A Framework for Economic and Environmental Benefit Through Renewable Energy Community

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A framework for economic and environmental benefit through Renewable Energy Community

Matteo Orlando, Lorenzo Bottaccioli, Stefano Quer, Massimo Poncino, Sara Vinco and Edoardo Patti

***Abstract*—The uprising necessity to lower CO_2 emissions and reduce energy expenditures fosters the shift toward renewable energy sources. Photovoltaic installations are the most widespread choice of renewable sources as they are relatively cheap and suited even for urban environments due to their small footprint. To reduce the initial investment and maintenance costs, the market is pushing customers to participate in Renewable Energy Community, i.e., groups of customers that share photovoltaic systems to satisfy their energy demand by maximizing self-consumption and minimizing energy withdrawal from the power grid (eventually, they can even sell production surplus). However, the organization of these communities brings new challenges, such as optimizing the facility and estimating its economic impact. This paper proposes a framework that combines geographical, meteorological, and demographic information to design optimal photovoltaic systems and evaluate the following economic benefits for the community members. To provide a complete analysis, we also consider the environmental benefit in terms of reducing CO_2 emissions. Our tests on several real-world case studies prove that our framework facilitates the installation of efficient photovoltaic systems, reducing both the energy withdrawn from the power grid and the CO_2 emissions.**

***Index Terms*—Photovoltaic installation, PV design, PV optimization, GIS-based design, Energy Community, CO Emissions**

I. Introduction

Nowadays, Renewable Energy Sources (RESs) provide approximately 14% of the global energy demand, and this percentage is estimated to rise to 50% in 2040-2050 [1]. This shift toward RES is pushed forward by the urgent necessity to reduce the global level of CO_2 emissions [2] through (i) international agreements [3] and the adoption of *carbon-taxes*, used by more and more countries to discourage the usage of fossil fuels [4], and (ii) the application of incentives for the deployment of RES systems, which have proved to be extremely effective in several countries [5].

In this context, PhotoVoltaic (PV) energy has a primary role as it is known to be a sustainable, cost-effective, reduced footprint source of energy that requires minimum maintenance [6]. Projections foresee that PV energy will provide 25% of the global power generation by 2040-2050 [7]. This success will be partially enabled by the fact that, compared with other renewable energy sources such as wind turbines, PV systems are also suited for urban and industrial environments [8].

The adoption of PV systems is also fostered by the diffusion of the *prosumer* paradigm, i.e., a new kind of energy market player that can both produce and consume energy. In the future, a prosumer will be able to use a PV system (or any other RES) not only to produce energy for self-consumption but also to sell production surplus [9]. Such a solution seems promising, thanks to affordable costs and government incentives. However, in the case of a single household, the initial investment and the economic effort needed to maintain the entire system may discourage such an environmental-friendly choice [10].

A possible solution to the above challenges is assessed by the emerging *Renewable Energy Community* (REC) paradigm, defined by the International Renewable Energy Agency as a group of citizens that work together to reduce their environmental and economic impact [11]. The key feature of a REC is "resource sharing", i.e., the idea of sharing PV modules and rooftops to bring benefits to the whole community [12]. RECs can facilitate the diffusion of renewable energy sources and encourage investments. At the same time, they can provide direct benefits to the members in terms of smaller energy costs and better energy efficiency, as proved by several initial studies [12]–[14].

RECs need detailed planning to achieve their main objectives, that range from obtaining profits for the stakeholders to acquiring equal benefits for all participants [15]. Selecting the correct REC schema depends on both demographic and geographic information. First of all, communities located in an urban environment may have limited space for the deployment of PV panels. Secondly, the latitude where the community is located deeply affects day length and, therefore, the quantity of energy produced. In addition, the demographic profile of the community delineates the budget for the investment, the expected savings or profits, and the projected required energy. As a consequence, it is of paramount importance to predict the impact of RES installations.

In this perspective, our goal is to facilitate the installation of RES. Focusing on PV technologies, we present an automatic software framework that exploits available geographic, demographic, historical data, and models of power generation to estimate the economic and pollution impact of the installation and to maximize the benefit for the REC.

Built upon our previous works [16], [17], the framework includes the four main stages outlined in Figure 1:

1) *PV installation planning and optimization:* The proposed framework automatically designs the most suitable PV installation, given the geographic constraints of the area of interest (modeled as Geographic Information System data, GIS) and historical data of irradiance. The algorithm explores different configurations to maximize irradiance exposure and power production, and it allows to place PV modules across different rooftops, as part of the REC sharing approach.

M. Orlando, L. Bottaccioli, S. Quer, M. Poncino, S. Vinco and E. Patti are with the Department of control and Computer Engineering, Politecino di Torino, Turin, Italy. Email: {name.surname}@polito.it.

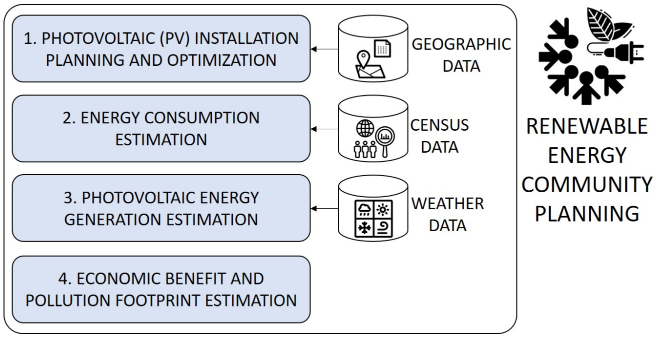

Fig. 1. Our solution to support the planning of RECs; we (1) exploit geographic information for planning district-level PV installations, (2) measure the energy power consumption for the district of interest from census data, (3) estimate the resulting yearly PV power generation from weather data, and (4) evaluate the economic benefit and pollution footprint to allow the REC to make informed decisions.

2) *Energy consumption estimation:* The power demand of the REC is estimated by considering the demographic information of the district. Census information is automatically elaborated to derive disaggregated power consumption traces reflecting the district inhabitants (e.g., in terms of family size and behavior).
3) *Estimation of power generation:* The output of the installation is obtained from power generation models of the PV modules. These are obtained from yearly traces of irradiance by taking into account the analysis of phenomena such as shading on the distribution of irradiance over the district.
4) *Estimation of the benefit for the REC:* In terms of (i) economic benefit, due to a reduction of energy demand from the grid thanks to self-production, and (ii) reduction of the pollution footprint, measured as a reduction of CO_2 emissions [18].

The proposed solution is applied to five districts in and around the city of Turin, a large city in northwest Italy, representing a wide variety of urban and suburban scenarios (in terms of population size and distinct building densities). It is however important to note that *this work does not propose a country-specific solution*. Indeed, the proposed framework is applicable to any geographic area with minor configuration changes (for example, required to leverage different latitudes [19], [20]) once that the necessary information are available.

The paper is organized as follows. Section II describes related works in literature and the main differences with our previous works [16], [17]. Section III gives some major hints on photovoltaic power generation. Section IV introduces our framework, and Section V applies it to the case studies. Finally, Section VI reports some concluding remarks.

II. Related works

A. RECs and PV installations

RECs play a crucial role in successful energy transitions as they increase the flexibility and resilience of energy systems, and spread the acceptance of bigger renewable energy projects [21]. RECs are composed of a variety of actors (such as households, public institutions, business activities, etc.) sharing the common goal of producing energy from renewable sources to maximize self-consumption, hence reducing the need to withdraw energy from the electric grid.

However, a simple installation of a shared renewable energy plant through an investment of a community is not enough to set up a REC. Many other challenges need to be taken into account, such as legal aspects, grid connections, demand flexibility policies, and storage systems [22]. The legal institution of a REC is the first challenge that needs to be analyzed since regulations vary from place to place. For example, EU and North America have distinct policies [23], [24] with differences even among countries [25]. In addition to that, due to the complexity of the system and the variety of actors involved, RECs need careful planning to ensure efficiency and success [26]. The first thing to consider is the type of renewable energy that should be deployed. As previously mentioned, cost reduction makes PV systems the perfect choice for a collaborative approach; thus, the literature provides several solutions to plan a PV system in a REC [27] or with Demand Response Policies [28], [29]. However, this work goes a step further as it focuses on the *optimization of the PV placement in the context of a REC*, providing a more efficient cross-rooftops configuration of the whole system with respect to traditional individual rooftop installations.

B. Optimal planning of PV installations

Finding optimum arrangements for RES is of paramount importance, and it has been analyzed from several perspectives in the literature.

Some works focus on the combination of different types of RESs and analyze their impact on the resilience of the electrical network [30]–[33].

Other works concentrate on the organization of the panels. GIS technologies, such as Digital Surface Models (DSMs) and other 3D modeling techniques, are used to analyze real scenarios allowing digital representations of the area under study [34]–[36]. Some works use GISs information to improve their estimates of the power production of PV systems. Other authors [37]–[39] use GISs to estimate power production in large areas (such as an entire region or an island) using low-resolution maps.

Sun et al. [41] use a similar approach to estimate the PV potential at a regional level, analyzing costs and benefits, and evaluating the reduction of CO_2 emissions. Anyway, their approach does not fully exploit GISs as it does not suggest any strategy to maximize the production of a PV system.

Raul et al. [42] propose a solution to evaluate PV production at the national level. They include in their work an economic analysis taking into consideration the different socioeconomic situations across the country. They use cadastral data and apply a correction factor to estimate the actual surface available for each PV module. Unfortunately, they do not consider the real topology of the rooftops and therefore they do not provide any configuration for the PV module.

Other works [34], [43], [44] analyze smaller geographical areas to evaluate power production of PV systems. However, only traditional panels installation are considered, and therefore, production is not optimized.

TABLE I
A SYNOPTIC COMPARISON BETWEEN OUR FRAMEWORK AND THE MORE SIMILAR WORKS RECENTLY PRESENTED IN THE LITERATURE.

	PV potential	**Available surface**	**Historical data**	**PV module specification**	**15 min resolution**	**Optimized placement**	**Load profile analysis**	**REC approach**	**Energy Savings**	**CO_2 emissions**
Baranay et al. [37]	✓	x	x	x	x	x	x	x	x	x
Khemiri at al. [38]	✓	x	x	x	x	x	x	x	x	x
Bergamasco et al. [40]	✓	x	x	x	x	x	x	x	x	x
Sun et al. [41]	✓	x	x	x	x	x	x	x	x	✓
Miranda et al. [42]	✓	x	x	x	x	x	x	x	✓	x
Kucuksari et al. [34]	✓	✓	✓	✓	x	x	x	x	x	x
Bracco et al. [43]	✓	✓	✓	x	x	x	x	x	✓	x
Huang et al. [44]	✓	✓	✓	x	x	x	✓	x	✓	x
Jacques et al. [45]	✓	✓	x	x	x	x	x	x	x	x
Bergamasco et al. [39]	✓	✓	✓	x	x	x	x	x	x	x
Damiri et al. [46]	✓	✓	✓	✓	x	x	✓	x	✓	x
Vinco et al. [47]	✓	✓	✓	✓	✓	✓	x	x	x	x
El et al. [48]	✓	✓	✓	✓	✓	✓	✓	x	x	x
Cielo et al. [49]	✓	✓	✓	✓	✓	x	✓	✓	✓	x
Syed et al . [50]	✓	✓	✓	✓	✓	x	✓	✓	✓	x
Our previous works [16], [17]	✓	✓	✓	✓	✓	✓	x	x	✓	x
Proposed	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Jacques et al. [45] use high-resolution Light Detection And Ranging (LiDAR) images to identify the rooftops on which installing the PV modules. However, they evaluate the power production without taking into account the exact position of the modules as they consider the entire rooftop as available.

Bergamasco et al. [39] take into consideration the rooftops of an entire city and use the GIS to select with high accuracy the rooftops available for the PV modules. Anyway, they do not give any indication regarding the actual placement of the module, and they provide a rough estimate of the power production considering the azimuth angle and the entire surface.

Another weakness of all previous works is that they do not use historical data to estimate energy production. However, it has been demonstrated that this information can be extremely effective in improving the accuracy for those approaches that use only data obtained through theoretical equations [51]. For such a reason, several studies use hourly or quarter-hourly historical data to provide more precise estimations with realistic sky conditions.

Damiri et al. [46] use meteorological and solar irradiance data to estimate the power production of a PV configuration placed over an industrial rooftop. However, even if they provide a feasible PV module configuration, they consider only a single rooftop.

Similar studies, like [47], [48], exploit historical data to identify the best placement for the PV modules over different buildings. However, they do not focus on RECs, and rooftops are considered individually and not as a shared resource.

All previously mentioned works consider a single building or household and not a REC, where different buildings can be organized as a single shared resource. Sharing rooftops allows cross-rooftop connections and, more in general, energy sharing, with enormous benefits in terms of power production [52], [53]. For this reason, Cielo et al. [49] use historical irradiation and disaggregated consumption data to evaluate the impact of shared PV systems on a community. However, irradiation is not used to optimize PV module placement and maximize production.

Syed et al. [50] evaluate the benefit of a PV system shared among households. The authors also compare household load profiles with energy production to evaluate the possible advantages of such a shared system. However, even in this case, the panels' position is not optimized to maximize energy production, and there is no analysis on the reduction of CO_2 emissions.

Overall, the novelties of our approach with respect to the previously mentioned works are summarized in Table I.

The framework proposed in this work is based on [16], [17] from which it derives the procedure related to evaluating the available surface and the model used to assess the energy production of a PV module. This framework, however, adds some major novelties and improvements with respect to our previous works [16], [17]. It introduces the possibility of testing PV configuration with modules arranged in different directions. This feature increases the optimization procedure's flexibility to maximize the system's production further. Moreover, we abandoned the previous approach used to estimate the economic benefits that were too tightly related to the cost of energy, which may widely differ from one place to another. Therefore in this work, we evaluated such benefits as the percentage of self-consumption since this gives a more general but still valid indication of the advantages obtained from participating in a REC. This approach required an additional step in the processing pipeline that uses census data and smart-metering measurements to provide accurate energy demand profiles for the REC under study. We analyze five different areas covering three different REC scenarios spanning from urban to rural (whose size ranges from about 6000 m^2 to about 144000 m^2) to optimize the PV system. We selected these areas to analyze scenarios with different characteristics, such as population and building height or distances. To summarize the primary novelties concerning [16] and [17] (references from the manuscript and below) are:

- The improvement of the cross-rooftops algorithm to find the suitable area for PV system installations by increasing the search space of the optimization problem under analysis.
- The reduction of the dependency of the economic benefit on the fluctuation of the prices of hardware and energy.
- The integration of new studies, which integrate both actual census data and real world household load consumption.
- The estimation of the environmental impact in terms of

CO2 emissions, which decrease by creating new RECs .

- The analysis of different case studies to analyze the possible impact of REC in various urban and rural scenarios"

Our framework uses fine-grained DSM together with historical weather data (with a resolution of 15 minutes) to provide an optimal configuration of the PV panels placement.

The PV module we consider can be easily changed with other models to ensure a more realistic estimation and increase the flexibility of our framework.

We assume all rooftops as belonging to a shared resource and we connect panels located on different buildings (i.e., we allow cross-roof connections). We prove that our estimated power production is always more significant than the one generated with an equivalent traditional installation. We compare the estimated power production with the aggregated power demand to evaluate the self-sufficiency capabilities of the REC. We estimate the reduction of pollutants (in terms of CO_2 emission) for the scenario without the REC.

III. Photovoltaic power generation

A PV module is a collection of photovoltaic cells using solar irradiance as a source of energy to generate direct current electricity (please, see the two leftmost pictures in Figure 2). The power production of a PV module changes as a function of the irradiance G, and the generated current and voltage increase proportionally to G [47] (with a more significant impact on the current production).

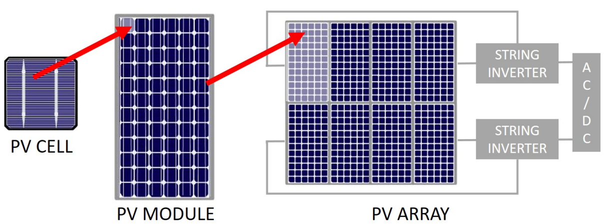

Fig. 2. PV cells (left-hand side) are connected in series to build a PV module (in the center). PV modules are then organized in a parallel connection of series strings to achieve the desired current and voltage levels (right-hand side).

As shown in Figure 2, in any installation, PV modules are typically connected in series and in parallel to achieve the desired voltage and current levels [54]. If two connected PV modules work with the same input irradiance, then their connection doubles the output power production. However, this is rarely the case, as in many areas obstacles such as chimneys, surrounding buildings, trees, etc., project shadows and cause a heterogeneous distribution of the irradiance [55]. Shading is critical for PV facilities, as the least irradiated module acts as a bottleneck for power production. In other words, when several modules are connected in series (parallel), the least irradiated module will provide the smallest current (voltage).

To limit the impact of shading, it is necessary to define a shading-aware topology (please, see the right-hand side of Figure 2). In this scheme, PV modules with similar irradiance levels are connected in series to form a string controlled by an inverter. The production of a series string is constrained by the least irradiated PV module, as the current production is equal to the minimum current production, whereas voltages are added. Series strings are then connected in parallel, to sum the current production of all strings. Such a parallel connection is then connected to an AC/DC inverter that makes power available to the utilities and/or to the grid.

IV. Methodology

Our main target is to build a framework to analyze the economic and pollution benefits that RECs can obtain by sharing PV installations. From a high-level point of view, our framework includes three main phases containing the six different steps represented by the numbered blocks in Figure 3:

(1) In the first phase, the framework uses DSM data to extract the surfaces of the rooftops on which it is possible to install PV modules. This analysis is then used to extrapolate the temporal evolution of irradiance and temperature for the area under study.
(2) The second module performs a statistical analysis of the data generated during the first stage to find the portion of the rooftops with the best irradiation condition (which is obviously expected to produce more power than poorly irradiated ones).
(3) In the third module, the previous evaluations are used to find an optimal configuration for the modules of the PV system.
(4) Such a configuration is then used by the fourth module to estimate the power production of the PV system with a procedure that uses DSM, meteorological data, and the datasheet of the PV cell.
(5) The fifth module estimates the power demand of each partner of the community.
(6) In the sixth and last module, the framework uses our estimates (in terms of power generation and power requests) to evaluate the potential savings in terms of both energy and CO_2 emissions.

A. Deployment area and irradiance

This first module (block (1) in Figure 3) is in charge of identifying the rooftops available for the PV facility. We use a Digital Surface Model (DSM) of the area under analysis to recognize encumbrances on rooftops and evaluate the evolution of the shadows during the day. The DSM files are analyzed by using GDAL [56], i.e., a tool to process geospatial information represented as raster or vector images. To achieve the best power production, we individuate those rooftop surfaces with the most suitable value of tilt angle and orientation by using two different GeoTIFF files: The first one stores information on roof slopes, and the second one collects information on aspect values. DSM files are then processed to extract only those surfaces with a slope in the range 15°–36°and the aspect in the range 240°–300°. This process identifies the rooftops oriented to the south with optimal irradiation, i.e., the ones with the highest potential to generate power [57].

Each one of the extracted areas is then coupled with the average height of the rooftop. This information is used to check whether it is possible to connect PV modules installed on different rooftops. Using this knowledge, we evaluate the evolution of irradiance and shadows over time using the model developed in [19]. This step speeds up the entire process as only rooftops suitable for PV facilities are taken into consideration by the following stages, thus reducing the overall amount of information we have to simultaneously manipulate and maintain a high spatial resolution.

B. Pre-placement performance evaluation

The second module (block (2) in Figure 3) locates the rooftop areas which receive the highest irradiation. To perform this step, it checks all possible placements on the identified roofs with panels oriented vertically and horizontally, and computes the 75-th percentile of the irradiance. These configurations are then sorted by a decreasing value of 75-th percentile to give the highest priority to the most promising ones in the following steps of the procedure. Further details of this phase are reported in [16].

C. Optimal placement algorithm

The third module (block (3) in Figure 3) identifies the best possible panel configurations selecting them from the sorted list generated by the previous module.

Our procedure selects the first, and most promising, configuration. Then, it runs through all remaining configurations to select the ones compatible with the selected one according to the following constraints:

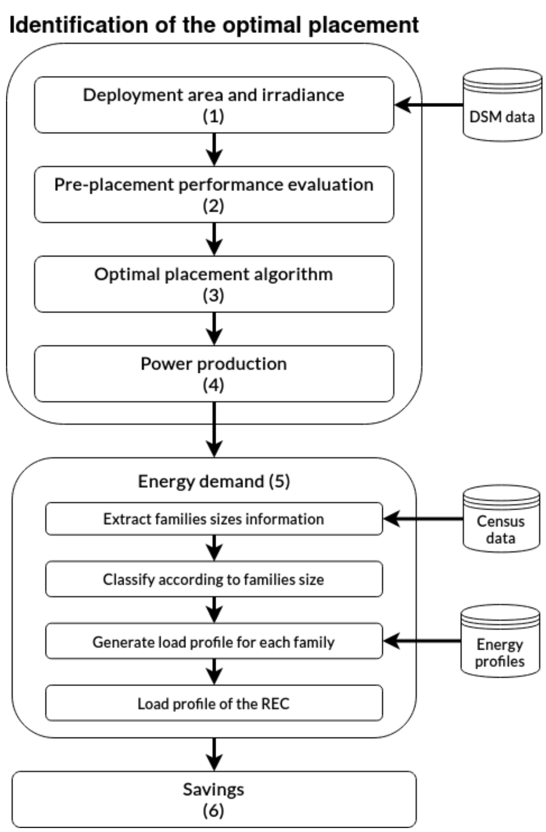

Fig. 3. Diagrammatic representation of our framework with its three main phases and six main pipeline steps.

1) Each new PV module should not overlap with previously placed modules.
2) The horizontal distance between two consecutive modules should not exceed a threshold *maxD*.
3) The vertical distance between two modules should not exceed a threshold *maxH*.

The two thresholds (*maxD* and *maxH*) are used to connect modules that are closed enough (horizontally and vertically, respectively) and to consider all rooftops of the community as a shared resource.

We iterate through the process until we obtain a series of S panels. Every time we select a configuration, we remove it from the list of the remaining ones. When we complete a series, we re-insert all positions that do not respect constraints (2) and (3) in the sorted list, whereas if a position does not respect constraint (1), we completely remove it from the list. We terminate the process when the number of available positions is less than S, as this condition implies that it is not possible to form a new complete series of PV modules.

The result of this procedure is a group, i.e., a set of PV modules placed on contiguous rooftops. The connection of PV modules is aware of voltage and current, and the connection of PV modules in series and in parallel respects the constraints of the inverter. In particular, series are of the same size as in the traditional placement. What changes is that our approach is aware of partial shading; connection is not based on physical contiguity but rather on the GHI information on the yearly irradiance distribution on the different PV modules. Due to the structure of the algorithm, PV modules that belong to the same series are indeed likely to have a similar evolution of radiance over time. This characteristic avoids bottleneck effects caused by the partial shading of one PV module of the series.

Notice that, in our experimental evaluation, this procedure is executed three times for each case study to consider three different panel orientations, i.e., the ones with only vertical panels, the ones with only horizontal panels, and the ones with both vertical and horizontal panels. The evaluation of different orientations is an important novelty with respect to previous works (such as [16], [17]) as our algorithm may place panels belonging to the same series not side-by-side, as it would happen in traditional PV configurations.

D. Power production

The fourth module (block (4) in Figure 3) estimates the yearly power produced by the identified configuration. During the first step, using the approach described in [54], this module evaluates the yearly traces of voltage and current for each PV module by extracting relevant information from datasheets of real PV modules. Then, it computes the overall power production, taking into consideration all PV modules and their connections (as defined in Section III): The current generated by a series of PV modules is limited by the module producing the minimum current, and the voltage generated by the entire PV installation is constrained by the series producing the minimum voltage. This methodology increases the flexibility of our framework since we can easily evaluate the power production obtained using PV modules with different characteristics.

E. Energy demand

This module estimates the hourly power demand of the community and compares it with energy production. The logic of this phase is reported directly inside the block (5) of Figure 3.

To estimate the power requirements, we use a real dataset provided by Midori s.r.l. [58]. This dataset contains the energy consumption profiles of more than 90 houses located in Turin and disaggregated at the appliance level. The dataset is pre-processed using the Jenks Natural Breaks method [59] to classify consumption data according to the number of inhabitants of each house. Using these results, we assign to each house a realistic power demand profile by selecting one of the houses with the same number of inhabitants. The results of this preliminary classification are combined with the census data [60] to build a realistic virtual population for the geographical area of interest. The resulting synthetic population is exceptionally realistic and presents different energy consumption behaviors tailored to the demographic composition of the area. The different profiles are finally combined to obtain a realistic profile for the entire community for one year.

F. Savings

In the last module (block (6) in Figure 3), we compare the power demand of the community with the power produced by its shared PV system to establish the degree of energy self-sufficiency and the reduction in CO_2 emissions. We compute the percentage of self-produced energy as the ratio between the yearly energy demand of the REC and the yearly energy production of the shared PV system. Moreover, to estimate the reduction in terms of CO_2 emission, we compare the case in which the yearly energy demand is satisfied only by fossil fuel energy sources with the case in which a portion of this energy is self-produced directly by the REC. In this case, we also consider the small but not negligible amount of CO_2 generated by all PV modules. CO_2 are computed following Equation 1.

$$CO_2 = \frac{(PV\,energy) \cdot (PV\,CO_2\,emissions)}{(Total\,energy\,demand) \cdot (fossil\,fuel\,CO_2\,emissions)} \tag{1}$$

V. Experimental Results

We test our framework on different neighborhoods in the city of Turin to verify our framework for a large variety of scenarios:

- *Town Center*: Area of a city with a high building density where buildings may have different heights, ranging from 3 to 7 or more floors. The age of the structures varies a lot, as we have both historical and modern buildings close to each other.
- *Outskirts*: Area with a medium density of buildings with very similar heights (from 1 up to 3 floors). Usually, buildings are populated by one or, at most two, families, and backyards often separate them. This category also includes villages.

TABLE II
Comparison between the total area of all rooftops and the area suitable for the installation of each one of the five case studies.

Case study	Buildings area (m^2)	Suitable area (m^2)	percentage	number of panels vertical	horizontal	mixed
Town center 1	5,702	909	15.9	176	184	208
Town center 2	4,032	808	20.0	136	184	152
Town center 3	9,275	1,553	16.7	456	384	656
Outskirts	3,233	804	24.9	72	40	96
Suburban	10,232	1,268	12.4	384	336	480

- *Suburban area*: Area with small houses located very sparsely on the territory, each owned by a single family.

We ran five experiments: Three located downtown, one in the outskirts, and one in the suburban area. We ran the proposed optimization procedure on a desktop equipped with Ubuntu 20.04, a CPU Intel(R) Core(TM) i7-8700 @ 3.20GHz, and 16 GBytes of RAM. We needed 22 minutes to obtain an optimal solution for all the case studies proposed in this work. The first objective of these tests is to prove that our framework builds PV installations that generate more energy than the ones placed by traditional methods. Our secondary objective is to prove that our configurations reduce energy withdrawn from the power grid and greenhouse gas emissions. For each outline, Table II reports the size of the portion of rooftops that could be used to deploy PV modules (i.e., the areas facing south and without encumbrances). Figure 4 shows the result obtained by our panel allocation algorithm for the first scenario. We highlight the entire surface in green and the selected area in red. It is worth noticing how the area suitable for the installations is just a tiny portion of the rooftop surface ranging from 12.4% up to almost 25%. We obtain similar results for all outlines, even with the ones including different building profiles, such as the Town Center Area 2 and the Outskirts Area. Moreover, the buildings of the Suburban Area cover three times the surface available in the Outskirts. However, the valuable surface is just twice as large as the one identified for the Outskirts. This information can be beneficial in identifying the areas that could benefit more from a PV system.

The next module of the framework identifies the optimal positions for the panels while respecting the constraints described in Section IV-C. For this test, we take into consideration PV

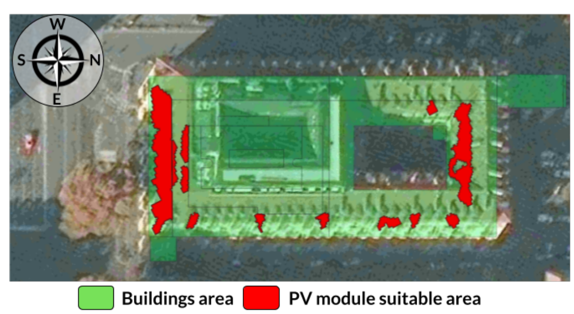

Fig. 4. A satellite image representing some real cross-building rooftops (highlighted in green color) with the area actually exploited to install PV modules (represented in red color).

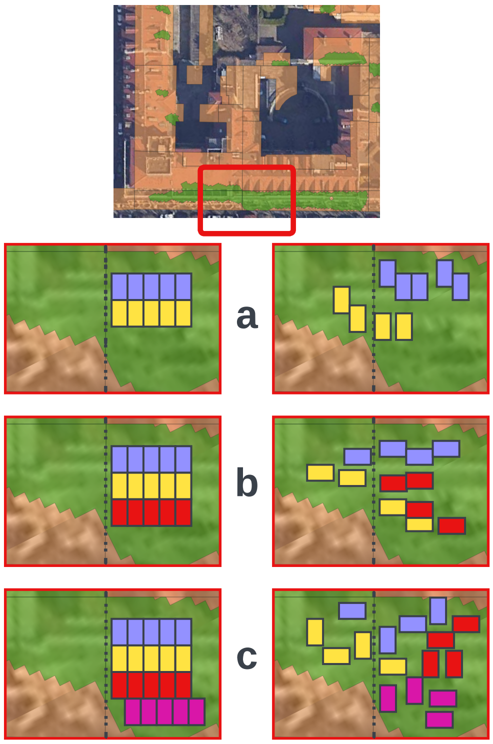

Fig. 5. The outcome of our placement algorithm. Case *a* compares a traditional placement to an optimal order considering only PV modules with vertical orientation. Case *b* corresponds to a conventional arrangement compared to an optimal one considering only horizontal PV modules. Case *c* compares a traditional placement with an optimal one considering modules with vertical and horizontal orientations. Please note that the number of PV modules may vary for each case, but the compared placements (optimal arrangement and traditional one) have the same number of PV modules.

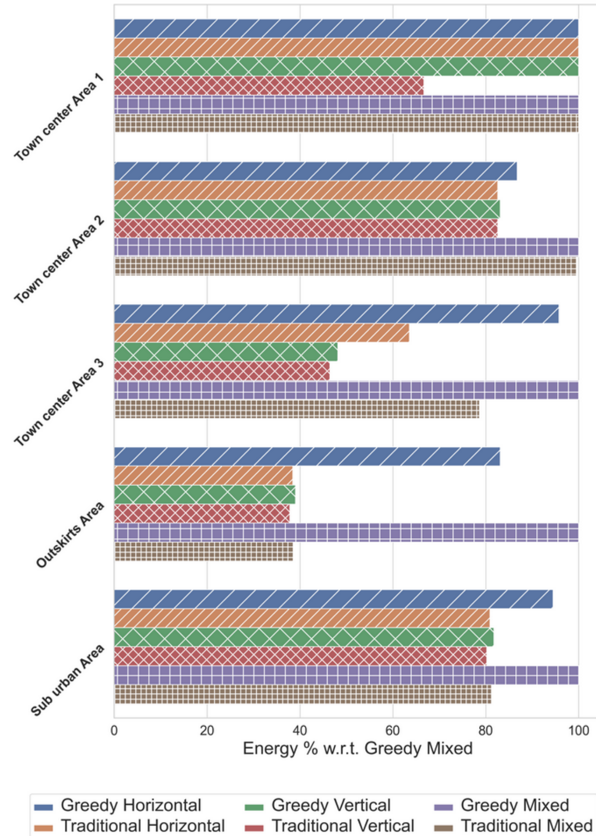

Fig. 6. Power production of the different placing algorithms for the different areas. Power production is normalized with respect to the solution proposed in this work, i.e., using a greedy placement and both vertical and horizontal orientation of PV modules.

modules of type MF165EB3 produced by Mitsubishi [61], and we consider a series of S=8 PV modules. Moreover, we adopted the methodology proposed in [54]. With the proposed approach, however, other models of PV modules can be obtained through their datasheets and used within the framework.

We set a maximum horizontal distance between adjacent panels of $maxD$=3 meters, and a maximum vertical difference of $maxH$=0.5 meters. Figure 5 shows some examples of PV configurations generated by our placement algorithm considering several adjacent rooftops. We can notice the different orientations considered by the algorithm, i.e., PV are modules placed only vertically (top), only horizontally (center), and both vertically and horizontally (bottom picture).

To better evaluate the performance of our placement algorithm, we compare its results with the ones delivered by a traditional algorithm. Thus, for each configuration (i.e., for each possible orientation considered by our algorithm), we generate a conventional layout with the same amount of PV modules placed on the same rooftop and orientation. This process ensures a fair comparison and therefore the higher power production w.r.t a traditional placement is due to the placement obtained by the algorithm, which exploits the following points:

- it places the PV modules to maximize the chances for a high irradiance level with specific stability throughout the day and the year. For this reason, PV modules are placed and oriented to match the irradiance distribution over the roof;
- it connects PV modules with similar irradiance patterns (e.g., all shaded in the afternoon and well irradiated in the morning) to minimize the impact of shading and the corresponding effect on the voltage and current of the connected PV modules.

Figure 6 compares the energy production of the different layouts for each district. In the first scenario, the power productions of the different placement algorithms are very similar. In contrast, the greedy algorithm consistently outperforms the traditional one in other situations. In particular, when the greedy algorithm considers both vertical and horizontal orientations, we obtain the best results, with improvements that vary from 15% to 60%.

As the panel configurations that guarantee the best power production are generated by the greedy algorithm and allowing panels with both orientations, we verify which percentage of the energy demand could be satisfied by these layouts. For each community under test, we compare the total energy consumption (obtained with the method introduced in Section IV-F) with the correspondent production of the panels. We show results in Figure 7. For each one of the scenarios analyzed, the plots represent the difference between the generated energy and the consumed energy. When the production is larger than the consumption, the values are represented in green color; plots are in red, otherwise. It is easy to notice that, only for some of the layouts and only for specific periods over the year, the production of the installation can completely satisfy (or even exceed) the energy demand. In particular, the best balance is obtained during the daytime of the summer for both the Town Center Area 2 and 3, and partially for the eutskirts Area.

However, even if RECs do not become self-sufficient, our PV installations are still beneficial. We evaluated the economic benefit obtained by REC as the percentage of self-consumption the PV system can provide. This indicator allows for generalizing the evaluation of the effectiveness of the REC since it depends mainly on the following:

- the building organization, which determines the configuration and the number of panels that could be installed;
- the geographic location, which influences the amount of power generated by the system.

Moreover, it still gives the participant of the REC an indication about the saving on the energy bills in percentage over one year. We indicated this value in Figure 8, which shows that our PV settings may reduce the amount of energy withdrawn from the power grid by a percentage varying between 6% to 45% over a year. We can also consider those values as the percentage saving of the REC participant on the energy bills. In addition to this, PV systems may have a very positive impact on pollution. Figure 9 shows that they can reduce up to 35% yearly CO_2 emissions. In this plot, we take into account the average amount of CO_2 emission due to the electricity generation derived from fossil fuels in Italy [62] and also the small (but still relevant) amount of emission related to the generation of PV panels. Our results show that, in the best case, the amount of CO_2 saved corresponds to the yearly emission of almost 1,180 cars [63].

While the proposed framework is agnostic to the precision of the input data, it is worth noticing how the precision of the result is strictly related to the precision of the input data provided by the user. Regarding the proposed test, as far as census data are concerned, population censuses are the most important statistical data used by policy-makers at all levels of government, as well as private businesses, households, nonprofit organizations, and researchers. It is well known that census data include several sources of problems, such as coverage (omissions or duplications) errors [64]. Moreover, even if the demographic study often validates census data to gauge their quality, this analysis is out-of-scope for our application. Consequently, we believe that census data are an essential source of information for our study.

Regarding the DSM data, we decided to use data with a resolution of 0.5 meters. A higher resolution would allow us to obtain a more precise evaluation; however, a higher precision would also imply a higher computational cost. In addition to that, high-resolution data are rare, often expensive, or difficult to obtain. On the other hand, a lower resolution reduces the precision of our evaluation since the identification of the suitable areas, and the estimation of the shadows would be less

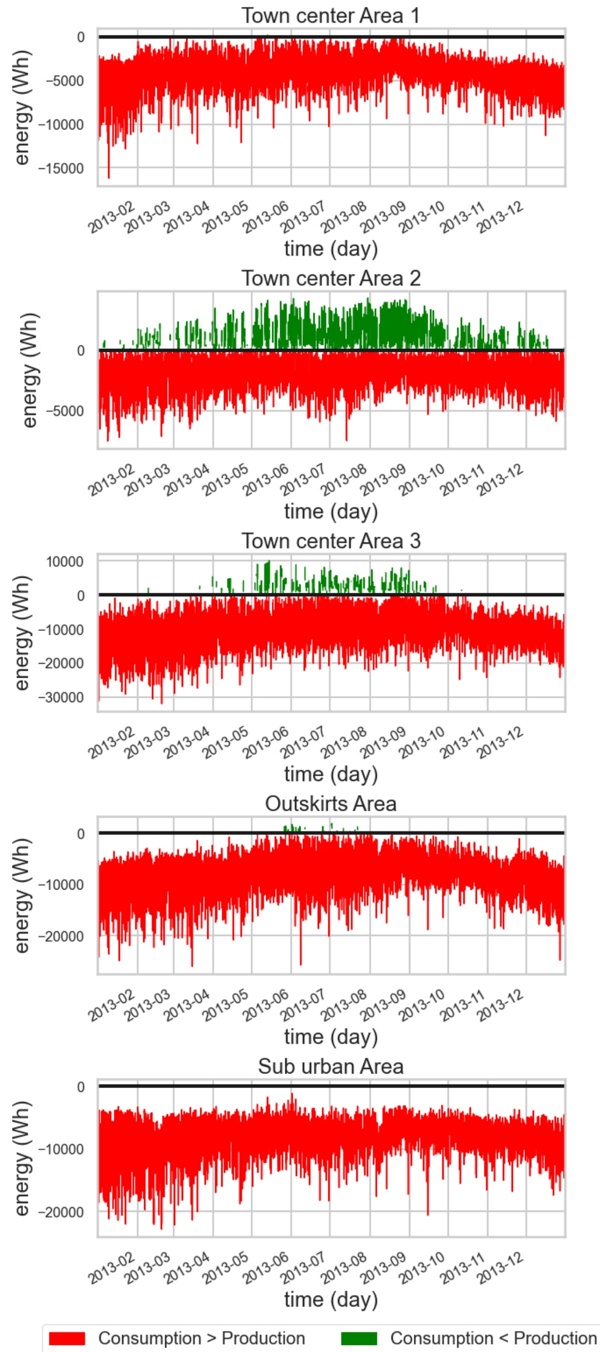

Fig. 7. Each graphic plots the difference between energy production and the energy demand of the community. The y-axis represents the power: The green color is used when the production is larger than the demand. The x-axis represents time, considering days as a time unit and one entire year.

precise. Thus, for our case studies, the resolution of 0.5 meters represented an excellent tradeoff to obtain sufficient precision. Moreover, our framework can manipulate DSM data with any resolution; consequently, users can choose the precision level they want to achieve and provide the DSM data accordingly.

VI. Conclusion

This paper proposes a framework that combines geographical, meteorological, and demographic information to identify

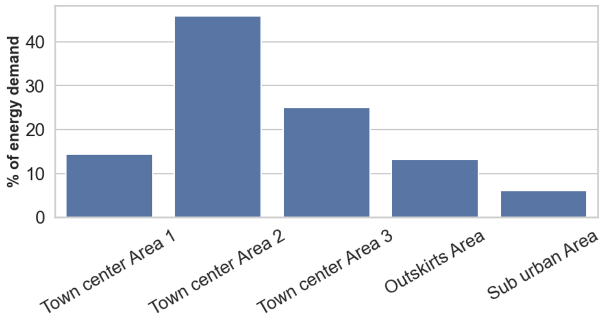

Fig. 8. Percentage of the energy demand that can be satisfied by a shared system over a year for each area under analysis.

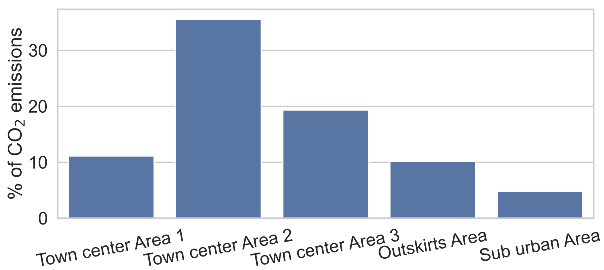

Fig. 9. Percentage reduction of CO_2 emissions enabled by a shared PV system over a year for each area of interest.

optimal photovoltaic installations, evaluate the subsequent benefits for the community members in reducing the energy withdrawn from the power grid, and verifying the potential benefits for the environment. To optimize the positioning process of our PV panels, we use GIS technologies and historical data, and we enable the possibility of connecting PV modules located on contiguous buildings. We use real disaggregated consumption data to evaluate the expected power demand and power saving, and estimate the reduction in terms of emission of pollutants. We verify our conjectures on different real scenarios in and around Turin, a large city in the northwest region of Italy. The promising results lead the way to real applications in the field.

Since we based our optimization phase on a greedy approach, future improvements of this work aim to substitute the greedy optimization procedure with algorithms based on machine learning, deep learning, or genetic algorithms. A further feature to extend the framework would be the disaggregation of consumption data of each REC member, which would help to analyze the economic interactions among its participants assessing possible novel business strategies. Finally, another significant improvement would be the development of a Graphical User Interface to improve the user experience.

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