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SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Executive Summary of the Thesis

Methods to mitigate energy poverty in a Renewable Energy Community

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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1. Introduction

The strong environmental policies, the crisis due to the COVID-19, and the war in Ukraine are putting increasing pressure on energy prices and contributing to the worsening of poverty in Europe, in particular energy poverty. According to the European Union [3], this phenomenon occurs when the household's energy expenses represent a too high percentage of total income. Families either have difficulty paying their bills or decide on their own to cut costs and deprive themselves of certain services, thus impacting health. This very complex phenomenon depends on numerous variables such as geographical area, the energy efficiency of homes, and social conditions, like the number of members per household, gender, or age [4].

Numerous indices have been created to track and measure the phenomenon, based on people's perceptions and on quantifiable data. Both these approaches have advantages and disadvantages and capture different aspects of the problem.
Europe and Italy fought the phenomenon by working mainly on bonuses that incentivize the efficiency of buildings or that repay part of the bills (electricity and gas bonuses).

Renewable Energy Communities (REC) are a new instrument created to encourage the installation of renewable energy systems and they could be a support for households at risk of energy poverty, in particular in saving their electricity bills. They are formed by groups of people, companies, cooperatives, or local authorities that self-produce and self-consume electricity generated by renewable energy plants. RECs are a European project born in 2018 with Directives 2018/2001 [2] and 2019/944, and Italy is currently in the process of final transposition through Decree-Laws 199/2021[5] and 210/2021. In this study, the latest official documents relied on the resolution of ARERA 120/2022 and 727/2022, and the draft decree of the MASE.

The shared energy which is subject to incentive is defined as the minimum between the energy consumed and produced by an Energy Community subtended by the same primary substation. The plants that produce the energy must not exceed a total capacity of 1 MW. Different premium tariffs are also defined for incentivized shared energy depending on the size of the plants. For small plants, the tariff is shown in Equation 1.

$$Tip_{(<200kW)} = \max(80 + \max(0; 180 - Pz); 120) \quad (1)$$

Finally, a correction tariff for photovoltaic plants of +4 €/MWh for central Italy areas and +10 €/MWh for northern regions is planned.
The Energy Community can autonomously define its own statute and determine how it divides its earnings among the members; there are no guidelines for this in the official documents. In this thesis, it was therefore decided to investigate this topic further by analyzing and developing various algorithms that take into account different aspects of Energy Communities. In particular, the focus was on the creation of algorithms that take into account the social status of households by means of an energy poverty index. The methods were then applied in order to compare the results to a case study, the emerging REC in the municipality of Teglio. The novelties of the paper reside in the definition of sharing methods in RECs also considering energy poverty and the development of a non-binary, yet continuous version of the LIHC for defining the depth of the energy poverty condition.

2. Methodology

In order to share the benefits among the REC members, it is necessary to calculate the energy and economic flows of the community. In this thesis, it has been decided to focus on photovoltaic plants only but the approach taken is general so that different configurations can be created.
Six typical days have been identified, each with its own frequency during the year on both the production and load side. Two profiles, work and holiday for the three seasons are created: winter, summer, and mid-season. The per unit production profile is the same for each plant and a correction factor is used according to the Italian geographical area in which the REC is located, north, central, or south, in order to obtain real values in terms of annual production.
For the demand side, six user categories were created, both residential and commercial, and constructed by making assumptions about the habits of its occupants. The categories are: "Old couple", "Young couple", "Family", "SME industrial, and commercial", and "Office/ School". Additional profiles that do not fit into any category can also be entered manually. In addition to the production and demand profiles, the specifications of each category (number of users and peak power) and each FV plant (peak power, capacity, and maximum power of the batteries and type of connection) are entered.
The main energy flows are self-consumption, energy fed into and withdrawn from the grid, and shared energy, calculated for each user i, for each day type d in each hour h.

$$SelfCons_{i,d,h} = \min(Load_{i,d,h}; Prod_{i,d,h}) + En\ battery_{i,d,h} \quad (2)$$

$$EnFed_{i,d,h} = (Prod_{i,d,h} - SelfCons_{i,d,h}) + DirectProd_{i,d,h} \quad (3)$$

$$EnWithdrawn_{i,d,h} = Load_{i,d,h} - SelfCons_{i,d,h} \quad (4)$$

$$EnShared_{i,d,h} = \min(EnFed_{TOT,d,h}; EnWithdrawn_{i,d,h}) \quad (5)$$

There are three main economic benefits. The first is the sale of the energy produced and not self-consumed. The price at which feed-in energy can be sold has not been made explicit in the latest documents so it was decided to refer to the November 2022 consultation document. If the fraction of shared energy with respect to the produced is greater than 70% it is valued at the minimum between the zonal price and the price cap, otherwise, the shared energy is valued at the zonal price and the remaining part at the minimum between the zonal price and the price cap. The price cap is set at 180 €/MWh according to the European Commission in EU 2022/1854[1] The second one is the incentive of sharing given by ARERA's reimbursement for the absence of losses and non-utilization of the transmission grid and the MASE premium tariff. the last economic benefit is the reduction of cost given by self-consumption. As there are no guidelines for the distribution of these benefits, the choice of which ones to give in input to the following algorithms is arbitrary.

Regarding the energy poverty index, the LIHC (low income and high cost) indicator was chosen[4]. This indicator puts households at risk of energy poverty if they have an energy

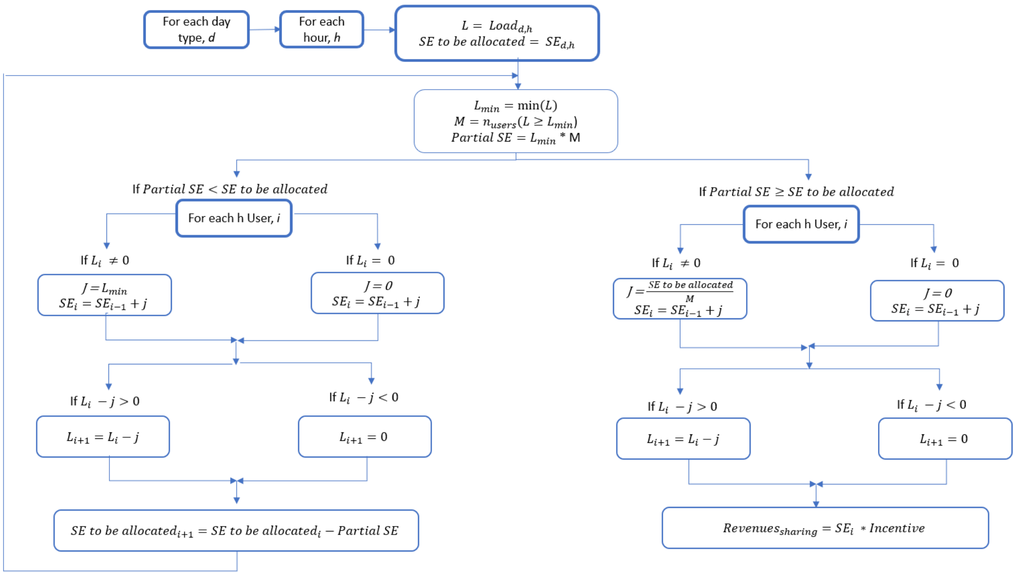


Figure 1: Block diagram for Packets algorithm.

expenditure above the national median value $P50(s_{e,i})$ and an income net of energy expenditure $(y_i - s_{e,i})$ below a threshold value, y^*.

$$LIHC = I\Big\{ [s_{e,i} > P50(s_{e,i})] \cup \left[\frac{(y_i - s_{e,i})}{Nind_{income}} < y^* \right] \Big\} \tag{6}$$

The median value of energy expenditure was obtained by summing the expenditure for electricity and gas, using ARERA's estimates of consumption with respect to points of withdrawal and their respective costs. In Equation 6, y^* is the income threshold that identifies a family at risk of poverty, equal to 60% of the median equivalent income (as defined by EUROSTAT) corresponding to 10 502 €/year per person.
The input data required are the household's energy expenditure, its annual income, and the number of recipients. The formula returns a value of 1 if the household meets both conditions otherwise 0. In addition to a "boolean" result, a "continuous" version of the index has also been created which returns a value between 0 and 1, the further away from 1 the greater the risk.

The energy poverty index is one of the three performance indices used to categorize each member of the community. The other two are the ownership percentage, i.e. the percentage that the individual user has put towards the initial investment of the facilities, and a sharing index. The latter assesses how closely consumption is aligned with production.

2.1. Sharing Methods

	Ownership	Sharing	Energy poverty
Owners	yes	no	no
Proportional	no	yes	no
Packets	no	yes	no
Shapley	no	yes	no
Owners + Proportional	yes	yes	no
Energy Poverty + Proportional	no	yes	yes
Energy Poverty + Owners	yes	no	yes
Energy Poverty + Proportional + Owners	yes	yes	yes

Table 1: Aspects considered in the different sharing mechanisms.

The first algorithm, "Owners", was developed considering an earlier study by Politecnico di Torino [7], it distributes the selected economic benefits only among those who contributed to the investment, in a proportional manner. Other algorithms were then analyzed that take into account each person's contribution to the creation of profit, i.e. how much the behavior is "virtuous". Two approaches were followed, one is based on a proportional index, which is calculated for each member as their load relative to the total REC load hour by hour. The hour-by-hour REC gains are distributed according to this proportional index.
The second approach, devised by PoliTo [7], distributes minimum packets of shared energy to each member, ordered according to their energy

demand. The process takes place through a sequence of iterations per hour, up to a maximum allocation equal to the energy demand. The algorithm is summarised through a block diagram in Figure 1.
A final algorithm is developed starting from the distribution system created by a research group of Politecnico di Milano [8]. The idea is to distribute the economic benefits of the community in a fair way considering each member's contribution to it. This is done using Game Theory and Shapley value, Equation 7. The Energy Community thus becomes a cooperative game where the members are the players. For each member his marginal contribution is calculated, evaluating through the function "Compute Value" the gains that the REC would get with and without a player. The algorithm scheme is represented in Figure 2. Compared to the original algorithm [10], the option of integrated systems with batteries and the presence of prosumers was added.

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n-|S|-1)!}{n!} (v(S \cup \{i\}) - v(S)) \tag{7}$$

where the set of actors in the community or players is called N, and $v(S)$ the value of the coalition, where $S \in N$.

Given the high computational burden of this algorithm [9], the "Owners" method and the "Proportional" method were combined to create an algorithm structured on two levels to obtain values similar to the ideal Shapley value.
In addition, two further bi-level methods were created that take into account the users' economic status. One method considers property and energy poverty while the other considers energy poverty and the "Proportional method". In both cases, the percentage of earnings allocated to the energy poverty step is 2% for each household considered to be at risk up to a maximum of 50%.
Lastly, a three-level algorithm was considered that takes into account all three aspects: energy poverty, ownership of the plants, and how much each user consumes in line with production.

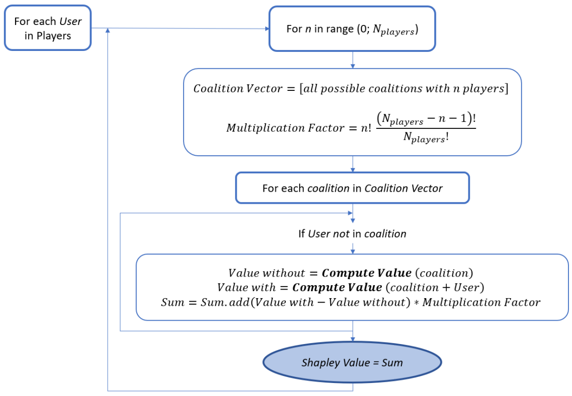
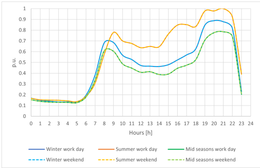


Figure 2: Block diagram for Shapley value algorithm.

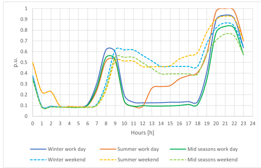
3. Case study: the REC of Teglio

The selected case study is an emerging Energy Community in the municipality of Teglio in Valtellina. It is located in a mountainous area characterized by a harsh climate, especially in winter. Households, therefore, have to bear large expenses for heating. This, together with the fact that the average salary is below the national value, places this municipality in a medium-high bracket at risk of energy poverty. In addition to this, it is inhabited by less than 5,000 people, it could therefore be the object of an Energy Community project partially financed by the PNRR allocation. This allocation will be used for non-repayable financing of up to 40% of the costs of setting up a new plant or upgrading an existing one.

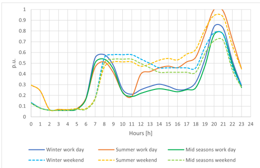
In the district, there are already three photovoltaic systems owned by the municipality located on the school in Teglio (5.93 kW), the school in Tresenda (18.96 kW) and on the sports arena (18.96 kW). Each of them is connected to the same POD as the utility on which it is located and they are integrated with lithium batteries, the first two with 15kWh and the one on the arena with 40 kWh. A battery cost of 1200 €$/kWh$ was taken into account. CAPEX is 1600 €$/kW$ and OPEX 26 €/year for plants under 30 kW, otherwise they are 1400 €$/kW$ and 21.5 €/year respectively.



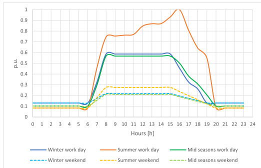
(a) Old couple



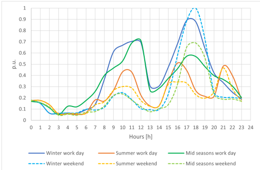
(b) Young couple



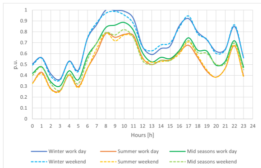
(c) Family



(d) Office and school



(e) Sports arena



(f) Nursing home

Figure 3: Load profiles for different categories of final users in different day types

With regard to the load, data provided by the municipality itself was used, which included the banded consumption of the two schools and the hourly profiles of the sports arena and the Teglio nursing home. The first two sets of data were only used to find the peak value of the final user and then use the profiles of the "Office/School" category. While the "sports arena" and the "nursing home" users were entered manually as they did not fit into any category.
In addition to these, it was decided to create an archetype of the population of Teglio, so 12 domestic users from the categories "Old Couple", "Young Couple" and "Family" were added. The share of each category, electricity consumption, heating expenditure, and annual income were estimated from Istat databases [6] and with reasonable hypotheses. The profiles are shown in Figure 3.

	Annual electricity consumption [kWh]	Electricity bill cost [€/kWh]	Natural gas consumption [m3]	Total energy expenditure [€/year]	Family annual income [€]
Old Couple 1	1490.16	0.35	1481	2446.86	25934.7
Old Couple 2	1530.44	0.341	1481	2447.18	24755.85
Old Couple 3	1570.71	0.32	1481	2427.93	22398.15
Old Couple 4	1610.99	0.307	1481	2419.87	21219.3
Young Couple 1	1533.97	0.331	1481	2433.04	28636.3
Young Couple 2	1592.97	0.319	1481	2433.46	23429.7
Family 1	2090.99	0.303	2058	3308.97	37685.27
Family 2	2121.3	0.292	2058	3294.82	36543.06
Family 3	2151.60	0.282	2058	3282.15	35401.20
Family 4	2181.91	0.278	2058	3281.97	33117.47
Family 5	2787.99	0.269	2635	4175.47	31975.61
Family 6	2878.91	0.252	2635	4150.99	30833.4
Teglio School	46818.17	0.27	-	-	-
Tresenda School	42831.47	0.262	-	-	-
Nursing Home	165058.78	0.25	-	-	-
Sport arena	24407.54	0.295	-	-	-

Table 2: Detailed input data regarding members of the Energy Community

Both the incentive for shared energy and the gains from the sale of energy were considered economic benefits to be shared among all community members. The investment in the plants is done only by the municipality and the community's purpose is a social one, so it will try to share as much as possible. Self-consumption is not shared because it represents an indirect economic flow and is, therefore, more complex to take into account, it will benefit the utility under which the plant is located.

4. Results

4.1. Reference case

The study started by analyzing the current scenario from both an economic and an energy point of view. The results show very low levels of shared energy. The Energy Community is too unbalanced in load compared to production, the plants are too small in size compared to the consumers they serve. For this reason, the energy input and shared are very low. In addition, the batteries above the two schools are poorly utilized: one never manages to charge, even when there is maximum production. These problems also translate into economic terms, the gains are very low, determined only by the savings on the electricity bill due to self-consumption, while the costs are very high, especially the batteries, that are not utilized. Considering a zonal electricity price of 150 $€/MWh$, an inflation rate of 6%, and a tax discount of 50% to be distributed over 10 years, a negative Net Present Value at 20 years is obtained, the investment is therefore not repaid.

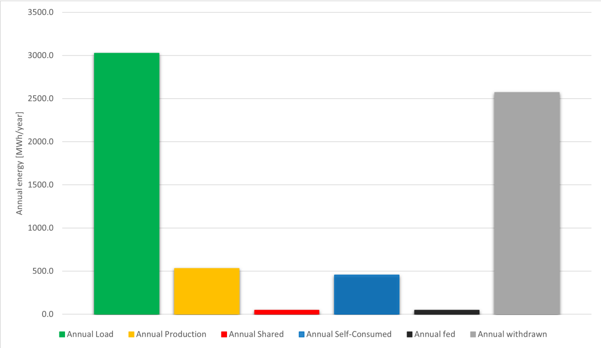


Figure 4: Annual energy quantities for the reference case.

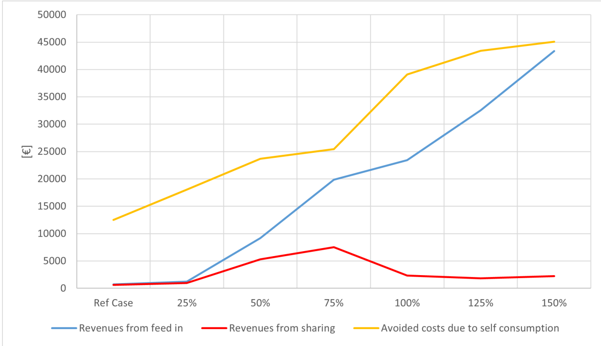
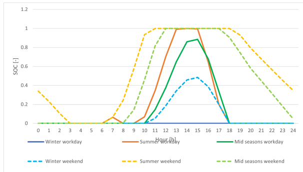


Figure 5: Community economic benefits for different scenarios.

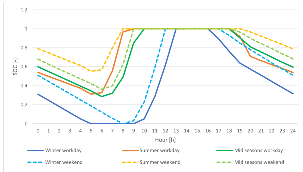
For this reason, it was decided to find an optimum point in terms of installed power.

4.2. Optimal PV sizing

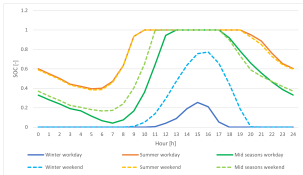
The logic that was followed was to increase the fraction of energy produced over annual energy consumed by 25, 50, 100, 125, and 150%. The extra power was added initially by integrating the existing installations up to the maximum potential and then adding installations on the other users, the nursing home, and domestic users (max. 10 kW). For non-domestic members, the photovoltaic installation potential was estimated using plant plans and satellite images. From Figure 5, it can be seen that in all scenarios the main economic benefit is self-consumption. This together with the feed-in gains always increase as the installed power increases, while shared energy has a maximum. The trends are closely linked to the different configurations, each time an installation is placed on a new utility the self-consumption increases. The NPV becomes positive from the first scenario and then always increases and the PBT also decreases from 24 to 10 years and then stabilizes at the value of 8 from the second scenario onwards. The best-chosen scenario for the energy community under analysis is the scenario that has a load production ratio of 75%. The shared energy is maximized and the utilities involved all belong to the municipality, therefore, the municipality will not only be the financier but also the physical owner. The energy flows of the six typical days and the state of charge of the batteries are shown in Figures 7 and 6.



(a) Teglio school battery

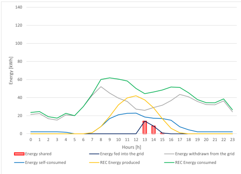


(b) Tresenda school battery

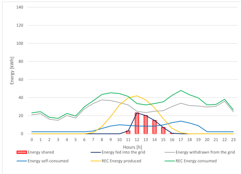


(c) Sports arena battery

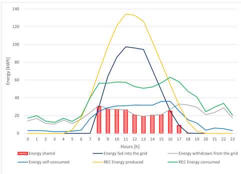
Figure 6: Trends of battery state of charge in the optimal case.



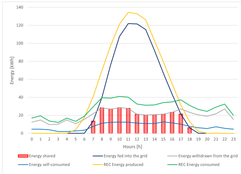
(a) Winter work day



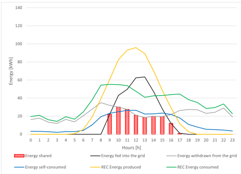
(b) Winter weekend



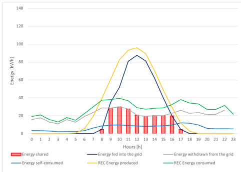
(c) Summer work day



(d) Summer weekend



(e) Mid seasons work day



(f) Mid seasons weekend

Figure 7: Trend during six typical days of energy flows in the optimum case.

All the algorithms described in the methodology section were then applied to the case study and the earnings each member obtained were calculated, Table 3. A maximum cap in terms of bill savings was set proportional to the investment made. For domestic users, this corresponds to 100%, not having contributed, and for the other users, it is 100% plus the possibility to return on the investment.
The Shapley results are the benchmark for the comparison. It is based on the assumption that the person who physically owns the system has also financed it, the largest beneficiary is, therefore, the one who has the largest plant, Teglio's school which has around 120 kW out of a total of 190 kW. However, the load part is also important in an Energy Community, as it can be seen that the nursing home, the largest load, earns a considerable profit even though it does not have any installations. The methods that come closer to Shapley's results are those that consider the "Owners" method, where physical location and ownership match. With only the "Owners" method, those who did not participate in the investment get nothing and have no incentive to be part of the community. The "Proportional" and "Packets" algorithms, on the other hand, are proportional to the load, the nursing home and domestic users are therefore highly repaid but do not take the production side into account.

The bi-level algorithm, which considers property, and the proportional method is very close to the Shapley results with the great advantage of a very low computational cost and greater simplicity. Algorithms that consider energy poverty give such a great benefit to vulnerable households that their electricity bills are fully covered. Each of the algorithms can be more or less fair depending on the configuration of the community, e.g. how the facilities are distributed, and the differences between the various members in terms of energy consumption and investment. For each algorithm, an economic analysis was conducted to assess whether the municipality is able to return on its investment, NPV, and PBT are shown in Figure 8. In all cases, the NPV is positive and the PBT is below the 15-year value, therefore, implementing measures for energy poverty mitigation does not compromise the business plan of the public administration

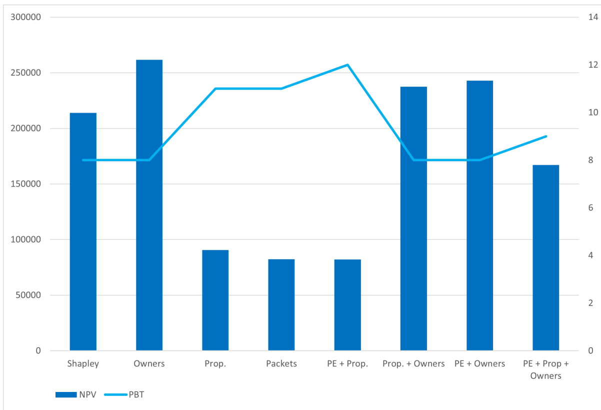


Figure 8: NPV and PBT for the municipality's investment in different sharing methods.

	Shapley	Owners	Prop.	Packets	Prop. + Owners	PE + Prop.	PE + Owners	PE + Prop.+ Owners
Old1	34	0	128	161	18	120	0	61
Old2	35	0	131	165	19	124	0	63
Old3	36	0	135	170	19	503	503	430
Old4	37	0	138	174	20	495	495	419
Young1	25	0	103	120	15	97	0	50
Young2	26	0	107	125	15	508	508	428
Family1	44	0	171	204	24	160	0	82
Family2	44	0	173	207	25	163	0	83
Family3	45	0	176	209	25	165	0	84
Family4	46	0	178	212	25	167	0	85
Family5	58	0	227	267	32	214	0	109
Family6	60	0	235	275	33	221	0	113
Off/Sch1	851	4226	5563	6657	4416	5229	3972	4698
Off/Sch2	18079	17402	5089	6422	15650	4784	16358	10796
Nurs.Home	3680	0	13012	7786	1852	12232	0	6246
SportsArena	4255	5729	1790	4201	5168	1682	5385	3609

Table 3: Earnings from grid feed-in and shared energy incentive for each member.

Finally, a sensitivity analysis was conducted to see how much the balance of the community changed depending on whether the users in energy poverty increased by constituting 50 and 100% of the domestic users in the community. All three algorithms involving the energy poverty index were applied and the bill savings for each member were calculated. Only the results of the algorithm combined with the Proportional method are shown in Table 4.
It is noticeable that between the base case and the first scenario the results do not change much, all users in poverty have their electricity bills paid off and the other users have a minimal reduction. In the second scenario, on the other hand, not all users in poverty have 100% savings, and the savings for the other users are much reduced. It is, therefore, necessary for the community to be composed of both categories.

	Shapley	Base Case (25%)	50% of users in PE	100% of users in PE
Old1	7%	23%	100%	100%
Old2	7%	24%	100%	100%
Old3	7%	100%	100%	100%
Old4	8%	100%	100%	100%
Young1	5%	19%	100%	100%
Young2	5%	100%	100%	100%
Family1	7%	25%	24%	100%
Family2	7%	26%	25%	100%
Family3	7%	27%	25%	100%
Family4	8%	28%	26%	100%
Family5	8%	29%	27%	86%
Family6	8%	30%	28%	89%
Off/Sch1	71%	106%	103%	98%
Off/Sch2	259%	140%	138%	132%
Nurs.Home	9%	30%	28%	24%
SportsArena	146%	110%	109%	106%

Table 4: Percentage saving on the electricity bill for each member with different percentage of users in energy poverty.

The LIHC index was finally calculated before and after applying the "PE + Proportional algorithm". From Table 5 it is possible to see that the situation in all cases improves but has not been overturned, the Energy Community has only decreased its electricity expenditure, and the problems of heating expenditure and low income still remain.

	25% users PE		50% users PE		100% users PE	
	before	after	before	after	before	after
Old1	1.00	1.00	0.78	0.87	0.78	0.87
Old2	1.00	1.00	0.75	0.84	0.75	0.84
Old3	0.77	0.85	0.77	0.85	0.77	0.85
Old4	0.74	0.83	0.74	0.83	0.74	0.83
Young1	1.00	1.00	0.78	0.87	0.76	0.85
Young2	0.79	1.00	0.79	1.00	0.75	0.84
Family1	1.00	1.00	1.00	1.00	0.71	1.00
Family2	1.00	1.00	1.00	1.00	0.69	0.76
Family3	1.00	1.00	1.00	1.00	0.68	0.75
Family4	1.00	1.00	1.00	1.00	0.68	0.75
Family5	1.00	1.00	1.00	1.00	0.61	0.65
Family6	1.00	1.00	1.00	1.00	0.61	0.66

Table 5: LIHC index before and after application of the "Energy Poverty + Proportional" bilevel algorithm.

5. Conclusions

The aim of this thesis was to present a complete overview of the RECs' internal revenue-sharing methods and to highlight how the community can use these algorithms to help users considered to be at risk of energy poverty. Among the algorithms analyzed, the Shapley value method remains the undisputed benchmark. Despite this, alternatives have been developed that focus for example on aspects not captured by the Shapley value, such as the social status of its participants, or which attempt to approach it by overcoming the barrier of communication complexity and computational cost. The case study shows that solutions can be found that bring great benefits to vulnerable families without placing too much burden on other members. Similar solutions could thus be effectively implemented and accepted by citizens. Despite this, the dynamic nature of the Energy Community places limitations on this study having carried out an analysis of a static configuration, the number of REC members may change over the years. Moreover, the Energy Community actually works on only one of the aspects that characterize energy poverty, which is the electricity bill. The expense of heating, especially for territories with cold climates, is a problem, a possible solution is to electrify the load. Energy Communities are thus not the answer to energy poverty but are one of the tools that will help mitigate it.

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