Politecnico di Torino
Dipartimento Energia "G.Ferraris"

Master's Degree Program in

Pianificazione Urbanistica e Territoriale/Urban and Regional Planning
Digital Skills for Sustainable Societal Transitions

Exercise 2

Solar Radiation and PV-STC potential

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A.Y. 2025 – 2026

Exercise 2. Solar radiation, solar technologies and energy production

N	Title	Type	Source	CRS	Resolution	Date	Link[1]	More details
1	DSM of Portland	Raster (.tif)	Department of Geology of Portland	WKID 102970 VCSWKID 105703	5 meters	2005 to 2014	Link	Converted to meters, then the resolution is downgraded from 1m to 5m
2	DSM of Turin	Raster (.tif)	Cartography Office of Piedmont	EPSG: 25832	5 meters	2011	Link	-
3	DTM of Turin	Raster (.tif)	Cartography Office of Piedmont	EPSG: 32632	10 meters	2001	Link	-
4	Portland's buildings shapefile	Shape file (.shp)	Metro's Data Resource Center (DRC)	EPSG: 26910	-		Link	The file is adjusted for this exercise
5	Turin's buildings shapefile	Shape file (.shp)	BDTRE	WGS84/UTM32N	-	2015-2019	Link	This shapefile is created using "Edifici" and"un-vol"[2]
6	Turin's Districts	Shape file (.shp)	Municipality of Turin	EPSG: 3003	-	2011	Link	Downloaded from Geoportale
7	Portland's zoning	Shape file (.shp)	Metro's Data Resource Center (DRC)	EPSG: 26910	-		Link	
8	Diffused global radiation	Number	PVGIS Website	-	-	2023	Link	From the PVGIS website
9	Linke Turbidity	Number	Meteonorm software	-	-	2023	Link	From Meteonorm software
10	Albedo	Number		-	-	-		

Table 1 – Table of data

You can DOWNLOAD all the data using this LINK[3] or through the students' portal.

Consideration: It is crucial to have the QGIS software installed and the "r.sun.insoltime" plugin. If it's necessary, you can use another PDF containing instructions regarding installing and working with QG

[1] Please note that although all links were functional during table preparation, they may not remain accessible.

[2] https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:6dacd512-8862-491a-a37b-c032cd54d081

[3] https://drive.google.com/drive/folders/1FZoE2Op93ytt6PtQ5NWbZ1KaEfKdgqOp?usp=sharing

Introduction

This exercise examines the potential energy production capabilities of solar technologies, specifically photovoltaic (PV) and solar thermal (ST) panels, in consideration of residential buildings. We will use a tool called “r.sun” from QGIS software for this assessment.

Our goal is to evaluate the energy potential of these solar technologies by considering the area's land features. By analyzing the costs of these technologies along with current energy prices, we can estimate how long it will take to pay back the initial investment in different scenarios. We will also look at energy consumption data to determine the potential for self-consumption.

The exercise includes clear paragraphs that explain important concepts and definitions. This helps users understand the main ideas thoroughly. Next, there are practical instructions on how to use QGIS. This step-by-step guide shows users how to get the necessary information and reach their goals. Throughout the guide, notes and images illustrate the key steps, making the process clearer and ensuring success.

1. Theoretical Framework

1.1. Solar Radiation

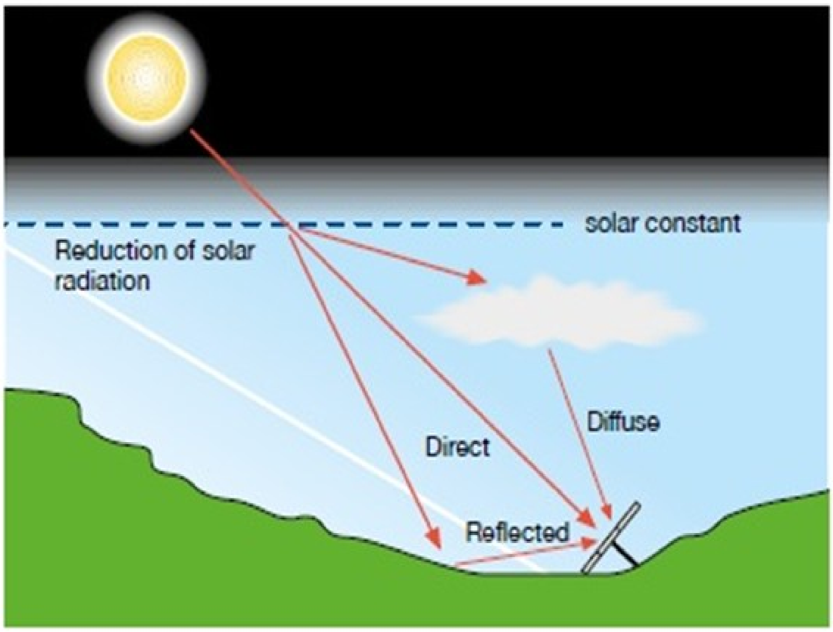


Figure 1. Solar radiation

Incoming solar radiation, or insolation, comes from the sun. As it travels, it changes due to the atmosphere, topography, and surface features. When it reaches the Earth's surface, it can be direct, diffuse, or reflected radiation. Direct radiation reaches us in a straight line from the sun without any obstacles. Diffuse radiation gets scattered by things in the atmosphere, like clouds and dust. Reflected radiation bounces off surfaces. The total amount of direct, diffuse, and reflected radiation is called total or global solar radiation (Fig. 1).

The solar geometry model is based on the work of Krcho from 1990 and was later improved by Jenco in 1992. This model uses equations that describe the Sun-Earth position and how solar radiation interacts with the atmosphere. These equations were originally developed by Kitler and Mikler in 1986. The model has been updated with findings and suggestions from a working group led by Scharmer and Greif in 2000. It calculates all three parts of global radiation (beam, diffuse, and reflected) under clear sky conditions, without considering how clouds affect radiation at different times and places.

Solar radiation tools (like r.sun) can perform calculations for point locations and entire geographic areas. This involves four steps:

1. The calculation of an upward-looking hemispherical **viewshed** based on topography.
2. Overlay the viewshed on a direct **sun map** to estimate direct radiation.
3. Overlay of the viewshed on a diffuse **sky map** to estimate diffuse radiation.
4. Repeat the process for every location of interest to produce an insolation map.

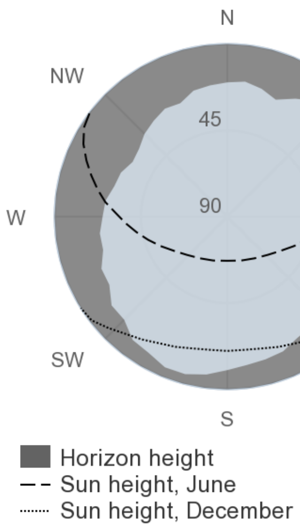
1.2. Viewshed

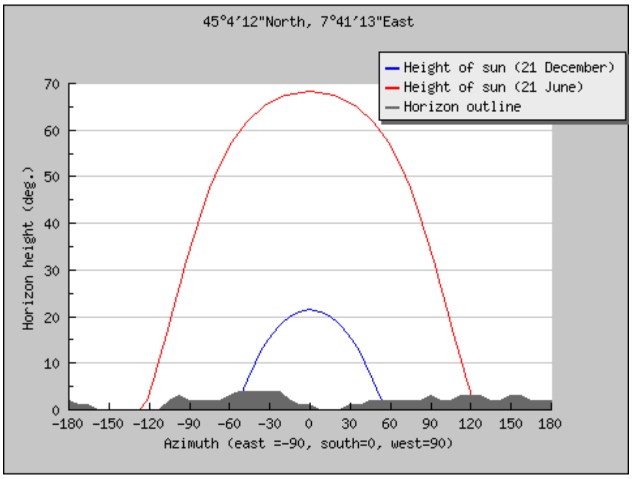
The viewshed is a representation of the entire sky that is visible or obstructed when viewed from a particular location ("i.e., a point"). A viewshed is calculated by searching in a specified number of directions around the area of interest and determining the maximum angle of sky obstruction, or horizon angle. For all other unsearched directions, horizon angles are interpolated. The results can be represented through a Cartesian diagram (Fig.6). The directions searched are expressed as azimuth angles on the x-axis, and the sun height and horizon angles are measured on the y-axis.

The same results can also be represented as a polar diagram (Figs 2 & 3) and Cartesian (Fig. 6) derived from the PVGIS website[4], with the solar height represented by concentric circles and the sun direction (azimuth angle) by the radius of the circle.

[4] https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#api_5.3)

For example, to see the viewshed of Turin or Portland, open the provided link then under the map, enter the Lat/Lon for Turin (45.0677, 7.6833) Portland (45.521, -122.6735), and then choose visualize results.





Figures 2 & 3 – Polar and cartesian sun maps

1.3. Sun Map

A sun map is a visual tool that shows the path of the sun throughout the day and across the year. It captures the sun's position at different times, measured in hours and days or months. The sun's movement is based on the latitude of the location and the time settings that create the sections of the sun map. Each section of the sun map has a unique ID and includes the zenith and azimuth angles of its center point. (Fig. 4)

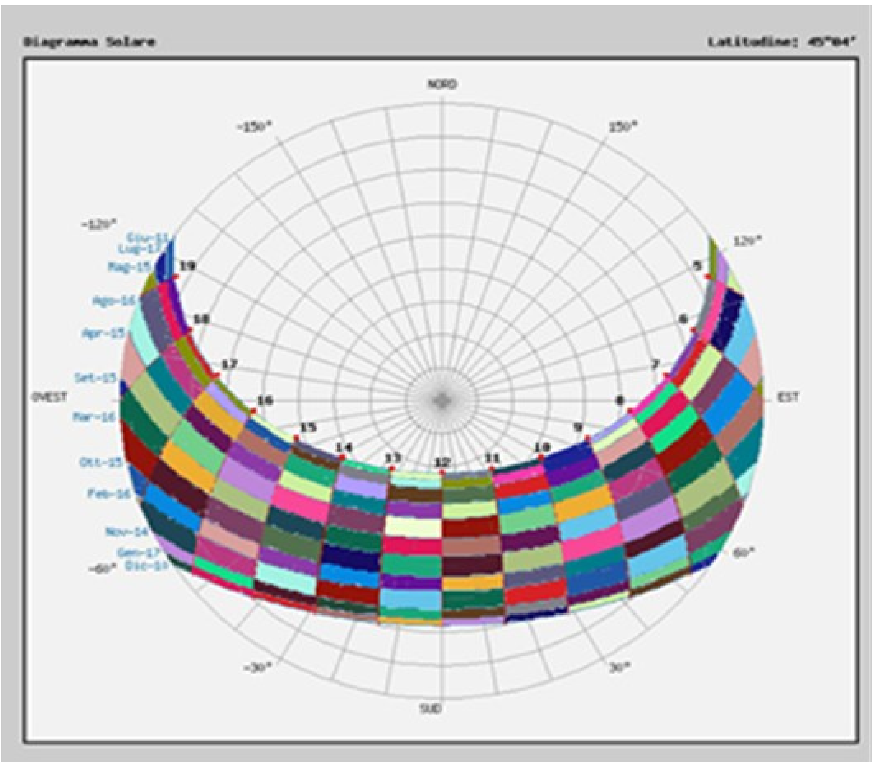


Figure 4 – Sun map

1.4. Sky Map

This map shows a hemispherical view of the sky, divided into sections based on zenith and azimuth angles. Each section has a unique identifier and includes the centroid zenith and azimuth angles. We calculate diffuse radiation for each section based on its direction (zenith and azimuth). Diffuse radiation comes from all directions in the sky due to scattering by elements in the atmosphere, like water vapor and particles. To calculate diffuse radiation for a specific location, we create a sky map. (Fig. 5)

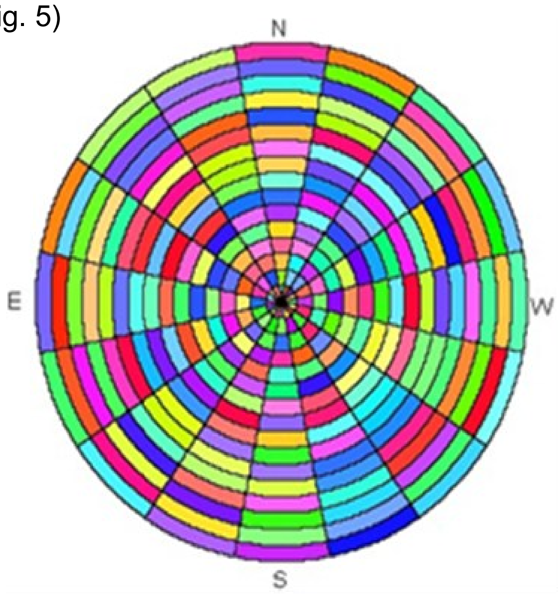


Figure 5 – Sky map

To evaluate Sun Map and Sky map, "[ENEA Solar Diagram Tool]"[5] is provided a tool by which. you can add the latitude and longitude of your municipality to view the diagrams. (Turin 45°04', 7°41') (Fig. 6, 7)

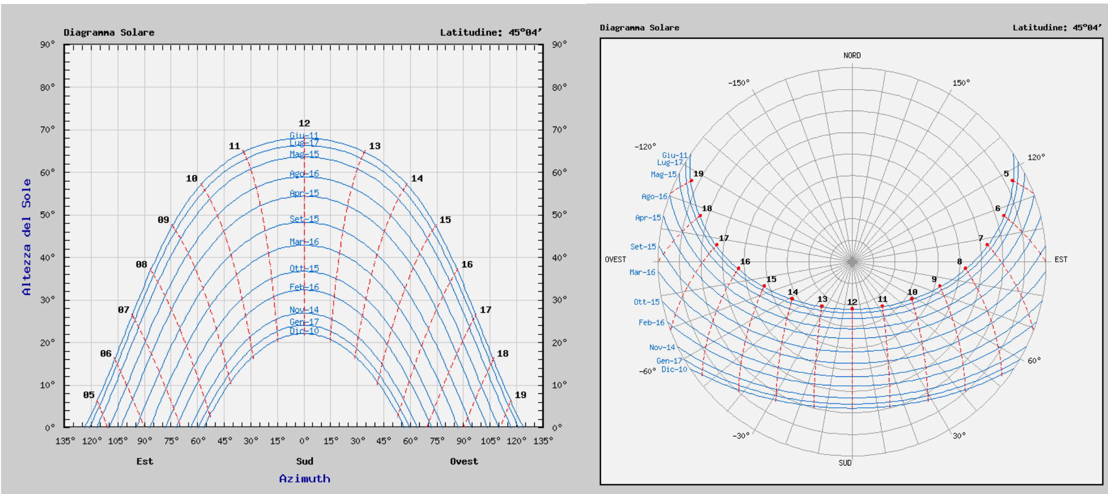


Figure 6 - Polar Diagram and Cartesian Diagram (Sun map of Turin)

[5] http://www.solaritaly.enea.it/StrDiagrammiSolari/X12Mesi1.php

1.5. How to calculate solar irradiation with viewshed, sun map and sky map

To calculate direct solar radiation, we first overlay the Viewshed on the Sun Map. We find the percentage of the visible sky in each sector by dividing the number of cells without obstacles by the total number of cells in that sector. We then determine the direct solar radiation for each point in the Digital Terrain Model (DTM) by adding up the values from all the sectors in the Sun Map.

For diffused solar radiation, we overlay the Viewshed on the Sky Map to find the percentage of visible sky in each sector. We calculate the diffused radiation for each sector in the Sky Map. Both calculations take into account the surface orientation by using the angle of incidence, which is the angle between the surface and a sector of the sky. The horizontal global solar radiation is the sum of the direct and diffused radiations for all the sectors of the Sun Map and the Sky Map:

$$Global\ (horizontal) = Dir + Dif$$
$$Global = Dir + Dif + Ref$$

2. Solar irradiation calculation

2.1. Table of inputs for r.sun.insoltime

No.	Input	Source	Type
2.2	DSM	Oregon department of geology[6] Piedmont region municipality[7]	Raster
2.3	Aspect	Derived from DSM	Raster
2.3	Slope	Derived from DSM	Raster
2.4	Linke Turbidity (TL)	Meteonorm Software[8]	Raster
2.5	Diffuse-to-global ratio (DG)	PVGIS Website[9]	Raster
2.6	Albedo	-	Number
2.7	Cumulative day number	-	Number
2.8	Sampling distance step coefficient	-	Number
2.9	Hourly frequency	-	Number

Table 2 – Table of inputs for r.sun.insoltime software

Note: It is essential to pay attention to the metadata and the Coordinate Reference System (CRS) of the files. For example, based on the metadata of Portland's DSM, the CRS is defined as *NAD_1983_2011_Oregon_Statewide_Lambert_Feet*. From this, we can conclude that the digital numbers (DN) of the pixels and the cell size are measured in feet. Therefore, if you need to change the CRS to one using meters as units, you also have to transform the pixel values from feet to meters.

For Turin, the appropriate CRS is EPSG: 32632 - WGS 84 / UTM Zone 32N or EPSG: 3003 – Monte Mario / Italy zone 1 (in meters), and it is necessary to make sure that all of your CRSs are set accordingly.

For Portland, the previously used CRS for the DSM was EPSG:6557 – NAD83(2011) / Oregon GIC Lambert (ft), and for the shapefiles, EPSG:2913 – NAD83(HARN) / Oregon North (ft). However, as the entire workflow is now standardized in meters, the recommended CRS is EPSG: 26910 – NAD83 / UTM Zone 10N in meters.

[6] Oregon Department of Geology and Mineral Industries. Digital Surface Model (DSM), Lidar Data Quadrangle Series [LDQ-45122E6, LDQ-45122E7]. Oregon Department of Geology and Mineral Industries. Accessed March 13, 2025. http://www.oregongeology.org/sub/lidardataviewer/ .

[7] Regione Piemonte. DSM 2009-2011 Piemonte ICE [Data set]. Regione Piemonte, 2009-2011. Accessed [Date]. http://creativecommons.org/licenses/by/2.5/it/ .

[8] Meteotest. Meteonorm, Version 8.0 [Software]. Meteotest AG, 2024. Accessed March 13, 2025. https://meteonorm.com/en/ .

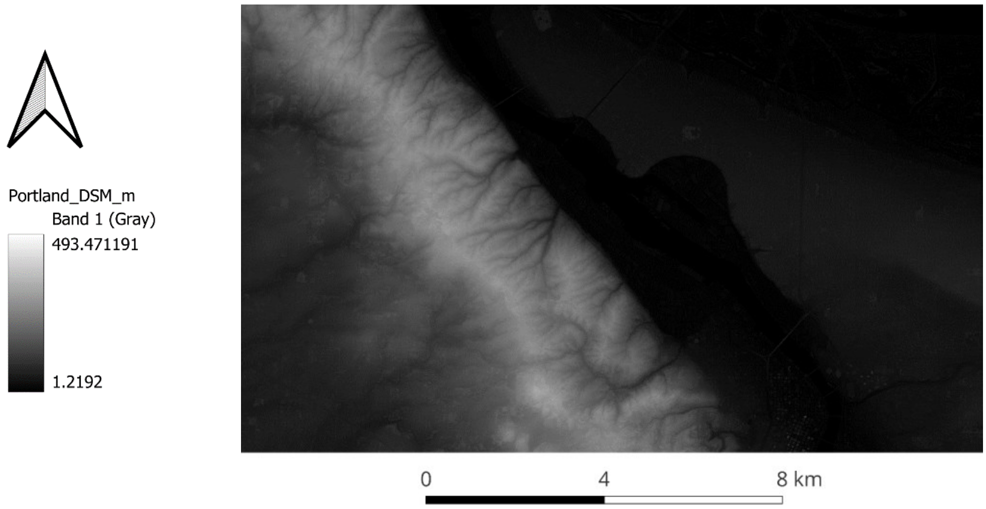
[9] European Commission, Joint Research Centre. PVGIS Solar Radiation and PV Performance Data for [Portland, Oregon]. European Commission. Accessed March 13, 2025. https://ec.europa.eu/jrc/en/pvgis .

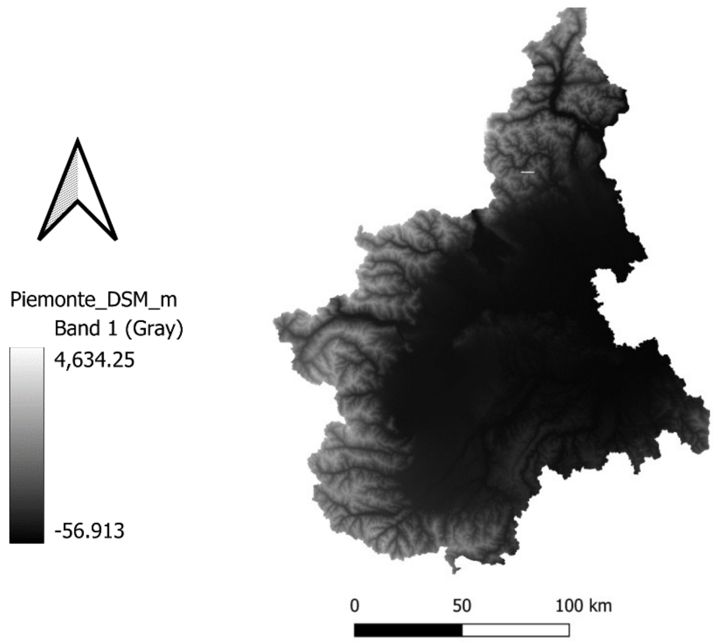
2.1.1. DSM/DTM

Digital Terrain Models (DTM), sometimes called Digital Elevation Models (DEM), is a topographic model of the bare Earth that can be manipulated by computer programs. The data files contain the elevation data of the terrain in a digital format related to a rectangular grid. Vegetation, buildings, and other cultural features are removed digitally, leaving just the underlying terrain. DTMs are used especially in civil engineering, geodesy & surveying, geophysics, geography, and remote sensing.

A Digital Surface Model (DSM) represents the Earth's surface, including all natural and built features such as vegetation, buildings, and infrastructure. Unlike a Digital Terrain Model (DTM), which depicts only the bare earth by removing objects, a DSM captures the actual elevations of the terrain along with surface features. The digital number (DN) of pixels represents the elevation of the area. (Figures 7 & 8)

In this stage, open QGIS and import the DSM.





Figures 7 & 8 – DSM of Portland and Piedmont

2.2. Clip raster

In many cases, you may need to clip the raster files to reduce the dimension of the area. In this case, you must use the "**clip raster**" tool in QGIS. To do so, from the menu toolbar, choose "**processing**" → "**toolbox**" → search for "**clip raster**" → "**clip raster by extent**" → Run

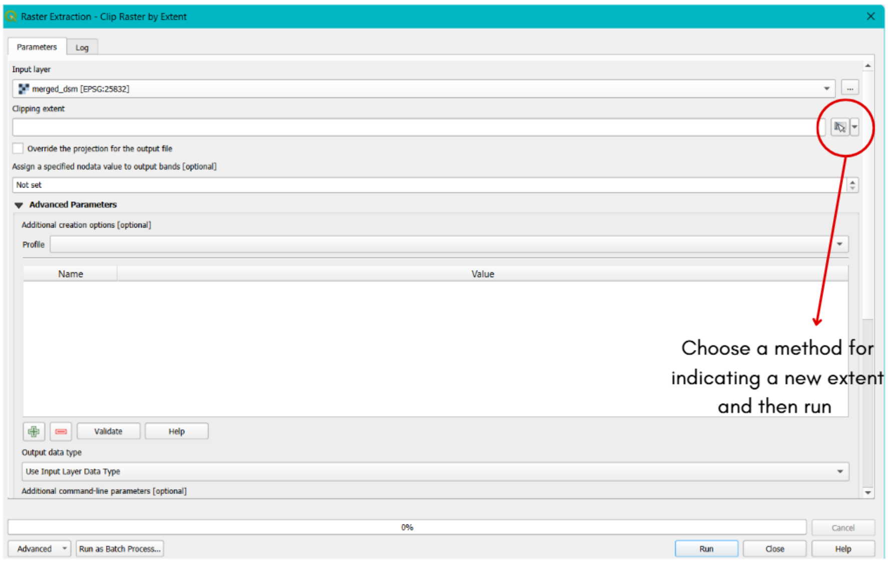


Figure 9 – Clip raster in QGIS

Important Note: It is crucial to bear in mind that as the presence of adjacent geographical features like the presence of mountains or hills around your study area can obscure the viewshed, and consequently can affect the solar irradiation, using clip raster should be implemented carefully and theoretically you should include all objects that can affect your analysis even they are far away.

2.3. Slope and Aspect Calculation

This step aims to produce the layer of Aspect (or exposure) and the layer of Slopes (in degrees) from a digital terrain model (DSM).

Aspect: Calculates the aspect of the Digital Terrain Model in the input. The final aspect raster layer contains values from 0 to 360 that express the slope direction: starting from North (0°) and continuing clockwise.

Slope: This algorithm calculates the angle of inclination of the terrain from an input raster layer. The slope is expressed in degrees. (Figure 10)

Note: Remember that if you clipped your DSM raster and you want to conduct the analysis based on the new clipped raster, you should continue with the new clipped raster for all following steps, including producing aspect and slope layers.

2.3.1. How to calculate Slope in QGIS

To produce a slope raster out of a DSM file, from the menu toolbar select "**processing**" → "**toolbox**" → search for "**slope**" → from "**raster terrain analysis**" choose "**slope**" → put your clipped_DSM to the elevation layer and name it as Turin_slope / Portland_slope → **"run"**

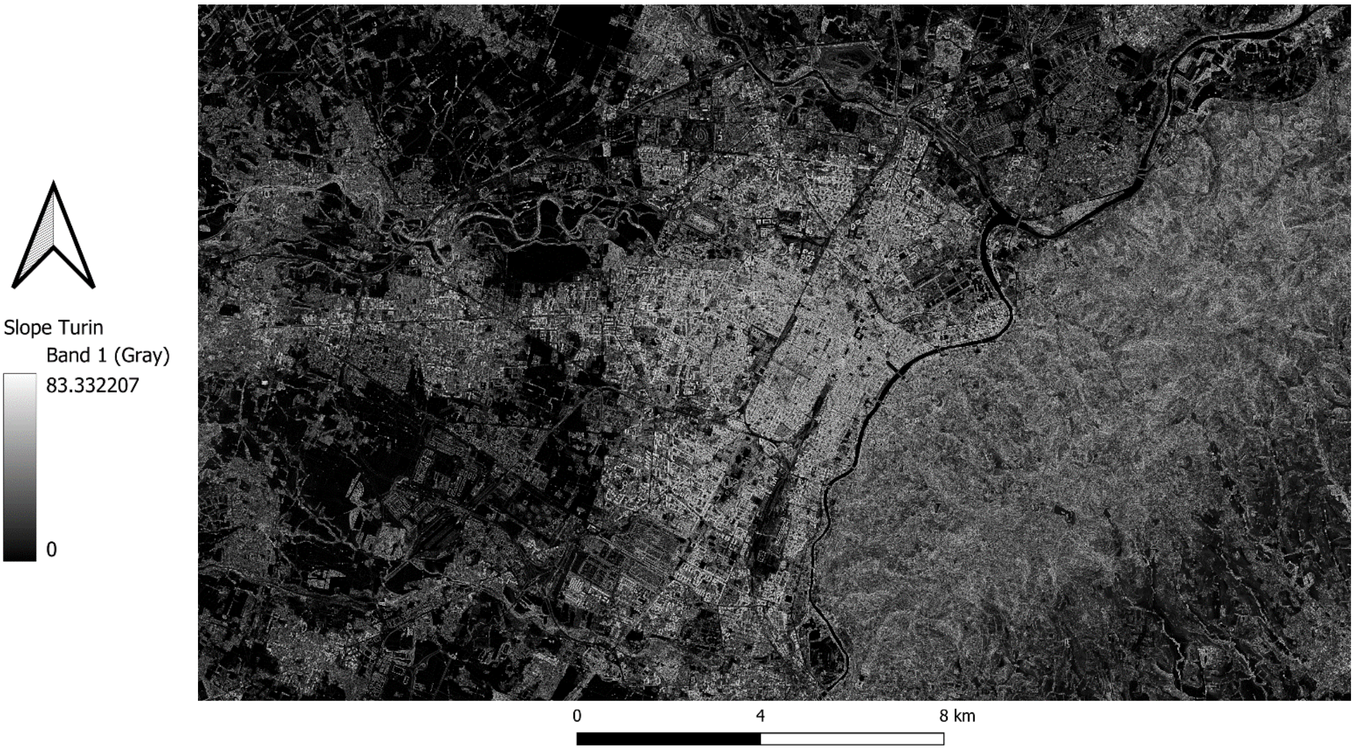


Figure 10 – Slope (Turin)

2.3.2. How to calculate Aspect in QGIS

Same as slope, menu "**toolbar**" → "**processing**" → search for "**aspect**" → from "**raster terrain analysis**" choose "**aspect**" → for elevation layer choose DSM file → "**run**"

Also, for rearranging the symbology, simply open the "**properties**" → "**Symbology**" →"**Singleband pseudocolor**"

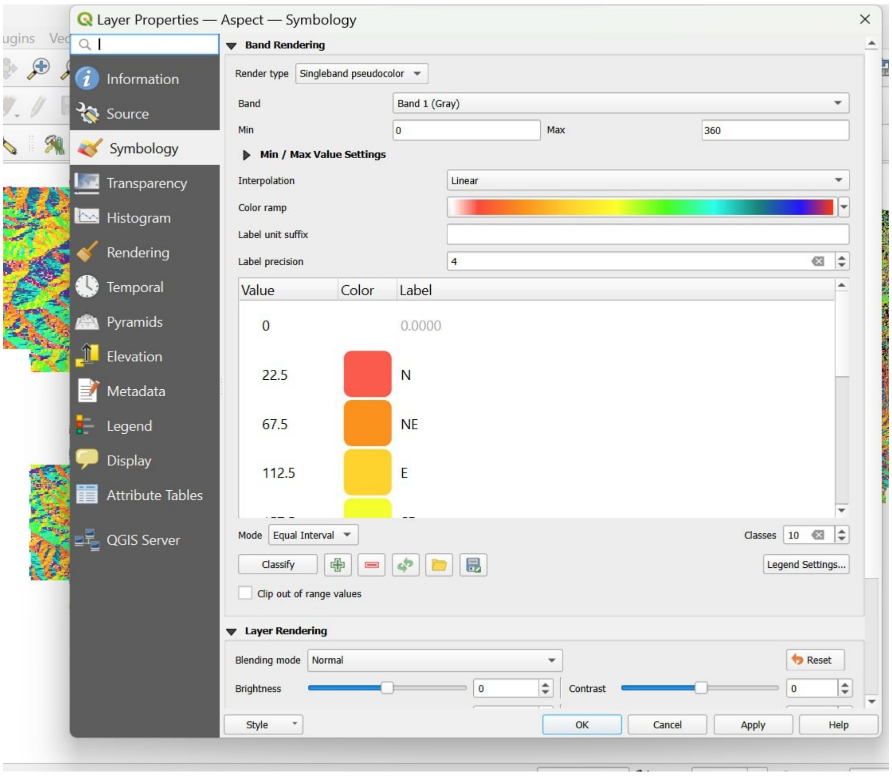


Figure 11 - Aspect symbology configuration

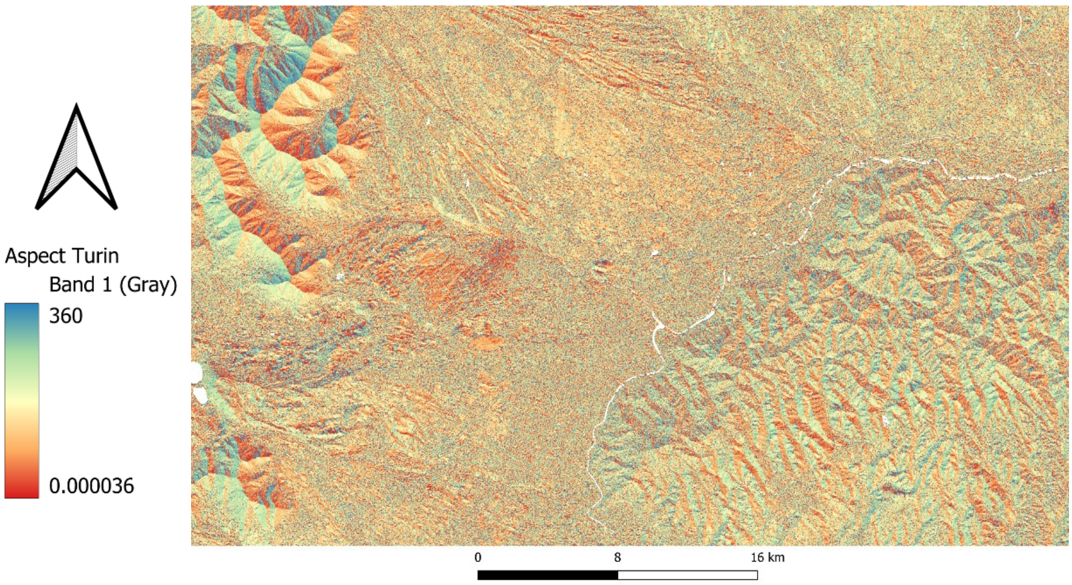


Figure 12 - Aspect symbology configuration

2.4. Linke Turbidity Coefficient (TL)

The Linke turbidity coefficient refers to the smog quantity in the atmosphere throughout a certain period. It is equal to 1.0 for a perfectly transparent atmosphere and to 3.0 as an average annual value for rural and urban areas. Referring to temperate climate areas in the Northern Hemisphere, monthly average values of the Linke turbidity coefficient are displayed in the following (Table 2):

Area/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
mountains	1.5	1.6	1.8	1.9	2.0	2.3	2.3	2.3	2.1	1.8	1.6	1.5	1.90
rural	2.1	2.2	2.5	2.9	3.2	3.4	3.5	3.3	2.9	2.6	2.3	2.2	2.75
city	3.1	3.2	3.5	4.0	4.2	4.3	4.4	4.3	4.0	3.6	3.3	3.1	3.75
industrial	4.1	4.3	4.7	5.3	5.5	5.7	5.8	5.7	5.3	4.9	4.5	4.2	5.00
city-industrial	3.6	3.75	4.1	4.65	4.85	5.0	5.1	5.0	4.65	4.25	3.9	3.65	4.38

Table 3 - Northern Hemisphere[10]

2.4.1. How to get the Linke Turbidity of our area

One option to get the Linke turbidity factor is to use the Meteonorm software[11], described earlier (or SODA dataset[12]). After installing Meteonorm, select your Municipality and check the Linke Turbidity (in the Piedmont Region, you can find Torino, Alessandria, and Novara). You can also add a new location knowing the latitude, longitude, and altitude. After this, take a screenshot and copy the monthly values (using the DEMO version).

Use this link to download the software → Choose demo version → Inside the software under the available locations choose "**locations**" → search for Torino IT or Portland OR → select "**add**" (select locations for calculations) → "**Next**" → Under atmospheric turbidity select "**edit turbidity**" → take a screen shot from the Interpolated column

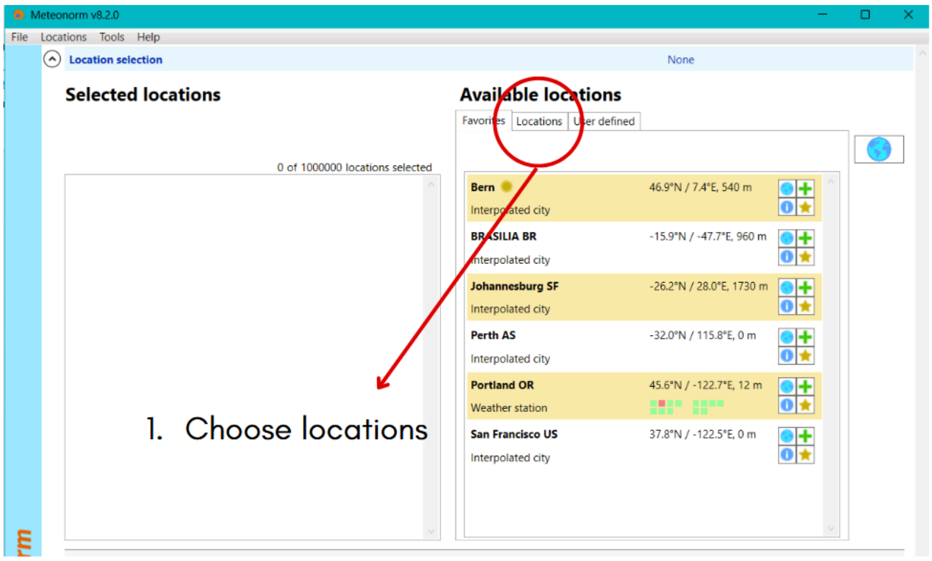


Figure 13 – Meteonorm software menu

10 https://grass.osgeo.org/grass72/manuals/r.sun.html

11 https://meteonorm.com/en/download

12 https://www.soda-pro.com/help/general-knowledge/linke-turbidity-factor

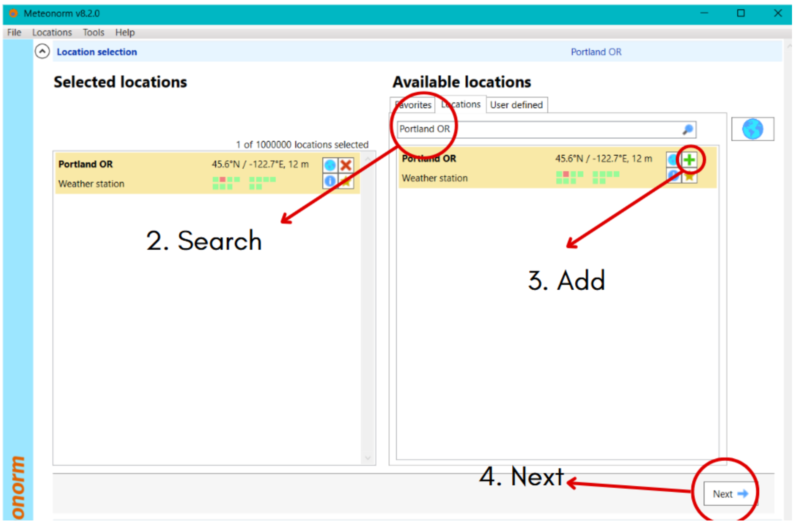


Figure 14 – Meteonorm software menu

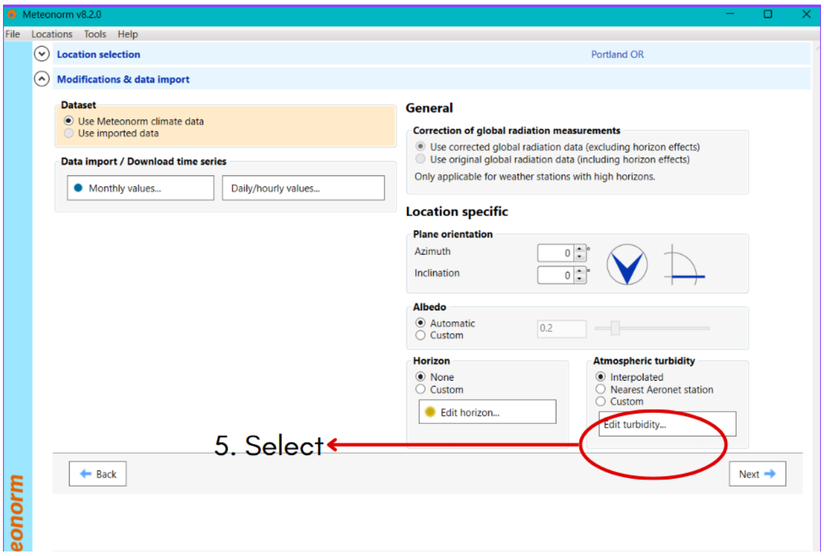


Figure 15 – Meteonorm software menu

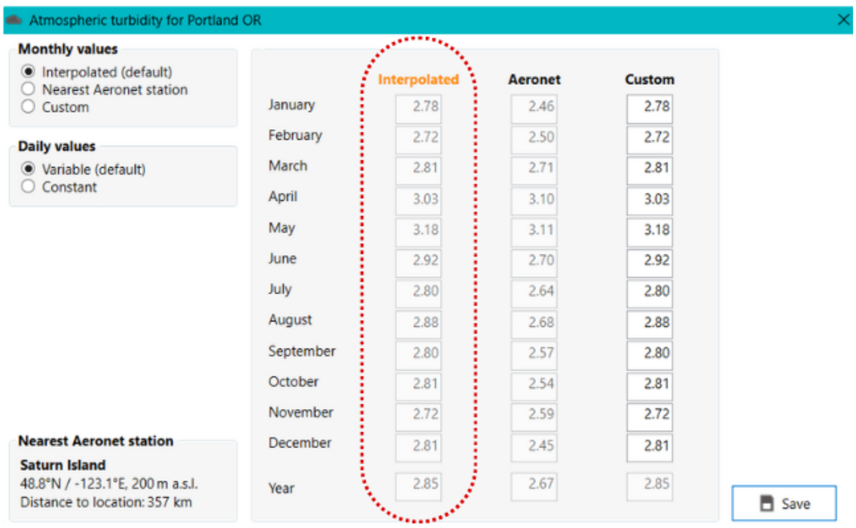


Figure 16 – Meteonorm software menu

Note: Do not rely on the numbers of TL in the picture and try to get the TL values yourself.

2.5. Diffuse-to-global radiation (DG)

Diffuse to global radiation is a ratio in which shows how much of the global radiation is diffused. For finding the DG you can use [PVGIS website][13], in procedure is in follow:

Open the PVGIS website → under the map search for your location by either entering the name (Turin IT, Portland Oregon) or latitude longitude (45.068 / 7.681, 45.521 / -122.674) → choose **Monthly Data** → set the **start year** and **end year** → check the **Global irradiation optimum angle** → check the **Diffuse/global ratio** → download the CSV file

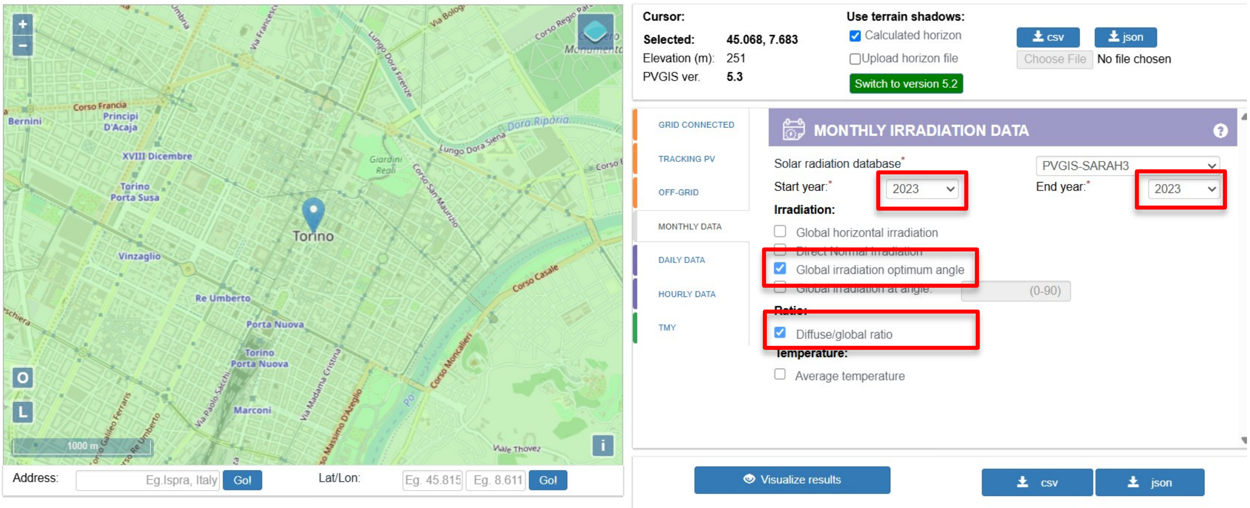


Figure 17 – PVGIS Website

Note: After downloading the CSV file, you will need to reorganize the content of the file in the following procedure:

Open the CSV file → Click on column A to select the whole column → From the menu bar on the top, select **Data** → Then, in the Data Tools, select **Text to Columns** → Inside the newly opened window, click **Next** → **Next** → **Finish**

[13] https://re.jrc.ec.europa.eu/pvg_tools/en/#MR

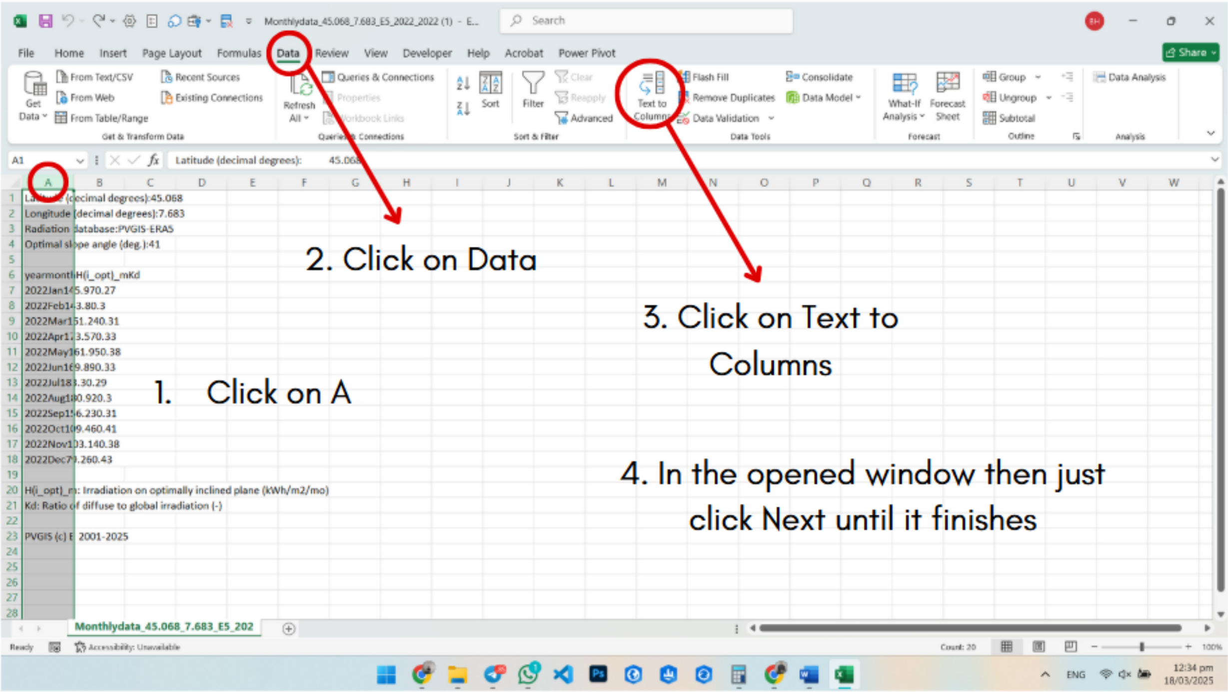


Figure 18 – Managing the DG CSV file

Important Note:

We have downloaded the data for LT and DG for our case study. However, we need to consider the input of LT and DG inside r.sun.insoltime is not a number, and it is in the form of a raster file (Matrix). Therefore, we must convert the numerical values into a raster format. This raster must align with your digital surface model (DSM), meaning that the number of pixels, the pixel size, and the pixel positioning of both raster files should match.

2.6. How to create the Linke turbidity factor (LT) and Diffuse-to-global irradiation (DG) raster?

To do so, we use the raster calculation tool in QGIS and divide the DSM raster by itself to change the value of all pixels to 1 and then multiply it by the value of LT or DG for each month. We repeat this process each month for both LT and DG. Finally, we will have 24 raster files.

Open your project in QGIS and import the DSM file → From the **toolbar menu** select **raster** then **raster calculator** → under the raster bands you can see your raster file, by double click on it you can add it for computation → inside the **raster calculator expression** box perform write ("DSM file's name@1"/ "DSM file's name@1") * Value of TL in January → Select the **output layer path** and save it as CityName_TL_Jan → repeat the process for DG and TL all months so you will have 24 files in total.

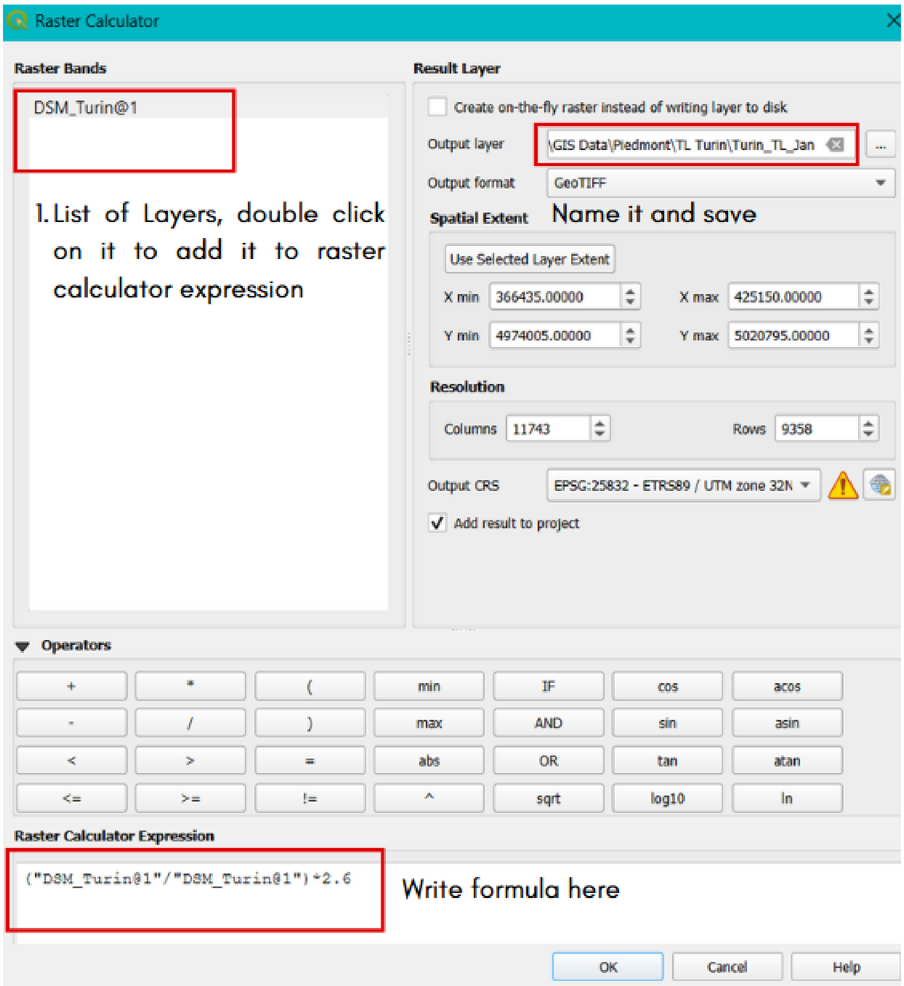


Figure 19 – Raster calculator in QGIS

$$("\text{DSM\_Turin@1}" \,/\, "DSM\_Turin@1") \;*\; LT/DG\ Value$$

2.7. Albedo

Albedo is the measure of a surface's reflectivity, expressed as the fraction of incoming solar radiation that is reflected rather than absorbed. It ranges from 0 (perfect absorber, like black surfaces) to 1 (perfect reflector, like snow or ice).

Note: 0.25 is a typical value in high-density cities, and 0.35 can be used for low-density cities

Surface	Albedo
Corrugated roof	0.1 - 0.15
Red/Brown roof tiles	0.1 - 0.35
Brick/Stone	0.2 - 0.40
Coloured paint	0.15 - 0.35
White paint	0.5 - 0.90
Concrete	0.25 - 0.70
Asphalt	0.05 - 0.20
Grass	0.25 - 0.30
Trees	0.15 - 0.18
Oceans	0.05 - 0.10
Ice	0.3 - 0.50
Old snow	0.65 - 0.81
Fresh Snow	0.81 - 0.88

Table 4 – Albedo values related to different surfaces

2.8. Cumulative day number

The cumulative day number is a number that starts from 1 to 365 in where 1 represents the first of January and 365 is 31 December.

2.9. Typical monthly days[14]

When we refer to "typical monthly days," we mean a specific day in each month where the solar irradiation is equal to the average daily solar irradiation for that month. In other words, if we calculate solar irradiation for a typical day and then multiply that value by the total number of days in the month, we will arrive at the total solar irradiation for that entire month.

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average Day[15]	17	16	16	15	15	11	17	16	15	15	14	10
Cumulative Average Day	17	47	75	105	135	162	198	228	258	288	318	344

Table 4 – Average day & cumulative average day

Note: The provided Table 4 is just dates suggested by Duffie and Beckman; it is not an immutable rule, and it can be changed based on the context of the study area.

2.10. Hourly frequency

Hourly frequency is used in the calculation of the sum of radiation for the whole day; the hourly frequency in question is the time elapsed between one irradiance calculation and the next one and therefore indicates only the level of calculation detail with which the software creates the map.

[14] John A. Duffie and William A. Beckman, *Solar Engineering of Thermal Processes*, 4th ed. (Hoboken, NJ: Wiley, 2013).

Note: It is recommended for this exercise to set the hourly frequency equal to 1h.

2.11. Sampling distance step coefficient

The default value is 0.5 h, but by entering, for example, 1 h, it is possible to speed up the calculations, producing "less reliable" results.

2.12. Run r.sun.insoltime

In this step, we calculate the solar radiation with "**r.sun.insoltime**" for Turin and Portland. This tool in QGIS computes direct (beam), diffuse, and reflected solar irradiation raster maps for a given day, latitude, surface, and atmospheric conditions. To open the tool:

Processing toolbox → GRASS → Raster → r.sun.insoltime

Note: For each of the simulations, insert the correct values of diffuse-to-global ratio and Linke Turbidity factor. It is advisable to name the raster files with the reference month to avoid confusion. There are also other tools of QGIS about solar irradiation that are used for the evaluation of the position of the sun (sun height, azimuth, …), like "r.sun.incidout", "r.sun.hours", and "r.sun.position". Now run the tool for each city for 12 months with different TL and DG as indicated in the figures below.

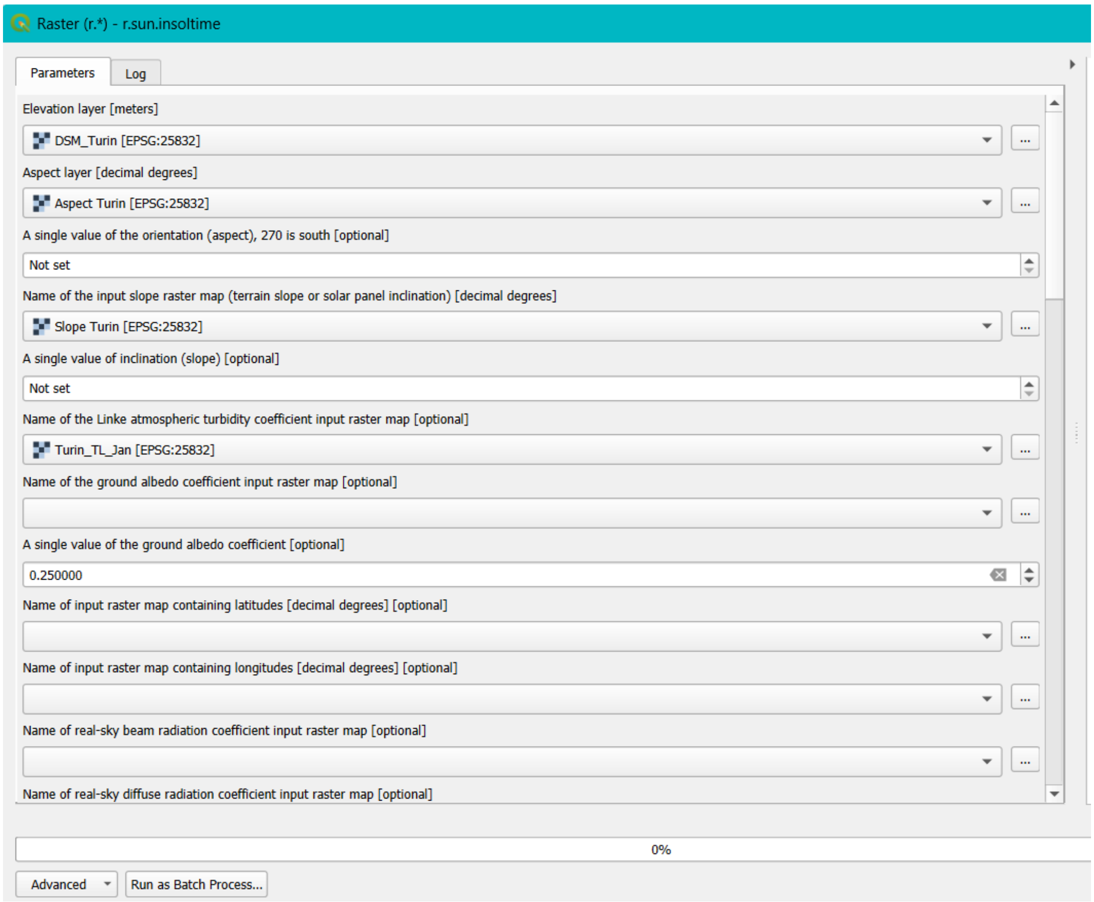


Figure 20 – r.sun.insoltime menu

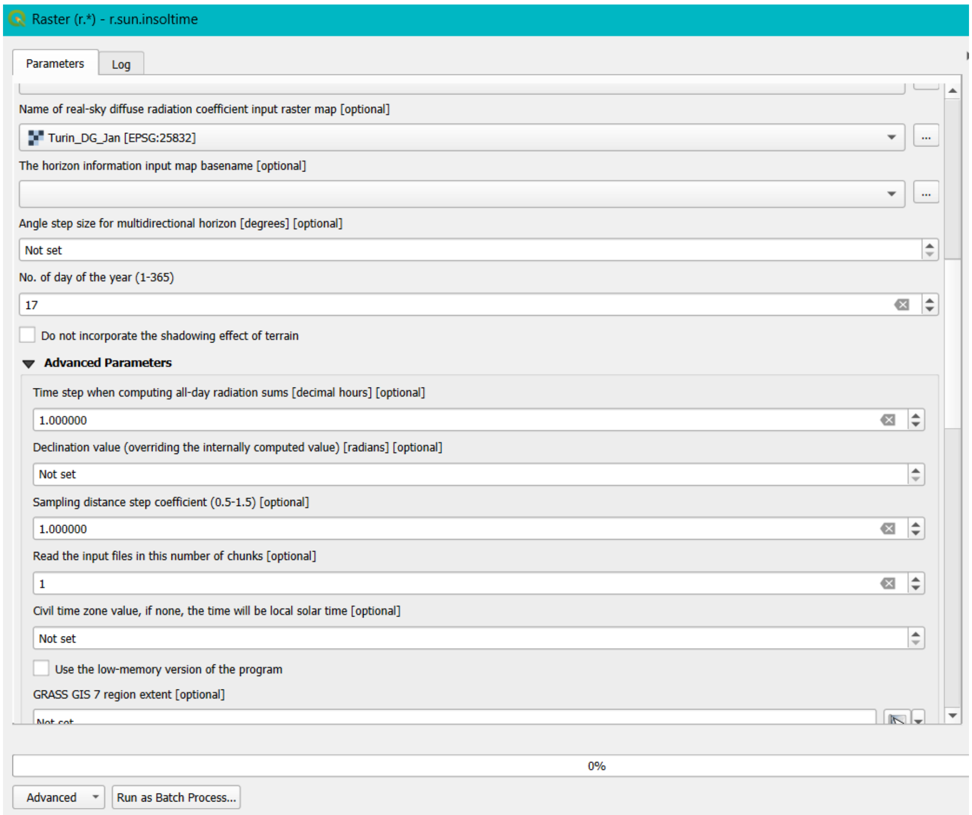


Figure 21 – r.sun.insoltime menu

NOTE: Among all possible outputs, we only use the last one. Please uncheck the others, except for the last one, which should be named appropriately and have the directory indicated where you want to save the file.

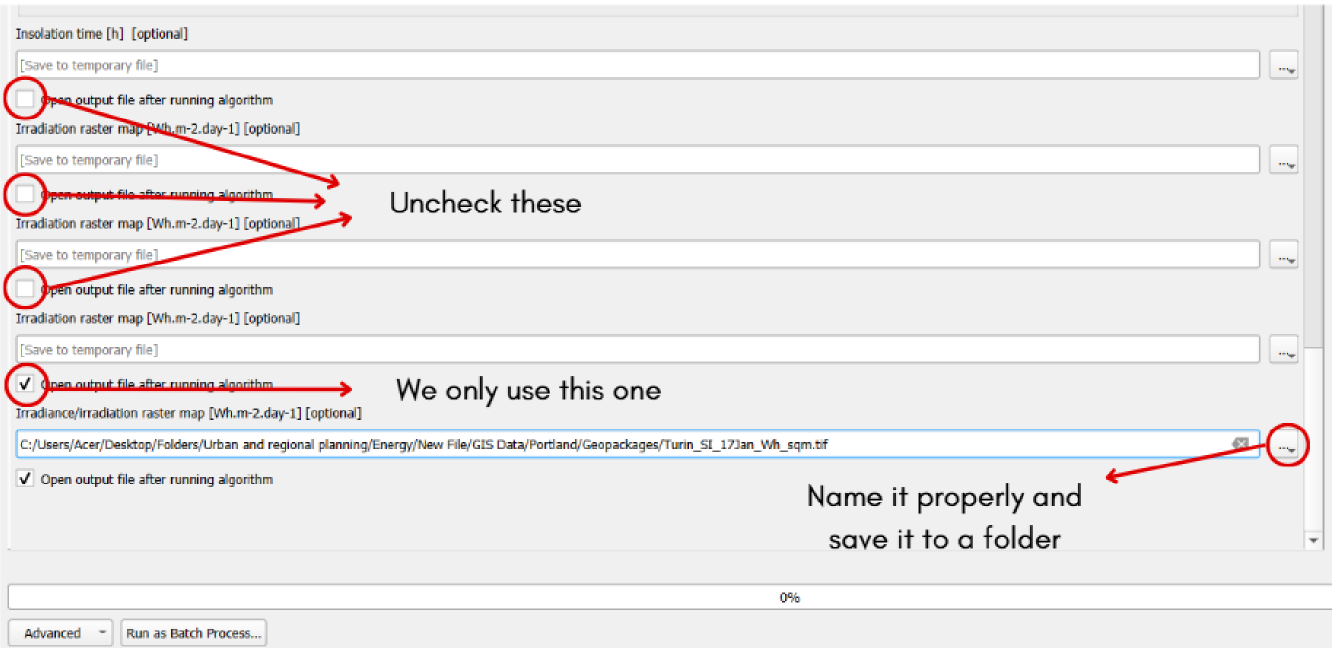


Figure 21 – r.sun.insoltime menu

Important remark: In the appendix you can find instruction for batch processing, in which you can calculate all month's solar irradiation all at once, however, as this analysis is intensive, it is highly recommended before running the tool, if you have opened any other application than QGIS, close them, make sure that you are freeing up RAM and CPU resources and then push run. Bear in mind that it may take up to 1h for each month, and during the computation, do not work with your pc.

2.12.1.1. Results of r.sun.insoltime

When the processing is complete, you can position yourself on each layer produced and use the right mouse button to call up the layer properties. From there, you can evaluate the Global Solar Radiation in **Wh/m²/day** for both Turin (Figure 22) and Portland.

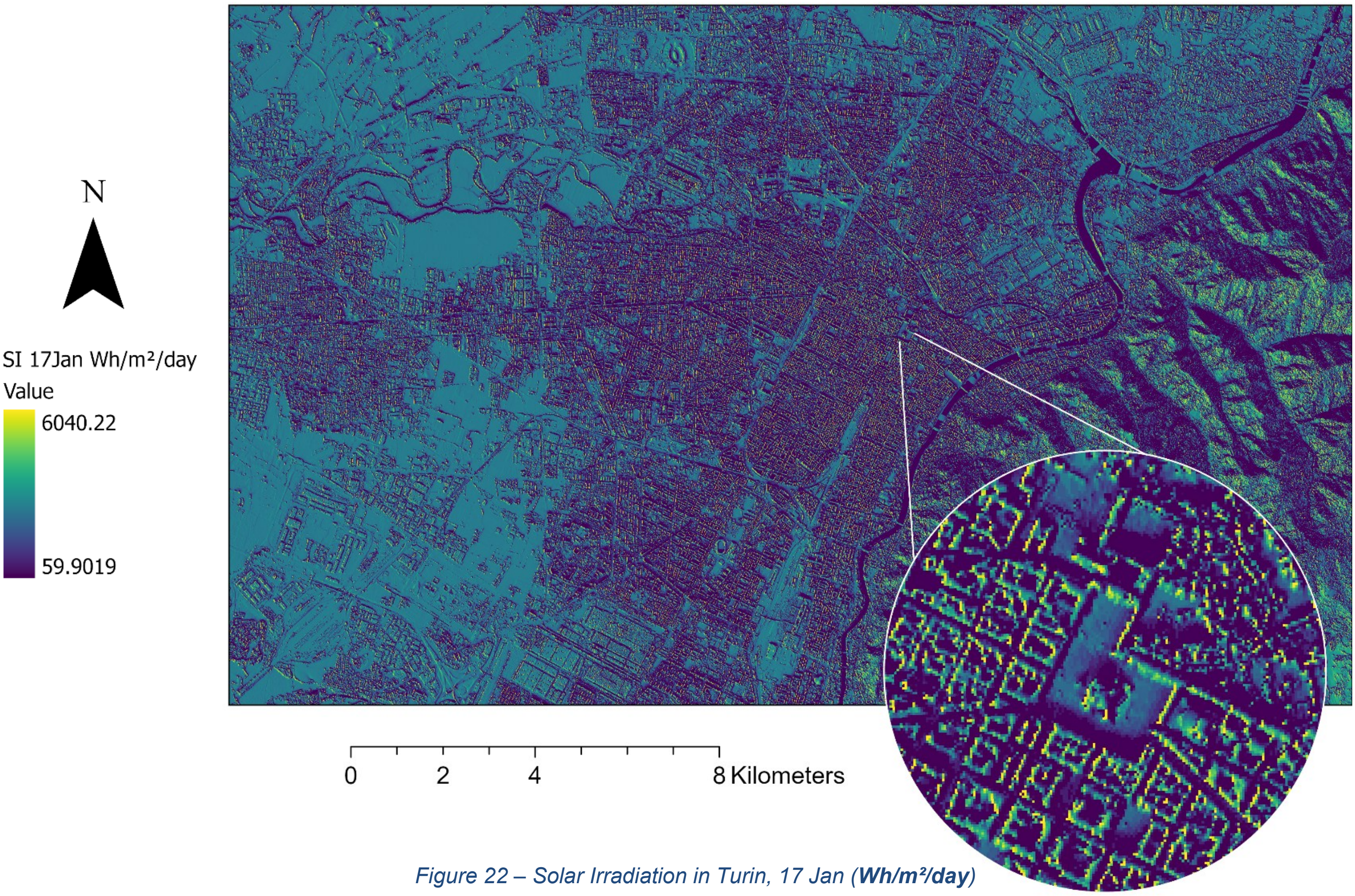


*Figure 22 – Solar Irradiation in Turin, 17 Jan (**Wh/m²/day**)*

To make your work easier, it's recommended to rename the raster files according to the corresponding months, using names like **Turin_SI_17Jan**, **Turin_SI_16Feb**, and so on. Be sure to include the unit of measurement **Wh/m²/day**. Also, we can convert **Wh** into **kWh** by simply dividing the raster files by 1000, shown as follows:

Raster → raster calculator → "Turin_SI_17Jan_Wh/sqm/day@1"/1000

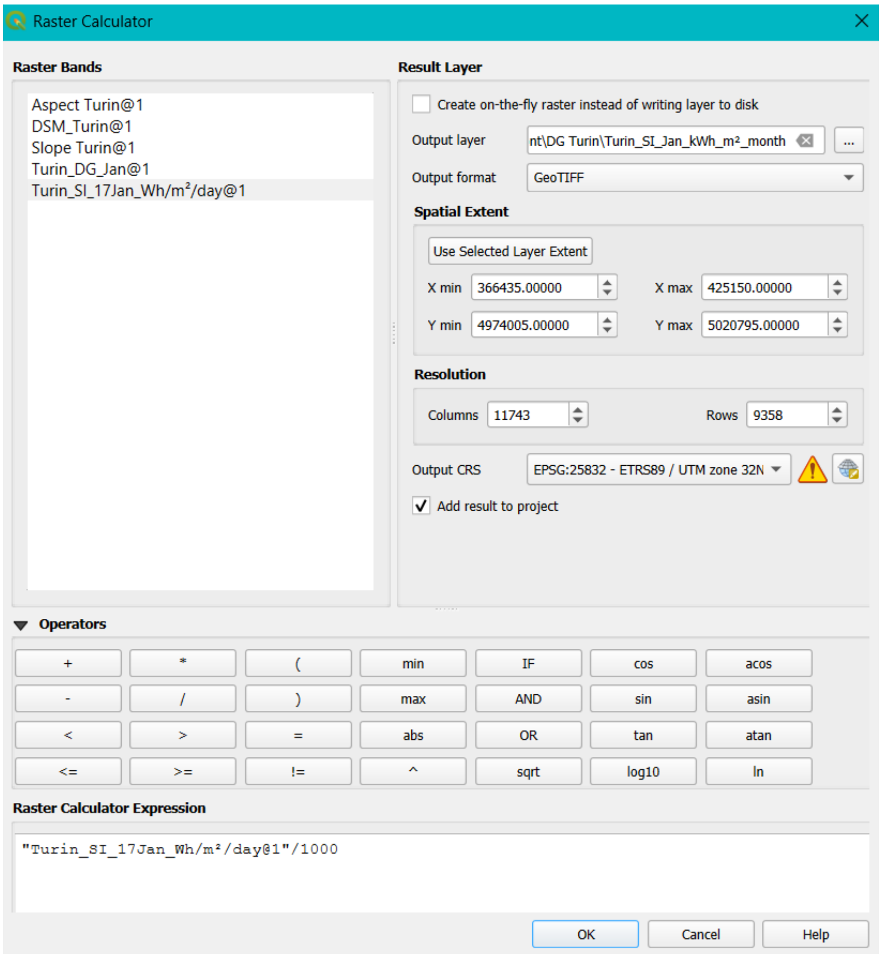


Figure 23 – Raster calculator

2.12.2. Average daily, monthly, and annual cumulative radiation

It is possible now from the produced daily solar irradiation propagate the monthly and annual solar irradiation. Remember that we conduct the calculation for the average day for each month. For example, for January we used 17th January, for February we used 16th February, and …

$$Monthly\ solar\ irradiation\ (kWh/m^2/month) = Avg.daily\ solar\ irradiation\ (kWh/m^2/day) * No.days\ in\ that\ month$$

Monthly Solar Irradiation (kWh/m²/month)	Avg. daily Solar Irradiation (kWh/m²/day)	No. days
Jan	17th Jan	31
Feb	16th Feb	28
Mar	16th Mar	31
Apr	15th Apr	30
May	15th May	31
Jun	11th Jun	30
July	17th Jul	31
Aug	16th Aug	31
Sep	15th Sep	30
Oct	15th Oct	31
Nov	14th Nov	30
Dec	10th Dec	31

Table 5 – Average day of the month and number of days in each month

$$\text{Annual Solar Irradiation } (\text{kWh}/\text{m}^2/year) = \sum_{m=1}^{12} Monthly\ Solar\ Irradiaition\ (kWh/m^2/\ month)$$

$$\text{Average annual solar irradiation } (\text{kWh}/\text{m}^2/\text{day}) = \text{Annual Solar Irradiation } (\text{kWh}/\text{m}^2/\text{year})/365$$

Note: All the calculations can be done through the raster calculator.

3. Calculation of energy production by roof-integrated PV technology

In this step, we aim to calculate energy production from solar irradiation using roof-integrated photovoltaic (PV) technology only for residential buildings. We have already prepared raster files that contain pixel values representing monthly and annual solar irradiation for each square meter. Now, we will assess how much solar energy is received by each building and subsequently calculate the potential energy production based on that data.

3.1.1. Table of input needed for the calculations

Name	Title NO.	Information needed	Source
Buildings' shapefile	3.2	Monthly solar irradiation (kWh/m²/m)	r.sun.insoltime
	3.4	Building area (m²)	User calculation
	3.5	Usage (Land-use or zoning)	Municipality
	3.7.1	Roof area for panel (m²)	User calculation
PV Technology	3.7	Efficiency (η)	Panel catalogue

Table 6 – inputs needed for the calculation of electricity with roof-integrated PV technology

3.1.2. Clip your buildings and raster files based on the assigned area

It is now recommended to reduce the number of computations by clipping the building footprint shapefile and the solar irradiation raster files to your assigned district.

To clip your building footprint or solar irradiation raster files, first select your assigned neighborhood from the district or neighborhoods layer. Then, export it as a new feature and save it.

Next, to extract the 12 monthly raster files for solar irradiation in the selected municipality, choose the municipality you wish to work on and extract the 12 solar raster files using a mask:

Raster → Extraction → Clip Raster by Mask Layer

For the "*Input layer,*" insert one by one the single-month solar raster files. For the "Mask layer," use the shapefile that contains your assigned neighborhood. Then identify the saved file path and name and run. Name the files like This operation must be repeated for all 12 raster files.

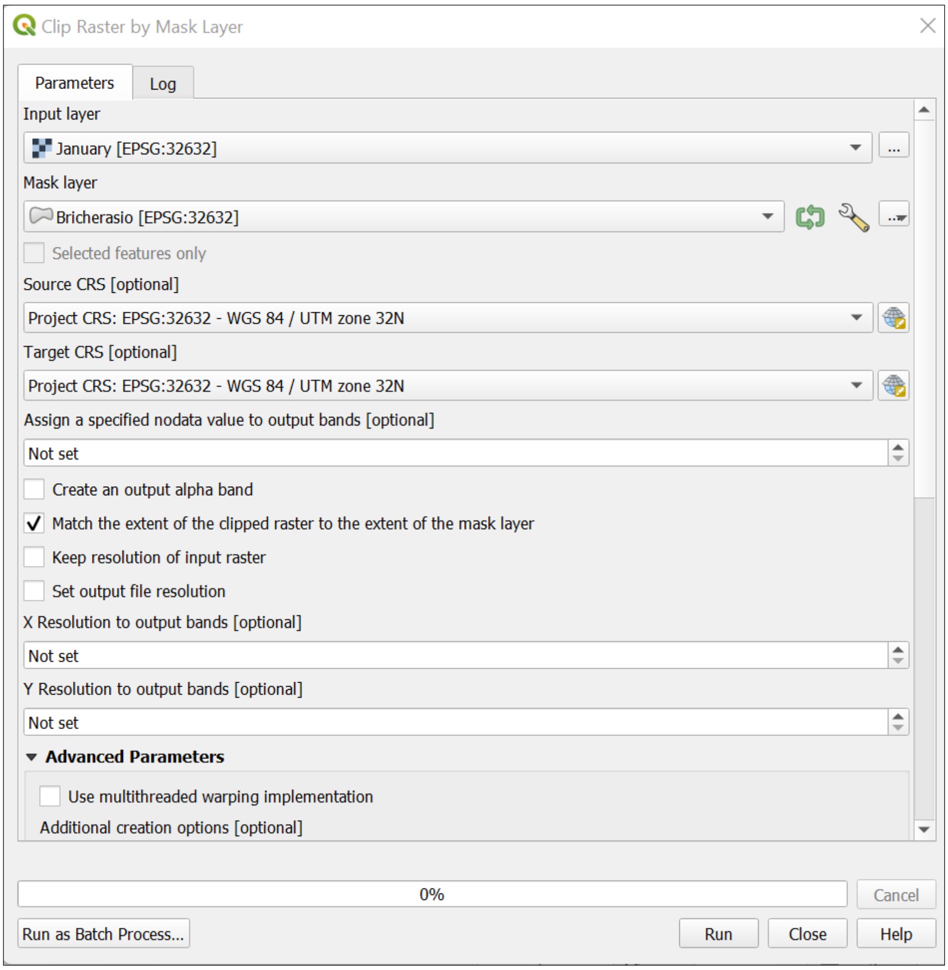


Figure 24 – Clip raster by mask layer

Figure 25 – Solar irradiation of 17 Jan (Clipped) in Portland

3.2. Assigning the value of Solar Irradiation to the buildings with zonal statistics

To assign the value of solar irradiance indicated by the DN of the raster files generated from r.sun.insoltime, we utilize a tool called zonal statistics. This tool summarizes the values of pixels located within building polygons and adds the summarized pixel values to the attribute table of each polygon. To achieve this, follow these steps:

From the above toolbar, select "**processing"** → Search for "**zonal statistics"** → inside the new window, for "**input layer"** insert your clipped building layer, and for **raster layer** insert your solar irradiation raster layer, then for "**output column prefix"**, for each month type the data like for 17Jan, 16Feb, and … → For "**Statistics to calculate"** only choose **Mean** → **"Run"**

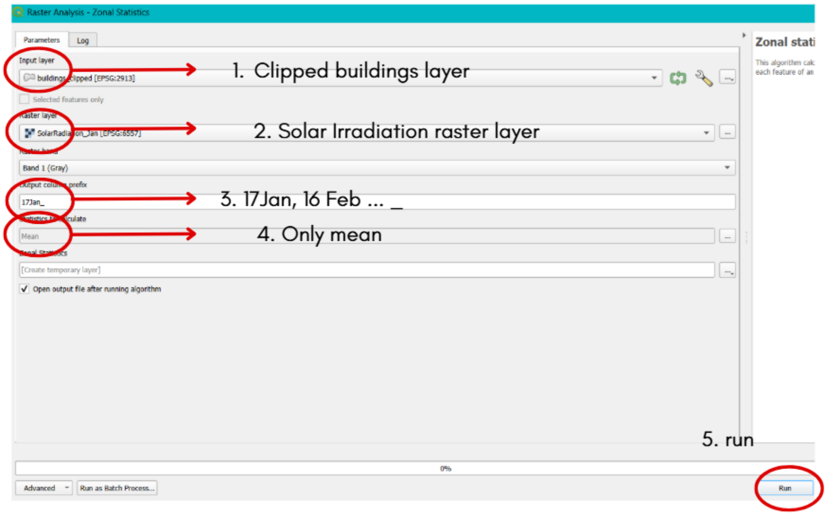


Figure 26 – Zonal statistics menu bar

Note: Using **zonal statistics** to summarize the solar irradiation received on a roof is theoretically incorrect. Ideally, we should focus on the areas of the roof where the solar panels will be installed. However, zonal statistics consider the entire roof area and provide an average value that includes data from parts of the roof where no panels will be installed, like adjacent to the objects that can occlude the sun beams.

Note: There are other methods to summarize the raster values within the polygons, like converting the "**Raster pixels to points**" then "**join attributes by location**" but this method is too time-consuming, and **zonal statistics** is much faster.

You should repeat this process until you assign all of the month's values in the attribute table of your building's shapefile. In the end, your attribute table should be like Figure 27.

Note: The table displays the average daily solar irradiation for each month. To calculate the total monthly solar irradiation, multiply the average daily values by the number of days in each month.

Note: If you previously converted the unit from **Wh/m²/day** to **kWh/m²/day** in the step "2.12.1." and then convert the **kWh/m²/day** to **kWh/m²/month** in step "2.12.2", then skip to next page, otherwise, you can convert the solar irradiation values from **Wh/m²/day** to **kWh/m²/month** by using **field calculator**.

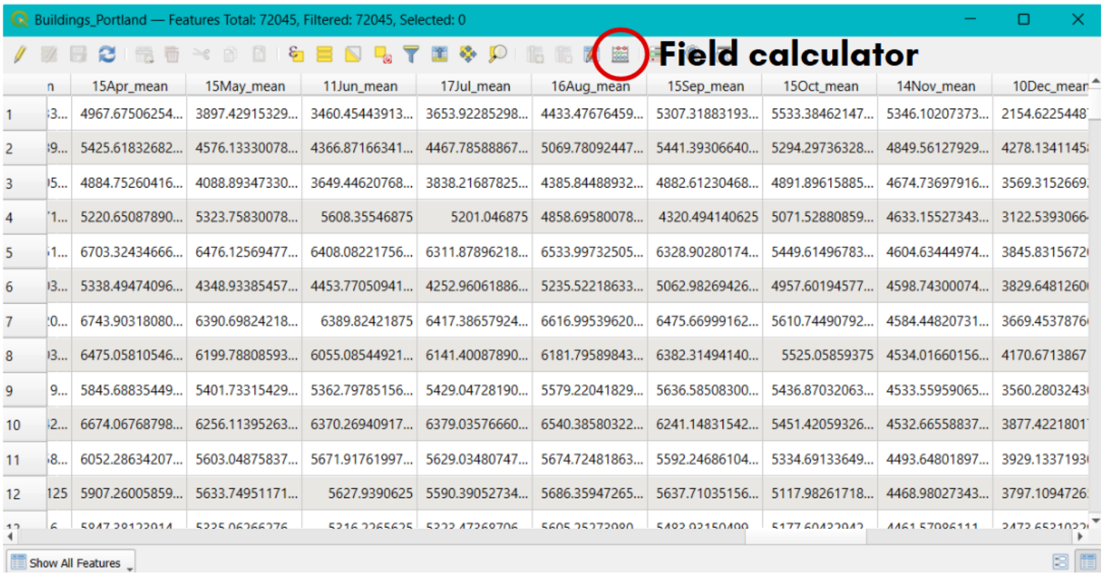


Figure 27 – Using field calculator

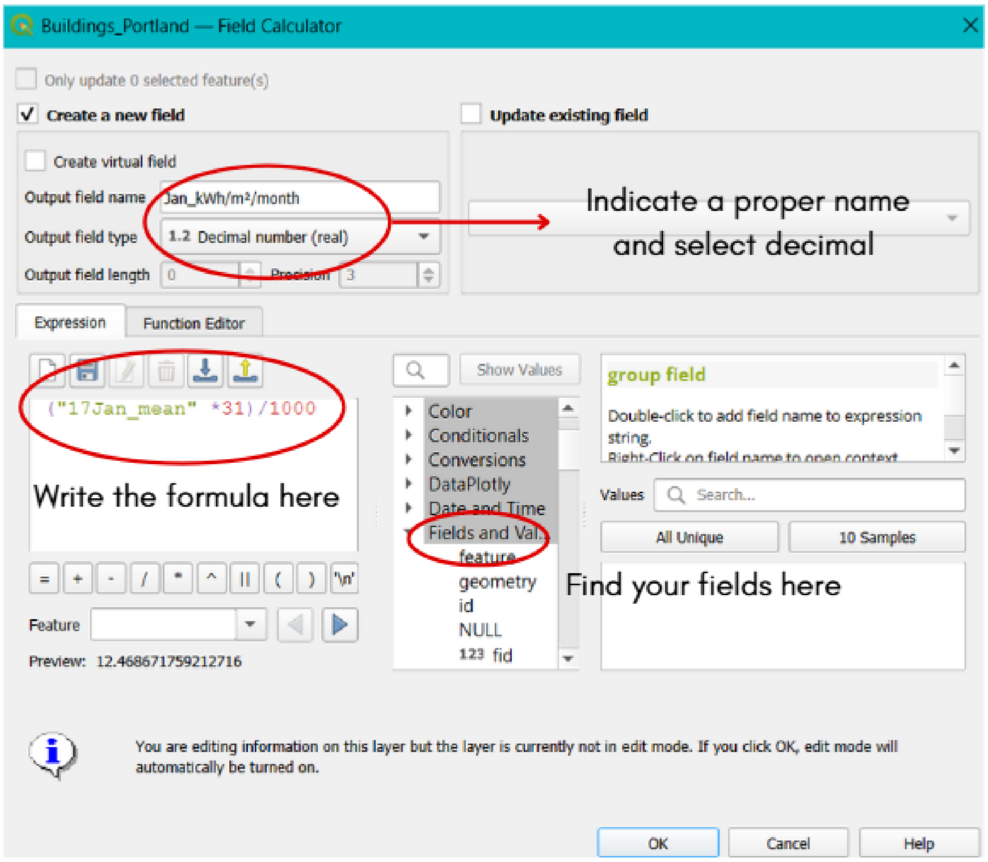
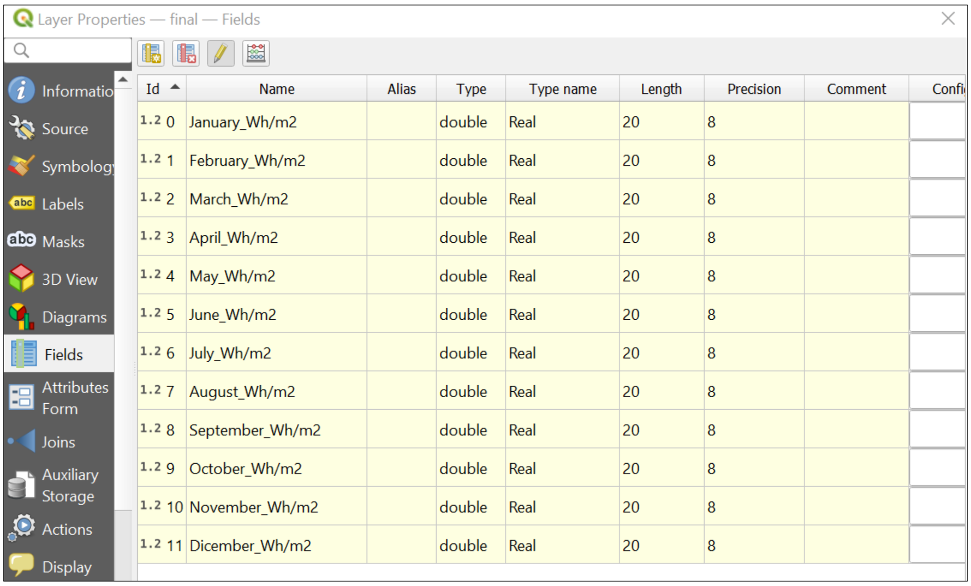


*Figure 28 – Field calculator expression for converting average day solar irradiatio into monthly, also converting the unit from **Wh/m²/month** to **kWh/m²/month***

Note: It is possible to enhance the appearance of the table by renaming the fields [VALUE] with the names of the month they refer to, opening the layer properties. To do so, in the layer's "**Properties**" go to the "**Fields**" tab, activate the editor, and change the name of the "Fields" using appropriate names. Once the names have been changed, close the editor and save the changes.



Id	Name	Alias	Type	Type name	Length	Precision	Comment	Confi
0	January_Wh/m2		double	Real	20	8		
1	February_Wh/m2		double	Real	20	8		
2	March_Wh/m2		double	Real	20	8		
3	April_Wh/m2		double	Real	20	8		
4	May_Wh/m2		double	Real	20	8		
5	June_Wh/m2		double	Real	20	8		
6	July_Wh/m2		double	Real	20	8		
7	August_Wh/m2		double	Real	20	8		
8	September_Wh/m2		double	Real	20	8		
9	October_Wh/m2		double	Real	20	8		
10	November_Wh/m2		double	Real	20	8		
11	Dicember_Wh/m2		double	Real	20	8		

Figure 29 – Organizing the field names in QGIS

Note: Based on the given instructions, you should calculate monthly solar irradiation, cumulative annual solar irradiation, and average annual solar irradiation.

In the field calculator, it is easy to do arithmetic calculations meanwhile creating a new column to store the results. To do so, "Create a new field" should be checked, and the name (preferably using underscores instead of spaces) and the type of information recorded in the column (Integer, Decimal, or might be Text) should be set. Finally, in the "Expression" section, it is easy to insert the formula using the arithmetic symbols listed below that section. If you need to use data from a specific column in the corresponding table, you can easily list the columns in the "Fields and Values."

Annual cumulative radiation means the sum of the 12 monthly values, in **kWh/m^2/year**. The calculation formula is "('jan'+ '+...+'nov'+'dec').

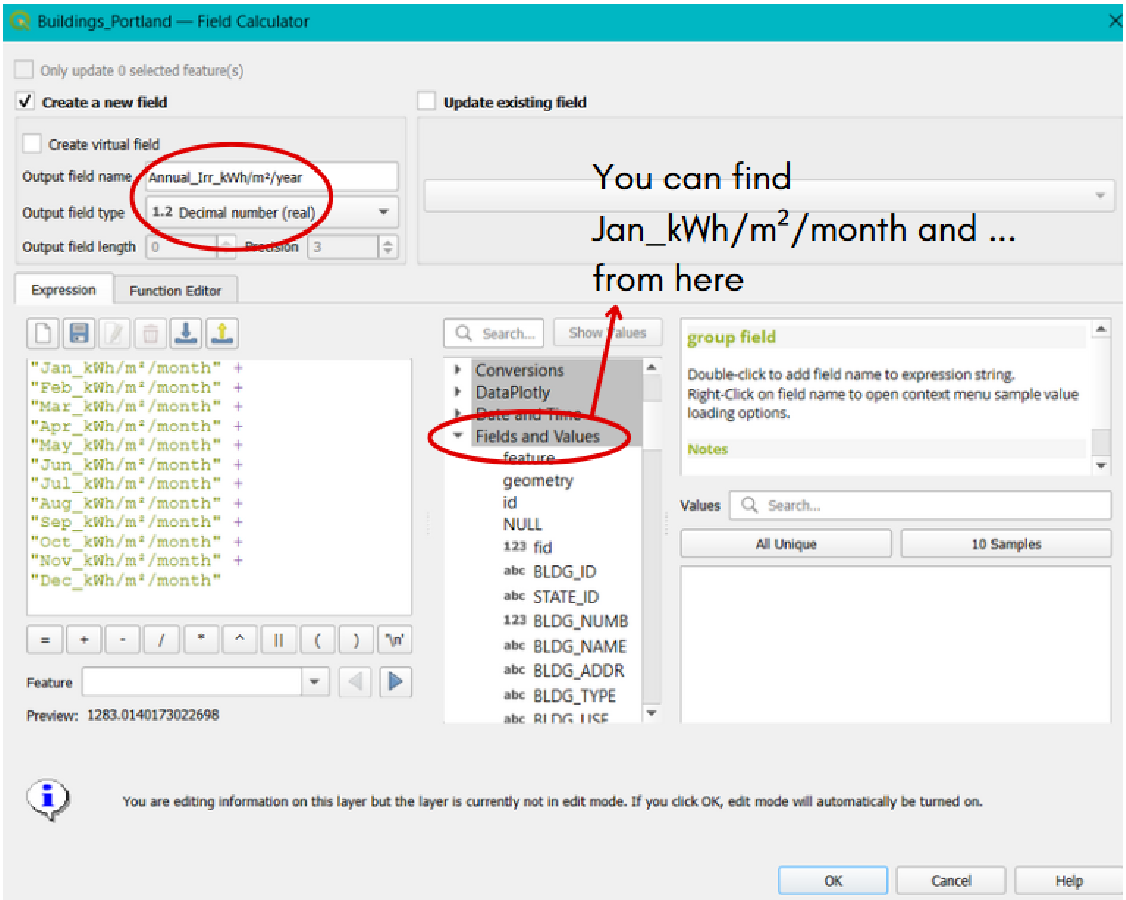


Figure 30 – Annual solar irradiation

Annual_Irr_kWh/m²/year = Jan_kWh/m²/month + Feb_kWh/m²/month + Mar_kWh/m²/month + Apr_kWh/m²/month + May_kWh/m²/month + Jun_kWh/m²/month + Jul_kWh/m²/month + Aug_kWh/m²/month + Sep_kWh/m²/month + Oct_kWh/m²/month + Nov_kWh/m²/month + Dec_kWh/m²/month

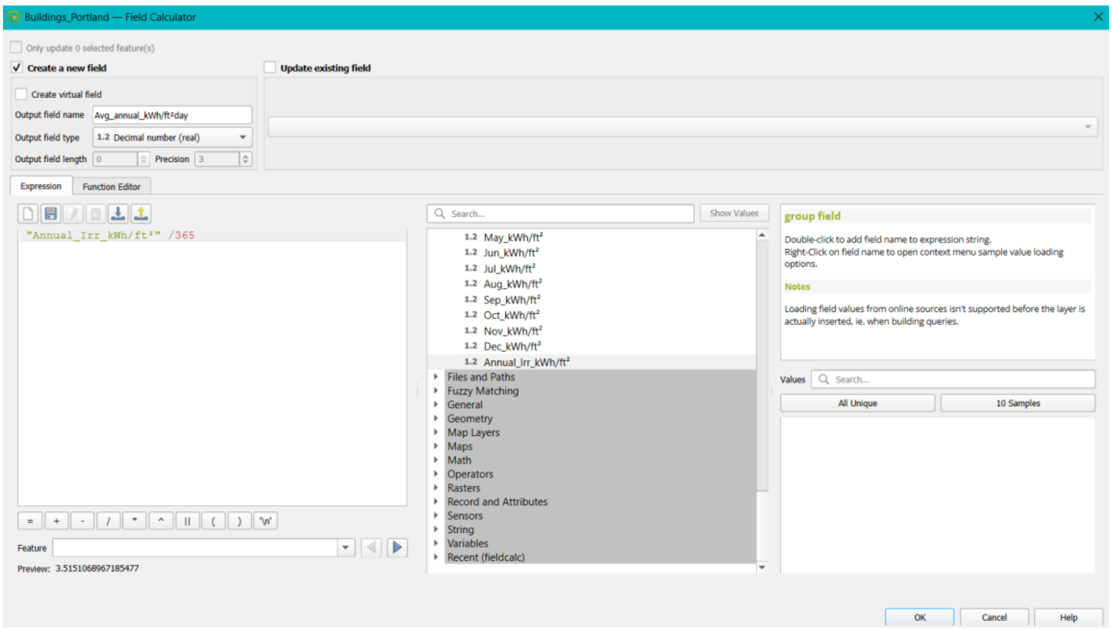
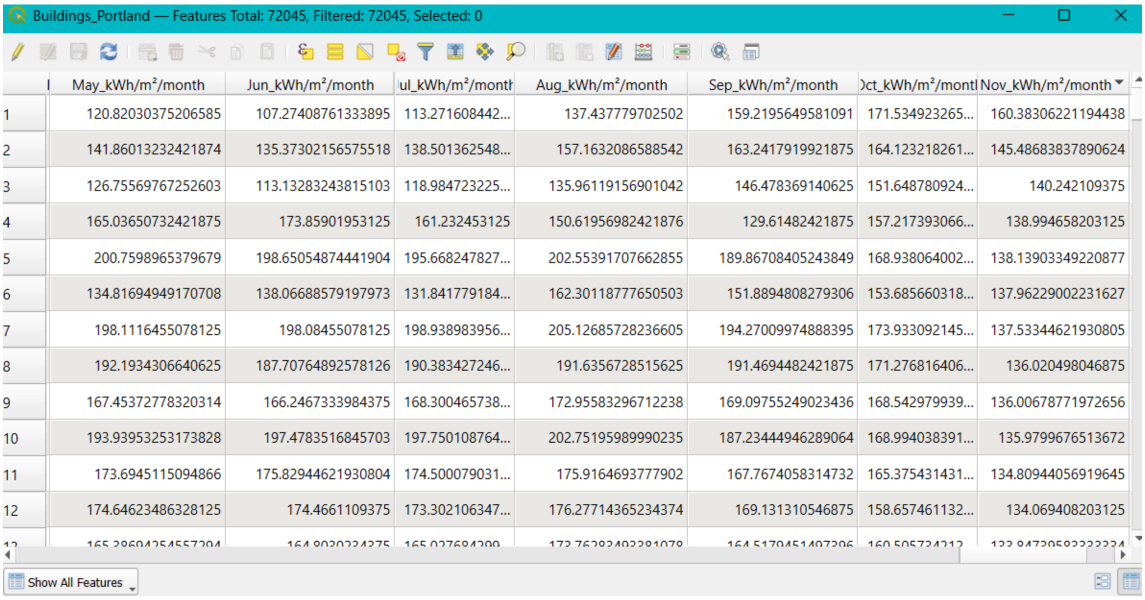


Figure 31 – Average annual solar irradiation



Buildings_Portland — Features Total: 72045, Filtered: 72045, Selected: 0

	May_kWh/m²/month	Jun_kWh/m²/month	ul_kWh/m²/month	Aug_kWh/m²/month	Sep_kWh/m²/month	)ct_kWh/m²/month	Nov_kWh/m²/month
1	120.82030375206585	107.27408761333895	113.271608442...	137.437779702502	159.2195649581091	171.534923265...	160.38306221194438
2	141.86013232421874	135.37302156575518	138.501362548...	157.1632086588542	163.2417919921875	164.123218261...	145.48683837890624
3	126.75569767252603	113.13283243815103	118.984723225...	135.96119156901042	146.478369140625	151.648780924...	140.242109375
4	165.03650732421875	173.85901953125	161.232453125	150.61956982421876	129.61482421875	157.217393066...	138.994658203125
5	200.7598965379679	198.65054874441904	195.668247827...	202.55391707662855	189.86708405243849	168.938064002...	138.13903349220877
6	134.81694949170708	138.06688579197973	131.841779184...	162.30118777650503	151.8894808279306	153.685660318...	137.96229002231627
7	198.1116455078125	198.08455078125	198.938983956...	205.12685728236605	194.27009974888395	173.933092145...	137.53344621930805
8	192.1934306640625	187.70764892578126	190.383427246...	191.6356728515625	191.4694482421875	171.276816406...	136.020498046875
9	167.45372778320314	166.2467333984375	168.300465738...	172.95583296712238	169.09755249023436	168.542979939...	136.00678771972656
10	193.93953253173828	197.4783516845703	197.750108764...	202.75195989990235	187.23444946289064	168.994038391...	135.9799676513672
11	173.6945115094866	175.82944621930804	174.500079031...	175.9164693777902	167.7674058314732	165.375431431...	134.80944056919645
12	174.64623486328125	174.4661109375	173.302106347...	176.27714365234374	169.131310546875	158.657461132...	134.069408203125

Show All Features

Figure 32 – Attribute table of the building's shapefile containing solar irradiation of all months

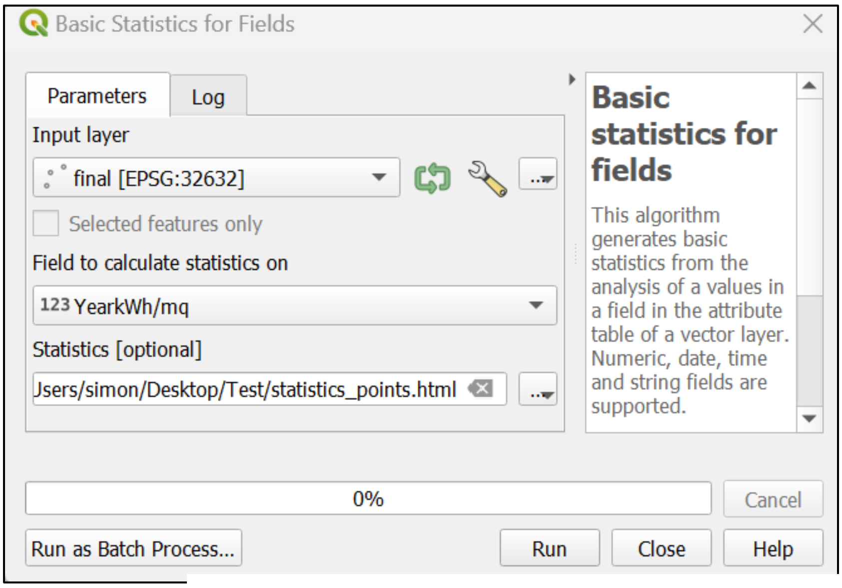
3.3. Compare the results with PVGIS

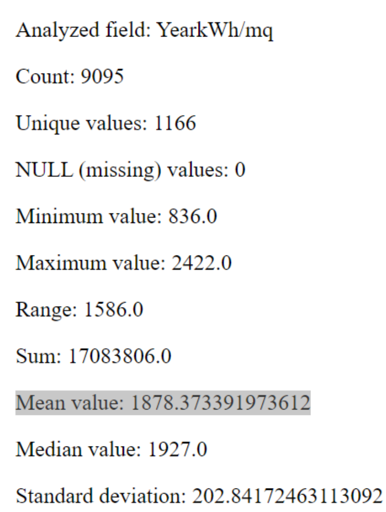
We can compare our results with other published results. To do so, we calculate the monthly and annual relative or percentage errors related to the <u>calculated horizontal solar irradiation H with QGIS</u> (mean or median value) and check monthly variations in comparison with <u>ENEA or PVGIS web tools</u>, in an Excel file. Relative Error formula:

$$\text{Relative Error} = (H_{\text{ENEA/PVGIS}} - H_{\text{QGIS}}) / H_{\text{ENEA/PVGIS}}$$

To evaluate the monthly and annual statistics of solar irradiation, use the **"Basic statistics for fields"** tool, considering the average values:

Processing Toolbox → Vector analysis → Σ Basic statistics for fields





Analyzed field: YearkWh/mq

Count: 9095

Unique values: 1166

NULL (missing) values: 0

Minimum value: 836.0

Maximum value: 2422.0

Range: 1586.0

Sum: 17083806.0

Mean value: 1878.373391973612

Median value: 1927.0

Standard deviation: 202.84172463113092

Figures 33 & 34 – Basic statistics menu in QGIS and the result

3.3.1. How to get monthly irradiation from ENEA or PVGIS

As mentioned, to check the validity of our results, it is useful to compare them with other published results, which we can find, like ENEA[16] and PVGIS[17]Both allow the verification of horizontal, sloping, and perpendicular surfaces. in this exercise, we only use monthly irradiation on a horizontal surface.

This procedure follows the prescriptions of the UNI Italian standard 8477/1 regarding the "Calculation of the supplies for building applications. Received radiant energy valuation", but it uses the maps of radiation on horizontal surfaces calculated by ENEA. It also includes the estimate of the effect due to the presence of obstacles, which, in some particular hours, can shield the Sun's rays.

Turin (45.061, 7.67)
Portland (45.52, -122.67)

Figure 35 – ENEA Website

[16] http://www.solaritaly.enea.it/CalcRggmmOrizz/Calcola1.php

[17] https://re.jrc.ec.europa.eu/pvg_tools/en/

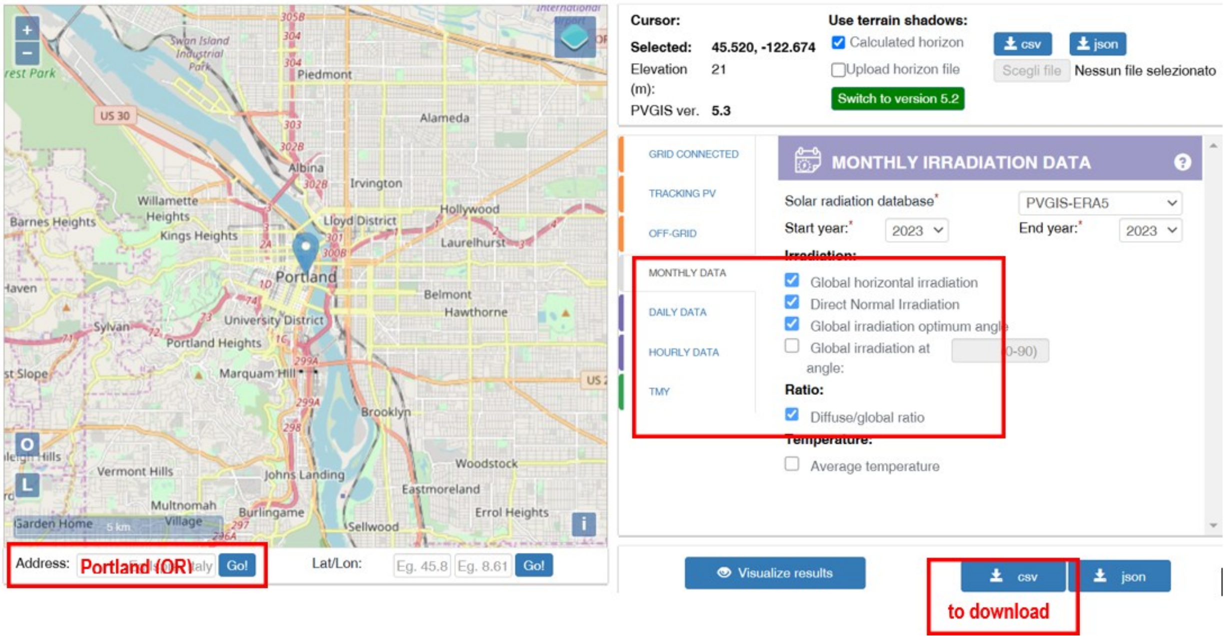
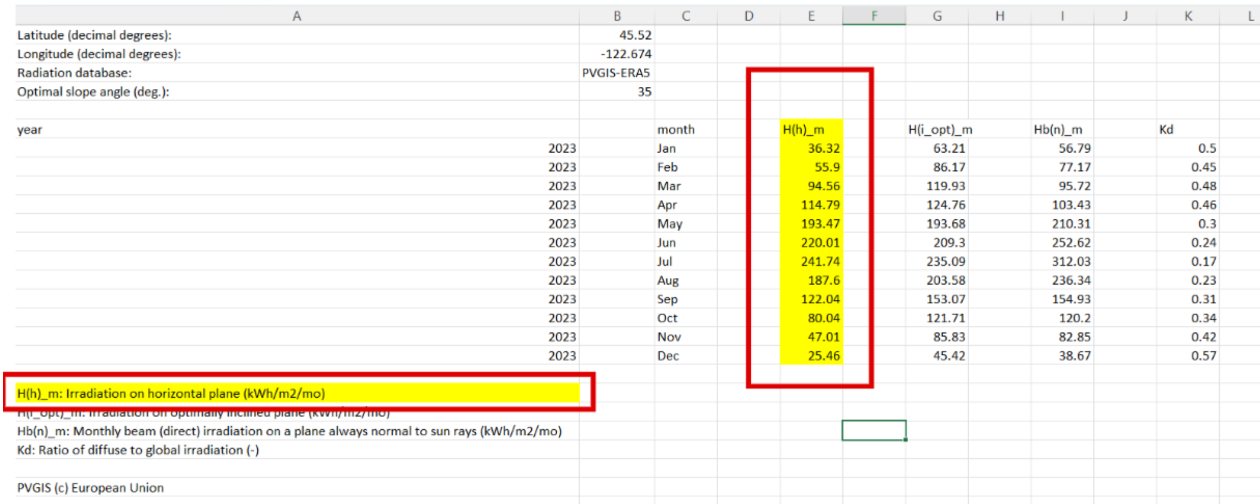


Figure 36 – PVGIS website

Note: If you need, check section 2.4 to see how to handle the CSV file.



Latitude (decimal degrees):	45.52						
Longitude (decimal degrees):	-122.674						
Radiation database:	PVGIS-ERA5						
Optimal slope angle (deg.):	35						
year		month	H(h)_m	H(i_opt)_m	Hb(n)_m	Kd	
	2023	Jan	36.32	63.21	56.79	0.5	
	2023	Feb	55.9	86.17	77.17	0.45	
	2023	Mar	94.56	119.93	95.72	0.48	
	2023	Apr	114.79	124.76	103.43	0.46	
	2023	May	193.47	193.68	210.31	0.3	
	2023	Jun	220.01	209.3	252.62	0.24	
	2023	Jul	241.74	235.09	312.03	0.17	
	2023	Aug	187.6	203.58	236.34	0.23	
	2023	Sep	122.04	153.07	154.93	0.31	
	2023	Oct	80.04	121.71	120.2	0.34	
	2023	Nov	47.01	85.83	82.85	0.42	
	2023	Dec	25.46	45.42	38.67	0.57	

H(h)_m: Irradiation on horizontal plane (kWh/m2/mo)
H(i_opt)_m: Irradiation on optimally inclined plane (kWh/m2/mo)
Hb(n)_m: Monthly beam (direct) irradiation on a plane always normal to sun rays (kWh/m2/mo)
Kd: Ratio of diffuse to global irradiation (-)

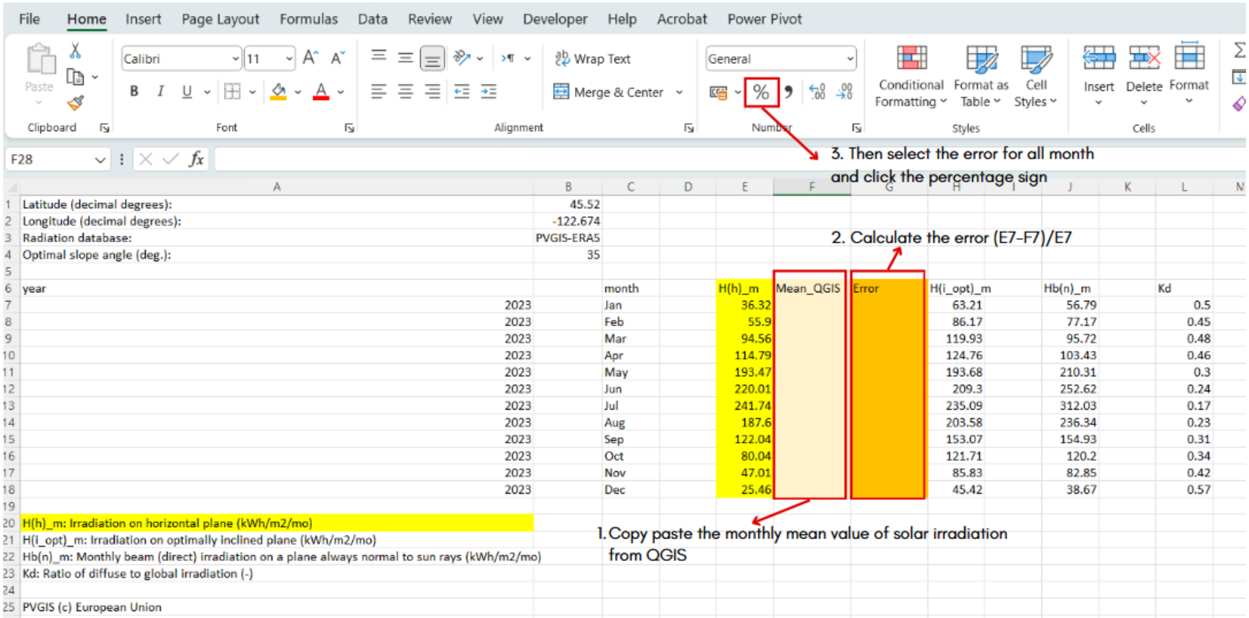
PVGIS (c) European Union

Figure 37 – CSV downloaded from PVGIS

3.3.2. How to compare the results

By now, you can get the average value of solar irradiation calculated in QGIS, and you downloaded the monthly solar irradiation derived from PVGIS or ENEA (only for Italian territory, now you can compare them using an Excel file. For example, you can use the CSV file downloaded from PVGIS. First of all, save the CSV file and change the format to "Excel workbook". Then:

next to the column "H(h)_m" which shows "Irradiance on horizontal plane **(kWh/m²/month)**", copy paste your mean value from QGIS for each month → then create another column to calculate the Relative Error by (H(h)_m – Mean_QGIS)/ H(h)_m and then check for showing in the percentage.



	A	B	C	D	E	F	G	H	I	J	K	L
1	Latitude (decimal degrees):	45.52										
2	Longitude (decimal degrees):	-122.674										
3	Radiation database:	PVGIS-ERA5										
4	Optimal slope angle (deg.):	35										
5												
6	year		month		H(h)_m	Mean_QGIS	Error	H(i_opt)_m		Hb(n)_m		Kd
7	2023		Jan		36.32			63.21		56.79		0.5
8	2023		Feb		55.9			86.17		77.17		0.45
9	2023		Mar		94.56			119.93		95.72		0.48
10	2023		Apr		114.79			124.76		103.43		0.46
11	2023		May		193.47			193.68		210.31		0.3
12	2023		Jun		220.01			209.3		252.62		0.24
13	2023		Jul		241.74			235.09		312.03		0.17
14	2023		Aug		187.6			203.58		236.34		0.23
15	2023		Sep		122.04			153.07		154.93		0.31
16	2023		Oct		80.04			121.71		120.2		0.34
17	2023		Nov		47.01			85.83		82.85		0.42
18	2023		Dec		25.46			45.42		38.67		0.57
19												
20	H(h)_m: Irradiation on horizontal plane (kWh/m2/mo)											
21	H(i_opt)_m: Irradiation on optimally inclined plane (kWh/m2/mo)											
22	Hb(n)_m: Monthly beam (direct) irradiation on a plane always normal to sun rays (kWh/m2/mo)											
23	Kd: Ratio of diffuse to global irradiation (-)											
24												
25	PVGIS (c) European Union											

Figure 38 – Comparing the results of QGIS with PVGIS

Finally, for creating a bar chart select all three columns (H(h)_m, Mean_QGIS, Error) and then from top menu bar select insert → Column or bar chart → 2D → When the chart was displayed, right click on it and select "change chart type" → down the list, select "combo" and for "Error" in chart type select "Line" and check the "secondary axis".

You can calculate the monthly relative errors of solar irradiation $\mathbf{H_{1kWp}}$ related to the calculated results of QGIS and ENEA or PVGIS:

$$Relative\ Error = \frac{H\ PVGIS\ -\ H\ calc, QGIS}{H\ PVGIS}$$

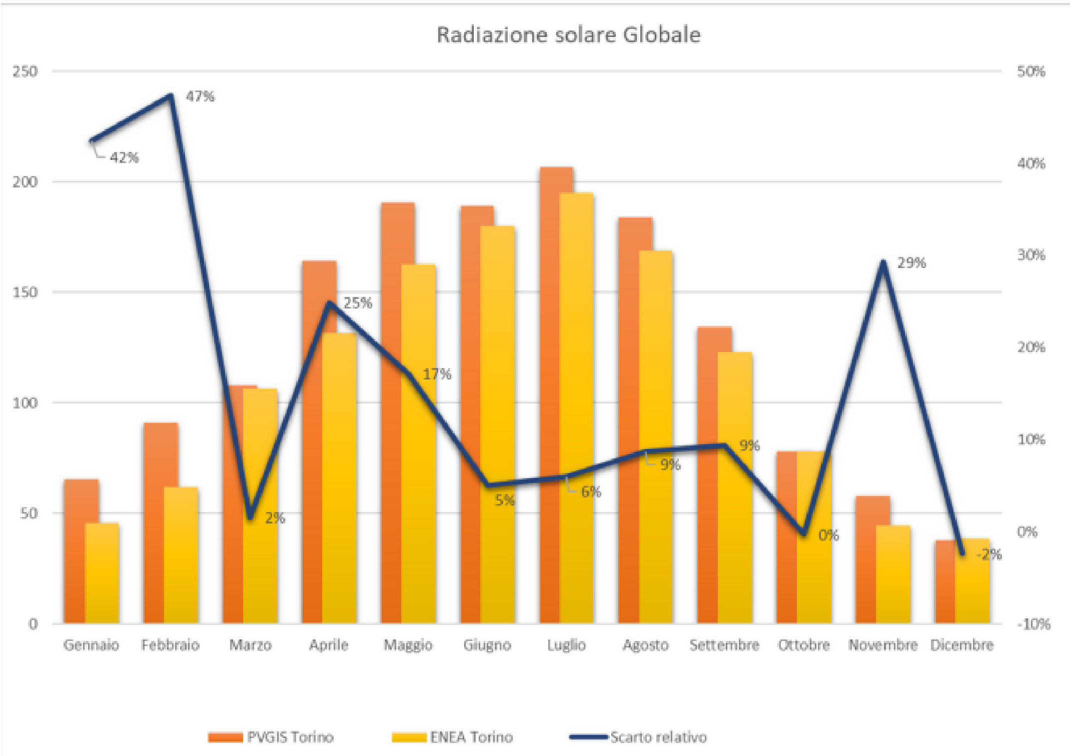


Figure 39 – Comparing the results of QGIS with ENEA

Note: The chart shows that errors are higher during cold seasons and lower in warmer seasons. This is mainly because your data analysis includes many points influenced by their surroundings. For example, one data point might be between tall buildings, near the shadow of a tree, or on top of a tall building without nearby objects. In contrast, the PVGIS values come from just one location under specific conditions. When the sun is at a steeper angle in colder seasons, the error increases. In warmer seasons, when the sun is more directly above the city, the error decreases because the influence of nearby objects is lessened.

3.4. Calculation of the area of each building

We need to know the area (m²) of each building to use it in further calculations like for example, estimating the area of the rooftop we have available for installing PV panels. To calculate area in QGIS:

Open the **attribute table** of the buildings' shapefile → Choose "**field calculator**" to create a new field → Name the field "area_sqm", change the "**output field type**" to "**decimal**" → Finally, inside the "**expression box**" type "$area" or, under the "**geometry**" double click on $area → ok

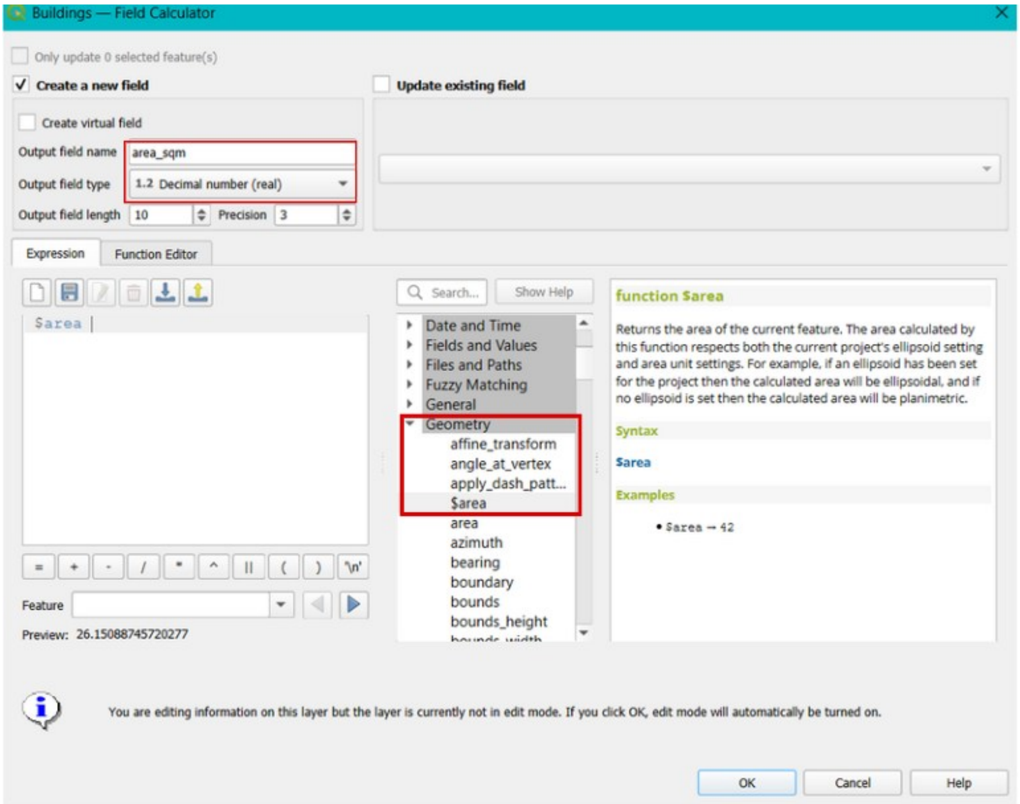


Figure 40 – Calculating the area of buildings [m²]

Important remark: It is highly recommended that if the attribute table already contains an "area" column, delete the column and create your area.

3.5. How to assign zoning types in buildings

*****For Portland**:

Recognizing that energy needs vary across different functions, such as residential and industrial, it is essential to understand the specific functions of buildings. This knowledge will enable us to estimate the energy requirements accurately and propose various strategies to meet those needs for different sectors.

We need:

1. Shapefile of the buildings
2. Shapefile of the zoning

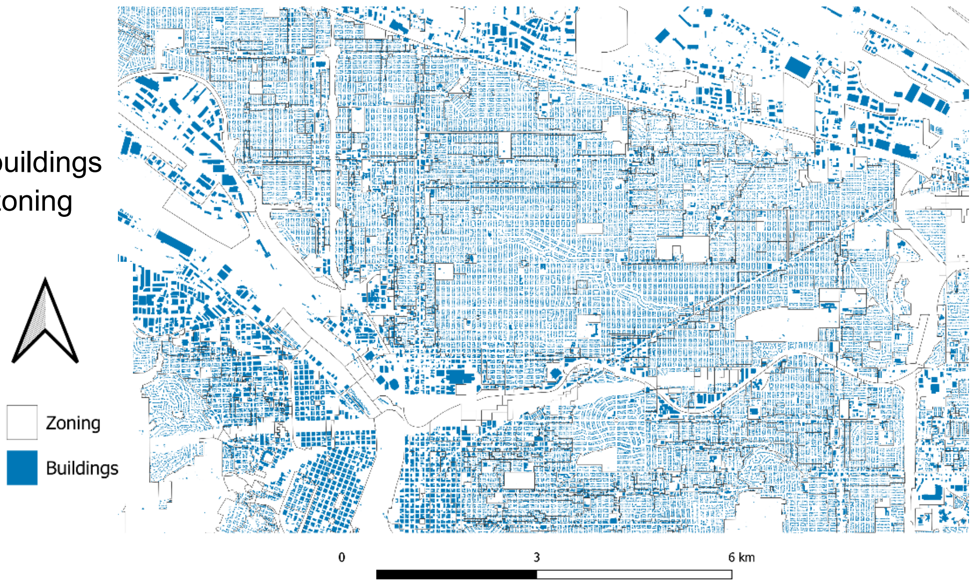


Figure 41 – Buildings and border line of zones in Portland

"Zongen_CL" contains information regarding the land use.

Note: There is a column "BLDG_USG" that contains usage, but it lacks some data for some buildings. This step aims to cover that void.

Code	Description
COM	Commercial
FUD	Future urban development
IND	Industrial
MFR	Multi-family residence
MUR	Multi-use residence
PF	Public facilities
POS	Public open space
RUR	Rural
SFR	Single-family residence

Table 7 – Code and description of ZONGEN_CL

Note: We simply need to join the attribute tables of buildings and zoning to see what the type of use of each building is.

Toolbar menu → **processing** → search for "**join attributes by location**" → Select "**Join feature in**" as buildings, select "**By comparing to**" as Zoning, keep the "**geometric predicate**" as "**intersect**" → Select "**fields to add**" and select only "**ZONGEN_CL**" → Select "**Join type**" as "**Take the attribute for the first matching only (one to one)** → **run**

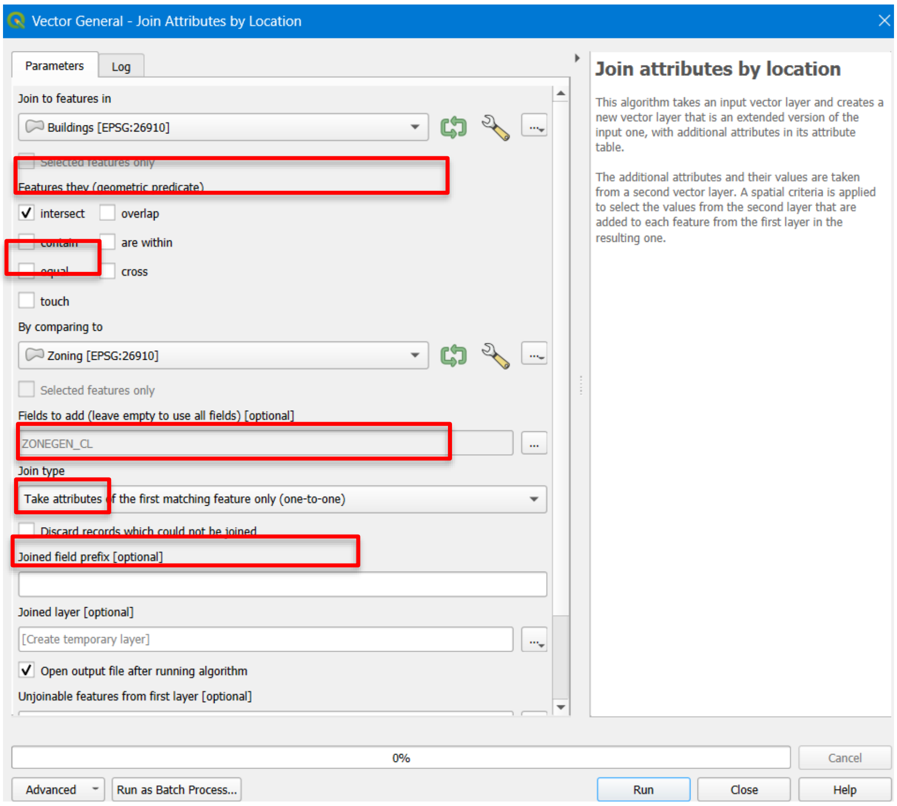


Figure 42 – "Joint Attributes by location" tool in QGIS

Now you have added the column "ZONGEN_CL" to all of your buildings. For more convenience, convert the codes to descriptions by creating a new field and the code below:

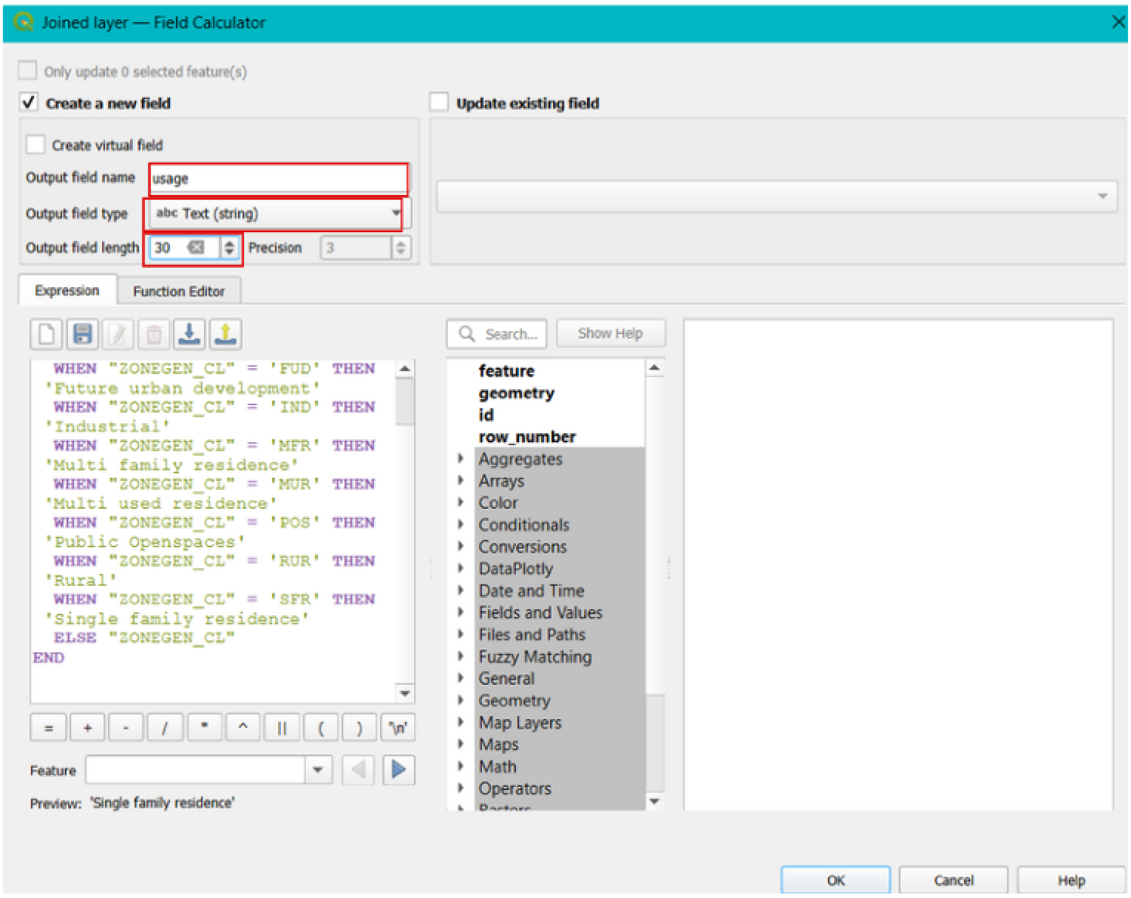


Figure 43 – The expression for converting the code into the description in the field calculator

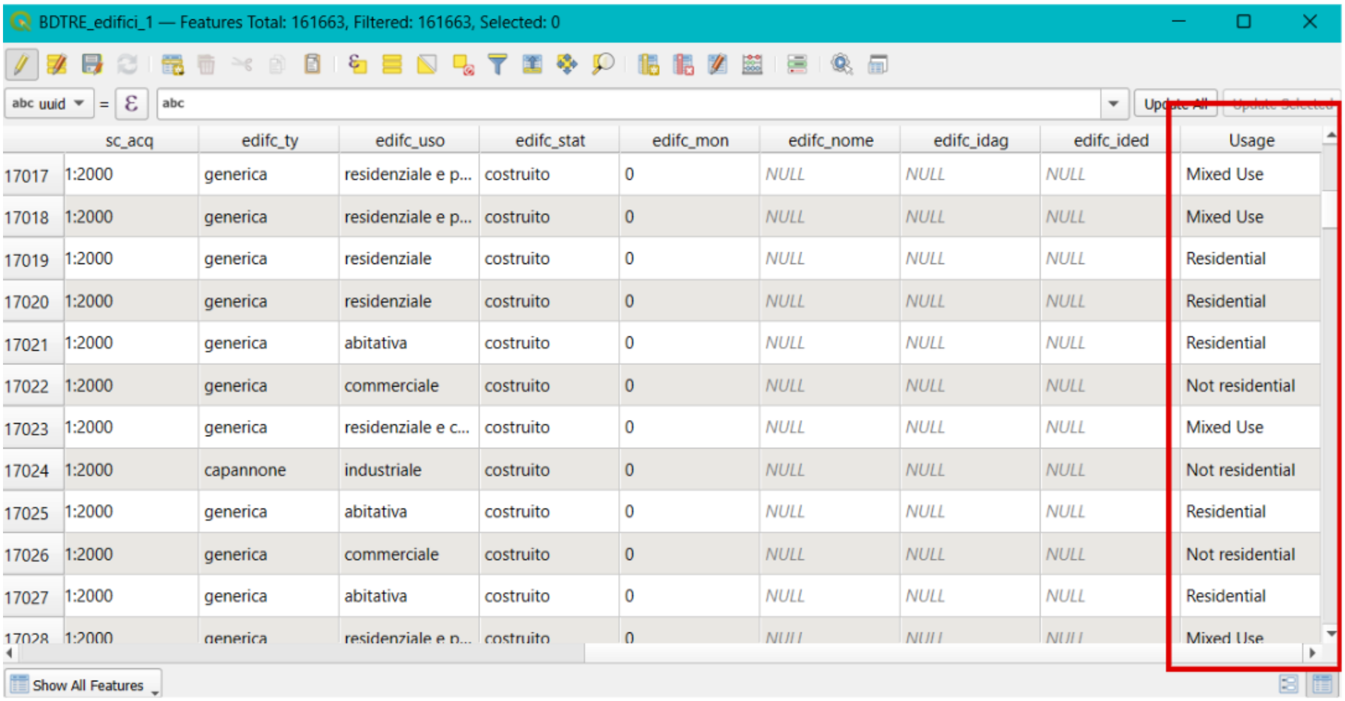
```
CASE
  WHEN "ZONEGEN_CL" = 'COM' THEN 'Commercial'
  WHEN "ZONEGEN_CL" = 'FUD' THEN 'Future urban
development'
  WHEN "ZONEGEN_CL" = 'IND' THEN 'Industrial'
  WHEN "ZONEGEN_CL" = 'MFR' THEN 'Multi family residence'
  WHEN "ZONEGEN_CL" = 'MUR' THEN 'Multi used residence'
  WHEN "ZONEGEN_CL" = 'POS' THEN 'Public Openspaces'
  WHEN "ZONEGEN_CL" = 'RUR' THEN 'Rural'
  WHEN "ZONEGEN_CL" = 'SFR' THEN 'Single family residence'
  ELSE "ZONEGEN_CL"
END
```

*****For Turin:**

For Turin, the buildings' shapefile already has some columns that provide information regarding the usage of the buildings. You can open the attribute table of the file and inspect the column "edific_uso", in which you can find different types of use for the buildings. As mentioned, we focus on residential buildings or partially residential buildings. So, we have to categorize our buildings again.

Open the **attribute table** of BDTRE_edifici → **field calculator** → **new field**, name it as "usage", change the output type to **string**, and increase the **output field length** to 30, then write the code below and ok

```
CASE
  WHEN "edifc_uso" IN ('abitativa', 'residenziale') THEN 'Residential'
  WHEN "edifc_uso" IN (
      'residenziale e agricolo',
      'residenziale e commerciale',
      'residenziale e produttivo',
      'residenziale e ricreativo',
      'residenziale e ufficio pubblico'
  ) THEN 'Mixed Use'
  ELSE 'Not residential'
END
```


BDTRE_edifici_1 — Features Total: 161663, Filtered: 161663, Selected: 0

	sc_acq	edifc_ty	edifc_uso	edifc_stat	edifc_mon	edifc_nome	edifc_idag	edifc_ided	Usage
17017	1:2000	generica	residenziale e p...	costruito	0	NULL	NULL	NULL	Mixed Use
17018	1:2000	generica	residenziale e p...	costruito	0	NULL	NULL	NULL	Mixed Use
17019	1:2000	generica	residenziale	costruito	0	NULL	NULL	NULL	Residential
17020	1:2000	generica	residenziale	costruito	0	NULL	NULL	NULL	Residential
17021	1:2000	generica	abitativa	costruito	0	NULL	NULL	NULL	Residential
17022	1:2000	generica	commerciale	costruito	0	NULL	NULL	NULL	Not residential
17023	1:2000	generica	residenziale e c...	costruito	0	NULL	NULL	NULL	Mixed Use
17024	1:2000	capannone	industriale	costruito	0	NULL	NULL	NULL	Not residential
17025	1:2000	generica	abitativa	costruito	0	NULL	NULL	NULL	Residential
17026	1:2000	generica	commerciale	costruito	0	NULL	NULL	NULL	Not residential
17027	1:2000	generica	abitativa	costruito	0	NULL	NULL	NULL	Residential
17028	1:2000	generica	residenziale e p...	costruito	0	NULL	NULL	NULL	Mixed Use

Show All Features

Figure 46 – BDTRE Edifici attribute table after categorization

3.6. Calculation of the electricity production with roof-integrated PV technology

In this stage, we want to calculate and estimate the amount of electricity that can be produced using roof-integrated PV technology. To calculate the photovoltaic potential, it is necessary to hypothesize various technological solutions, each one of which is characterized by a particular efficiency and panel size. Usually, the most used modules are **monocrystalline silicon** and **polycrystalline silicon** ones.

Photovoltaic modules[18]	Efficiency values[19]
Monocrystalline silicon	η_{MC}= 23% (0.23)
Polycrystalline silicon	η_{PC} = 19% (0.19)
Thin film	η_{FS} = 10% (0.10)

Table 7 – Different PV panel technologies with their efficiency

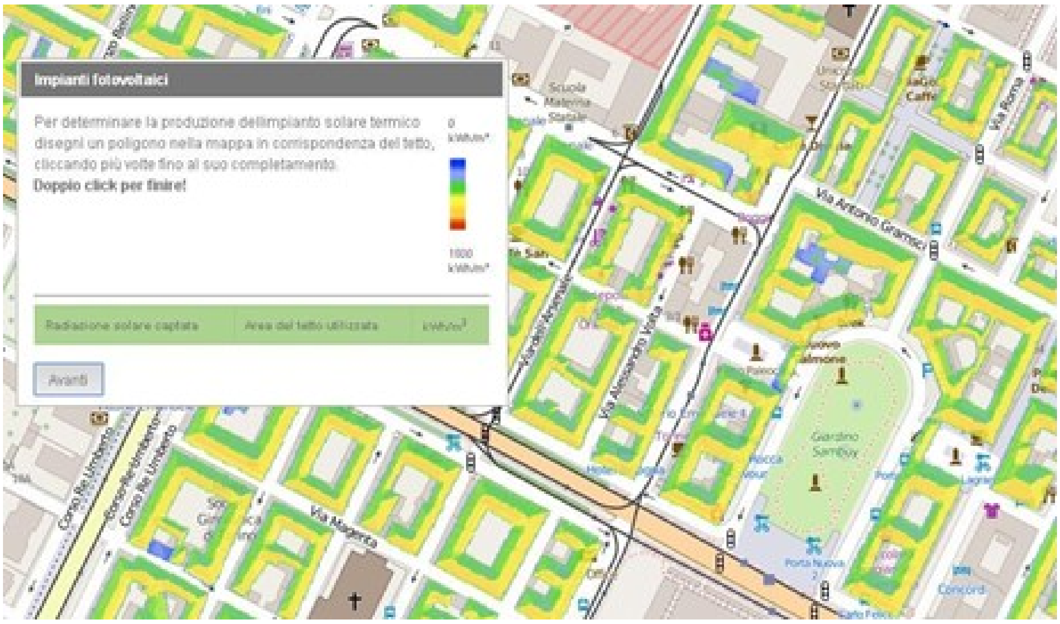


Figure 47 – BDTRE Edifici attribute table after categorization

Note: The energy production by photovoltaic technologies from solar radiation incidents can be calculated using the Suri correlation[20]:

[18] https://css.umich.edu/publications/factsheets/energy/solar-pv-energy-factsheet

[19] η (eta) is a Greek sign, in engineering usually indicates efficiency

[20] "Potential of solar electricity generation in the European Union member states and candidate countries", Marcel Suri, Thomas A. Huld, Ewan D. Dunlop, Heinz A. Ossenbrink, Solar Energy 81 (2007) 1295–1305.

$$(1) \quad E = PR \times Hs \times S \times \eta$$

Equation 1 – for the calculation of energy that can be produced on the rooftop of a building

E is the electrical energy produced by month/year (kWh/y)
PR is the performance ratio index of the system (≈ 0,75)
Hs is the cumulative monthly/annual solar radiation (kWh/m^2/y)
η is the conversion efficiency, that is, the ratio of incident solar energy to produced energy

$$(2) \quad \eta = \frac{\mathrm{Wp}}{S \times I\,stc}$$

Equation 2 – Efficiency

W_p is the peak power of the panel (equal to 1 kW$_p$, which corresponds to about 6-8 m^2 of PV surface)
S is the working-active surface of the panel [m^2] (about 30-40% of the roof area)
I_{stc} is the tested solar irradiance under standard test conditions STC (1 kW/m², 25°C at sea level)

With the combination of the relations (1) and (2), the electrical energy yearly produced is obtained (with Wp/Istc = 1000/1000 = 1): (*equation 3*)

$$(3) \quad E\ 1kWp = PR \times Hs \times \frac{Wp}{Istc}$$

Equation 3 – equation to calculate the energy that can be produced with 1 kWp of PV

3.6.1. How to calculate energy production from PV panels in QGIS

By now, we have calculated the monthly solar irradiation and assigned it to our buildings. We also calculate the area of each building. Now we only need to calculate the total area that is used for installing PV Panels, which is 30% - 40% of the total area of each building. Finally, we can calculate the production for 3 types of PV technologies (Monocrystalline silicon, Polycrystalline silicon, thin film)

To begin, we create a new column, name it “PV_area”, and dedicate 35% of the building's area for installing PV panels.

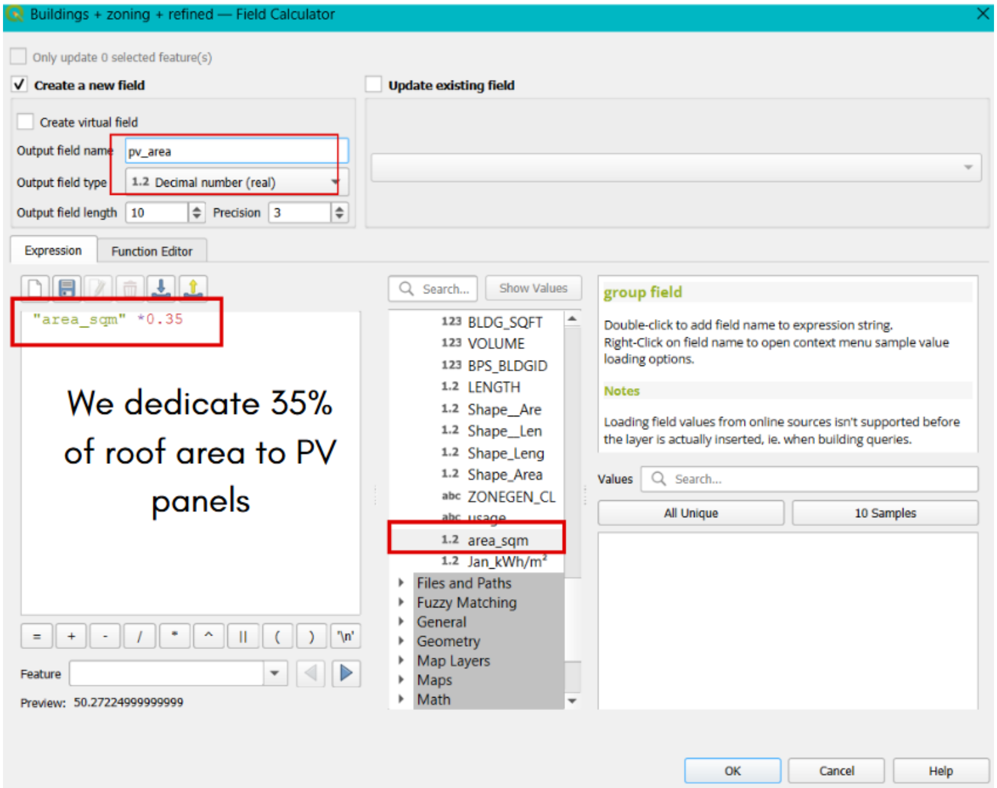


Figure 48 – Calculating PV area [m²]

3.6.2. Monthly energy production based on equation 1

Now is possible to calculate the energy production for each month. We calculate the energy production for all months, consequently, we will have 12 new columns that show the production of energy (**kWh/month**). Use the field calculator inside the attribute table of the buildings shapefile to perform the calculation.

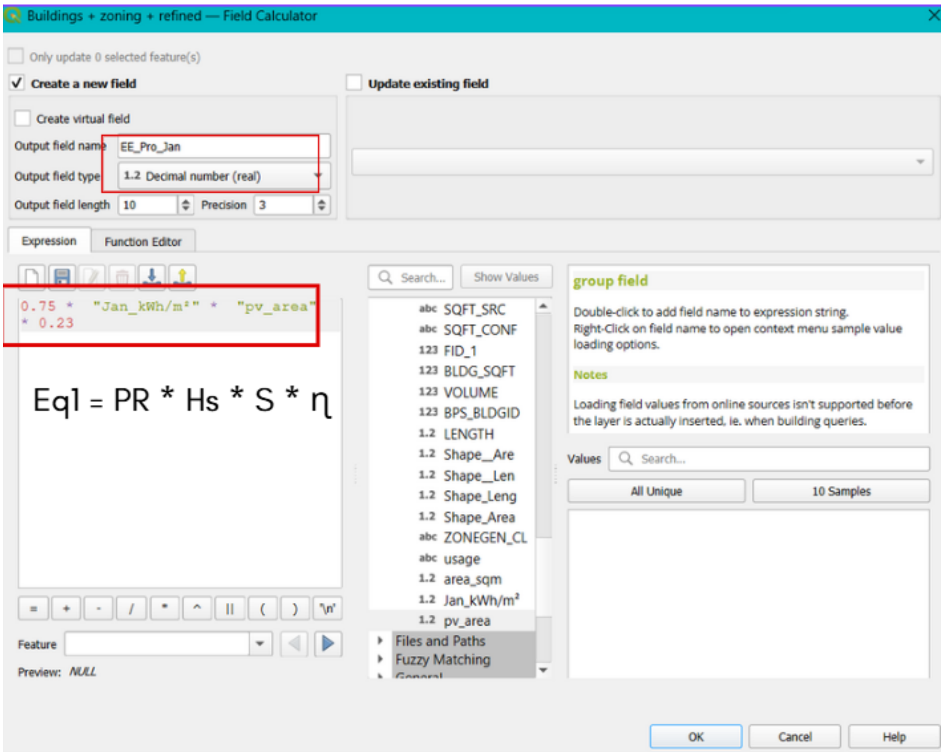


Figure 49 – Energy production calculation for each building based on equation 1

3.6.3. Annual energy production based on equation 1

After calculating the monthly energy production for all buildings, we can now determine the annual energy production for each building. This can be done easily by using a field calculator to sum the energy production for each month. The result would be EE_Pro_Ann (**kWh/year**).

"EE_Pro_Jan" + "EE_Pro_Feb"+
"EE_Pro_Mar" + "EE_Pro_Apr"+
"EE_Pro_May" + "EE_Pro_Jun"+
"EE_Pro_Jul" + "EE_Pro_Aug"+
"EE_Pro_Sep" + "EE_Pro_Oct"+
"EE_Pro_Nov" + "EE_Pro_Dec"

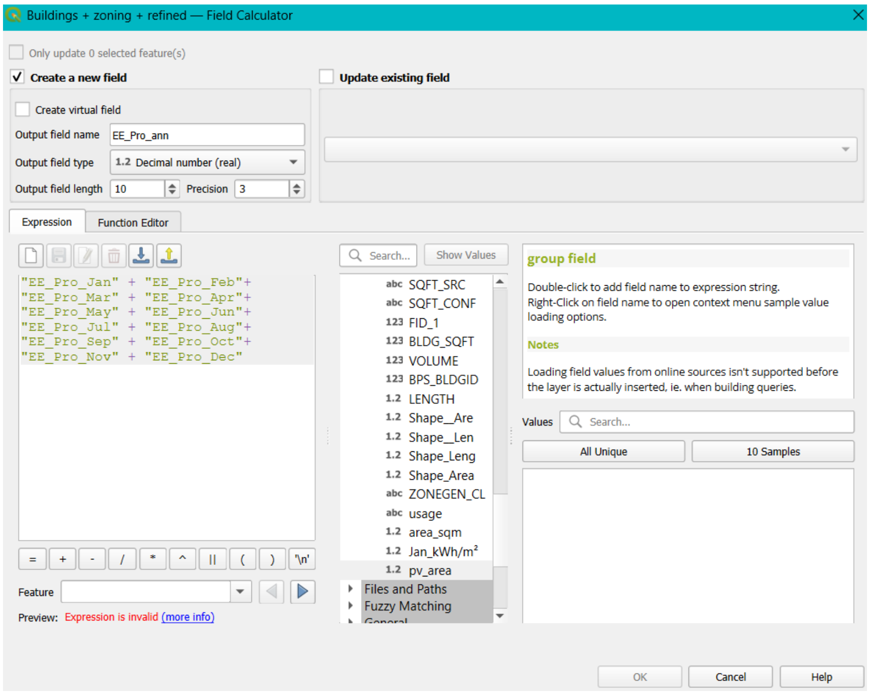


Figure 51 – Annual energy production [kWh/year]

3.6.4. Estimating the effectiveness of energy production for buildings with equation 3

Calculation of equation 3, in which we do not consider the dimension of the system, is helpful to evaluate which part of the territory, the solar technology is more effective with $E_{1kWp.}$ You can also calculate this field for all months.

0.75 * "Jan_H" * 1
0.75 * "Feb_H" * 1
...

0.75 * "Annual_H" * 1

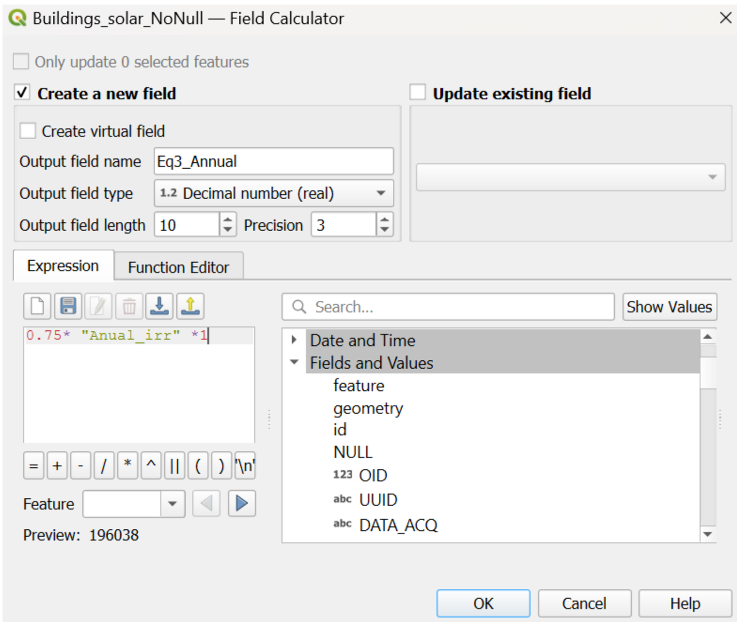


Figure 52 - Calculation of Annual energy production by Eq3

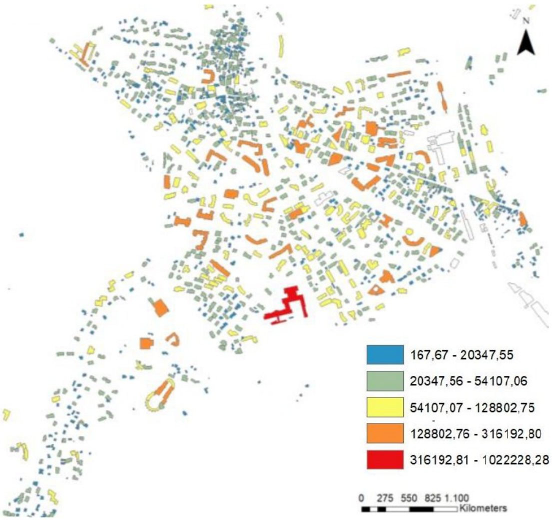


*Figure 53 The energy produced by PV roof-integrated technology on industrial buildings in Bardonecchia (**Eq.1** considering the 30-40% of roof surface)*

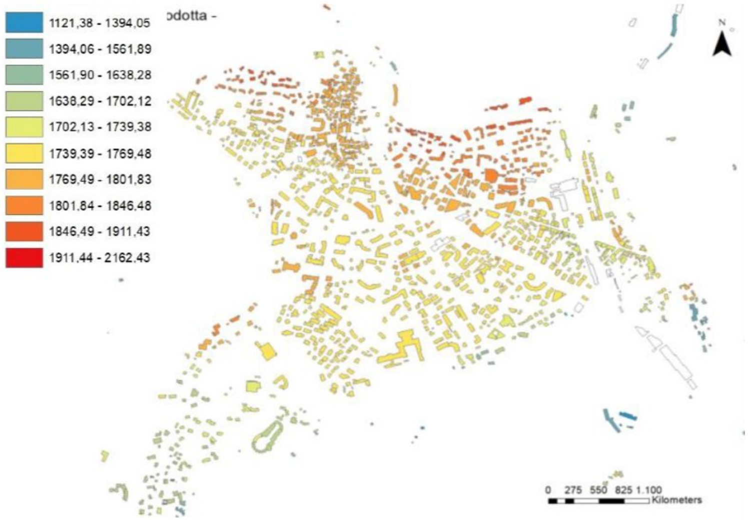


*Figure 54 The energy produced by PV roof-integrated technology, with **1 kWp** on industrial buildings in Bardonecchia (**Eq.3** considering 1 kWp installed on each building roof)*

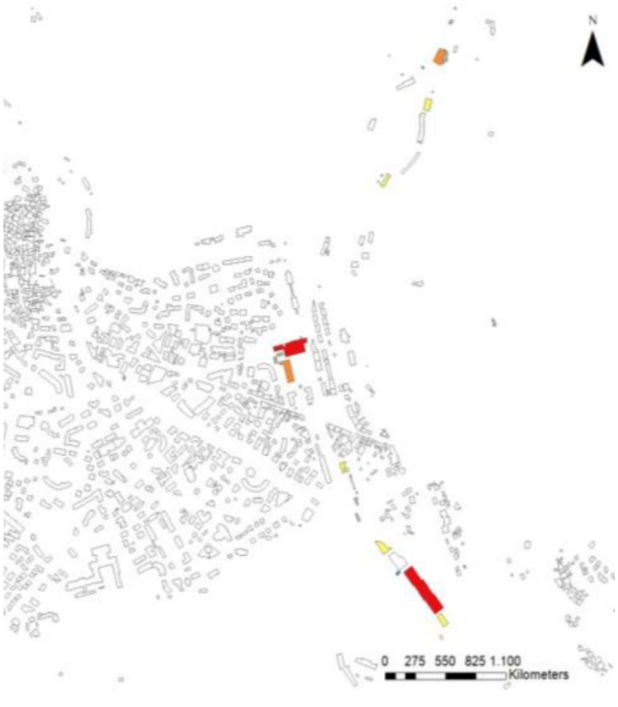


Figure 55

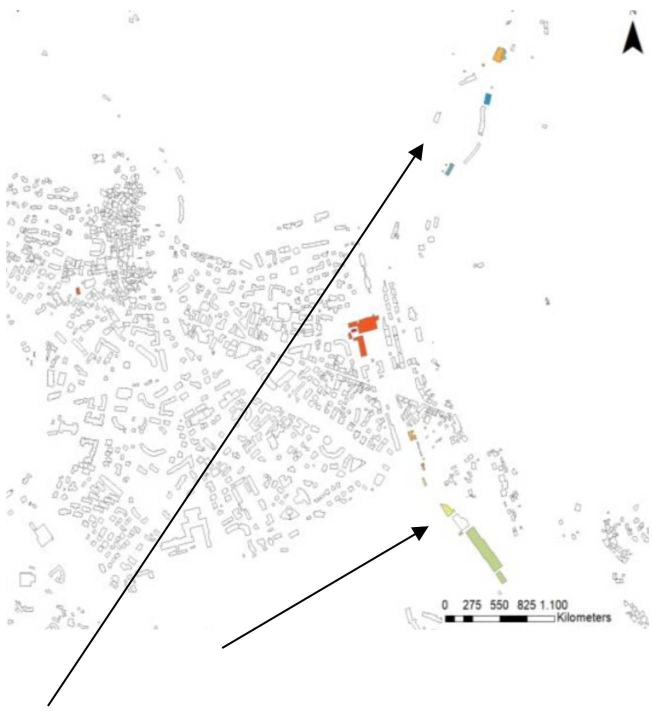


Figure 56

In Figure 56, the "blue" and "green" industries do not have a favorable position and therefore will produce less energy for the same installed power. The analysis can be concluded with the energy production of the different types of buildings.

For the Piedmont Region, if the building use is not available, it is possible to download the Piedmont PRGs tiling **(**Mosaicatura dei Piani Regolatori del Piemonte)[21] by following the procedure explained before. Also, refer to the solar portal of the Metropolitan City of Torino or the Environmental Insights Explorer that analyzes Google Maps data[22] to provide, for example, the solar energy potential of a city.

3.7. Comparison of QGIS and PVGIS PV production with roof-integrated PV technology

Now, we can compare the results with the PVGIS website[23] with monthly and annual relative errors. which allows the estimation of the radiation on a horizontal or an inclined surface and the energy that can be produced through photovoltaic technology.

You can calculate the monthly and annual relative errors of energy production $\mathbf{E_{1kWp}}$ related to the calculated results of QGIS and PVGIS:

$$Relative\ Error = \frac{E\ PVGIS\ -\ E\ calc, QGIS}{E\ PVGIS}$$

Open the PVGIS website → Search for your desired location (Turin IT, Portland OR) → In the grid-connected tab, set the variables exactly as indicated in the following picture → Download the CSV file

[21] http://www.cittametropolitana.torino.it/cms/ambiente/risorse-energetiche/osservatorio-energia/portale-solare

[22] https://insights.sustainability.google/

[23] https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html,

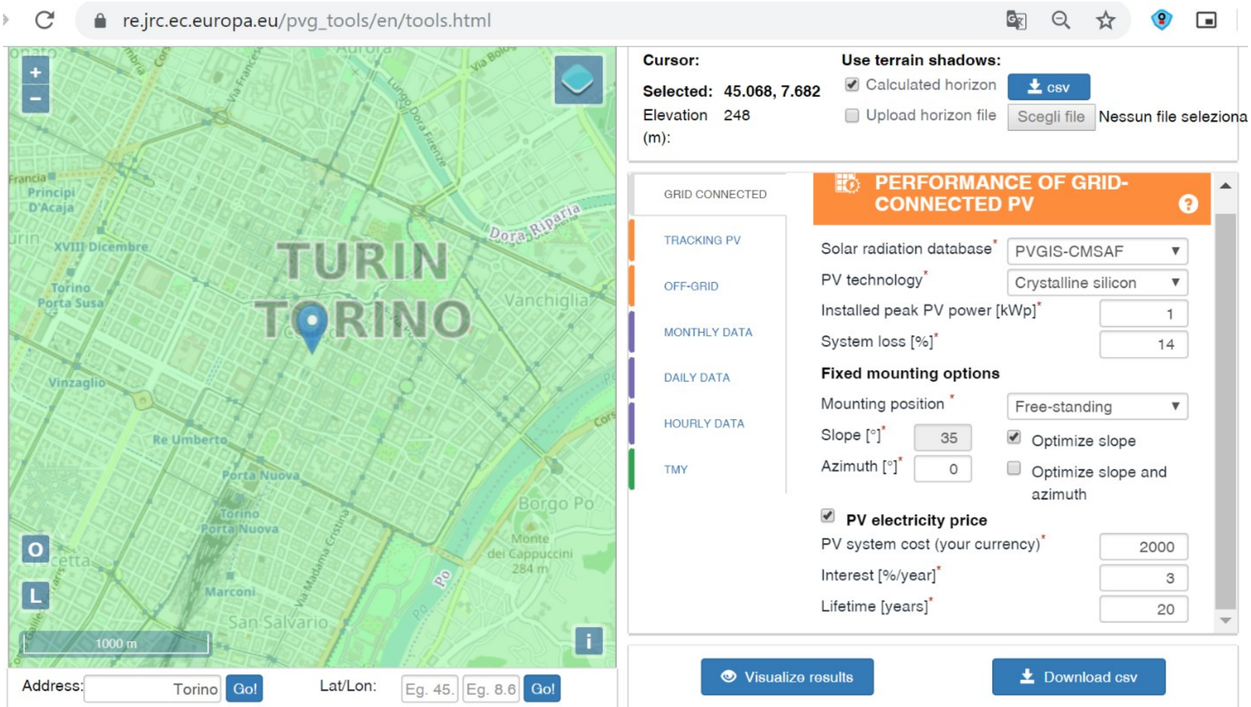
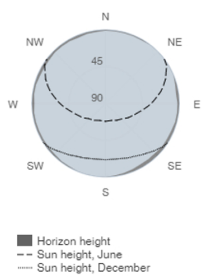


Figure 57 – PVGIS website



Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

Provided inputs:

Latitude/Longitude:	45.068, 7.682
Horizon:	Calculated
Database used:	PVGIS-CMSAF
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

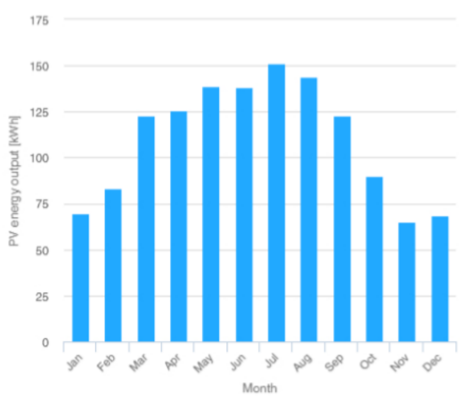
Simulation outputs

Slope angle:	38 (opt) °
Azimuth angle:	0 °
Yearly PV energy production:	1320 kWh
Yearly in-plane irradiation:	1690 kWh/m²
Year to year variability:	59.10 %
Changes in output due to:	
Angle of incidence:	-2.7 %
Spectral effects:	1 %
Temperature and low irradiance:	-7.6 %
Total loss:	-21.9 %
PV electricity cost:	0.132 per kWh

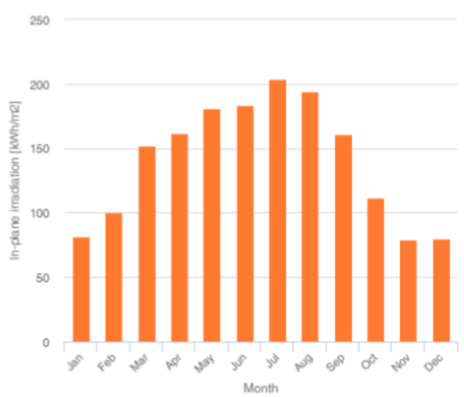
Outline of horizon at chosen location:

Figure 55 – PVGIS website, visualizing the results

Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	69.5	82	7.83
February	83.5	100	13
March	123	152	14.9
April	126	162	16.6
May	139	181	11.4
June	138	184	10.2
July	151	204	11.1
August	144	194	10
September	123	161	9.14
October	89.8	112	14.4
November	65.4	78.9	13.9
December	68.4	80.1	11.1

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Figure 58 – PVGIS website, visualizing the results

4. Energy Consumption (Electricity)

In this section, we want to estimate the energy consumption in each building. To do so in this exercise, we calculate the energy consumption by considering the number of families in each building and the average consumption of each family in a year, consequently, we can estimate the consumption for each building in a year.

Important Note: In this exercise, we calculate the energy production for all buildings without considering their usage (Residential, commercial, industrial, …). However, for energy consumption, we focus solely on residential buildings and exclude other types. By comparing energy production and consumption for residential buildings, we can analyze whether the energy needs of these buildings are met by their own production. In either scenario, we can plan for the creation of energy communities that facilitate the sharing of energy produced for other sectors.

$$E_{el} = E_{el,pro\ family} \cdot Number\ of\ families.$$

E_{el} = Energy consumption in a building (**kWh/year**)
$E_{el,\ pro\ family}$ = Average energy consumption of a family in a year (**kWh/year**)

1 family consumption (kWh/year)	Amount
Portland, Oregon[24]	~2900 kWh/year
Italy[25]	2000-2700 kWh/year

Table 9 – Annual electrical consumption for appliances in households in Portland and in Italy

[24] https://jacobsheating.com/blog/portland-oregon-home-energy-statistics/ and https://www.eia.gov/consumption/residential/index.php

[25] https://www.arera.it/dati-e-statistiche

4.1. Correction of buildings' database: filtering non-heated buildings

Consumption calculations will only be performed for buildings designated as "Residential." However, the current buildings layer includes all building types, so we need to temporarily exclude non-residential buildings. There are several methods to exclude these buildings, but it is recommended to use the **"filter"** function in QGIS for this purpose.

To do so, first make sure that the "**toggle editing**" is off, then right-click on the building's layer. Select "**properties**" → select "**Source**" → then under the "**Provider Feature Filter**" select "**Query Builder**" → In the opened window you can see the fields, simply double click on the field that contains buildings' usage (For Turin it's "usage") then put the "=" sign, select the "**sample**" bottom and double click on the "Residential" (you can also copy paste the code below and put it into the box) → click **ok** → to check if everything is correct, you shouldn't have any building that is not residential

Turin:

```
"usage" = 'Residential'
```

Portland:

```
"usage" = 'Multi family residence'
or "usage" = 'Multi used residence'
or "usage"  =  'Single family
residence'
```

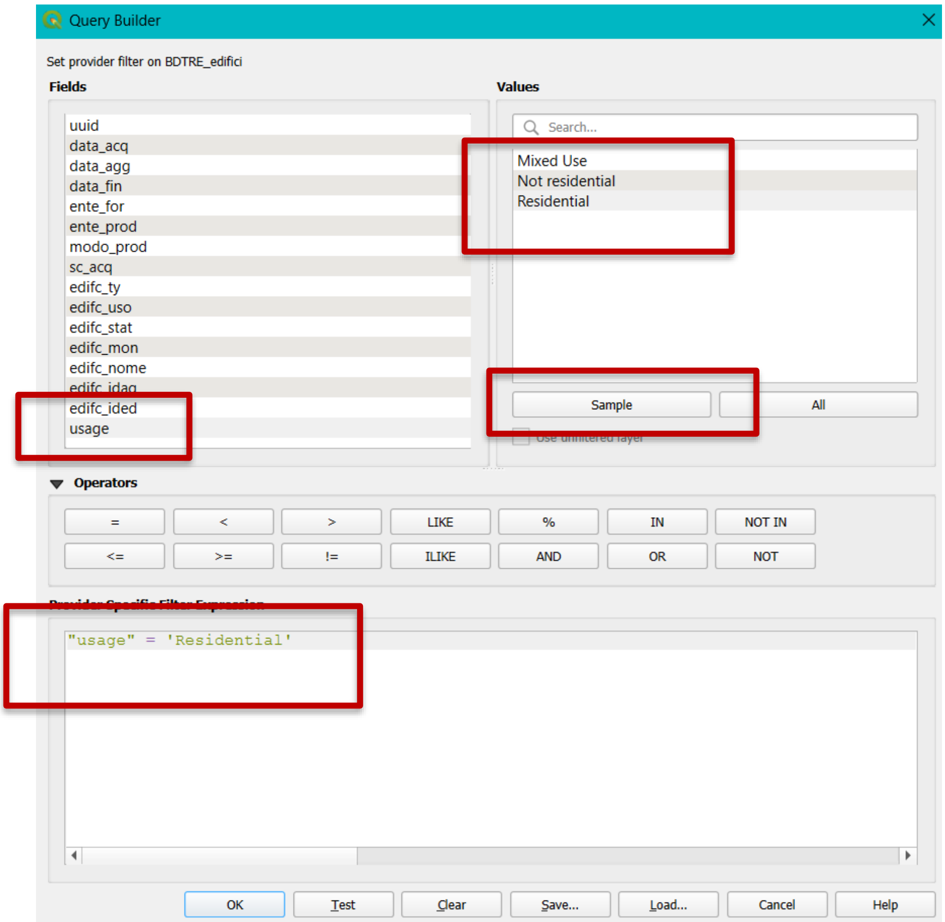


Figure 59 – Filtering the features based on the attribute

Moreover, among the residential buildings, also the ones below 40-50 m² or under 3 m height should be deleted. This is mostly because, though they are categorized as residential, but they are mostly used as "garages" or, in the case of heights, anomalies.

To do so, open the attributes table of the buildings layer, open "**Select features using an expression**" → write the expression (indicated below) → click on **"Select features"** → delete

For Turin:	"area_sqm" < 40 or "un_vol_av" <3
For Portland:	"area_sqm" < 40 or "AVG_HEIGHT" <3

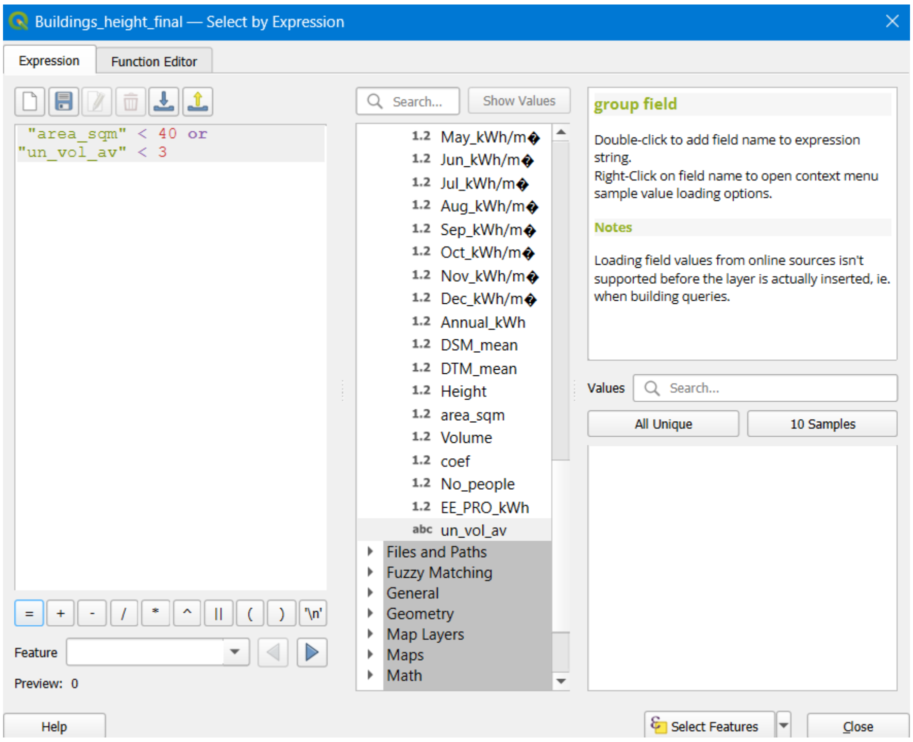


Figure 60 – Selecting features by expression in QGIS

4.2. Calculation of electrical consumption in Turin

Data	Source
Area of each building	Calculating in QGIS
Height of each building	DTM[26] and DSM
Population in a block	ISTAT[27]
Avg family size	ISTAT[28]

Table 10 – Table of inputs for calculation of consumption at building level in Turin

In Italy, the Istituto Nazionale di Statistica[29] (ISTAT) provides statistical data that we can use to determine the number of families in each building. It is important to note that ISTAT offers information on the population at the block level, rather than for individual buildings. To address this issue, we calculate a coefficient that reflects the number of people per cubic meter (m^3) in each block, using the population data for the block and the total volume of buildings within it. Finally, we can multiply this coefficient by the volume of each building to estimate the population inside that building.

$$NO.People\ in\ a\ building\ = \frac{No.people\ in\ a\ census\ block}{total\ volume\ of\ \ buildings\ in\ that\ block} \times volume\ of\ that\ building$$

$Avg.size\ of\ a\ family\ in\ Italy\ =\ 2.3$ inhabitants/family

Important Note: Remember, by saying buildings, we only mean "residential buildings".

4.2.1. How to prepare the number of people in a census block

To download the census data, open the ISTAT web page, then under the "Territorial bases - final data (1991-2021)" download the zip file for Piedmont (2021), then under the "Census variables (1991-2021)" download zip file for "Population and Housing Census (xls-csv)". Then extract them and put them in a proper folder.

[26] https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:3ffe6b7b-9abe-4459-8305-e444e8eb197c

[27] https://www.istat.it/notizia/basi-territoriali-e-variabili-censuarie/

[28] ISTAT (Italian National Institute of Statistics), *Households and Population Projections 2020–2040* (Rome: ISTAT, November 2021), https://www.istat.it/wp-content/uploads/2021/11/Households-and-population-projections.pdf.

[29] https://www.istat.it/

Now, open the "R01_21", then "SHP", and import it into your project in QGIS. This shapefile contains polygons that display the census "Blocks". If you check the attribute table of this shapefile, it does not contain the census data, it is because the census data is inside the other folder you downloaded. Open the "Dati_regionali_2021" folder. This folder has some Excel files, among them the file with the name "R01_indicatori_2021_sezioni" contains information for the Piedmont Region. Now let's import the CSV file into QGIS. To do so, simply drag and drop it into your project.

Now we have a polygon that contains blocks, and a table that contains information. We need to connect them, if you check the **attribute table** of the blocks and table of population data, you will find a mutual column with the name of "**SEZ21_ID**", this column contains unique id for each block, with the help of this column we will join the shapefile with the table as indicated in the following instruction:

Right click on "R01_21_WGS84" and select **properties**, then select "**Joins**" → in the new opened window click on ✚ and for join layer select "table R01_indicatori_2021_sezioni_R01" and then for both "**Join field**" and "**Target field**" select "**SEZ21_id**" and then under the "**Joined fields**" select "**P1**" and "**PF1**" then for "**custom field name prefix**" just remove the predefined text, then ok → it may take some seconds to be implemented.

Now, if you check the polygon that contains blocks, in the attribute table, you can find two new columns "**P1**" and "**PF1**" which contain population in that block. You can modify the symbology of the census polygon to just keep only the stroke to see the border of blocks.

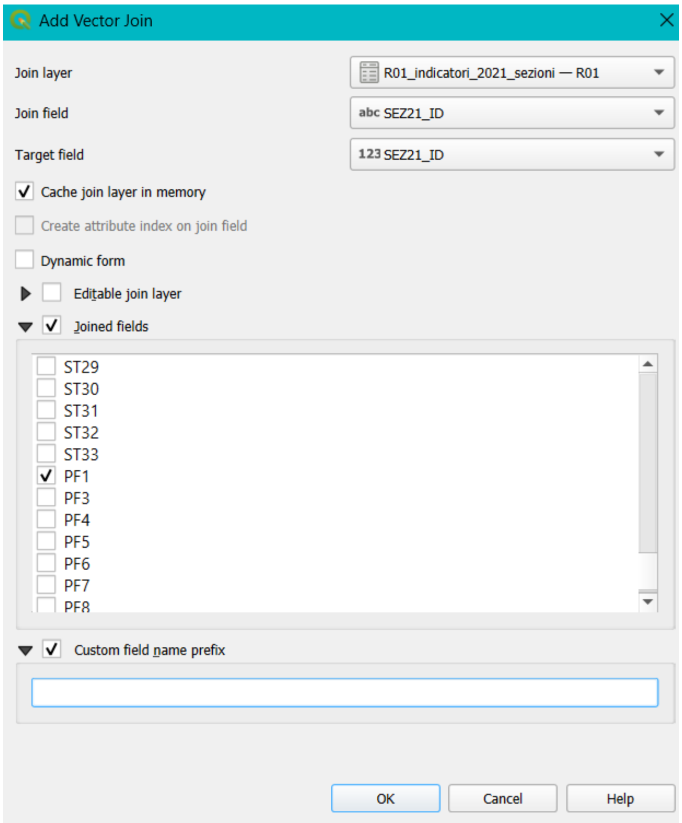


Figure 61 – Join tables in QGIS

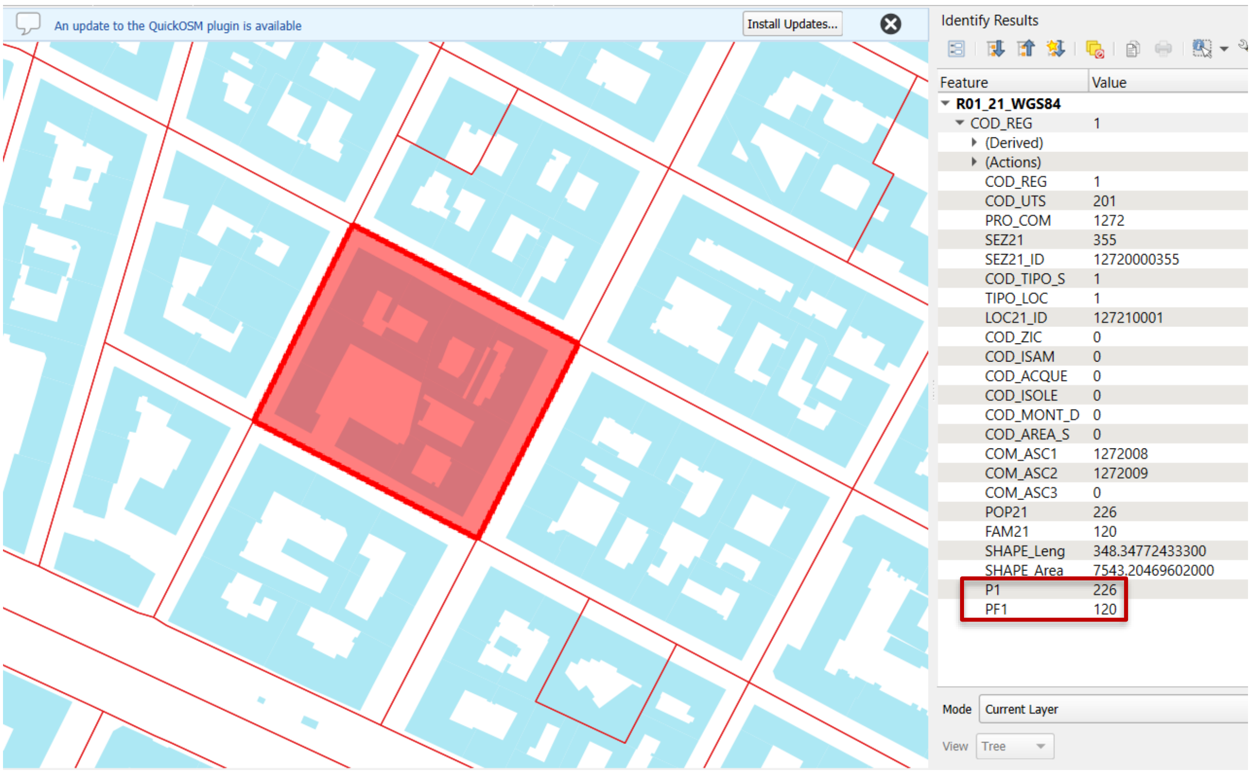


Figure 62 – The census blocks in QGIS

4.2.2. How to calculate the volume of buildings in Turin

$$Volume\ (m^3) = Area\ (m^2) \times Height\ (m)$$

In the attribute table of the shapefile of the buildings of Turin, there is a column named as "**un_vol_av**" that contains the value of the height of the buildings.

Note: It is crucial to calculate the volume only based on the "Residential buildings".

Note: If we don't have information about height in the attribute table. We can calculate the height of the buildings by subtracting a Digital Surface Model (DSM) from the Digital Terrain Model (DTM) raster file.

Now, by having the height of the buildings, we can calculate the volume of all buildings. To do so, create a **new column** and name it "Volume" → in the expression type "area_sqm" * "height" → press **ok**

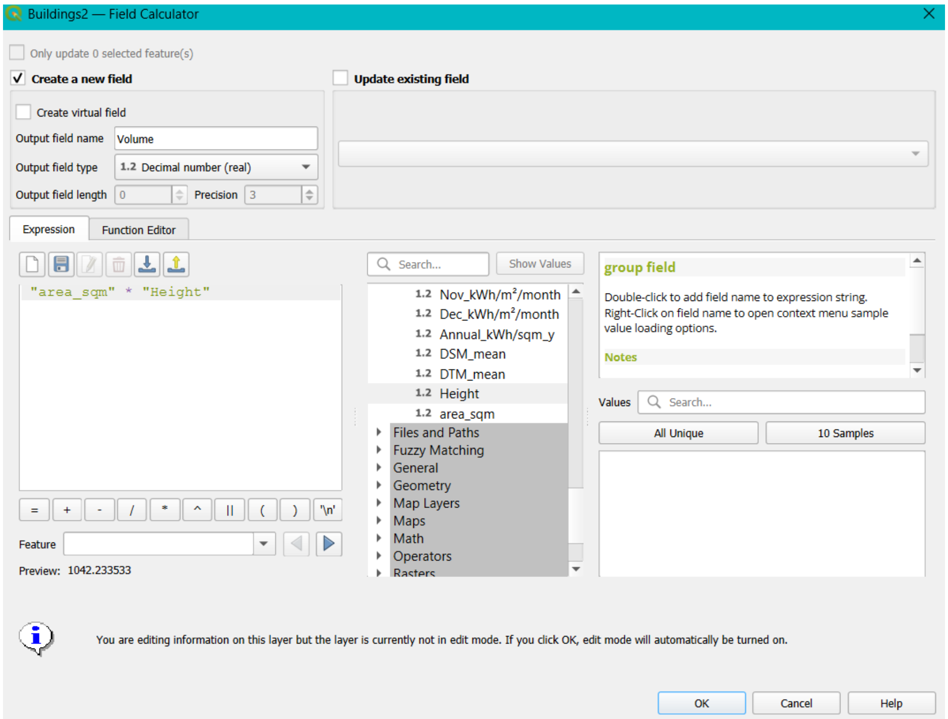


Figure 63 –Calculating the volume [m³] for each building in QGIS

In this step, we want to assign the total volume of buildings inside each census block. As mentioned before, we want to calculate a coefficient resulting from (Total number of people in a block / total volume in a block), which gives us a coefficient for each m³.

From above **toolbar** menu select **processing** → search for **join attributes by location (summary)** → for "**Join to feature in**" select the census layer, where the features are

"**Contain**" by comparing to "Buildings" → For "**fields to summarize"** only select the "**Volume**" field and for summarize to calculate only select "**sum**" → **run**

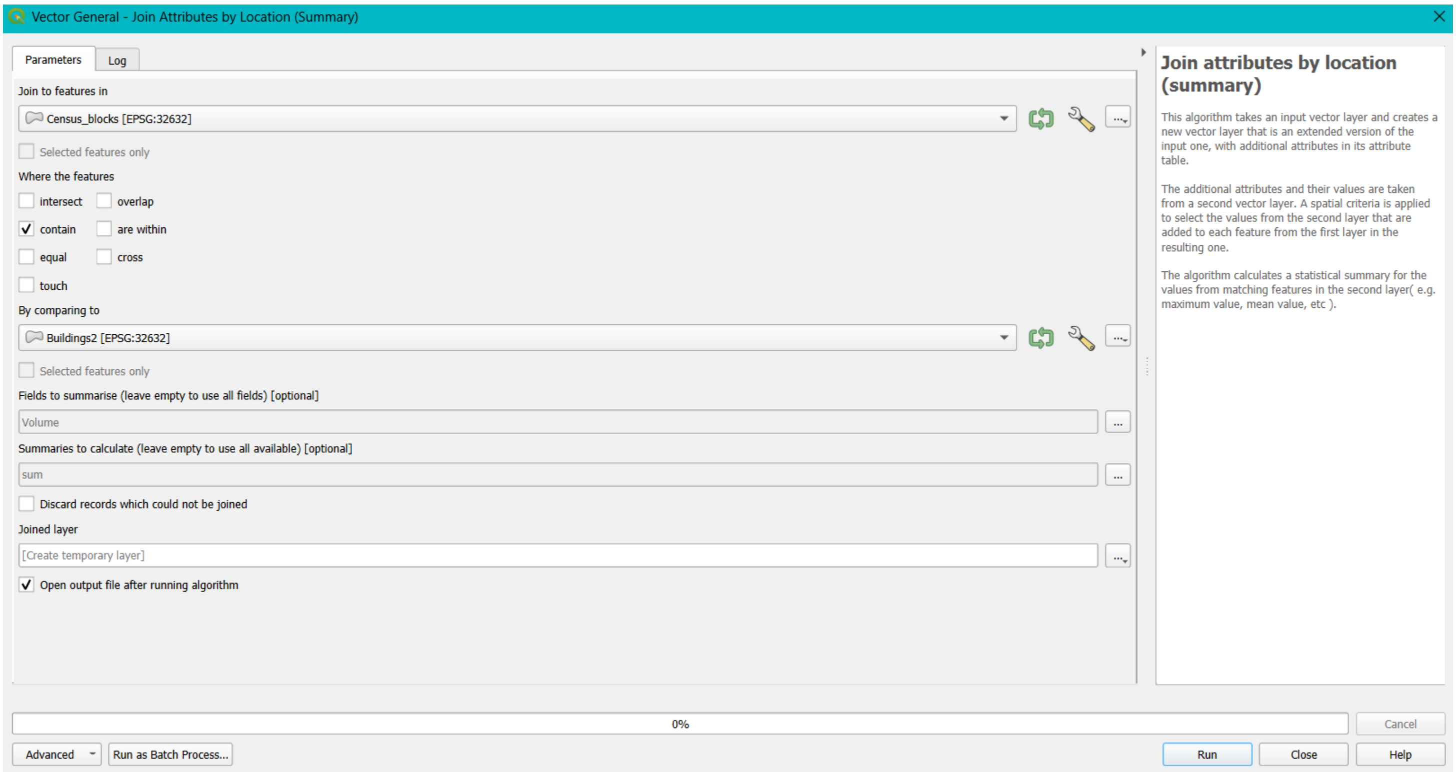


Figure 64 – Calculating the volume [m³] for each building in QGIS

Then, we need to calculate the population coefficient → create a **new field** and name it "coef" → select the format field as **decimal** and in the **expression,** type → "PF1" / "Volume_sum" → **run**

Now we need to assign the calculated coefficient in the census layer to all of our buildings, we need again to use **processing tool** this time we use join attribute table by location (**NOT SUMMARY**) → For "**join to feature in**" select buildings, for "**geometric predict**" use "**are within**", "**by comparing to**" select "**census**" that contains coeff → **run**

Finally, in the produced layer, open the attribute table and create a **new field** and name it "n_families" and calculate it by "coeff" * "Volume"

Volume	coef	No_people
1042.233533	0.003	3.127
4275.266125	0.003	12.826
536.268005	0.003	1.609
599.700704	0.002	1.199
1762.68246600...	0.002	3.525
2236.80016799...	0.003	6.71
2340.877118	0.007	16.386
2592.834703	0.002	5.186
1349.801721	0.002	2.7
603.534875	0.003	1.811
5867.218334	0.002	11.734
367.813173	0.003	1.103
2844.06960000...	0.002	5.688

Figure 65 – Calculating the number of people based on volume and volume coefficient

Note: There are still some buildings that, though they are categorized as "Residential," lack "coeff" value in "Census". This anomaly is small and negligible.

4.1.3 How to calculate electrical consumption in Turin

Now we can calculate the consumption easily, by knowing that each family is 2.3 on average, and per family, the yearly consumption is 2700 kWh/year. Simply, we should create a new column and name it Cons_kWh/year, and it is calculated by No_people * 2700.

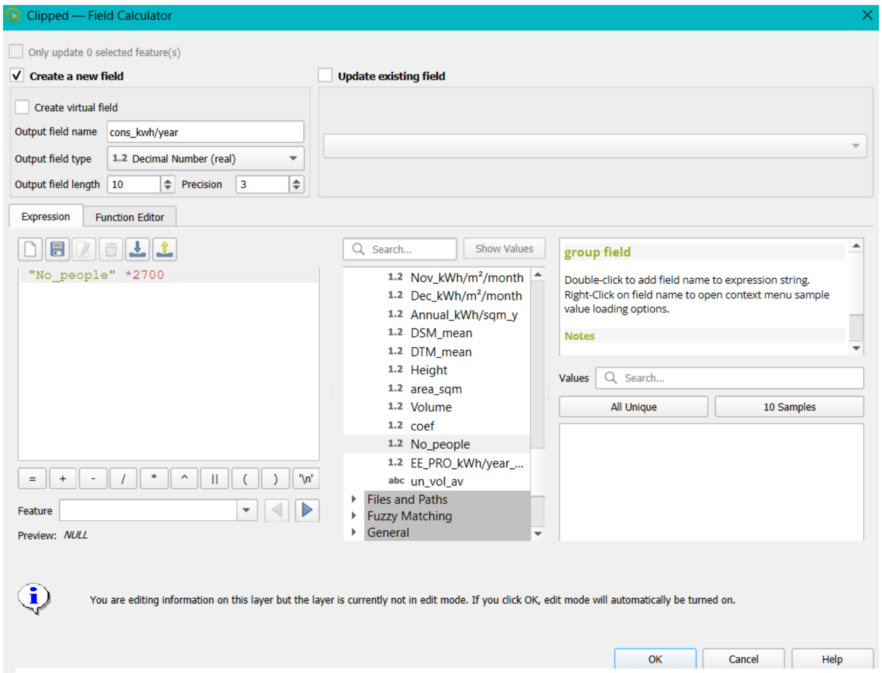


Figure 66 – Calculation of yearly thermal consumption in Turin

*Figure 67 – Calculating the energy consumption for each building **[kWh/year]***

4.2. Calculation of electrical consumption in Portland

As mentioned before, the average consumption can be calculated by multiplying the number of people in each building by the average consumption of a family.

If you examine the attribute table of buildings in Portland, you will find information about the building's usage (as we previously corrected), average height, number of floors, and more. However, there is no information available regarding the number of families in Portland. To estimate the number of people, we will use the building area and building usage as a basis for our calculations.

$$If\ usage = SFR \rightarrow No.family = 1$$

(SFR is 'Single residence family')

$$If\ usage = MUR \rightarrow No.family = \frac{Area * (No.story - 1)}{130}$$

(MUR is 'Multi used residence')

$$If\ usage = MFR\ and\ area > 130 \rightarrow\ No.family = \frac{Area * No.story}{130}$$

(MFR is 'Multi family residence')

$$If\ usage = MFR\ and\ area < 130 \rightarrow No.family = 1$$

$$If\ usage\ \neq MUR\ or\ SFR\ or\ MFR \rightarrow No.family = 0$$

```
CASE
   WHEN "usage" = 'Single residence family' THEN 1
   WHEN "usage" = 'Multi used residence' THEN ("area_sqm" *
("NUM_STORY" - 1)) / 130
   WHEN "usage" = 'Multi family residence' AND "area_sqm" >
130 THEN ("area_sqm" * "NUM_STORY") / 130
   WHEN "usage" = 'Multi family residence' AND "area_sqm" <
130 THEN 1
   ELSE NULL
END
```

Now, by having the number of families in each building, we can create a new field, name it as "cons_kWh/year" and calculate the electrical consumption by Number of families * 2900 (kWh/year/family).

4.3. Planning for energy communities

In this analysis, energy production is calculated by considering all buildings, including residential, commercial, industrial, and others. In contrast, energy consumption is assessed only for residential buildings. This approach allows us to evaluate the current situation in each neighborhood by comparing local production with residential consumption. By identifying neighborhood with energy deficits or surpluses, we can pinpoint where self-production falls short or where overproduction occurs.

By exploiting the potential of energy production with photovoltaic technology, we can also share the excess production on one building roof with another building that is part of the same **renewable energy community**. This increases self-consumption and therefore the self-sufficiency of the two buildings. If the sharing of over production involves an entire neighborhood, as a renewable energy community, they can exploit better the potential of energy sharing.
This evaluation must be made instantly with respect to energy produced, consumed, self-consumed, and shared.
In this exercise, the assessments can be done monthly to account for the seasonality of energy production with solar technologies.

5. Economic Analysis (PV-electricity)

In this step, we want to examine the economic point of view regarding the implementation of PV technology for producing electricity for residential needs. Here's the table for acronyms used in this analysis.

Acronym	Expanded Form
$Cost_{inv,PV}$	Investment Cost related to PV panels
CB	Energy cost before using PV panels
CA	Energy cost after using PV panels
ES	Economic savings
SPT	Simple payback time

Table 11 – List of acronyms used in economic analysis

5.1. Investment cost ($Cost_{inv,PV}$) or cost of installation of PV panels

The investment costs depend on the power of the PV systems (C_{PV} can be estimated with 1800 [€/kWp] for roof-integrated systems):

$$Cost_{inv,PV} = Cost_{PV} \cdot P_p \quad [€]$$

and the potential PV power is:

$$P_p = \frac{A_C}{5-8} [kW]$$

where:

Pp in kW_p $[kW]$: is the peak/nominal power of the PV system installed. Is the maximum power a PV system can produce under STC; generally, $1\ kW_p$ of a monocrystalline or polycrystalline silicon with efficiency of 18-24% corresponds to about to $5-8\ m^2$).

A_C $[m^2]$: is the active collector area; we can be assumed as 30-40% of the roof's surface (to evaluate only the well-oriented part of the roof without obstacles).

For this exercise, to calculate the installation cost, we use a relative expense based on the power installed $\mathbf{P_p}$:

if P_p>20 kW: 1000 €/kW; if 6≤P_p≤20 kW: 1500-1600 €/kW and if P_p<6 kW: 1800-2000 €/kW[30]

It means that based on the efficiency you chose (η), the area needed for 1 kWp is between 5-8 m², consequently, if you divide the total roof area dedicated to PV panels by the area needed for 1 kWp you can calculate the peak power that is possible to install Pp.

[30] https://www.iieta.org/journals/ijht/paper/10.18280/ijht.390101

If a building has Pp > 20 kW, then for each kW we pay 1000 €
If a building has 6 ≤ Pp ≤ 20 kW for each kW we pay 1500-1600 €
If a building has Pp < 6 kW, for each kW we pay 1800-2000 €

Note: On average, you can assume that for 1 kWp we need ~7 m², so we need to divide the total surface of PV panels for each building by 7:

("area_sqm" *0.35)/7

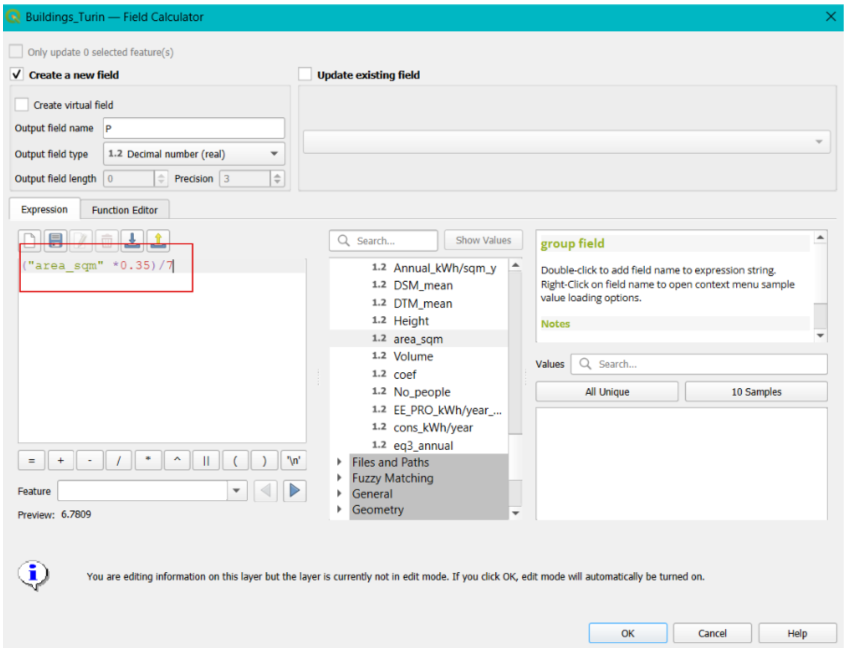


Figure 68 – Calculating Pp

```
CASE
   WHEN "Pp" > 20 THEN "Pp" * 1000
   WHEN "Pp" BETWEEN 6 AND 20 THEN "Pp" * 1500
   WHEN "Pp" < 6 THEN "Pp" * 1800
END
```

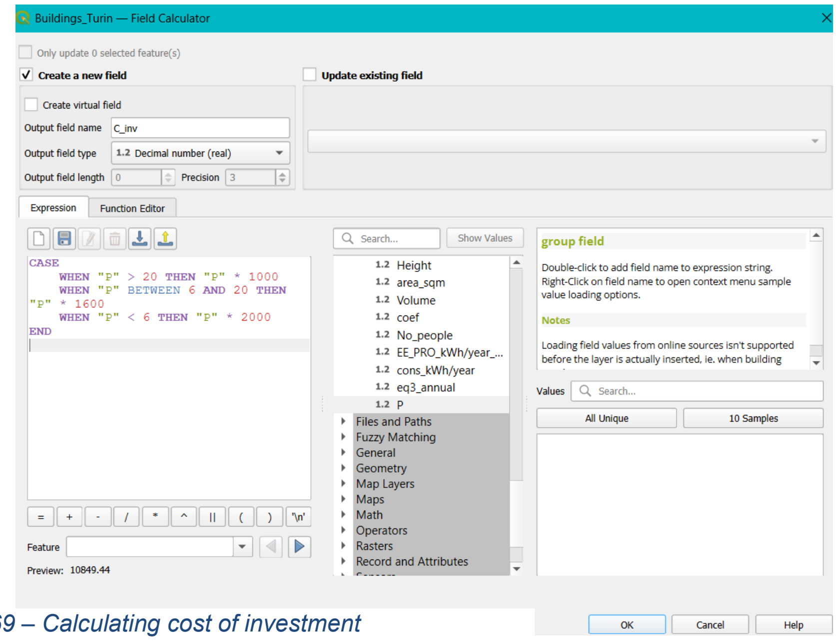


Figure 69 – Calculating cost of investment

5.2. Consumption cost, economic savings, and revenue (Electricity)

Consumption cost (€) refers to the cost of Electrical Energy withdrawn from the network. This cost, based on the location and city, is different. For Italy, from the ARERA[31] you can obtain the cost of electricity for each kWh. In this exercise, the price of electricity withdrawn from the network for ***Turin*** is ***0.29 €/kWh,*** *and for* ***Portland***[32] *is* ***0.20 €/kWh.***

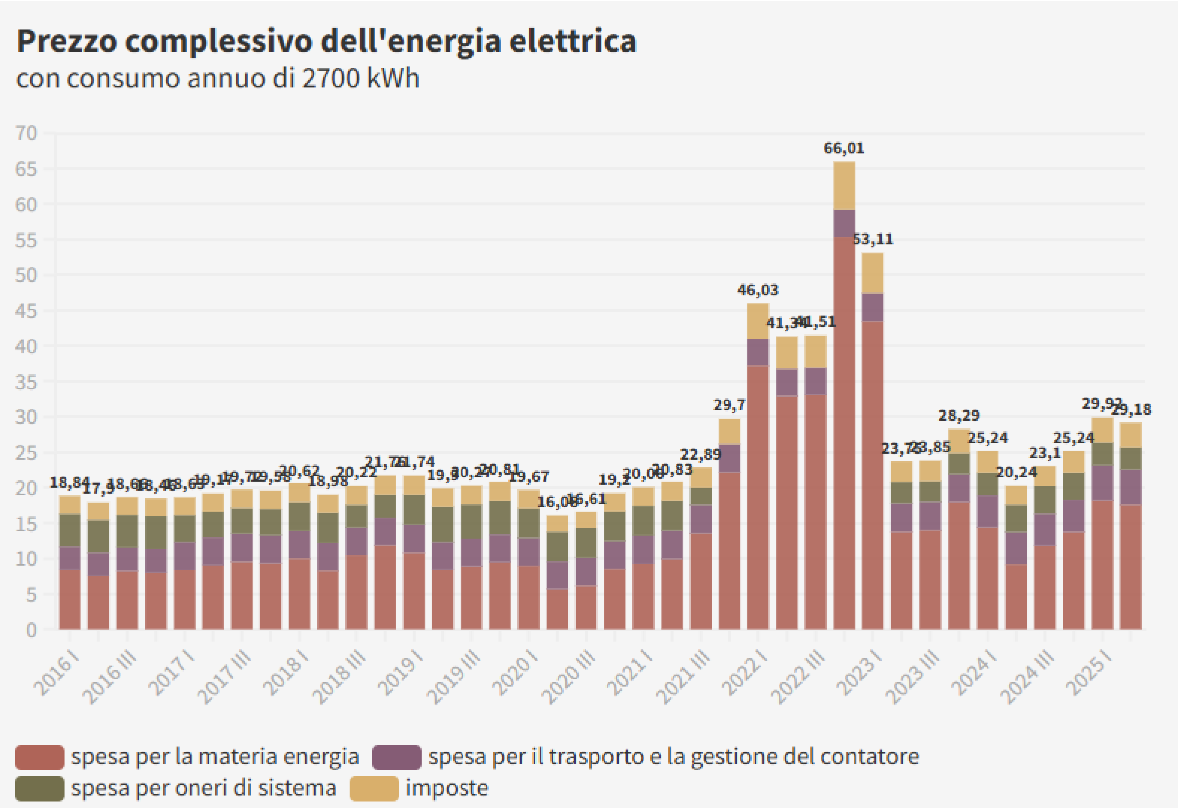


*Figure 70 – Electricity price with 2700 **kWh** annual consumption in Turin*

We previously calculated the consumption (**kWh/year**) for Turin and Portland, now, just by considering that each kWh costs 0.29 €, we can reach the cost of consumption.
Note: This cost is assumed to be the cost without own electricity production by PV panels, in other words, it is the Cost Before (CB) PV panels interventions.

To do so, open the attribute table of your buildings. Create a new column and name it CB_euro, and in the expression, put the code for calculating the consumption cost.

$$Consumption\ Cost\ (CB) = Consumption\ \left[\frac{kWh}{year}\right] * 0.29\ [\frac{€}{kWh}]$$

Note: The mentioned cost (0.29 euro/kWh) is for Turin.

[31] https://www.arera.it/dati-e-statistiche
[32] https://www.energysage.com/local-data/electricity-cost/or/washington-county/portland/#:~:text=monthly%20electric%20bill-,Electric%20bills%20in%20Portland%2C%20OR,renewable%20energy%20and%20energy%20efficiency.

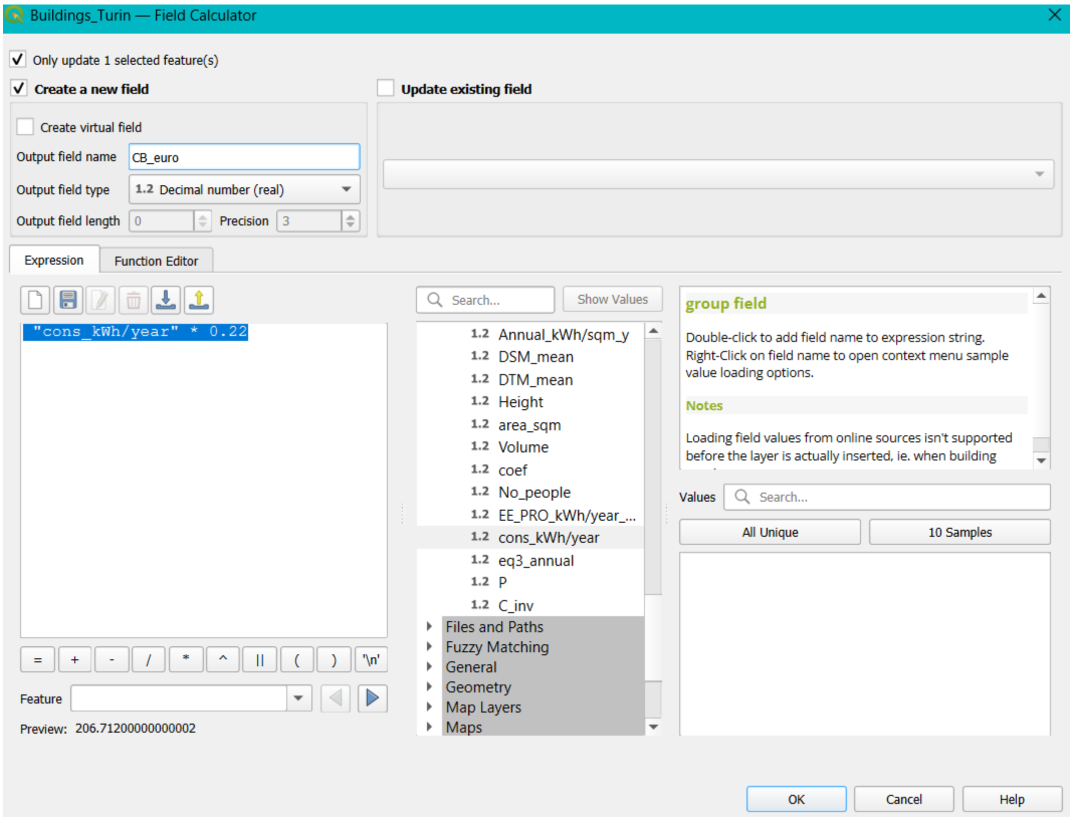
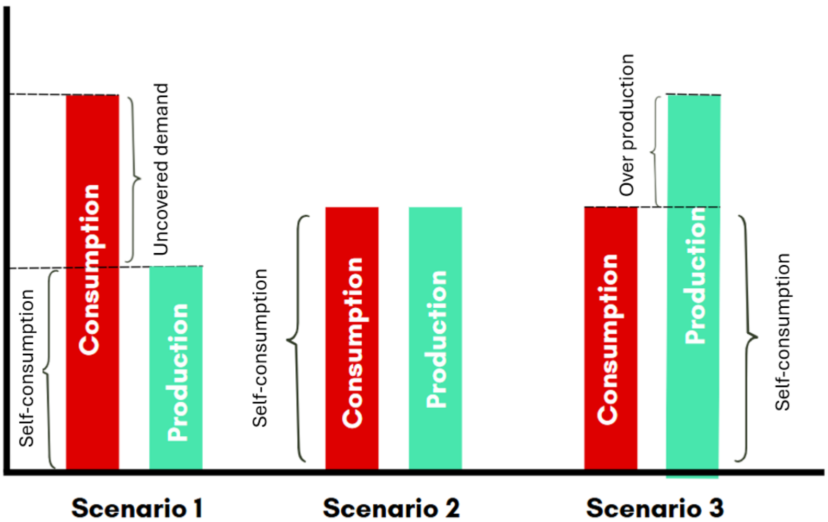


Figure 71 – Calculating the cost of consumption before intervention

5.2.1. How to calculate the Consumption Cost After PV panels interventions, Economic Savings and Revenue

It is quite important that after the installation of PV panels and starting to produce your electricity, 3 different scenarios may happen:



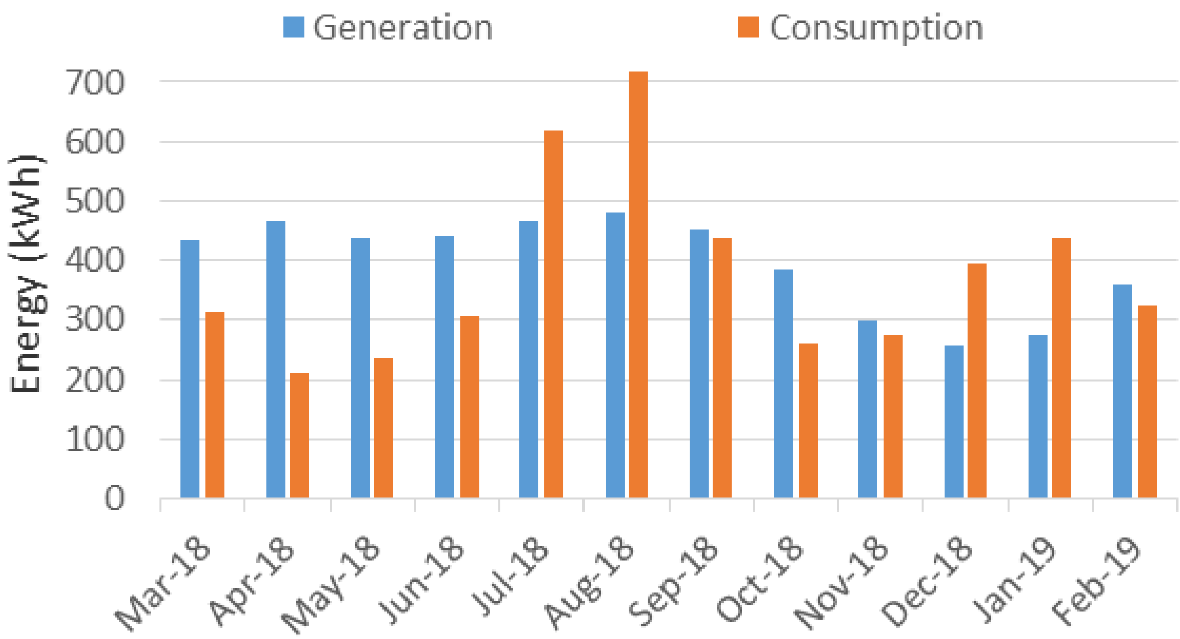


Figure 73 – Production and consumption values during the year

Economic Savings refers to the amount of money that we save instead of spending on taking energy from the network after implementing the PV panels interventions.

For instance, if we used to pay 1,000 euros for electricity annually before installing PV panels, and after the installation, our bill dropped to 600 euros per year, we are therefore saving 400 euros by generating our energy.
Note: When our production is more than our needs, we can sell the over-produced energy to the network. The Cost of Electrical Energy injected into the network is **0.10 €/kWh[33].** This is called Revenue.

Scenario 1:

Part of the electricity you need is produced by PV panels, but it doesn't fully cover your needs. In this scenario, you only have to pay for the electricity that you take from the network, in other words:

$$Self - consumption\ SC = min(Consumption; Production)[kWh]$$

$$Economic\ Savings\ (ES)\ [€] = Self - consumption\ [kWh] \times\ 0.29[€/kWh]$$
$$Revenue = 0$$

[33] https://www.gse.it/servizi-per-te/fotovoltaico/ritiro-dedicato/documenti

Scenario 2:

When you produce as much as you consume then your Consumption Cost is zero.

$$Economic\ Savings\ \ [€] = Self - consumption\ [kWh] \times\ 0.29[€/kWh]$$
$$Revenue = 0$$

Scenario 3:

When you produce more than you need. In this case, you cover all of your consumption costs, and you can also sell your surplus production to the network.

$$Economic\ Savings\ [€] = Self - consumption\ [kWh] \times\ 0.29 + Revenue\ [€/kWh]\ .$$
$$Revenue\ [€] = Over - production\ [kWh] \times 0.10\ [€/\mathrm{kWh}]$$

5.2.2. How to implement CA, ES, Revenue for 3 scenarios in QGIS

CA: By using **"field calculator"** we can create a new column and name it as CA_euro. Remember, set the output field type as "decimal".

```
CASE
   WHEN "cons_kWh/year" > "EE_PRO_kWh/year"
      THEN ("cons_kWh/year" - "EE_PRO_kWh/year") * 0.29
   WHEN "cons_kWh/year" <= "EE_PRO_kWh/year"
      THEN 0
END
```

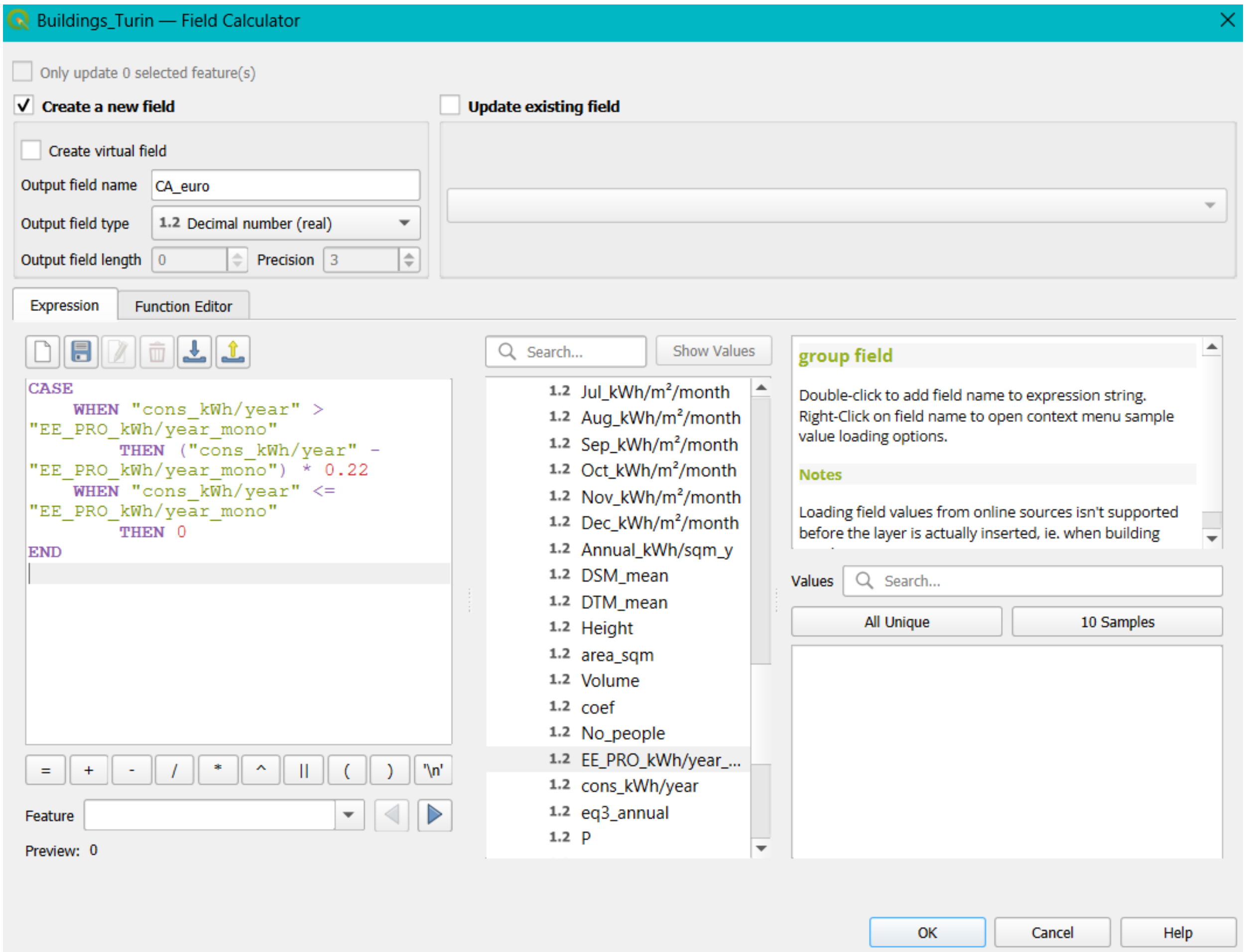


Figure 74

ES + Revenue: By using the **field calculator**, create a new field and name is ES_euro. Remember that change the output field type to decimal. (Here we put the revenue as part of economic savings.)

```
CASE
        WHEN  "cons_kWh/year" > "EE_PRO_kWh/year" THEN
"EE_PRO_kWh/year" * 0.29
        WHEN  "cons_kWh/year" = "EE_PRO_kWh/year" THEN
"EE_PRO_kWh/year" *0.29
        WHEN  "cons_kWh/year" < "EE_PRO_kWh/year" THEN
"cons_kWh/year" *0.29 + ( "EE_PRO_kWh/year" - "cons_kWh/year" )*0.1
        END
```

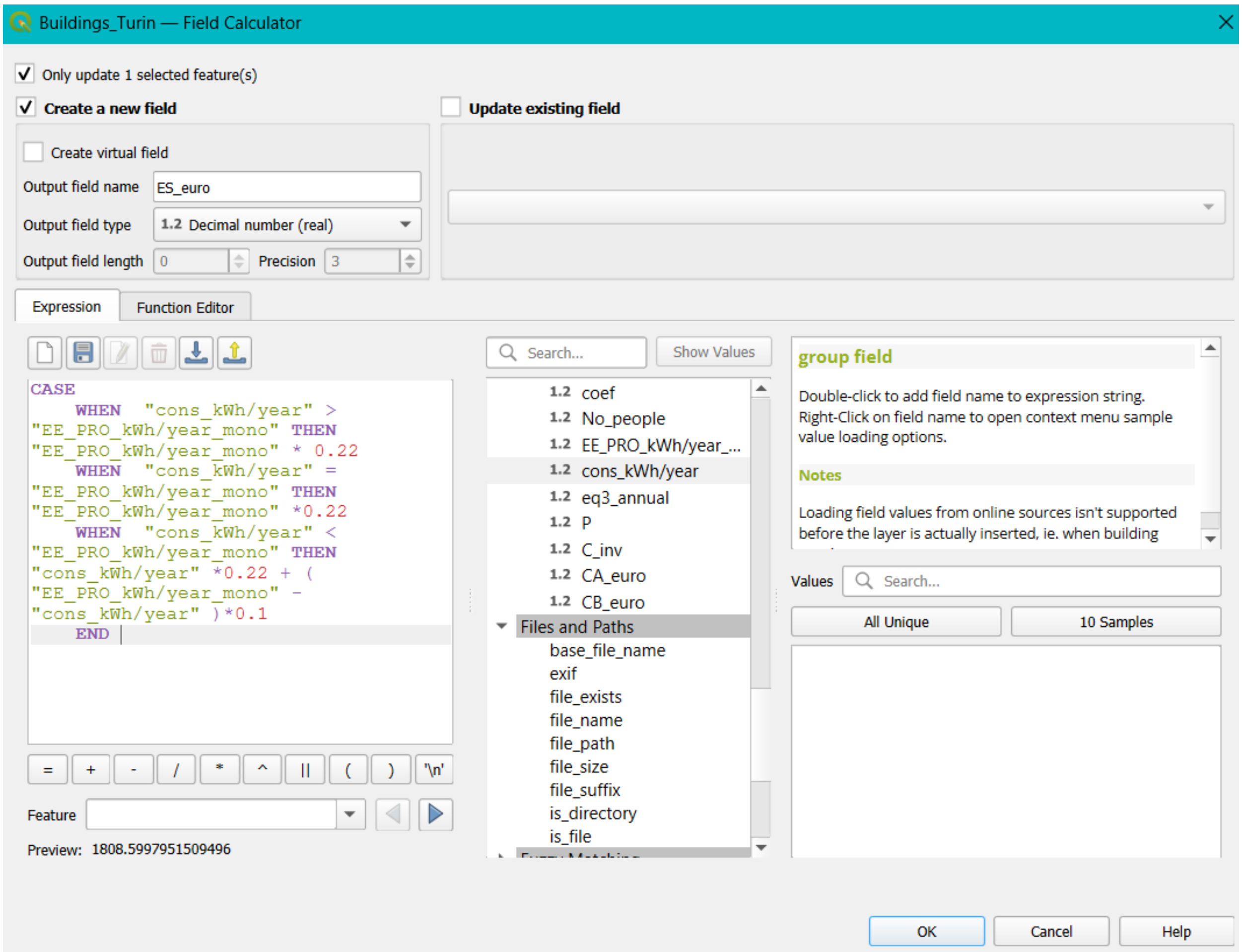


Figure 75 – Calculation of economic savings in QGIS

5.3. Calculation of Simple Payback Time (SPT):

The single payback time refers to the duration (in years) it takes for our investments to generate economic savings that equal the initial investment. For example, if we spend 20,000 euros to install photovoltaic (PV) panels and save 5,000 euros annually due to our own energy production, it will take 4 years for the investment amount to be fully recovered.

$$SPT\ [year] = \frac{Cost_{inv,PV}\ [€]}{Economic\ Savings\ [€/year]}$$

5.3.1. How to do it in QGIS

By using the field calculator, create a new field, name it SPT, and select the output field type as decimal.

```
"Cost_inv" / "ES_euro"
```

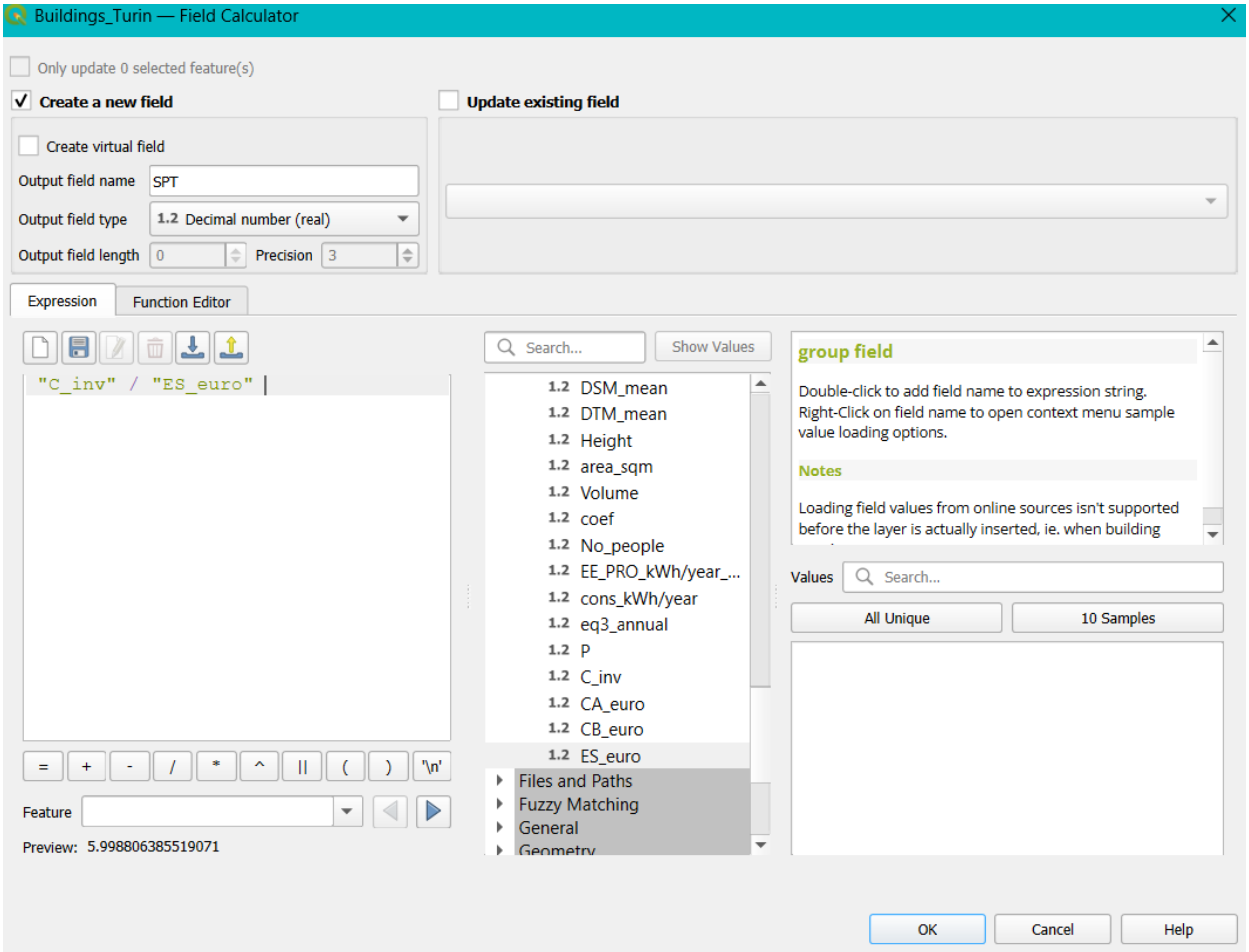


Figure 76 – Calculation of SPT in QGIS

6. Calculation of Solar Thermal Potential

While we previously analyzed and estimated producing electrical energy from solar irradiation, we can also produce thermal energy from solar irradiation. This simulation process aims to evaluate the energetic performance of a **Solar Thermal Collector (STC)** used to produce **domestic hot water** (DHW).

Nowadays, in developing countries, the increase in electricity access and in the energy consumption through distributed energy solutions leads to the search energy energy-saving strategies. For this reason, Solar Thermal Systems have been widely developed to improve their performance and deployment. Due to the low cost, easy operation, and minimal need for maintenance, STS has been widely installed in buildings, they can provide the production of DHW and supply space heating/cooling.

6.1. How does STC work?

STS consists of different components. **Solar collectors** are the key component of active solar-heating systems because they gather the sun's energy, transform its radiation into thermal energy, and then transfer this heat to a thermo-vector fluid (in this case, water).

As shown in the next figure, the performance of a solar collector can be evaluated by applying an energy balance that defines the amount of incident solar energy (Qs) converted into useful heat (Qu) transferred to the fluid carrier.

$$\eta_{coll,m} = \frac{Q_u}{Q_s}$$

$\eta_{(coll,m)}$ = Monthly efficiency of the system

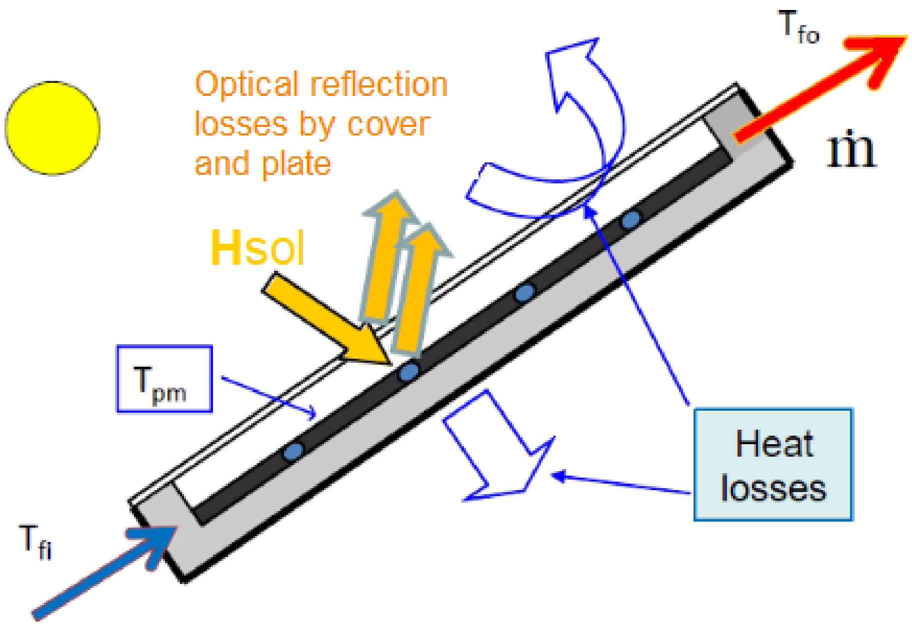


Figure 77 - Solar collector energy balance and thermal efficiency. (Source: "Engineering of Thermal Processes" Duffle & Beckman)

Considering this energy balance, it is possible to evaluate the *Solar Thermal Potential* as the **monthly useful thermal energy**, hence the fraction of the solar irradiation intensity (H_{sol}) converted into thermal energy for each month, as shown in the following equation:

$$Q_u = \mathrm{PR} \cdot A_C \cdot H_{sol} \cdot \eta_{coll,m}$$

Variable	Unit	Description
A_c	m^2	Collector gross area assumed equal to 30-40% of the surface of the roof (calculated with QGIS for each roof)
$\boldsymbol{H_{sol}}$	$\left[\frac{Wh}{m^2}\right]$	Monthly incident solar irradiation intensity (calculated with QGIS for each month on each roof)
$\boldsymbol{\eta_{coll,m}}$	-	Solar collector monthly efficiency. (Collector efficiency at different irradiances and fluid temperature differences[34]

Table 12 – Variables, units and description of Useful thermal heat production formula

The solar collector thermal efficiency is the most useful parameter in order to predict the yearly energy produced and to choose the best collector with reference to the system location and boundary conditions. In this exercise, the thermal efficiency is evaluated according to the *European Standard EN 12975-2*:

$$\eta_{coll} = \eta_o - a_1 \cdot x - a_2 \cdot I \cdot x^2 \quad (*)$$

$$x = \frac{T_m - T_a}{I} = \frac{\Delta T_m}{I} \quad \left[\frac{m^2 K}{W}\right] \rightarrow \quad \eta_{coll} = \eta_o - a_1 \cdot \frac{\Delta T_m}{I} - a_2 \cdot I \cdot \left(\frac{\Delta T_m}{I}\right)^2$$

Variable	Unit	Description
$\boldsymbol{\eta_o}$	-	optical efficiency: the fraction of the incident solar radiation energy on the glass cover which is transferred as thermal energy inside the absorber surface
$\boldsymbol{x}$	$\left[\frac{m^2K}{W}\right]$	Reduced temperature difference
$\boldsymbol{a_1}$	$\left[\frac{W}{m^2K}\right]$	Linear heat loss coefficient
$\boldsymbol{a_2}$	$\left[\frac{W}{m^2K^2}\right]$	Non-linear heat loss coefficient
$\boldsymbol{I}$	$\left[\frac{W}{m^2}\right]$	Solar irradiance that can be downloaded by PVGIS at average daily irradiance data [35] or calculated by dividing the solar irradiation by the hours of light in each month $I = \frac{Hsol}{h}$ $\mathrm{W/m^2}$

Table 13 – Variables, units, and description of the collector monthly efficiency formula

[34] https://www.volker-quaschning.de/articles/fundamentals4/index_e.php

[35] *https://re.jrc.ec.europa.eu/pvg_tools/en/#MR*

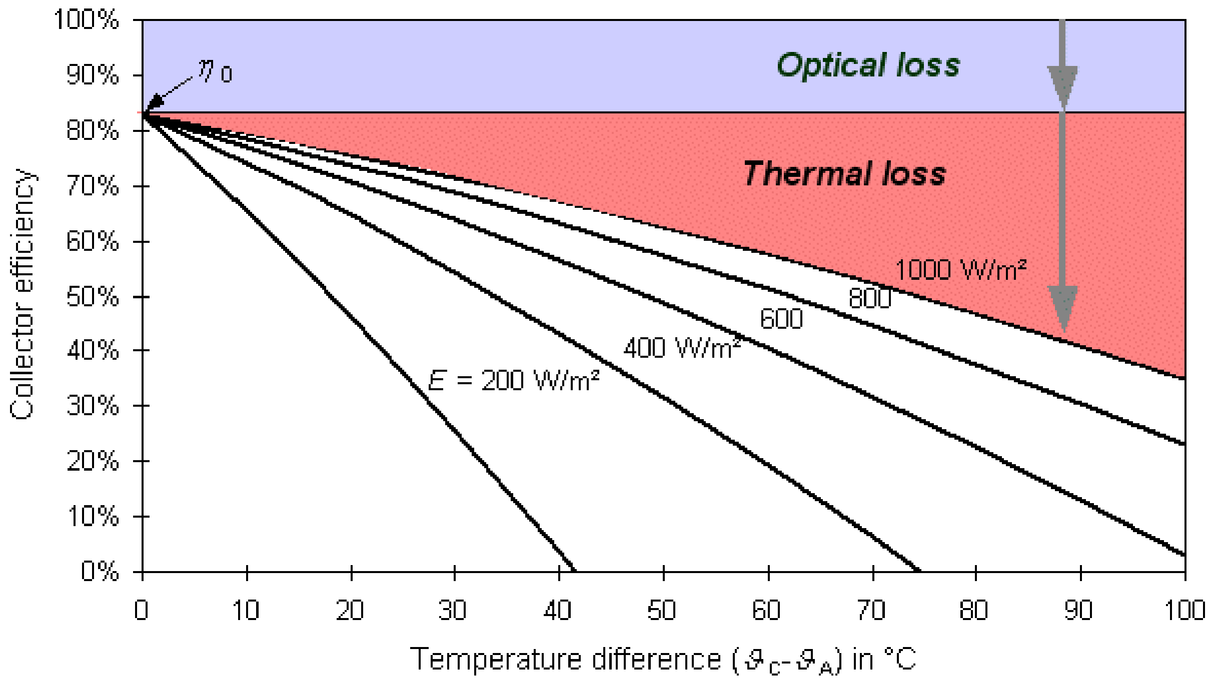


Figure 78 – Relation between collector efficiency and temperature difference

The quality of a solar collector strongly depends on η_o , a_1, a_2 coefficients.

- The *optical efficiency* $\eta_o = \tau\alpha$ includes all the optical losses during the conversion from solar radiation to thermal energy; it does not depend on the mean fluid temperature, but only on the optical properties of the collector material. For this reason, it is defined as the product of the transmission coefficient of glazing τ and the absorption coefficient of the plate α.
- The *heat loss coefficient* $a_1 \left[\frac{W}{m^2K}\right]$ is considered a thermal transmittance (same physical dimension); it permits evaluating the heat losses during conduction, convection, and infrared radiation heat transfer; it presents a linear dependency for the reduced temperature difference x. As displayed in Figure 78, this parameter is useful in order to detect the collector quality: high quality corresponding to the low value of a_1, low quality to high value of a_1. Hence, the quality of a solar collector increases by reducing the heat losses during the heat transfer.
- The non-linearity of the heat transfer at high temperature introduces the last coefficient $a_2 \left[\frac{W}{m^2K^2}\right]$ that presents a quadratic dependency with respect to x. It also permits to detect the heat losses, but with a lower order of magnitude than a_1.

To calculate the solar collectors' monthly efficiency $\eta_{coll,m}$, it is necessary to evaluate the *Reduced Temperature Difference,* defined as the temperature difference between the mean fluid temperature T_m and the external air temperature T_a divided by the global solar irradiance I:

$$x = \frac{T_m - T_a}{I} = \frac{\Delta T_m}{I} \quad \left[\frac{m^2K}{W}\right]$$

For simplicity, the mean fluid temperature can be calculated as the arithmetic average between the inlet fluid temperature ($T_{IN} = 15\,°C$) and the outlet fluid temperature ($T_{OUT} = 45\,°C$). Hence, it is a constant value:

$$T_m = \frac{T_{IN} + T_{OUT}}{2} = 30\,°C$$

The air temperature of the external environment depends on the location; therefore, it varies during the year. Its monthly average value can be derived from ARPA Piemonte[36] or PVGIS[37].

Then, after this calculation, the last parameters necessary for the $\eta_{coll,m}$ evaluation are the optical and heat loss coefficients η_o , a_1, a_2 described in the previous section. These values depend on the solar collector type, which can generally be obtained from the catalog of the company. These values can be obtained from the following links:

Notice that these two different types are different from a technological point of view, but at the same time from an economic point of view. Generally, the vacuum tube solar collector is more expensive than a flat-plate solar collector.

Finally, the useful global thermal energy required by the user can be determined by considering the summation of each useful thermal energy for each specific month:

$$E_{th,TOT} = \sum_{i=1}^{12} E_{th,i}$$

Solar Collector Type	Solar Collector Model	Absorber Area A_c	ηo	a_1	a_2
Flat-plate collector	Fototherm AS Series[38]	1.63 m²	47.2 %	7.96 W/m²·K	0.00 W/m²·K²
Evacuated Tube Collector	Beretta SCV-25[39]	2.77 m²	70 %	1.15 W/m²·K	0.011 W/m²·K²
Flat-Plate collector	VFK 140 D[40]	2.33 m²	85.5 %	2.411 W/m²·K	0.039 W/m²·K²

Table 14 – Solar Thermal collectors' information

[36] https://www.arpa.piemonte.it/dato/banca-dati-storica-dati-giornalieri-mensili

[37] https://re.jrc.ec.europa.eu/pvg_tools/en/#MR

[38] https://drive.google.com/file/d/1oT9Fd8lHOYa74u9rCZ6bcxdwXu_qWuJr/view?usp=drive_link

[39] https://drive.google.com/file/d/1hO6SdeNPkj_6zq9eh7PBbEX6psIWp3TQ/view?usp=drive_link

[40] https://drive.google.com/file/d/1cXtmeoYKz1-4g05WNrY4L1jApFzD_Tm9/view?usp=drive_link

The three parameters that are assumed constant during the calculations are the η_0, a_1, and a_2 coefficients. The monthly value $\frac{\Delta Tm}{I}$ varies for each month. For this reason, the collector efficiency is also a monthly value.

The parameters according to the UNI/TS 11300-4:2012 standard are:

Collector type	ηo	a_1 [W/m²·K]	a_2 [W/m²·K²]	IAM
Evacuated tube collectors with flat absorber	0.90	1.8	0.008	0.97
Evacuated tube collectors with circular absorber	0.90	1.8	0.008	1.00
glazed flat-plate collectors	0.78	3.5	0.015	0.94
unglazed flat-plate collectors	0.76	15	0	1.00

Table 15 – The parameters according to the UNI/TS 11300-4:2012 standard

IAM (incidence angle modifier): The transmission-absorption product of a collector is an indicator of how much of the solar radiation incident on it is transmitted from the transparent cover of the collector to the absorber below and how much of it is absorbed by the absorber and then transferred to the fluid. This product thus expresses the goodness of the optical performance of the collector.

As displayed in the following Excel sheet, all the parameters necessary to evaluate the solar collectors' efficiency are determined. In this example, we consider a high-quality (HQ) vacuum tube solar collector.

		Ta [°C]	Tm [°C]	Ore luce [h]	H [Wh/m2]	I [W/m2]	n_o	a1	a2	x [m2K/W]	x2 [m2K/W]	n_{coll}
Gennaio	31	1,4	30	257,7	26820	104,07	0,7	1,15	0,011	0,2748	0,0755	**0,2975**
Febbraio	28	2,3	30	284,48	48920	171,96	0,7	1,15	0,011	0,1611	0,0259	**0,4657**
Marzo	31	4	30	354,64	152972	431,34	0,7	1,15	0,011	0,0603	0,0036	**0,6134**
Aprile	30	8,5	30	395,1	205115	519,15	0,7	1,15	0,011	0,0414	0,0017	**0,6426**
Maggio	31	13,1	30	446,09	296910	665,58	0,7	1,15	0,011	0,0254	0,0006	**0,6661**
Giugno	30	17,6	30	456,9	304766	667,03	0,7	1,15	0,011	0,0186	0,0003	**0,6761**
Luglio	31	20,8	30	466,55	266583	571,39	0,7	1,15	0,011	0,0161	0,0003	**0,6799**
Agosto	31	20,1	30	420,36	233214	554,80	0,7	1,15	0,011	0,0178	0,0003	**0,6775**
Settembre	30	16,5	30	368,1	179594	487,89	0,7	1,15	0,011	0,0277	0,0008	**0,6641**
Ottobre	31	8,8	30	326,43	105933	324,52	0,7	1,15	0,011	0,0653	0,0043	**0,6096**
Novembre	30	4,2	30	278,1	30244	108,75	0,7	1,15	0,011	0,2372	0,0563	**0,3599**
Dicembre	31	2,2	30	260,09	19275	74,11	0,7	1,15	0,011	0,3751	0,1407	**0,1539**

Figure 79 – Collector monthly efficiency's table of variables

H [Wh/m²] is the solar irradiation value indicated for each month separately, which can be obtained from QGIS using r.sun.insoltime. Ore Luce is the total hours of sunlight monthly. For Italian cities-territories, the ratio between monthly irradiation and the number of lighting hours can be used from the ENEA solar atlas. By knowing the monthly values of the solar collectors' efficiency ($\eta_{coll,m}$) , the gross area of the solar collector (Ac [m²]), and the monthly solar irradiation (Hm [kWh/m²]), it is possible to evaluate the monthly useful thermal energy produced (Qu) using this equation:

$$Q_u = A_C \cdot H_m \cdot \eta_{coll,m} \quad [kWh]$$

Finally, the **global (annual) useful thermal energy** required by the user can be determined by considering the summation of each useful thermal energy for each specific month:

$$Q_{u,TOT} = \sum_{i=1}^{12} Q_{u,i} \quad [kWh]$$

Very Important Note: *While we initially planned to dedicate 35% of the building footprint area to installing thermal collectors, it is important to remember that, unlike electricity generated by photovoltaic (PV) panels, surplus thermal energy cannot be fed back into the grid. Any excess hot water produced becomes waste, which is neither economically efficient nor environmentally sustainable. Therefore, it is crucial to generate only as much thermal energy as is needed, to avoid overproduction, while for electricity production by PV panels, we only consider economic evaluations.*

To manage this effectively, we can focus on the months of June-July, when solar irradiation reaches its peak. If no overproduction occurs during these peak months, it is unlikely to happen during the rest of the year. To regulate thermal production based on actual demand, we must first estimate the required thermal energy. Once the need is known, we assume that the useful thermal energy produced in July (Qu_{July}) equals the consumption ($Cons_{July}$). From this assumption, we can calculate the necessary collector area (Ac).

$$Assuming: Qu, July \left[\frac{kWh}{m}\right] = Cons\ July \left[\frac{kWh}{m}\right]$$

$$Then: Cons\ July = Ac\ .H\ July.\eta_{coll,July}$$

$$Ac = \frac{Cons\ July}{H\ July * \ \eta_{coll,July}}$$

Consequently, in order to be able to estimate the potential production for the whole year, first, we should calculate the energy consumption for domestic hot water.

7. Energy Consumption for Domestic Hot Water DHW

We can calculate domestic hot water consumption based on thermal energy needs, similar to how we previously calculated electricity consumption. The daily per capita energy consumption for domestic hot water (DHW) is as follows:

$$Q_{u,d} = V \cdot \rho \cdot c_p \cdot \Delta T/\varepsilon = V \cdot \rho \cdot c_p \cdot (T_{OUT} - T_{IN})/\varepsilon$$

- $V = 50 - 70\,\frac{l}{d} = 0.05 - 0.07\ m^3/day$ is the daily volume of hot water consumed by a single person
- $\rho = 1000\ \frac{kg}{m^3}$ is the water density
- $c_p = 4.186\ \frac{kJ}{kgK}$ or 1.163*10^{-3} $\frac{kWh}{kgK}$ is the water's specific heat
- $\Delta T = (T_{OUT} - T_{IN}) = (45 - 15)°C = 30°C = 30\ K$ is the temperature difference between the outlet and inlet temperature of water through the solar collector
- ε is the efficiency of a heat exchanger (i.e., 0.9) or the heat boiler (i.e., 0.8-0.9).

The result obtained, expressed in **kWh**, is valid for **one person per day**. Therefore, this figure must be multiplied by the number of days (either for the month or the year) and by the number of inhabitants. This approach allows for the assessment of the total monthly and yearly thermal energy consumption, which is the value used for the subsequent economic analysis. At this point, all the necessary data to evaluate overall thermal and electrical consumption is available.

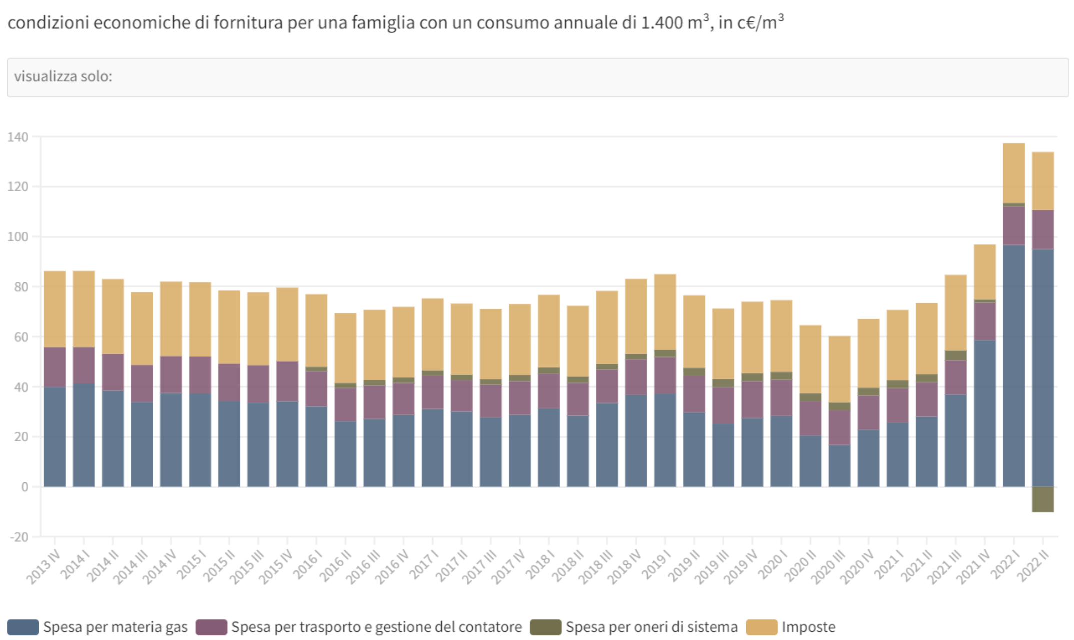


Figure 80 Economic conditions for families with annual consumption of 1,400 m³ (c€/m³) other data: https://www.consumer.bz.it/it/confronto-prezzi-combustibili-riscaldamento-alto-adige

https://sisen.mase.gov.it/dgsaie/prezzi-annuali-carburanti?pid=12

7.1. How to calculate the consumption of thermal energy in QGIS

Now, to calculate the consumption (kWh/year) per family for domestic hot water, first we open the attribute table and create a new column and name it as t_cons_kwh, then:

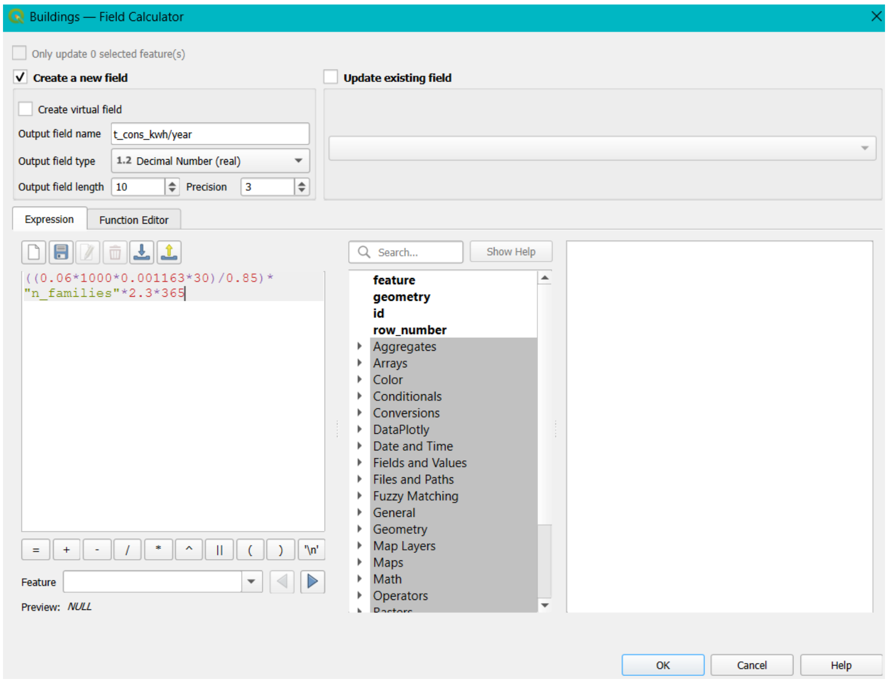


Figure 81 – Calculation of thermal consumption in QGIS

(0.06*1000*0.001163*30)/0.85* "n_families"*2.3*365

7.2. Finishing the calculation of potential solar thermal energy production

By estimating our consumption, we can calculate the area (Ac [m²]) needed for installing thermal collectors to produce the required amount of energy in July. As previously mentioned, we aim to produce exactly what we need for that month to avoid overproduction. July was chosen for this calculation because it has peak solar irradiation. By ensuring we do not overproduce in July, we can effectively prevent overproduction for the entire year.

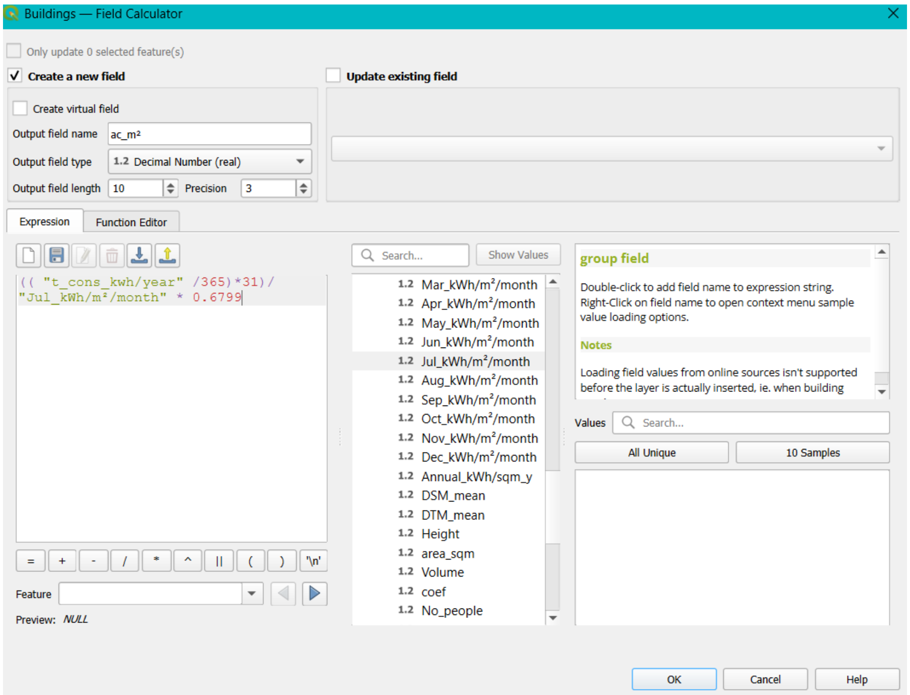


Figure 82 – Calculation of Ac in QGIS

((“t_cons_kwh/year”/365)*31)/”Jul_kWh/m²/month”*0.6799

Bear in mind to check for any anomalies, including the comparison between the actual area of the buildings and the area needed for installing collectors (Ac). Naturally, Ac shouldn’t be bigger than the area of the building.

Next, with the use of Ac [m²], having the solar irradiation H [kWh/m²/month] and the collector efficiency $\eta_{coll,month}$, we can calculate the thermal energy production [kWh/month] for each building. It is obvious that because the value of collector efficiency and solar irradiation varies in each month, we should calculate the production for each month separately.

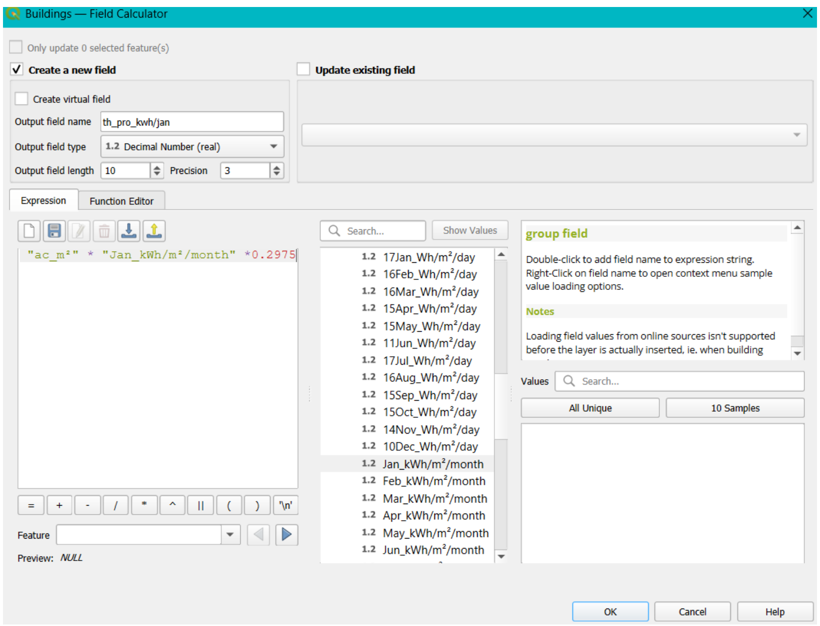


Figure 83 – Calculation of thermal energy production in QGIS

7. Economic Analysis (Thermal)

Similar to the economic analysis of PV panels, we can also conduct an economic analysis to assess the monetary aspects of this intervention. As previously calculated, we have a thermal cost for each building. By installing STC, we can produce our energy, so consequently we do not have to pay as before, while the implementation of this technology has an initial cost. Also, by considering that we avoid overproduction, then we may only have two scenarios: most probably our production meets the consumption in July, and in other months we have underproduction.

7.1. Investment Cost ($C_{inv,ST}$) for the installation of STC

In this exercise, we assume the price averagely per m² of the solar thermal collectors installed on the roof (Ac). Moreover, this price varies based on the technology used.

Vacuum Tube Solar Collectors	$\boldsymbol{Cost_{STC} = 1200\ €/_{m^2}}$
Flat-plate Solar Collectors	$Cost_{STC} = 800\ €/_{m^2}$

Table 16 – Price of different STS based on 1m²

For example, to estimate the overall initial cost, we simply have to calculate:

$$Flat\ Plate\ collector: C_{inv,STC} = Ac * Cstc \rightarrow IC = Ac * 800$$

$$Vacuum\ Tube\ collector: C_{inv,STC} = Ac * Cstc \rightarrow IC = Ac * 1200$$

7.2. Consumption cost, economic savings, and SPT

7.2.1. Consumption cost before the implementation of intervention (CB):

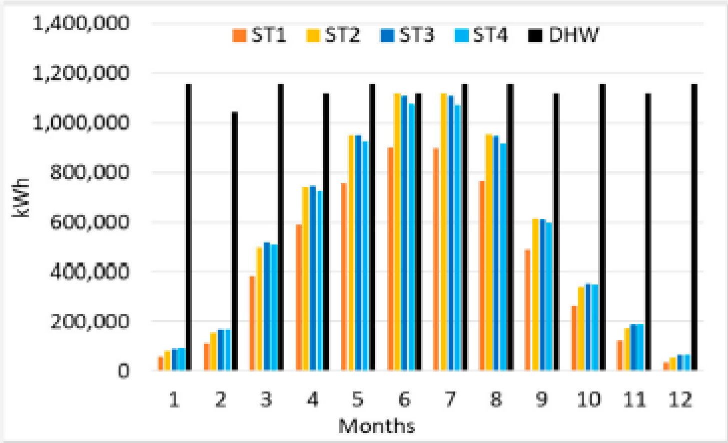
Now, by having the overall energy consumption [kWh/ month or year] in each building, we can also calculate the energy cost for the buildings. To do so, we only need to know the price of energy for 1 kWh. It is important to know that the price of energy for 1 kWh is different based on the source of energy. In this exercise, we assume the cost:

Thermal Energy Cost – Natural Gas: $0.113\ €/_{kWh}$[41]

$$CB\ [€] = E\ th, user \left[\frac{kWh}{m}\right] * 0.113\ €/_{kWh}$$

[41] https://www.consumer.bz.it/it/confronto-prezzi-combustibili-riscaldamento-alto-adige

7.2.2. Consumption cost after the implementation of intervention (CA):



(a)

Figure 84 - Solar energy technology assessment (year 2014):
(a) Comparison between domestic hot water (DHW) consumption of the residential sector and solar thermal (ST) production, considering four collector typologies (with average efficiencies of: ST1 = 0.59, ST2 = 0.77, ST3 = 0.80, and ST = 0.79)[42]

As shown in Figure A, the thermal energy production based on different solar thermal systems (ST1, ST2, ST3, ST4) is shown, while the solar thermal needs for DHW are shown in black. From the figure, it is decipherable that there is no month with overproduction. Now, we can calculate the energy cost simply by subtracting the production from the DHW needs.

$$CA\ [€] = (E\ th, ST - E\ th, user) \left[\frac{kWh}{m}\right] * 0.113\ {€}/_{kWh}$$

7.2.3. Economic Savings

Economic savings here again regard the amount of money that we are not paying because of self-production. In other terms, economic saving here is just the multiplication of production by the price of energy.

$$ES\ [€] = \ E\ th, ST\ \left[\frac{kWh}{m}\right] * \ 0.113\ {€}/_{kWh}$$

[42] https://iris.polito.it/retrieve/handle/11583/2848300/399581/applsci-10-07112.pdf

7.2.4. Simple payback time (SPT)

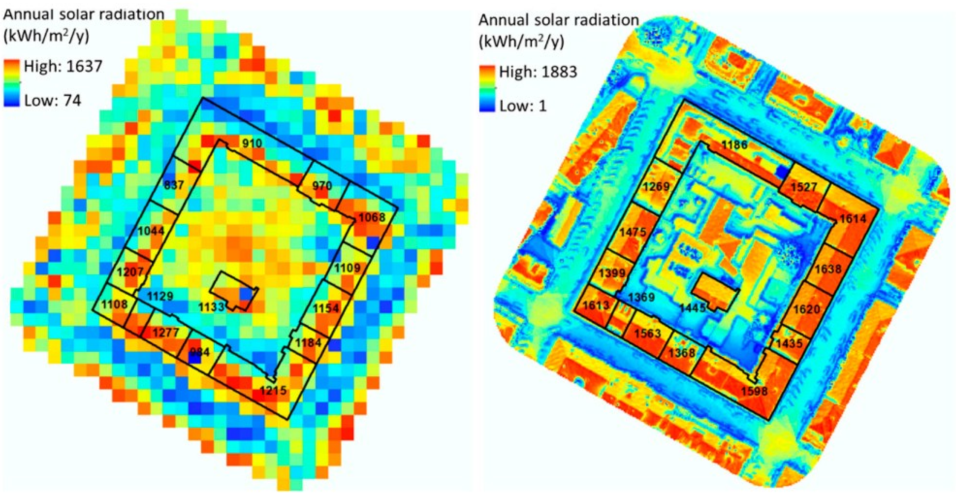
Now we can calculate how many years it takes for our investment to be compensated by the savings because of self-production. Here, the difference with PV panels is that we do not have overproduction anymore, then there is no revenue, and the simple payback time just depends on the cost of investment ($Cost_{inv,\,ST}$) and economic savings (ES):

$$SPT\ (year) = \frac{Cost_{inv,ST}}{ES}$$

8. Final consideration

When conducting economic analyses, it is essential to consider the possibility of simultaneously installing both a photovoltaic (PV) system and a solar thermal (ST) system. Typically, only 30-40% of the total available surface area can be utilized, so a portion of this area can be designated for PV panels, while the remaining area can be allocated for ST collectors. Alternatively, the entire available surface can be used for either the PV or ST system.

After evaluating different possible layouts, it is important to identify the scenario that offers the most economic benefit and explain why it is the most advantageous. The accuracy of the input data is crucial for achieving better outcomes, and a precise demand-side management (DSM) analysis is necessary for these evaluations.
[43]

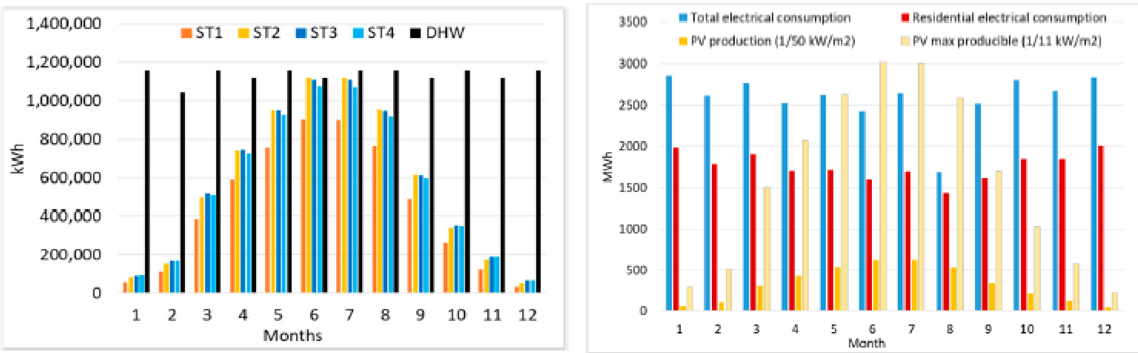


(a) (b)

Figure 1. Annual solar radiation (kWh/m^2/year) (**a**) using a DSM of 5 m and annual local climatic data; (**b**) using a DSM with a precision of 0.5 m and monthly local climatic data.

[43] https://www.mdpi.com/1996-1073/14/13/4018

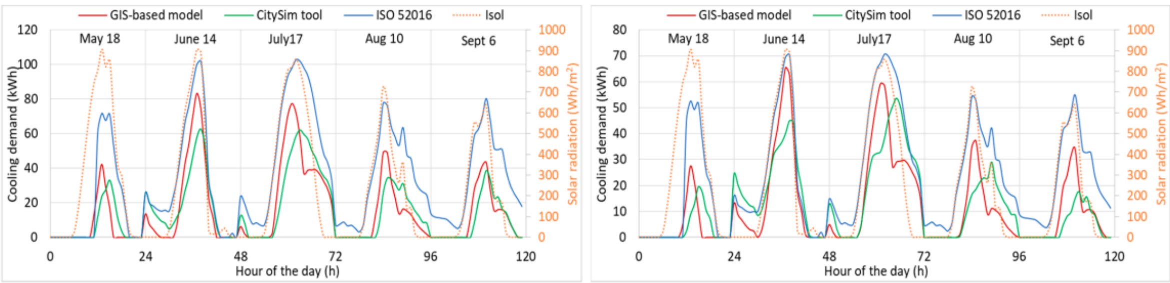
The following graphs represent the energy production and consumption, both for PV (b) and ST (a) systems. More in detail, regarding the Solar Thermal technology, the graph (a) shows that the ST sizing must be identified by the user thermal energy demand (DHW: Domestic Hot Water) during the summer months with higher solar irradiance (June or July). For this reason, the energy demand coverage for DHW will never be 100% and in this way the excess of DHW is never lost; this means that in the case the roofs' available surface is mainly dedicated to the ST collectors, the ST system should be able to meet the thermal energy demand during the summer months and not during the winter months.



(a) (b)

Figure 83 - Solar energy technology assessment (year 2014):
(a) Comparison between domestic hot water (DHW) consumption of the residential sector and solar thermal (ST) production, considering four collector typologies (with average efficiencies of: ST1 = 0.59, ST2 = 0.77, ST3 = 0.80, and ST = 0.79);
(b) Comparison between electrical consumption, photovoltaic (PV) production with coefficient K = 50 m²/kW (according to the Decree 28/2011), and PV max producible.[44]

With RES technologies and especially with solar ones, the load-correlation is one of the main indicators to consider. In the following graphs can be observed the positive correlation between the solar irradiation with the cooling load of residential buildings in Turin in typical warm days.



(a) (b)

Figure 5. Comparison of the hourly cooling demands for the five typical summer days simulated with the GIS-based model (in red), the CitySim tool (in green) and the hourly method according to ISO 52016 (in blue), on the secondary axis the solar radiation expressed in Wh/m² is indicated (in yellow): (**a**) a residential building built in 1961–1970 with SW (azimuth +30°) orientation; (**b**) a residential building built in 1919–1945 with SE (azimuth −60°) orientation.[45]

[44] https://iris.polito.it/retrieve/handle/11583/2848300/399581/applsci-10-07112.pdf

[45] https://www.mdpi.com/1996-1073/14/13/4018

9. Appendix

9.1. Batch processing r.sun.insoltime

This instruction is useful for batch processing, which means that you run r.sun.insoltime for computing solar irradiation for several months all at once. To perform the batch processing for this tool, you should have prepared all the required inputs, including DSM, Slope, Aspect, TL for all months, and DG for all months.

Open QGIS, from the top menu bar, open "**processing"**, search for "**r.sun.insoltime**" → When the tool opened, on the left down of the window, you can find the option "**run as batch processing**".

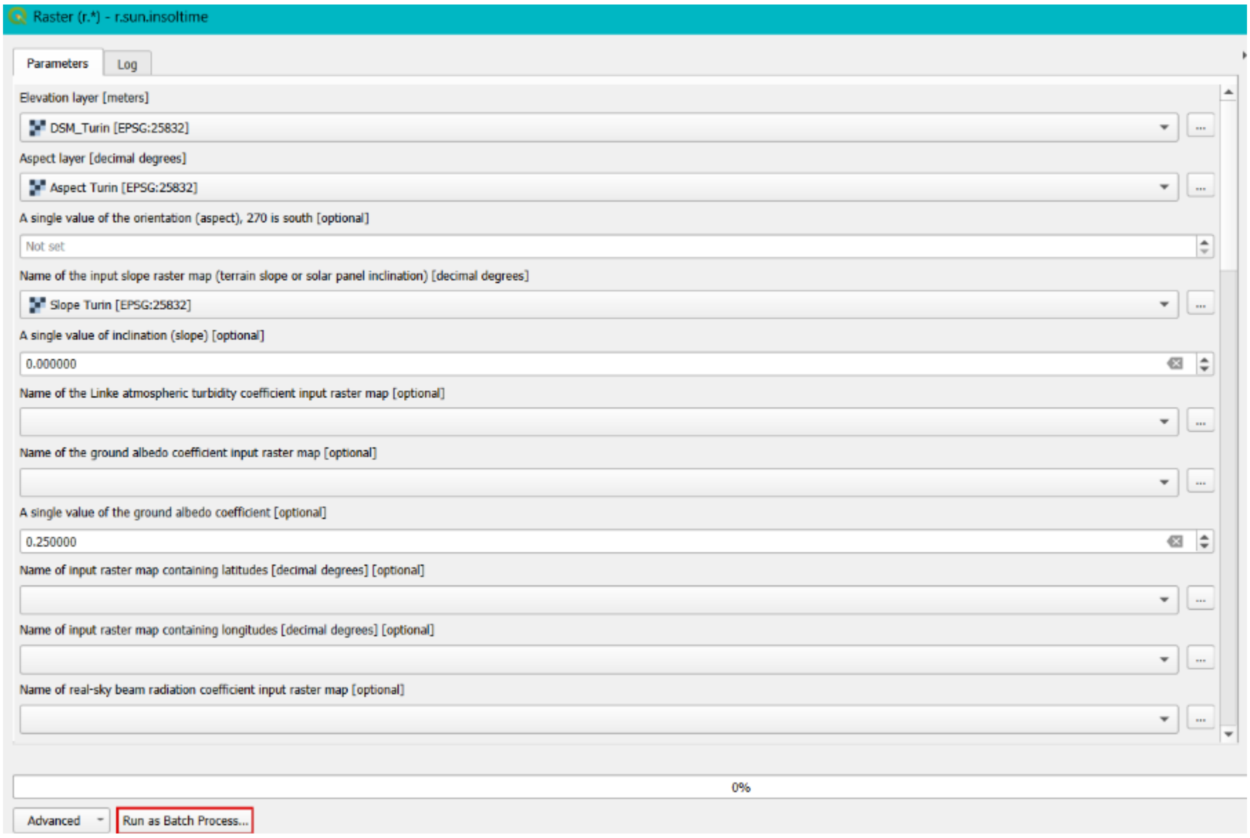


Figure 88 - r.sun.insoltime tool menu

Then, in the batch menu, add 11 more rows, and according to the figures, fill all the columns.

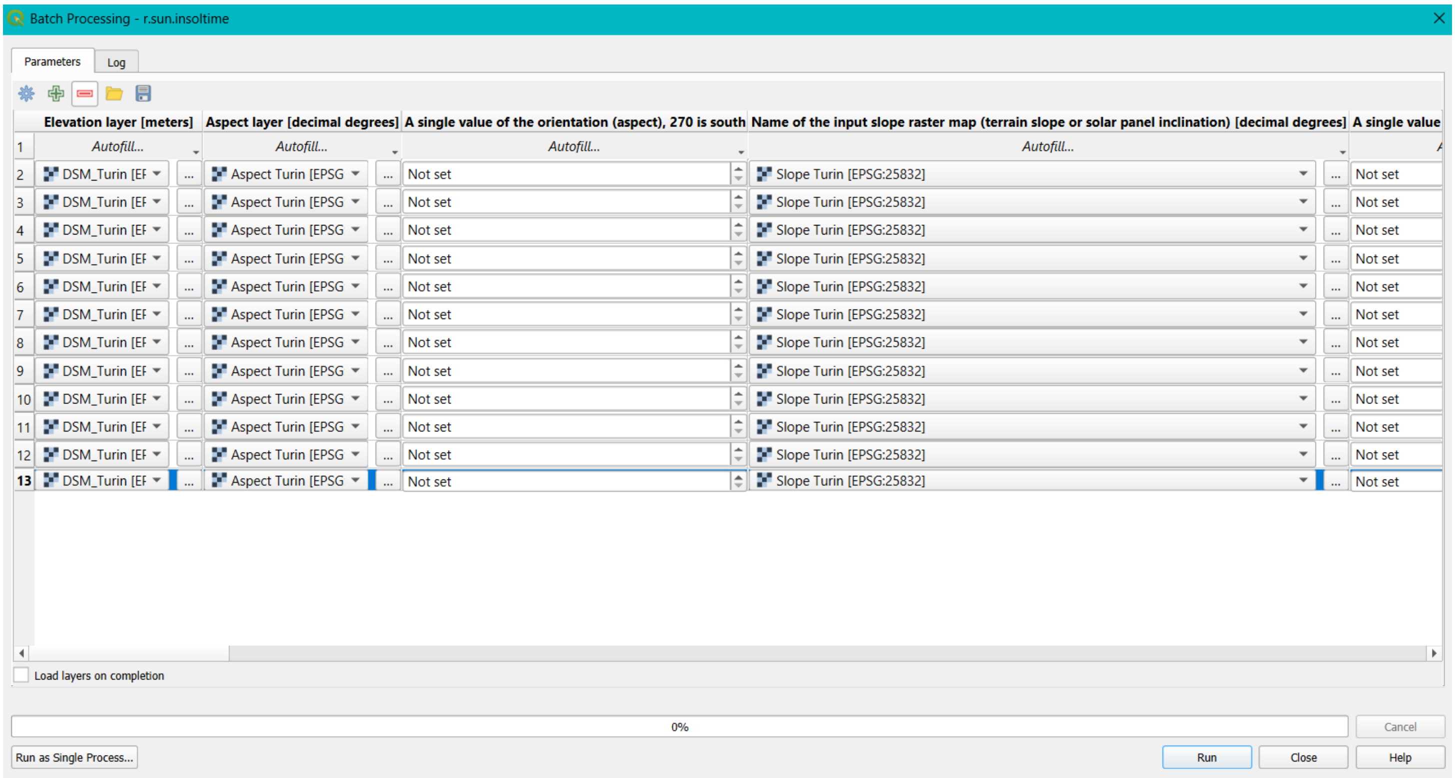


Figure 89 – r.sun.insoltime batch processing menu

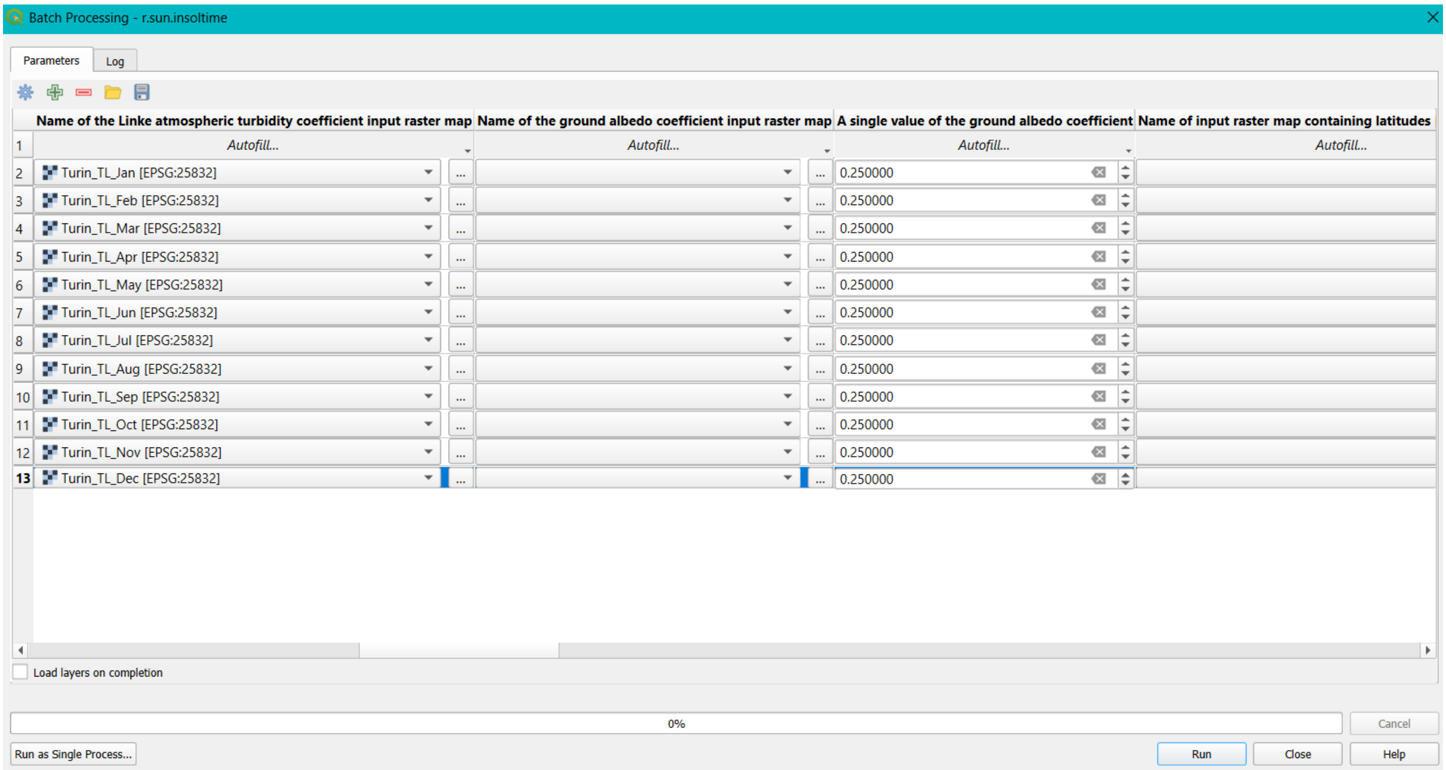


Figure 90 – r.sun.insoltime batch processing men

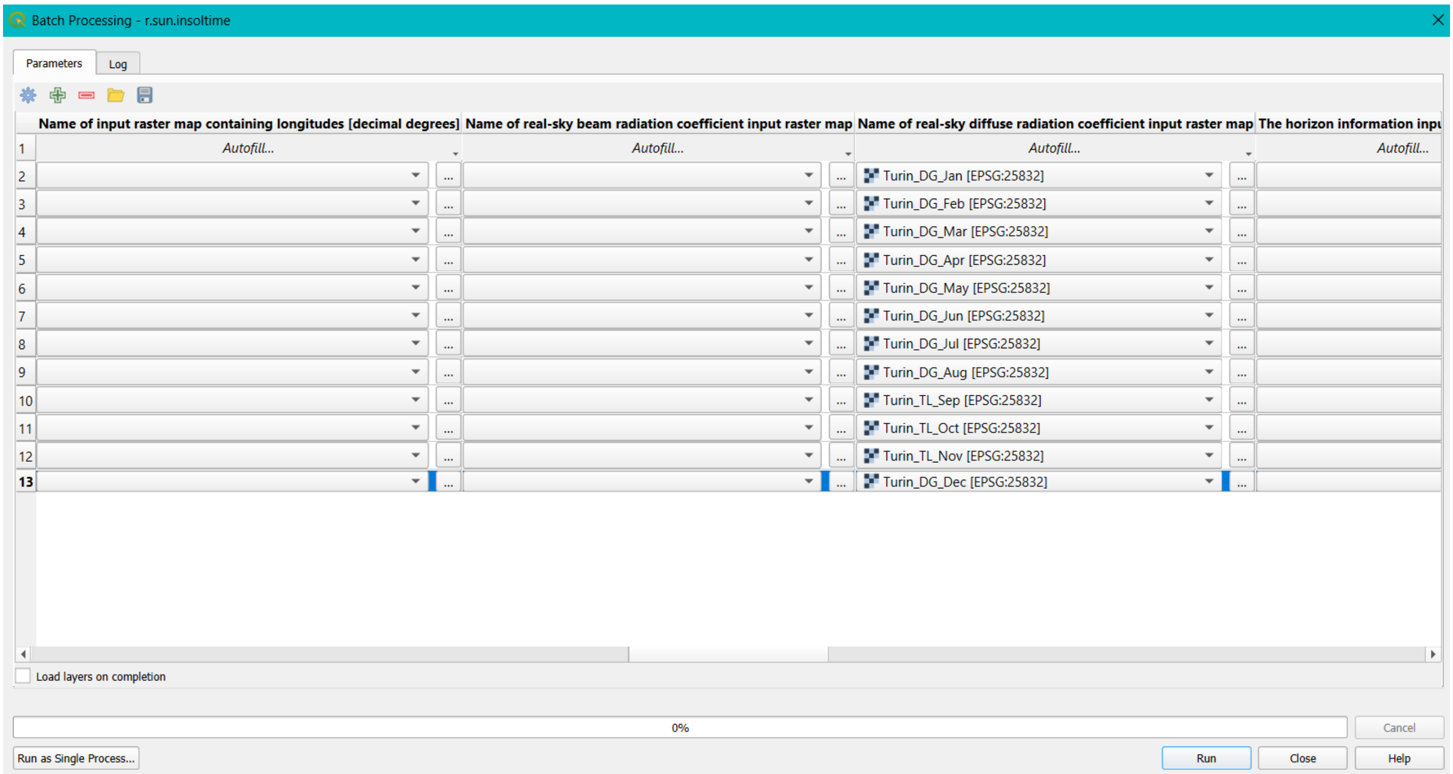


Figure 91 – r.sun.insoltime batch processing menu

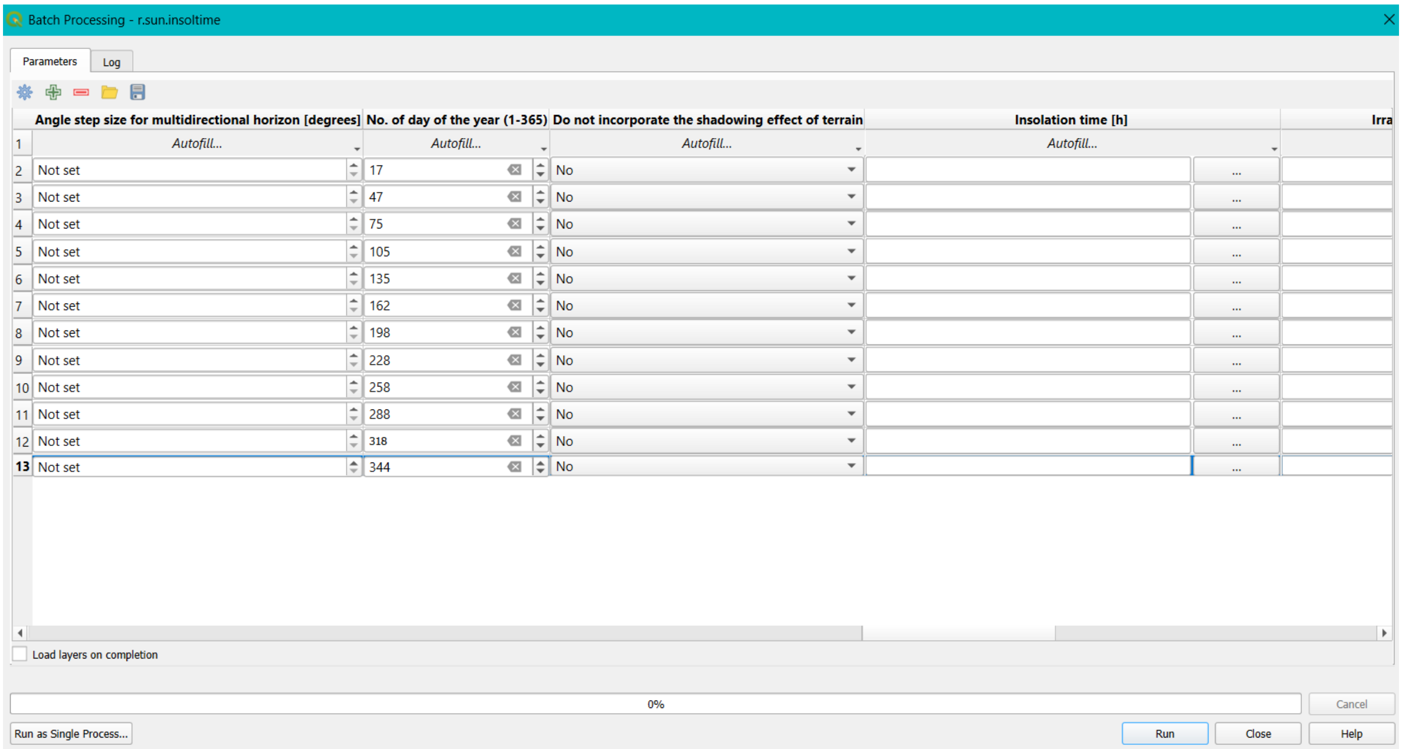


Figure 92 – r.sun.insoltime batch processing menu

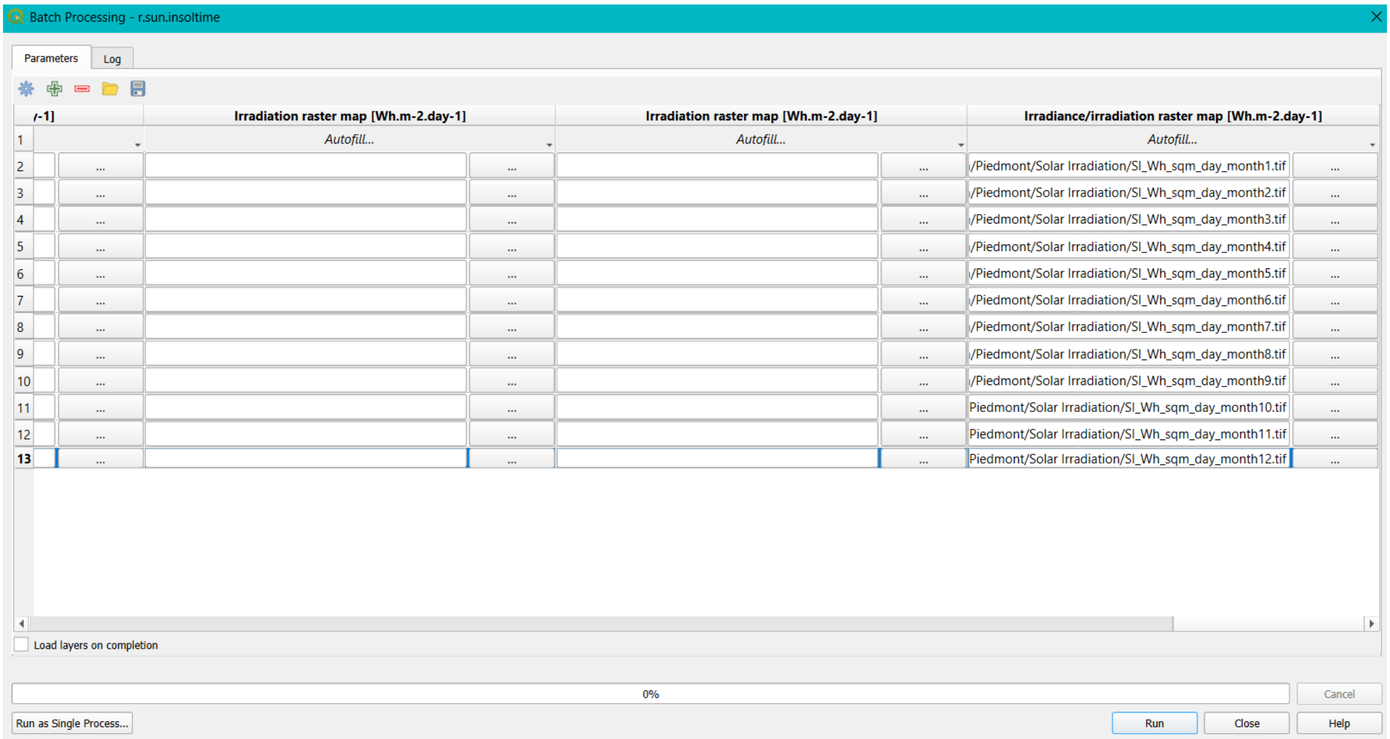


Figure 93 – r.sun.insoltime batch processing menu

Note: After running the tool, it may take nearly one hour each month. To minimize errors or crashes, it is advisable to close all other applications (especially Chrome) before running the tool and to leave your laptop free.

9.2. Calculating the height of the buildings using DSM and DTM

In this section, we want to calculate the height of the buildings using the DTM and DSM. This method is suggested as a last resort if there is no other authentic information regarding the height of the buildings.

Very important note: *When working with geospatial data, it is crucial to consider the metadata, which contains information that may be very important. In our case, as we want to compare a DSM with a DTM, it is crucial to check first, their CRS (Both vertical and horizontal) are conforming to each other; otherwise, we may miscalculate everything. The second important thing is to consider the year the file is prepared, for example, if the DSM is produced in 2011, it doesn't contain any information about buildings constructed after 2011. The third important point is to consider the resolution of the cell size. It means that the DSM has a 5-meter resolution. It means that the DSM isn't reliable for buildings below 25 m².*

Note: Make sure that you previously deleted the buildings below 40 m² and non-residential usages.

Import the DSM and DTM of Turin in your project as well as the shapefile of buildings → from "toolbar" menu, "**processing**", search for "**Zonal statistics**" → Define input layer as "Buildings" and raster layer as "DTM", for "Output Column prefix" write "DTM_" and for "Statistics to calculate" only select "Mean" → run → Repeat the process for DSM

Now you have two new columns with the names of "DSM_mean" and "DTM_mean", now by subtracting them, you can find the height of your building. → New column → "DSM_mean" - "DTM_mean".

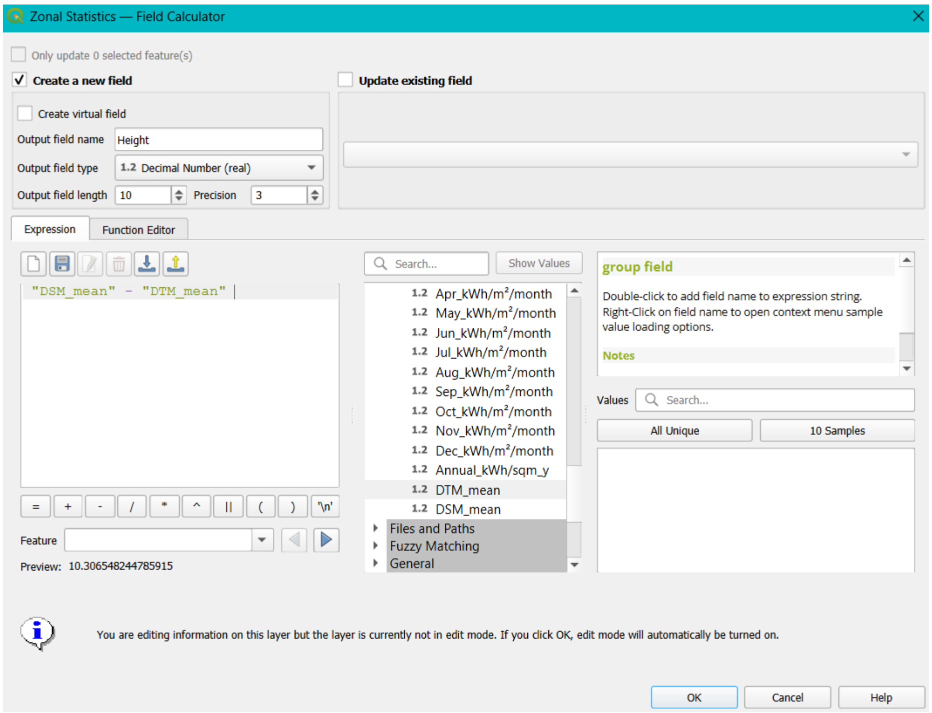


Figure 94 – Calculation of height for buildings

Note: Please note that when checking the height of the buildings, you may come across some structures with negative heights or heights less than 3 meters. If you examine these buildings on the map, you will find that they are mostly located within a block of other buildings. This issue arises for several reasons, including the precision of the LiDAR data. The quality of the survey is influenced by how many points are recorded per square meter. Additionally, the surrounding buildings can obstruct the view during the LiDAR acquisition process, leading to improper recordings. Errors can also occur due to inconsistencies between the temporal resolutions of the Digital Surface Model (DSM) and the Digital Terrain Model (DTM). Although this error is significant, we will disregard it for this exercise.

Figure 95 – the buildings with height anomalies

In the attribute table of the buildings, select "Select features using an expression → In the expression box, type "Height" < 3 → delete the selected buildings

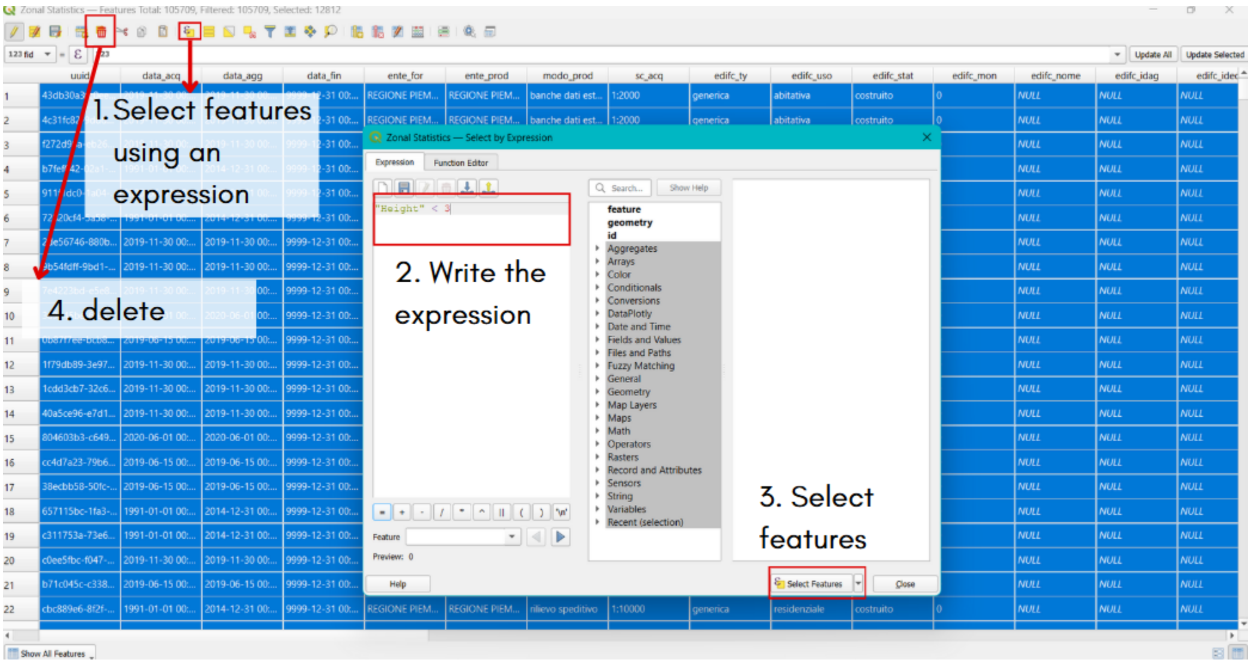


Figure 96 – How to select and delete buildings under 3 meters height

9.3. Calculating the efficient area (m²) on the roof which receives higher solar irradiation

Previously, we assumed 30-40% of the roof area would be dedicated to installing photovoltaic (PV) panels. In this methodology, we aim to calculate the area of each building's roof that receives the suitable amount of solar irradiation for installing PV panels or solar thermal collectors, in other terms, we will now focus on selecting only the parts of the roof that are most suitable for PV panel installation based on their exposure to sunlight. The requisite inputs needed are noted in the following table.

Name	Type
Building's footprint	Shape file
Annual solar irradiation [kWh/m²/year]	Raster

Table 17 – List of inputs

Note: In this example, we use a raster file with 5-meter resolution; logically, the finer resolution leads to better results.

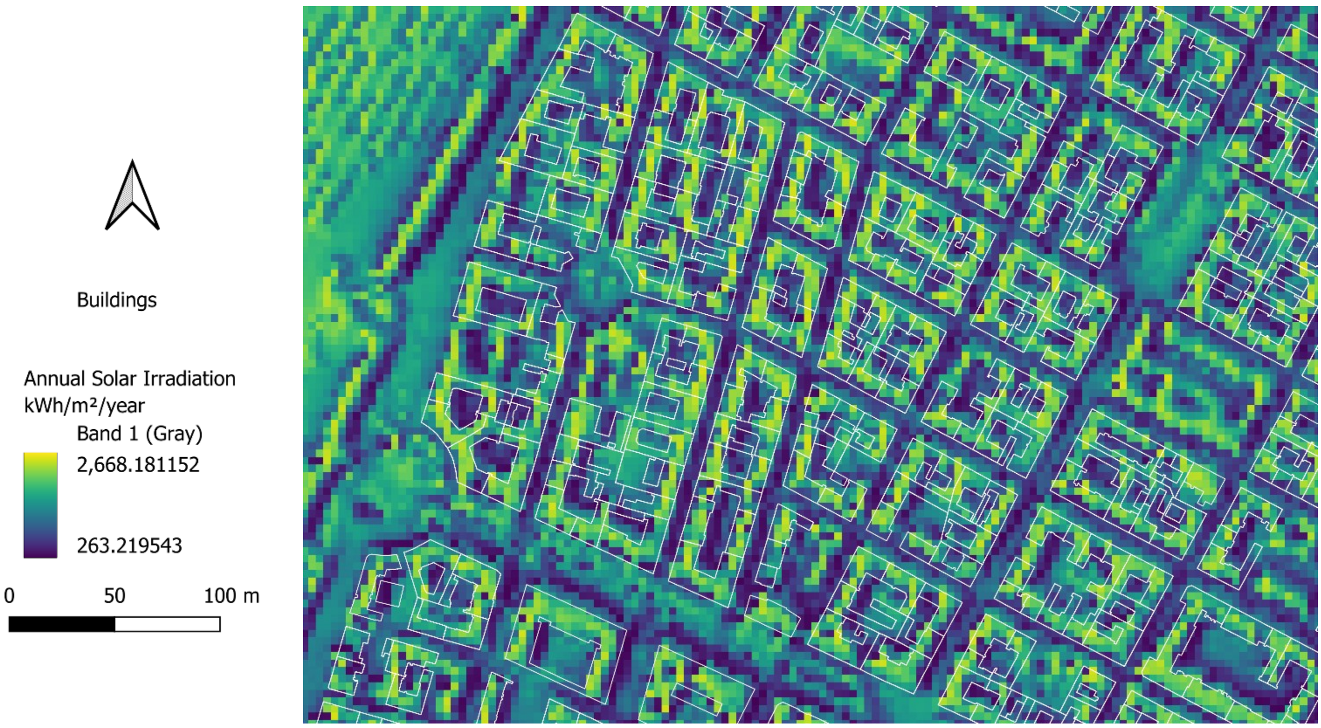


Figure 97 – Annual Solar Irradiation and buildings' footprint

The figure above clearly indicates some parts inside the buildings' footprint in which the solar irradiation is more intense. Now we want to only extract the pixels in which the solar irradiation is favorable. To do so, in this case of Turin, the desired annual solar irradiation is more than 1200 kWh/m²/year, so we select only the pixels that meet this requirement.

To do so, open "**Raster Calculator**" → put the annual solar irradiation raster file in "**Raster Calculator Expression**" and type >= 1200, name the file properly, and select ok.

Note: Make sure that your files share a similar CRS.

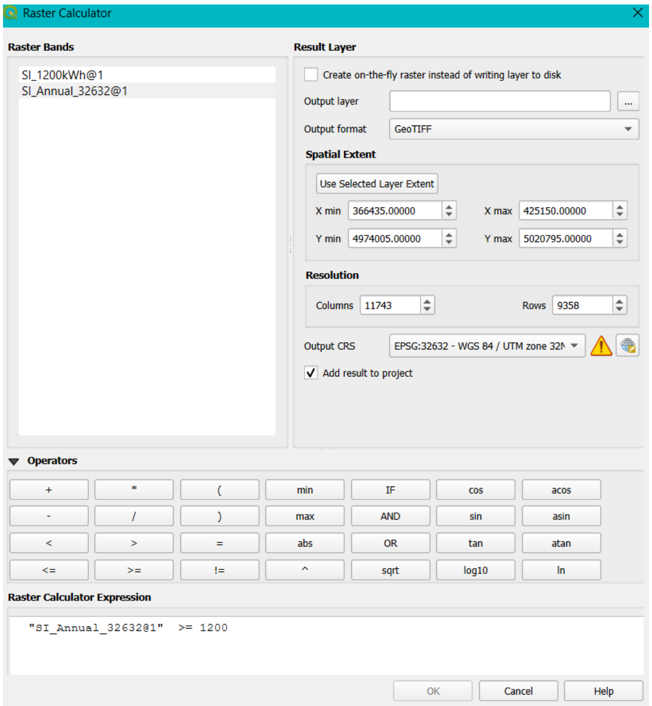


Figure 98 – Selecting the pixels with value higher than 1200

Note: The result raster file only has pixel values of 0 and 1, in which 0 is a pixel that didn't meet the requirement and 1 is a pixel which is more than <u>1200 **kWh/m²/m²/year** solar irradiation for Turin</u>.

Figure 99 – Map of pixels with above or under 1200 kWh/year solar irradiation

Next step is to calculate how many of the pixels with 1 value are located inside a building. To do so, we can either use "zonal statistics" or "pixels to points" and then "summarize

From the top bar menu select processing → Search for zonal statistics → For input layer select the buildings' footprint shape file, for the raster select the binary raster file, for "Statistics to calculate" only select "sum" → run

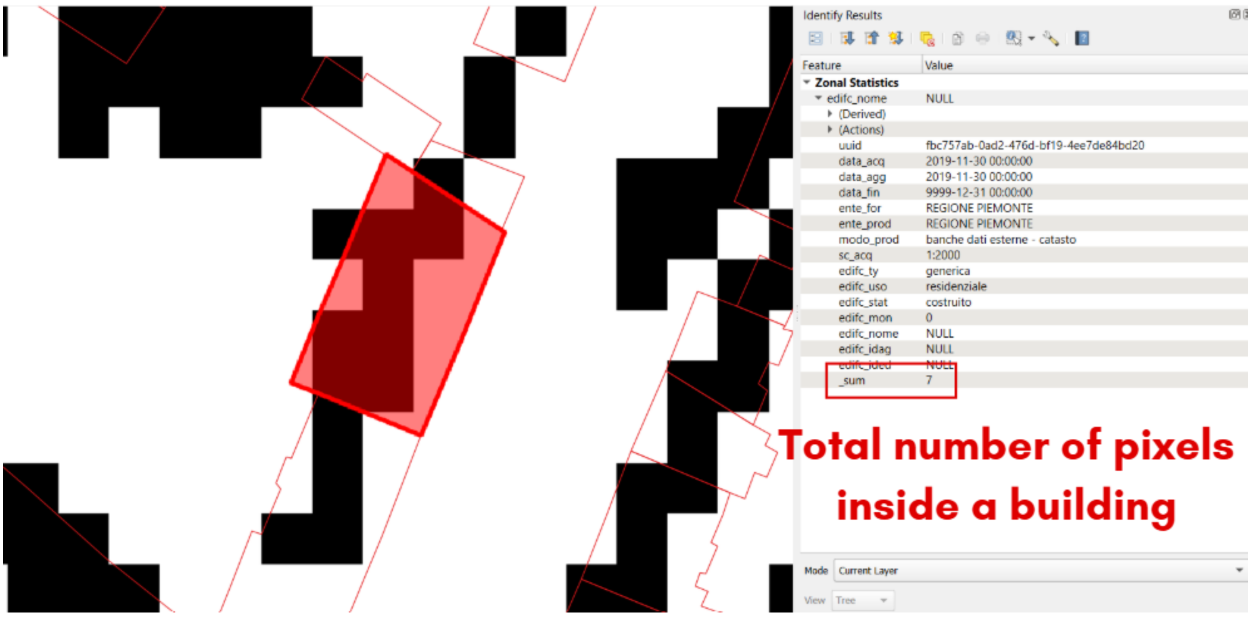


Figure 100 – Zonal statistics result

Note: It is important to know that the "**zonal statistics**" tool only **counts a pixel as inside a polygon if its center point falls inside** the polygon's boundary.

Now, by knowing the number of pixels in each building and pixel size (resolution), we can calculate the area in each building suitable for installing PV panels. To do so, we only need to create a new column in the attribute table and calculate it based on:

$$Total\ area\ of\ pixels = (Resolution\ size)^2 * Number\ of\ pixels\ inside\ the\ building$$

For example, if each pixel has a resolution of 5 meters, then each pixel cell covers an area of 25 square meters. If there are 3 pixels inside a building, the total area suitable for installing photovoltaic (PV) panels would be 75 square meters.

10. References

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