

Article

Renewable Energy Communities as Means of the Fulfilment of Sustainable Energy and Climate Action Plans in Historic Urban Districts: The Case Study of Villorba—Treviso (Italy)

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Abstract

Renewable Energy Communities (RECs) are increasingly recognized as a key tool to foster the local integration of renewable energy and to achieve sustainable climate and energy targets. In Italy, they could be particularly beneficial in municipalities combining heritage constraints with large industrial areas. This study focuses on Villorba (Treviso, Veneto), where the installation of photovoltaic (PV) panels on historical buildings is restricted, while a considerable stock of industrial buildings offers high potential for renewable energy deployment. A mapping of the building stock and PV potential based on Geographic Information System (GIS) was combined with hourly building energy simulations using an EnergyPlus-based tool. Several scenarios of PV installation on industrial roofs were assessed and compared against Villorba's Sustainable Energy and Climate Action Plan (SECAP) targets. The results show that PV systems installed on industrial buildings could significantly contribute to the electricity demand of the residential and municipal buildings. However, a more realistic approach should consider the concurrent generation and demand for electricity. The results with such an approach highlight that reduced PV capacities can achieve similar levels of local electricity self-consumption, thus decreasing investment costs and avoiding grid imbalances. This study demonstrates the strategic role of RECs in heritage-sensitive contexts and supports more resilient and realistic SECAP planning.

Keywords: Renewable Energy Communities (RECs); Sustainable Energy and Climate Action Plan (SECAP); heritage-sensitive context; photovoltaic (PV) systems; electricity self-consumption



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1. Introduction

The necessity to absorb the emerging overproduction of electricity by systems based on renewable energy sources led to the introduction of Renewable Energy Communities (RECs) in Italy in 2019, in implementation of related European Directives. The establishment of these communities was driven by the objective of fostering an open and voluntary aggregation of renewable energy producers and consumers, with a view to promoting a collective energy management paradigm. A Renewable Energy Community (REC) is defined by an open, voluntary and autonomous participation model. The control of such a corporation is exercised directly by its members or shareholders. Participants in a REC may be individuals, small and medium-sized enterprises (SMEs), territorial entities or local authorities, including municipal governments. However, for private enterprises,

community membership does not necessarily have to represent their primary economic or industrial activity. The primary objective of a REC is not the generation of financial profit, but rather the creation of environmental, economic and social benefits for its members and the area in which it operates [1]. Thus, one could doubt the convenience of industrial companies in taking part in RECs. However, energy cost reduction and corporate social responsibility are benefits bringing direct savings and higher corporate green reputation. Moreover, the agreement at the basis of each REC might increase the revenue for the REC partners (including companies) exporting electricity. The success of renewable energy communities is contingent on the presence of local skills and resources, as well as the capacity to promote inclusive and cooperative processes. In particular, the involvement of relevant local actors is essential to strengthen cooperation [2], openness to citizens, appropriately scaled design geared towards the equitable distribution of benefits, together with communication and socio-environmental impact measurement strategies, as well as careful analysis of the local context [3]. RECs also function as a laboratory for social and civic innovation, as they are structured through forms of governance shared among stakeholders and promote energy capitalization models that directly involve citizens in the sustainable management of the territory [4].

In Italy and Europe, the existence of collective models of energy production and distribution is well documented, with the majority of such models having been developed in peripheral areas. Historical precedents can be identified in the Val di Funes energy community, established in 1921 in South Tyrol [5], and the Lugo di Grezzana energy community, founded in 1923 in Verona [6]. The introduction of RECs facilitated the extension of these models to encompass the entire country, with communities being organized within the same primary substations, that is to say, within those areas served by the same electrical station that receives high or very high voltage energy and converts it to medium voltage through one or more transformers. This system facilitates the generation of energy from local energy mixes, through multi-sectoral and integrated interventions, calibrated to the available resources and respecting environmental and landscape values. A total of 421 RECs have been created in Italy to date, with an average power output of around 104 kWp per community [7], from 2 kWp in Canal San Bovo (province of Trento) to 1800 kWp in Quaregna Cerreto (province of Biella). As one can see from the range of peak power installed in Italian RECs (from 2 kW to 1800 kW), there is no minimum limit to peak power in Italian regulation and a renewable energy system with a peak power of 2 kW can be registered as a REC.

RECs represent a subset of the instruments at the disposal of local authorities, with the objective of reducing local energy consumption and achieving the targets stipulated within their Sustainable Energy and Climate Action Plans (SECAPs). Since 2008, a significant number of European municipalities have voluntarily participated in the Covenant of Mayors, an initiative aimed at reducing CO₂ emissions by a minimum of 20% by 2020. In order to achieve this objective, each signatory administration developed a Sustainable Energy Action Plan (SEAP), a strategic tool based on an initial emissions analysis (EIB, Emissions Inventory Baseline). The SEAP defined measures, timeframes and responsibilities for the transition to a more sustainable energy model. Greenhouse gas emissions, calculated within it, were broken down by different sectors, such as heating of buildings, differentiation in electricity consumption, road transport and so on [8]. Such initiatives were widely applied, particularly in Italy, Spain and Belgium [9]. The overarching objective of the Covenant was to empower municipalities to assume a pioneering role in the global effort to mitigate climate change.

In 2015, the global agreement in Paris and the UN Agenda for Sustainable Development led to the mandate for a global assessment of climate change. For the European Union,

this resulted in the introduction of the “Covenant of Mayors for Climate and Energy”, thus leading to the SECAP, which is an evolution of the previous SEAP. This initiative requested that local governments, provinces and regions of Europe reduce CO₂ emissions by 40% by 2030, through the drafting and observance of SECAPs.

The present article employs a case study to demonstrate the manner in which RECs can contribute to the achievement of the objectives defined in SECAPs. The case study that has been selected is Villorba, a small urban center located in the Po Valley, in the northeastern part of Italy, which is of interest for the following reasons:

- The city comprises numerous historical buildings, with the implementation of PV panels being precluded due to considerations pertaining to the landscape.
- The city hosts a large number of industrial buildings, whose roofs offer large space for photovoltaic (PV) system installation. Since the early 2000s, industrial activities have been decreasing because of a confluence of factors (the post-2007-08 economic crisis, the emergence of COVID-19, international economic competition, globalization process, conflicts, etc.); as a consequence, several industrial buildings remained unoccupied and underutilized ([10,11]). Also, for these buildings, the installation of PV systems on the roof could contribute to generating value while waiting for new use destinations. Finally, many industrial buildings in the Po Valley host roofs containing fiber cement. Thus, the installation of PV systems could take advantage of the renovation actions aimed at decommissioning such a material from existing buildings.

In consideration of the aforementioned characteristics, Villorba serves as an example for a substantial proportion of the Po Valley in Italy, a land of about 42,000 km² hosting about 15 M inhabitants [12]. This region is characterized by large industrial areas and the necessity to preserve numerous historic buildings, both architecturally and in terms of landscape. In this regard, the Veneto region is often referred to as the “homeland of industrial buildings”; however, no up-to-date estimate about the state of use as well as use destination of industrial buildings [13] is available, with the exception of a small number of studies by SMARTLAND srl and Confartigianato [14]. As a consequence, it is often difficult to achieve a reliable estimation of the energy consumption of such activities.

The purpose of this article is twofold: firstly, to analyze the territory according to the needs for abatement of CO₂ emissions; secondly, to assess how industrial buildings can be involved in making historic buildings more sustainable.

2. Materials and Methods

2.1. The Case Study: Villorba (Treviso, Veneto, Italy)

The city covered by the research is Villorba, in the province of Treviso, in the Veneto Region, Italy, geolocated as shown in Figure 1.

The city has about 18,000 inhabitants and has been a relatively important industrial site, with almost 100 manufacturing companies operating in various sectors. The district covers a territory of about 30.5 km² [15]. The urban fabric includes approximately 3685 residential buildings, distributed across areas that combine historic buildings (including numerous heritage houses), post-war residential complexes, and more recent industrial facilities. The local economy consists of small enterprises specializing in various sectors, such as metallurgy and mechanical engineering. In general, buildings do not exceed four floors in height and the majority (57% of the total) were constructed between 1961 and 1990, following a period of significant economic growth and technological development after the initial postwar reconstruction.

The building constructions have been considered as shown in Tables 1 and 2.

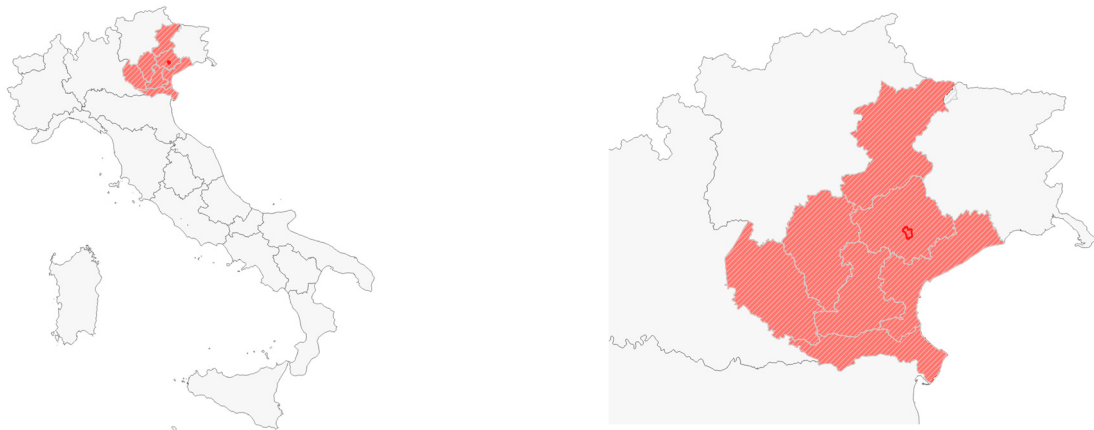


Figure 1. Geolocation of the case study (Villorba). Highlighted in red, the region it belongs to; outlined in red, the municipality under study.

Table 1. Opaque building constructions.

Name [-]	Material Name [-]	Thermal Conductivity [W/(m·K)]	Density [kg/m ³]	Specific Heat [J/(kg·K)]	Thermal Resistance [m ² ·K/W]	Thickness [m]
Floor_01	Plaster, external	0.9	1400	900	-	0.02
	Slab (mortar + clay hollow blocks + concrete joists)	0.457	900	940	-	0.24
	Screed, lightweight concrete	0.58	900	960	-	0.1
	Ceramic tiles	1.47	1700	850	-	0.015
Roof_01	Plaster, internal	0.7	1400	900	-	0.02
	Slab (mortar + clay hollow blocks + concrete joists)	0.457	900	940	-	0.24
	Screed, lightweight concrete	0.58	900	960	-	0.06
Wall_01	Plaster, internal	0.7	1400	900	-	0.02
	Hollow bricks	0.4	1800	900	-	0.12
	Air gap	0	0	0	0.16	0.04
	Hollow bricks	0.4	1800	900	-	0.08
Wall_02	Plaster, internal	0.7	1400	900	-	0.02
	Bricks	0.72	1800	900	-	0.25
	Air gap	0	0	0	0.16	0.04
	Hollow bricks	0.4	1800	900	-	0.08
Floor_02	Plaster, external	0.9	1400	900	-	0.02
	Slab (mortar + clay hollow blocks + concrete joists)	0.457	900	940	-	0.24
	Screed, lightweight concrete	0.58	900	960	-	0.06
	Ceramic tiles	1.47	1700	850	-	0.015
Floor_03	Gravel	1.15	1700	840	-	0.2
	Lightweight concrete	0.3	1200	960	-	0.2
	Screed, lightweight concrete	0.58	900	960	-	0.06
	Ceramic tiles	1.47	1700	850	-	0.015

Table 1. *Cont.*

Name [-]	Material Name [-]	Thermal Conductivity [W/(m·K)]	Density [kg/m ³]	Specific Heat [J/(kg·K)]	Thermal Resistance [m ² ·K/W]	Thickness [m]
Wall_03	Plaster, internal	0.7	1400	900	-	0.02
	Bricks	0.72	1800	900	-	0.25
	Air gap	0	0	0	0.16	0.04
	Hollow bricks	0.4	1800	900	-	0.08
	Plaster, external	0.9	1400	900	-	0.02

Table 2. Transparent building constructions.

Name [-]	U-Factor [W/(m ² ·K)]	Solar Heat Gain Coefficient [-]	Visible Transmittance [-]
Window_01	6	0.8	0.8
Window_02	2.7	0.7	0.7

Most of the buildings have a consolidated Heating, Ventilation and Air-Conditioning (HVAC) system layout in the area, whose main characteristics have been hypothesized as defined in Table 3.

Table 3. Main data about the heating system, cooling system and domestic hot water production system.

Heating system	Generator—Device type	Alpha	Natural Gas Boiler
	Generator—Efficiency	%	80
Cooling system	Generator—Device type	-	Heat pump
	Generator—Energy Efficiency Ratio (EER)	-	6.71 @ 20 °C θ_{Outdoor}
			4.54 @ 25 °C θ_{Outdoor}
			3.61 @ 30 °C θ_{Outdoor}
			3.24 @ 35 °C θ_{Outdoor}
			2.40 @ 40 °C θ_{Outdoor}
Domestic hot water production system	Generator—Device type	-	Natural Gas Boiler
	Generator—Efficiency	%	80

As for the internal heat gains and aeration/infiltration, the hypotheses collected in Table 4 have been chosen as the typical representation of occupancy in residential buildings.

Table 4. Main input data for the internal heat gains and aeration/infiltration.

Scope	Parameter	Unit	Building Typology
People	Floor area per occupant	m ² /person	25
Lights	Maximum specific wattage	W/m ²	7
	Minimum illuminance	lux	300
El. Equipment	Maximum specific wattage	W/m ²	5
Gas equipment	Maximum specific wattage	W/m ²	8
Aeration	Nominal volume flow rate	ach	3
Infiltration	Nominal volume flow rate	ach	0.3

Table 4. Cont.

Scope	Parameter	Unit	Building Typology
Domestic Hot Water	Consumption	l/(person·day)	40
Heating	Set-point temperature	°C	21
Cooling	Set-point temperature	°C	27

2.2. Phases of the Research

The calculations contained in this paper are structured around the following method, consisting in steps, each of which is covered in the corresponding paragraph:

- Update of the Regional Technical Map (RTM);
- Collection of technical data of PV systems in the district;
- Calculation of the electricity needs of buildings in the district;
- Subdivision of the territory into primary substations;
- Evaluation of the contribution of the industrial buildings to the district's energy balance;
- Verification against targets contained in the SECAP of Villorba.

The overall consequent workflow is briefly outlined in Figure 2, where the colors of the boxes depend on the data source (green for SECAP information, yellow for General Development Plan—GDP—data, red for the RTM shapefile, and blue for information retrieved from the institutional company managing the national electricity grid, i.e., Gestore dei Servizi Energetici—GSE). The details needed to better understand Figure 2 are given in Sections 2.3–2.7.

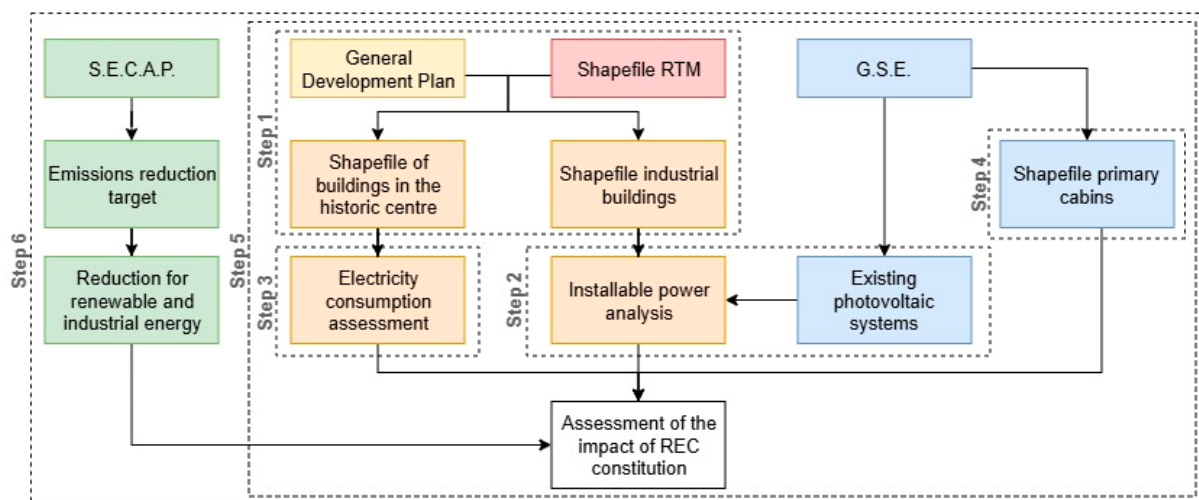


Figure 2. Outline of the workflow followed in this research.

2.3. Update of the Regional Technical Map (RTM)

The Regional Technical Map (RTM) of Villorba is made available by Regione Veneto, and its latest update dates back to 2003 [16]. It contains various shapefiles; however, in this phase, only the shapefiles named “fabbric”, i.e., the ones representing the buildings (“fabbricato”, in Italian), as well as an image of the municipal GDP published in 2013, are uploaded to a Geographic Information System—GIS ([17,18])—in order to gather the industrial buildings and the ones sited in the historic center (Figure 3a). Then, the shapefile has been updated by the authors through comparison with updated satellite images, thus identifying any new building or demolition. This is the outcome of this phase of the study and is represented in Figure 3b.

AREE INDUSTRIALI e CENTRI ABITATIVI di Villorba

Fonte: PAT Villorba : TAV 4.1 MOSAICO PRG COMUNI LIMITROFI. Elab_09_Mosaico_PRG

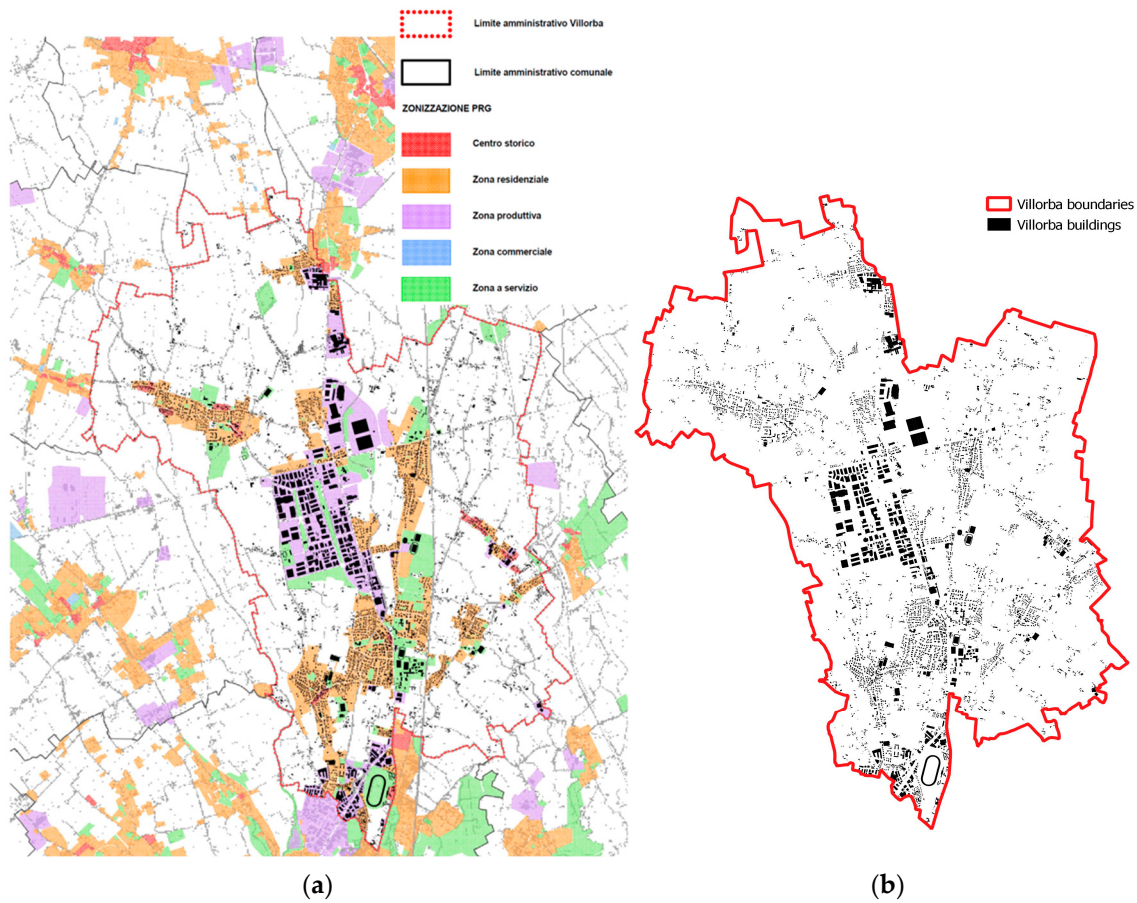


Figure 3. Superimposition of the GDP on the “fabbric” component of the RTM (a) (GDP and RTM, post-processed by the authors); representation of the updated shapefile (b). The buildings are displayed in black.

2.4. Collection of Technical Data of PV Systems in the District

Through the national portal named GSE-Atlaimpanti [19], the nominal power and position of each PV system existing in Villorba were gathered. This information has been added to the shapefile shown in Section 2.3. Then, the PV systems possibly installed on industrial buildings were hypothesized by assuming the peak PV capacity through (1):

$$P_{kWp} = \frac{A_i}{8} \left[\text{m}^2 \right] \quad (1)$$

where:

- P_{kWp} is the peak PV capacity [kW_p];
- A_i is the building footprint area [m²];
- 8 is the average building footprint area required to install 1 kW_p of PV panels [m²/kW_p].

The value of 8 m²/kW_p is calculated from [20], by assuming:

- Nominal conversion efficiency of PV panels: 22%. This value is typical for top-level monocrystalline silicon [21], considering that future PV panels are expected to further improve the nominal conversion efficiency.
- Mutual distance between solar panel arrays given by a distance ratio equal to 0.75, which results in a suggested optimal tilt equal to about 15°, when aiming at the maximum PV generation over the PV panel area.

As a result, the PV panel area is equal to 1 m² per 1.7 m² of roof area, which brings us to an equivalent efficiency (i.e., referred to the roof area) equal to 12.8%, which results in about 8 m²/kWp.

The outcome of this phase of the study consists in the shapefile integrated with georeferenced PV systems, existing (on any building) and possible (on industrial buildings).

2.5. Calculation of the Electricity Needs of Buildings in the District

At this stage, the building energy simulation of each building is performed. In these calculations, the geometry of each building as well as the peak capacity and position of the PV systems were gathered from the shapefile developed in the frame of Sections 2.3 and 2.4. As for the buildings' characteristics and occupancy settings, the hypotheses described in Section 2.1 have been considered. The calculations were performed by means of a software based on the well-established software EnergyPlus [22] (in its version named 24.1.0) and developed by the authors in the frame of a previous publication [23]. The software developed considered each building as a single zone and calculated the resulting energy consumption for each building and each energy carrier (i.e., gas and electricity), at each hour of the year, as well as the concurrent electricity production from PV systems, thus considering electricity self-consumption. Therefore, the overall energy balance of the district was calculated, at each hour of the year. However, the calculations considered just residential and tertiary buildings. In fact, industrial buildings have a wide variability of consumption according to manufacturing activities and production volumes. However, typically, the energy consumption of industrial buildings is far higher than their simultaneous production of electricity from photovoltaics, except on holidays and weekends, when production chains slow down. As a result, during holidays and weekends, the production of electricity from PV systems installed on industrial districts is available to cover the concurrent energy needs of residential districts.

The simulations carried out, however, covered an entire year, based on a typical test reference year [24], and the results were filtered by limiting to holidays and weekends. Consequently, a map of the spatial distribution of electricity consumption and production on holidays and weekends only was achieved and georeferenced by means of new attributes in the shapefile achieved in Section 2.4. This is the result of this phase of the study.

2.6. Subdivision of the Territory into Primary Substations

At this stage, it is important to group buildings within primary substations. In fact, based on the structure of the Italian electricity grid, the buildings served by the same primary substation can share electricity with no impact on the rest of the electricity grid. Hence, RECs are required to include buildings served by the same primary substation. For this purpose, the interactive map made available by the company managing the Italian electricity grid (Gestore Servizi Energetici—GSE) was used [25], where one can associate each primary substation serving Villorba to the buildings served. Villorba is served by four primary substations, as shown in Figures 4 and 5. However, only the largest substation (AC001E00881) has been examined, since it includes four historic districts and the largest industrial area in Villorba. As a consequence, the values resulting from the building energy and simulations will not refer to all the territory of Villorba, but to a subset of buildings in Villorba, consisting of residential, tertiary and industrial buildings.

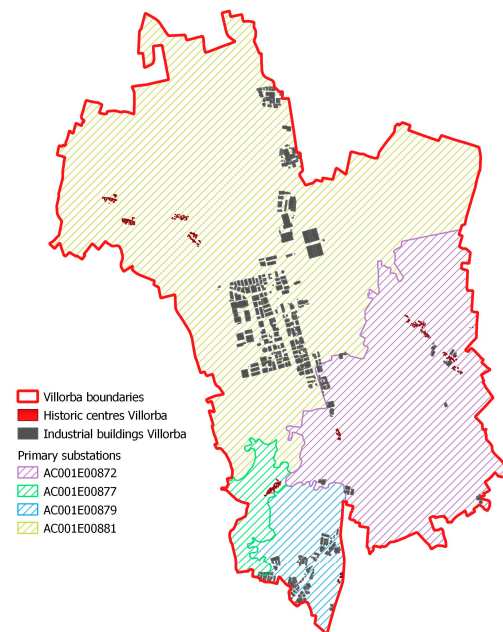


Figure 4. Territorial subdivision into primary substations (in grey: industrial buildings; in red: buildings belonging to the areas defined as historic centers by the GDP).

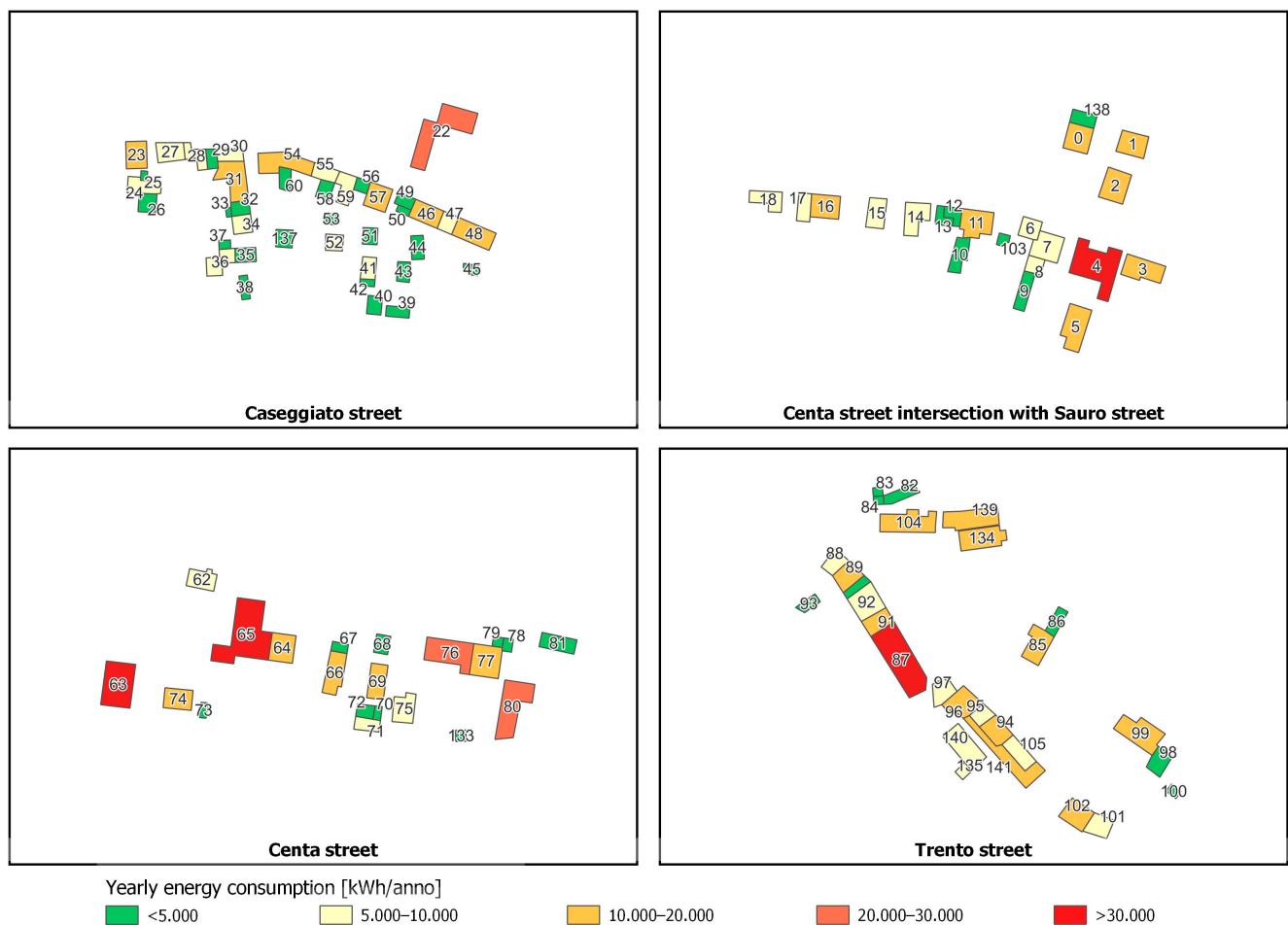


Figure 5. Visualization of the electricity consumption of each building, by means of a color palette.

2.7. Evaluation of the Contribution of the Industrial Buildings to the District's Energy Balance

The energy balance in the district was obtained by calculating, hour by hour, the energy consumption of each building as well as the generation of electricity from the serving PV system, thus considering a consistent estimation of PV electricity self-consumption. In particular, as for the estimation of PV electricity self-consumption at the district level, the PV electricity in excess from industrial buildings during weekends and holidays was calculated as a direct contribution to concurrent electricity consumption in residential premises and in historic buildings. Thus, it is possible to estimate how much industrial buildings can contribute towards a zero-electricity balance within the district, thus offsetting the electricity consumption taking place at historic buildings, on which the installation of PV systems is often prohibited.

2.8. Verification Against Targets Contained in the SECAP of Villorba

The results gathered in Section 2.7 were compared, in terms of CO₂ emissions, with the provisions of the SECAP implemented by the municipality of Villorba, according to the items relating to industry and the use of renewable sources to produce electricity.

In particular, the SECAP of Villorba has been published in 2019 [26] and it is important to note that the industrial sector is not regarded as a key objective of the Covenant of Mayors in this document, since industrial activities are influenced by broader national or regional policies and cyclical factors that are difficult for local authorities to control. Consequently, this sector has been excluded from the energy and emissions balance sheet, as clear from Table 5, which summarizes the most relevant data encountered in the SECAP of Villorba. It displays the measured/calculated energy consumption and renewable energy production, in addition to the mitigation targets established for 2030 concerning the implementation of new PV systems.

Table 5. Main relevant targets set in the SECAP of Villorba.

		2010		2016		2030 (Target)
		Electricity	Gas	Electricity	Gas	Electricity
Total energy consumption per sector [GWh/y]	Municipal buildings and equipment/facilities	0.65	3.85	0.49	3.80	
	Tertiary buildings and equipment/facilities	39.80	34.18	43.90	30.14	
	Residential buildings	21.54	84.71	18.13	69.57	
	Public illumination	1.30		1.32		
Total energy consumption [GWh/y]	All sectors	63.29	122.74	63.84	103.51	
Local energy production [GWh/y]	PV systems and micro hydroelectric systems	1.34		4.88		6.95

3. Results

In this section, the main results achieved in the study are presented. They refer to Sections 2.5, 2.7 and 2.8.

3.1. Calculation of the Electricity Needs of Buildings in the District

The building energy simulation mentioned in Section 2.5 considered the buildings in their current conditions, i.e., with building envelope and HVAC systems with characteristics typical in this area. In particular, the typical layout of the HVAC system in this area uses a natural gas boiler providing heating energy and domestic hot water. Thus, the building

energy simulation estimates both electricity (for lighting, generating cooling energy and other electric appliances) and natural gas energy consumption, in each building. Moreover, the software also calculates the generation of electricity from PV systems as well as its self-consumption in the served building or its delivery to the main distribution grid. This output data is summarized in Table 6, showing the yearly energy consumption in terms of electricity and natural gas as well as the yearly generation of electricity from PV systems, in each building. In this table, the estimated generation of electricity from possible PV systems installed on the roofs of the industrial buildings is grouped in the last row. Moreover, in Figure 5, the yearly electricity consumption of each building is visually shown by means of a color palette.

Table 6. Yearly energy consumption in terms of electricity and natural gas as well as yearly generation of electricity from PV systems, in each building, estimated by means of building energy simulations. The cells background follows a palette ranging from green (lower values) to red (higher values), with reference to the single column.

Code [-]	Electricity—Yearly energy consumption [kWh/y]	Electricity—Yearly energy self-consumption [kWh/y]	Electricity—Yearly energy export to grid [kWh/y]	Natural gas—Yearly energy consumption [kWh/y]	Code [-]	Electricity—Yearly energy consumption [kWh/y]	Electricity—Yearly energy self-consumption [kWh/y]	Electricity—Yearly energy export to grid [kWh/y]	Natural gas—Yearly energy consumption [kWh/y]
0	12,008	3193	1508	52,399	59	8400	-	-	31,860
1	11,256	-	-	43,287	60	2403	-	-	11,385
2	13,875	-	-	51,075	62	9136	-	-	32,304
3	14,326	-	-	55,887	63	35,722	-	-	74,638
4	30,297	-	-	104,569	64	12,381	-	-	42,053
5	16,753	-	-	63,696	65	40,982	3844	-	101,066
6	7027	-	-	34,756	66	13,004	-	-	40,129
7	6738	-	-	42,202	67	1422	-	-	10,546
8	5034	-	-	30,258	68	2417	-	-	13,864
9	4084	-	-	32,648	69	10,792	-	-	36,249
10	4414	-	-	29,923	70	1968	-	-	10,321
11	14,328	-	-	63,091	71	5695	-	-	21,568
12	2291	-	-	16,774	72	2076	-	-	11,090
13	2065	-	-	12,214	73	944	-	-	6225
14	5938	-	-	42,793	74	10,289	-	-	29,797
15	9602	-	-	41,591	75	5234	-	-	26,994
16	18,100	-	-	59,706	76	20,877	-	-	59,363
17	6746	-	-	27,508	77	16,737	-	-	49,564
18	8842	-	-	39,661	78	1208	-	-	10,156
22	27,358	-	-	110,281	79	1892	-	-	11,041
23	10,206	-	-	44,813	80	23,290	3075	27	66,005
24	8678	-	-	34,114	81	4687	-	-	20,542
25	581	-	-	5922	82	3256	-	-	14,321
26	2983	-	-	18,270	83	1669	-	-	9368
27	9325	-	-	42,486	84	804	-	-	7065
28	6686	-	-	29,317	85	12,810	-	-	46,288
29	4029	-	-	21,144	86	2734	-	-	13,629
30	6017	-	-	27,399	87	34,885	-	-	76,353

Table 6. Cont.

Code [-]	Electricity—Yearly energy consumption [kWh/y]	Electricity—Yearly energy self-consumption [kWh/y]	Electricity—Yearly energy export to grid [kWh/y]	Natural gas—Yearly energy consumption [kWh/y]	Code [-]	Electricity—Yearly energy consumption [kWh/y]	Electricity—Yearly energy self-consumption [kWh/y]	Electricity—Yearly energy export to grid [kWh/y]	Natural gas—Yearly energy consumption [kWh/y]
31	16,431	2895	239	46,429	88	6740	-	-	24,176
32	4863	-	-	20,874	89	14,227	-	-	40,124
33	457	-	-	4827	90	4398	-	-	22,934
34	6357	-	-	22,396	91	13,412	-	-	38,316
35	2719	-	-	17,972	92	7372	-	-	37,017
36	9006	-	-	35,613	93	1839	-	-	9200
37	1911	-	-	9842	94	15,307	-	-	40,308
38	1842	-	-	9103	95	5725	-	-	19,620
39	2267	-	-	14,290	96	19,152	-	-	48,505
40	2435	-	-	15,895	97	8091	-	-	25,730
41	5905	-	-	21,839	98	3878	-	-	21,638
42	962	-	-	6746	99	18,765	4388	1253	54,647
43	4712	-	-	18,428	100	1052	-	-	7855
44	2698	-	-	15,771	101	8719	-	-	25,689
45	1152	-	-	7969	102	11,547	-	-	36,440
46	15,828	-	-	42,202	103	1129	-	-	5372
47	5533	-	-	19,185	104	18,947	-	-	62,319
48	13,800	-	-	40,267	105	9815	-	-	26,255
49	4089	-	-	15,740	133	1084	-	-	7119
50	845	-	-	6316	134	16,177	-	-	50,680
51	2229	-	-	12,432	135	6126	-	-	18,951
52	5122	-	-	18,350	137	2683	-	-	14,492
53	1013	-	-	6275	138	3133	-	-	20,645
54	16,512	-	-	49,803	139	17,816	-	-	58,463
55	9583	-	-	30,386	140	8060	-	-	36,896
56	3384	-	-	19,465	141	18,697	-	-	56,775
57	10,327	-	-	35,907	Industrial buildings	-	-	16,830,306	-
58	2363	-	-	11,698					

The values shown in Table 6 are calculated along the entire year, but, in the case of the industrial buildings, the accounted value of exported electricity is limited to Saturdays, Sundays and holidays, i.e., when electricity consumption in companies and factories is lower and electricity generated by their PV systems can be assumed to be mainly exported. If the electricity generated along the whole year by the PV systems installed on the industrial buildings were considered, then the exported electricity would be much higher, i.e., 56.8 GWh instead of 16.8 GWh. As one can see in Table 6, some other buildings in the district simulated are provided with a PV system (namely, buildings 0, 31, 65, 80 and 99), but their contribution to the electricity balance of the district is negligible, compared with the contribution of the PV systems which could be installed on the roofs of the industrial buildings. Finally, one can see that the overall yearly electricity consumption in the district simulated could be widely covered by the electricity yearly generated by the PV systems installed in the district, and, in particular, on the industrial buildings (0.955 GWh versus 16.8 GWh).

3.2. Evaluation of the Contribution of the Industrial Buildings to the District's Energy Balance

The results shown in Section 3.1 represent the estimation of energy consumption of each building alone. However, the amount of electricity hourly exported from the PV systems could be even more than the concurrent electricity consumption in the other buildings. In this case, the district can take advantage of just part of the exported electricity and the share not being concurrently consumed is exported out of the local primary substation. To take these events under account, at each hour, the sole amount of generated electricity concurrently consumed by the buildings in the district is considered in this subsection. Also in this subsection, the PV systems installed on the industrial buildings are supposed to contribute to the district only on Saturdays, Sundays and holidays.

When also considering the concurrent hourly electricity consumption of the district simulated, the actual self-consumption of electricity in the district is equal to 114.1 MWh, which is much lower than the amount of electricity available as exported electricity from the PV systems installed on the industrial buildings (i.e., 16.8 GWh). This happens because the concurrent electricity consumption is often far lower than the available electricity exported by the PV systems. This can be easily visualized by means of Figure 6, showing the cumulated occurrences of the values of the electricity export/import ratio. In fact, the electricity exported from the single buildings is lower than the electricity consumption in the district in just 46% of the time and this ratio may also reach very high values (up to about 650). Therefore, many times, most of the electricity is not consumed within the district and must be exported out of the primary substation. Consequently, this analysis shows that the current profile of electricity consumption in the district does not allow us to appropriately take advantage of the available electricity generated by local PV systems; thus, technologies able to increase the actual self-consumption of electricity within the district should be applied. Such technologies are usually named “demand response technologies” and consist in devices and control strategies shifting electricity use in periods when PV electricity overproduction or lower electricity prices take place. In this regard, heat pumps providing heating and domestic hot water, prospected by current laws also for existing buildings, should greatly increase electricity self-consumption. Additional technologies such as storage technologies should be considered as well, since they allow PV systems to limit electricity export and increase self-consumption, whereas, when applied on the users' side, they allow the storage of energy when the electricity price is low. However, currently, these technologies are not yet economically convenient without subsidies from the government [27].

After these results, an additional analysis was developed; several lower PV capacities were set and the corresponding solar PV coverage of the REC as well as the accumulated occurrences of the electricity export/import ratio were calculated. In particular, the authors focused on the following installation capacities:

- 1% of the PV capacity considered in Section 3.1 (simulation PV0.01);
- 2% of the PV capacity considered in Section 3.1 (simulation PV0.02);
- 3.5% of the PV capacity considered in Section 3.1 (simulation PV0.035);
- 5% of the PV capacity considered in Section 3.1 (simulation PV0.05);
- 10% of the PV capacity considered in Section 3.1 (simulation PV0.10).

The results achieved are collected in Table 7, together with the same results obtained for the PV capacity considered in Section 3.1 (PV1.000). From Table 7, one can see that with much lower PV capacities, hence with much lower overall costs (both in PV installation costs and in national grid infrastructures, as shown in [28]), the self-consumed electricity is far from decreasing proportionally. For instance, in simulation PV0.10, i.e., a PV capacity 90% lower than in the reference simulation (PV1.000), the yearly electricity self-consumption of the REC is just 8.7% lower and, even in simulation PV0.01, with a PV capacity 99% lower

than in the reference simulation, the yearly electricity self-consumption of the REC is only 33% lower, since about 73% of the time, the electricity generation from the PV systems is fully self-consumed within the REC.

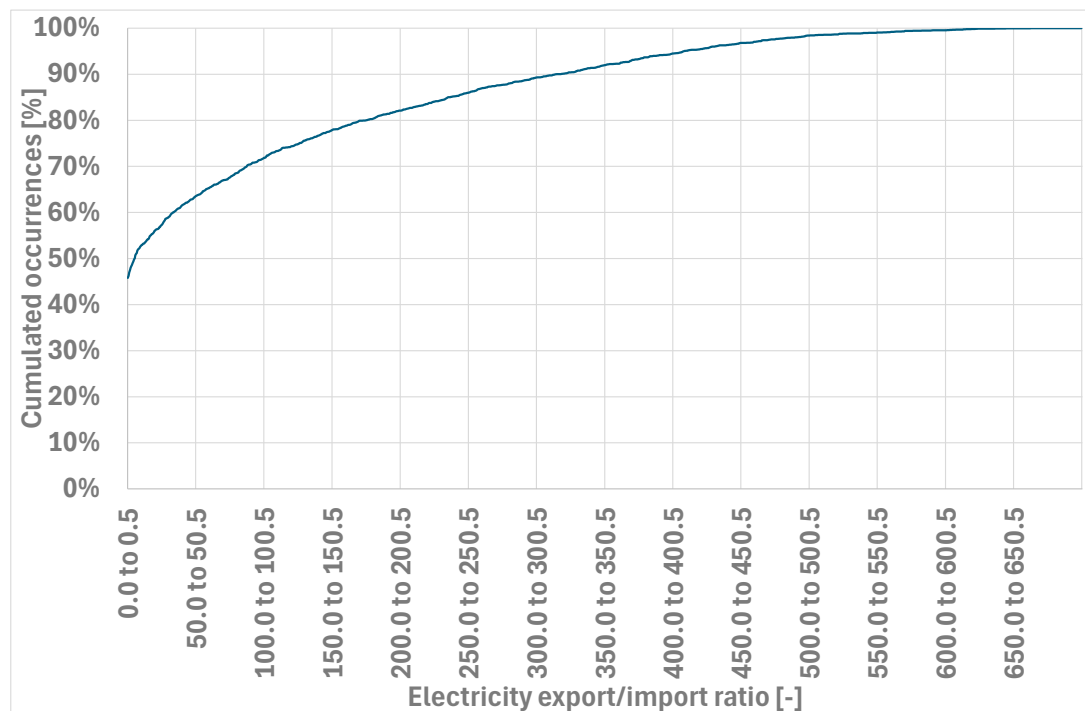


Figure 6. Cumulated occurrences of the values of electricity export/import ratio.

Table 7. Yearly electricity generation, yearly electricity self-consumption of the REC and accumulated occurrence of values of the electricity export/import ratio below 1, at several PV installation capacities.

Simulation Code	Yearly Electricity Generation [GWh]	Yearly Electricity Self-Consumption of the REC [MWh]	Cumulated Occurrence of Values of the Electricity Export/Import Ratio Below 1 [%]
PV0.010	0.17	76.4	73%
PV0.020	0.34	88.1	65%
PV0.035	0.61	95.7	60%
PV0.050	0.84	98.8	58%
PV0.100	1.68	104.1	55%
PV1.000	16.83	114.1	46%

3.3. Verification Against Targets Contained in the SECAP of Villorba

A comparison of the current and targeted energy consumption set out in the SECAP with the results of the simulations (Table 8) shows that the installation of PV systems on the roofs of industrial buildings in the municipality of Villorba, if connected to a REC with other buildings in the area, would make it possible to greatly reduce the electricity consumption of the residential and municipal sectors defined in the plan, given that, also in the SECAP, the energy consumption of the factories has been neglected, since it widely depends on the goods produced. It is worth noting that Table 8 results as follows:

- The results in the section SECAP consider all the area of Villorba.
- The results in the section REC simulation consider not only the residential and industrial buildings, but also the rest of Villorba. For this purpose, in the simulation, only

PV systems installed on industrial buildings are considered (in fact, the existing PV systems, placed on residential buildings, are already considered in the SECAP) and the consequent local electricity production is added to the local electricity production contained in the SECAP with reference to year 2016. As one can see, about 10% of the roof area of the industrial buildings would be sufficient to achieve the targets set by SECAP for year 2030. As can be seen in Table 7, in correspondence with 10% of the available PV capacity on industrial buildings, concurrent electricity self-consumption is about 55% of the generated electricity, which is significantly higher than the value of 46%, achieved by the first simulation performed in this study, corresponding to the full PV capacity available on the roofs of the industrial buildings.

Table 8. Comparison of local electricity production from SECAP and building energy simulation of the REC.

	SECAP			REC Simulation					
	2010	2016	2030 (Target)	PV0.010	PV0.020	PV0.035	PV0.050	PV0.100	PV1.000
Local electricity production [GWh/y]	1.34	4.88	6.95	5.05	5.22	5.49	5.72	6.56	21.71

4. Discussion

It is remarkable to note that, in the SECAP, the district energy balance is assessed without considering the concurrent production and consumption of electricity (as in Section 3.1), whereas this paper explicitly accounts for it (Section 3.2). The latter approach is clearly more sustainable for national grid infrastructures. It is therefore advisable that municipalities—being the administrative entities most closely aligned with the scale of primary distribution substations—adopt this methodology when developing their own energy balances as well as in SECAPs. Moreover, in Italy, municipalities oversee the process of approval of the permissions to build PV systems.

The comparison between the results of Sections 3.1 and 3.2 demonstrates that ignoring the simultaneity of production and consumption leads to clear overestimations of the local contribution from PV systems, with several counterproductive implications:

- Targets may be set whose achievement would substantially unbalance the electrical grid. Since this imbalance could occur simultaneously across bounding municipalities, such surplus generation would be difficult to exploit.
- Already today (and increasingly in the future), surplus generation of electricity from PV systems causes very low market value for the generated electricity, thus decreasing the return on investment of PV systems.
- When concurrent electricity generation and consumption is considered as a planning criterion, much smaller PV capacities, thus lower capital expenditures, provide nearly the same solar local coverage. In short, it allows for targets that are both economically more achievable and structurally more sustainable.

Finally, introducing concurrent electricity generation and consumption at the SECAP level would also highlight, at the municipal scale, potential strategies for demand-side management (e.g., demand response, rescheduling of working shifts) and/or supply-side measures (e.g., favoring PV systems with specific tilt/azimuth angles configurations to enhance production in certain seasons or times of day as well as storage technologies).

5. Conclusions

RECs have recently emerged in Italy as a key instrument for integrating renewable energy into local energy systems and achieving decarbonization targets. In municipalities with historical centers, restrictions on PV installation limit the potential for renewable energy generation, while underutilized industrial buildings offer significant untapped opportunities. This paper investigates the case of Villorba (Treviso, Veneto, Italy), a municipality characterized by a large share of historical buildings and a substantial stock of industrial buildings [18]. A geographic information system (GIS)-based mapping of building stock and PV potential was combined with hourly building energy simulations using an EnergyPlus-based tool to estimate electricity consumption, PV generation, and self-consumption at district scale. Several scenarios of PV capacity installation on roofs of industrial buildings were assessed and compared against the targets of Villorba's Sustainable Energy and Climate Action Plan (SECAP). The simulations developed show that the target set by the SECAP of Villorba by 2030 can be easily achieved by installing PV systems on 10% of the roof area available on the industrial buildings included in the district considered (simulation named PV0.100), which ensures a level of self-consumption significantly higher than the starting simulation, which considered the full PV capacity available on the industrial buildings included in the district considered (simulation named PV1.000), equal to 55% and 46%, respectively.

The results reveal that PV installations on the roofs of industrial buildings could widely offset the target set in SECAP for year 2030. As a result, RECs installed on industrial building roofs can play a strategic role in enabling energy transition in heritage-sensitive contexts. More importantly, when simultaneity between electricity generation and demand is accounted for, smaller PV capacities achieve comparable levels of local self-consumption to larger systems, while reducing capital expenditures. Considering concurrent generation and demand at municipal scale would lead to more sustainable planning, avoiding overestimation of local contributions from renewable energy sources and preventing grid imbalances. This approach would promote the spread of RECs and highlight demand-side management and supply-side strategies as essential complements to PV deployment. Integrating such methodologies into local SECAPs would result in more realistic, resilient, and community-driven energy planning. Indeed, if such analyses are introduced during the drafting phase of the SECAP, municipalities would be able to accurately identify the actual renewable energy needs, tailoring strategies to maximize the local exploitation of PV electricity generation. This would transform SECAPs from strategic planning documents into operational frameworks, thus providing realistic guidelines for renewable energy deployment in line with local energy dynamics.

Future developments of this research will focus on refining the methodology by incorporating more detailed, site-specific data into the GIS database. For instance, information on the type of industrial activity (e.g., NACE—Nomenclature statistique des Activités économiques dans la Communauté Européenne—codes) could be used to estimate sector-specific load profiles, while distinguishing between active, underutilized, or vacant buildings would allow for a more accurate assessment of actual PV integration potential.

Additional research directions may include:

- Coupling the GIS-based PV potential with high-resolution smart meter data to better capture hourly and sub-hourly load dynamics;
- Extending the analysis to energy demand flexibility, by evaluating the role of storage systems and demand-side management strategies in enhancing self-consumption and reducing grid stress;
- Considering economic and regulatory frameworks, such as incentives, tariff structures, and governance models for RECs, to assess financial feasibility and stakeholder participation;

- Integrating multi-energy systems (e.g., heat pumps, district heating, or electric mobility) into the assessment, thereby broadening the scope beyond electricity to a comprehensive local energy system perspective;
- Performing scenario analyses under climate change projections, which may alter both solar generation potential and local energy demand patterns.

By pursuing these extensions, the methodology could evolve into a robust decision-support tool for municipalities, enabling them to design RECs and SECAPs that are technically feasible and sustainable.

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Abbreviations

The following abbreviations are used in this manuscript:

EIB	Emissions Inventory Baseline
GDP	General Development Plan
GIS	Geographic Information System
HVAC	Heating, Ventilation and Air Conditioning
NACE	Nomenclature statistique des Activités économiques dans la Communauté Européenne
PV	photovoltaic
REC	Renewable Energy Community
RTM	Regional Technical Map
SECAP	Sustainable Energy and Climate Action Plan
SME	small and medium-sized enterprise

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