Annex 1: Cover Page

ÉCOLE POLYTECHNIQUE
MSc&T STEEM

Academic Year 2018-19
Morales, Javier

INTERNSHIP REPORT

A GIS-based methodology for PV Solar Parks Site Selection and regional solar potential assessment: case study in the shire of La Segarra, Catalonia

NON-CONFIDENTIAL REPORT

Referent teacher:
Pere Roca i Cabarrocas

Internship tutor:
Xavier Massa

Internship dates:
1/04/19 to 31/09/19

Annex 2: Declaration of Academic Integrity

Declaration of Academic Integrity

Hereby I, [Name], confirm that:

1. The results presented in this report are my own work.
2. I am the author of this report
3. I have not used the work of others without clearly acknowledging it, and quotations and paraphrases from any source are clearly indicated.

Name, date,

Javier Morales Bellsolà 2/09/19

Signature

Annex 3: Rating Form

RATING FORM

We wish to thank you for hosting and supervising our student for his/her research internship. Ecole

Polytechnique rates research internships, taking into account three criteria:

- the training period
- the written report provided by the student to Ecole Polytechnique
- the defense

This form will allow the instructor to evaluate the first criterion. This evaluation form has to be completed by the host organization's internship supervisor. This evaluation should be a true representation of the intern's work, and will be taken into account for the school's official grading of student.

We would be grateful if you could fill in this form as completely as possible and email it to the instructor at Ecole Polytechnique and to the research internship coordinator at least one week before the defense:

uyen-chi.nguyen@polytechnique.edu (STEEM1)
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NAME OF THE STUDENT: JAVIER MORALES BELLSOLÀ

HOST ORGANIZATION: KM0.ENERGY

NAME OF THE TUTOR (Scientific supervisor): PERE ROCA I CABARROCAS

AUTONOMY	Excellent	Good	Intermediate	Weak
WORK COMMITMENT	Excellent	Good	Intermediate	Weak
INITIATIVE	Excellent	Good	Intermediate	Weak
WORK OUTCOME	Excellent	Good	Intermediate	Weak
GENERAL BEHAVIOR	Excellent	Good	Intermediate	Weak
PROFESSIONAL INTEGRATION	Excellent	Good	Intermediate	Weak
PRESENTATION OF THE WORK	Excellent	Good	Intermediate	Weak

COMMENTS :

Work quality:

Written report:

SUPERVISION OF THE INTERN

Everyday	Weekly	Monthly

Content

1. Abstract

Transitioning to a society with almost null fossil fuel usage based on an alternative energetic model not dependent on fossil fuels nor nuclear power and based on decentralized energy system 100% renewable based with own resources by 2050 is a quite ambitious objective for Catalonia specially taking into account that renewables barely represented a 5% of total primary energy and a weak 8,5% of final brute energy in Catalonia in 2017. Nuclear centrals decommissioning is forecasted for 2027 but fulfilling such objective would require an equivalent solar capacity addition of around 7-times as much solar PV capacity as there is in place today, every year, for the following 8 years. The Spanish transition to renewable energies is being based on concentrating generation in fewer but bigger installations. However, a centralized model based on big installations would not be successful is Catalonia where land availability is scarce and geographic characteristics make it difficult for megaprojects to be developed. Therefore, this project will be centered in defining and applying a GIS-based methodology to conduct regional solar PV potential assessments aimed at siting small-medium solar parks (1-20 MW) within the Catalan territory. The methodology will be tested in the Catalan region of La Segarra using a two-stage framework approach. On a first stage, areas restricted for solar parks' development will be discarded according to pre-defined constraints to obtain a rough solar regional potential. On a second stage, several criteria as solar radiation, topography or accessibility considerations will be used to screen remaining lands and identify most optimal areas for solar parks' development. Results obtained in the study case of La Segarra have shown that if all optimal potential would be used in the region would be used, total generation would be of 3.231 GWh (7,1% of Catalan electricity consumption) whereas in the rough potential scenario it would be of 19.400 GWh (42,6% of Catalan electricity consumption) requiring, however, the occupation of a quarter of the total regional surface (clearly not feasible). The greatest density of potential is to be found at the eastern areas of the region.

2. Motivation

My work at km0.energy in Terrassa, Catalonia, Spain pivoted significantly since my arrival at the company in April 2019. Initially, my work was meant to give support to technical department by conducting solar potential solar parks simulations via commercial softwares (PVsol or Rated Power) and location plots (with AutoCAD).
However, given the youth of the company, which was created as a start-up in late 2018, resource availability was limited, and no more software licenses could be bought, making it difficult to conduct work appropriately. After realising other gaps at the company, I proposed to create a department on GIS (Geographic Information System). Among other chores (preliminary technical and economic

analysis of PV solar parks, energy consulting and back-office commercial support) GIS has been my main project in these last 4 months at the company.

When I arrived, the company's GIS was being outsourced to a freelance professional that had conducted some analyses to map solar potentials and analyse territorial characteristics. However, the degree of concreteness, automation and usefulness of the system was limited and only the 2 technical profiles in the company (note the company has currently 6 working professionals) could access the information. Moreover, such information was mostly descriptive and did not offer any framework that could facilitate manager's nor technical-people decision-making processes.
I had previous experience in working with GIS but I was by no means an experienced user. However, since I started using it, I had always been interested by its potentialities and I realised a good opportunity to train myself into it while simultaneously contributing to the company's objectives.

For a company working in the solar industry, GIS is a tool that may be used for resource assessment (i.e. solar irradiation), resource planning and may also be used to take integrate, in a visual environment, relevant information related to PV solar installations' development. Moreover, a GIS platform (maybe linked to a Business Intelligence/SCADA/Big Data platform) may be useful to track if an installation (or a set of installations) already in place is yielding expected results and provide in a georeferenced user-friendly visual tool how different plants are performing in real-time.

My work has been mostly focused on developing a platform to guarantee prospective location of solar parks in Catalonia taking into account restrictions of distinct nature (environmental, urbanistic, legislative etc.) with the aim of automatically finding the optimal locations and avoiding potential costs of pre-studies in locations where i.e. urbanistic norms do not allow the construction of a solar park. The objective of such a project has been that of creating a remotely accessible map server where most desirable parcels are plotted with linked information about each of them.
The development of the platform will enhance a new methodology of working that should help the company adopt a complementary way to select where to develop new installations in a 'push' manner, that is, selecting a certain location according to its aptitude to host a park. So far, the operations of the company were being 'pulled' by clients (or owners) interested in hosting solar PV installations in their owned lands. This meant, sometimes, that the company was elaborating pre-studies (with their associated costs) in areas where no solar parks could be built or in places where the economical yield of the park was not optimal (due to low irradiation, inappropriate land orientation among other reasons). With the platform in place, the company should be able to (i) automatically identify where solar parks are to be developed to guarantee the piece of land accomplishes a set of pre-defined requirements without having to conduct case-by-case pre-studies and (ii) help to the identification of optimal solar parks' siting plots to the company's commercial department and (iii) directly check if a given plot in any place within the Catalan territory might be used as ground for a solar park installation.

3. Content

The present section is aimed at summarizing the content of the project and to indicate where contents are to be found.
Section 4 will outline specific objectives of the project and its scope.
Section 5 will provide an introduction to the project framework and will present the state of play of renewable energy, especially focusing on solar, at different geographical scopes (Europe, Spain and the region of Catalonia) and the challenges and actions to be taken to mitigate climate change.
Section 6 will explain the analysis framework used in this study and the methodology to find solar parks' siting locations and conduct solar PV regional potential assessments using GIS.
Section 7 will describe the GIS creation process, starting by defining necessary data and where it has been obtained, its preparation for analysis, the process followed to treat it its and finally a presentation of the results.
Section 8 will review the objectives raised at the beginning of the project and propose futures lines of work to improve the solar siting GIS that has been created during this study.

4. Objectives

This study has the objective to develop a methodology, based on multicriteria assessment for identification of locations for solar PV installations and elaboration of regional solar potential evaluations in previously defined geographical study areas within the Catalan territory. The methodology, however, could be adapted for its application to other territories. The GIS-based application derived from the methodology development should be able to identify where ground-mounted solar parks could be developed. The application will be best suited to scout areas to host installations in the range of 1 to 20 MW.

The specific objectives that have been identified after analysing the companies' interests should be aimed at:

- Setting up an up-to-date database of potential locations for the installation of future solar parks.
- Being able to elaborate fast solar PV potential assessments in areas within Catalonia where the company has interest to develop solar parks' projects
- Providing information to company's stakeholders to help them identify where the greatest solar potentials are to be found.
- Building an application that may allow to know if a given parcel in Catalan territory is well-suited for hosting a solar park of if there is any restriction that would impede the development of the project.
- Make the application user experience intuitive, assuring access to this information to a heterogeneous audience without background or knowledge about GIS.

All those objectives will be tested on a case study for the shire of La Segarra, a region in central Catalonia, for which a database of all plots in the area will be created and a solar potential assessment will be conducted.

5. Context

The objective of this section is that of providing some context on the Catalan energy system, starting by defining the current energy model and dimensioning the challenges to materialize a compulsory and especially urgent energy transition. When thinking about energy transitions, prospective scenarios aimed at defining possible future evolutions of a given energy model are usually hypothesized and they need consistent renewable potential studies that complement them to guarantee that such hypothesized scenarios are plausible.
The fact that the energy transition in Catalonia is just being set into motion and there is yet no official publicly available document or report published by the Catalan administration describing renewable energy potential in Catalonia -even if prospective projects are already in place- justifies the need of addressing not only the spatial question on where installations should be set up first (which is the main drive of this study) but also how much capacity can be installed and if, once it is in place, it would be enough to guarantee enough power-and especially energy-to secure a 100% renewable, affordable and secure energy model for Catalonia. It is also relevant to mention that the Catalan energy/power system model of the future will most certainly not be based on a few big installations rather on many small geographically sparse installations for which the spatial dimension of energy, that is, where energy/electricity is produced and consumed will be much more relevant than it is in the current model.
In the following subsections the current status of Catalan energy model in terms of supply of primary, final energy and electricity mix will be shortly reviewed with a particular emphasis on solar PV generation (5.1) and the evolution of renewable energy in Europe, Spain and particularly in Catalonia will be discussed both from a regulation and installed capacity point-of-view (*5.2*).
The extension of this section is justified as the study aims to justify the need of accurate potential studies to address energy transition challenges.

5.1. Energy in Catalonia. Current status

As no updated data is publicly available, all data and figures in this section will be referred to year 2017. [1]

Primary Energy

Primary energy consumption in Catalonia was of 25.517,5 ktoe (thousands of tonnes of oil equivalent) in 2017. Oil remained the main source of primary energy due to its dominance in the transportation sector representing 46% of total primary energy consumption while nuclear (25%) and natural gas (22%) stayed far below. (*Figure 1*) **Renewables barely represented a 5% of total primary energy.**

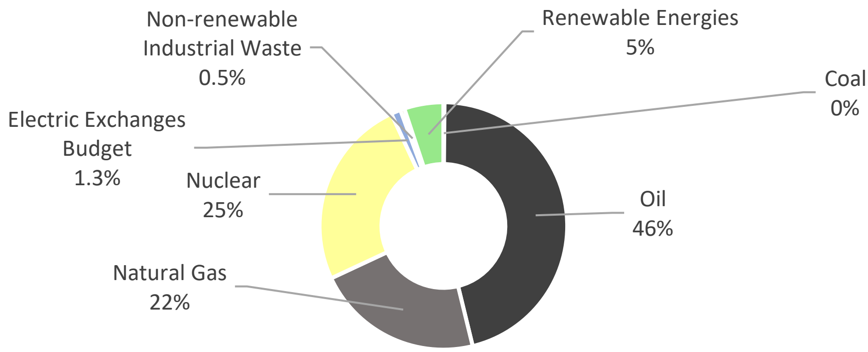


Figure 1: Primary energy consumption by source (25.517,5 ktoe) in Catalonia in 2017. Own elaboration with data from (ICAEN 2018)

When analyzing its historical evolution (*Figure 2)* primary energy consumption in Catalonia has been growing steadily in recent years with a relative increase of almost a 10% in the last 4 years (2013-2017) which in absolute terms translates into almost 2.300 ktoe.

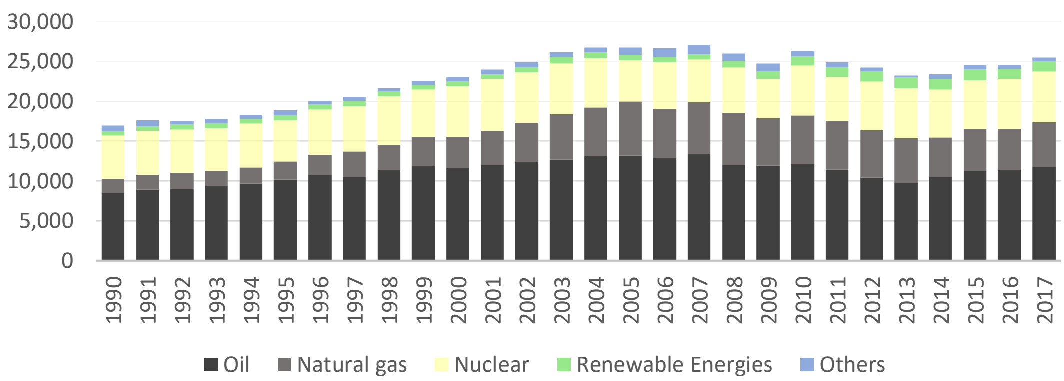


Figure 2: Primary energy consumption evolution by source [1990-2017]. Own elaboration with data from (ICAEN 2018)

The maximum consumption value was registered in 2007 with 27.077,7 ktoe. Regarding this maximum, the consumption of 2017 is around a 6% lower; placing current primary energy consumption (2017) at a level equivalent to that of years 2002-2003.

[1] Except for electricity mix data which is available for year 2018.

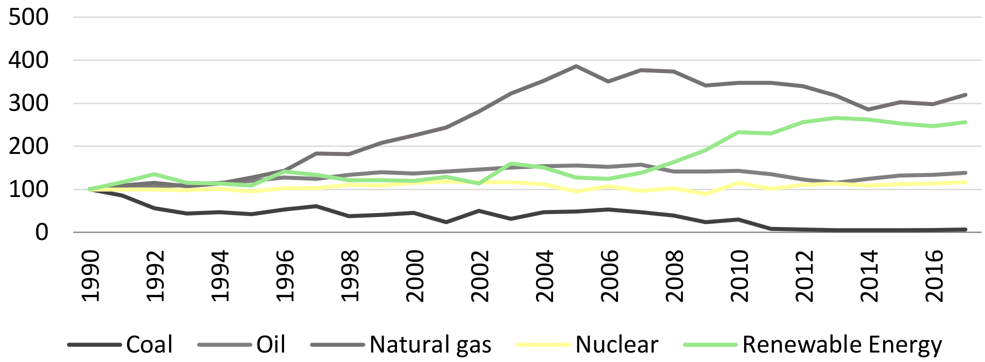


Figure 3: Relative evolution of primary energy consumption for different energy sources (Base 1990 = 100) [1990-2017]. Own elaboration with data from (ICAEN 2018)

In the period 1990-2017 the energy vector with the greatest relative increase (*Figure 3*) has been natural gas reaching a peak value of almost 400 a few years ago that stays today slightly above 300 (3 times more consumption from natural gas today than in 1990) followed by renewables with a value of 250 (2,5 higher renewable energy consumption today than in 1990). However, **in the last five years, primary energy consumption from renewables has stagnated while oil and nuclear have been slightly increased.**

Final Energy

As it is the case for primary energy, final energy also registers an increase of almost a 7% in recent years (2013-2017). (see Figure 4). Final consumption increment can be mostly attributed to the growth of fuel consumption which has increased by an 8,4% in the period 2013-2017.

Oil derived energy resources represented almost half of final consumption (49%) in 2017 (see Figure 5) followed by electricity (26,5%) and natural gas (20,3%). Note how data aggregation does not allow to discriminate the share of renewable energy in the electricity mix that will be covered in subsection *Electricity Mix*. **Non-electrical renewable energy (solar thermal, biomass and biofuels) barely represented a modest 3,3% of total final energy consumption in 2017.**

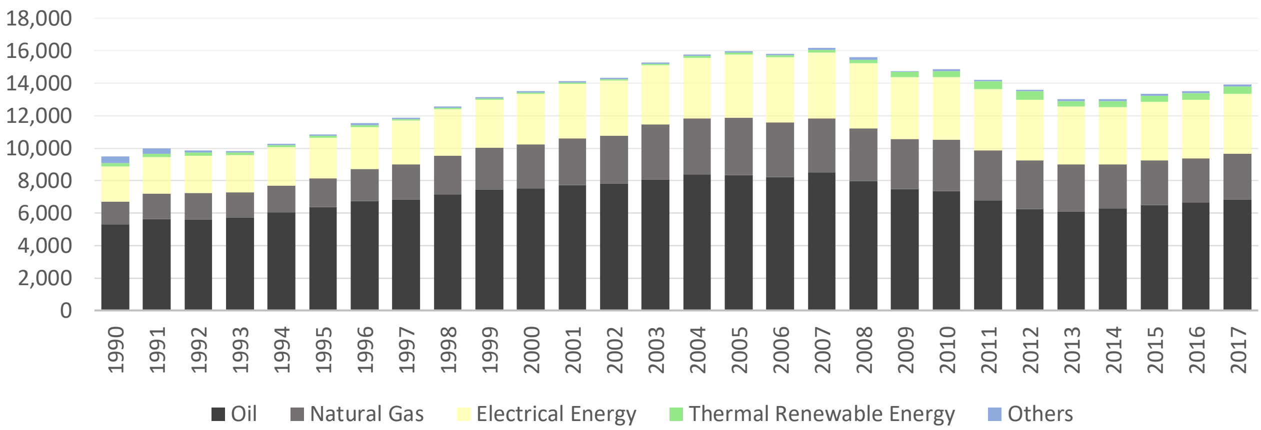


Figure 4: Final energy consumption evolution by source [1990-2017] Own elaboration with data from (ICAEN 2018)

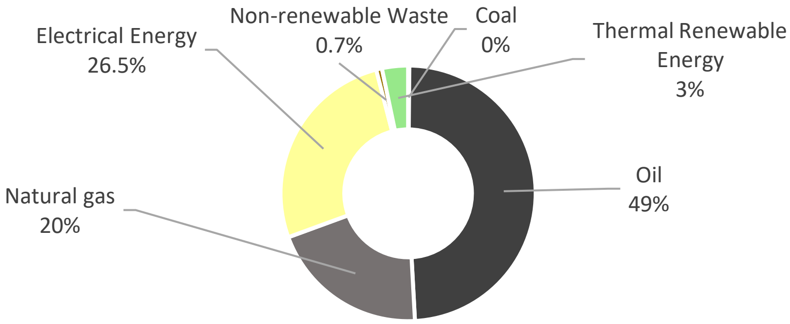


Figure 5: Final energy consumption by source (13.912 ktoe) in Catalonia in 2017. Own elaboration with data from (ICAEN 2018)

When looking at consumption by sector, transportation and industrial sectors represented relative shares of 40,3% and 30,2% respectively of 2017's final energy consumption. The remaining 30% was distributed between residential (14,2%), services (12,2%) and primary (3,8%).
The fact that transportation is by far the greatest consumption sector deserves attention as it sets some boundaries to energy transition objectives for Catalonia as analyzed in this study**. If the transportation sector remains fossil-dependent, there will always be a threshold above which no energy-mix improvements are to be achieved by increasing renewable energy installed capacity. Note how if the electricity mix was completely renewable based, there would still be a 69% of fossil fuel sourced energy in the final energy mix.**

Renewable energy installations stagnated and every year it is further away from the objectives set by the Catalan government according to the PECAC (Energy and Climate Change Plan in Catalonia) which aimed to fulfill 20-20-20 European policy requirements (see 5.2 for more information) 2020 according to which renewable energies should provide a 20% of final gross energy consumption. The figure below shows how **in 2017 only an 8,5% of final brute energy in Catalonia was being produced through renewable energies, extremely below expectations.** Several reasons may explain the situation according to the director of the Catalan Institute of energy, Manel Torrent (El Pais 2019): the change of retribution of this kind of installations derived from Law 24/2013 (see below); a decree approved by Catalan Government in 2009 to foster wind and solar parks that has ultimately acted as a barrier for renewable energy development and general opposition to new renewable installations. The figure below shows forecasted renewable energies irruption in Catalonia (dotted blue) and real evolution (continuous blue) in recent years. Note how the value reached in 2017 (dotted orange) is far below the objectives of 20% (dotted pink).

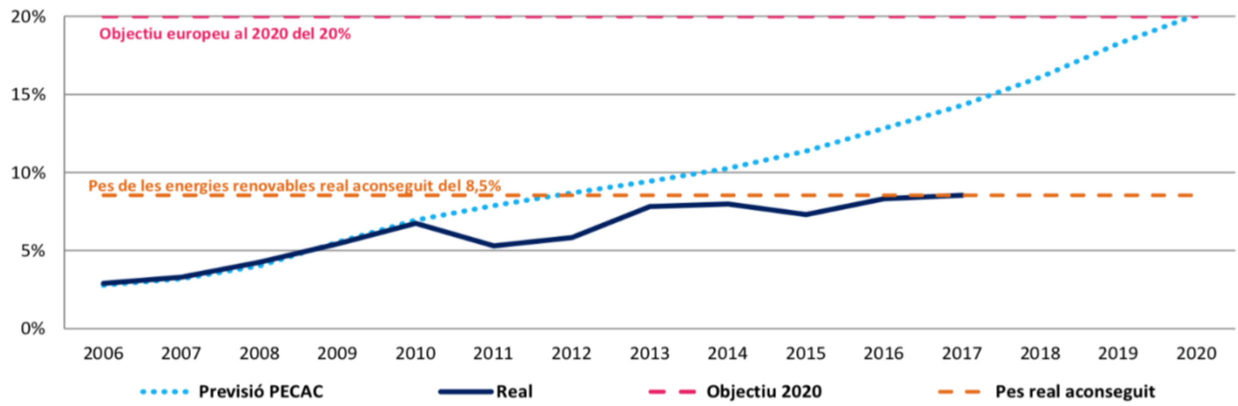


Figure 6 :Evolution of renewable energy supply in relationship with brute final energy consumption.Source: (ICAEN 2018)

Energy Supply and Self-sufficiency Index

A high fossil fuel share in the energy mix in territories without primary fossil energy resources is usually linked with a high dependence on energy imports to guarantee supply.

In Catalonia the degree of self-sufficiency (the share of primary energy obtained through own energy resources over total primary energy consumption) has suffered a downward trend since the nineties and even if it reached a local peak (34,3%) in 2013, it has dropped again at a 30,5% in 2017. This value is especially alarming taking into account that nuclear electricity is considered an own primary energy resource even when most uranium concentrates are extracted in countries such as Namibia, Russia or Niger and converted and enriched-to obtain enriched uranium to feed the nuclear reactors- in countries such as Russia, France, the US or Canada. ENUSA -the national uranium supply company in Spain-reports to have one of the most diversified enriched uranium supply systems of the world by claiming to export from many different countries evidencing, on the one hand, the existence of a high dependency on raw material imports to run Spanish nuclear centrals and, on the other, the fallacy that nuclear in Spain is considered as an 'own' primary energy source.

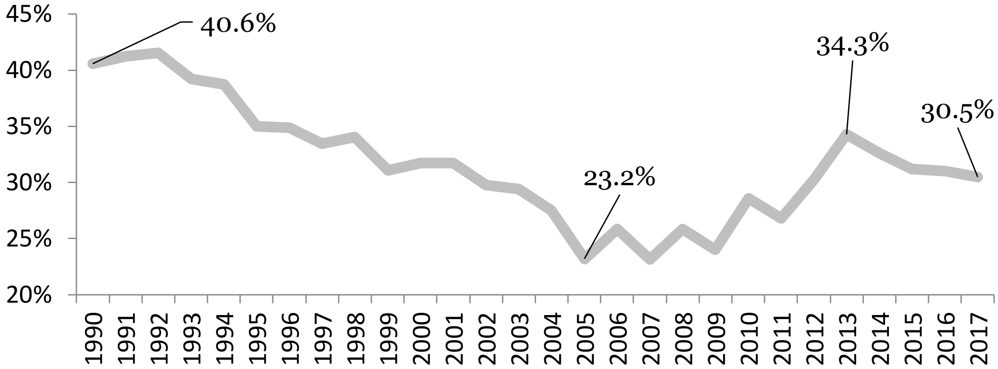


Figure 7: Degree of self-sufficiency (in %) of the Catalan Energy system [1990-2017]. Own elaboration with data from (ICAEN 2018)

The analysis of the distribution of energy production in Catalonia yields an 82% of nuclear sourced primary energy followed by a 14,5% of renewable energy (solar, wind, hydro, biomass, renewable waste and biofuels). Oil (2%) and non-renewable waste (1,8%) have a limited contribution.

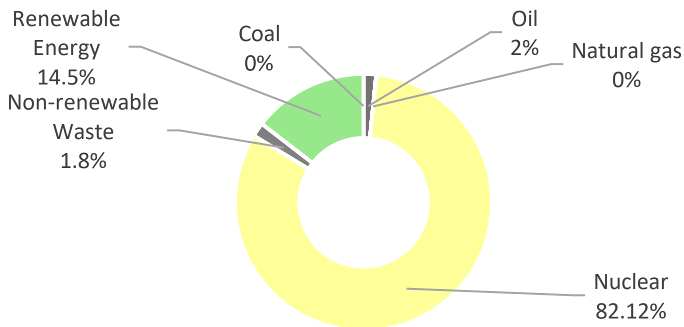


Figure 8: *Primary energy production by source (7.780 ktoe) in Catalonia in 2017. Own elaboration with data from (ICAEN 2018)*

It is worth mentioning how the absolute primary energy production value (7.780 ktep) contrasts with primary energy consumption (25.517,5 ktep) highlighting again the huge share of energy sources that needs to be imported to match demand.

Electricity Mix

Electricity mix in Catalonia in recent years (2010-2018) has been based on nuclear (around 50%); natural gas (around 20%); non-renewable cogeneration (around 10%), hydro (around 10%) and others (5%) as shown in Figure 9.

In year 2018, Electrical production in Catalonia was of 44.717,3 GWh, from which a 20,5% was produced through renewable energies, mostly hydro and wind power. Almost half of electrical production (49,1%) came from nuclear energy. (see Figure 10)

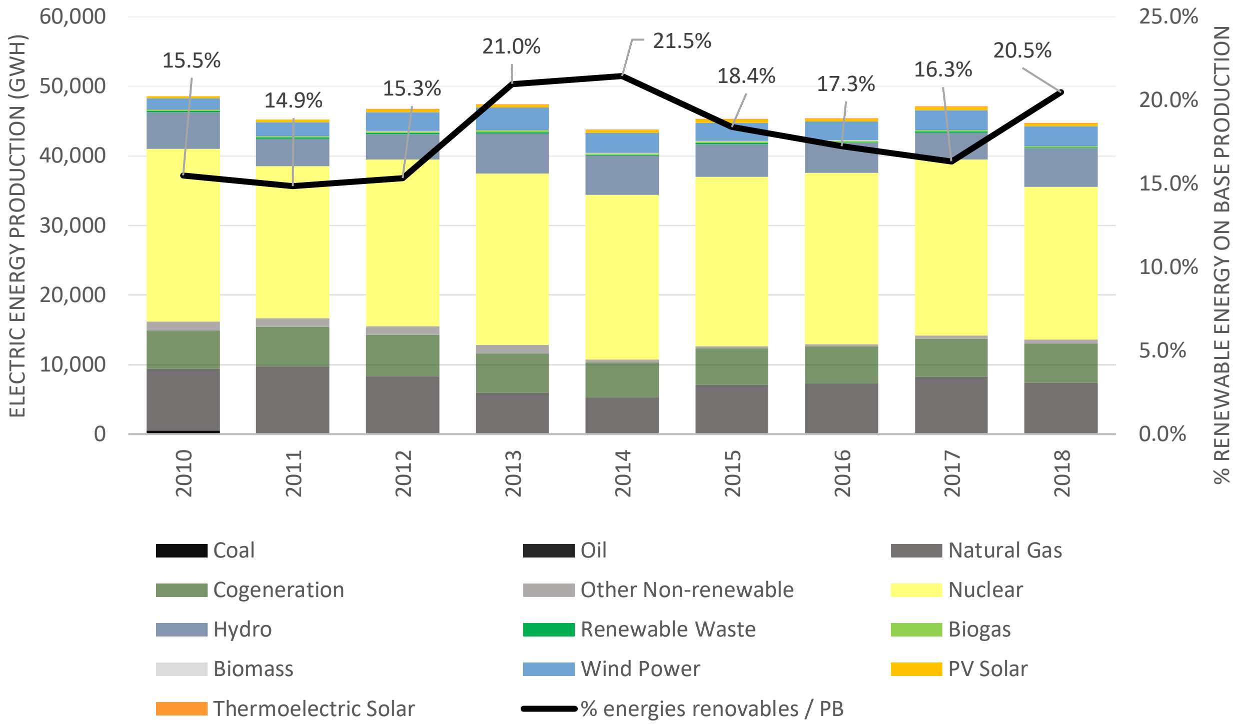


Figure 9: Electrical energy production evolution by source [2010-2018]. Own elaboration with data from (ICAEN 2019)

The big fraction of nuclear power, which is a key technology in current Catalan energy model, has been lately under debate. Catalan government through its 2017 Law of Climate Change (see *Energy transition in Catalonia*) expressed its aim to close all atomic reactors no later than 2027. Contrarily, the Spanish State which is the authority that has the competence in such matters-is in pursue to extend the lifetime of certain centrals until 2035. Further negotiation between Spanish government and companies owning each of the centrals (Ascó I, 1.032 MW; Ascó II, 1.027 MW and Vandellòs II, 1.087 MW) will determine when centrals are finally dismantled.

Nonetheless, if objectives by Catalan government aimed at of nuclear decommissioning were set into place, nuclear capacity should be compensated by a massive renewable energy deployment. The order of magnitude[2] of such necessary arrangement would be of 9.568 MW -if nuclear capacity was to be substituted through wind power- and of 15.335 MW if substituted by solar. The process followed to calculate such values has considered capacity factors- ratio of actual electrical energy output of a certain installed capacity over a given period of time to the maximum (nominal) possible electrical energy output over that period- obtained through current nuclear, solar and wind installed capacity (MW) and generated electricity (MWh) in 2018 Catalonia (Red Eléctrica de España 2019; ICAEN 2019; Asociación Empresarial Eólica 2/19/2019). Capacity factors in Catalonia's electric 2018 mix were of 82,62% for nuclear; 26,19% for wind power and 16,34% for solar.

The implications of such results help to dimension the magnitude of the efforts that need to be put in place if political proposals want to be materialized**. Turning down Catalan nuclear centrals by 2027 by means of solar capacity addition would mean deploying, every year, 7-times as much solar PV capacity as there is today for the following 8 years. Equivalent efforts to compensate lacking nuclear capacity by wind power would imply installing almost current wind power capacity every year for the next 8 years. The pace at which such capacity additions are put into place will determine whether energy transition objectives are being fulfilled in time.**

[2] Note this is just a very rough estimate, taking into account average 2018 Catalan capacity factors and assuming constant capacity factors over time (assumption that in practice is never fulfilled). This estimate should be understood as a first approach subject to a relatively high degree of inaccuracy.

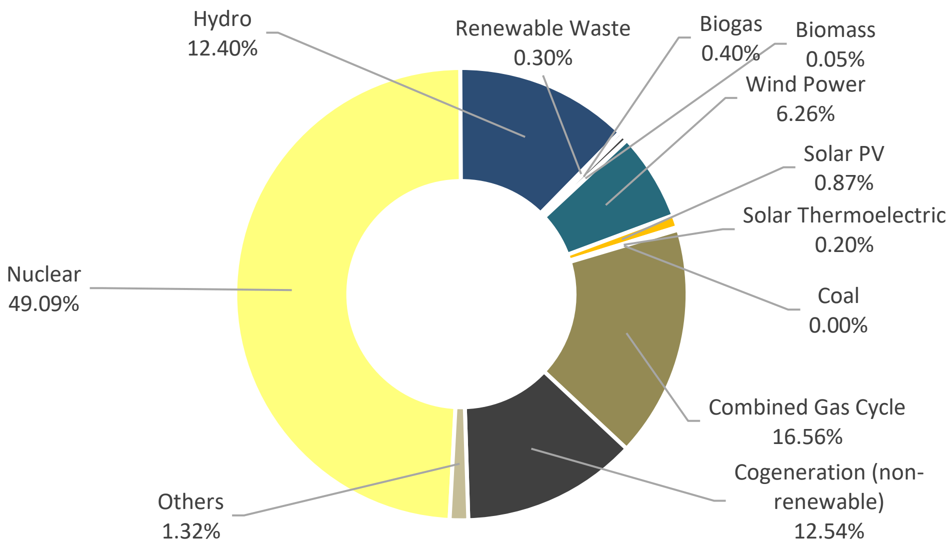


Figure 10: Production electricity mix (47.147 GWh3) in Catalonia in 2017. Own elaboration with data from (ICAEN 2018)

5.2. The energy transition in Europe, Spain and Catalonia. Legislative framework and prospective scenarios

The fight against climate change was able to gather in December 2015 the representatives of about 200 countries at the Climate Summit (COP21) encouraging the first global agreement to limit greenhouse gas emissions and tackle global warming. Such agreement, known as the Paris Agreement, will enter into force in 2020 and will oblige the countries gathered there to fight against climate change in the next decade, and to define and plan the future of renewable energies.
The European Commission presented in late 2016 the regulatory framework that will govern European policies in the coming years to ensure the achievement of the energy and climate objectives set for the 2030 horizon and that will replace the directives that led to the European positioning, popularly known as the 20 renewable , 20 efficiency and 20 emissions in the 2020 horizon. The *Clean Energy for All Europeans - unlocking Europe's potential growth (European Commission 2019)*, consists of a legislative package that includes, among others, new directives in the field of renewable energies, energy efficiency in buildings, the electricity market and governance rules of the Union of Energy-a legal framework of mandatory compliance by the states that will allow the European Union to join the inescapable energy transition towards a new energy model based on clean energy.
Presented proposals are framed in three main objectives:

- Prioritizing energy efficiency policies,
- Retake leadership in renewable energies deployment
- Favor a relevant and fair role for energy consumers

Quantitatively, the objectives proposed by the Commission in this new package refer to a reduction of greenhouse gas emissions of 40% compared to 1990, improvement of energy savings and energy of 32,5%, and contribution of renewable energies of 32% by 2030. Such objectives, in terms of efficiency and renewable energies, must be achieved jointly but not unilaterally by the states, which places many doubts on the table regarding which countries will be the first to address this challenge and the last ones in the queue.

[3] 4.054 if measured in ktoe as it has been done in previous figures. Note how this value contrasts with primary energy consumption by source (7.780 ktep)

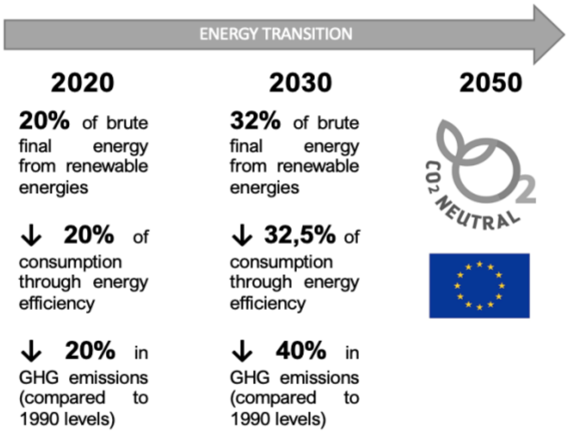


Figure 11: Energy Transition objectives as defined by the European Comission's Winter Package. Own elaboration

The Commission proposes a new framework that gives consumers an active and central role in the new energy model: wider energy supply, access to energy price comparison tools, the possibility of producing and selling self-produced energy, greater transparency, etc. Likewise, a series of measures are also contemplated to protect the most vulnerable consumers and minimize energy poverty.
Moreover, this new legislative ecosystem, opens the door to a more distributed and democratic energy model, allowing consumers the freedom to produce renewable electricity without facing undue restrictions, and to ensure that they receive compensation for the electricity they inject into the grid. For small power photovoltaic installations, often linked to housing, it determines that there will be no permits or authorizations and notifications will suffice to legalize installations.

Accordingly, it identifies consumers' right to organize themselves communally with the purpose of producing, storing, consuming and selling energy of renewable origin, which directly links buildings that produce energy and guarantee the possibility of recharging vehicles as elements to store and favor the management of the requested and the management of renewable sources.

On the other hand, the package also incorporates the principle of non-retroactivity in the mechanisms of renewable energy economic compensation, but it is not clear enough to guarantee the priority of dispatch for new renewable installations.

The adoption of this regulation by the European Union will force an in-depth review of the energy policies that Spain has promoted in recent years. According to the European Commission, implementing the energy targets in the 2030 horizon will involve a mobilization of 177.000 M € public and private annual as of the year 2021, which will generate up to an increase of 1% of GDP during the next decade and will create around 900.000 new jobs.

The legislative package "clean energy for all European citizens" should become an adequate tool to set the path towards a new distributed, clean and democratic energy model. However, the objectives set in the 2030 horizon are still unambitious if we are to face the challenge of achieving a 100% renewable European energy system in the 2050 horizon. The European legislative package sets a pathway for countries to follow that will surely affect Spanish energy policy in the years to come, especially after the reform of the Spanish electricity sector in 2013 (see above) that resulted in a strong punishment for renewable energies, both in its remuneration and in legal security, both necessary to guarantee new investments in the future.
In order to understand the evolution of renewable energy deployment in the past and its possible evolution in the years to come, a revision of Spanish legislative framework and the measures put forward by the Spanish government in recent years will be reviewed in the following subsection. As solar is the main target of this study emphasis will be put in PV solar regulation.

Solar PV regulatory Framework in Spain. An overview

Since the end of the 20th century Renewable Energy Systems (RES) have received attention from different Spanish governments leading to energy policies favoring RES deployment and establishing targets for renewable energy generation.
The first Plan for the Promotion of Renewable Energies (PFER 2000-2010) had the objective to generate 30% of electricity from RES by 2010 -providing half of wind energy-, 12% of primary energy and 5,75% of biofuels.

In 2005, The Renewable Energy Plan (PER) 2005-2010 replaced the PFER, whose results had been deemed insufficient. The revision maintained the commitment to cover at least 12% of total primary energy consumption with renewable sources in 2010, as well as the incorporation of the two indicative EU objectives of 29,4% of electricity generation with renewable energies and 5,75% of biofuels in transport for 2010. The target of wind energy increased from 9.000 MW to 20.155 MW and for solar PV it went from 135 to 400 MW.

In June 2010, its successor, the *National Action Plan for Renewable Energies 2010-2020 (PANER)* was presented to the European Commission incorporating the objectives set by Directive 2009/28 / EC of the European Parliament and of the Council, concerning the promotion of the use of energy from renewable sources. Finally, in November 2011 the new Renewable Energy Plan (PER) 2011-2020 was approved replacing both the PER 2005-2010 and the PANER 2010-2020, in accordance with the mandates of Royal Decree 661/2007, by which the activity of electrical energy production would be held in special regime according to Law 2/2011 of Sustainable Economy.

The PER 2011-2020 proposed renewable energies to represent 20,8% of final gross energy consumption in Spain by 2020, with a contribution from these sources to transport consumption of 11,3% in that same year, exceeding the mandatory minimum targets established for Spain by the renewable energy directive (20-20-20), which matched average global objectives for the EU. This 20,8% of gross final consumption of energy through the contribution of renewable energies, supposed a percentage of 39% over total electricity consumption.

In order to materialize the strategic elements to guarantee the successive RES plans objectives many laws and decrees have been put forward by the Spanish government in recent years:

- **Royal Decree 436/2004** and the **RD 661/2007**- defined renewables as an 'special regime' electric power production activity- successfully promoted the mobilization of private investment in renewables, with the aim of implementing and developing these innovative technologies, meet international commitments to reduce CO_2 emissions and starting the path towards a sustainable energy model and of future. From 2004, thousands of citizens and small Spanish companies chose to become producers or investors of renewable energies allocating their resources to the implementation of clean energy generating technologies.

- **RD 661/2007** guaranteed rights and a stable compensation for RES developers or adopters, through a premium[4] for the energy generated during the entire useful life of the facilities "to encourage their implementation, for their contribution to the objectives of the special regime". Otherwise, at that time, no one would have dedicated any time, effort or investment to this type of energy production sources. The modification of the regulations for the sale of electric power to the grid for photovoltaic installations was approved and premiums were granted to produce electric power under the special regime. Such premiums were set starting from amounts of 0.44 € / kWh during the first 25 years of life of the installation and would fall to

[4] Under a feed-in premium (FIP) scheme, electricity from renewable energy sources (RES) are typically sold on the electricity spot market and RES producers receive a premium on top of the market price of their electricity production. FIP can either be fixed (i.e. at a constant level independent of market prices) or sliding (i.e. with variable levels depending on the evolution of market prices).

0.35 € / kWh from the 26th year onwards. Moreover, premiums would be updated according to CPI evolution. (Ministry of Industry, Tourism and Commerce; Spanish Government 2007b)

- **RD 661/2007** and **ITC / 3860/2007**, revised compensatory premiums upwards from January 1, 2008, encouraging a spectacular rise of installed photovoltaic power, and Spain went from having 350 MW of installed power in 2007 to about 2.500 MW at the end of 2008. (Ministry of Industry, Tourism and Commerce; Spanish Government 2007a)

- Remuneration changes led to the entry into force of **RD 1578/2008**, which fixed FIP to a regulated price of € 0.34 / kWh installed on roofs or facades and € 0.32 / kWh for facilities. Such legislative changes also defined the appearance of revised annual installed power quotas force and stipulated that new rates would not grow accordingly with CPI but rather decrease as the power quotas were being completed. (Ministry of Industry, Tourism and Commerce; Spanish Government 2008)

- **Royal Decree Law 2/2013** that modified **RD 661/2007,** eliminated the option of market price plus premium for those technologies to which it was applicable and determining the remuneration according to the tariff of all the facilities of the so-called special regime. (Head of State; Spanish Government 2013b)

- **Law 24/2013**, of December 26, of the Electricity Sector, established the granting of a specific remuneration regime for renewables through a competitive concurrency procedure. (Head of State; Spanish Government 2013a). In addition to the remuneration for the sale of the energy valued at the market price, such new regime would allow the facilities to receive specific remuneration during their regulatory useful life, consisting of a retribution to the investment (CAPEX) and a retribution to the operations (OPEX). This measure, however, meant in practice the end of Feed-In-Premium compensation schemes in Spain and was followed by a massive drop in PV deployment indexes causing bankruptcy to a significative amount of generation installations in operation. According to ANPIER (Spanish Association of PV energy producers) (ANPIER 2015) cumulative legislative cuts amounted to 55% of the revenues that were initially guaranteed to producers according to previous laws and prevented the payment commitments for producers who, following the Ministry's financial suggestions, were indebted to financing up to 80% of the value of the plants.

- One of the most controversial legislative measures was set in 2015 through the **RD 900/2015** enabling the so-called 'Sun Tax' that aimed to tax self-consumed energy with the justification that self-consumers used a backup service from the grid to cover their energy needs, whenever their facilities were insufficient that needed to be paid for. (Ministry of Industry, Tourism and Commerce; Spanish Government 2015)

- In November 2018 (via the **RDL 15/2018)**, the **RD 900/2015** was abolished. **RD 244/2019** gives continuity to the provisions on **RDL 15/2018**, regulating aspects not defined in the previous legislation and allowing electrical self-consumption in 3 modes: (i) without surpluses, (ii) with surpluses receiving compensation and (iii) with surpluses not subject to compensation. The RD also allows for collective self-consumption and facilitates administrative procedures for installations' legalization. (Ministry for Ecological Transition; Spanish Government 2019)

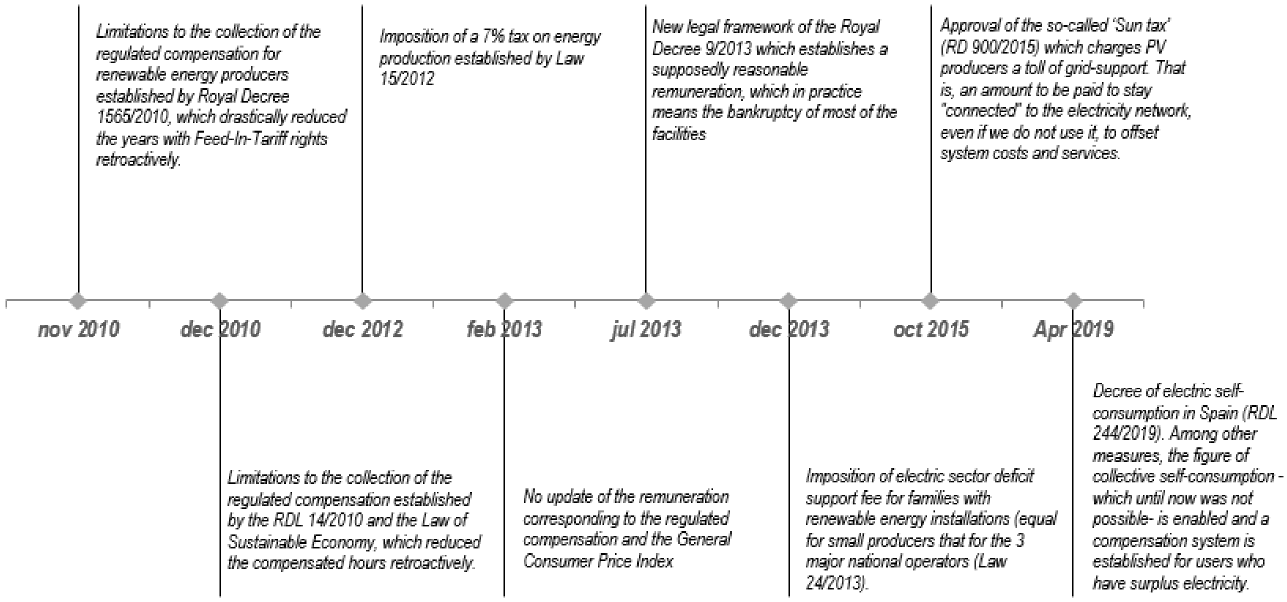


Figure 12: Timeline of relevant renewable energy (emphasis on PV Solar) legislation in Spain (2010-2019)

Even if the conditions of departure around 2005 offered the opportunity for solar energy developers to start a business activity with a reasonable profit margin (although not free of uncertainties) the photovoltaic technologies had by then not reached their degree of maturity and it seemed clear that regulatory incentives were necessary to encourage the sector's development and guarantee sustained RES deployment.

As legislative measures ceased to support RES, and retroactive cuts came along, interest in the sector fell leading to a stagnation of the PV sector after 2013. (see Figure 13). Note especially how added capacity suffers a dramatic decrease after the end of government support to feed-in-premium's mechanisms (2013). Legislative and financial uncertainty may also help to explain the slowdown of PV installed capacity in recent years.

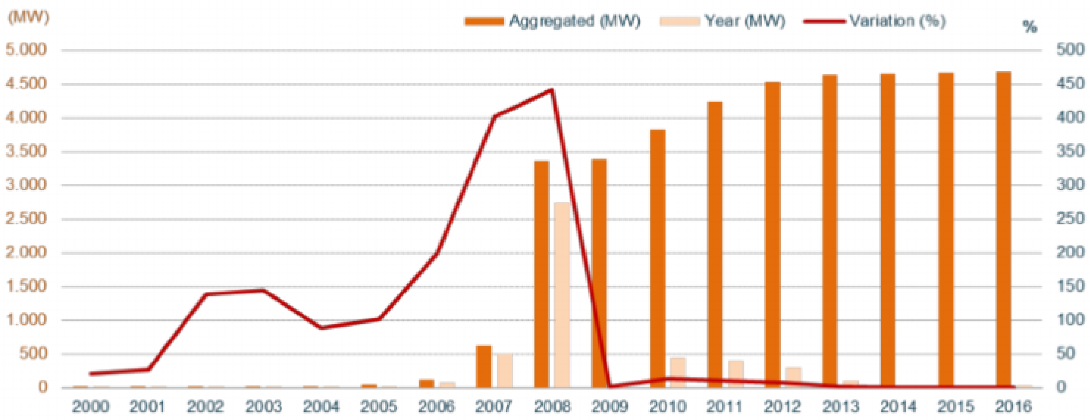


Figure 13:Photovoltaic solar installed capacity in Spain, 2000-2017 Source: (European Environment Agency 2018)

Solar PV Perspectives in Spain

A fairly consistent regulatory framework, a fall in component prices- especially those of solar panels- the appearance of big economies of scale and the enhancement of investment incentives have made it possible to give new hope to the solar sector in Spain, allowing installations to be profitable (without incentives) in most locations.

Global solar PV market trends may help to justify current situation in Spain. The International Technology Roadmap for Photovoltaic (ITRPV) demonstrates (see Figure 14) how module prices have dropped tremendously experimenting a 22,8% price decrease for every doubling of cumulative PV module shipments (ITRPV 2018). Such high shipment volumes have provoked an exponential increase of global cumulative installed capacity in that has reached 509,3 GW in 2018, with a year-to-year relative growth of around 30% (Solar Power Europe 2019).
Moreover, the price of solar PV is now very competitive. According to IRENA's database, in 4 out of 5 cases, 2020 commissioned PV solar long-term electricity prices should provide cheaper electricity than any coal, oil or natural gas alternative option (IRENA 2019) and most importantly, that should happen without renewable energy support financial assistance schemes.

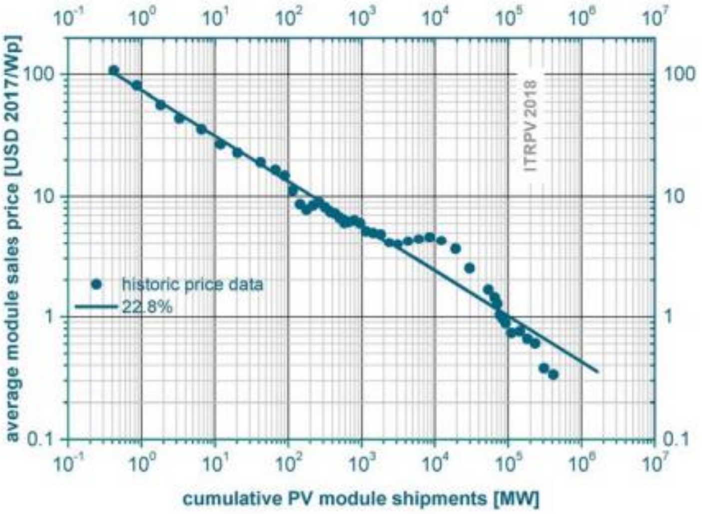


Figure 14: Learning curve for module price as a function of cumulative PV module shipments. Source: (ITRPV 2018)

This year 2019 will most likely be a tipping year for solar PV installations for 3 main reasons: i) solar PV is no longer seen as a residual energy source rather a central technology in the Spanish electricity mix in the years to come; ii) after several years on-hold, big ground-mounted installations will be set-up again this year and iii) new self-consumption legislation is propelling interest in smaller-scale projects especially for roof-mounted systems though not exclusively.

This situation translates into Spanish Administrations receiving high volumes of requests to install new plants that, if all were to be set up, would serve to multiply by eleven current operational PV solar power in the country in the years to come. Permission applications for renewable energy installations (solar and wind) to *Red Eléctrica de España*-the system operator in charge of managing and granting authorizations-have skyrocketed. With data up to February 2019, the company had granted an access permit for 47.700 MW (27,400 MW of photovoltaic solar) and had 62.600 MW (53.600 MW of photovoltaic) in process. (El País 2019)
Nonetheless, the way this deployment is going to be made is still uncertain. The Spanish transition to renewable energies is being based on perpetuating the current centralized energy model, substituting fossil fuel run centrals by renewable energy big-sized projects. The adjudication of the last auctions put forward by the Spanish government in January 2016 (Ministry of Industry, Tourism and Commerce; Spanish Government 01/2016) and May 2017 of 3.000 MW (Ministry of Industry, Tourism and Commerce; Spanish Government 05/2017) and July 2017 of 5.000 MW (Mincotur 07/2017) with the objective to fulfill 20-20-20 European Policy commitments have been concentrated in major companies. In the penultimate auction, 3.000 wind power MW were adjudicated to 6 companies with 3 of them- Forestalia, Gas Natural and Endesa-concentrating 90% of the total. Similarly, in the last auction 3.900 MW of solar PV were distributed between rather big stakeholders ACS, Endesa, Forestalia and Gas Natural Fenosa whereas 1.100 MW of wind power were adjudicated to a few companies among which Alfanar-Capital Energy received a 70% of the total.
Such strategies have been criticized by the Spanish National Association of Photovoltaic Producers (ANPIER) (Cinco Días 2017) arguing that the government is penalizing small and medium-sized photovoltaic companies and defending that the Spanish Energy Ministry should favor social facilities

scattered throughout the territory. Critics with energy policy measures hold that concentrating the entire renewable generation into a single technology and in a single locations offers no electricity price advantage (indeed it does diminish costs for solar developers, increasing their benefits) and prevents, on the other hand, that certain territories with high unemployment rates and no access to industrial fabric host renewable energy installations. The debate on whether the transition should be made through renewable energy megaprojects or via distributed smaller renewable energy installations is still an ongoing debate. However, megaprojects can only be put forward in certain areas and most likely both models (centralized and distributed) will have to coexist and complement each other to achieve energy transition objectives. A territory where a centralized model based on big installations would not be successful is Catalonia where land availability is scarce and geographic characteristics make it difficult for megaprojects to be developed. Therefore, this project will be centered in siting locations that may host small/medium solar parks (1-20MW) having in mind a radical change in the electric system as a whole from a centralized to a distributed model that is already being kickstarted.

Energy transition in Catalonia and prospective scenarios

The 22nd May of 2019 the Clean Energy for All Europeans Package (introduced in the precedent subsection) was formally approved by the Council of ministers by the EU. Member states have since then 18 months to transpose the policy package into national law. The proposals presented by the European Commission are in line with the strategic axes of the proposal of the bases of the National Agreement for Energy Transition (Pacte Nacional per a la Transició energètica or also referred to as **PNTE**) an agreement by Catalan institutions and civil society regarding the energy model that needs to be built and how regulations, planning and behavior need to change to transcend the current model energetic model and walk towards a new energy cleaner, decentralized, distributed, fair and democratic model (see Figure 15).
Catalonia's new energy policy as derived from the **PNTE** is structured around seven main strategic axes:

- Guaranteeing the right of access to energy
- Guaranteeing supply and energy security in Catalonia
- Reach maximum levels of energy conservation and energy efficiency
- Maximize the use of own renewable energy sources
- Fostering research and energy innovation
- Democratizing of energy and society participation
- Exerting full competences in an EU framework

Figure 15: National Pact on the Energy Transition in Catalonia

The principles defended by the **PNTE** were introduced and approved by the catalan parliament in July 2017 through the Climate Change Law (Llei 16/2017, del Canvi Climàtic) which elevated the strategies related with the energy transition to a legal status.
The final objective of such law was that of reducing GHG emissions, minimizing vulnerability towards climate change impacts and fostering the transition to a carbon neutral, innovative, competitive and resource-usage efficient economy.

The key aspects of the law are reviewed below (Catalan Institute of Energy (ICAEN) 1/24/2019) :

- Transitioning to a society with almost null fossil fuel usage and reaching an economic and energetic model not dependent on fossil fuels nor nuclear power by 2050.
- Developing a decentralized energy system powered 100% by renewable energy, mostly via own renewable resources.
- Materializing specific objectives towards the transition:
    - Definition of a plan of decommissioning of all nuclear centrals by 2027.
    - Define actions to enhance non fossil fuel run vehicles by 2030.
- Creating a public fund, the Climate Fund, as an instrument for the execution of mitigation and adaptation policies and actions: promotion of renewable energies, networks decentralization…

Derived from the new legislative framework, a prospective energy strategy in a 2050 horizon (Proencat 2050) has been put forward by the Catalan Government. Proencat is an ongoing project with the objective of accurately evaluating possible future evolutions of the Catalan energetic model in the long run integrating technical, economic and environmental criteria.
Among other objectives there are the **assessment of the renewable generation potential in Catalonia**, the integration of such technologies, the needs for development and storage of energy, the need for new energy infrastructures, the evolution of energy technologies and the their cost reductions, the definition of the role of nuclear energy and fossil fuels by 2050 during this transition scenario or the governance of the new energy model.

Renewable energy generation potential in Catalonia

For the scope of the current thesis, the most relevant aspect of Proencat 2050 are the renewable energies' potential studies in Catalonia which have analyzed resource potential and associated installed capacity of:

- Solar PV
    - Big scale (ground-mounted installations)
    - Small scale (roof-mounted installations)
- Wind Power
    - Both on-shore and off-shore

Even if the results of such studies are yet to be published (as Proencat is still a Work-In-Progress project) some preliminary results from a presentation by (Catalan Institute of Energy (ICAEN) 1/24/2019) held in Barcelona are used for discussion.
According to the cited presentation, available surface for PV solar development accounts for a 13% of total surface amounting to a total of 4104,4 km^2. However, as the authors recognize not having considered all possible incompatibility factors, they assume that only a 10% of the selected areas would potentially be used as solar parks, obtaining a final 410,4 km^2 of suitable land (1% of Catalan surface).
The methodology followed by the study is similar to other assessment studies and is based on selecting certain uses of land where solar PV can be installed (namely scrublands or lands with other herbaceous crops) filtering them according to several land characteristics (terrain altitude, terrain slope, terrain orientation and land environmental compatibility) and obtaining the set of 'suitable' lands.

Superfície total de Catalunya	32.107,2 km^2	100,0%
Selecció de 11 categories MCSC – nivell 5	9.299,4 km^2	29,0%
Superfície després de corregir per altitud, orientació i compatibilitat ambiental	4.104,4 km^2	13,0%
Superfície disponible final després d'aplicar el factor d'utilització (10%)	410,4 km^2	1,3%

Table 1:Surface availability for solar energu developments on Catalonia

The result of such studies yields a ground-mounted solar PV potential of 27,4 GW in Catalonia which according to the cited presentation would generate a total of 45.549 GWh every year. When comparing this value with electric energy demand of 47.847,8 GWh-at power plants busbars according to Catalan Electric Balance of 2018-the conclusion is that exploiting all the potential would almost cover current electric demand. Figure 16 shows a geographic distribution of solar potential both in capacity and in generated electric energy. Two shires (Noguera and Segarra, the one analyzed in this study) appear to hold the biggest potential.

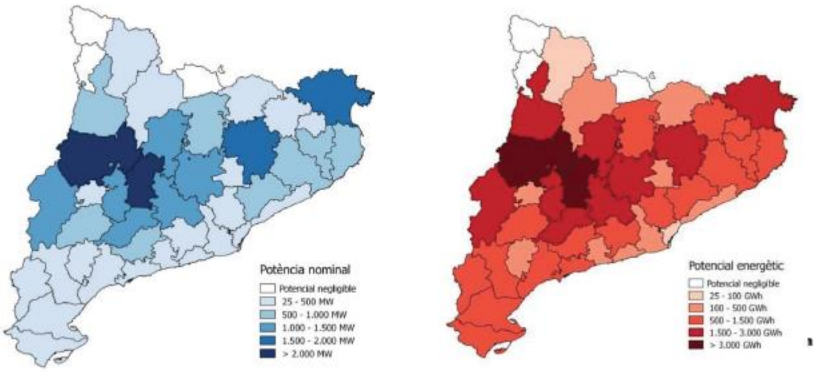


Figure 16 Big-scale:Ground-Mounted Solar PV Potential in terms of installed capacity in MW (left) and total generation yearly generation (right). Source: (Catalan Institute of Energy (ICAEN) 1/24/2019)

The cited presentation also provides values of roof-mounted solar (small-scale) solar potential of which though out of the scope of this analysis is worth mentioning. This potential is mostly is mostly concentrated on densely-populated areas (Barcelona and its surroundings) and **concludes that roof-mounted solar PV capacity in Catalonia is of 19,3 GW which could generate 24.307 GWh yearly, enough to fulfill half of current electricity demand.**

However, even if those potentials are in place, there is no sign of photovoltaic new installations being installed in Catalonia in recent years. Cumulative installed solar PV capacity has remained almost constant in recent years (Figure 17) and constitutes only a 5% of total installed capacity in Spain.

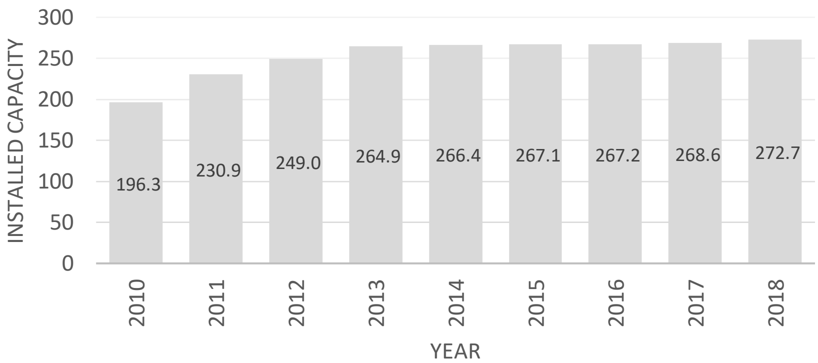


Figure 17: Historical evolution of solar PV installed capacity in Catalonia (2010-2018). Source: Own elaboration with data from ICAEN.

In absolute terms, Catalonia's solar PV installed capacity only represents a 5,3% of that of Baden Württemberg (5.000 MW) in Germany, a German land with similar population and territorial configuration. The findings of this study could offer valuable information to reverse this situation.

6. Analysis framework and methodology for solar parks' siting with GIS

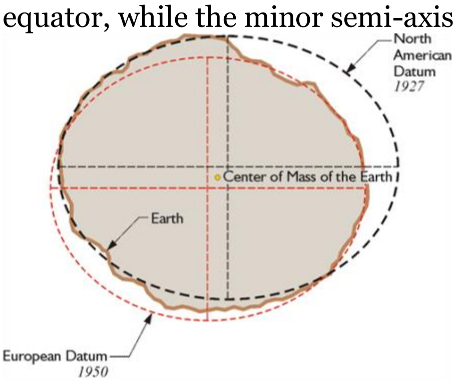
This section will present basic notions of GIS, the framework that has made this analysis possible in 6.1; will discuss criteria to evaluate solar potential based on previous studies in 6.2 and will explain the chosen criteria and how the methodology has been developed in this study at 6.3.

6.1. Theoretical Introduction to GIS

A geographic information system (GIS) is an application made up of hardware, software, data, users and an organizational framework, which allows to record, store, manage, analyze, consult, visualize, present and spread any type of geospatial information.
The most relevant and differentiating characteristics of geographic information systems are (i) their ability for explicitly storing the geographic position and the geometrical shape of the entities or phenomena represented in the information system and, as a result, (ii) the capacity to interrelate information of several entities or phenomena by means of the position and the capacity to perform spatial operations with the geometric shapes of the entities or phenomena that are being represented. The indispensable conditions to make effective these unique capabilities of geographic information systems are, on the one hand, the georeferencing of the different geospatial data sets, preferably according to the same spatial reference system, and, on the other hand, the spatial representation of the geometrical form of entities or phenomena by means of appropriate spatial data models such as the vector data model or the raster data model. (see 6.1.2).
When analyzed from a software point of view, a GIS can be understood as a platform that integrates functionalities of computer-aided design (CAD) for data production, database management systems (DBMS) for data management and queries, data analysis tools for spatial data analysis and visualization tools for visualizing, mapping and display cartographic representations.
The functionalities linked to GIS have traditionally been classified in five categories (Conolly and Lake 2006; Jones 1997) :data acquisition, spatial data management, database management, data analysis and data visualization.
From a theoretical point-of-view, a GIS requires certain characteristics to provide its functionalities that will be discussed in the following subsections: spatial reference framework, spatial data models, spatial data adquisition systems, spatial data analysis capabilities and spatial data visualization.

6.1.1. Spatial reference framework

This framework enhances the representation of physical locations and objects on earth surface. The first step is to define a coordinate system with a determined origin and orientation. In a GIS environment, those are known as spatial reference systems (SRS) or coordinates reference systems (CRS) and they are usually characterized through length, width and height- the 3 spatial dimensions- expressed in cartesian coordinates as x,y,z or through latitude and longitude when spatial positions have been parametrized in spherical coordinates.
Provided that the earth is far from being a perfect ellipsoid and due to its intrinsic surface roughness, models have been created to represent the earth as a 'perfect' ellipsoid. An ellipsoid is a tridimensional shape that can be obtained by the revolution of a 2D ellipse around an axis. Note how ellipses are ovals that can be defined through a major axis (or 2 semi-major axis) and a minor axis (or 2 semi-minor axis). In the case of the earth, the semi-major axis is the radius from the center of the Earth to the equator, while the minor semi-axis is the radius from the center of the Earth to the pole.



Several ellipsoids or spheroids have been defined along history (Clarke 1866, GRS 1980, WGS 1984 etc.) each one of them defined by the lengths of the major and minor axes of their underlying ellipses. Datums are 'corrected ellipsoids' generally generated above each particular spheroid with the capacity to incorporate local variations in elevation in contrast to spheroids, for which the rotation of the ellipse creates a completely smoothed surface around the world.

Figure 18: Schematic representation of datums approximating the earth's geoid. Source: GPS forLand Surveyors

A specific spheroid or datum can be selected for use in a specific geographic area, when that particular spheroid works exceptionally well by mimicking the geoid for that part of the world. In the case of

Europe, the datum European 1950 would approximate accurately the geoid in that particular area whereas in North America the datum NAD83, based on spheroid GRS 1980 may work better.

Once the datum has been defined, the 3D datum representation needs to be expressed in a 2D plane coordinate system through a process of map projection. Further discussion of differential geometry would be needed to analyse with property how such vector transformations are carried out. The basic objective, however, is that of transforming objects on the earth surface into objects in a projection surface that can be a cylinder, a plane, a cone….Transverse Mercator (UTM) is a popular projection, specially used in topographic maps, that uses corrected cylindrical projections according to which the equatorial plane hosts the axis of the cylinder and the meridians the tangent lines. As no distortion takes place in the projection surface whenever the cylinder and the earth meet each other (in the central meridian), TM is especially advantageous in areas with north to south long extent. Size, shapes, location and location of the study area, thus, affect the choice of map projection.

The last element to tackle to describe spatial reference frameworks are coordinate transformations. When using spatial data, two sets coming from different sources rarely come in the same system of reference and coordinate transformation aimed at harmonizing input data needs to be carried out in order to be able to align spatial data one on top of other.
When transforming coordinates from a CRS (i) to a CRS (ii) different methodologies are to be used according to the nature of the datums and the projection methods in which input data are expressed:

- *Case a: direct transformation*, regardless of map projection, the first data source expressed in CRS (i) can be transformed into CRS (ii) through complex polynomial functions that always come along with a certain degree of error.
- *Case b: same datum but different projection*. An example would of this would be found whenever one data source is expressed i.e. in Lambert conformal conic projection of datum NAD83 and the second in using a WTM projection also based on datum NAD83. In such case, projected coordinates of CRS (i) are transformed back to common datum coordinates and then furtherly transformed to the desired CRS (ii).
- *Case c*: *different datum and different projection*. In this case, CRS (i) needs to be transformed to its original datum before the projection, the approximated to datum via regression or other methods of 3D to 3D transformations and then projected to CRS (ii). That is called datum-to datum transformation. However, this method is actually quite inaccurate. An alternative would be transforming CRS (i) into a geocentric CRS which would need a greater degree of complexity in exchange of higher accuracy. In practice, however, GIS software always operates computing datum to datum transformations.

Moreover, most GIS software support on-the-fly projection allowing users to forget about coordinate systems of different spatial datasets which are automatically placed on top of each other even when based on different map projections.

6.1.2. Spatial Data Models

The objective of spatial data models is that of representing spatial reality in an abstract way. The way this should be made is still a subject of debate focused on defining what conceptualization of the geographical area is most appropriate: an object-based vision that understands the reality formed by entities described by thematic and spatial properties; or a field-based view, according to which reality is best described by means of magnitudes that vary continuously in space and that can be measured as attributes associated with locations (Goodchild 1992).
The object-based view has derived in what is known as vector models and assumes that space is made of discrete features. Such features can be buildings, parcels, point of interest or electric networks. The field-based approach understands space as continuous phenomena such as terrain height or temperature. This approach divides space in a set of homogeneous grid cells which hold information about a variable across space. According to this categorization, the natural environment (elevation,

precipitation or temperature) are usually modeled via raster grids while built environment and administrative data (zip code areas, parcels or countries) are better represented through vector models.
Vector data features can be points, lines or polygons and each one of them provides three types of information: spatial location, relationships between them and attributes. Figure 19 shows how a tree could be modeled in a GIS according to the vector model. A point is used to locate the tree on the map and complementary information of the tree is stored in the form of attributes within the tree feature. The feature also stores information about the relationships it bears with other geometric entities. Such rules -known as topology- describe spatial associations between points, lines polygons and are based on rules that guarantee features in the model are well defined (i.e. polygons are closed bodies, polygons do not overlap etc.) Note how three attributes are assigned to the feature in Figure 19: the name of the tree, its height and its age. Features can technically have as many attributes as needed whenever computation power and format is able to manage them.

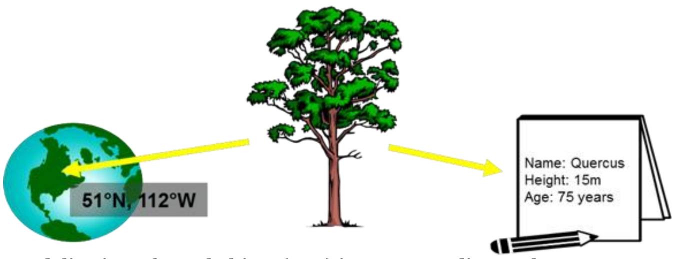


Figure 19: Modelization of a real object (tree) in GIS according to the vector representation.

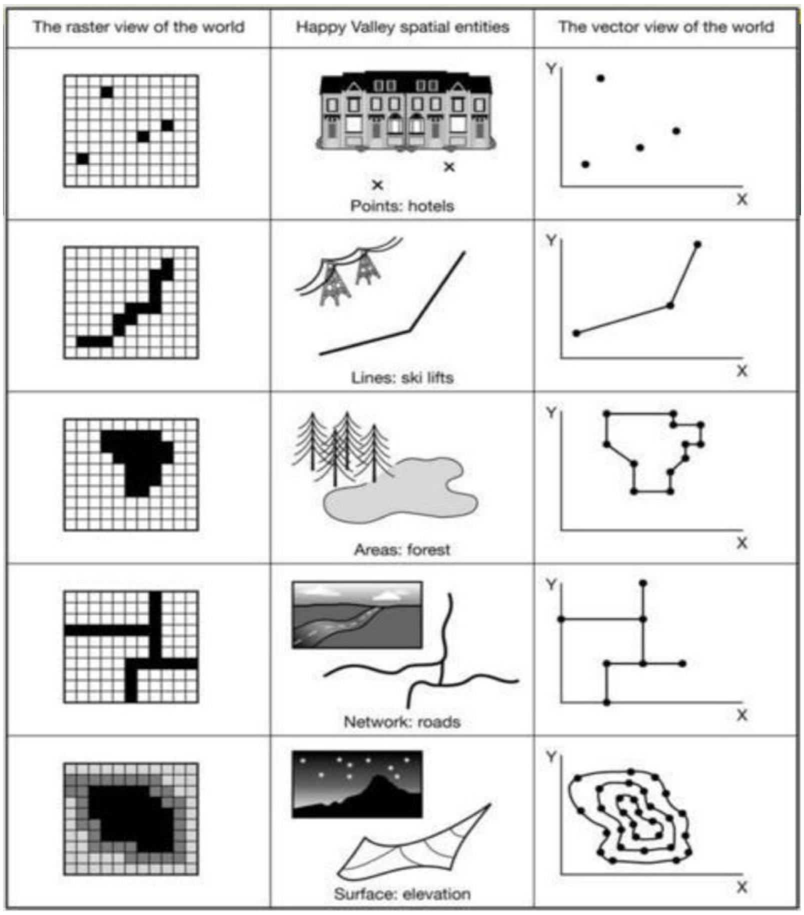


Figure 20:Spatial Data Models according to a raster view (left); vector view (right)

Raster models, on the other hand, are defined as a collection of grid elements or pixels creating a 2-dimensional array, like that of digital images. A pixel is only allowed to take a single attribute value so additional layers are required if more than one attribute is needed. The number and size of pixels on a raster will determine the spatial resolution of the model.

Figure 20 describes some differences in the way vector and raster spatial data model the real world. Discrete objects in physical space (i.e. a set of hotels on a map), 'line' profiles (electric power lines or ski lifts) and polygonal areas (i.e. a lake) are better described through the vector model (check cases 1 to 4 in the figure below) whereas terrain elevation may be easily characterized through a raster model.

It is worth mentioning that raster and vector models complement each other when conducting spatial analyses and each of them is more appropriate for certain sets of input data. Main differences between models have been highlighted in relevant literature (Olaya 2016); Cartographic Institute of Catalonia 2013). The following table reviews some of the most important ones:

Concept	Raster	Vector
Resolution of the spatial representation	Lower resolution, less detail, appropriate for sampling data with continuous variation in space, not suitable for cartography	Higher resolution, more detail, more appropriate for data of objects with well-defined limits, suitable for presentation cartography.
Ease of representation of the entities that model elements of real world	Does not represent entities as such, only the values of one of its attributes in each set of raster data. All cells are independent, other objects are not recognized than cells.	It represents entities explicitly by means of individually identified geometric elements.
Explicit representation of spatial relationships between represented entities and phenomena	Does not represent spatial relationships between the entities since it does not represent entities as such. Raster geometry is fixed (a grid) and the only spatial relationships is found between neighboring cells.	Represents topological spatial relationships between the geometric elements that represent the entities.
Ease of data acquisition	Some types of data (especially those from remote sensing) are captured directly in raster.	Data requires generally a drawing process except when it is obtained from topography or GPS
File size and computer storage efficiency	Poorly efficient as there is a lot of redundant information (each layer requires all entities in the grid with a value, even if most of them are 'empty'). Each piece of thematic information (attribute) requires a unique raster layer.	More efficient, once geometric entities have been defined, many thematic attributes may be stored in the attribute table of that single vector layer.
Ease of data analysis programming and operations management	Geoprocessing, field analysis and spacial analysis are usually easier to program. Some analysis operations only available for raster data representation.	Basic analysis operations and geoprocessing may be difficult to program. Allows network analysis.

Table 2: Differences between vector and raster spatial data models. Own elaboration based on Olaya, ICGC and other relevant literature

6.1.3. Spatial Data Acquisition

Spatial data acquisition is the process of collecting and encoding spatial data for database inclusion. Data collection may be the most time-consuming and expensive of setting up a major GIS facility (GISWEB: Department of Geomatics, University of Melbourne 2015).When acquiring spatial data the initial step is defining whether data should be stored in vector or raster format as this may condition the process and technology used for the acquisition.
Major spatial data sources are third-party sources. Governments and local administrations usually offer Open Data Infrastructures with all kinds of spatial data: demographic, environmental, urbanistic, infrastructural among others.

However, several methods exist to obtain spatial digital data when data is not available is not suitable for the objective for which it is needed. GPS or similar sensing technology, aerial photography, satellite imaging or Lidar systems can be useful technology for spatial data production.
Global Navigation Satellite Systems-such as GPS-are methods for positioning objects on earth, and ultimately on maps, by comparing time differences between signals emitted by distinct satellites and a specific receiver from which we would like to know its position.

Aerial photography is also a common way to acquire spatial data. Topographic maps, roads, buildings and power lines data has been obtained this way. Drones are increasingly offering inexpensive means of obtaining spatial data via aerial photography.

Satellite images are also a powerful source of spatial data particularly when data is aimed at studying or manage natural problems (Voigt et al. 2007). Also, satellites offering higher resolution imagery and image recognition algorithms can automatically capture higher volumes of data with great degree of accuracy. Hyperspectral imaging and multispectral imaging have offered the ability to capture a larger

variety of information; for instance, hyperspectral imagery can be used to quickly identify natural resources such as oil.
Lidar (Light Detection and Ranging) is based on an aircraft mounted, computer-controlled laser that records high precision spatial data in 3D that can be used, for example, to develop high-density terrain models. (USC Dornsife: Spatial Science Institute 2019)

6.1.4. Spatial Data Analysis

Spatial Data Analysis deals with spatial problem modeling, operation, combination of geospatial data and obtention and examination of results and is a fundamental function of any GIS software. GIS datasets are managed in layers which enable GIS-practitioners to work and analyze information stored in different layers with the objective of answering geospatial questions. Stacking layers with different types of data is at the core of spatial analysis.

Such layers are logical sets of geographic data that can be used to generate maps. In the example of the following figure, a study area is a modelled through a set of five layers representing (a) the administrative boundaries of the cities and counties within the area of study; (b) the streets distribution; (c) the buildings spatial distribution; (d) the land use-cover information and (e) the orography.

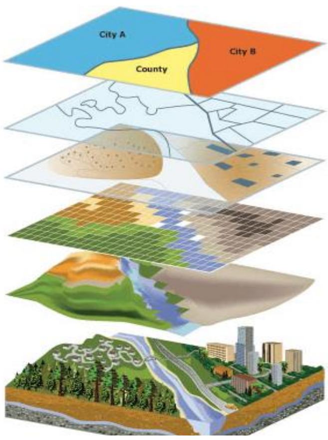


Figure 21: GIS layered structure. Source:ESRI

Note how several layers such as (a) are modeled in a vector representation whereas layer (d) is represented as a raster. Each of the layers holds one or more attributes. Layer (a) could attach attributes indicating city population or surface area whereas (b) could store the names of each street and its longitude for example. Land-use cover displayed in raster layer (d) would store a grid cell with values associated to different colors for each type of land-use: river, built-environment, green-areas etc.

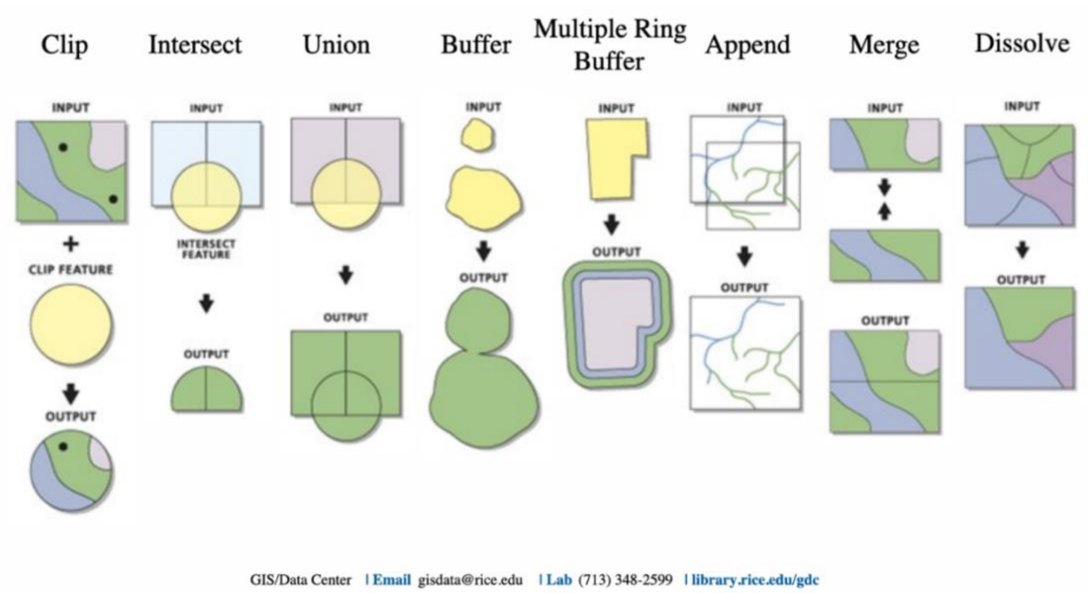


Figure 22: Basic geoprocessing vector tools in GIS. Source: Rice University GIS Data Center

When working with GIS, layers and geographical data may be manipulated through geoprocessing operations which take input datasets and transform them into desired output datasets. Geoprocessing provides a broad set of tools to perform GIS tasks ranging from simple areas of influence and polygon overlays to complex regression analysis and image classification; simpler operations- such as converting a group of data from one format to another-or more complex operations aimed at modeling and analyzing complex spatial relationships- calculation of optimal routes through a transport network, analysis of patterns in locations of crimes, floods predictions after a storm etc.

Each type of spatial model (vector and raster) has own specific geoprocessing tools. Vector models in GIS software usually come along with buffering, clipping, dissolve, intersect, union tools among some others whereas raster processing allows classification, overlay or spatial aggregation operations (see Figure 22).

Among main vector geoprocessing tools *clipping* allows to extract certain features or an area of a given spatial data frame; *intersect* integrates in an output layer spatial features and attributes of geometrically matching input layers; *union* is a type of intersection that preserves features and attributes of all input layers; *dissolve* unifies attributes of adjacent polygons removing unnecessary boundaries whereas *buffering* is a useful tool to create areas of influence that can be used for proximity analysis (i.e. finding all restaurants at a radius of less than 1km of a given location etc.).

Raster data allows *classification* which allows the categorization of pixel values into a predefined number of categories; *overlay* that enhances the possibility to conduct logical or arithmetic operations with grid cells values of two input raster layers or *spatial aggregation* that allows for coarser resolutions of a spatial data raster layer by means of mean, mode or other types of aggregation methods of values in subsets of adjacent cells.
Provided that in spatial analysis it is common to have data in both vector and raster formats, vector-to-raster and raster-to-vector conversions are very common and are supported by major GIS software. Unavoidably as conversion processes are approximations they come along with a certain degree of error.

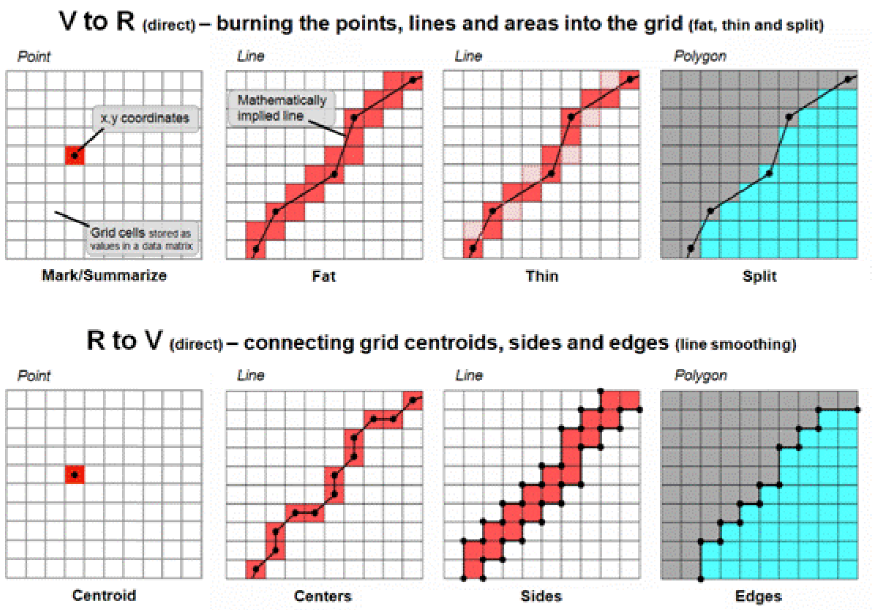


Figure 23: Basic procedures for direct calculation-based vector to raster conversion (VtoR) and the reverse (RtoV). Source: Innovative GIS

Note how each type of vector feature (points, lines and polygons) has specific methods for conversion. Vector-to-raster conversion may be quite straightforward for points if the grid resolution is appropriate when points are relatively scattered but it can get complex when i.e. two points fall within the same grid cell as such detail will not be captured by the resolution of the output raster layer. Vector-to-raster conversion for lines may be done in multiple ways. Figure 23 shows two alternatives:

fat and thin. The *fat approach* 'colours' the raster grid cell whenever the line entity in the vector models touches the output raster cell grid whereas the *thin approach* only 'colours' the output raster grid whenever the line entity passes through a given cell for a length above a predefined threshold. A similar methodology is adopted to burn vector polygons into a raster layer.
The strategy for Raster-to-Vector conversion is the reverse process and is aimed at converting grid centroids in points, connecting centroids of adjacent coloured cells to form lines that can act as boundaries between newly created polygons in the vector output layer.

6.1.5. Mapping and geo-visualization

Geovisualization is one of the major strengths of GIS and its most common output 'maps' act as a powerful communication support. Visualization consists in the generation of ephemeral graphic products that are consumed interactively. Such representations can be used to produce presentation-ready maps, but also as a main feature of exploration and consultation of spatial and thematic data, since results of a consultation require visualization and at the same time visualization is the medium through which interactive queries are carried out. Thus, it is common to create a distinction between simple data visualization and cartographic documents (for presentation) elaboration.
Visualization features various content selection operations, presentation forms and symbolization. Most common visualization products are 2D cartographic displays through interactive query layers, in the form of the various types of thematic map. Complementary functionalities (or plugins in software terms) allow data to be presented through statistical graphs, supported by external applications.
In maps visualisation concepts such as scale (ratio between distance on a map and real distance on earth surface); legend (visual explanation of symbols used on a map) or orientation (relationship between directions on a map and corresponding cardinal directions in reality) are extremely relevant to create self-explanatory, intuitive and ultimately useful maps.

6.2. Solar PV from a spatial point-of-view. Criteria to assess regional potential for solar power generation.

Solar energy is a low-density power supply that requires wide areas to generate decent amounts of power. One of the main blocks to the development of solar energy is the variability of solar radiation across geography which poses the question on where installations should be located to guarantee feasible and successful PV developments. Siting analysis is the initial step to any PV solar project and needs to take into account multiple criteria and restriction parameters that may modify the cost and potential performance of the installation, ultimately conditioning the feasibility of the solar park. GIS has proven an effective tool for various site selection studies (Rumbayan and Nagasaka 2012) offering the possibility to automatically replicate analysis across various regions specific studies once a methodology has been defined requiring, nonetheless, high-computational resources (Melius et al. 2013). The following subsections will discuss key aspects of which parameters are relevant when conducting solar siting assessments.

Physics fundamentals on solar radiation and its geographical dependence

Solar radiation or solar resource refers to the amount of electromagnetic radiation emitted by the sun. Such solar radiation can be captured and transformed into sustainably generated electricity by using solar PV technology. Since photovoltaic solar energy is based in the conversion of solar radiation into electrical energy by means of the so-called photovoltaic effect, the production of electrical energy obtained in a certain installation will be linked to the amount of solar resource, that is, the amount of incident solar radiation at the location where panels are to be installed.

Surfaces on the earth's spheroid receive sun rays at varying angles comprised between 0º (totally slanted) and 90º (completely vertical) according to their geographical location. Vertical rays provoke the earth receives maximum levels of energy whereas the obliquus rays provoke light scattering and less energy available at earth surface.

Geographical location plays an important role in determining the temporal variability of solar radiation on the earth surface due to the latitudinal dependence of daylight duration or its seasonal variation (Bel and M. Bandi 2018). Note how midlatitudes both in the northern and southern hemispheres receive more solar radiation than other areas. (see Figure 24)

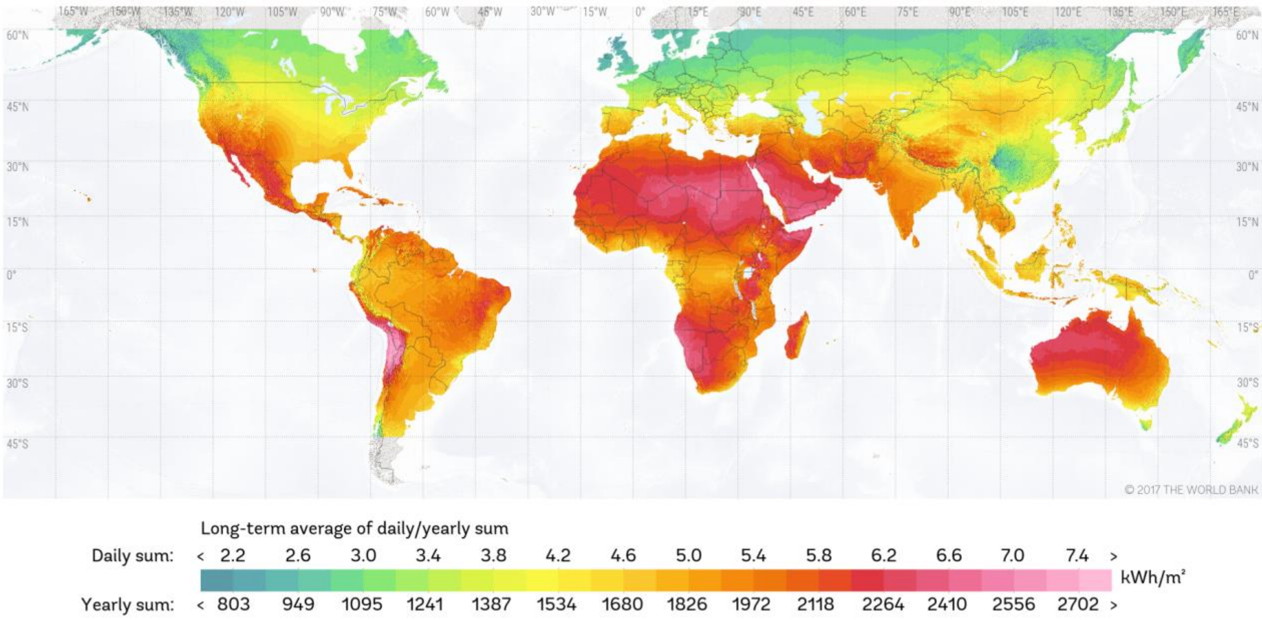


Figure 24:Solar Resource Map. Global Horizontal Radiation. Source: World Bank, SolarGIS

This can be easily explained by analysing translation and rotation earth's motions. The rotation of the earth provokes hourly changes in sunlight. In the central hours of the day, the sun is high provoking higher insolation on earth surface whereas during night-time insolation is inexistent. Rotation around a 23.5^0 tilted axis also conditions the amount of sunlight received at a location. Solar radiation in the summer is increased due to longer sunlight incidence in longer days. The earth translation movement in an elliptical motion makes the earth receive slightly more energy when it is closer to the sun (that happens when it is summer in the southern hemisphere and winter in the northern one) which may explain why mid latitudes in the southern hemisphere receive slightly more insolation than northern counterparts.

Solar Irradiance is the power per unit area (expressed in watt per square metre, W/m^2), that a surface on earth receives from the sun and varies according to location, season, weather conditions, time of the day etc. and can be integrated over a given time period (usually a year) to obtain what is known as solar irradiation or radiant solar energy density.
Solar irradiation is defined as the physically available solar radiation on earth's surface (Angelis-Dimakis et al. 2011) an is an essential variable to estimate solar energy potential. It is usually expressed in kilowatt-hours per square meter day (kWh / m2 day) or kilowatt-hours per square meter year (kWh / m2 year).

From solar radiation to solar potential

Many studies at global, European or national scales have been conducted in recent years to assess solar radiation. Meteorological satellite data and/or interpolation methods are the most typical methods for the determination of solar radiation and have been used, for instance, by the Heliosat method or the Meteonorm databases (Perpiña Castillo et al. 2016).

However, even if solar radiation is a key feature to estimate solar potential, theoretical potential is significantly reduced when multicriteria analyses considering environmental, normative, technical or social restrictions are put into place. The determination of factors that constraint solar energy systems deployment will help identifying suitable areas for installation.

Precedent literature has defined relevant criteria to evaluate solar potential. Starting from a theoretical potential (i.e. solar irradiation) a series of restrictions need to be introduced to obtain technical or real potential. The following definitions adapted from relevant publications may help to understand different levels of 'potential' assessment (IRENA-KTH 2014):

- Theoretical potential: refers to the resource that is available without taking into account conversion losses or efficiencies and is linked with the maximum amount of physically available energy.
- Geographic potential: takes into account restrictions for renewable energy employment. Geographic data allows for a definition of a set of exclusion criteria for which potential cannot be taken advantage of and to estimate available land accurately.
- Technical potential: is obtained as the geographic potential once conversion losses and other conditionings (i.e. need of spacing between generation technology) have been accounted.

When particularizing a transformation from theoretical potential to a technical one, the restrictions to be implemented differ according to the technology under study.

Discussion of geographic restriction parameters to assess solar potential

Even if photovoltaic systems have significant advantages in terms of environmental impact when compared with traditional non-renewable sources and have greater levels of public acceptance as has been reported in studies from (Tampakis et al. 2013) renewable energy reduced energy density and the need of large areas to generate decent amounts of power may cause undesirable impacts on landscape, land-use or biodiversity. (Graebig et al. 2010)

Contrary to fossil fuel-based electricity, PV solar does not emit GHG and does not produce noise (as i.e. wind power) nor odours (i.e. biomass combustion) but findings on (Carlisle et al. 2016) suggest that visual impact of large-scale solar facilities does matter for support of such technologies and that preference for buffer sizes, and thus proximity of proposed large-scale solar facilities, do change depending on the type of land where the solar park is being installed. This results may indicate, on the one hand, that social acceptance to solar development may only exist if solar facilities are located in areas with concrete current land uses as unused, degraded or low productivity agricultural land or in areas with grassland or scrublands as suggested in (Turney and Fthenakis 2011). On the other hand, rejection to solar parks seems to increase whenever such parks are 'big' and are close, beyond to 'one's backyard' to certain types of valued land in the area. Rejection diminishes whenever dimension and/or distance to valued areas.

According to (Perpiña Castillo et al. 2016) other non-ideal locations for parks' development are characterized by forest land cover, extreme remoteness, terrain instability or high degree of existing urbanistic development.

The set of technological, ecological, environmental or legislative criteria that support a PV energy potential assessment have been categorized as a) binary constraints and b) suitability variables. The framework included in (Perpiña Castillo et al. 2016) has been the main methodological support study for this analysis.

Criteria	Description	Data source
Constraints	Protected and sensitive natural areas	(EEA, 2013a; EEA, 2013b)
	Built-up areas, wetlands, water bodies and forest	CORINE LC-refined (Batista e Silva et al., 2013a)
Suitability factors	Solar radiation	PVGIS project (EC, 2013a, 2013b)
	Topographic parameters (slope, aspect, elevation)	SRTM, 2013; PVGIS project (EC, 2013a, 2013b)
	Population potentially affected	JRC population grid map (Batista e Silva et al., 2013b)
	Proximity to roads	Teleatlas
	Proximity to the electricity grid	EC-DG REGIO

Table 3: Main constraints and factors determining the overall suitability for PV systems deployment. Source (Perpiña Castillo et al. 2016)

However, many other factors might have been considered. A collection of relevant papers on this domain have been reviewed to list factors have been considered in other similar studies. Table 4 compile examples of binary constraints and suitability factors in other publications. The distinction between binary constraints and suitability variables is clarified in section 6.3.

SUITABILITY FACTORS

Category	Subcategory
Environmental	Land use and cover
	Agrological capacity
Distance Buffers	Distance to urban areas
	Distance to main roads
	Distance to power lines
	Population density
	Distance to Wildlife
Economic Feasibility	Land cost
	Maintenance cost
	Transmission Losses
	Generated Energy
	Electricity Demand
	Levelized Cost of Energy
	Construction Cost
Climatic	Solar Irradiation
	Average Temperature
	Humidity
Orographic	Slope
	Orientation
	Elevation
Social	Public Acceptance
	Effect on Agriculture
	Employment Opportunities

BINARY CONSTRAINTS

Category	Subcategory
Environmental	Protected Land
	Landscape areas
	Wildlife areas
	Sand areas and sand dunes
	Watercourses and streams
	Natural disaster areas
	Coastal Areas
Geologic	Soft soil
Infrastructural	Airports and Military Zones
	Water Infrastructure
	Roads and railroad network
Cultural	Cultural Heritage
	Archaelogical sites
	Community interest sites
	Paleontological sites
Land Use	Urban land
Orographic	Elevation
	Mountain Areas
Social	Visual Impact

Table 4: Binary constraints for solar parks siting in precedent literature. Own elaboration based on work of (Al Garni and Awasthi 2018)

Among all binary constraints and suitability factors some of them are more relevant than others. Essential binary constraints are protected lands, urban lands, wildlife areas, watercourses and wetlands, high landscape areas, high value agricultural land and high-altitude areas. Analogously, most important suitability factors are solar irradiation, proximity to power lines and substations and orography. Criteria selected in this study is accurately defined in 6.3.

Discussion of technical restrictions parameters to assess solar potential

Energy conversion efficiency of photovoltaic technology depends on a set of parameters.
Among them some affect the modules directly: module surface reflectivity (dependent on the angle of incising light); light conversion efficiency (related to sunlight incoming spectrum); PV module temperature (determined by air temperature, wind speed or light intensity) and others are caused by installation characteristics (panel orientation, panel tilt angle or panel shading). When assessing technical solar potential some assumptions regarding the type of installation, module inclination etc. need to be made.

6.3. Solar PV Potential Studies based on GIS: Methodology development

Once GIS has been introduced and relevant literature has been reviewed, it has been possible to develop and own methodology.

On a first phase, an identification of binary constraints and suitability factors has been conducted. Such identification will be key to determine which data (see 7.1**Error! Reference source not found.** for detailed data description) will be needed for the analysis.

Binary constraints are the set of criteria that cancel the possibility of development of a solar park at a given area, may it be due to technical unfeasibility, environmental restrictions or territorial incompatibilities. On the other hand, **suitability factors** quantify the appropriateness of a given area to host a solar park.
In order to make the explanation clear, an analogy to the symbology of a traffic light will be used. Whenever any of the pre-defined constraints is present at a location, the area will turn 'red' for solar park development. Starting off from an empty map, the application of binary constraints colors in red all areas subject to any binary constraint to indicate such area is not available for solar parks' development.
Having excluded all 'red' areas, suitability factors are sequentially used to define whether a location turns orange-whenever the score in one or several suitability factors is not high enough-or green-in cases it acquires decent scores according to suitability factors. Both orange and green designated may be used to quantify technical solar potential as there is no single approach to such type of assessments. In this study, as it will be seen in 7.4 there will be no 'orange' rather two types of green areas namely rough potential (less restrictive) and optimal potential (more restrictive):

Binary constraints

Binary restrictions are constituted by layers of land protection of different nature. They can be natural or artificial and are very closely related with territorial regulation and policy. To facilitate the explanation these restrictions are divided into three groups: i) Environmental constraints; ii) Territorial and Urbanistic Constraints and iii) Land Use constraints.

Environmental constraints:
Environmental constraints may be present in locations with sensitive natural areas such as nationally designated protected areas, natural patrimony, ecological connectivity areas or wetlands. In Catalonia, the system of protected areas is currently ruled in accordance with the model established by Spanish Law 12/1985, of June 14, on natural areas. On the one hand, this Law contemplates the plan of natural interest spaces, a plan of a sectoral nature whose objective is the identification of the natural spaces that are considered necessary to ensure, in accordance with the values, ecological, scenic, cultural, social, didactic and recreational activities, in order to grant them basic protection. On the other hand, it grants a second level of protection for national or natural parks, reserves, etc.

Several protection programs have been considered to define environmentally constrained areas:

- *Plan of National Interest Spaces (PEIN):* main plan aimed at conserving the geological heritage, the habitats and the most representative and best-preserved ecosystems of the Catalan territory, protects a 31% of total surface.

- *Natura 2000*: most important European policy initiative for the conservation of nature, stablishes the EU legal framework that guarantees the protection of natural heritage. Natural and semi-natural species, habitats and state of conservation of habitats and species are protected through a network of natural spaces. In Catalonia, there are 115 areas declared as Special Conservation Areas (ZEC) and 73 as Birds Protection Zones (ZEPA) (data as of December 31, 2015). It is also worth mentioning that a large fraction (95%) of PEIN areas are also part of the Natura 2000 network in accordance with Law 12/2006, of measures in the field of the environment, which advocated for the integration of the Natura 2000 network into local prevalent legislation PEIN. The approval of the Catalan Natura 2000 proposal (Government Agreement 05/09/2006) led to a considerable extension of the PEIN.

- *Wetlands:* considered as biologically rich ecosystems and simultaneously fragile and vulnerable, they have been object of preservation and conservation by Catalan authorities. An inventory of 2980 wetlands developed by the General Directorate of Environmental Policies to guarantee its protection are available in digital cartography.

- *Geological Patrimony:* defined as the set of non-renewable natural resources of scientific, cultural or educational value that help to study and interpret the evolution of the Earth's history and the processes that have modeled the earth, places of geological interest are areas that need to be preserved according to the Catalan Environmental Department.

- *Special Protection Natural spaces:* Natural spaces of special protection (ENPE) are singular types of protected natural spaces, designated specifically for their scientific, ecological, cultural, educational, landscape and recreational interest. ENPEs have higher a degree of protection than other natural protected areas, have their own legal regulation and an individualized and especially careful management. They are designated and classified according to Law 12/1985, of natural spaces, and cover an area of 284.774 hectares of land and 6,020 hectares of marine life in the context of the Catalan territory. 4 categories classify the 73 spaces of special protection in Catalunya: national parks (1), natural parks (14), natural reserves (64) and natural places of national interest (7).

Therefore, any piece of land intersecting with any of the buffers that the previous restrictions have defined, will be excluded (and painted in red on the map following the traffic light symbology) as a restricted solar park siting area.

Territorial and Urbanistic constraints:

Decree 147/2009 regulates the administrative procedures for the implementation of photovoltaic solar installations in Catalonia. The legislation in place has been deemed retrospectively as an ineffective legislation (see above) and is in the process of being derogated[5]. However, for the past ten years and still today is the binding legislation and it determines that the location of solar photovoltaic parks must be carried out on land that meets any of the following conditions:

1. Land qualified for urban planning as industrial (...)

[5] https://participa.gencat.cat/processes/parcseolics/f/2542/

2. Land classified by urban planning as non-urban land not subject to a special protection regime[6] and accomplishing any of the following conditions:
    - a) Being located contiguously, either to areas of industrial use, or to agricultural and livestock buildings and facilities with proximity to water and electrical grids (...)
    - b) Being located on lands whose natural state has been seriously degraded by a previous activity (...)as long as they do not represent a benefit for those who have failed to restore it. Excluded are those lands that have been affected by forest fires in accordance with the provisions of the applicable legislation.
    - c) Being located in lands considered suitable for the implantation of these facilities by the municipal urban plan or have been ordered by a special urban Plan that specifically provides for these locations.
3. Land that, as part of infrastructures of large comparable facilities or their bonded areas, present the best conditions for their solar use, when sectoral regulations allow it. (i.e. close to a drinking water treatment plant, an electrical substation...)

In this study, some of the lands with potential to host solar parks according to the legislation have been deemed as restricted.

Lands in industrial areas such those of case (1) have been considered inappropriate to develop solar parks for 2 main reasons: i) industrial warehouses usually host roof-mounted PV installations (out of the scope of this study) for self-consumption and ii) potential greater than 1 MW could only be installed on the ground on big factories or industries with abundant surfaces of unused land. Though not exempt of controversy, the determination of these areas as restricted areas has been driven by company's management decisions.

Lands that fall in case 2.c are not very abundant-if there are any- in Catalan territory. As of today-10 years after the legislation was firstly put in place- no single municipality in Catalonia has defined special urban plans for allocation of renewable energy technologies in particular geographical areas. Only Avià, a small municipality of less than 5.000 inhabitants, proposed in October 2018 a revolutionary municipal urbanistic plan-pioneer in Spain-allowing facades to be covered by solar panels (Nació Digital 2018). Such plan, however, did not either way define preferent areas for solar parks' siting. These areas, if they exist, do not represent binary constraints.

For the object of this study, thus, only lands on cases 2.a and 2.b and 3 could become possible locations to host solar parks. However, the legislation poses a condition on areas that fall on case 2.[7] They have to be outside of protected areas which may be environmental (PEIN or Natura 2000)-in which case they have already been filtered by the environmental constraints and do not need any additional filtering – or urbanistic-territorial in which case they may be constrained.

How to determine whether they should or not be constrained by urbanistic-territorial legislations?

The first condition is related to the size of the solar park size. As a general rule and according to 149/2009 solar parks in Catalonia should not exceed 3 hectares when located close to agricultural or grazing areas and new installations should be 500 m apart from any other existing installation. For the case of lands adjacent to existing industrial land, installations should not exceed 6 ha. In cases when lands have been classified territorially and/or strategically by urban planning mechanisms and as long as efficient solar panels are used, solar parks will be able to exceed the 6 ha size limitation. In practice, this size condition is generally not applied.

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[6] Special protection regimes are described in Urbanistic

[7] According to the declaration of climatic emergency announced by the Catalan government in May 2019, specific restrictions for solar parks at non-protected areas may no longer apply. However, no political measures have been put forward yet to define how that manifesto is going to be implemented.

The second condition is related with the type of protection of certain pieces of land. Two interrelated levels of protection coexist, namely urbanistic and territorial.

Urbanistic

According to urbanistic legislation, non-urban land is qualified in 3 different categories[8]: rustic, protection and sectorial protection.

- 1. Rustic (Code N1): land that without having a specific value, should be excluded from urbanistic transformation processes that rule municipal urbanistic planning.
- 2. Protection (Code N2): land characterized by specific value (forest, agricultural, ecological…) that municipal planning aims to preserve.
- 3. Sectorial protection (Code N3): land on which a high degree of protection is justified. Among these areas there are PEIN, Natura 2000 network and wetlands (already discussed above).

Taking back the light jam symbology, lands qualified as N2 (protection land) or N3 (sectorial protection land) would become red areas for solar parks' developments.

Territorial

According to Catalan Law 1/1995 territorial management is subject to the Catalan General Territorial Plan which is an instrument that defines the objectives of territorial balance to assure a sustainable land development and guarantee environmental preservation. This Plan defines the basis for coherence of sectorial territorial plans and partial territorial plans. On the one hand, Sectorial territorial plans have incidence in all Catalan land and are related with strategic axes of territorial policy (mobility, infrastructures, environment, energy, agriculture, forestry or even sports). On the other hand, partial territorial plans define how land planning should be made in specific geographical areas of Catalonia: Metropolitan Barcelona, Ponent, Alt Pirineu and Aran, Region of Girona, Central Counties, River Ebro Counties and Region of Tarragona.

Territorial plans ground in open spaces; urban settlements and transport networks. Urban settlements and transport networks are restricted areas for the development of solar parks.
According to territorial planning norms, open spaces are qualified in 3 types of grounds:

- Ground subject to preventive protection (partially related with rustic land as defined by urbanistic legislation).
- Ground subject to territorial protection (partially related with protection land as defined by urbanistic legislation): agricultural or landscape interest lands, mountain areas or strategic potential grounds fall within this category.
- Ground subject to special protection (partially related with sectorial protection as defined by urbanistic legislation): PEIN, Xarxa 2000, special protection lands or high value agricultural land fall on this category.

Therefore, on a territorial scale, both territorial protected spaces and special protected ones are restricted as solar parks' siting areas and would only be possible in preventively protected lands.

Land use constraints:

Though this criterion does not respond to any specific legislation, land-use changes may be object of social opposition to solar parks' development. Though large-scale solar projects are usually located far away from settlements to remote areas, social opposition may not only be based on distance to inhabitants' homes. The constraints defined here respond to the objective of limiting parks' developments in lands that are perceived by local population as 'valuable' even if located far away from their homes (see the work of (Carlisle et al. 2014; Carlisle et al. 2015; Carlisle et al. 2016).

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[8] There is still another category: authorized activities. Those are used for lands with specific uses (i.e. mining) legally implemented taking into account surrounding land protection.

This limitation will restrict construction of parks in any area of forest, may it be protected or not; on agricultural parcels that may be deemed of high value for citizens in a particular area (respecting economic substrate of communities) and on consolidated high-value permanent crops (high-value vineyard, or high-value olive…).

All those reviewed conditionings will provoke consequent red areas in associated potential maps.

Suitability factors

This study has selected relevant factors that assess solar park suitability with the objective to be useful for decision making. Some variables have been treated coarsely without the degree of academicism or concision that would be required if this analysis had been driven by scientific purposes.
However, considered factors take into account recommendations on literature and are similar to those of other solar PV potential assessments. The justification of why certain criteria has not been included is justified below.

Irradiation

The effect of solar irradiation is probably the most important suitability factor for solar parks' siting. Solar radiation can be measured according to different methods of measuring. It is generally accepted that Solar Global Horizontal Irradiation (GHI) is the most accurate metric to measure solar radiation for solar potential assessment.
Note how as sunlight passes through the atmosphere it is deviated, absorbed, scattered due to interaction with clouds, air molecules, dust, water vapor…creating what is known as diffuse solar radiation. On the other hand, direct solar radiation refers to the fraction of sunlight reaching the earth surface with no diffusion. GHI is the sum of both diffuse, indirect radiation and direct beam radiation and will be the metric used for this study. It is reasonable to define irradiation thresholds in relative value as distinct regions. In Catalonia insolation values oscillates between 1200 kWh/m2.year and 1800 kWh/m2 according to own estimations based on data extracted from European PV GIS (Huld et al. 2012).

Topography: slope, orientation and elevation

Topography is a factor that conditions spatial distribution of solar radiation and also determines the suitability of certain installations as terrains with steep slopes make construction difficult and more expensive (Brewer et al. 2015). Installation of PV modules on steep grounds may create foundation stability problems and erosion. Earth's surface slope has an effect on optimal orientation of PV modules. When slopes are limited (i.e. <3%) orientation is not relevant as support structures may compensate terrain slope to a desired optimal. On the other hand, whenever slopes go above a certain threshold (i.e. >10%) solar parks should only be built facing south. Even south oriented grounds are not optimal for solar parks' siting whenever their slope exceeds a certain threshold (i.e. 15%). Threshold values for solar parks' location according to relevant literature range from <3% (Uyan 2013) to <15% (Perpiña Castillo et al. 2016; Arnette and Zobel 2011).In this study, the threshold has been set at 15% slopes for southern, southern-east and southern-west facing lands; 10% for west or east facing lands and 5% for east-north, west- north or north facing lands. High elevation areas have also been deemed restricted for solar parks development. All areas with elevation >1000m will not be considered 'suitable'.

Road accessibility

As roads are expensive assets and as solar parks need to be accessible by vehicles transporting modules, inverters, cabling and other, transformers and other installation elements sites should not be located far away from roads (Janke 2010). Wide (>3m) roads will be necessary to guarantee appropriate O&M of the solar park so only paved roads will be considered in the analysis.
A buffer with a radius of 1km has been created to assure that proximity to the roads' network is accomplished. Areas outside such buffer would be less suitable for solar parks' development.

Proximity to electrical distribution grid

Spanish normative requests solar installations' developers to ask for a connection point to the Distribution System Operator (DSO)-Endesa in Spain- for a new installation that needs to be validated by the DSO. The DSO then elaborates a techno-economical study to guarantee the grid is ready to accept the power of the solar park and to evaluate the costs that could have for the company.

Solar park distance to power lines may affect its economic feasibility. The closer a project is from the grid, the lower the line-loss transmission expenses and the cheaper it will be to connect. (Charabi and Gastli 2011). For the size of the installations that will be put forward (1-5 MW) the voltage of the grids to which the installation will be connected will be in the range of 10 to 25 kV so distance to the electric lines should be evaluated in such terms (i.e. proximity to a 400 kV transport line would not be useful).

Relevant Non-included factors

- Air temperature: this variable plays a key role in PV system performance as it affects module temperature. All module manufactures give information on a module's temperature coefficient. Manufacturers rate panels' sensitivity to changes of module temperature in terms of efficiency deviations in module efficiency whenever they are working at non-Standard Test Conditions (Cell temperature of 25º, solar irradiation of 1000 W/m2 and air mass of 1.5). Common values of solar cell temperature coefficients range between -0.2 and -0.5%/ºC and express the percentage of efficiency decrease of a module for each degree above 25ºC in cell temperature. Higher air temperature forces cell temperature rises through heat transfer mechanisms. The reason why this factor has not been considered is justified as temperature variations on a relatively small area (as can be a shire or a municipality) do not vary significantly enough when location is modified. This factor should absolutely be considered if the geographical scope of the analysis was bigger (i.e. a whole country or a region where several types of climates coexist).
- Distance to urban areas and distance to electricity demand: Several studies have considered solar parks should be located away from urban areas (Sánchez-Lozano et al. 2014) whereas others consider (Aydin et al. 2013) that projects close to electricity demands may have a higher economical yield. As there is no clear agreement on which strategy is best, it has been decided not to incorporate this aspect into the model.

Even if main relevant criteria have been discussed, data availability has limited the scope and the level of detail of the analysis carried out.

The analysis framework has finally defined a set of binary restrictions classified in 3 categories: Environmental (5 items), urbanistic (1 item) and territorial (2 items) and a set of suitability factors classified as well in 3 categories: climatic (1 item), topographic (3 items) and accessibility (1 item) as shown in Figure 25. Proximity to the electrical distribution network has not been included due to lack of available data.

Section 7 will describe in detail all data sources that have been used in this study and more specifically how the GIS has been created. Figure 25 provides and overview of the methodology that has been followed to create a GIS-based tool for solar parks' siting.

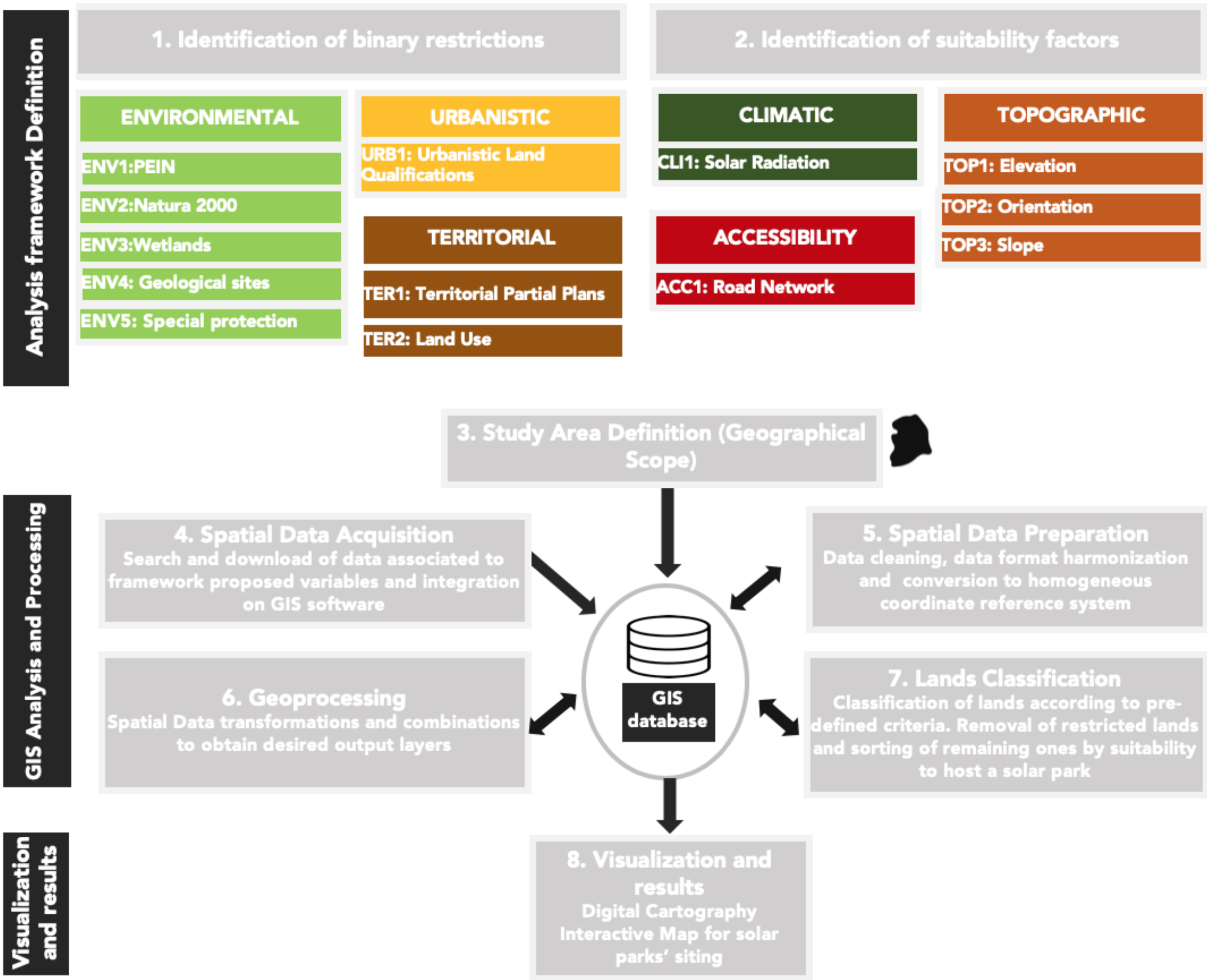

Figure 25: Graphical representation of the methodology followed to create a GIS-based tool for solar parks' siting. Source: Own elaboration

7. Description of the GIS creation process

The GIS creation has been developed with the help of open source software QGIS in the version 3.4 Madeira linked to GRASS (as the main functions and tools provider) and to python 3.6. as the programming language used for scripting of geospatial processing and layer handling operations. **Even if the description of the GIS creation process could potentially by applied to any geographical scope, the study area that will be analyzed for this explanation will be the region of Segarra in central Catalonia.**

The process of GIS creation has been structured in 4 main steps:

- Spatial data gathering and layer obtention
- Data preparation
- Geoprocessing
- Visualization and results

7.1. Spatial data gathering and layer obtention

Data acquisition processes are usually tedious and time-consuming. The websites of the different sources have been manually scraped one-by-one to obtain desired spatial data. Once having been downloaded they have been classified and ordered in directories to facilitate their processing. The following tables show all spatial data packages that have been used for the analysis. They are split in two different tables. The first refers to binary constraints whereas the second one refers to suitability factors. Data packages have been obtained for different geographical scopes: some of them come at a European level, Spanish, Catalan, regional or even at a municipal scale.

Spatial data packages have been sorted according to a code to facilitate layer handling. The following tables give information about what the data is about (category and subcategory); where does it come from (source); the reference system and datum in which it has been obtained (coordinate reference system); a short description and the date when the data was last updated (date of publication).
In the following sections, the code will be used to refer to each one of these data packages.

Code	Type	Category	Subcategory	Source	Coordinate Reference System	Description	Last Update
ENV1	BC	Environmental	Plan of National Interest Spaces (PEIN)	Natural Environment Planning Service (General Directorate for Environmental and Natural Environment Policies).Catalan Government	UTM-31N / DATUM ETRS89	Limits of natural interest spaces as defined in the Plan of natural interest spaces of Catalonia and subsequent modifications that have occurred.	18/03/2019
ENV2	BC	Environmental	Natura 2000	Natural Environment Planning Service (General Directorate for Environmental and Natural Environment Policies). Catalan Government	UTM-31N / DATUM ETRS89	Limits of the natural areas of Catalonia that are part of the Natura 2000 network in accordance with Directive 2009/147 / EEC, and areas of special conservation (ZEC) in accordance with Directive 92/43 / EEC.	11/10/2018
ENV3	BC	Environmental	Wetlands	Teritory and Natural Patrimony of Catalonia. Catalan Government	UTM-31N / DATUM ETRS89	Wetlands and their delimitations as defined in the Inventory of wetlands of Catalonia	11/03/2011
ENV4	BC	Environmental	Geological Patrimony	Geologic and Cartographic Institute of Catalonia	UTM-31N / DATUM ETRS89	Delimitations of the spaces of geological interest collected in the Inventory of Spaces of Geological Interest of Catalonia.	31/12/06
ENV5	BC	Environmental	Special Protection Natural Spaces	Natural Environment Planning Service (General Directorate for Environmental and Natural Environment Policies) Catalan Government	UTM-31N / DATUM ETRS89	Limits of the figures defined in Law 12/1985, of natural spaces: national park, natural places of national interest, natural reserves and natural parks. It also contains the limits of wildlife reserves defined in Legislative Decree 2/2008,	12/04/17
URB1	BC	Urbanistic	Urbanistic Land Qualifications	Urbanistic Map of Catalonia (MUC). Department of Territory and Sustainability. Catalan Government	UTM-31N / DATUM ETRS89	Synthetic map that allows continuous reading of the urban planning of the Catalan territory, resolving differences in coding, language and representation that the different regional or municipal urban plans currently in force have.	01/01/2019
TER1	BC	Territorial	Territorial Partial Plans	Territorial Partial Plans.Department of Territory and Sustainability. Catalan Government	UTM-31N / DATUM ETRS89	The Partial Territorial Plans establishes the territorial model of functional areas with a horizon of 15-20 years stablishing among other issues, territorial degrees of protection for open spaces systems.	2006-2013 depending on the geographical region
TER2	BC	Territorial	Uses and land cover	Department of Territory and Sustainability. Catalan Government	UTM-31N / DATUM ETRS89	Uses and land cover in Catalonia in 2013 created by the Remote Sensing and Geographic Information Systems Research Group [CREAF, UAB]	03/12/13
TER2	BC	Territorial	SIGPAC and land use	Ministry of Agriculture, Fisheries and Food. Spanish Government	UTM-31N / DATUM ETRS89	SIGPAC is a graphical database of all digitized cultivation plots as defined in EC 1593/2000 and allows the geographical identification of parcels declared by farmers in any land-related aid scheme, including information associated to these plots.	01/01/2019

Table 5: Packages of Spatial Data used for the analysis. Binary Constraints (BC). Source: Own elaboration

CL1	SF	Climatological	Solar Radiation	European Comission: Joint Research Centre. PV GIS	Geographic (lat,long) DATUM WGS84	Yearly average global irradiance on a horizontal surface (W/m2) period 2005-2015	01/01/2016
TO1	SF	Topographic	Elevation	Geologic and Cartographic Institute of Catalonia	UTM-31N / DATUM ETRS89	Digital Terrain Elevation Model of Catalonia with a resolution of 15x15m	01/01/2012
TO2	SF	Topographic	Orientation	Geologic and Cartographic Institute of Catalonia	UTM-31N / DATUM ETRS89	Orientation map of Catalonia with resolution 2m that classifies territory according to cardinal land orientation in degrees° (0-360)	01/01/2012
TO3	SF	Topographic	Slope	SIGPAC, Ministry of Agriculture, Fisheries and Food. Spanish Government	UTM-31N / DATUM ETRS89	Average cadastral plot slope in %	01/01/2019
AC1	SF	Accessibility	Road Network	Spanish National Geographic Institute	Geographic (lat,long)/ DATUM ETRS89	Linear database, continuous and with implicit topology of the Spanish road network.	22/05/2019

Table 6: Packages of Spatial Data used for the analysis. Suitability Factors (SF). Source: Own elaboration

Besides all layers in precedent tables, two additional auxiliary layers have been introduced in the GIS: (i) defining the administrative limits of the area of the study (Segarra) from now on, referred to as LIM1 and obtained from the Catalan Cartographic and Geologic Institute (ICGC) and (ii) an orthoimage (aerial photograph) of the area, from now on ORT1 (also from ICGC) as the background GIS layer.

7.2. Data preparation

As explained in 6.1 spatial data coming from different sources comes in different formats, coordinate reference systems and projections and is usually not available for specific study geographic areas. This means that lot of work and time has been devoted not only in data gathering but also in data harmonizing once it had already been fetched. How this has been made will be explained in this section.
Data preparation may be referred to the spatial component of spatial data (CRS and projection) or to attribute data (revise 6.1.2). Also, single spatial data packages operations'-all operations that need to be applied to a single layer to leave it ready for joint analysis- have been considered within this section.
As far as the spatial component is concerned, fortunately, few reprojections have been necessary as most data came in CRS UTM-31N/Datum ETRS89.
However, more polishing has been needed for attribute data as data formats of different layers did not match. Attributes as any other data is organized in types and structures. Examples of types are characters or strings, real numbers, integer numbers, logical statements…Some spatial data (i.e. TER3) has needed conversion from of certain attributes from one type to another (i.e. from numeric codes expressed as strings to numeric codes expressed as real or integers).
As spatial data packages preparation in GIS is basically specific and different for each of the datasets, the process that has been followed will be described 'one-by-one'.

Binary factors: Environmental (Codes ENV1 to ENV5)

The pre-processing of environmental data has been relatively straightforward. As the intention was not so much that of identifying which protection was affecting each area rather knowing which areas were subject to any kind of environmental restriction, the 5 data packages have been merged into a single layer and all attributes have been deleted. Then, a dissolve operation has been applied to obtain a big, non-divided unique plot including all restricted areas. As this layer contained information of all Catalonia, it has been clipped through an intersection with LIM1 to make it fit the administrative limits of the region.
Finally, an attribute with the name of the region and the size of the restriction area has been added.
These processes have been relatively fast, and no especial computational effort has been required.

Binary factors: Urbanistic and territorial (Codes URB1, TER1 and TER2)

Urbanistic data for all Catalan territory has been clipped and fit into the LIM1 (all plots outside the study region have been deleted). Some attributes of no use for the objectives of the study have also been erased. A very similar process has been conducted for TER1.

As for TER2, two spatial data packages (i) the Uses and Land Cover Map of Catalonia and (ii) the SIGPAC a graphical database of cultivation plots at a Spanish level have been preliminarily analyzed. As the formats and coding of (i) was not clear enough, and to avoid any possible interpretation mistake, land uses spatial data has been finally obtained from the SIGPAC database. The preparation of SIGPAC has required quite a long time as information was only available at a municipal level. Spatial vector data (in shp format) has been downloaded municipality-by-municipality to be merged afterwards in a single multi-municipality layer to cover the area of study. This aggregation has yielded a total number of polygons (subplots) of around 113.000 with which a GIS layer is able to work appropriately.[9]

Suitability factors: Solar radiation (CLI1)

CLI1 (solar radiation) data has been downloaded at a European scale, has been re-projected to match the GIS coordinate reference system (UTM-31N/ETRS89) and has been clipped to match LIM1. The resolution of the data has not allowed a finer analysis. 2750m has been the smallest available raster grid cell size (resolution). A raster-vector conversion (to enable further processing) has been performed to the solar radiation raster layer. Once in vector format, the main layer's attribute *solar radiation*, has been transformed from yearly average solar radiation (W/m2) to a yearly total irradiation (kWh/m2).

Suitability factors: Topographic (TOP1 to TOP3)

TOP1(elevation) has been an interesting factor to analyze from a methodological perspective and will be described with a greater degree of detail. Expect other suitability factors not to be described as concisely as this one, rather in a similar degree of detail as it has been done for binary constraints. TOP1 has needed several transformations to be readily available for further analysis. Fetched as a raster with very high resolution (2m), the set of operations applied are reviewed in Figure 26.

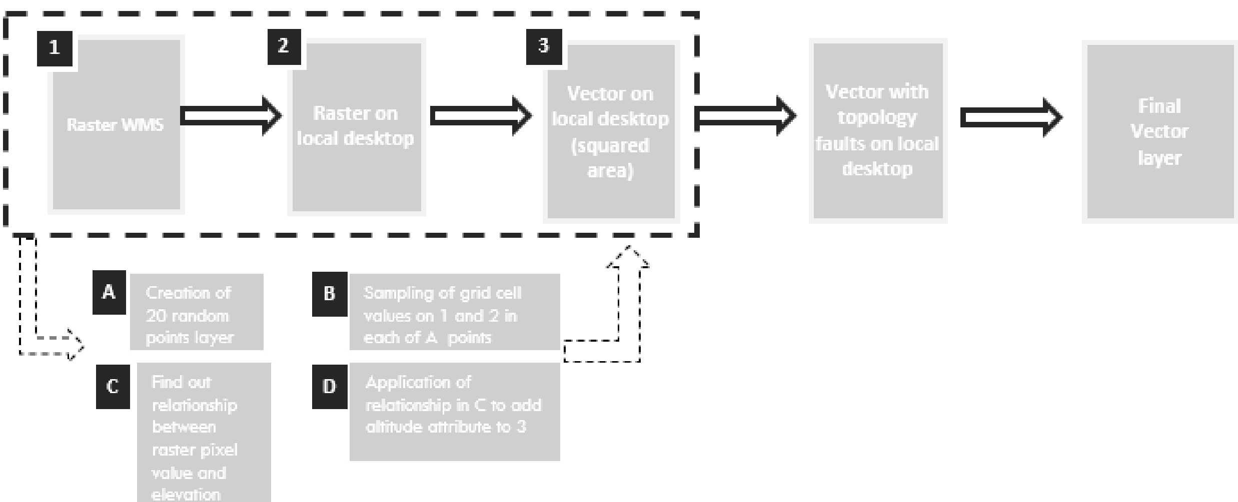

Figure 26: Flowchart of all pre-processing operations applied to TOP1: Elevation suitability factor. Source: Own elaboration

Initially, a connection to an ICGC (Catalan Cartographic and Geologic Institute) hosted WMS (Web Map Service) has been built. The hosting service has allowed the download of data at original resolution but due to computational constraints, it has been decided to reduce resolution to 50m grid-cells (process 1 to 2 on Figure 26); to further convert it to a vector layer. However, the process to convert 1 to 3 has not been trivial.

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[9] Shapefiles-the format of vectorial information that has been used for the analysis-has a limitation of around 2GB per layer and around 70 million points attributes. Note that since these layers are polygon layers, an estimate of maximum number of polygons to work appropriately would be around 1 million.

Generally, raster layers store pixels as computers store images. Each raster is formed by a set of pixels and each pixel value describes how 'bright' that one pixel is. Grayscale images or single band rasters (as is the case of digital elevation models) express the brightness of a pixel in a byte format on a value stored on a 8-bit integer. According to this codification, the range of possible pixel values is comprised between 0 and 255 being 0 the value corresponding to black and 255 to white. According to this codification, grid cells appearing in black should correspond to low elevation lands whereas white grid cells should correspond to high elevation lands.

Rasters available in WMS format can sometimes be accompanied by html information (analogue to attributes on vector data) that complement the raster information. However, once the raster has been downloaded, the color codification (and no longer html attributes) is the only information available. It is also worth mentioning that pixel values may change when the area of study is reduced. If a range of 0 to 255 pixel values is used to codify altitudes from 0 to 3500m on a vaster geographic area (i.e. all Catalan territory) and the study area only has elevations between 300 to 800m, pixel values of the study area will be lighter (read higher in value) than those of the original raster.

In order to address the problem of converting pixel values of original raster WMS layer 1 to attribute values on vector local layer 3 (see Figure 26) a series of steps have been needed.
First, an auxiliary 20 random points layer (A on Figure 26) has been created. Second, for each of those sampling points, verification of the html elevation value on the WMS raster webpage, pixel value of 1 and pixel value of 2 have been registered and stored on a csv file (B on Figure 26). Third, the file extraction has allowed to define, one the one hand, the conversion ratio between 1 pixel values and 2 and, on the other hand, a linear regression model to predict altitude as a function of raster 2 pixel data values (C on Figure 26). Fourth, this linear model has been TR used to predict altitude from raster colors that has been then included as an attribute in 3. The raster resolution of 2 (50m) has conditioned the size of polygons in 3 that only register changes in altitude every 50 meters.

With 3 in place it has been intersected with LIM1 to fit the study area. However, this process (as it usually happens when applying geometric operations to vector layers obtained from raster) has yielded topological errors (i.e. gaps between polygon borders or overlapping between them) in 4. The application of a buffer with distance 0 has allowed to correct topological issues in 5.

TOP2: Orientation has required similar treatment as TOP1 with some differences. As the orientation input layer was a multiband raster, 'colour codification' has had to be translated in three dimensions according to the RGB color model (in contrast to one-dimensional grayscale color model). RGB-color models-represent colors as an addition of the level of red, green and blue they contain respectively (i.e. pure red would be expressed as 255,0,0). Raster data has been converted to vector (with a resolution of 200m) and pixel values on the raster have been 'translated' onto an orientation attribute that has been implemented in the output vector layer as a value between 0 and 360 (0 being the north). Size of the layer has been adjusted to match LIM1. Topology errors have also needed some attention but have been solve through buffering and successive topological faults' checks.

TOP3: Slope values could have been obtained from the elevation raster TOP1 but computational power scarcity has made such analysis unsuitable. As an alternative, an attribute at the SIGPAC layer contained average plot slope for the 123.000 parcels in the area of study at the project's coordinate reference system and in vector format. Thus, no further pre-processing has been required.

Suitability factors: Accessibility (ACC1)

ACC1: Road Network has needed a re-projection from geographic coordinates (latitude, longitude) to UTM-31N (project coordinates). The network of roads has been filtered according to criteria defined in *Road accessibility* and only highways, freeways and conventional roads (only paved ones) have been kept in the layer. Other types of roads (pathways, non-paved roads) have been eliminated.

7.3. Geoprocessing

To start, it is worth reminding that geoprocessing consists on managing numerical processes all of which are subject to a certain degree of error and to a certain amount of computation time. The degree of error in geoprocessing is generally not trivial to calculate so it has only been done in some of the processes when computing it has not implied additional effort. Nonetheless, as the aim of this application is that it yields 'good-enough' results fast, it has been deemed acceptable to sacrifice some accuracy and level of detail in favor of obtaining fast results.

The aim of the geoprocessing has been to integrate all the spatial information stored in different layers into a single vector layer to which all attributes from different layers will be attached.
As owners usually identify their properties through a cadastre[10] code that univocally fingers a plot, starting off from a cadastral codes' layer would have been the most appropriate way to begin the processing. However, cadastral information is only available for download municipality to municipality and gathering all study area data would have taken very long time. In order to solve this issue, it has been noticed that SIGPAC had a way to codify agricultural parcels very similar than that of the cadastre.
An example of codification of a parcel both by the cadastre and the SIGPAC is shown below. As it may be noticed, SIGPAC codes can easily be transformed onto cadastral ones.

CADASTRE 25031A017002200000XX

	Province	Municipality	Aggregation	Zone	Polygon	Plot	Subplot
SIGPAC:	25	31	0	0	17	220	0

SQL programming has been used to convert SIGPAC identification codes to cadastre format. This has defined a geometric layer with all 113.771 subplots in La Segarra with their cadastral identification code added in an attribute field. As cadastre code normally identify plots (and not subplots) each of the subplots has been matched to the plot it belonged. This assignation has yielded 38.708 plots codified with the 14th first digits of their associated cadastral code.

As our interest was that of linking valuable information to plots (and not to subplots) a dissolve operation has been applied to the subplot layer to obtain a plot aggregated layer. The resulting layer, called from now one PLO1 has been the initial layer of the analysis. The initial layer (PLO1) contained all plots geometries' and an attribute field (*ref_cad*) to identify them according to their cadastral reference. For clarity, from now on, layers will be referred to in CAPITAL LETTERS and attributes in *lowercase letters and italics*.

Along the geoprocessing, the PLO1 layer has been updated repeatedly with additional spatial data. As a first step, some additional attributes have been added to PLO1: a field including the municipality to which each plot belongs (*id_municip*) and its area in hectares (*area_hecta*).

The process of aggregation of data as attributes in the PLO1 layer has been divided in two-stages. One to attach layers containing binary constraints information and a second one to attach suitability factors information.

Aggregation of binary constraints to the plots layer

Environmental

The main objective of this task has been identifying which plots could be affected by environmental restrictions according to criteria presented previously: and has been divided in 5 subtasks.

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[10] The paper cadastre divides the land into smaller and smaller subdivisions, first the Province and then the Municipality. This in turn is divided into polygons, these in plots, and plots in subplots. The cadastre serves exclusively so that the public administration can charge property taxes to landlords.

- Step 1: intersection between PLO1 and the layer containing all environmental restrictions ENV1to5. This process has fractioned ENV1TO5 in as many polygons as divisions exist in the plots' layer PLO1 yielding as output an auxiliary layer.
- Step 2: creation of field *env_protec* -dummy variable- in the auxiliary output layer of Step 1 to define which cadastral codes were being 'touched' by the environmental restriction layer (1 if touched, 0 if not touched). Also, creation of an attribute field *env_percen* to calculate, for each plot, the surface of ENV1 intersecting it.
- Step 3: field join operation to attach the 2 fields created in Step 2, to the PLO1 layer.
- Step 4: definition and execution of a Search Query Language (SQL) function that taking as inputs attribute *env_area* (plot area with environmental restriction) and attribute *ha* (total plot area) calculates the percentage of total plot area affected by an environmental restriction.
- Step 5: Update and saving of the plot layer PLO1 with the 2 newly created attributes *env_protec* and *env_percen*. After these operations, all plots in PLO1 will have attributes that indicate if they belong to any environmentally restricted area and to which extent.

Urbanistic

The main objective of this process has been that of classifying plots according to their urbanistic qualification according to the information on the Urbanistic Map of Catalonia. The urbanistic spatial data layer URB1 was quite big, so this process has taken huge computational effort and long time. As with the environmental layer, the processing operations have been divided in several subtasks.:

- Step 1: dissolve operation to group polygons contained in layer URB1 by their urbanistic qualification code. The output has been an auxiliary layer where all polygons sharing the same urbanistic code have been 'merged' to make part of a unique multi-part polygon. 32 polygons corresponding to the the 32 land qualifications in which the Urbanistic Map of Catalonia (MUC) have been created.
- Step 2: intersection between PLO1 and the output of Step 1. The output has been an auxiliary layer where plots in PLO1 containing more than one urbanistic qualification, have been divided in as many chops (or polygons) as different urbanistic codes exist within it. Over 80.000 closed polygons have been generated creating a massive spatial data layer. Note how the initial plot layer PLO1 included around 38.000 plots, meaning that on average, 2 different urbanistic qualifications coexisted in every plot.
- Step 3: creation of 2 new attributes using SQL functions: *urb1_area* to compute the area each urbanistic qualification holds within a particular cadastral plot and *urb_perce* to quantify the percentage of surface corresponding to each urbanistic qualification.
- Step 4: creation of a SQL function to iterate through all the polygons in the output auxiliary layer from Step2 and flag those ones predominant in their respective cadastral references. This 'flag' has been stored in an attribute dummy variable *urb1_max* in the auxiliary layer that has assigned a value of 1 to predominant polygons (in own cadastral reference) and 0 otherwise. Note that for each cadastral reference, only one polygon (holding a particular urbanistic qualification) may be predominant (and thus flagged). As a consequence, non-flagged polygons have been eliminated from the auxiliary layer.
- Step 5: Spatial field join operation to add the data in the output auxiliary layer from Step4 to the plot layer PLO1 by using cadastral code as a matching field. PLO1 has only stored two additional fields: *urb1_code* indicating the predominant urbanistic qualification of each plot and *urb1_perce* indicating the percentage that the predominant urbanistic qualification represents within the plot.

The analysis operation has been generally successful though some inconsistencies have emerged. From a total of 38.708 plots, 141 plots (0,1%) could not be matched so they have remained empty values. On the other hand, numerical errors have yielded some inconsistent results (i.e. identification of non-urban related urbanistic codes in urban areas) with those cases totaling around 217 additional plots (1,4%). Overall reliability of the geoprocessing is, thus, over 98%.

Territorial

The two main territorial restriction factors, TER1 -storing information about territorial partial plans protection types- and TER2 - storing information about land use-have been treated differently.
TER1 data processing has been analogous as the one explained for URB1 and thus it will not be explained in detail again. The objective has been that of identifying, for each plot, the territorial level of protection that applies. The success rate of the matching has been similar to that of URB1 with 141 (0,4%) plots that could not be assigned a territorial level of protection and 217 (0,6%) yielding inconsistent results possibly due to numerical errors.
TER2 data has not needed any further processing as input data (sourced from Spanish SIGPAC) already came with data at a plot level.

Aggregation of suitability factors to the plots' layer

Climatological

The objective of this process has been that of assigning to each cadastral code information about the level of Global Horizontal Radiation (GHI) on it. Provided the big grid size and low degree of detail of the input layer CLI1 and the fact that irradiation the stored value is a yearly average, the associated radiation magnitude should be understood as a rough estimate.
On a first stage, an intersection between PLO1 and the CLI1 has been performed and stored at an auxiliary layer. As the high size of the radiation data layer was much bigger than that of plots (plots were mostly within a unique radiation area) the auxiliary layer has then been dissolved by cadastral reference. Next, a spatial join between the auxiliary layer and PLO1 has been conducted. Finally, yearly solar radiation expressed in kWh/m2 has been stored in PLO1 as an attribute field called *cli1_GHI*.

Topographic

Topographic suitability factors TOP1 (elevation) and TOP2 (orientation) have needed extensive geoprocessing to be attached to the PLO1 layer whereas TOP3 (slope) has already been obtained at a plot level from SIGPAC input data.

The steps followed for TOP1 geoprocessing-that has taken long hours- are described below:

- Step 1: statistical grouping of the elevation variable TOP1 in intervals of 20m.
- Step 2: intersection between TOP1 and PLO1 to obtain an output auxiliary layer with cadastral geometries divided for each elevation level category.
- Step 3: computation of a python function that for each plot has calculated the average value of elevation TOP1 grid cells falling within it. This value has been stored in the PLO1 layer as an attribute *top1_elev*.

TOP2 on the other hand, has followed a similar approach but some issues regarding angles averaging have been found. As TOP2 input was a grid layer where each cells' orientation was represented by a number between 0 and 360 with origin in the geographic north, averaging in an ordinary was not possible. Note how averaging a plot containing two equal polygons one facing slightly to the north-west (i.e. 355 value) and another one facing north-east (i.e. 5 value) would yield an average value of 130 (pointing towards the south-east) and not of 0 (pointing to north as a correct calculation should obtain). To solve this issue, a python function[11] has been used to aggregate for each cadastral code, all different orientation polygons falling within it. The result of this computation has been stored in an attribute *top2_value* indicating the average orientation value (0-360) of each plot.
This attribute has then been 'translated' into cardinality as a string of characters representing each of the 8 main cardinal orientations: North, Northeast, East, Southeast, Southwest, West and Northwest and has been stored as *top2_orien* in the PLO1 plot layer.

[11] Adapted from http://rosettacode.org/wiki/Averages/Mean_angle

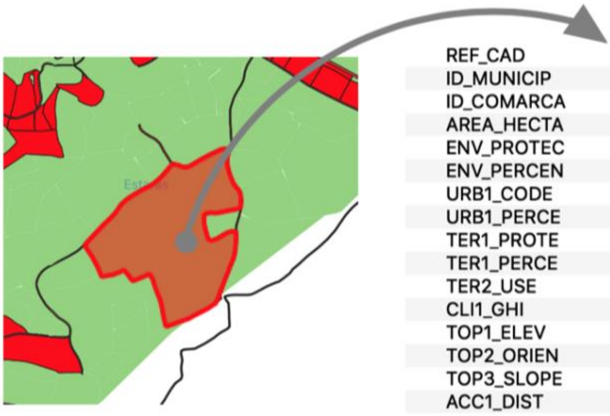
For TOP3, an attribute called *top3_slope* has been created to indicate average plot slope in %.

Accessibility

The suitability factor ACC1 has been calculated with data regarding the road network with some filters. The process followed is described below:

- Step 1: Buffer creation: 3 buffers with varying radius have been create around the road network with radius of 500m, 1000m and 1500m.
- Step 2: Intersection of the 3 output layers of Step 1 and the plot layer PLO1 (one-by -one) to yield 3 auxiliary layers.
- Step 3: For each of the 3 output layers from intersections of step 2, attributes *acc1_500m*, *acc_1000m* and *acc_1500m* respectively have been created to flag plots contained in each of the buffers. Note how plots closer to the road network will be flagged at all 3 layers whereas plots that located further away may not be touched by any of the buffers.
- Step 4: Spatial join of each of output layers of Step 3 to the PLO1 plot layer.
- Step5: Conditional statements definition to assign to each plot only one category (<500m,<1000m,<1500m or 'poorly connected') in an attribute called *acc1_dist* and update and save of PLO1)

Once all data has been processed and introduced into a unique GIS shapefile (PLO1) the information available will be treated for results' presentation and visualization. Figure 27 shows the aspect of a plot with its associated attribute table after geoprocessing. Note how the table includes the identifier of the parcel (REF_CAD) and all the thematic information that will be used for further classification. Codes on attribute *urb1_code* correspond to urbanistic qualification codes according to the Urbanistic Map of Catalonia (only in Catalan)[12] whereas codes on *ter2_use* correspond to SIGPAC Land cover classification (only in Spanish)[13].



REF_CAD	25107A00500338
ID_MUNICIP	ESTARAS
ID_COMARCA	Segarra
AREA_HECTA	18,78455
ENV_PROTEC	0
ENV_PERCEN	0,000
URB1_CODE	N1
URB1_PERCE	99,825
TER1_PROTE	Sòl de protecció preventiva
TER1_PERCE	100,000
TER2_USE	TA
CLI1_GHI	1656,0
TOP1_ELEV	695,46
TOP2_ORIEN	SW
TOP3_SLOPE	10,9
ACC1_DIST	<500m

Figure 27:Aspect of a plot geometry (left) and its associated attribute table (right) after geoprocessing. Source: Own elaboration

7.4. Visualization and results

Once all the geoprocessing has been carried out, any of the variables stored as attributes on the GIS layer PLO1 may be plotted and visualized. The following set of figures show outputs obtained when mapping variables (or combination of them) within qGIS. Taking the information shown on Figure

[12] http://territori.gencat.cat/web/.content/home/06_territori_i_urbanisme/07_observatori_territori/mapa_urbanistic_de_catalunya/caracteristiques_tecniques/metodologia/documents/codificacio_i_glossari_muc.pdf

[13] https://www.fega.es/sites/default/files/Nota_web_resumen_datos_SIGPAC_2018.pdf

27 as a reference, all different restriction criteria have been plotted to identify areas where they apply and start grasping which areas will be restricted and why.

Firstly, environmentally protected areas have been plotted. Figure 28 shows the output map obtained from the combination of attributes *env_protec* and *env_percen*. Whenever a plot is partially covered by the environmental restriction layer, it appears colored in red. The intensity of red defines the degree of overlay between the restriction layer and the plot surface. Note how certain urban areas (i.e. Guissona in the center of the figure) may slightly intersect with the protection layer and how plots close to the restriction layer boundary, are only partially affected (lighter red) by the restriction.

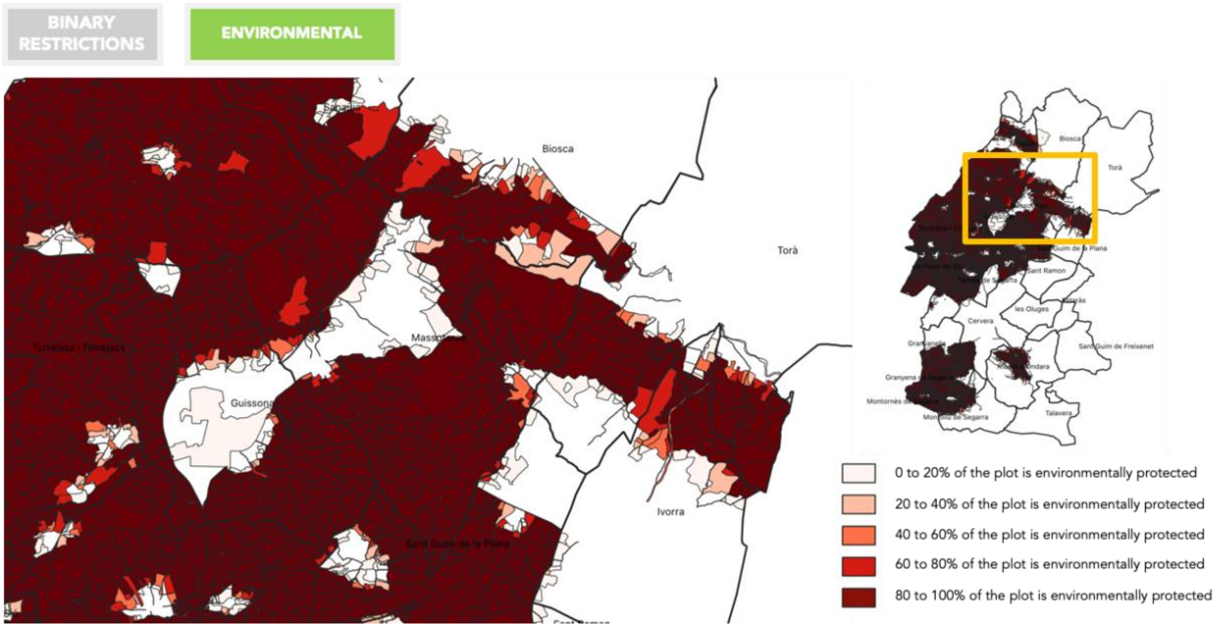


Figure 28: Map representation of environmentally protected areas on GIS. (Left: zoomed view; Right-top: overview map of Segarra's region; right-bottom: legend.) Source: Own elaboration.

Similarly, the urbanistic qualification restricted areas (URB1) have been mapped. Only lands with an N1 qualification according to Catalan Urbanistic Map have been considered 'not urbanistically protected'. This means as it can be seen on Figure 29 that urban settlements (i.e. Torà at the right-center of the figure) are restricted as are other areas that fall on cases presented in section 6.3.

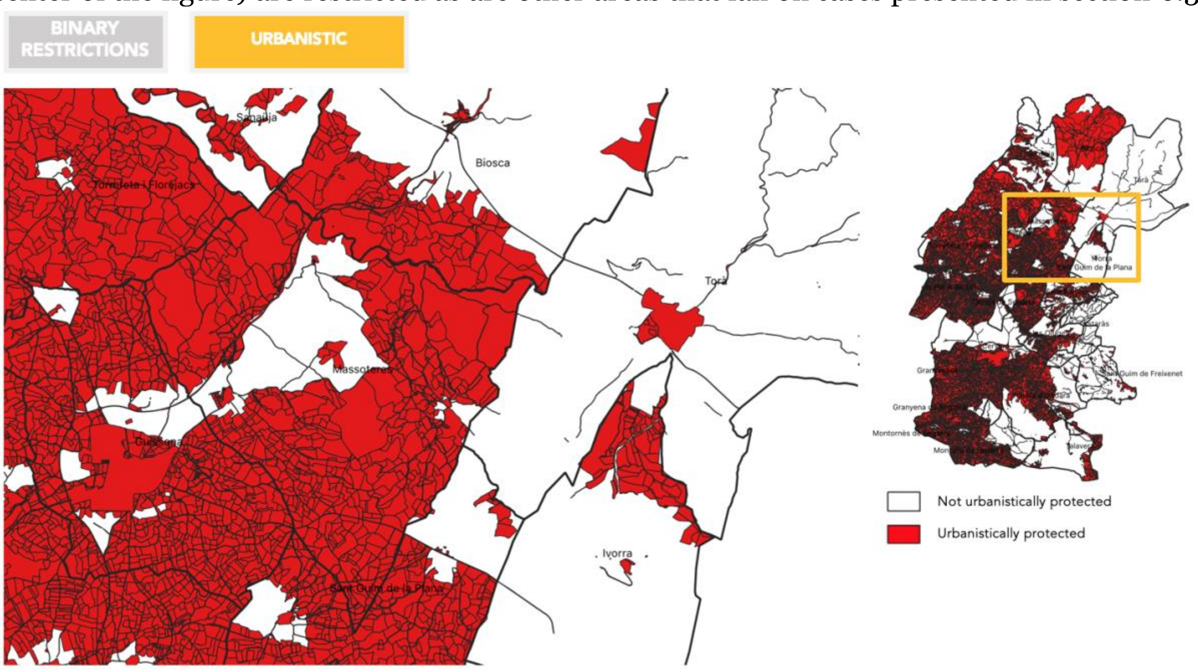


Figure 29: Map representation of urbanistically protected areas on GIS. (Left: zoomed view; Right-top: overview map of Segarra's region; right-bottom: legend.) Source: Own elaboration.

As far as areas where territorial plans' protection (TER1) applies it can be seen that most affected plots fall completely within the restriction area. This happens as the size of territorial restriction areas is much bigger than that of the plots and thus, it is unlikely that plots are 'chopped' by the restriction layer boundary. This translates into an almost binary classification of PLO1 plots when the restriction is applied.

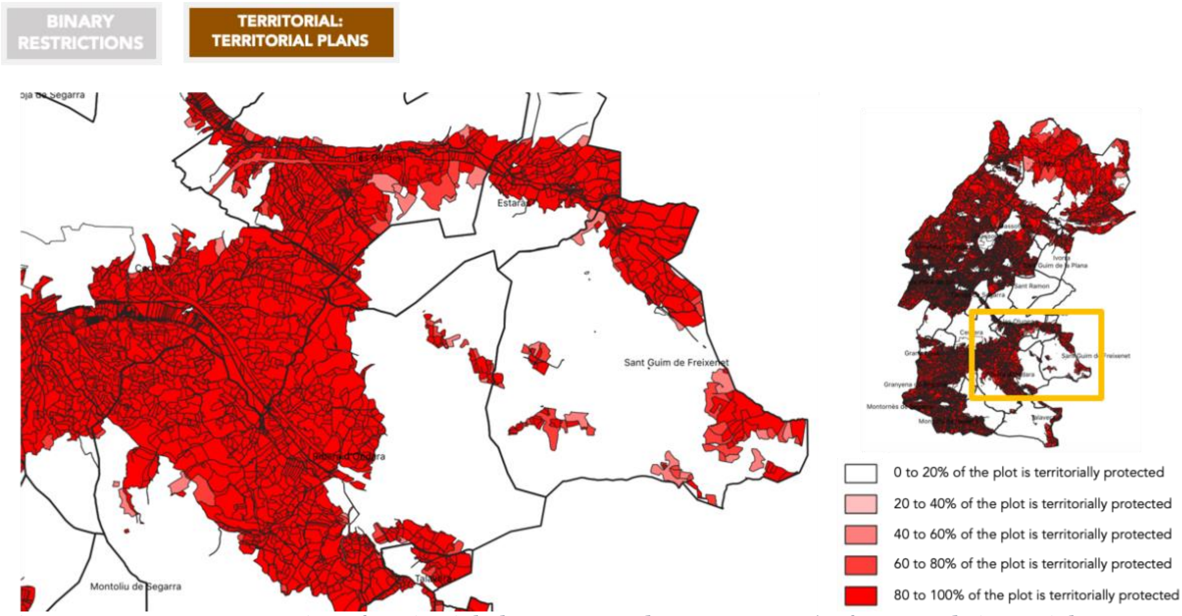


Figure 30: Map representation of territorial plans protected areas on GIS. (Left: zoomed view; Right-top: overview map of Segarra's region; right-bottom: legend.) Source: Own elaboration.

Finally, land use constraints (TER2) are much more scattered throughout the territory than previous layers as their determination has not been defined by legislations or policy instruments rather as a consequence of human activities. As the list of possible land uses is made out of 30 categories, some uses have been defined as restricted (i.e. roads, high value vineyards or olivars, buildings, urban settlements, forest areas, landscape value areas…). On the other hand, non-restricted areas include arable land, grazing land or orchard spaces.

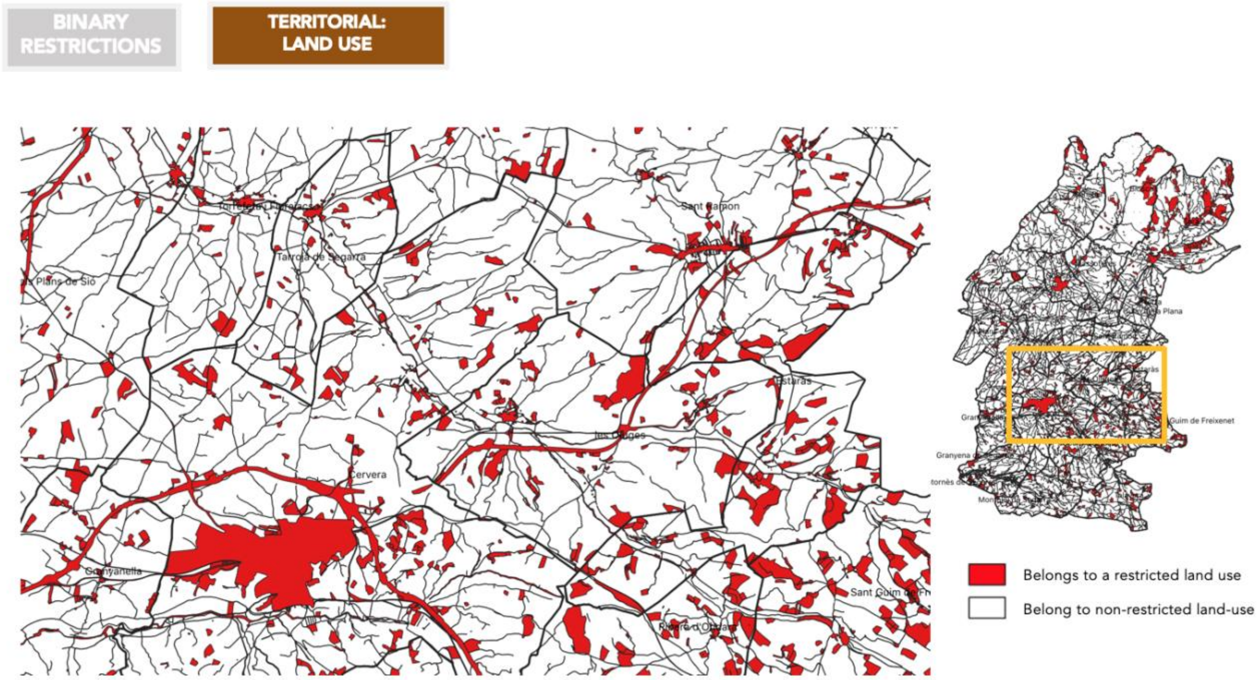


Figure 31: Map representation of land use protected areas on GIS (Left: zoomed view; Right-top: overview map of Segarra's region; right-bottom: legend.) Source: Own elaboration.

Once all binary restrictions have been excluded from the plots' layer, it has been possible to compute what would be total available area for solar park developments without considering suitability factors. This value has been called **rough potential (obtained if only binary restrictions are applied).** Then, applying sequentially suitability factors, remaining plots have been screened to obtain only those passing all the filters (optimal locations).
The process for obtaining optimal locations could have been carried out using composite indexes (i.e. weighting each of the suitability factors and combining them all together into a homogeneous variable to give each plot a score). However, it has been deemed more appropriate to set up thresholds to each of the suitability variables above (or below) and 'discard' locations not accomplishing them.

The conditions for screening have been the following:

- CLI1: Solar radiation >1500 kWh/m2
- TOP1: Elevation<1000m (all plots accomplish that in La Segarra)
- TOP2: Orientation facing S, SE or SW
- TOP3: Slope below 15%
- ACC1: Location at a distance<500m to the road network

The result has yielded a more restrictive set of lands to develop solar parks which has been called **optimal potential (obtained if both binary restrictions and suitability factors are applied)**.
Figure 32 shows in green color plots that have not been affected by any binary constraint. Darker green is used to plot rough potential and lighter green for optimal potential.
The screening process has yielded all plots adequate for solar parks development.

However, computing potential solar PV capacity that could be installed in such selected plots, has needed some extra effort. To define how many panels or how much PV panel area may be fit in a piece of land, several assumptions need to be made: the type of installation, the inclination of the panels, mutual shading avoidance considerations…For this computation, a fix installation with panel inclination of 30 degrees has been considered. The applied distance between strings (aimed at avoiding mutual shading) of panels has been defined using the formula and the layout in Figure 33.
Under the specified setup (fixed and 30º tilted installation) each square meter of land could host around 0,45 square meters of panels which is equivalent to a PV density of around 66 Wp per each m2 (or a MWp for every 1,5 hectares of available land).

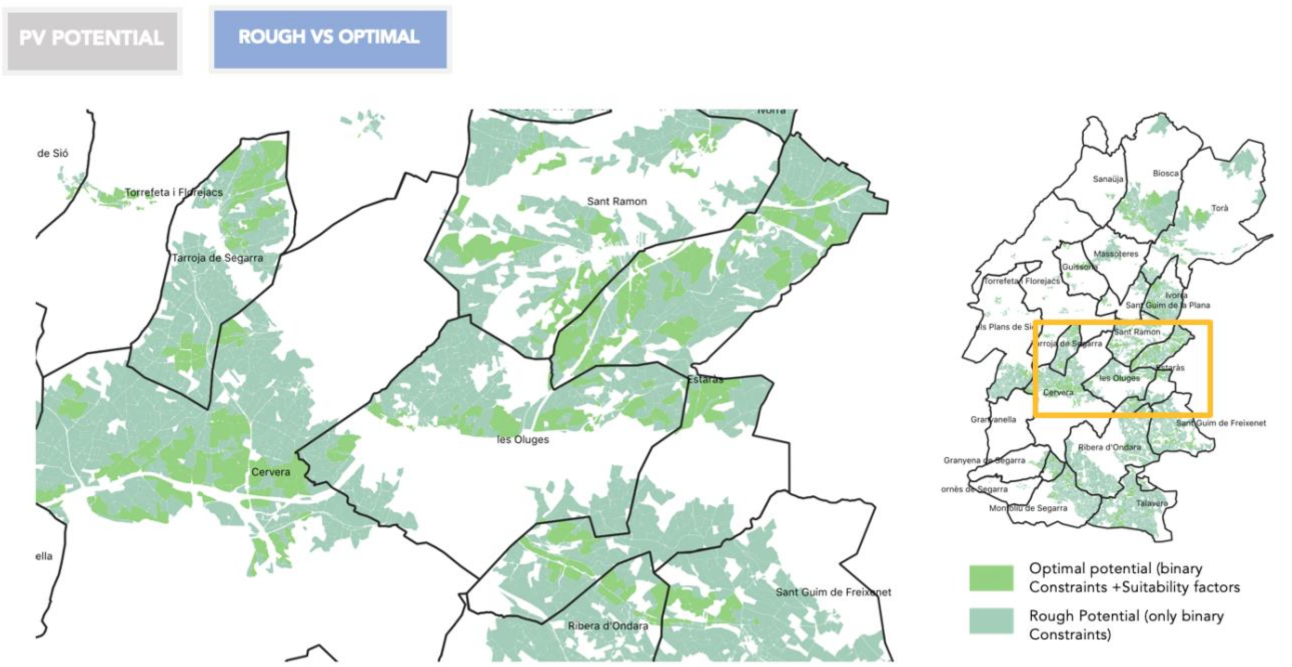


Figure 32:Map representation of rough solar potential areas and optimal solar potential areas in the Region of Segarra. (Left: zoomed view; Right-top: overview map of Segarra's region; right-bottom: legend.) Source: Own elaboration.

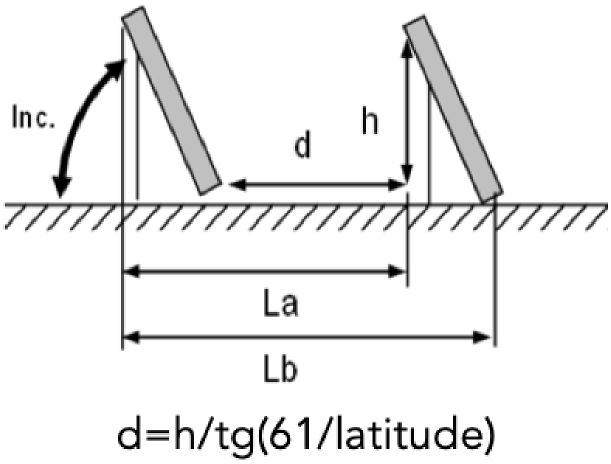


Figure 33: Solar panel layout and formula to avoid mutual shading. Source: ICAEN

Using the relationship found previously, computing an estimation of installed capacity that can be fit in a certain plot is straightforward.

Similarly, it is also interesting to know how much electricity would be produced if identified areas in La Segarra had the PV solar capacity in place.

A very simple model has been used to estimate that variable. The model can be formulated as *E=Eff. A. SR* with *E* being total electricity generated (Wh); Eff. being the average efficiency of the PV solar system; A being the area of PV panels (m) and SR being effective solar radiation (considering possible losses due to shading or non-optimal inclination) in (Wh/m2).

Assuming commercial PV solar panels offer an average efficiency of 17% and considering an 85% efficiency of the rest of the installation (losses on the panel, joule losses, inverters losses etc.) Eff. has been approximated to a value of 14,45% (17%.85%). Panel area A has been estimated as A_{land} multiplied by the occupation ratio of 0,45 (0,45 square meters of PV panels for each square meter of available land) obtained previously and SR has taken the value of attribute CLI1 or (CLI1_GHI in Figure 27).

GIS has allowed to compute plot by plot the total adequate area and through new attributes, also the installed capacity or the its potential generated electricity.

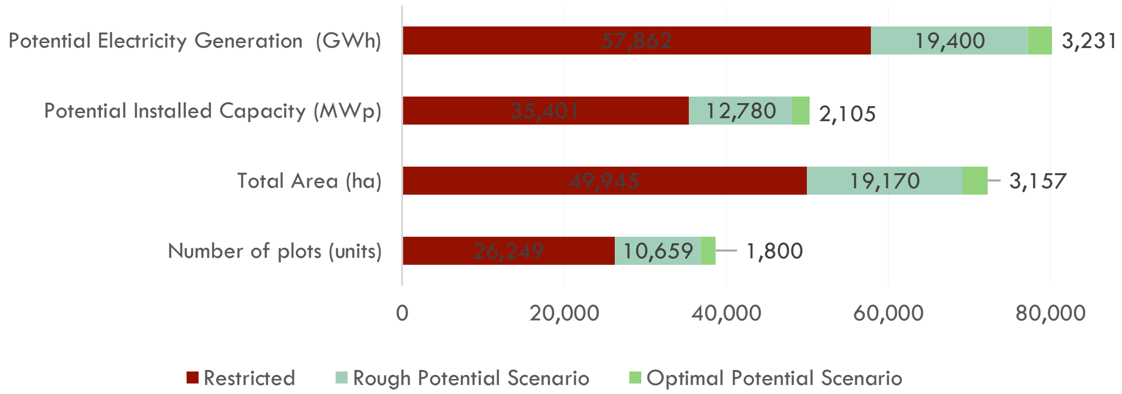


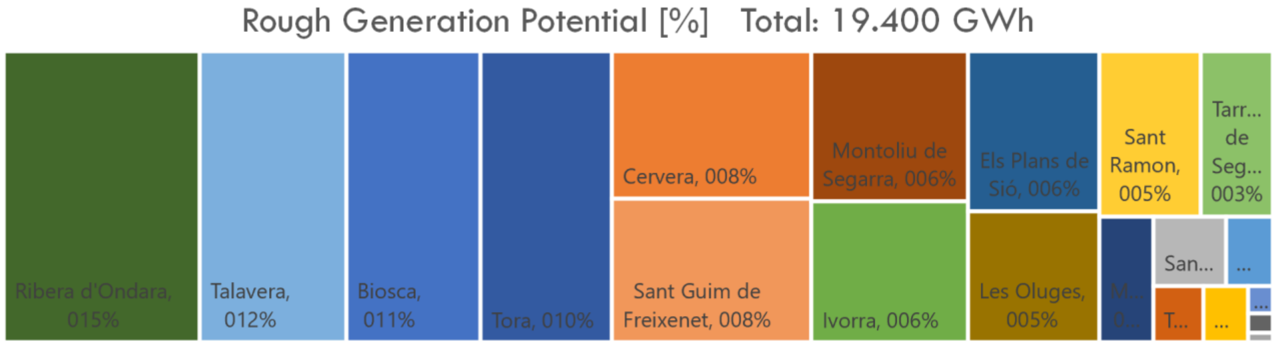
Figure 34: Review of aggregated results of GIS PV Solar Potential Calculations

Figure 34 gives some insight on how much potential there is in La Segarra region and classifies it in restricted (red), rough potential (darker green) and optimal potential (lighter green).
Several metrics are used to express this potential namely Potential Electricity generation, Potential Installed capacity, Total Area or Number of plots.

When comparing the obtained results for Electricity generation and potential installed capacity with those presented by the Catalan Institute of Energy (see Figure 16) they appear to be consistent. According to their results, installed capacity in Segarra region should exceed 2.000 MW. In this study, even in the most restrictive scenario (optimal potential) total potential capacity would be of 2.105 MW. **Total generation according to the optimal potential scenario would be of 3.231 GWh (7,1% of Catalan electricity consumption) whereas in the rough potential scenario would be of 19.400 GWh (42,6% of Catalan electricity consumption). However,**

fulfilling the rough potential scenario would imply covering more than a quarter of the regional area with PV panels (clearly not a feasible option) whereas a 4,3% of total regional area would be needed to materialize the potential as defined in the optimal scenario.

Finally, rough generation potential and optimal generation potential have been distributed by municipality (22 municipalities in total) to identify villages and areas in la Segarra region that would be more well-suited to host future solar parks. The results are shown in Figure 35. It is worth highlighting how villages with higher potential change as the filtering methodology is modified. Ribera d' Ondara holds the greatest rough generation potential whereas it falls fourth when optimal generation potential is considered. Biosca appears to hold the greatest potential according to the optimal generation scenario representing 15% of total region potential.



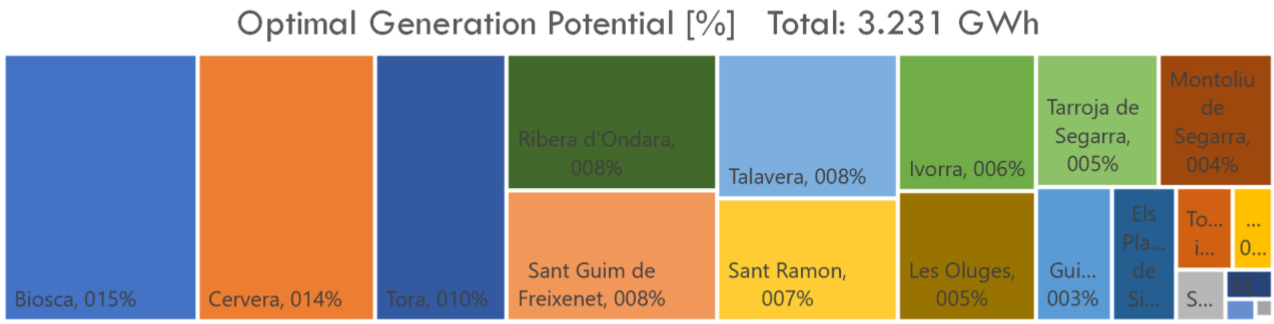


Figure 35: Distribution of rough and optimal generation potential by municipality in Catalan region of La Segarra

The eastern areas municipalities hold the greatest potentials both in the rough generation potential scenario and in the optimal one. Talavera and Sant Guim de Freixenet, though not having great potentials on an absolute value, present high densities of potential within their boundaries making them ideal candidates for future solar parks' siting.

8. Conclusions and recommendations

To conclude, this project has allowed me to enlarge the knowledge acquired during the MSc. STEEM program offering me the possibility to investigate in fields of my interest from which I knew little (or nothing) before starting the process. The project has been scientific in some aspects (of course behind every step there has been a research of relevant literature), technological in some others (I have had to refresh some programming skills I had left behind after finishing my bachelor), has had a management impact (as my managers now have much less work in finding out whether a park may be developed or not at a particular location) and all of this applied to the energy environment, specifically to the field of solar PV making it a real STEEM cross-disciplinary project. Moreover, writing the context section has obliged me to delve into the state-of-the-art in solar legislation in Spain and all related legislation. Likewise, the project has been an opportunity to review in depth, energy transition policy documentation in which I am particularly interested.

Throughout the process I have come to realize that though technology may be a relevant aspect of any engineering project many other factors (that bear little relationship with the project per se) may appear in the way. This project has given me a broad perception of what energy developments are really about.

Most of the objectives proposed by the project have been accomplished: definition of a methodology for solar parks siting, development of a GIS plots database to support the solar parks' location siting process, utilization of the methodology to conduct regional potential assessment. Also, the output of the project outputs will most likely be a useful tool for the company providing managers with relevant information to facilitate their decision-making processes in the future.

However, my lack of experience in GIS analysis, programming and steep learning curves have made the process much slower than it would have been if all knowledge needed to carry out the process would have been there from the beginning. As a result, I reckon that some of the functionalities of the platform need further refining. This project could be considered the seed of a greater project of setting up a location intelligence platform at the company which is still far away.

Three main objections (or objectives for development) have been identified for the platform.

The first objection is that it is by no means an intuitive or user-friendly platform. Some training is needed to interact with it and even if it is much faster than previous company's way of siting solar parks' potential locations, the process is far from being automatized.

Another downside is that it is only available on a desktop and can only be accessed by one user at a time. This is a strong limitation for a tool that was aimed to be used anytime by anyone at the company.

Third, related with the precedent one, is related with the ease access to the information. Even if the platform allows to be used for any user on a desktop computer, it is yet not available for mobile devices and needs to be wholly downloaded from a cloud server every time it needs to be used. That is not convenient, especially for users that do not interact with the platform on a daily basis.

In order to two main approach changes would be needed: the first one would be migrating the architecture of the application from a shapefile-based application to spatial data format more appropriate for webmaps generation (i.e. JSON). Second, implementing geodatabases (in contraposition to shapefiles) as the substrate to store spatial data.

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