage solutions.

To limit storage solutions as well as the injection of renewable energies into the grid (which creates an adverse impact on it), local consumption of energy in micro-grids or self-consumption of the energy produced should be considered. Thus, the spatial dispersion of renewable energies can be an advantage as it can allow them to be exploited locally, thus limiting the losses that can be induced during their transportation and distribution (reduction of the electricity sent to the national grid). Among the renewable energies, solar energy has many advantages: 1) it has a strong potential, 2) is a mature and competitive technology and 3) allows buildings (which are the first source of energy consumption) to contribute to the production of renewable energy, thanks in particular to the unused space on the roof (and possibly also on façades). However, solar energy cannot cover alone the needs of the whole territory (for

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example at night or on cloudy days). It is therefore important to study the complementarity of solar energy with other energies such as wind or hydropower to meet the need at every moment and thus limit storage and the use of the grid.

Despite the fact that energy is mainly consumed in cities, rural mountainous areas are the best locations for energy harvesting, as it offers large space and resources (like biomass from agriculture and livestock). These territories are isolated with less developed electricity networks, thus need autonomy and energy security but have quite strong environmental constraints (temperature, reflection, masks due to relief).

It could thus be interesting to study the possibility for these territories to be electrically or energetically self-sufficient, given their high potential and low energy intensity (compared to cities), with a view to limit energy transportation. Thus, we need to be able to estimate solar energy accurately in time and space, for each building and considering particular challenge of rural area as local climate, topography and also climate change.

This paper presents the whole framework (workflow, data, case studies) that will be employed to deal with all the above problems. The paper will be structured as followed: the section 2 will present an overview of the literature that helps us to define the methodology, the section 3 will present preliminary results that justify the study that will be conducted, the section 4 will present the framework of our work (including the methodology and the case studies that will be used thereafter).

2. State of the art

In order to determine the adequation between the demand and the production at the scale of a mountainous territory, it is necessary to determine solar potential for this place. The estimation of the solar potential has been widely discussed in the literature. However, the main works focus on estimating the solar potential at an urban scale (Barrag et al., 2019; Brito et al., 2012; Lobaccaro et al., 2019; Redweik et al., 2013). There are also many works relating to the estimation of solar potential at large scale: solar potential have been evaluated for Spain in (Izquierdo et al., 2008) through the use of statistical sampling, for Mexico in (Rosas-Flores et al., 2019) by estimating the number of panels possible to be installed by household with the methodology of peak sun hour, in Switzerland (Assouline et al., 2017, 2018) with machine learning approach or also in large region (Bergamasco & Asinari, 2011; Kodysh et al., 2013).

However, only few studies investigate solar potential in rural areas. For instance, in (Notzon et al., 2021), the study concerns buildings located in the Alps, researching for the self-consumption suitability of solar panels while considering the presence of snow and particular demand. Finally, two publications concern small villages in Switzerland. (Mavromatidis et al., 2015) study the village of Zernez, calculate the solar potential while considering the surrounding topography, use Swiss norms to define typical electrical profile in order to model the demand, and use the concept of Energy Hub which allows them to be linked to grid modelling and storage. The location of the photovoltaic systems to be installed is then optimized to limit costs while maximising the share of renewable energy. Similarly, (Mohajeri et al., 2019) study the village of Hemberg, develop a new workflow combining several modelling tools (ArcGIS, QGIS, CitySim, Homer, Meteonorm), which allow them to evaluate different strategies for sustainable development of the village. Indeed, it models heating and cooling demand, solar and wind potential considering future typical weather files and evaluate the influence of retrofitting and expansion of the village. Thus, it can be seen that there is a lack of study concerning rural and mountainous territories that must be filled.

The estimation of solar potential is a harsh task that needs to be handled with the numerical tools appropriate in term of both spatial and temporal scales. Several software could be used to study solar potential but Grasshopper environment with Ladybug plugin has been often used recently (with Honeybee for energy demand simulation) (Evola et al., 2020; Freitas et al., 2020; Hoseinzadeh et al., 2021; Notzon et al., 2021; Xu et al., 2021). In particular, the workflow developed by (Naboni et al., 2019) has drawn our attention: the workflow developed uses the software Rhinoceros and the Grasshopper environment and combines several plugins (Ladybug, Honeybee, Dragonfly, Butterfly) which allows to take many aspects into account (solar potential, energy demand, urban microclimate, climate change, fluid dynamic). Grasshopper is a python-based plugin, which allows to conduct parametric studies and can also be found in CitySim software (Peronato et al., 2017). These works have allowed us to define the numerical tools that will be used in the workflow.

Modelling building energy demand has been also widely discussed in the literature and lots of different methodologies could be employed, which depend mainly on the data availability and the objectives of the modelling. Building energy modelling could be classified into top-down (aggregated data (socio-econometric and technological indicators and building energy use)) and bottom-up approaches (disaggregated data)(Hu et al., 2021; Torabi Moghadam et al., 2017). Bottom-up approaches can also be classified into sub-categories : physics-based model (analytical model, implemented in energy building modelling software), data-driven model (based on machine learning algorithms) and hybrid model (Wong et al., 2021). However, all these different methodologies are applied to case studies where lots of data are available (like energy consumptions per building, wall materials, year of construction). Top-down models could be the most suitable in our study, as it uses statistics and can deal with the lack of data.

After having estimated the solar potential and the energy demand, it is important to analyze this solar potential to encourage the deployment of solar systems. As the transportation of electricity induces energy losses, it is important to see if the energy produced could be used at local scale. Therefore, recent studies are focusing on the study of the matching of demand and production. It can be done at building scale for Net Zero Energy Buildings (Lund et al., 2011), including wind energy or storage (Cao et al., 2013). It can also be done at a larger scale, using TABULA and ISTAT database in order to model the energy demand and then finding the best locations for solar panels (Groppi et al., 2018), considering the evolution of the demand with prospective scenario (Groppi et al., 2018) or at a national scale (Al-Ghussain et al., 2021). Some studies also employed indicators as for example self-consumption rate (share of the electricity generated by the PV system that is consumed by the buildings where the panels are located), the self-sufficiency rate defines as the percentage of electricity demand that could be supplied by the PV systems or ramp rates (sudden variations of power due to the infection of electricity on the grid) to optimize the part of solar potential that will be transformed in electricity through PV panels (Freitas et al., 2018; Thebault and Gaillard, 2021).

3. Preliminary results

The first study carried out consisted in showing the interest of studying mountainous territories. For this, data collected in a previous study were used. The available data concern the territory of the Greater Geneva (Thebault et al., 2022). It contains the annual electrical consumption, the ground surface, the maximum installable solar panels surface, the electrical energy potentially producible in one year, the maximum peak power installable and the self-consumable energy per building. For each building in the Greater Geneva area, the altitude has been found by using a Digital Elevation Model DEM) in QGIS software. The DEM used was made under the framework of the Copernicus program and available for the European continent. As the goal is to study the influence of altitude, data concerning Geneva were removed by keeping only data were the altitude is above 470 m (the maximum altitude of Geneva is 463 m).

Two indicators were defined for this study:

- Annual PV system energy potential production (kWh/m²/y) divided by annual electric consumption (kWh/m²/y). It is an indicator providing some insight on the self-sufficiency potential, which allows to see if a building could, theoretically (on a yearly basis), produce enough electricity to match its consumption. Of course, without any electrical storage solution, this indicator is not an actual self-sufficiency indicator.
- Annual PV system energy potential production (kWh/m²/y) divided by ground surface (m²). It allows to assess the usable roof surface compared to the building footprint.

These two indicators have been plotted against altitude (Fig. 1 and 2). It appears that as altitude increases, the energy situation is different from that in the plain which requires a specific attention. On Fig. 1, it seems that the ratio between the energy that can be produced by solar systems and the energy consumed per building is getting higher when the altitude increases. Thus, the match between consumption and production is increasing with the altitude on an annual basis. It can be explained by the fact that when the altitude increases, the territory become more rural. There are more houses with garden than apartment blocks. Buildings are therefore less impacted by overshadowing and self-shadowing effect. It can also be assumed that, with increasing altitude, there is less impact of far shadow caused by mountains (mask effect). However, attention should be paid because only the electric consumption is available. It could be possible that the share of housing in mountainous areas where heating is provided by biomass, gas or oil boilers is greater than in urban areas.

Similarly, on the Fig. 2, it appears that the ratio between the energy that can be produced by PV systems and the ground surface is increasing with altitude. Thus, the energy that can be produced by one building should be more important if this building is located in a mountainous area rather than in the plain. It could also be explained by shadowing effect of neighboring buildings and mask effect. It could also be explained by the fact that apartment blocks have a smaller share of roof surface compared to houses (and in addition, these roofs are also used for facilities, like HVAC equipment (heating, ventilation and air-conditioning)). Thus the electricity produced by solar systems is reduced due to the smallest surface of panels.

The majority of the housing stock that will be present in 2050 is already built. The main actions to be implemented to control the consumption of buildings are the renovation of these buildings and installation of solar systems to increase the production of renewable energy (and reach the carbon neutrality). It is therefore important to study the buildings already present on the territory.

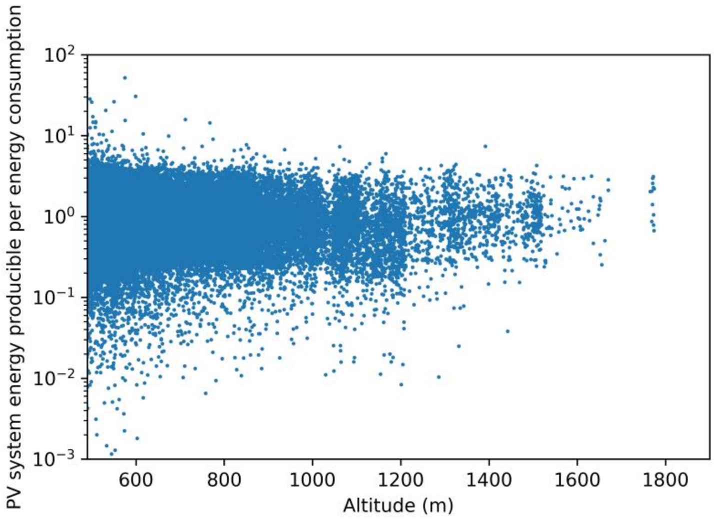


Fig. 1: Energy producible by solar systems divided by energy consumption according to altitude, per building (of the greater Geneva area)

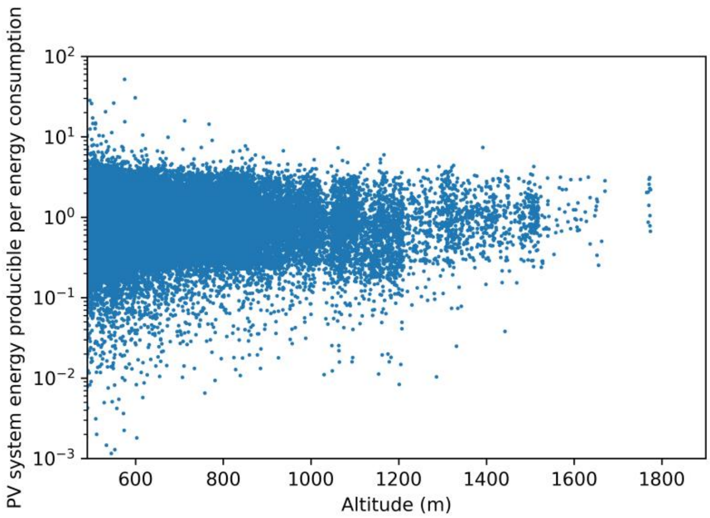


Fig. 2: Energy producible by solar systems divided by ground surface according to altitude, per building (of the greater Geneva area)

4. Framework

4.1 Methodology

After having investigated the actual literature background about solar modelling and renewable energy matching with demand in rural area and see that mountainous buildings present a good potential to harness solar energy, we present a working environment combining several software/plugins in order to study the solar potential (Fig.3). One possible combination could be the use of Rhinoceros for the 3D modelling of the study case and the use of the Grasshopper environment to compute parametric study. In Grasshopper, the plugins employed would be Ladybug for the estimation of the PV generation potential, Honeybee to simulate the energy demand, Dragonfly and Butterfly to consider the climatic specificities of the studied region (UWG, fluid dynamics, heat island effect). Meteonorm and QGIS/ArcGIS will also be used respectively to obtain climate data and mapping building in an appropriate model for solar analysis.

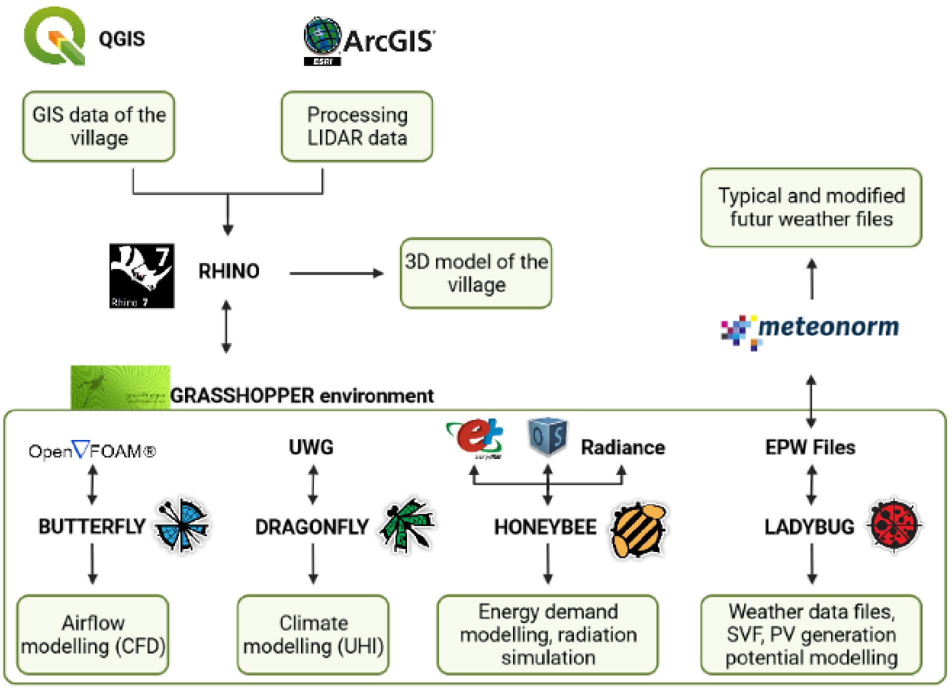


Fig. 3: Proposed workflow that will be implemented in the study

Before selecting the appropriate workflow to conduct our study using a multi-scale approach, several tools will be compared that are available for solar potential modelling including ArcGis using the Solar Analyst or CitySim software (which also offer the possibility of parametric modelling with a Python plugin and Grasshopper plugin).

Our approach, presented in the workflow in Fig. 3, is intended to be multi-scale, focusing at the same time on production and consumption at individual house level but also at the scale of the municipality. Indeed, the individual level is important to be precise in the modelling of solar potential and energy building consumption and the larger scale will allow to see if aggregation of the demand and the production could improve the matching between demand and supply. The selected software are relevant to answer this question as Rhinoceros coupled with Grasshopper plugins (Ladybug and Honeybee) could be used to study the scale of the neighborhood, like houses in the center of the selected rural village, and ArcGIS and Solar Analyst module could be used at a larger scale like the whole area.

The study of the solar potential will be focused on urban/rural territory, and more particularly on the specificities of a mountainous area. There will be a need to consider the topography (mask effect of the surrounding mountain), the local climate (specific climatic data of the area, effect of the wind in a valley) and the presence of snow in the winter season. The influence of climate change on the solar potential will also be investigated through the use of future weather files (considering exceptional event like heat waves). As it will be explained in the next section, it is particularly challenging to model rural territories because very few data are available compared to cities.

The objective is to consider the solar potential in the energy mix at the scale of a village and its influence on the share of renewable energies in the electricity mix. Thus, the goal will be also to model the energy demand-considering the influence of local climate on the demand. Several methods will be experimented to model the demand: using historical data of the studied area, using typical electric profiles depending on the type of building and number of inhabitants or using simulation tools (like CitySim or Honeybee plugin of Rhinoceros) (or using statistical methods). For the first two methods, the modelling should predict future consumption profile according to climate evolution.

Finally, the self-consumption and self-sufficiency at the scale of the village will be studied. The maximization of the self-consumption (maximization of the dynamic response of production to demand), limitation of storage options and minimization of the grid interactions could be possible through the optimization of the location of photovoltaic installations. The potential of other renewable energies, as for example wind energy with CFD studies, could be potentially investigated.

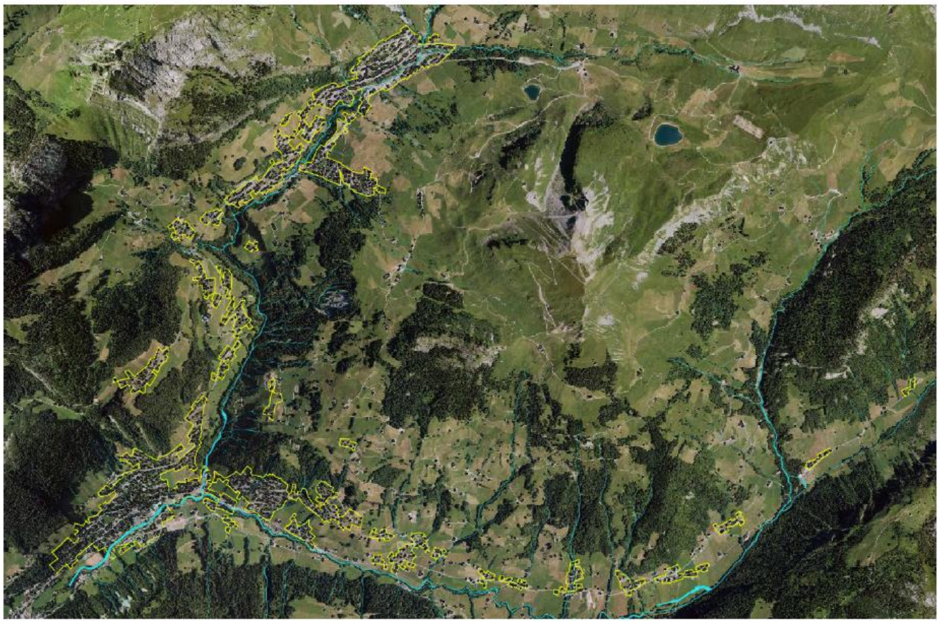
4.2 Case studies

The small town of Le Grand Bornand (Fig. 4 (a)) has been selected as a case study because this city, located in the French Alps (Fig. 4 (b)), is part of the project "Grand [La]Bo", in progress between the University of Savoie Mont Blanc and the territory of Le Grand Bornand and its actors. This project aims at investigating the impact of the town on its surrounding, on three themes: agriculture, tourism, and local community life (which includes energy, waste, air and water quality). The project wishes to carry out a transdisciplinary territorial diagnosis with the aim of having a sustainable trajectory (development of soft tourism for example), while keeping a sustainable economic model for the station and raising the awareness of political actors on these issues. The village faces particular stakes, as it wants to keep the image of a traditional mountainous village but become an attractive place for tourism with its ski station during winter (and summer).

However, very few data are available for this area. Actually, as the energy consumption is localized mainly in the city, rural areas are not much under studies, and the only data available is the village cadaster. Thus, it is not possible to have access to building geometry data, to population distribution, or even to building's height or year of construction, which are the data used by most of the methodology to estimate solar potential and building consumption. Currently, the National Institute of Geographic and Forest Information (IGN) is conducting a campaign to acquire high-density LiDAR data over the entire French metropolitan territory in order to offer the finest 3D description ever established on the scale of the entire country. The campaign has started this year and the first LiDAR tiles are publicly available. However, the selected area has not been yet recorded. In France, access to data is not easy also because of the privacy legislation, especially for residential building consumptions, that are measured but not publicly available. Concerning meteorological data, the weather stations are often located close to big cities, at airport for example. As urban weather generators are employed to correct these measures and make them correspond to the reality, the suitability of using these measures for rural areas must be verified. The lack of data is a real problem in our case study, it will be explained below how to deal with this issue.

For these reasons, as a first step an initial study will be carried out on a village of mid-mountains areas close to Le-Grand-Bornand but located in conurbation of the Greater Geneva where much more data are available. This first study will allow to become familiar with the tools that will be employed and understand the various problems that could be encountered during the use. The first step of the work will be to study the influence of the mountainous location, mainly through the topography and the temperature, compared to plain location. A particular attention will be put on the meteorological data.

In the long run, the goal will be to compare the results obtained with those of another small city in the Pyrenees in the Spanish part, as the topography would be similar. It would allow to see the impact of the climate and local specificities, like urban morphologies or building typologies. However, the methodology employed to study the area could change if the availability, the format, or spatial or temporal accuracy of data are different.



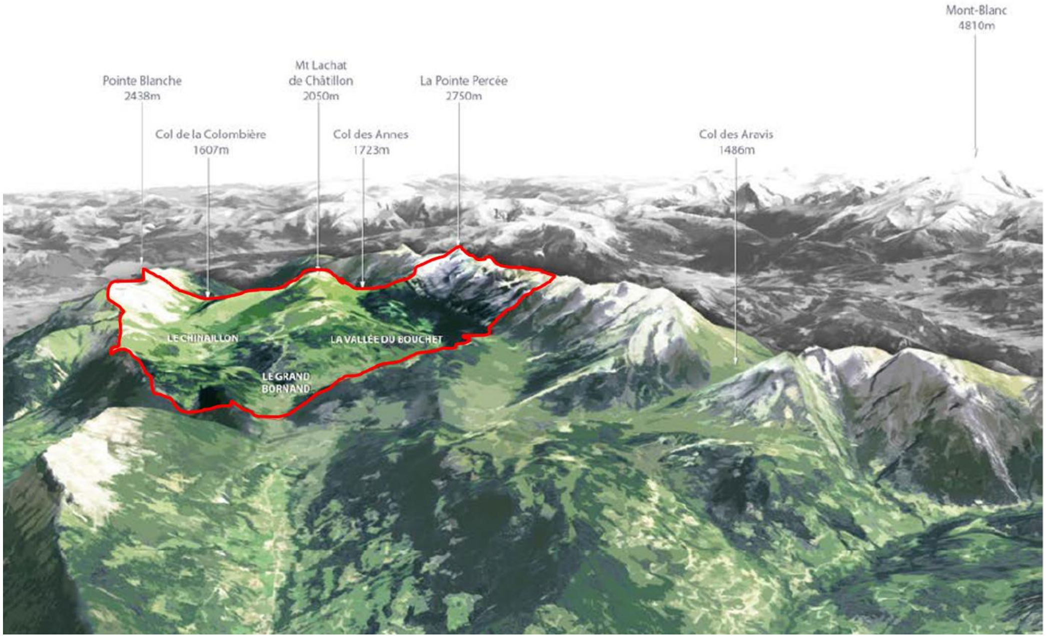


Fig. 4: Urban envelope of the village (a) and aerial view of the municipal territory (b) of Le Grand-Bornand (P.L.U. Le Grand Bornand)

5. Conclusion

In the present paper, it has been shown that there is a lack of studies concerning the modelling of solar energy and building energy consumption in mountainous territories. Moreover, it has been shown that the buildings in these areas present specific energetic situation. As these territories are isolated, it is relevant to study them and see if they could be self-sufficient (to avoid the transportation of energy). A workflow has been presented, which combines several numerical tools in order to study the solar potential in a mountainous area and the methodology that will be conducted. The territories that will be investigated are presented.

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