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ORIGINAL ARTICLE

Modeling and mapping solar energy production with photovoltaic panels on Politecnico di Torino university campus

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Abstract Educational institutions have significant impacts on the society and environment they are inhabiting, and they can have a big role in influencing various development fields, including sustainability. The environmental sustainability of universities was critically analyzed recently. These bodies can contribute to the sustainability of cities due to their social role in shaping the future generations. The aim of this work is to analyze Urban Building Energy Modeling with a place-based approach using the open-source software QGIS in predicting energy production with photovoltaic solar technologies on the rooftops of the central university campus of Politecnico di Torino. This modeling can help in assessing the energy security and affordability of current and future sustainable scenarios considering their impact on climate change. This study evaluates the accuracy of urban scale QGIS-based energy modeling with a comparison of measured data available from the monitoring activity of LivingLab of Politecnico di Torino, the free tool PVGIS, and the web tools of ENEA. The QGIS modeling accuracy depends on the different precisions of the Digital Surface Model used to describe the built environment (i.e., 1 m or 5 m) and the climate input data (monthly and annual diffuse-to-global radiation and Linke turbidity factor). Moreover, this assessment can be used to map the results of new photovoltaic systems improving the energy and environmental performance of university campuses. The results of this work shed light on the significance of different input data for energy simulation tools at neighborhood-urban scale. The result shown accuracies in PV production of 10 to 37% with different spatial resolutions of the 3D built environment and of 14 to 15.2% for temporal resolution of solar irradiation variables.

Keywords University campus sustainability · Energy efficiency · Energy modeling · Photovoltaic panels · Environmental sustainability · QGIS · Open-source tool

Nomenclature

CSAT	Campus sustainability assessment tool
D/G	Diffuse-to-global radiation
DSM	Digital Surface Model
GM	Green Metric
HEI	Higher educational institutions
MAPE	Mean Absolute Percentage Error
PE	Percentage Error
PV	Photovoltaic
SC	Self-consumption
SCI	Self-consumption index
SS	Self-Sufficiency
SSI	Self-Sufficiency Index

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STARS Sustainability Tracking, Assessment & Rating System
T_L Linke atmospheric turbidity coefficient

Introduction

Research background

Energy consumption is continuously increasing in urban environments, which demonstrates the importance of assessing the effects of this increase in climate change phenomenon. Public buildings play an important role in introducing energy efficiency measures and stimulating the actions taken toward decarbonized building stock. One of the important documents that highlights the leading role of public buildings is the Energy Performance of Buildings Directive (2010), which describes the public sector as the leading example in which member states shall follow in transforming buildings into nearly zero-energy buildings. It encourages both public and private bodies to set out roadmaps with measurable indicators to reduce GHG emissions and ensure higher energy efficient building stocks. University campuses are among the various bodies that have considerable effect on the global energy consumption of cities. These higher education institutions (HEIs) have both direct and indirect impacts on the environment, that can be reduced by technical measures (Alshuwaikhat and Abubakar, 2008). The first official declaration signed by HEI members is the Talloires Declaration (1990) with ten recommended actions to involve universities in carrying effective action for sustainable future. Point 5, *Practice Institutional Ecology*, highlights the necessity of creating examples from these educational bodies to establish institutional ecology policies.

Given their position in the community, universities are important bodies in increasing the awareness towards social and environmental issues and minimizing the negative impacts (e.g., increasing the use of renewable energy sources RES, reducing the energy consumption by using smart controls, encourage recycling, support equity, etc.). Following the Talloires Declaration, many academic institutions started to act for achieving environmental sustainability in their campuses. In Italy, many universities are members of RUS (Italian University Network for Sustainable Development, 2023), including Politecnico di Torino. Among the goals of this network is to create a community able to develop best practices with particular attention to the achievement of Sustainable Development Goals (SDGs).

There are several successful applications in the EU that indicate the importance of having sustainable campuses. A sustainable campus can be defined as a responsible community that is actively engaged in minimizing the negative environmental and social impacts through their multi-disciplinary activities (Cole, 2003).

Tian et al., (2022) highlighted the importance of considering the geographical location of the campus and involve the locally available Renewable Energy Sources (RES) (e.g., lake cooling, geothermal energy, etc.) and stresses the importance of considering the seasonal efficiency by representing the optimization process applied to some case studies.

Besides the successful sustainability applications, Amaral et al. (2021) analyzed the unsuccessful applications to give the actual image and highlight the causes. Missing measurement and verification procedure is one of the reasons for unsuccessful energy efficiency strategy implementation. The analysis is summarized by identifying four problem categories: technical, economic, climatic, and behavioral aspects, which affect the success in accomplishing expected performance levels. However, Sonetti et al., (2016) analyzed some campus sustainability assessment tools (CSATs) by comparing two university campuses which have different urban settlements: the first with scattered settlement over different parts of the city, lacking green spaces (Polito-Italy), whereas the second is a large university campus outside the city (Hokudai-Japan). The comparison gives the ranking of both universities based on the Green Metric tool (UI-GreenMetric, 2010) initiated by the University of Indonesia in 2010. GM provides an open access database about university rankings which is defined by a numerical metric system based on 6 criteria: settings & infrastructure (15%), energy & climate change (21%), waste (18%), water (10%), transportation (18%), education & research (18%). The study showed that Hokudai University had a higher ranking than Politecnico di Torino (Polito) by 71 positions in 2014. Nevertheless, considering 2022, Polito ranked the 15th both in Energy & Climate Change criteria and in overall score, compared to the other included Italian universities in the ranking list. It is also ranked

20th among 1050 worldwide universities in 2022, based on the overall score that considers the 6 assessment criteria (Fig. 1). However, the analysis showed that tools using quantitative assessment metrics do not allow a flexible approach that considers site specific features, such as GM. Thus, with the analyzed two case studies, the work emphasizes that using local assessment tools is crucial to obtain more fair assessment results. These local assessment tools must consider the site-specific constraints and variables when evaluating the campus sustainability (e.g., local climate, campus morphology, number of users, available functions etc.). However, it should be mentioned that the GM has some uncertainties in the assessment process. The most important one is comparing universities using data with different levels of accuracy (Boiocchi et al., 2023).

Moreover, Dawodu et al. (2022) demonstrates that most of these assessment tools emerged after the establishment of SDGs in 2015, showing the importance of having such metrics in intensifying the actions taken toward sustainable urban environments. The work analyzed numerous articles on campus sustainability assessment tools and defined 12 sustainability categories in which *operations-environmental* has the highest percentage distribution compared to the other dimensions (30% for operations-environmental, with the second highest percentage for the education dimension with 17%). Energy use is the most considered aspect in operations-environmental category, but the sustainability measures related to the use of RES are still lacking. Some of the reasons for this lack are the costs and the planning of investment for using RES.

According to the analyzed 1194 articles by Dawodu et al., the STARS (Sustainability Tracking Assessment & Rating System, 2010) has the highest frequency rate among other assessment tools, followed by the Green Metric (GM) and AISHE (Assessment Instrument for Sustainability in Higher Education). STARS allows universities to participate in their system to gain points and earn a STARS report according to classes ranging from Bronze (lowest) to Platinum (highest). AISHE, developed by the Dutch Foundation for Sustainable Higher Education, is a star ranking system ranging from 1 to 4 that universities can freely utilize. It serves as both an assessment tool and as an instrument for preliminary policy and strategy scenarios. However, it is a paid service if universities require individual assessments conducted by professional assessors.

Another supportive organization for university sustainability is the ISCN (International Sustainable Campus Network, 2007) founded in 2007, with the

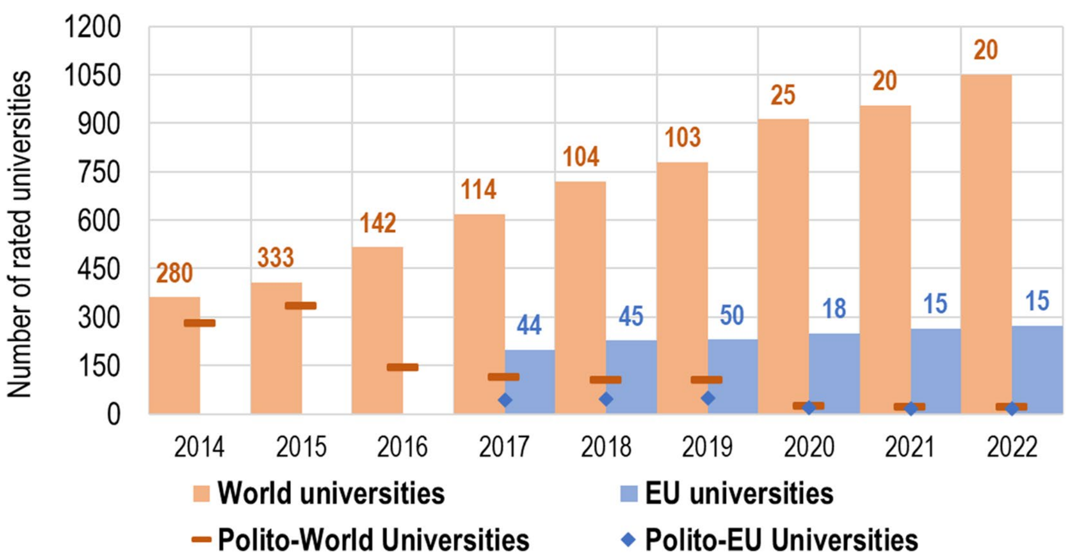

Fig. 1 Polito's overall ranking according to GreenMetric's 6 criteria. The numbers and shapes on bars indicate the position of Polito in the overall ranking among other universities

aim of developing and contributing to sustainable development. In their Best Practices 2018 report, presented in the World Economic Forum, they listed the different contributions of some universities to meet the targets of SDGs (2018 WEF-ISCN Report: Educating with Purpose, 2019). This report is useful to analyze the objective and results of the projects accomplished by universities from all over the world, also providing the contact reference for further updates about the project if needed. Polito is among the contributors to this report, presenting the Green Team project (Polito, Sustainable Campus, Green Team, 2015), which aims to create an engagement campaign for students by using communication, which is a powerful tool in increasing awareness and knowledge on campuses.

Considering the above-mentioned tools and organizations that measure campus sustainability, it is also possible to include Geographical Information System (GIS) based approaches to act as a preliminary decision tool for the implementation of sustainability measures within university campuses. GIS is widely considered to be a powerful tool for spatial analysis. Bergamasco and Asinari (2011) presented a methodology to assess the available roof area in Piedmont region for the installation of roof integrated Photovoltaic (PV) panels, stating that previous works mainly assumed the roof area as an input data only. The analysis, performed with ArcGIS, uses solar radiation maps and technical regional maps for geographical data. Another study by Pintor et al. (2015), analyzed the available daily solar irradiation using r.sun tool in GIS and identified possible sites for ground mounted PV farms. It uses typical days per month to reduce simulation runs from 365 to 12 using the days suggested by Duffie and Beckman, 1991. The results of the simulations are validated with measured irradiation data and showed a similar irradiation trend over a year and a Mean Absolute Percentage Error (MAPE) of 8.53%. The suitability of PV installation is mapped based on four criteria: physical, environmental, socio-economic, and risk. The study concluded that r.sun tool is able to model the incoming solar radiation with reasonable MAPE values considering large analysis area.

A more recent study by Mutani et al. (2023) used urban building energy modeling (UBEM) to analyze the production from PV panels using the open-source software Quantum Geographic Information System (QGIS). The presented approach allows the evaluation of spatial distribution of energy consumption and production in urban areas, which is essential to realize smart cities. The solar irradiation analysis uses r.sun.insoltime of GRASS plug-in tool within QGIS with defined average monthly sun and sky characteristics. The 3D environment is described using a digital surface model (DSM) that is obtained by using digital elevation model (DTM) and building heights. This 3D description of the built environment allows the consideration of shadows from nearby urban elements, which is crucial in assessing solar radiation on roofs. The results of the presented methodology showed that using QGIS with available open-source input data can obtain energy models with MAPE of 5.2%.

The analyses in the presented literature show that it is possible to integrate free open-source tools to provide new protocols and Web GIS platforms for preliminary predictions of campus sustainability ratings.

Knowledge gap and the objective of this work

The proposed methodology introduces a novel approach to assess in improving campus sustainability levels by integrating district-urban scale energy analysis with site-specific spatial and climatic characteristics. Given that the energy aspect is among the most important category in evaluating campus sustainability levels, there is a need for a comprehensive energy assessment approach that not only focus on individual buildings and overlook broader urban context, but considers the entire 3D built environment within the university campus and its surroundings. The use of district-urban scale approach can also give a more complete image considering the whole area within the university, making it possible to include not only the rooftops but all the available surfaces when analyzing solar energy potential.

Following these, we believe that there is a need for a methodology that utilizes open-source tools and databases to be used as a pre-feasibility assessment tool for new intervention scenarios to increase campus sustainability levels. This approach can be also used to highlight the weight of site-specific characteristics in the final energetic indexes when comparing university campuses within different urban contexts. This is important because knowing only the quantitative results of campus sustainability indexes is not enough for a fair comparison but highlighting the local characteristic is also important as mentioned previously, given in the analysis of Sonetti et al. (2016).

The objective of this work is to test a place-based methodology to model the solar irradiation and then energy production with photovoltaic (PV) technology considering the whole 3D built environment using QGIS 3.28 version (Quantum Geographic Information System). This methodology consents to represent the solar irradiation distribution within the university campus and its urban surroundings. Then, PV production can be simply evaluated by selecting the more suitable surfaces based on their solar exposition.

The challenge of solar urban-scale modeling is the availability of accurate geo-databases representing the 3D built environment and the capability to represent the monthly variations of solar components and atmospheric turbidity.

The objective is to evaluate the accuracy of solar urban-scale modeling using different input data with:

- 2 spatial resolutions: using a Digital Surface Model (DSM) with a spatial resolution of 1 m or 5 m to represent the 3D urban environment
- 2 temporal resolutions: using annual or monthly diffuse-to-global solar irradiation ratios (D/G) and Linke turbidity factors (T_L) to characterize the solar irradiation

The solar irradiation, calculated with the different input data explained above, was tested considering the measurements of the LivingLab, which is the central monitoring portal of Politecnico di Torino, and other free Web-tools. The solar irradiation was simulated for the typical monthly days and analysed for each building of the university campus. For PV production, the urban-scale methodology was validated using the measured data from LivingLab of three buildings in the central campus of Politecnico di Torino (Polito), namely: Cittadella, Ex_Fucine, and DIATI/DISAT (in Fig. 2). A second comparison was performed using the web-tool PVGIS (JRC Photovoltaic Geographical Information System, 2023) to have a double validation. The accuracies of the presented

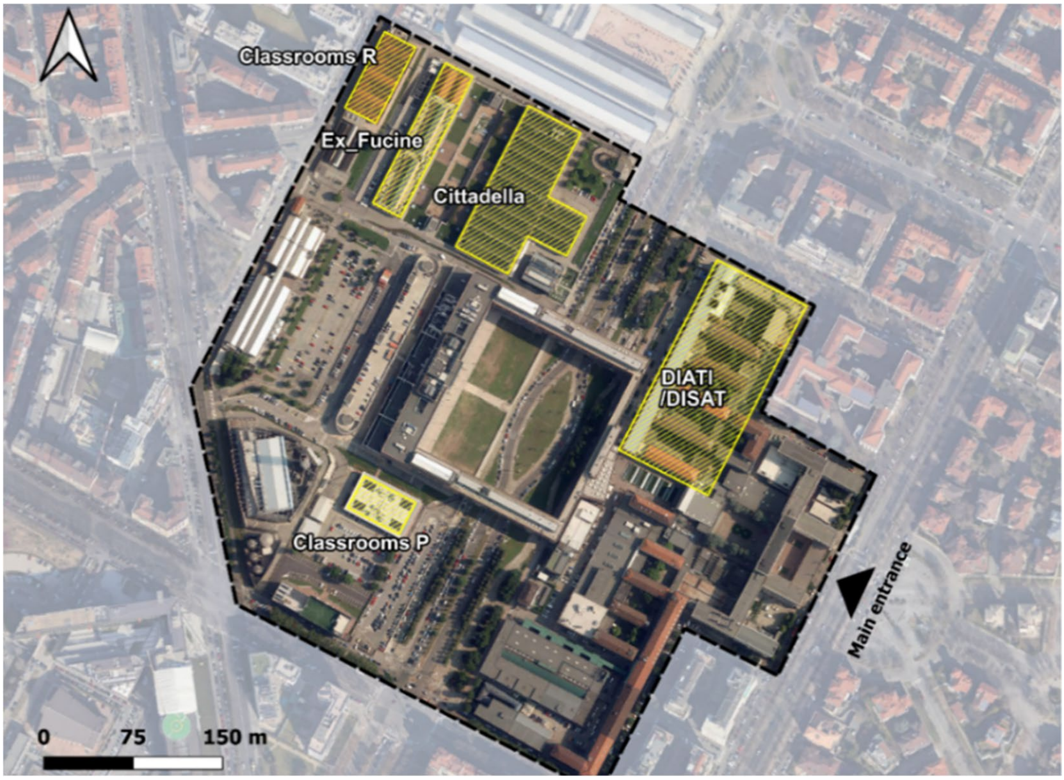

Fig. 2 Central campus of Politecnico di Torino (Polito)

urban modeling using different input data can be used as a reference for future applications that use similar approach with different input data availability.

The scale of the analyzed modeling is useful because it allows us to include the surrounding spaces when the consumption is high and the available rooftops in the campus are not sufficient. Moreover, the presented methodology can be used to assess the improvement in energetic indexes (i.e., Self Sufficiency Index SSI, and Self Consumption Index SCI) for future campus applications since the energetic index is among the most important criteria for improving the sustainability rating of a university. In this work other two PV systems on buildings Classrooms R and P were included in the final evaluation of the global SSI analysis for the university campus in Politecnico di Torino (in Fig. 2).

The analyzed assessment tool is presented in this paper as follows: Sect. 2 describes the methodology of QGIS-based PV production analysis, focusing on geodatabases with different accuracies, pre-processing analyses to manage the geodatabase and adjust the input data, and finally presenting the model validation steps. The analyzed case study is described in Sect. 3, followed by the modeling results and discussion in Sect. 4. The work is concluded with further considerations and development suggestions in Sect. 5.

Materials and method

The methodology of this work is based on using the open-source software QGIS to simulate the solar irradiation on building rooftops. Following that, the production from PV panels will be calculated using the simulated irradiation data. Figure 3 illustrates the general methodology for assessing building energy production modeling using an urban approach. The presented methodology is flexible because it shows how alternative supporting data can be adjusted and used when specific data are not available. For example, if a Digital Surface Model (DSM) is absent, it can be generated from a Digital Terrain Model (DTM) using the DSM generator tool in QGIS, considering

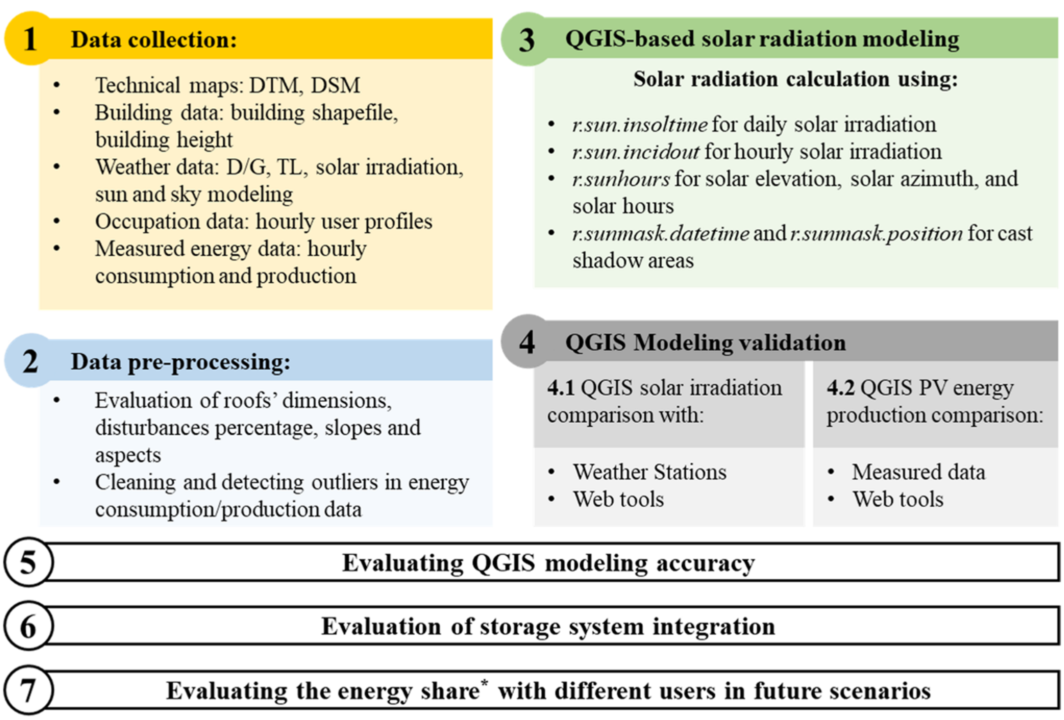

Fig. 3 General methodology workflow for QGIS-based PV production calculation *energy share: it is the self-consumption, which is the PV production that is instantaneously consumed by the prosumer or other users

the availability of building height. Similarly, building footprints can be extruded using the building height to generate a 3D model in case other related data are absent. This ensures the applicability of the model considering different input data availability about the climatic conditions and geographic characteristics.

Moreover, the model validation (step 4) is presented in this modeling by comparing the simulated results with two different sources. Future works that use similar approach can estimate the accuracy of their model using the errors presented in this work. In this case, model validation results can be used for future analysis as a reference and step 4 and 5 can be skipped for future analysis.

The following sections provide in detail the used input data and QGIS tools in this work, which are part of the represented general methodology in Fig. 3.

Data collection

The availability of accurate input data plays a crucial role in achieving realistic results, especially when conducting assessments on a larger scale. In this work, all the data used were obtained from open-source databases.

Technical maps and building data The building shapefiles, as well as the digital surface models (DSMs), were sourced from different databases. The 1 m DSM was obtained from the City of Turin, while the 5 m DSM and the building shapefile were downloaded from the BDTRE database of the Piedmont geoportal (Base Dati Territoriale di Riferimento degli Enti piemontesi), which is a geographical database providing technical cartographies of the Piedmont territory.

Weather data The monthly and annual weather data used for diffuse-to-global (D/G) solar irradiation ratio is the average values between 2006–2020 from ENEA (ENEA, Solaritaly, 2023). Another used weather data input is the Linke atmospheric turbidity factors (T_L) which were obtained from Meteonorm version 8.0, a tool that provides time series weather data. It's important to note that Meteonorm doesn't allow the selection of a specific year for turbidity calculation, instead, it uses long-term climatic data from various sources to estimate typical atmospheric conditions for a specific location. All the previously mentioned data are adjusted to be used as input data in QGIS in the required format.

Measured energy data The measured data for the current production and consumption of the analyzed PV systems are obtained from LivingLab. These measured data are used to validate the QGIS model.

Data pre-processing

The input data mentioned in the previous section are adjusted to be used as input data in QGIS following the required file formats.

Weather data pre-processing

The weather input data, related to D/G and T_L, for solar irradiation simulation are created for each month as a raster image using the raster calculator in QGIS. The average monthly and annual D/G and T_L values are provided as raster images for the irradiation simulation of *r.sun.insoltime* tool in QGIS (26 raster images: 12 monthly D/G, 12 monthly T_L, 1 annual D/G, 1 annual T_L). Using monthly weather data or average annual data for each simulated average daily day will be tested to analyze the role of input weather data resolution in model accuracy.

Geographical and building data pre-processing

The slope and aspect of the terrain are calculated using the processing toolbox in QGIS by providing the DSM raster file as elevation layer. The slope of the terrain is defined by degrees, whereas the aspect is defined by a range from 0–360 degrees: with 0 representing north, 90 representing east, 180 representing south, and 270 representing west. The slope and aspect are not only required for solar irradiation simulations, but are also important for future PV scenarios, to optimize the productivity of the new PV array based on the available roof slope and orientation.

Another aspect that is considered in the pre-processing phase is the DSM creation year. The DSM of 5 m precision was created between 23.12.2011/27.02.2012, (Geoportale Piemonte, DSM 5m, 2023) whereas DSM of 1 m is created around 2023. Due to this fact, the PV systems of Classrooms P and R were not used for model validation since the available DSM file (DSM 5 m) do not include these buildings which had been renovated recently.

The surface area of the currently available PV panels in the campus are created as a polygon shapefile in QGIS. The area is calculated using the field calculator in the attribute table of the shapefile. This area is corrected using the tilt angle of each PV panel.

Measured data pre-processing

Hourly production, consumption, and weather data can have some anomalous values related to, e.g., dysfunction of the monitoring system. These data are analyzed to avoid any irrelevant or missing values.

The reference year used for the measured data is 2022, because it includes the monitoring of the analyzed buildings, covering almost all hourly values, unlike the previous years which lack the measurement for most days. Typical days should be selected considering the average monthly temperature; by choosing the day of the month with similar daily air temperature. We started using the typical days suggested by Duffie and Beckman (1991) Table 1.6.1, and then checking the nearby days if the suggested days by the reference lack too many hourly monitored data by LivingLab, or if that day is not an average day for that month.

Solar irradiation and PV production using QGIS modeling

The steps used in QGIS to simulate solar irradiation are illustrated in Fig. 4. The simulated average daily irradiation results for each month will be used in calculating the electrical energy production from PV panels.

The QGIS tool selected for simulating solar irradiation for 12 typical days is *r.sun.insoltime*, which provides the daily incident solar irradiation on a surface using: the DSM, slope and aspect calculated using the DSM, the D/G ratio (diffuse-to-global solar irradiation ratio), and the atmospheric turbidity (T_L). By using the DSM as the 3D representation of the campus, the shadow effect from the surrounding is also considered in the QGIS modeling. For this analysis, the selection of typical days for irradiation simulation is to represent the seasonal comparison of solar irradiance. However, there are other tools that can be used for solar calculations in QGIS, including hourly irradiation simulation, for example:

1) *r.sun.incidout* which gives hourly irradiation data, but it requires the repetition of the process 24 times each day (a batch process could be used in this case).
2) *r.sunhours* which calculates solar elevation, solar azimuth, and solar hours for a specific time (hour, minute, and second).

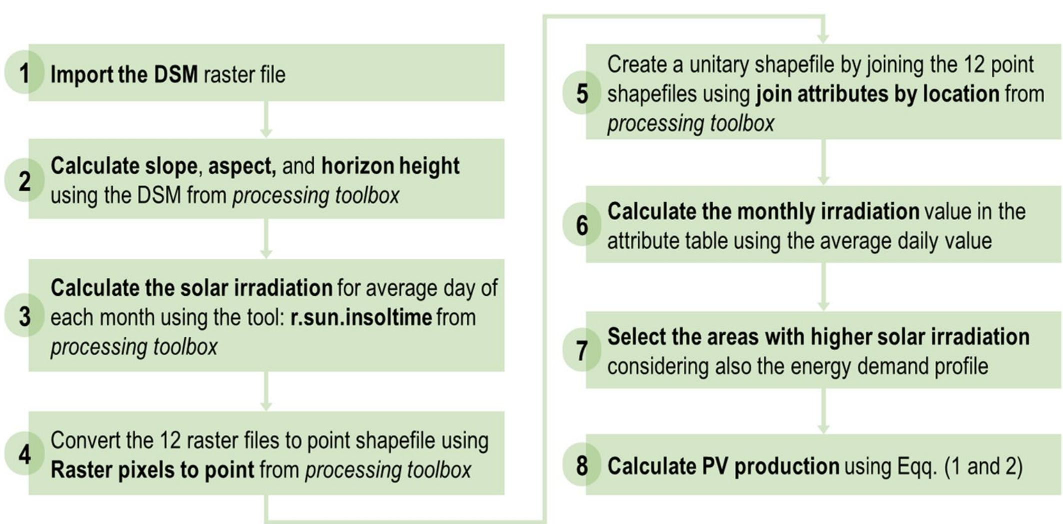

Fig. 4 QGIS steps for calculating PV production

3) *r.sunmask.datetime* and *r.sunmask.position* which calculates cast shadow areas from sun position and elevation raster map.

The QGIS model is tested by using two DSM precisions (1 m and 5 m), to test the influence of the spatial resolution on model accuracy. Moreover, the weather data (inserted in step 3 in Fig. 4) related to D/G and T_L are tested by using two temporal resolutions: average monthly and average annual values are used as input data for each daily simulation.

Model validation

The QGIS model is validated using two validation steps:

- First, comparing the results of solar irradiation simulated in QGIS with the solar irradiation data of three different sources: PVGIS, ENEA, and LivignLab 2022. The comparison with different weather data sources is provided to give insights on the different errors that can be obtained by comparing the model with webtools, national archive data, and weather stations.
- Secondly, the energy production for 12 typical days is calculated using the solar irradiation simulated in QGIS and Eq. 1, based on the work of Suri et al. (2007). The calculated production are compared with the measured production data of LivingLab related to 2022. To avoid comparing QGIS modeling with the measurements of a specific year, the calculated production will be also compared with PVGIS web-tool. The data used from PVGIS for this validation is the average incident solar irradiation values between 2005–2020 on each analyzed PV system, considering its azimuth, tilt angle, and the custom horizon height. The custom horizon height used in PVGIS is obtained from QGIS for each PV system, using r.horizon.height tool. Finally, these average irradiation values obtained from PVGIS for each typical day will be used to calculate the energy production using Eq. 1. However, this manual procedure in using PVGIS for each roof is time consuming on a large area, but a Phyton code in QGIS could be used to make an API call to send and get data from PVGIS simulations.

Another validation is performed on the working surface area of PV panels created in QGIS using the steps explained in Sect. "Geographical and building data pre-processing". In this study, the calculation of area using Eqq. 1 and 2 are employed to verify the area calculated in QGIS. The calculated area (S) and available efficiency (η) should yield the power output of the panel (Wp), which is available from the LivingLab. By using the Eqq. 1 and 2 and utilizing the available data from LivingLab it was possible to achieve a correction factor that can be also used as a reference for future similar analyses to define the real working surface area of the PV panel.

Similarly, it is important to correctly define the average solar irradiation on the panels. In QGIS, the building shapefile of BDTRE allows the calculation of solar irradiance over the entire roof area. However, this approach can lead to an incorrect average solar irradiation value. Therefore, it is suggested to use the average solar irradiation on the actual working surface of the PV modules.

The aim of the presented validation step is to assess the accuracy and applicability of this district-urban scale QGIS-based methodology in analyzing PV production for future campus sustainability scenarios. The results of the model validation presented in this work can be used as a reference for future works that uses similar analysis.

Below are the equations used in this analysis: Eq. 1 is used to calculate the electrical energy production using the net PV area, and together with Eq. 2 it was possible to find a correction factor to pass from gross to net PV area in the QGIS modeling knowing the panel power from the LivingLab:

$$\boldsymbol{E} = PR \bullet H_s \bullet S \bullet \eta \quad (1)$$

$$\boldsymbol{E} = PR \bullet H_s \bullet W_p / I_{stc} \quad (2)$$

where:

E = electrical energy produced in a certain period (kWh).
PR = the performance index of the system takes into account the cell heating losses, module performance asymmetries, shading, reflections and inverter efficiency (PR ≈ 0.75).
H_s = cumulative solar irradiation (kWh/m^2).
S = the net surface of the panel (m^2).

η = the average conversion efficiency of PV panels (%).
W_p = the peak power of the panel (kW).
I_{stc} = tested solar irradiance under Standard Test Conditions (STC: 1 kW/m^2 and 25 °C at sea level).

Case study

Politecnico di Torino is one of the historical engineering schools in the North-West part of Italy founded in 1906 and born from the Royal Application School for Engineers. It hosts 1217 teaching stuff and 39,350 students, of which 24% are international students (2023).

In this work, the central campus of Politecnico di Torino is analysed. The methodology of the assessment tool explained previously is applied on three buildings in the central campus of Polito: Cittadella, Ex_Fucine, DIATI/DISAT. The PV systems of these buildings will be used for applying and validating the QGIS-based PV production modeling. The other PV systems, Classrooms R and P, are used later for the global analysis of the campus; to calculate the increase in self-sufficiency index (SSI) after testing future scenarios.

As observed from Table 1, the buildings on the campus exhibit various orientations, predominantly SE (southeast), SW (southwest), and NW (northwest). Out of the total available vacant roof areas of 3426.7 m^2, 60% are oriented towards SE while 40% are oriented towards SW. This distribution allows for capturing maximum solar irradiation throughout the day. Considering the user profile of the campus, with high consumptions between 9 a.m. and 6 p.m., the use of PV panels with different orientations may help in increasing the self-consumption even in the early morning and in the late evening.

A study by Mutani and Todeschi (2021) analyzed solar energy using different roof orientations, emphasizing the significance of utilizing diverse roof orientations rather than solely relying on south-facing roofs. This approach enhances the solar potential as a renewable energy source. The research demonstrated that self-consumption (SC) increases significantly when combining NW orientation with either SE or SW orientations, as the energy production covers the total energy demand. However, incorporating NE panel orientation also boosts the SC, but in this case using a battery storage system is essential since the energy produced using NE orientation will be required later, particularly during peak demand hours from 9 a.m. to 7 p.m.

The campus's consumption in 2022 was about 15,000 MWh and maintained a constant value throughout the year, with higher consumption occurring in summer, particularly in July, due to cooling demand. The current self-sufficiency index is 5.1% mainly from the available PV systems and a little quota comes from the automotive power generators of the FEV Laboratory. Additionally, the hourly consumption profiles show a constant pattern throughout the day including nighttime, which is the reason behind the great consumption compared to the daily PV production. This nighttime and weekend consumption created a hurdle in achieving high self-sufficiency index (SSI) because the consumption is always much higher than the produced energy from PV panels. The reason behind this nighttime consumption was not investigated in detail but could be a consequence of the high presence of continuously working servers, calculation centers, and laboratories but also some monitoring problems. Overall, in this analysis, the real SSI is believed to be higher than what is presented.

The monthly percentage of nighttime consumption (9 p.m. – 5 a.m.) compared to the overall consumption, except of August which is an Italian holiday period, is as follows (in brackets nighttime plus weekend): 33% (57%) for January, April, October,

Table 1 PV data of the analyzed buildings

Building	Power [kWp]	Efficiency [%]	Azimuth [°]	Tilt [°]	PV Production* [kWh]
Cittadella	630	23.30	33	26	477,226.9
Ex Fucine	31	20.60	NW: 123 SE: -57	27	12,500.1 17,265
DIATI/DISAT	144	22.10	33	26	151,185.3
Class-rooms P	49	21.00	33	10	41,619.1
Class-rooms R	46.8	20.70	R1-R2:8 R4: 24	10	12,869.2

* The PV production gives the cumulated production monitored by LivingLab for 2022

and December; 31% (52%) for February, May, and November; 30% (49%) for March and September; 29% (49%) for June and July. This demonstrates that almost third of the current campus consumption is due to a quite constant nighttime consumption.

Figure 5 gives an example of the hourly energy consumption and production for a typical winter (left graphs) and summer day (right graphs). The high PV production of Cittadella and DIATI/DISAT are plotted separately to allow the readability of the other buildings, which have lower PV plant size compared to them. Between 9 p.m. and 5 a.m. there is an hourly constant consumption of about 1250 kWh in winter and 1400 kWh in summer. The use of a secondary vertical axis in red consents the comparison between the high consumptions (represented with the lines) with the current PV production (represented with bars).

The following section will present the modeling results by analyzing three buildings: Cittadella, Ex_Fucine, and DIATI/DISAT. However, it is important to note that the production data for Ex_Fucine contains numerous missing hourly measurements due to frequent malfunctions in the monitoring system.

For future scenarios, the PV areas highlighted in yellow and pink in Fig. 6 will be utilized for the new PV systems. The cumulative production from the currently available PV panels and the hypothesized new PV systems will be used to assess the increase in self-sufficiency index (SSI) of the campus.

Results and discussion

This section provides the results of:

1) solar irradiation simulated in QGIS, compared with the other three references (PVGIS, ENEA, LivingLab 2022),
2) PV production calculated by using the solar irradiation simulated for 12 typical days in QGIS software. The calculated PV production is compared with the measured data by LivingLab and PVGIS web-tool.

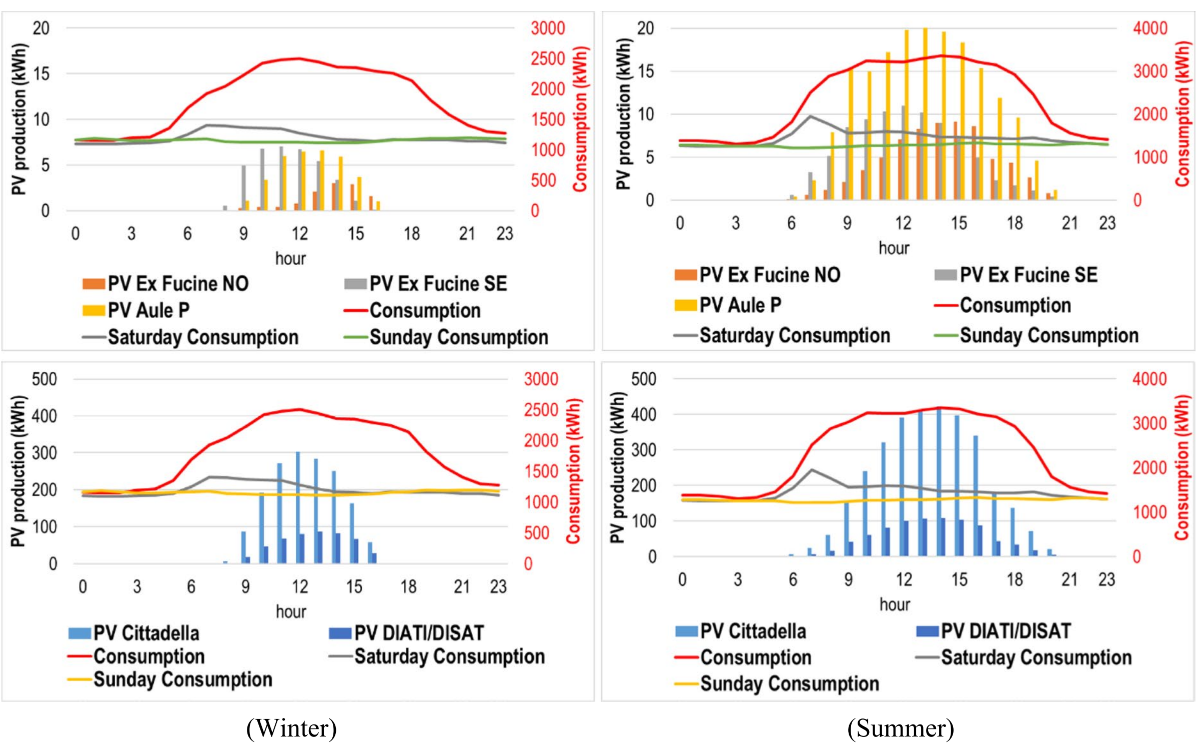

Fig. 5 Hourly measured consumption and production data from LivingLab (in 2022)

Solar irradiation results

The simulated irradiation in QGIS is the global incident irradiation on the different oriented and sloped surfaces. To validate the irradiation simulations correctly with the other three references, that represent global horizontal irradiation, four flat roofs from the campus are selected.

The solar irradiation is calculated in QGIS using *r.sun.insoltime* tool. This tool uses the topography, solar parameters, specified day in the year, and weather input data for the simulation. For topography inputs, the DSM, slope, and aspect raster files explained previously are used. The selected day in the year for each month are given in Table 2 together with the monthly and annual weather data.

The first analysis compares using different temporal resolutions: monthly or annual D/G and T_L values as input data for the irradiation simulations in QGIS. The MAPE values presented in Table 3 show that using monthly input data resulted in slightly lower error compared to annual input data. In general, the reason behind higher error for lower spatial resolution (i.e., 5 m DSM) is the solar irradiation pixels that fall onto the polygon that represent the building; when the pixel is on the edge of the building, the value of solar irradiation considers both the roof and ground values. In the following analyses the solar irradiation using monthly weather data will used for the calculation of PV production.

Figure 7 provides the monthly solar irradiation comparison between the three references and the

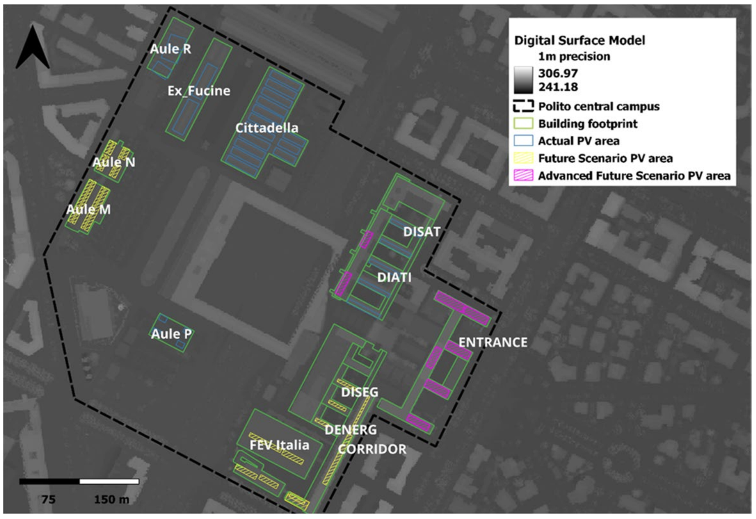

Fig. 6 DSM of 1 m with: building roof area of BDTRE shapefile (green), current PV area for solar irradiation analysis (blue), hypothesized future PV roof (yellow and pink)

Table 2 Monthly and annual average diffuse-to-global irradiation (D/G) and Linke turbidity factor (T_L)

	17 Jan	16 Feb	16 Mar	15 Apr	15 May	14 Jun	12 Jul	6 Aug	18 Sep	15 Oct	17 Nov	10 Dec	Annual
D/G	0.50	0.49	0.46	0.47	0.46	0.43	0.39	0.40	0.43	0.50	0.55	0.52	0.45
T_L	2.58	2.79	3.26	3.77	3.74	3.76	3.51	3.43	3.34	3.25	2.84	2.55	3.24

Table 3 MAPE values comparing solar irradiation results using monthly and annual input weather data

Temporal resolution	Spatial resolution	PVGIS	ENEA	LivingLab 2022	avg. MAPE
annual D/G and T_L	1 m	5.3%	4.8%	27.1%	15.2%
	5 m	5.2%	14.3%	34.4%	
monthly D/G and T_L	1 m	11%	25%	17%	14.0%
	5 m	13%	8%	10%	

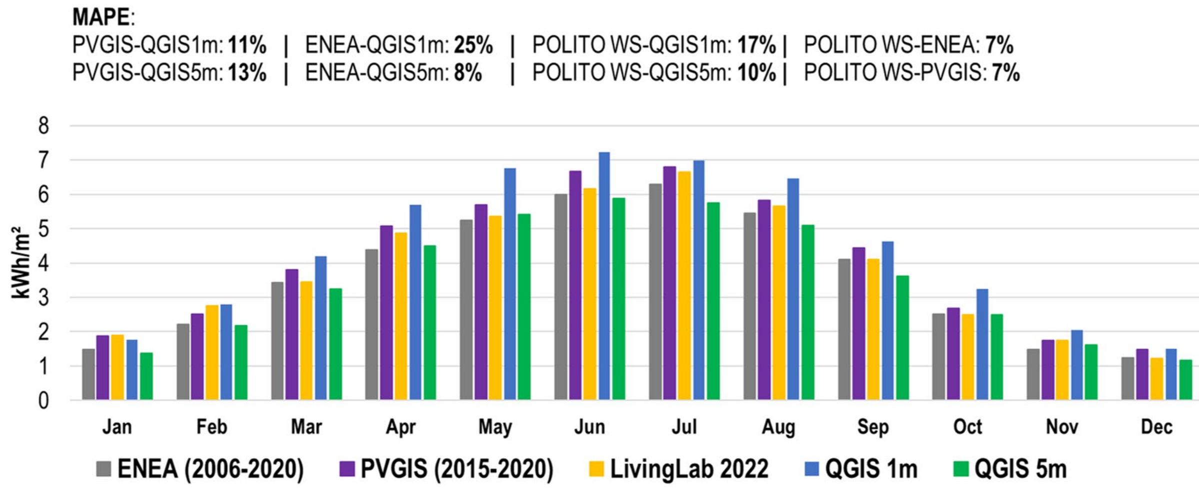

Fig. 7 Average daily solar irradiation comparison for each month between QGIS simulation (1 m and 5 m) and the three weather data references on the horizontal plane of four flat roofs on the campus entrance

QGIS modeling. Both ENEA and PVGIS exhibit a similar annual MAPE of 7% when compared to the monitored data of LivingLab 2022. However, it's notable that ENEA shows higher errors during winter compared to PVGIS when each is compared to LivingLab 2022 data.

When comparing each of the three references with QGIS modeling, we can observe that the DSM of 5 m resulted in lower MAPE than 1 m DSM when compared with ENEA and LivingLab. This can be attributed to an overlap mismatch in QGIS between the raster image of DSM and the building shapefile. In this case, the shift of DSM with 5 m precision, which uses average values for each pixel of 25 m^2, showed lower sensitivity to the overlap problem and resulted in closer values to the average daily solar irradiation reported by ENEA and POLITO WS. Despite the average annual errors, Fig. 7 is important to represent the monthly trend of the simulated solar irradiation, which aligns correctly with the references.

The second analysis compares using different spatial resolutions: the selected flat roofs for irradiation comparison are used to also compare the roof area when using DSM with 1 m or 5 m. Since the results of solar irradiation simulations are converted to point shapefiles (as provided in Fig. 4, step 4), it is possible to evaluate the roof area considered by each DSM resolution using the number of points on the roof and comparing it with the real roof area.

Table 4 shows the MAPE values considering the real roof area from BDTRE building shapefile for the four flat roofs and the area sum of the DSM points falling on that roof. The area of each point is calculated by multiplying the number of points with the

Table 4 The percentage error (PE) range and the mean absolute percentage error (MAPE) for the roof area comparison using the selected four roofs on the campus entrance

Building no. (with flat roofs)	points per roof (DSM 5 m)	25 * no. of points (DSM 5 m)	points per roof (DSM 1 m)	Real roof area BDTRE (m^2)
1	16	16*25 = **400**	**440**	**439.1**
2	26	26*25 = **650**	**609**	**609.9**
3	22	22*25 = **550**	**595**	**594.6**
4	18	18*25 = **450**	**445**	**447.2**
PE range		0.6 – 8.9%	0.1 – 0.5%	
MAPE		5.9%	0.2%	
Simulation time		About 20 min (1 month)	About 1 h (1 month)	

resolution of that DSM: 1 m^2 for DSM 1 m – 25 m^2 for DSM 5 m.

The DSM of 5 m showed a MAPE of 5.9% considering four analyzed roofs, while DSM of 1 m showed a lower error of 0.2%. Considering the simulation time of the whole area presented in Fig. 2 (with an area of 0.23 km^2), 5 m DSM has a simulation time of approximately 20 min per month, while 1 m has a simulation time of 1 h. However, it's important to note that this simulation time highly depends on both the total analyzed area and the precision of the utilized 3D representation input (whether it's DSM or DTM). For instance, based on other analyses conducted by the authors in the city of Turin, where the total area analyzed was 130.2 square kilometers, using a 1 m DSM required approximately 13 days to complete the simulation of the entire city.

Figure 8 shows the results of solar irradiation simulation with 1 m (a) and 5 m (b) DSM precisions for July 12 on the pitched roofs of DIATI/DISAT buildings. It can be observed not only the different accuracy in solar irradiation but also in the evaluation of the irradiated area (by the pixel points). However, the relation between the precision of the input data and their processing time is an important aspect to be considered for any pre-feasibility analysis.

PV production results

In the production analysis there are two main variables that influence the errors: the irradiation quota on the PV area and the net working surface area of the PV panel. The former is already presented in the previous section and concluded that 5 m DSM resulted in overall closer values to the references while 1 m DSM showed better results when it is compared to PVGIS only. Considering the working surface area of the PV panels, the gross PV area is obtained from the orthophotos in QGIS and corrected firstly by using the slope of the roof (tilted area = projected area/cos[slope°]). Then, this calculated area is compared with the available data of installed power and efficiency from LivingLab for each PV array. With this comparison it was possible to find a correction factor to pass from gross to net PV area. In this case, the used correction factor is 0.82, meaning that 82% of the PV area available from QGIS will be used in Eq. 1 for the production calculation. This number can be used for future applications, having similar approach, as a general correction factor to pass from gross to net PV area. Further studies with predefined safety or maintenance regulations for the panels should use custom calculated correction factor for the net PV area. The PV production calculated using Eq. 1 with the net PV area and the solar irradiation simulated in QGIS are validated with the measured data of LivingLab for the year 2022. This year was chosen because it has a more complete hourly production data as explained in Sect. "Measured data pre-processing". At this point, it is useful to check if the used year for validating the model is an average year compared to other years. Figure 9 illustrates the average daily solar irradiation for the used year (2022) and the average daily solar irradiation considering another four years.

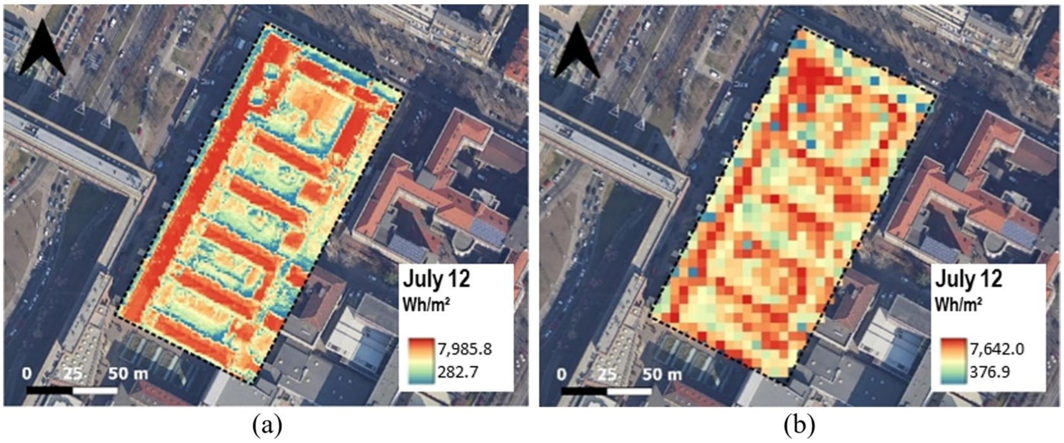

Fig. 8 Solar irradiation raster images in QGIS for Cittadella considering different DSM precision: a) 1 m, b) 5 m

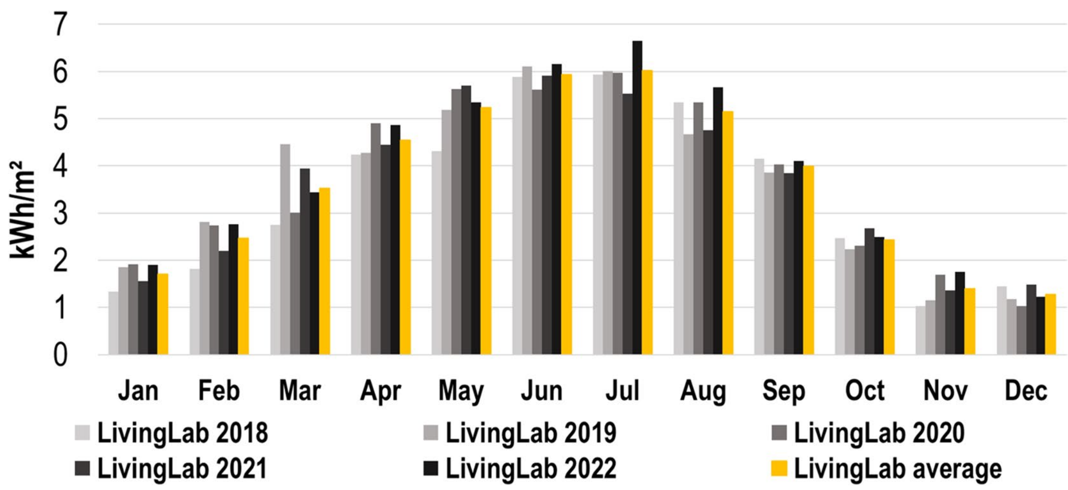

Fig. 9 Average daily solar irradiation for each month considering different years

It is possible to conclude that 2022 was an average year and doesn't have a peculiar trend.

The results of QGIS modeling for PV production, both with 1 m and 5 m DSM precisions, are illustrated in Fig. 10 by comparing the production from QGIS modeling, the measured data of LivingLab, and PVGIS.

The results obtained from the QGIS modeling demonstrate better accuracy during summer months when solar irradiation levels are high (e.g., for Cittadella 1 m: 23% MAPE for winter and 11% for summer compared to PVGIS, and 38% MAPE in winter and 7% in summer compared to the measured data from LivingLab 2022). This is related to the lower values of solar irradiation in winter; in this case a lower absolute difference between the simulated and the measured data will result in higher MAPE values in winter. Table 5 provides some examples comparing the daily production on 14 June and 10 December for Cittadella and Ex_Fucine. It is clear that smaller absolute differences in December results in higher MAPE compared to the higher absolute differences in summer.

The annual MAPE between the QGIS-based PV production modeling and the references are illustrated in Table 6. The overall average results for the four PV systems show that using higher spatial resolution results in lower error considering the comparison with two different references: LivingLab measurements and PVGIS. The MAPE values are respectively 11–10% for 1 m DSM and 36–37% for 5 m DSM. These results also show that using web-tools for evaluating the model accuracy has quite similar results compared to measured data.

The presented PV production calculation results in this section are important to provide the accuracy of this methodology using different input data precision and validation sources.

The steps presented for QGIS-based PV production calculation allow to make a pre-feasibility analysis on a neighborhood-urban scale to select the suitable areas for solar technologies, considering the solar irradiation and available area.

Evaluation of current and future PV share

The new hypothesized PV systems illustrated previously in Fig. 6 are analyzed with the presented QGIS-based methodology, using the spatial and temporal resolutions that resulted in lower errors in the previous section; 1 m DSM and average monthly weather input data.

The production from the hypothesized new systems will be used to analyze the increase in self-sufficiency level of the campus compared to the current PV production and the self-sufficiency index (SSI).

For the new PV characteristics, a *bifacial module with dual glass* is used, which is one of the highly used panels for new applications. The panels have a dimension of 1.1 m × 2.3 m, with an efficiency of 23.8%. In the future scenarios, three different orientations are considered: SE, SW, and NW. The gross

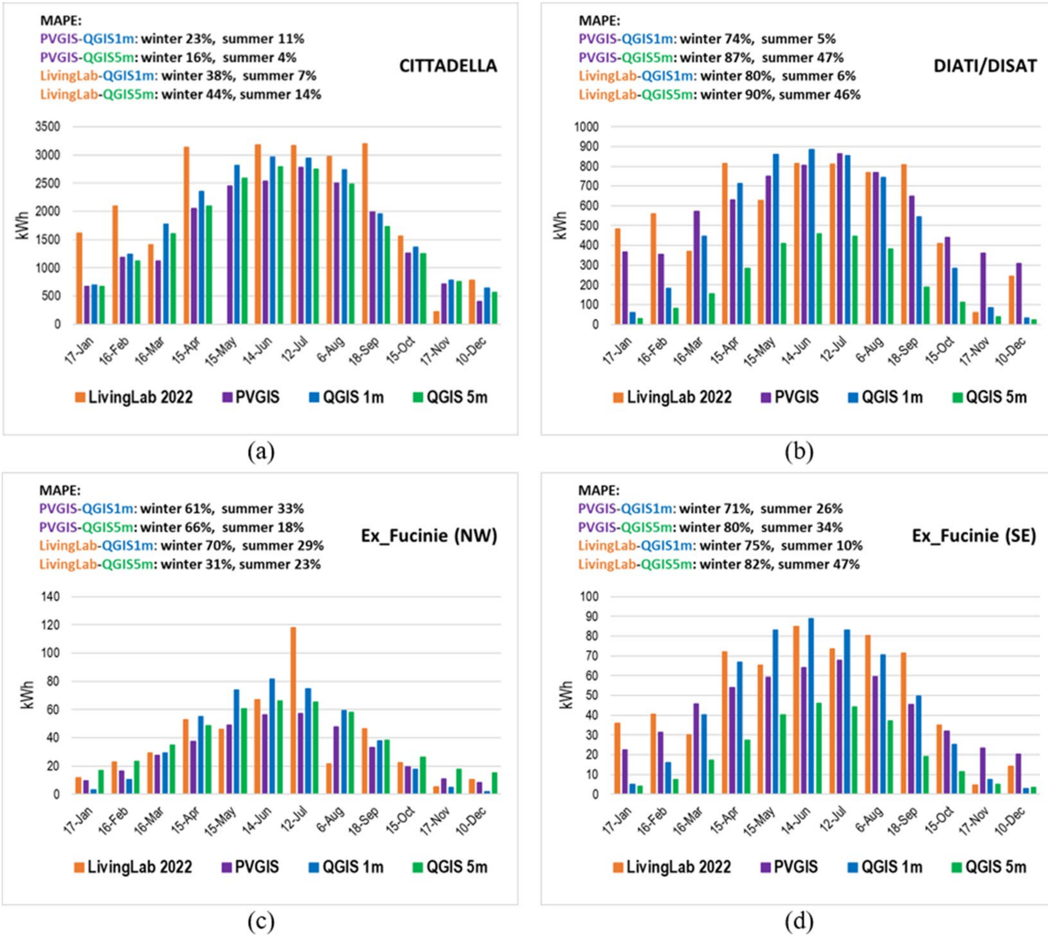

Fig. 10 PV production comparison of QGIS modeling

Table 5 Comparing the difference in MAPE for the production of typical day in winter (10 Dec) and summer (14 June)

	Cittadella		Ex_Fucine (NW)	
	14 Jun (kWh)	10 Dec (kWh)	14 Jun (kWh)	10 Dec (kWh)
QGIS 1 m model	2960.1	638.8	81.4	1.8
LivingLab 2022 measurements	3180.3	776.5	67.0	10.3
Absolute difference	220.2	137.7	14.4	8.5
MAPE (%)	7%	18%	21%	83%

area of this module is used to calculate the number of panels that fit into the polygons drawn for the future PV scenarios (pink and yellow areas in Fig. 6). The future scenario has 1060 panels, while the advanced future scenario has an extra 821 panels. The panel tilt is calculated with QGIS and is the average slope of each used roof, or 10° for flat roofs. The net area of the PV panels is calculated using the correction factor found previously, which is 82% of the gross area, and this area is used in Eq. 1 to obtain the PV production.

The solar irradiation for gable roofs is simulated as the incident solar irradiation using the DSM in QGIS. But considering the flat roofs, a correction analysis is carried out to calculate the incident solar

Table 6 Comparing the annual MAPE between QGIS modeling and two different references

	LivingLab 2022		PVGIS	
	DSM 1 m	DSM 5 m	DSM 1 m	DSM 5 m
Cittadella	17%	24%	1%	9%
Ex_Fucine (NW)	1%	4%	21%	26%
Ex_Fucine (SE)	11%	57%	2%	50%
DIATI/DISAT	16%	61%	17%	62%
Average MAPE	11%	36%	10%	37%

irradiation on 10° tilted panels. The calculation of the monthly mean solar radiation on an inclined surface and orientation is carried out knowing: geographic coordinates of the locality, solar irradiation on horizontal plane and angles of solar panels defining their orientation and tilt. This procedure complies the UNI 8477/1:1983 Italian standard: "Calculation of energy gains for building applications. Evaluation radiant received energy".

The monthly solar irradiations on a horizontal plane must be known in advance and can be obtained from (for years 2006–2020):

- Satellite images of the cloud cover acquired by EUMETSAT with a spatial resolution of about 1km x 1km
- ENEA Italian Atlas of Solar Radiation for 243 Italian cities.

In this work, the horizontal solar irradiation simulated in QGIS on the flat roof was corrected for each month for the two different orientations SW and SE according to UNI 8477/1:1983 (in Table 7).

Figure 11 shows the results of annual PV production from the analyzed roofs, considering both current PV systems and the new hypotheses (compare with Fig. 6 for clarity). The PV production illustrated on the whole roof helps in verifying the optimal placement of the new PV modules according to the received solar irradiation and available area.

The results of the two PV scenarios, namely the future scenario (Fig. 6, yellow) and the advanced future scenario (pink + yellow in Fig. 6), are illustrated in Fig. 12.

The future scenario has a total net PV area of 2523.7 m^2 and would contributes to the current self-sufficiency index (SSI) with an average annual increase of 8% (±0.8%), across the five buildings in the central campus of Politecnico di Torino. Similarly, the advanced future scenario, with an extra net PV area of 1760.3 m^2, contributes to the current SSI with an average annual increase of 11% (±1.2%). For the summer period, the future scenario yields an average SSI of 10% (±0.42%), while the advanced future scenario achieves an average SSI of 14% (±0.59%). During winter, the future scenario showed an average SSI of 6% (±3.91%), whereas the advanced future scenario reaches 8% (±5.21%). These results provide the increase in SSI considering the variance due to the errors presented in the previous sections.

Considering district-urban scale modeling approaches, it is quite challenging to provide an average error rate for production estimation. For example, many recent works that analyzed the errors in solar potential estimations are using different modeling, calculation, and validation approaches. For example, Fakhraian et al. (2021) reviewed around 50 works on PV production estimation, but the provided errors are mainly for PV area estimation or irradiation estimation using imagery data (e.g., LiDAR), statistical data, or machine learning approaches. Another work by Cheng et al. (2020) analyzed the potential of solar energy on building roofs and façades. The work presented the result of simulating solar irradiation with theoretical values and correcting it with sunshine hours obtained from a meteorological database. The root-mean-standard error (RMSE) values ranged from 0.13 to 0.67 kWh/m^2/day for analyzes 10 cities, showing that correcting the simulated solar irradiation data with measured sunshine hours improved the model. However, there are no calculated errors in the literature for PV production estimation, on district-urban scale, using a simulated solar irradiation validated

Table 7 Monthly correction factors for horizontal solar irradiation of 10° tilted surfaces

	1	2	3	4	5	6	7	8	9	10	11	12
SW	1.20	1.13	1.08	1.04	1.01	1.00	1.00	1.02	1.06	1.10	1.15	1.21
SE	1.13	1.08	1.05	1.02	1.01	1.00	1.00	1.02	1.04	1.07	1.10	1.14

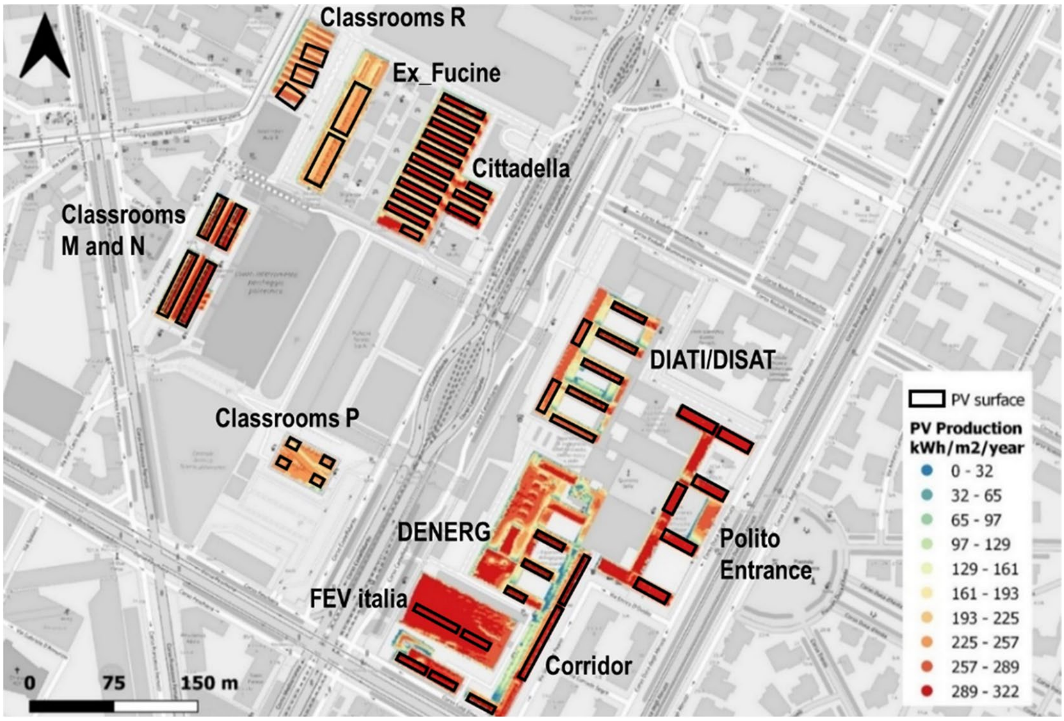

Fig. 11 Annual energy production of PV panels simulated in QGIS with 1 m DSM

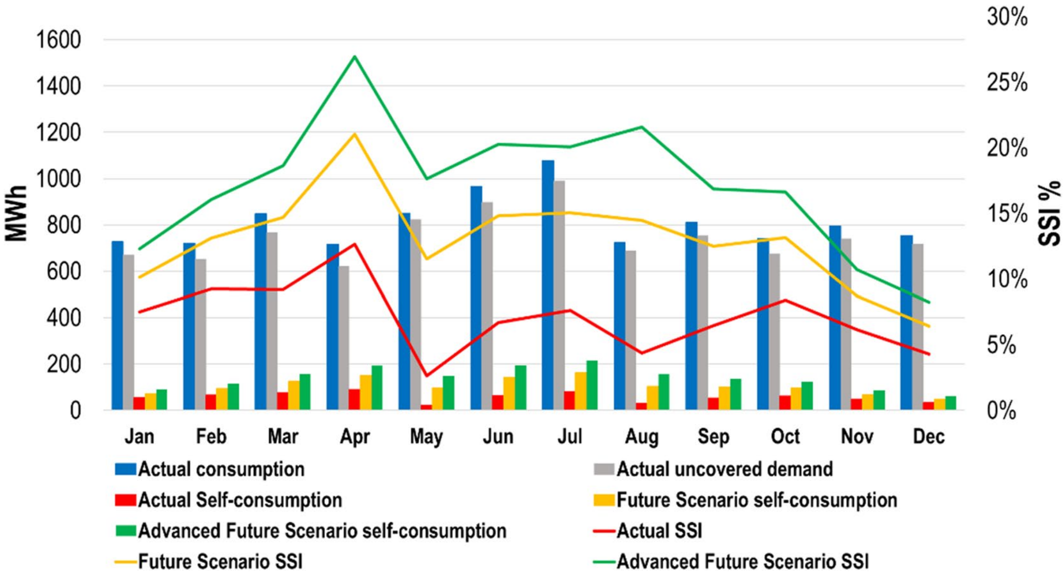

Fig. 12 Monthly consumption and self-consumption considering the actual and suggested PV systems in Polito central campus

with real measured data. Thus, the presented MAPE values in this work can give insights for future applications on the accuracy of this methodology.

Following the results presented in Fig. 12, it is important to note that in all cases, the self-consumption index (SCI) is always 100%. This is because the total PV production is instantaneously consumed due to significant energy consumption, particularly during nighttime and the summer months with space cooling. Considering the SSI, the presented results show that a considerable increase can be obtained by using some of the available and suitable roofs in Polito's central campus for new PV implementations.

However, the SSI could be increased by energy efficiency measures, like installing battery storage systems to optimize the use of solar energy production, and this step can be included in the presented QGIS-based methodology as explained in Todeschi et al. (2021). Considering battery storage systems, they have an important role in maintaining the continuity of energy supply and avoid interruptions, which in turn results in higher self-consumption levels as well. In the case of university campuses, the use of battery storage systems could be less effective since there is high continuous consumption, even at night (e.g., servers, surveillance systems, etc.). In this work the use of batteries is not analyzed since university campuses have high consumption during the whole year and the production will be instantly self-consumed reaching 100% SCI. Moreover, with the availability of calculated PV production and panel efficiency it is possible to estimate the power of the newly implemented panels using Eq. 2. The advanced scenario has a total power of 600.6 kWp, while advanced future scenario has an extra 425.4 kWp of installed power. To make economic evaluations having the power installed, the cost of 1,000 €/kW_p can be used for installed plants over 20 kW of power (Todeschi et al., 2021). In this case the economic index can be also included in future analysis, together with the energetic indexes, to provide a comprehensive assessment for new proposed scenarios.

Finally, the result of this modeling show that the presented methodology can provide a robust framework for future analysis due to the district-urban scale approach. This scale can be used for feasibility analysis of Energy Communities (ECs) or collective self-consumption systems; by evaluating the energy share between the campus and the surrounding buildings. Future proposals for improving the methodology of this work include the calculation of PV production using the available roof areas of the surrounding residential buildings, which have different consumption profiles (ARERA, 2024). This will help in improving the self-sufficiency and self-consumption levels of the connected buildings (Fig. 13).

Conclusions

This work aimed to analyze a possible assessment tool for analyzing future university campus sustainability levels. This assessment is based on using the open-source tool QGIS to simulate the solar irradiation using different spatial and temporal resolutions. The simulated solar irradiation is used to calculate the energy production from four existing PV systems on three buildings in the central campus of Politecnico di Torino. The results of this modeling are compared with the measured data of LivingLab for the year 2022, and with PVGIS web-tool. The overall evaluation of the model revealed the Mean Absolute Percentage Error (MAPE) values that can be obtained using the presented methodology with different input data precisions.

The results of this work show how the accurate description of the built environment with a detailed DSM and the monthly values of diffuse-to-global solar irradiation ratio and the Linke turbidity factors can affect the quality of the outcomes. From the presented results, it is possible to conclude that the precision of the DSM plays an important role in achieving accurate results especially for roofs with very close surrounding buildings due to higher shadow effect. For example, for DISTI/DISAT the 5 m DSM showed 46% MAPE for summer months while DSM 1 m showed only 6% (Fig. 10, b). This difference in errors is lower for Cittadella, which showed MAPE of 7% and 14% for 1 m and 5 m DSM respectively, since it doesn't have adjacent buildings as in DIATI/DISAT.

Following the model validation, the QGIS assessment was subsequently employed to analyze new PV scenarios, namely the future and advanced future scenarios (Fig. 6). The implementation of the advanced future scenario could yield a significant increase of 11% (± 1.2%) in the Self-Sufficiency Index (SSI) considering the current state of the campus, which is currently at 5.1%. This finding is noteworthy since the widely used campus sustainability ranking tools, like Green Metric, utilize the SSI as a key indicator for evaluating campus sustainability.

The analysis also sheds light to the importance of data pre-processing, which helped identify the

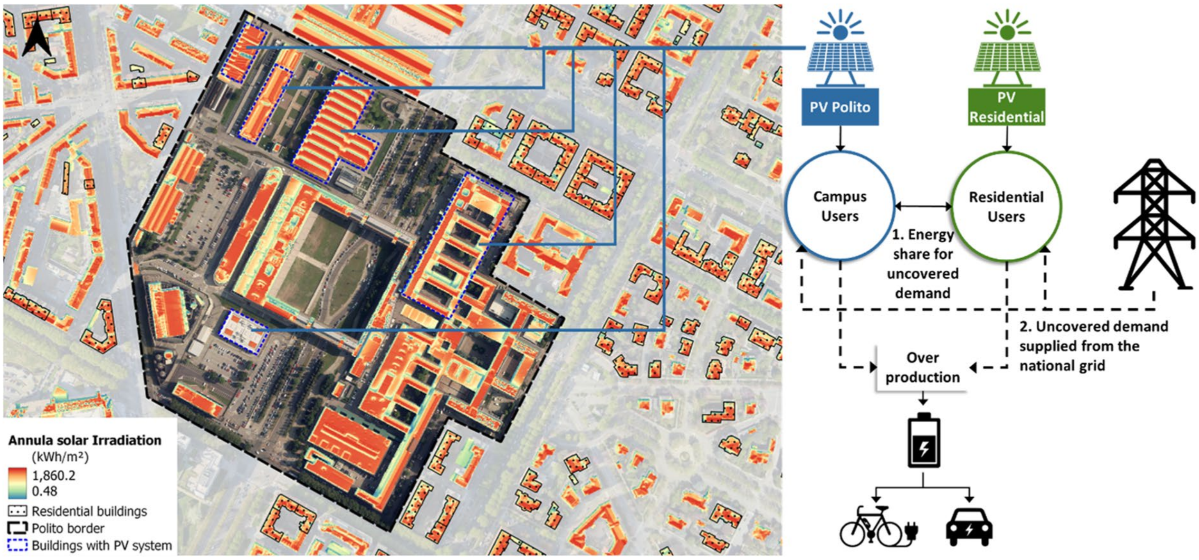

Fig. 13 Energy share scenario for future development

nighttime consumption that accounts for a high consumption percentage through the whole year (Sect. "Case Study"). This explains the low SSI values despite the considerable total PV power installed on the campus. However, the SSI reaches 20% when excluding the nighttime and weekend consumption. This shows that an energy audit should be implemented to reduce the consumption first and then to include PV plants, sizing it based on the demand, to optimize the SSI.

In conclusion, the QGIS-based methodology of this work can be useful for pre-feasibility analysis of future scenarios to test the effectiveness of implementing RES in university campuses, considering its spatial distribution within the urban area. The results of the assessment can be used to predict the sustainability ranking of future campus renovations. Furthermore, the methodology allows the creation of communicative maps that effectively illustrate past and future actions aimed at enhancing the sustainability

Table 8 SWOT analysis for the methodology of the presented assessment tool

S (strength) • assessment on large scale urban context • capacity to scale up the modeling from building to neighborhood-district scale and viceversa • acceptable simulation time and precision for a pre-feasibility analysis	W (weakness) • input data availability • input data accuracy: lower precision will result in higher errors (e.g., hourly, daily, monthly or annual data; DSM or DTM with 0.2 m, 1 m, 5 m, 10 m, 20 m, 50 spatial resolutions) • high simulation time considering large areas with high precision (e.g., city scale with 1 m or 0.5 m DSM)
O (opportunities) • spatial distribution analysis of energy share opportunities between the campus and the surrounding urban context (e.g., energy communities) • the multiple use of solar maps in a city by different stockholders: citizens, university, public administration, companies etc. for different types of analysis; from building to district-urban scale	T (threats) • big-data management (e.g., data cleaning and outlier detection) • lack of expertise in statistical analysis • low QGIS knowledge (e.g., use of plugins to evaluate the real urban environment)

of university campuses. These maps serve as valuable tools for visually showcasing the initiatives undertaken or planned for promoting sustainability in university campuses. Finally, the effectiveness of this methodology can be summarized providing the SWOT analysis of this assessment tool: Table 8

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Data Availability We can share data upon request (e.g., solar irradiation data).

Declarations

Conflict of interest The authors have no conflict of interest.

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