

Targeting Energy Poverty in Piacenza through Renewable Energy Communities: Assessing Capacity Needs with a Rule-Based Approach

TESI MAGISTRALE IN ENERGY ENGINEERING

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Abstract: Energy poverty continues to affect millions across Europe, especially in countries with old buildings and unequal income distribution such as Italy. This thesis focuses on the residential sector of the city of Piacenza and aims to estimate the amount of Renewable Energy Community (REC) capacity required to alleviate the energy burden of energy-poor households, reducing the ratio of energy expenditure to income to the 10% threshold.

The synthetic dataset developed in this study simulates energy performance, income and energy consumption characteristics for all residential households in Piacenza. All inputs and parameters are derived from publicly available data from institutions in Emilia-Romagna, Lombardy and national Italian sources. A rules-based classification system is applied to segment the population into three clusters: Vulnerable, Energy Poor, and Non-vulnerable groups, based on the energetic class, annual bill and annual income. Priority is given to households with EPC ratings between E and G and a ratio of energy expenditure to income above 10%, as they represent realistic and impactful targets for REC interventions.

The study builds on an optimization model that determines the installed PV capacity required to reduce the energy burdens of the selected households. Lastly, a dual sensitivity analysis is conducted to assess the impact of varying energy burden limits (from 10% to 100%) and community-sharing incentive rates (30% to 50%) on total REC production.

Results show that strategic filtering significantly reduces unrealistic energy capacity, lowering the required REC capacity from 148 MW to 72 MW. Specifically, including all households with an energy burden between 10% and 100% results in a required capacity of 148 MW, while considering those with burdens between 10% and 30% reduces the requirement to 72 MW. This demonstrates how narrowing the eligible population makes REC interventions more realistic and policy relevant.

Key-words: Energy poverty, Renewable Energy Communities, Piacenza, synthetic dataset, energy burden, sensitivity analysis, EPC classification, residential energy modeling

1. Introduction

1.1 Motivation

Energy poverty is a problem that affects millions of people across Europe. It can be measured through different indicators, reflecting both economic and energy performance dimensions. According to the European Commission, at least 40% of the EU population (around 180 million citizens) would be classified as energy poor if one would follow a 'union approach', in which someone is energy poor by at least one indicator. [1]. In particular, Italy faces inequalities when it comes to accessibility to affordable and efficient energy due to the structural conditions of buildings, as out of 25.7 million homes, as many as 17.5 million (equal to 68% of the total) date back to before 1980 and 51.8% of properties fall into the least efficient energy classes (F and G) [2]. Combined with economic vulnerabilities, 22.9% of the population earns less than €10,000 annually [3], which corresponds to the 60 % of the national median equivalized disposable income (after social transfers) contemplated by Eurostat [4], it contributes to a growing and complex energy challenge in this country.

In this context, Renewable Energy Communities (RECs) importance has increased to alleviate energy poverty while accelerating the energy transition. These refer to groups of people who come together to produce, consume, and manage their energy resources collectively. They enable households and communities to reduce their energy bills, improve living conditions, and enhance social and economic resilience [5]. Moreover, through government incentive schemes that reward the virtual or physical sharing of electricity.

This thesis focuses on the municipality of Piacenza, located in Emilia-Romagna, a region where no detailed energy poverty mapping currently exists. It aims to evaluate the impact of REC deployment and how it can be optimized to reduce energy poverty in residential buildings by supporting selected households in reducing their electricity consumption and receiving an economical benefit through incentives due to virtual energy sharing.

1.2 Objectives of the thesis

The objective of this thesis is to develop and apply a methodology to assess the potential of Renewable Energy Communities (RECs) as an economic and social policy tool to alleviate energy poverty in local and small cities, where microdata is often incomplete or unavailable.

To achieve this, a rule-based framework is designed to identify energy poor households in Piacenza that could be supported through a REC scheme. This is done through the simulation of a synthetic dataset from publicly available national and city-specific sources. The study estimates key parameters like energy performance, area of each household, energy consumption, annual bill, energy burden and vulnerability level. These estimates enable the calculation of the energy gap, in € and kWh, required to reduce the energy burden level below the 10% threshold.

The approach uses an optimization model that calculates the PV capacity required, under different scenarios and assumptions, to meet the energy burden objective. These scenarios are analyzed through a dual sensitivity analysis, while varying the energy burden thresholds (e.g., 10–30%, 10–40%, 10–50%) and the percentage of total PV energy shared with the community (e.g., 30%, 40%, 50%).

The novelty of the thesis comes from how the data and policy gap is addressed for Piacenza through the development of a synthetic dataset to approximate local conditions. Since no detailed

assessments of REC potential or household-level vulnerability exist for the city. Moreover, the use of a rule-based classification makes the identification of vulnerable groups transparent and directly aligned with national and EU definitions of energy poverty. A dual sensitivity analysis that tests both energy burden thresholds and incentive-sharing schemes provides a clearer picture of how different policy choices affect REC deployment, making the results both replicable and relevant for local decision-makers.

1.3 Literature review

1.3.1 Energy Poverty: Definitions and Thresholds

Energy poverty refers to the inability of a household to afford efficient and reliable energy. We based our threshold for energy poverty through the definition imposed by the European Energy Poverty Observatory (EPOV), which has historically supported the use of the 10% energy burden threshold as an indicator. Meaning that those households which spend more than 10% of their income on energy bills are generally classified as energy poor [6]. Moreover, it is possible to refer to the Low-Income High Costs (LIHC) approach, which combines high energy costs above the national median with low household income below the poverty line [7]. This indicator defines that a house is energy poor if its required energy costs are above the national median and its residual income, after paying energy bills, falls below the poverty threshold [8].

Taking these definitions into consideration, the high-income households are excluded even if they face high bills, under the justification that REC interventions are not designed to subsidize households with high consumption preferences.

At the same time, some studies highlight that households with very high energy burdens are often associated with structural inefficiencies, poor thermal performance or outdated infrastructure, rather than being income related. Half of Italy's housing stock falls within EPC classes F and G, and many were built over 40 years ago with minimal efficiency standards [9]. Moreover, 65% of buildings were constructed before the first law on energy saving criteria and 25% of it has never undergone any work of maintenance or improvement [10]. These studies suggest that those households with high energy burdens typically require structural renovations or retrofits, rather than participating in a REC. For this reason, the exploration of different scenarios given by a dual sensitivity analysis is better than applying a fixed cut-off energy burden level, so it is possible to capture a more realistic REC deployment layout.

1.3.2 Income and Poverty Metrics in Italy

Absolute poverty thresholds based on household composition and location in Italy are reported annually by ISTAT and Eurostat. For instance, a single adult living in a northern metropolitan area, like Piacenza, is considered poor if earning less than €834.66 per month, roughly €10,000 annually [4].

This thesis uses €10,000 as the upper income threshold to define "Vulnerable" households. In contrast, for the classification of "Energy-poor" an income ranging between €10,000 and €55,000 is used in this study to exclude high-income households, even if they have high burden, as they can absorb higher energy costs.

This approach is consistent with the Low-Income High-Cost (LIHC) indicator, which identifies energy poor households when its energy costs are above the national median and if their remaining income after expenditure falls below the poverty level [11]. For this reason, high-income households

with also high energy burdens are not considered, since they will remain above the poverty thresholds after paying the energy bills.

According to national statistics, the median disposable income per household in Italy is approximately €30,000 [12], so this makes the upper threshold of €50,000 a conservative limit that remains nearly double of the median. Thus, ensuring a policy-relevant focus on those that are truly at risk.

1.3.3 Energy Efficiency and Building Stock in Italy

Italy's energy poverty rises from the high presence of old buildings. More than 17.5 million homes (equal to 68% of the total) are considered old and energy inefficient. Their construction date back to before 1980 and 51.8% of properties fall into the least efficient energy classes (F and G) [2].

Moreover, a report by ENEA in 2022 reported that by the end of 2019, 74.1% of residential buildings have an EPC of E, F or G. While by the end of 2024 the share slightly decreased to 70.4%, which shows a small improvement in around 4 years [13]. According with Italian certification rules, these energetic classes have the worst energy performance (EP gl, nren), where class E starts around 90 kWh/m² and class G around 160 kWh/m². Meaning that these houses are the first candidates for being selected to participate in a REC due to their potential for energy savings that can be obtained.

1.3.4 REC Policy Framework in Italy

Italy issued the EU Renewable Energy Directive (RED II, 2018/2001) through Decree 199/2021, which promotes the use of energy from renewable sources and moreover, supports the creation and implementation of renewable energy communities. These can be initiatives from citizens or entities that can self-produce, consume, store and/or share renewable energy and at the same time receive an economical benefit depending on the size of each independent PV system. There is no limit to the total installed capacity that a REC can incorporate. However, each individual generating system cannot exceed the capacity of 1 MW [14].

According to Gestore dei Servizi Energetici (GSE) there are three different tariffs for allocation of incentives based on the size of the PV system installed [15], [16].

Maximum premium rate (Tip) based on capacity installed:

- Small (<200 kW): €120/MWh
- Medium (200–600 kW): €110/MWh
- Large (>600 kW): €100/MWh

This is an incentive given to the owners of the PV system per kWh of energy that has been shared within their REC. Tariffs can vary depending on the hourly zonal price (Pz) and on a territorial correction factor, which allows the region of Emilia-Romagna to increase their maximum premium rate by +€10/MWh [15].

The incentive received is ultimately shared between owners, participants and, if needed, to a third party who might oversee installation and maintenance. As the energy shared to households increases, their revenues and burden reductions improve. To capture this effect, the model explores different sharing levels, so it is possible to assess the impact of this parameter.

1.3.5 REC Modeling and Distribution Mechanisms

Research projects [17], [18] have developed frameworks to model how RECs can distribute incentives, like equal sharing, proportional sharing or value-based sharing.

- Equal sharing: every household is given the same amount, regardless of consumption or need.
- Proportional sharing: incentives or shared energy are allocated in proportion to each household's consumption, shared energy or energy gap.
- Value-based sharing: methods like Shapley Value allocate benefits depending on the marginal contribution of a household on the collective output.

In this thesis the focus is on proportional sharing. While usually RECs define proportional sharing based on the energy contributed by each member, in this study the term is adapted to reflect proportionality to energy consumption or gap, aligning it with the aim of reducing energy burdens rather than rewarding production. As in [18], proportional allocation, based on consumption or energy needs, is commonly used in pilot REC projects because of the simplicity and ease of implementation in comparison to value-based sharing as Shapley value, which computational complexity arises with a high number of players.

1.3.6 Policy Measures for Household Clusters

Addressing energy poverty through policies require a differentiation between households depending on their level of vulnerability. As highlighted in [19], not all households face the same economic and energy efficiency constraints, and therefore a cluster-based policy design is more effective than uniform measures.

Classification through clustering yields three groups:

- Vulnerable households, where the economic issues are mainly caused by other factors not related to energy. For this group, policies can help to avoid energy costs becoming an additional burden [19]. Typical measures and policies include bonuses like direct income support or direct bill discounting through special tariff for grid costs and system charges [20].
- Energy Poor households, which represent the largest cluster suffer a combination of low incomes with high energy inefficiencies and energy costs. In this case energy efficiency policies are essential, like building performance improvements to reduce long-term consumption and burdens and financial aid through RECs to allow them to reduce their burden and have the option for investments in the long term.
- Non-Vulnerable households are not economically constrained and may still face low building performance but have the capacity to invest in improvements and reduce their consumption and bills. However, they may benefit from non-financial policies like

regulatory simplification or removal of bureaucratic barriers to facilitate voluntary investments.

This framework highlights the importance of targeted policies to each cluster to optimize public resources and ensures they are allocated where they have the highest impact.

1.4 Structure of the thesis

- Chapter 2: Methodology
This chapter details the creation of the synthetic dataset, including classification rules, energy burden calculations and filtering logic. It also describes the REC design assumptions, incentive logic and the optimization model used to determine the number and type of RECs required.
- Chapter 3: Input Data for the Case Study
This chapter presents all the input data used to generate the synthetic database for the case study.
- Chapter 4: Results
This chapter presents base case findings and analyzes how different sensitivity settings impact the required REC capacity and the shared energy volumes.
- Chapter 5: Conclusions
This chapter summarizes the key findings of the research, reflects on the limitations and policy interventions suggested and outlines recommendations for further development.

2. Methodology

2.1 Synthetic Database Creation

Due to the unavailability of a public database that combines income, building energy performance and energy consumption for households in Piacenza, a synthetic dataset of more than 12,000 residential households has been generated. This set will store several parameters needed to run the simulations, including the energy class (EPC: Energy Performance Coefficient), area of the house, income level, specific energy consumption and others derived from them to evaluate energy poverty. These include yearly bills, yearly energy consumption and energy burden.

The number of households simulated refers to the number of residential households registered in Piacenza according to ISTAT census [21].

2.1.1 Energy Performance Certification (EPC) Assignment:

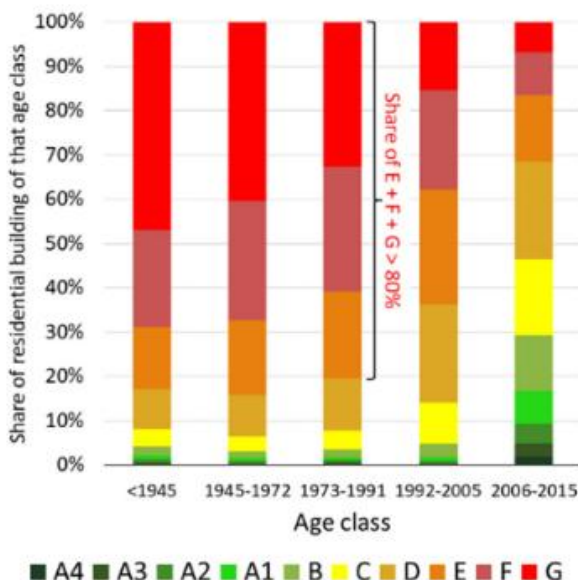
Following the database base for the length of the database, it is possible to assign an EPC to each of them. Using public information from Ministero dell'Economia e delle Finanze IRPEF [3] is possible to know the era of construction from each household, as their share is available.

Table 1: Age class of buildings in Piacenza

Age Class	Share of Houses Constructed in Period	# Households Constructed in Period
< 1945	0.22	2,658
1945 – 1972	0.44	5,315
1973 – 1991	0.25	3,019
1992 – 2005	0.07	841
> 2006	0.02	241
Total	1	12,074

Figure 1 illustrates the relationship between the age class of residential buildings and their EPC, which was taken from the Italian EPC database [22]. For example, older buildings, especially those built before 1991, are mostly composed of the most inefficient classes E, F, and G, representing more than 80% of the total from the first three age classes. On the other hand, buildings post 1991 display a gradual shift toward higher EPCs (C, B, and A). This reflects the progress on energy efficiency standards in Italy.

Figure 1: National EPCs statistics – age class vs EPC [22]



For cleanliness Figure 1 can be translated into Table 2.

Table 2: National EPCs statistics – age class vs EPC

Energy Class	<1945	1945-1972	1973-1991	1992-2005	>2006
A4	0.00%	0.00%	0.00%	0.00%	2.07%
A3	1.02%	0.40%	0.50%	0.83%	4.15%
A2	1.02%	0.81%	0.50%	0.36%	4.15%
A1	1.02%	0.81%	0.50%	0.83%	7.88%
B	1.50%	1.99%	1.99%	2.50%	12.03%
C	3.50%	2.99%	4.50%	10.11%	17.84%
D	10.01%	10.01%	11.99%	24.14%	21.16%
E	12.98%	15.00%	19.01%	23.07%	12.86%
F	20.99%	27.00%	29.02%	21.05%	9.96%
G	47.97%	41.00%	32.00%	17.12%	7.88%
Total	100%	100%	100%	100%	100%

Thus, following Equation 1, Table 3 is obtained, which is a detailed breakdown of the number of EPCs in each age class.

$$Households_{ij} = Buildings_j \times Share_{ij} \quad (1)$$

Where:

- $Households_{ij}$ = households in EPC class i and construction period j ,
- $Buildings_j$ = households built in construction period j ,
- $Share_{ij}$ = share of EPC class i in construction period j .

Table 3: EPC vs Age class in Piacenza

EPC	<1945	1945-1972	1973-1991	1992-2005	>2006	Total	Avg Share
A4	0	0	0	0	5	5	0.04%
A3	27	21	15	7	10	80	0.66%
A2	27	43	15	3	10	98	0.81%
A1	27	43	15	7	19	111	0.92%
B	40	106	60	21	29	256	2.12%
C	93	159	136	85	43	516	4.27%
D	266	532	362	203	51	1414	11.71%
E	345	797	574	194	31	1941	16.08%
F	558	1435	876	177	24	3070	25.43%
G	1275	2179	966	144	19	4583	37.96%
Total	2658	5315	3019	841	241	12074	100%

2.1.2 Simulating Specific Energy Consumption EP_{gl}, nren [kWh/m²]:

Since all EPCs have been obtained, a simple simulation can be done to assign an energy performance value [kWh/m²] to each energetic class. A uniform random value between the lower and upper thresholds of its EPC class was assigned, following report [23] from SIAPE.

Table 4: Specific Energy Consumption per Energetic Class

EP _{gl} , nren (kWh/m ²)		
Higher than	Class	Less than
0	A4	22.0
22.0	A3	46.9
46.9	A2	62.1
62.1	A1	75.5
75.7	B	90.3
90.3	C	109.9
109.9	D	137.8
137.8	E	171.4
171.4	F	219.5
219.5	G	320.1

Thus, each household seen in Table 3 now gets an assigned EP_{gl}, nren value drawn from Table 4 ranges.

2.1.3 Simulating Building's Area:

Each households' area (m) was simulated using [24] as base. The normal distribution is used, applying VSM (Valore Stimato di Mercato) Media and Standard Deviation. However, these values are assigned depending on the income range that each household has. This approach reflects the relationship between income and dwelling size, with higher income households typically having larger areas.

Table 5: Distribution of the number of owners, total income and VSM of all dwellings

Income range (euro/year)	# Owners	Share	VSM		
			Mean	Std Dev	Variation Coeff %
Less than 10,000	1,510,138	13.4%	107,480	116,926	109
From 10,000 to 26,000	4,926,556	43.8%	126,733	123,376	97
From 26,000 to 55,000	4,007,422	35.7%	177,048	172,329	97
From 55,000 to 75,000	381,561	3.4%	266,833	278,518	104

Income range (euro/year)	VSM				
	# Owners	Share	Mean	Std Dev	Variation Coeff %
Over 75,000	410,062	3.6%	413,517	532,613	129
	11,235,739	1			

For this reason, first is needed to determine the income range from each residential house, IRPEF report database [3] establishes the share of buildings belonging to each category in Piacenza. Then the area is simulated according to the VSM parameters for that bracket.

Table 6: Share of Buildings in each Income Bracket in Piacenza

Income brackets (€/year)	Share	Amount
Less than 10,000	22.89%	2765
From 10,000 to 26,000	43.77%	5285
From 26,000 to 55,000	26.35%	3181
From 55,000 to 75,000	3.24%	391
Higher than 75,000	3.75%	452

Using the average share for each EPC determined so far in the synthetic data sheet and combined with Table 6, a detailed distribution can be obtained applying Equation 2.

$$H_{ij} = N_j \times S_i \quad (2)$$

Where:

- H_{ij} = number of households in income bracket j with energy class i,
- N_j = total number of households in income bracket j,
- S_i = average share of energy class i in the building stock.

This approach assumes that the distribution of energy class and income level are independent from one another, due to the absence of microdata linking these variables.

Table 7: EPC vs Income Bracket Distribution

Energy class	Avg Share	Income Bracket (€/year)					Total
		Less than 10,000	10,000 - 26,000	26,000 - 55,000	55,000 - 75,000	Over 75,000	
A4	0.04%	1	2	1	0	0	5
A3	0.66%	18	35	21	3	3	80
A2	0.81%	22	43	26	3	4	98
A1	0.92%	25	49	29	4	4	111

Energy class	Avg Share	Income Bracket (€/year)					Total
		Less than 10,000	10,000 - 26,000	26,000 - 55,000	55,000 - 75,000	Over 75,000	
B	2.12%	59	112	67	8	10	256
C	4.27%	118	226	136	17	19	516
D	11.71%	324	619	373	46	53	1414
E	16.08%	444	850	511	63	73	1941
F	25.43%	703	1344	809	99	115	3070
G	37.96%	1050	2006	1207	148	172	4583
Total	100.00%	2765	5285	3181	391	452	12074

The joint distribution obtained in Table 7 will serve as the basis for the next step, where household areas are simulated within each EPC-Income subgroup.

It is also required to calculate which is the average EPC for the city. For that a number is assigned to each energetic class in increasing order from G to A4 and Equation 3 is applied.

$$W_i = Share_i \times Value_i \quad (3)$$

Where:

- W_i = Weighted Average i ,
- $Share_i$ = Average Share of class i ,
- $Value_i$ = Number assigned to class i .

Table 8: EPC vs Income Bracket Distribution

Energy Class	Value	Avg Share	Weighted Avg.
A4	10	0.04%	0.0041
A3	9	0.66%	0.0596
A2	8	0.81%	0.0649
A1	7	0.92%	0.0644
B	6	2.12%	0.1272
C	5	4.27%	0.2137
D	4	11.71%	0.4684
E	3	16.08%	0.4823
F	2	25.43%	0.5085
G	1	37.96%	0.3796
		1.0000	2.3728

Hence, according to Table 8, the average class from Piacenza is 2.3728. This weighted average represents the overall EPC level of the city.

To transform the average class into the average class price [25] is consulted, extracting the Capitalization of Energy Labels Table data referring to climatic zone E to Table 9. Since values are shown on a logarithmic scale, Equation 4 is used to transform them into percentage values that have class G as reference (e.g. A house with Energy Class C is 19% more expensive than the same house but with Energy Class G).

$$\text{Price Increase vs Class G (\%)} = \exp^{\text{Zone E log}} \quad (4)$$

Table 9: Capitalization of Energy Labels

Energy class	Prices Increase vs Class G (%)	
	Price Class	Zone E log
A1	1.33	0.282
A2	1.33	0.282
A3	1.33	0.282
A4	1.33	0.282
B	1.25	0.224
C	1.19	0.172
D	1.14	0.129
E	1.10	0.091
F	1.05	0.048
G	1	

Since the average class falls between F and E, the reference price is interpolated as a weighted average of the two classes.

$$\text{Ref. Avg Class Price in Piacenza} = (0.3728) \times \text{Class Price}_E + (1 - 0.3728) \times \text{Class Price}_F \quad (5)$$

So, the average price of the m² in Piacenza is 1815 euro/m² [26] and the reference average class price is 1.066, calculated with Equation 5.

Finally, the specific Reference Price in €/m², Mean Area and Area Standard Deviation can be calculated for each income bracket and each energy class following Equation 6, Equation 7 and Equation 8.

$$\text{Reference Price, } i \left(\frac{\text{€}}{\text{m}^2} \right) = \frac{\text{Avg Price Piacenza} \left(\frac{\text{€}}{\text{m}^2} \right) \times \text{Class Price, } i}{\text{Ref. Avg Class Price in Piacenza}} \quad (6)$$

Where:

- Avg Price Piacenza $\left(\frac{\text{€}}{\text{m}^2} \right) = 1815$
- Class Price, $i =$ Price Increase of class i vs Reference Class G (%)
- Ref. Avg Class Price in Piacenza = 1.066

Table 10: Reference Price for each Energy Class

Energy Class	Reference Price, i [€/m ²]
A4	2256,55
A3	2256,55
A2	2256,55
A1	2256,55
B	2129,40
C	2021,50
D	1936,41
E	1864,21
F	1785,75
G	1702,06

Higher EPC classes (A to C) show higher prices compared to lower classes (E to G). Each class is assigned a specific reference price, proportional to its capitalization relative to the city's average EPC.

$$\text{Mean Area, } ij \text{ (m}^2\text{)} = \frac{\text{VSM mean, } j}{\text{Reference Price, } i} \quad (7)$$

$$\text{Std. Dev. for Area, } ij \text{ (m}^2\text{)} = \frac{\text{VSM std dev, } j}{\text{Reference Price, } i} \quad (8)$$

Where:

- $\text{Mean Area, } ij \text{ (m}^2\text{)}$ = mean house area (m²) for energy class i in income bracket j ,
- $\text{VSM mean, } j$ = estimated mean market value, in €, of a house in income bracket j ,
- $\text{Reference Price, } i$ = reference price in €/m² for houses in class i ,
- $\text{VSM std dev, } j$ = estimated std dev market value, in €, of a house in income bracket j ,
- $\text{Std. Dev. for Area, } ij \text{ (m}^2\text{)}$ = house std dev area (m²) for energy class i in income bracket j .

Table 11: Mean and Std. Dev. of each Energy Class for First Income Bracket (less than €10,000 per year)

Energy class	Mean Area (m ²)	Std Dev
A1	47,63	51,82
A2	47,63	51,82
A3	47,63	51,82
A4	47,63	51,82

Energy class	Mean Area (m ²)	Std Dev
B	50,47	54,91
C	53,17	57,84
D	55,50	60,38
E	57,65	62,72
F	60,19	65,48
G	63,15	68,70

This procedure is repeated for all income brackets. Household areas are then simulated using a normal distribution and the mean and standard deviations of each EPC–Income subgroup.

2.1.4 Simulating Incomes:

In order to simulate this parameter, the normal distribution is used once again. The values are simulated while using a mean and standard deviation specific to each income bracket as in Equation 9. The mean is obtained from the IRPEF database and the standard deviation from a public national microdata developed by Banca d'Italia [27].

Table 12: IRPEF Mean Annual Salary per Income Bracket

Income bracket (€/year)	Number of Residents	Total Salary of Residents	Mean Salary
Less than 10,000	15,688	71,434,724	4,553.5
From 10,000 to 15,000	7,901	99,498,742	12,593.2
From 15,000 to 26,000	24,516	509,374,003	20,777.2
From 26,000 to 55,000	22,759	796,770,289	35,009.0
From 55,000 to 75,000	2,619	166,811,561	63,692.8
From 75,000 to 120,000	2,202	201,950,894	91,712.5
Higher than 120,000	1,267	279,882,626	220,901.8
	76,952		

Table 12 can be grouped differently to fit the standard of five brackets to ensures consistency with the EPC–Income structure used earlier.

Table 13: IRPEF Mean Annual Salary per Income Bracket - Grouped

Income bracket (€/year)	Number of Residents	Total Salary of Residents	Mean Salary
Less than 10,000	15,688	71,434,724	4,553.46
From 10,000 to 26,000	32,417	608,872,745	18,782.51
From 26,000 to 55,000	22,759	796,770,289	35,009.02
From 55,000 to 75,000	2,619	166,811,561	63,692.84
Higher than 75,000	3,469	481,833,520	138,896.95
	76,952	2,125,722,839	27,624.01

Table 14: Banca d'Italia Income Standard Deviation - Grouped

Income bracket (€/year)	Standard Deviation
Less than 10,000	2,356.9
From 10,000 to 26,000	4,461.9
From 26,000 to 55,000	8,198.3
From 55,000 to 75,000	5,765.3
Higher than 75,000	178,884.3

It should be noted that the income bracket above €75,000 the standard deviation is very large, due to the difference in extremes on high income households. However, this group is not the focus of the REC analysis, as energy poverty interventions are not targeted at them.

2.1.5 Energy Bill & Burden calculation

Annual energy consumption (kWh/year) and bill (€/year) is calculated by considering the Energy Cost (€/kWh), which is the weighted average cost of both gas and electricity, which was calculated as 0.1944 €/kWh, combining electricity (0.3128 €/kWh, 39% share) and natural gas (0.1125 €/kWh, 61% share), following Equation 10.

$$\text{Consumption} \left(\frac{\text{kWh}}{\text{year}} \right) = \text{House Area} (m^2) \times \text{Specific Consumption} \left(\frac{\text{kWh}}{m^2} \right) \quad (9)$$

$$\text{Energy Cost} \left(\frac{\text{€}}{\text{kWh}} \right) = \text{Electricity Cost} \left(\frac{\text{€}}{\text{kWh}} \right) \times \text{Electricity Weight} (\%) + \text{Natural Gas Cost} \left(\frac{\text{€}}{\text{kWh}} \right) \times \text{Natural Gas Weight} (\%) \quad (10)$$

$$Bill \left(\frac{\text{€}}{\text{year}} \right) = Energy \text{ Consumption} \left(\frac{kWh}{\text{year}} \right) \times Energy \text{ Cost} \left(\frac{\text{€}}{kWh} \right) \quad (11)$$

$$Energy \text{ Burden} (\%) = Bill \left(\frac{\text{€}}{\text{year}} \right) \div Income \left(\frac{\text{€}}{\text{year}} \right) \quad (12)$$

2.2 Clusters Assignment

Following the construction of the synthetic database, households were grouped into three clusters. This was performed through the rules-based logic scheme, which determines the criteria to assign households to each cluster. The reason this approach was used, instead of clustering through unsupervised machine learning algorithms, is to ensure clarity when defining clusters, which is needed for further correct policy development. Clusters considered are:

- Vulnerable: households with an income lower than the Northern Italy poverty threshold of 10,000 euro [4], referred to a single adult.
- Energy Poor: households with income higher than the poverty thresholds but lower than 55,000 euro, an energy burden higher than 10% and an EPC belonging to the worst performing classes (E, F, G). This group represents the primary target of REC interventions, as they combine structural inefficiencies with financial stress.
- Non-vulnerable: Those cases which don't meet the criteria of Vulnerable or Energy Poor. They generally have enough financial resources to manage their energy costs, thus are not considered energy poor or at risk and do not require financial support.

The structure was set by the literature reviewed from [6], [7], [8] detailed in Chapter 1.3: Literature Review.

2.3 Gap and Energy Requirement Estimation

Once clusters are defined, the next step is to calculate the energy gap, which is ultimately the total energy required to be shared with the community. It is equal to the sum of all energy gaps of all selected households to bring their energy burden down to the 10% threshold. This financial gap is calculated as follows:

$$Gap (\text{€}) = \text{Max}(0, Bill - 10\% \times Income) \quad (23)$$

This way cases where the bill is smaller than ten percent of the income are not accounted for, assigning a value of 0 for their gap.

The Gap (€) can be converted into an equivalent Energy Gap (kWh):

$$Shared \text{ Energy Needed} (kWh) = \frac{\sum Gap (\text{€})}{Avoided \text{ Tariff} + GSE \text{ Tariff} \times Community \text{ Share}} \quad (34)$$

Where GSE Tariff corresponds to the incentive structure given to the REC due to energy sharing and dependent on their size. Avoided Tariff (€0.16/kWh) is due to virtual energy sharing and savings

from transmission and distribution network services. Community Share is the percentage of shared energy from the total produced, which varies depending on the actual consumption of the PV system owners. Varying this parameter allows us to test different REC distribution scenarios, from low sharing (30%) to high sharing (70%), as detailed later in the Results section.

2.4 Total Benefit Calculation

After estimating the energy requirements, the monetary benefit to selected households needs to be calculated. These benefits come from GSE tariff incentive and avoided electricity system charges.

The total benefit, perceived by the household side, can be calculated as per Equation 15.

$$Total\ Benefit_i = E_i \times (T_{avoided} + \alpha \cdot T_{GSE,i}) \quad (45)$$

Where:

- E_i = total shared energy from REC type i (kWh),
- $T_{avoided}$ = avoided electricity tariff (€/kWh),
- $T_{GSE,i}$ = GSE incentive tariff for REC type i (€/kWh),
- α = community share (%).

This formulation ensures that both cost savings and incentive revenues are captured in proportion to the amount of energy shared within the community.

2.5 Model Optimization for REC sizing

To determine the best combination of PV systems and their size, a linear optimization model is implemented in Python, with the objective to minimize the installed capacity while meeting the total energy demand.

PV system types:

- Small (< 200 kW)
- Medium (< 600 kW)
- Large (> 600 kW)

It is important to clarify that a REC can include multiple PV plants and each individual plant must not exceed 1 MW.

Objective Function:

$$\min \sum_{i \in PV\ types} \left(\frac{kW_i}{Household\ Benefit_i} \right) \times Num_i \quad (56)$$

Constraints:

- Total shared energy from the REC must meet or exceed total household energy gap:

$$\sum_i (n_i \times Shared\ Energy_i) \geq Shared\ Energy\ Needed\ (kWh) \quad (67)$$

$$Shared\ Energy_i = Capacity_i \times Yield \times Community\ Share \quad (78)$$

Additional assumptions:

- Annual PV production in Piacenza is set at 1359.29 kWh/kW/year, based on the PVGIS calculator.
- Shared energy and incentives are distributed proportionally to household gaps, simplifying the sharing scheme.

This approach ensures the model identifies the smallest feasible REC configuration that still addresses the selected energy poverty thresholds under different sensitivity scenarios.

2.6 Sensitivity Analysis

As discussed before, there are two critical variables in the model that defines the PV capacity that needs to be installed. Therefore, this analysis is implemented to assess the impact of these assumptions on total shared energy, which directly affects REC size.

2.6.1 Energy Burden Thresholds

The definition of energy poor depends on the upper limit threshold of acceptable energy burden. As reviewed before, the baseline of 10% is applied. However, higher thresholds are also considered to understand how total required capacity changes as the range to be considered increases from a base of 30% to 100%, where all burdens are considered. Thus, the analysis tests the following ranges.

- 10% to 30%
- 10% to 40%
- 10% to 50%
- 10% to 60%
- 10% to 70%
- 10% to 80%
- 10% to 90%
- 10% to 100%

2.6.2 Community Share

The share of incentives distributed to households depends on the model of the REC and on the surplus that is available after covering the owners' investment recovery and maintenance costs. Since there is no standard value for this parameter, a range from 20% to 70% of community sharing is tested, so different outcomes can be tested from modest to strong sharing.

2.6.3 Dual Analysis

Combining these two variables allows the exploration of possible trade-offs between more households to benefit from incentives and higher PV capacity needed. This dual sensitivity analysis ensures that the results are clear and consistent under different scenarios.

3. Data

3.1 Input Data for Synthetic Sheet Creation

The creation of the synthetic dataset used in the different sections of the study relied on several data sources. Household distribution by construction period and income bracket for the city of Piacenza was obtained from IRPEF (Dipartimento delle Finanze). The classification of buildings according to their energy performance was based on the EP_{g,l,nren} (kWh/m²) thresholds provided by SIAPE

(ENEA), which define the EPC class boundaries according to Piacenza’s climatic zone, which is zone E.

To determine the mean and standard deviation values for each income bracket, the Banca d’Italia database is consulted. Information from OMI (Osservatorio del Mercato Immobiliare) was used to estimate the average building areas through the cost per square meter in Piacenza. Energy prices were sourced from ARERA, while CENED data provided the shares of gas and electricity consumption, which were used to construct a weighted average cost of energy. Finally, PVGIS data was employed to model solar energy production under the climatic conditions specific to Piacenza.

3.2 Data for REC Incentive Assignment

This section recaps some extra data that was needed for the computations done in the methodology section.

Figure 2: Monthly Solar PV Production - Piacenza

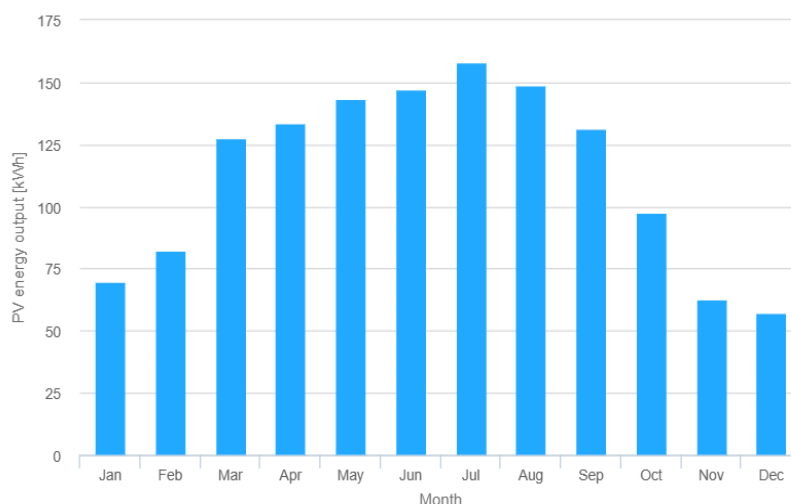


Figure 2 shows the solar PV production for a specific year, which adds on to 1359.29 kWh/year. This is data simulated from the PVGIS platform of the European Commission, for the city of Piacenza, which is on the climatic zone E.

Table 15: REC Types Capacity and Annual Energy Production

REC Type	Capacity (kW)	Annual PV Yield (kWh/kW)	Annual Production (kWh)
Small	Up to 200	1359.29	271,858
Medium	From 200 to 600	1359.29	815,574
Large	From 600 to 1000	1359.29	1,359,290

While, Table 15 calculates the annual production, in kWh, for each REC type according to the maximum capacity of each type.

Table 16: REC Types GSE Tariff

REC Type	Base Tariff (€/MWh)	Max Variable Bonus (€/MWh)	Regional Bonus (€/MWh)	Max GSE Tariff (€/MWh)
Small	80	40	10	130
Medium	70	40	10	120
Large	60	40	10	110

Table 17: Bill Cost: User Side

Component	Value (€/kWh)	Comment
Energy Procurement + Retail	0.187	Avoided
Transport & Meter Management	0.063	Not avoided
Taxes	0.031	Not avoided
General System Charges	0.032	Not avoided
Total Estimated Cost	0.313	

Ultimately, tariffs given as an incentive to PV owners for sharing energy, depending on their REC capacity [15], are expressed in Table 16, while the calculation of the avoided cost from the user side [28] is seen in Table 17.

3.3 Assumptions

- a) PV Yield: constant annual PV production in Piacenza is assumed to be 1359.19 kWh/kW/year as per PVGIS.
- b) Energy Costs: fixed weighted average cost of 0.1944 €/kWh is applied, and future volatility of prices is not considered.
- c) Household Needs: they don't receive more energy or financial benefit than they need to reach the 10% energy burden threshold.
- d) Sharing Mechanism: shared energy and incentives are distributed proportionally to each household's financial gap.
- e) Independence of Income and EPC: Income brackets and EPC distribution are assumed to be independent, due to lack of microdata linking them.

- f) Technology Assumptions: PV systems are assumed to operate at constant annual yield without degradation, outages, or curtailment.
- g) REC Sizing: the optimization model selects the most cost-efficient REC combinations that satisfies total household energy gaps.

4. Results

4.1 Distribution of Household Types

This section analyzes the characteristics of the synthetic dataset obtained from the simulation for Piacenza, presenting the distribution of energy classes, income brackets and their combined distribution.

Figure 3: Distribution of Households by EPC

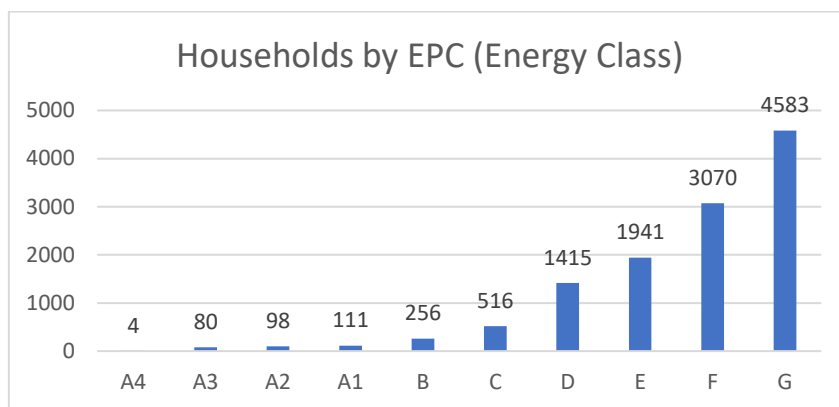


Figure 3 shows the distribution of households across their energy classes. It reflects the building stock for the city, showing that most households are concentrated in the worst energy classes E, F and G ($\approx 80\%$). This indicates that most of the residential population resides in inefficient houses, which contributes directly to the increase in energy consumption and thus, higher bills. This level of inefficiencies complies with the literature reviewed on [13], since retrofits and/or new constructions are less common compared to old building stock.

Figure 4: Distribution of Households by Income Bracket

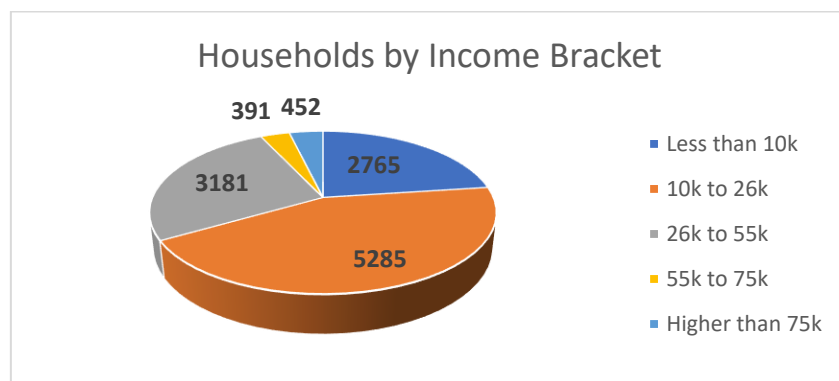
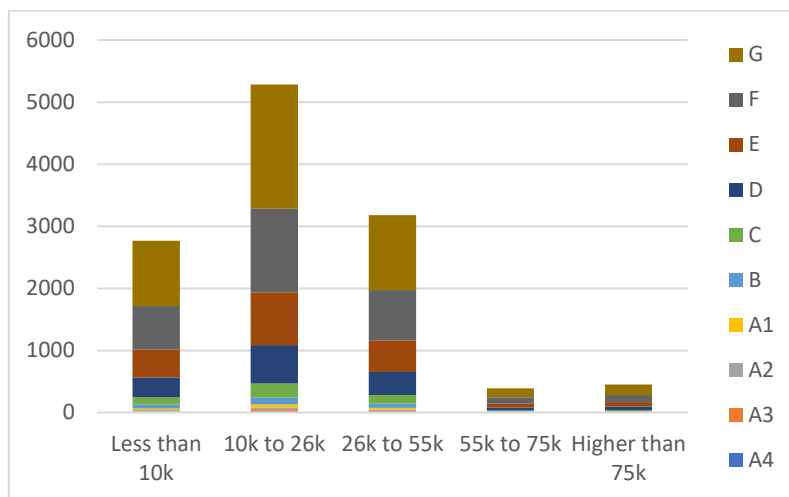


Figure 4 presents the distribution of households by income bracket. The majority of households fall within middle to low income, where a significant portion earning less than €10,000 a year, which is below the national poverty threshold.

Figure 5: Income Bracket vs. EPC Distribution

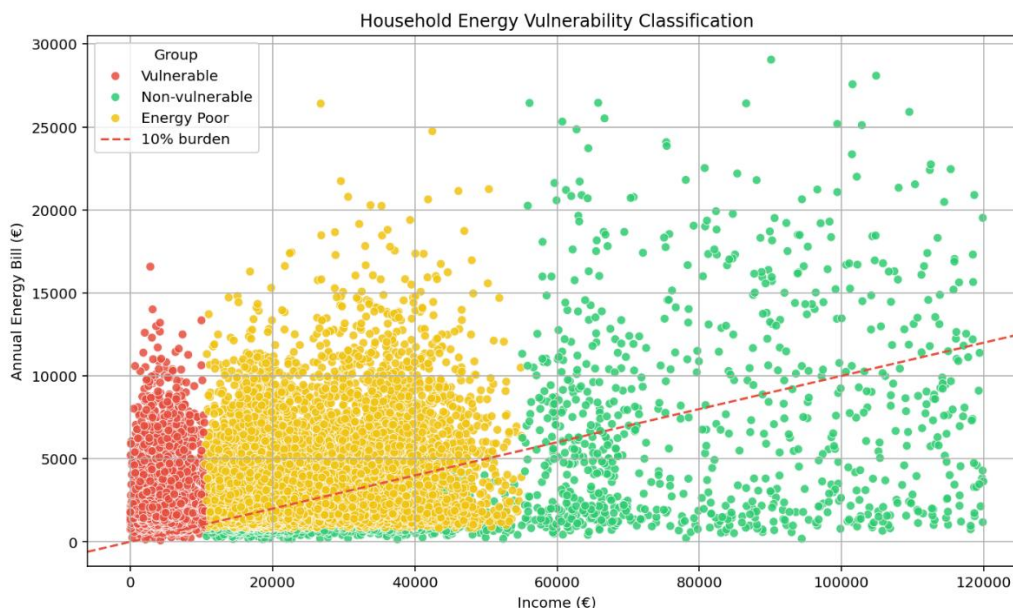


Meanwhile, Figure 5 combines both parameters. This highlights the distribution of EPC in each income bracket, which links low income with poor energy efficiency.

Figure 6 shows the results of the clustering according to the rule-based approach suggested, using the synthetic dataset as input. The x-axis represents households' income and the y-axis their annual energy bill. Each point on the graph corresponds to a simulated household: red points correspond to Vulnerable households (income below €10,000), yellow points correspond Energy Poor households (income between €10,000 and €55,000 & energy burden < 10% & EPC E, F, G) and green points to Non-Vulnerable households. While the red dashed line indicates the energy burden threshold of 10%.

This visualization confirms that this approach yields a clear segmentation of clusters. The Vulnerable cluster is concentrated towards the low income & high burden side; the Energy Poor cluster spreads through intermediate incomes; the Non-Vulnerable cluster concentrates towards high income & low burden region. This plot supports the use of simple, rule-based thresholds for clear policy targeting and REC incentive distribution.

Figure 6: Rule-Based Household Vulnerability Clustering



4.2 Energy Burden Gaps and Household Energy requirement

The next step is to quantify the amount of shared energy that is required by selected households to reduce their energy burden threshold to 10%. Table 18 considers the total energy gap (in kWh) that needs to be covered by solar PV generation under different burden and community share scenarios.

Table 18: Energy Gap Required in Each Scenario

Energy Burden	Required Shared Energy (kWh)					
	Community Share (%)					
	30%	40%	50%	60%	70%	Total
10 – 30%	29,176,406	27,787,054	26,524,006	25,370,788	24,313,672	133,171,925
10 – 40%	42,921,147	40,877,283	39,019,224	37,322,736	35,767,622	195,908,013
10 – 50%	52,132,479	49,649,980	47,393,163	45,332,591	43,443,733	237,951,946
10 – 60%	56,883,594	54,174,852	51,712,358	49,463,995	47,402,995	259,637,795
10 – 70%	58,773,111	55,974,392	53,430,101	51,107,053	48,977,593	268,262,250
10 – 80%	59,934,254	57,080,242	54,485,685	52,116,743	49,945,212	273,562,136
10 – 90%	60,209,154	57,342,052	54,735,595	52,355,786	50,174,295	274,816,883
10 – 100%	60,589,649	57,704,427	55,081,499	52,686,651	50,491,374	276,553,599

These results show that the required energy grows notably, around double, as the range of targeted households increases from 10-30% to 10-100%. For instance, at a community share of 40%, the shared energy required increases from 27.8 GWh/year to 57.7 GWh/year, when moving from the smallest to the highest burden range. At the same time, as the community share increases, total required energy decreases. This happens due to the increase in incentives at larger share values, which is reflected in bill reductions so there is less additional energy needed to bring households to the 10% burden threshold.

In the following sections, one case will be used as base from the sensitivity analysis, which represents the energy burden range of 10% to 30%. Meanwhile, the complete set of scenarios and results is provided in Appendix 7.1 and 7.2 for further reading, including REC distribution and capacity requirements.

4.3 REC Distribution

To convert the energy requirements into renewable energy communities three possible sizes are considered: small, medium and large. Tables 19 report the number of PV systems required, the aggregated capacity, the corresponding shared energy delivered and the resulting total benefit under different burden ranges.

Results indicate dominance and preference for large systems, which have a capacity up to 1 MW. Meanwhile, medium and small ones don't play a significant role, indicating that meeting the energy requirements depends on larger scales structure.

For example, in Table 19, when considering an energy burden range of 10-30% & a community share of 30%, the total installed capacity is 71,600 kW, producing 29 GWh/year of energy and an economic benefit of €6.4 million. As the burden range increases to 10-100% the number of PV systems required also increases as there are more households to be served.

Another observation that can be made is that for the same energy burden, as the community share increases, the installed capacity and energy share decreases. However, the total benefit remains stable. This is due to the incentive structure, which ensures that selected households consistently achieve the targeted reduction in energy burden regardless of the level of sharing.

Overall, the model suggests that using large scale systems is the most effective way to comply and alleviate energy poverty in Piacenza, as they can deliver the required energy with fewer installations. At the same time, smaller capacity systems yield a higher remuneration per kWh, which could give better benefits per unit but would require a much higher number of installations to meet the same demand.

Table 19: REC Capacity and Benefit: 10-30% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	1	71	71,600	29,197,549	6,424,195
40%	1	0	51	51,200	27,838,259	6,431,508

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
50%	0	2	38	39,200	26,642,084	6,451,462
60%	1	0	31	31,200	25,445,909	6,439,772
70%	0	1	25	25,600	24,358,477	6,434,634
Total	2	4	216	218,800	133,482,278	32,181,571

4.4 Impact of Burden Thresholds and Incentive Sharing on REC Outcomes

To better understand the impact of varying energy sharing levels, this section shows in Figure [6] the installed capacity required across different burden thresholds.

As seen in previous section 4.3, the increase of community sharing doesn't change much the total benefit perceived by households, but it does change the total installed capacity. For instance, as in Figure 7, for a community share of 30%, 71,600 kW of capacity is required, while at 70% level, only 25,600 kW, representing a reduction of $\approx 65\%$. This illustrates how higher community sharing improves system efficiency by reducing the total installed capacity necessary to achieve the same economic relief for households. In Figure 8 presents the results of the sensitivity analysis across all burden ranges. As expected, as the burden range widens, the number of households selected does as well, which leads to an increase also in the required capacity installed.

Figure 7: Total Capacity Required: 10-30% Burden

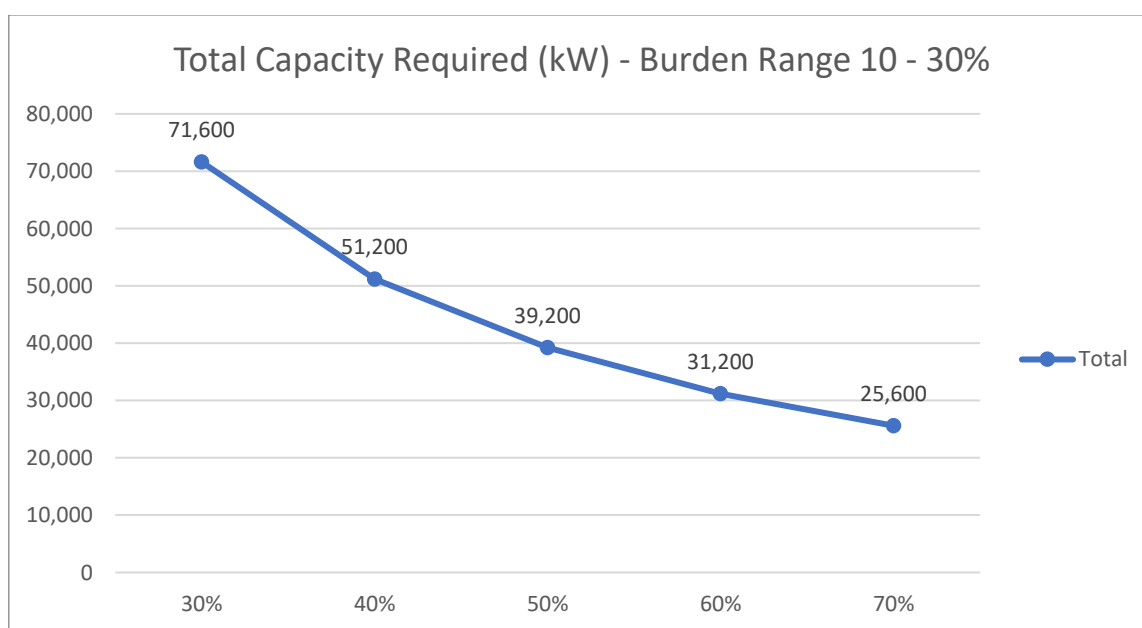
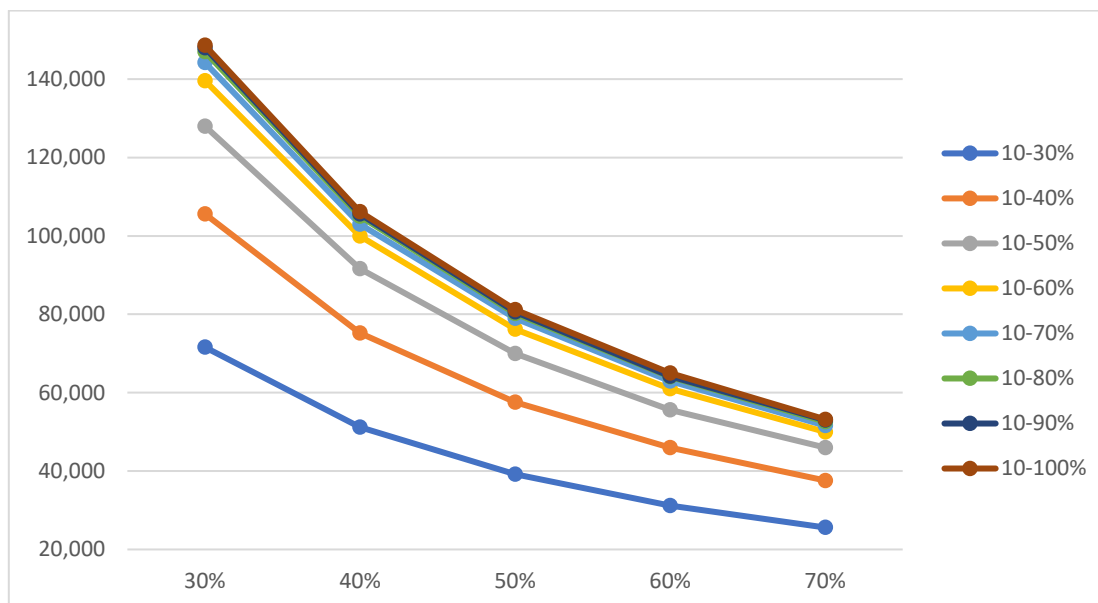


Figure 8: Total Capacity Required: 10-30% to 10-100% Burden



4.5 Policy applications for different households' clusters

Classifying households in Piacenza into Vulnerable, Energy-Poor and Non-Vulnerable provides a framework for developing and implementing policy measures tailored to each cluster. This segmentation references [19], where different municipality profiles are associated with specific economical, technical or bureaucratic interventions.

4.5.1 Vulnerable Households

These are households with an annual income level below the poverty threshold (€10,000). This includes efficient and inefficient buildings, since for them the main barrier to access sustainable energy is economic. Policies should focus on reducing financial barriers.

This cluster can benefit through:

- Direct income support in means of social transfers and/or welfare schemes as the Regional Social Fund in Emilia Romagna [29] and Social Allowance (Assegno di Inclusione) [30].
- Administrative simplification for accessing welfare benefits.
- Integration with broader assistance programs like Inclusion Allowance [31].

4.5.2 Energy Poor Households

This group represents the most critical target for intervention, defined by a high energy burden (>10%) and an annual income level between €10,000 and €55,000. For these households, structural improvements in building performance and REC benefits are required.

This cluster can benefit through:

- Dedicated REC participation schemes to ensure the energy burden reduction due to shared generated energy.
- Targeted energy efficiency retrofits with combination of REC participation.
- Reduced or zero interest loans for building renovation or return of investment.

4.5.3 Non-vulnerable Households

Households with high incomes with no differentiation between energy classes as those with high energy expenses do not represent an issue and can afford to invest in energy efficiency to reduce their consumption. This cluster benefits from regulatory simplification and removing bureaucratic barriers.

4.6 Limitations of the Model

Due to the lack of public available data specific to Piacenza regarding household energy and income data, the analysis is based on a synthetic dataset. Therefore, a combination of regional and national statistics and data, along with assumptions used for EPC and income simulation, were used to estimate households' characteristics. This approach unavoidably introduces uncertainty in the accuracy of the modeled households, even though it enables realistic estimates.

Also, the household categorization into three specific clusters was carried out using a rule-based approach, which considers fixed thresholds for differentiation, ensuring transparency and policy relevance.

The REC model doesn't consider potential transaction costs, administrative delays or factors influencing the sharing of energy and household participation. Moreover, spatial constraints, like rooftop availability, were not considered.

In Table 20 an overview of the data is provided to observe the geographic level of each source. As discussed, some data was only available at country level, while other data at city specific level.

Table 20: Data Overview

Used For	Territory Level	Description	Source
EPC distribution	Italy	Distribution of energy classes according to construction era.	ENEA
EPC assignment	Piacenza	Distribution of construction era of buildings in Piacenza.	MEF
Simulation Energy Consumption	Italy, Climatic Zone E	Energy consumptions thresholds by energy class.	SIAPE
Simulating Building Area	Italy	Distribution of mean and std. Dev. Of house market values per income bracket.	Dipartimento delle Finanze
Simulating Building Area	Piacenza	Distribution of buildings according to their income bracket.	IRPEF
Cost of squared meter	Piacenza	Market price of the squared meter in Piacenza used for calculations.	Osservatorio del Mercato Immobiliare

Used For	Territory Level	Description	Source
Income Simulation	Piacenza	Data regarding the mean values of salaries in each income bracket.	MEF
Income Simulation	Italy	Data regarding the std. Dev. values of salaries in each income bracket.	Banca d'Italia
Cluster Assignment	Northern Italy	Criteria for the selection of clusters and thresholds.	STATISTA
Energy Poor Definition	Europe	Definition of energy poverty threshold.	European Parliament
PV Energy Production	Piacenza	PV energy production yield per kW installed in Piacenza.	PVGIS

5. Conclusions

In this thesis the potential of Renewable Energy Communities (RECs) is examined as a tool to alleviate energy poverty in Piacenza. This is done through the construction of a synthetic dataset of households, where a rule-based classification is applied. The model categorizes families into three clusters: Non-Vulnerable, Energy Poor and Vulnerable, which provides a basis for REC participation under different energy burdens and energy community sharing scenarios.

Results reveal that RECs can indeed make a significant impact on reducing energy poverty, when benefits are focused on the part of the community that most needs it. In this case, it shows that these communities can help to reduce the energy burden of households to less than the energy poverty threshold (10%). On the other hand, non-vulnerable households can be mainly supported through regulatory simplification and even participate through investment on RECs to reduce their consumption. Meanwhile, vulnerable ones are considered to benefit from financial programs/social policies like Regional Social Funds and Social Allowance.

Even though results are favorable, the model is subject to limitations, which are the reliance on a synthetic database rather than household level microdata, using fixed rules for clustering instead of a machine learning approach.

Future work could refine these results by using and substituting real household microdata when available, experimenting with alternative clustering methods such as unsupervised machine learning, considering different REC layouts and incentive schemes along with including spatial constraints, rooftop availability and grid constraints.

In conclusion, this thesis demonstrates that RECs, when designed with equity and inclusion as the main objective, can become a practical tool for addressing and alleviating energy poverty in

Piacenza. Moreover, the study also highlights how the energy transition can not only point towards decarbonization, but also as a means of social protection of a community.

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7. Appendix

7.1 Sensitivity Analysis REC Distribution Results

Table 21: REC Capacity and Benefit: 10-40% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	1	105	105,600	43,062,307	9,474,442
40%	1	0	75	75,200	40,887,443	9,445,869
50%	0	1	57	57,600	39,147,552	9,475,747
60%	0	0	46	46,000	37,516,404	9,491,650
70%	0	1	37	37,600	35,776,513	9,448,996
Total	1	3	320	322,000	196,390,219	47,336,703

Table 22: REC Capacity and Benefit: 10-50% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	0	128	128,000	52,196,736	11,483,282
40%	0	1	91	91,600	49,804,386	11,506,118
50%	0	0	70	70,000	47,575,150	11,513,186
60%	0	1	55	55,600	45,345,914	11,475,452
70%	0	0	46	46,000	43,769,138	11,555,052
Total	0	2	390	391,200	238,691,324	57,533,091

Table 23: REC Capacity and Benefit: 10-60% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	1	139	139,600	56,927,065	12,524,688
40%	0	0	100	100,000	54,371,600	12,559,840
50%	0	2	75	76,200	51,788,949	12,537,004
60%	0	0	61	61,000	49,750,014	12,586,754
70%	0	0	50	50,000	47,575,150	12,559,840
Total	0	3	425	426,800	260,412,778	62,768,125

Table 24: REC Capacity and Benefit: 10-70% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	1	0	144	144,200	58,802,885	12,937,124
40%	0	0	103	103,000	56,002,748	12,936,635
50%	0	0	79	79,000	53,691,955	12,993,453
60%	0	0	63	63,000	51,381,162	12,999,434
70%	0	1	51	51,600	49,097,555	12,965,751
Total	1	1	440	440,800	268,976,305	64,832,397

Table 25: REC Capacity and Benefit: 10-80% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	0	147	147,000	59,944,689	13,187,832
40%	0	0	105	105,000	57,090,180	13,187,832
50%	1	0	80	80,200	54,507,529	13,192,181
60%	0	0	64	64,000	52,196,736	13,205,774
70%	0	1	52	52,600	50,049,058	13,216,948
Total	1	1	448	448,800	273,788,192	65,990,566

Table 26: REC Capacity and Benefit: 10-90% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	0	148	148,000	60,352,476	13,277,545
40%	0	1	105	105,600	57,416,410	13,264,496
50%	0	1	80	80,600	54,779,387	13,258,651
60%	0	2	63	64,200	52,359,851	13,252,914
70%	0	0	53	53,000	50,429,659	13,313,430
Total	0	4	449	451,400	275,337,782	66,367,035

Table 27: REC Capacity and Benefit: 10-100% Burden

Comm. Share	PV system Type			Total Capacity (kW)	Total Shared Energy (kWh)	Total Benefit (€)
	Small	Medium	Large			
30%	0	1	148	148,600	60,597,148	13,332,107
40%	1	0	106	106,200	57,742,639	13,339,420
50%	1	0	81	81,200	55,187,174	13,356,655
60%	0	0	65	65,000	53,012,310	13,412,114
70%	1	0	53	53,200	50,619,960	13,366,334
Total	3	1	453	454,200	277,159,231	66,806,630

7.2 Sensitivity Analysis Required REC Capacity

Figure 8: Total Capacity Required: 10-40% Burden

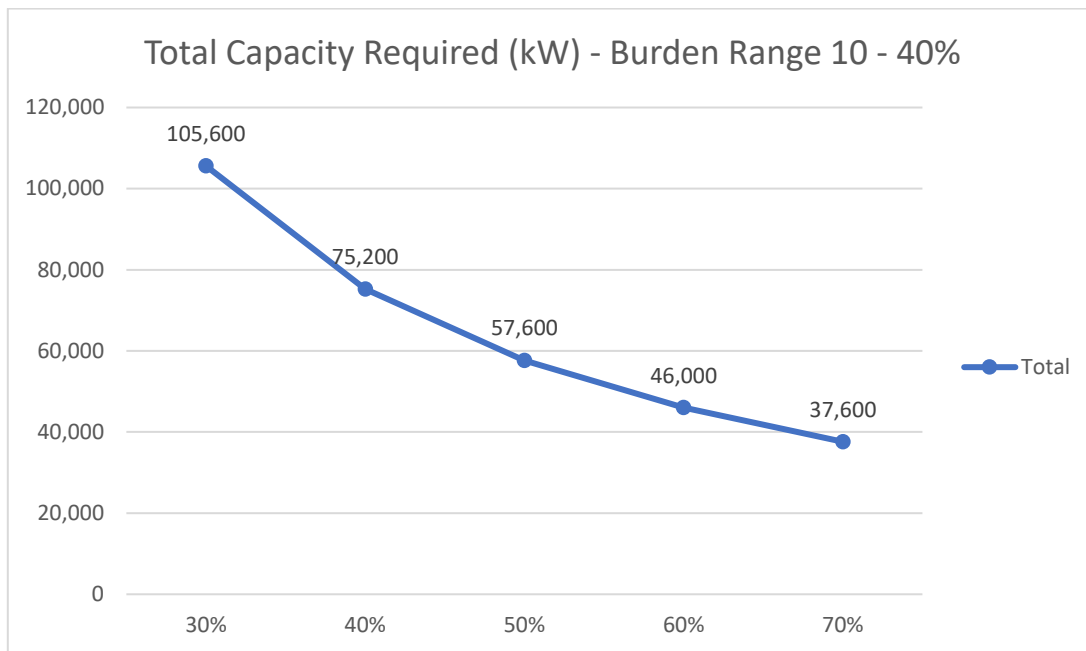


Figure 9: Total Capacity Required: 10-50% Burden

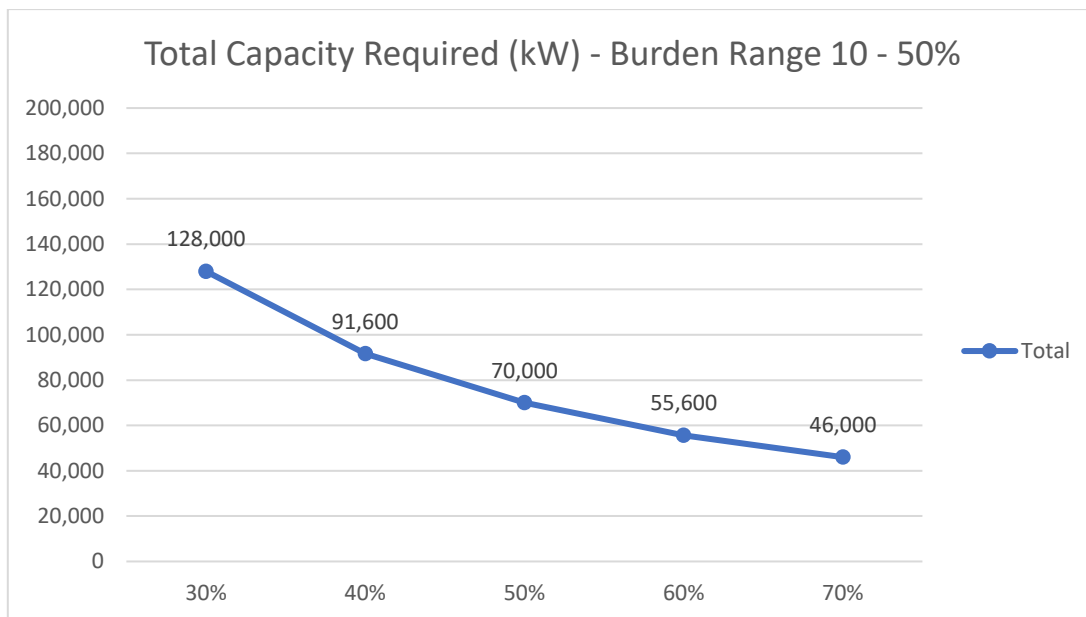


Figure 10: Total Capacity Required: 10-60% Burden

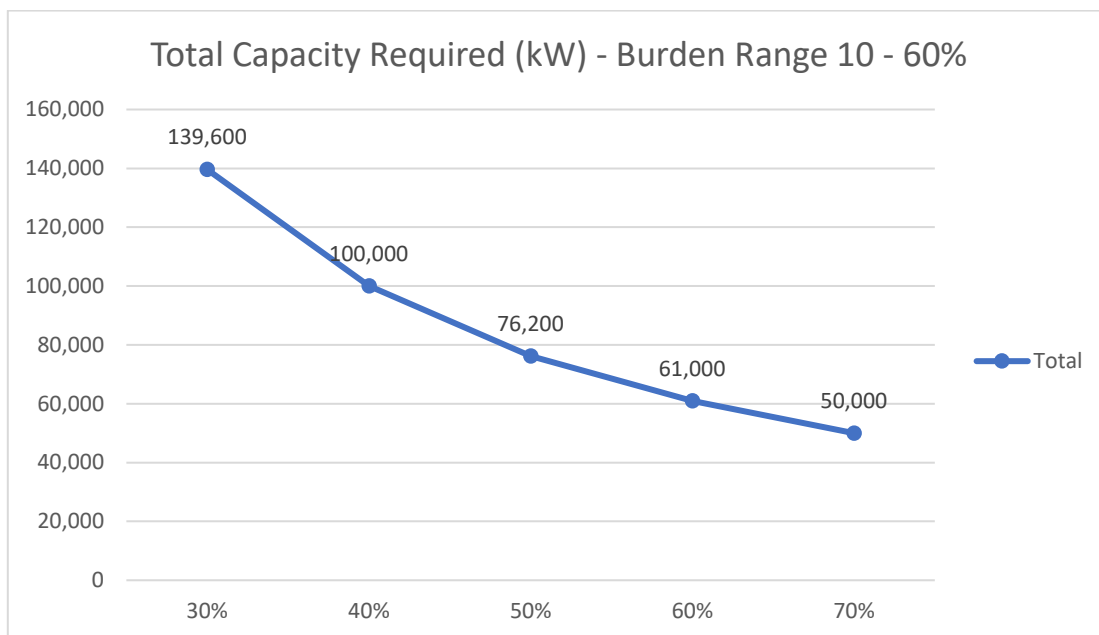


Figure 11: Total Capacity Required: 10-70% Burden

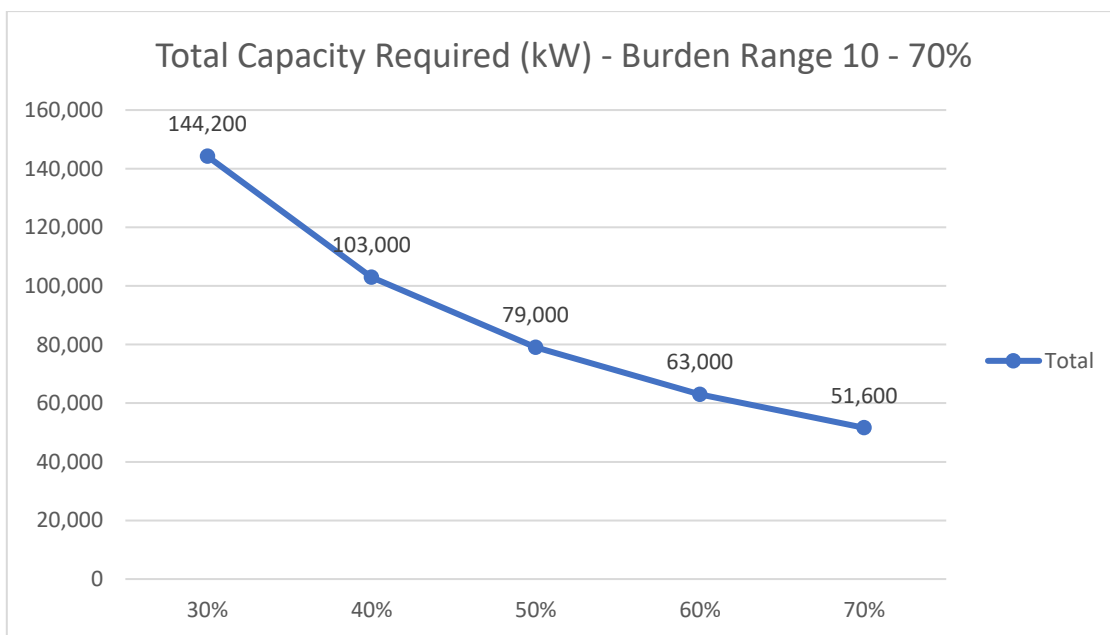


Figure 12: Total Capacity Required: 10-80% Burden

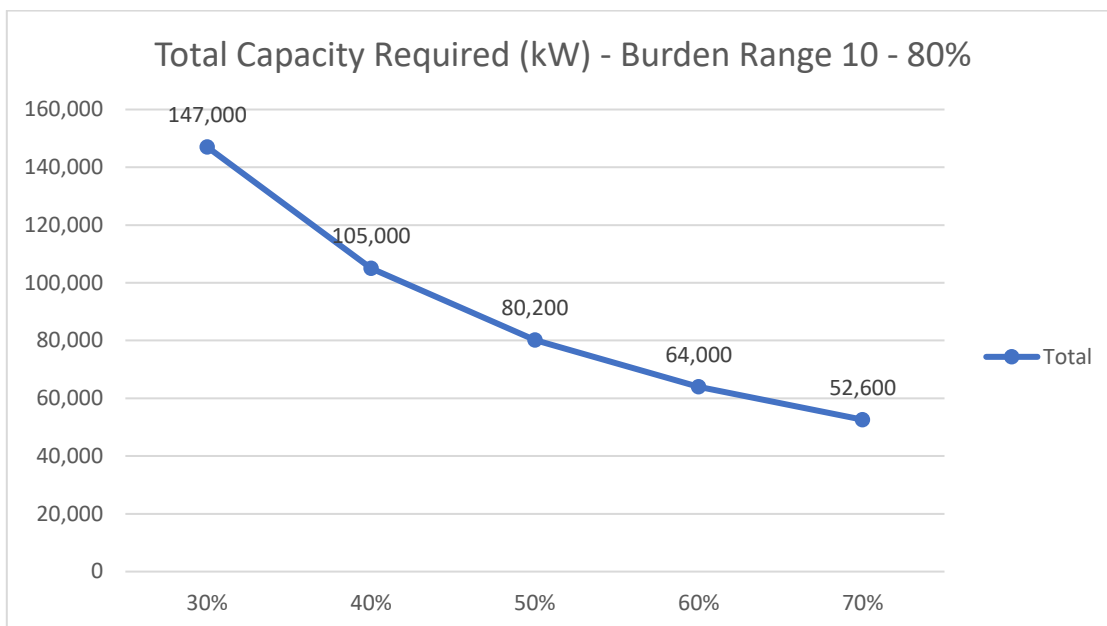


Figure 13: Total Capacity Required: 10-90% Burden

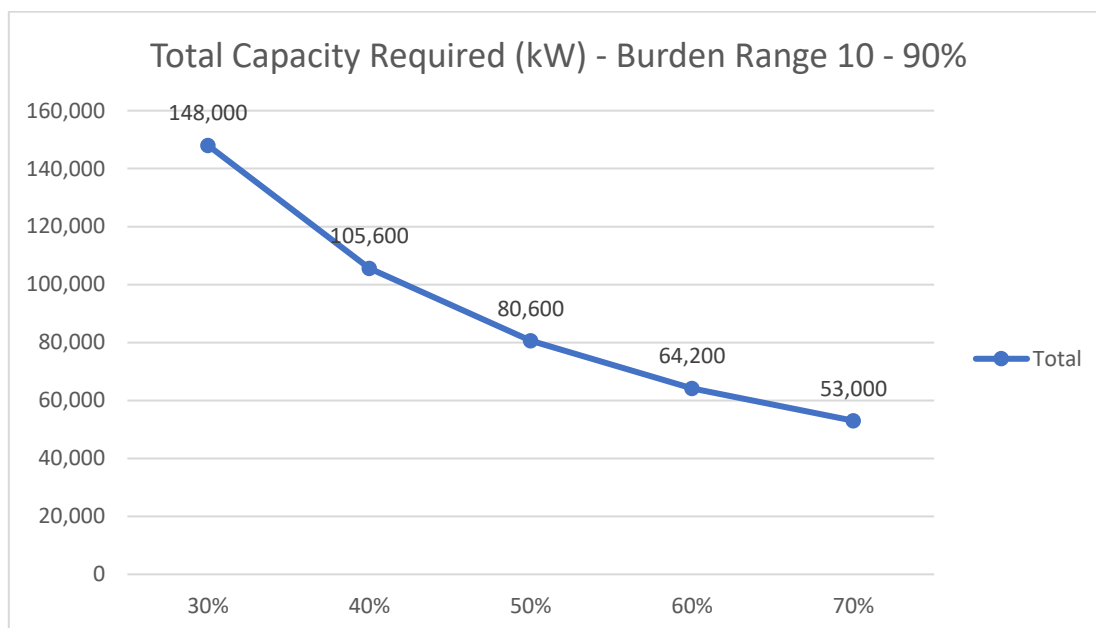
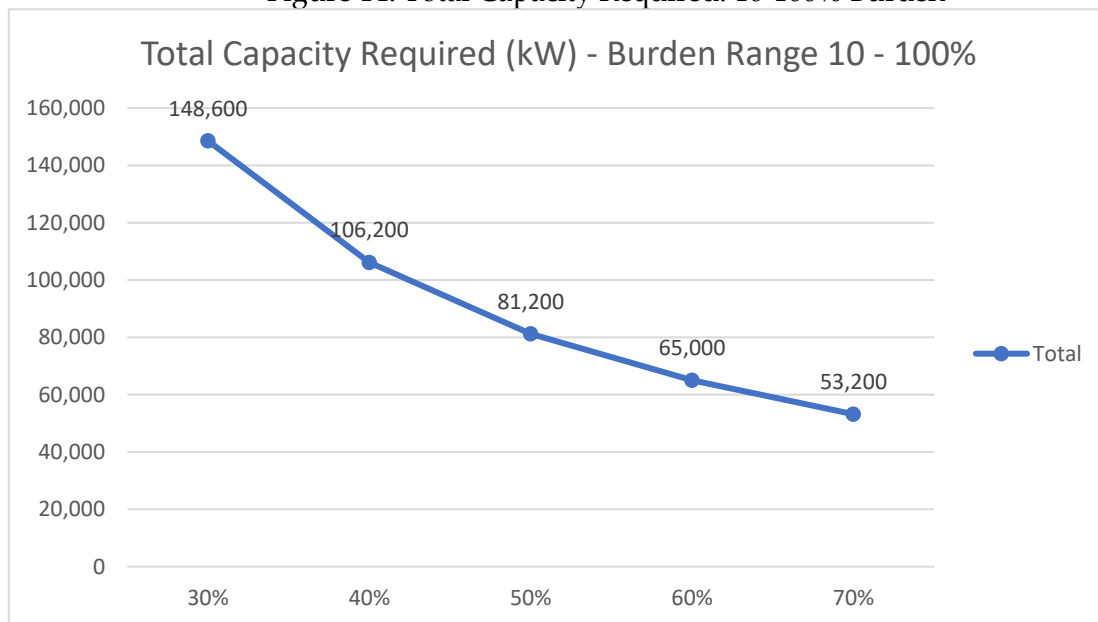


Figure 14: Total Capacity Required: 10-100% Burden



7.3 Python Code Used for Simulation of Synthetic Data

```

1  import pandas as pd
2  import numpy as np
3  import matplotlib.pyplot as plt
4  import seaborn as sns
5
6
7  # Loading Data
8  input_file = 'Testing_results.xlsx'
9  output_file = 'Final_results.xlsx'
10
11 # Opening Input File
12 df = pd.read_excel(input_file, sheet_name='Base Case')
13
14 # EPC thresholds
15 epgl_ranges = {
16     'A4': (10.0, 22.0),
17     'A3': (22.0, 46.9),
18     'A2': (46.9, 62.1),
19     'A1': (62.1, 75.5),
20     'B': (75.5, 90.3),
21     'C': (90.3, 109.9),
22     'D': (109.9, 137.8),
23     'E': (137.8, 171.4),
24     'F': (171.4, 219.5),
25     'G': (219.5, 320.1),}
26
27 # Step 1: Energy Performance generation
28 def generate_epgl(energy_class):
29     if energy_class in epgl_ranges:
30         low, high = epgl_ranges[energy_class]
31         return np.random.uniform(low, high)
32     return np.nan
33
34 df['EP_gL (kWh/m2)'] = df['Energy Class'].apply(generate_epgl)
35
36 # Step 2: Area generation
37 def generate_area(mean, std):
38     area = np.random.normal(loc=mean, scale=std)
39     if area < .30:
40         area = np.random.normal(loc=mean, scale=std)
41
42 df['Energy Class Num'] = df['Energy Class'].map(energy_class_map)
43
44 # Step 4: Income generation
45 income_stats = {
46     "Less than 10k": {"mean": 4553.46, "std": 2356.923, "min": 0, "max": 10000},
47     "10k to 26k": {"mean": 18782.51, "std": 4461.88, "min": 10000, "max": 26000},
48     "26k to 55k": {"mean": 35009.02, "std": 8198.338, "min": 26000, "max": 55000},
49     "55k to 75k": {"mean": 63692.84, "std": 5765.33, "min": 55000, "max": 75000},
50     "Higher than 75k": {"mean": 138896.95, "std": 178884.3, "min": 75000, "max": 120000},
51 }
52
53 def generate_income(bracket):
54     if bracket not in income_stats:
55         return np.nan
56     stats = income_stats[bracket]
57     # Generate a value and re-draw if outside the min/max range
58     while True:
59         income = np.random.normal(stats["mean"], stats["std"])
60         if stats["min"] <= income <= stats["max"]:
61             return round(income, 2)
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79

```

```

80 df["Income (€)"] = df["Income bracket (euro)"].apply(generate_income)
81
82 # Step 5: Calculations for Bill and Energy Burden
83 df["Bill (euro)"] = df["Annual Energy Consumption (kWh)"] * (0.11*0.61 + 0.3128*0.39)
84 df["Energy Burden"] = df["Bill (euro)"] / df["Income (€)"]
85
86 # Step 6: Rules for plotting
87 def classify_energy_vulnerability(row):
88     burden = row["Energy Burden"]
89     energy_class = row["Energy Class Num"]
90     income = row["Income (€)"]
91
92     if income <= 10500:
93         return "Vulnerable"
94     else:
95         if income <= 55000:
96             if burden > 0.1:
97                 return "Energy Poor"
98             else:
99                 if energy_class <= 3:
100                     return "Energy Poor"
101                 else:
102                     return "Non-vulnerable"
103             else:
104                 return "Non-vulnerable"
105
106
107 df["Vulnerability Group"] = df.apply(classify_energy_vulnerability, axis=1)
108
109 # Plot
110 plt.figure(figsize=(10, 6))
111 palette = {
112     "Vulnerable": "#E74C3C",
113     "Energy Poor": "#F1C40F",
114     "Non-vulnerable": "#2ECC71"
115 }
116
117 sns.scatterplot(
118     data=df,
119     x="Income (€)",
120     y="Bill (euro)",
121     hue="Vulnerability Group",
122     palette=palette,
123     alpha=0.85
124 )
125
126 # Add burden lines
127 plt.axline((0, 0), slope=0.10, color="#E74C3C", linestyle="--", label="10% burden")
128
129 plt.title("Household Energy Vulnerability Classification")
130 plt.xlabel("Income (€)")
131 plt.ylabel("Annual Energy Bill (€)")
132 plt.grid(True)
133 plt.legend(title="Group")
134 plt.tight_layout()
135 plt.show()
136
137 df.to_excel(output_file, index=False)
138
139
140

```

7.4 Python Code Used for Model Optimization

```

1 import pandas as pd
2 import pulp
3
4 # Loading Data
5 input_file = 'Final_results.xlsx'
6 df = pd.read_excel(input_file)
7
8 # Sensitivity parameters
9 burden_lower = 0.10 # fixed lower bound
10 burden_upper = [0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1] # variable upper bound scenarios
11 community_shares = [0.3, 0.4, 0.5, 0.6, 0.7] # % of GSE incentive to households scenarios
12
13 # Fixed assumptions
14 avoided_tariff = 0.187 # €/kWh avoided
15
16 tariff_per_kWh = { # €/kWh incentive from GSE
17     "small": 0.13,
18     "medium": 0.12,
19     "large": 0.11
20 }
21
22 pv_yield = 1359.29 # Piacenza-specific PV yield (kWh/kW/year)
23
24 rec_sizes_kw = {"small": 200, "medium": 600, "large": 1000}
25
26 # Store results
27 results = []
28
29 # Loop through sensitivity parameters
30 for upper in burden_upper:
31     for comm_share in community_shares:
32
33         # Step 1: Filter Targeted Households
34         df_target = df[
35             (df["Vulnerability Group"] == "Energy Poor") &
36             (df["Energy Burden"] >= burden_lower) &
37             (df["Energy Burden"] <= upper) &
38             (df["Energy Class"].isin(["E", "F", "G"]))
39         ].copy()
40
41         if df_target.empty:
42             results.append({
43                 "Burden Range": f"{int(burden_lower*100)}-{int(upper*100)}%",
44                 "Community Share": f"{int(comm_share*100)}%",
45                 "Households Targeted": 0,
46                 "n_small": 0,
47                 "n_medium": 0,
48                 "n_large": 0,
49                 "Total Capacity (kW)": 0,
50                 "Total Shared Energy (kWh)": 0,
51                 "Total Benefit (€)": 0,
52                 "Required Shared Energy (kWh)": 0
53             })
54             continue
55
56         # Step 2: Value per kWh (large REC conservative)
57         value_per_kWh = avoided_tariff + tariff_per_kWh["Large"] * comm_share
58
59         # Step 3: Gap to cover
60         df_target["Target Bill (€)"] = 0.10 * df_target["Income (€)"]
61         df_target["Gap to Cover (€)"] = (df_target["Bill (euro)"] - df_target["Target Bill (€)"]).clip(lower=0)
62         df_target["Shared kWh Needed"] = df_target["Gap to Cover (€)"] / value_per_kWh
63         total_shared_kWh_needed = df_target["Shared kWh Needed"].sum()
64
65         # Step 4: REC production and benefit
66         prod_per_REC = {k: v * pv_yield for k, v in rec_sizes_kw.items()}
67         shared_energy_per_REC = {k: prod * comm_share for k, prod in prod_per_REC.items()}
68         benefit_per_REC = {
69             k: shared_energy_per_REC[k] * (avoided_tariff + tariff_per_kWh[k] * comm_share)
70             for k in rec_sizes_kw
71         }
72         cost_weighted = {
73             k: rec_sizes_kw[k] / benefit_per_REC[k] for k in rec_sizes_kw
74         }
75
76         # Step 5: Optimization
77         model = pulp.LpProblem("Minimize Weighted kW Adjusted by Revenue", pulp.LpMinimize)
78         x = {k: pulp.LpVariable(f"n_{k}", lowBound=0, cat='Integer') for k in rec_sizes_kw}
79

```

```

80     model += pulp.lpSum(x[k] * cost_weighted[k] for k in x), "Minimize Adjusted kWh"
81     model += pulp.lpSum(x[k] * shared_energy_per_REC[k] for k in x) >= total_shared_kwh_needed
82
83     solver = pulp.PULP_CBC_CMD(msg=False)
84     status = model.solve(solver)
85
86     if status == pulp.LpStatusOptimal:
87         n_small = int(x["small"].varValue)
88         n_medium = int(x["medium"].varValue)
89         n_large = int(x["large"].varValue)
90
91         total_shared_energy = sum(x[k].varValue * shared_energy_per_REC[k] for k in x)
92         total_benefit = sum(x[k].varValue * benefit_per_REC[k] for k in x)
93         total_capacity = sum(x[k].varValue * rec_sizes_kw[k] for k in x)
94
95         results.append({
96             "Burden Range": f"{int(burden_lower*100)}-{int(upper*100)}%",
97             "Community Share": f"{int(comm_share*100)}%",
98             "Households Targeted": len(df_target),
99             "n_small": n_small,
100            "n_medium": n_medium,
101            "n_large": n_large,
102            "Total Capacity (kW)": round(total_capacity, 2),
103            "Total Shared Energy (kWh)": round(total_shared_energy, 2),
104            "Total Benefit (€)": round(total_benefit, 2),
105            "Required Shared Energy (kWh)": round(total_shared_kwh_needed, 2)
106        })
107     else:
108         results.append({
109             "Burden Range": f"{int(burden_lower*100)}-{int(upper*100)}%",
110             "Community Share": f"{int(comm_share*100)}%",
111             "Households Targeted": len(df_target),
112             "n_small": None,
113             "n_medium": None,
114             "n_large": None,
115             "Total Capacity (kW)": None,
116             "Total Shared Energy (kWh)": None,
117             "Total Benefit (€)": None,
118             "Required Shared Energy (kWh)": round(total_shared_kwh_needed, 2)
119         })
120
121     # Save results to Excel
122     results_df = pd.DataFrame(results)
123     results_df.sort_values(by=["Burden Range", "Community Share"], inplace=True)
124     results_df.to_excel("Sensitivity_Analysis_with_REC_Breakdown.xlsx", index=False)
125
126     print("\n=== Sensitivity Analysis Results ===\n")
127     print(results_df.to_string(index=False))
128     print("\nResults saved to 'Sensitivity_Analysis_with_REC_Breakdown.xlsx'")
129
130

```