Optimal integration of PVs and biomasses in an Italian renewable energy community

Isabella Pizzuti*, Erfan Tajialli-Ardekani
Department of Astronautical, Electrical and Energy Engineering-DIAEE
Sapienza University of Rome, Italy
isabella.pizzuti@uniroma1.it - erfan.tajalliardekani@uniroma1.it

Alessandro Corsini, Giovanni Delibra
Department of Mechanical and Aerospace Engineering-DIMA
Sapienza University of Rome, Italy
alessandro.corsini@uniroma1.it - giovanni.delibra@uniroma1.it

ABSTRACT
On December 2021 Italy increased the maximum size of renewable energy plants in Renewable Energy Communities (RECs) from 200 kW to 1 MW. As RECs become larger and more complex in terms of mix of prosumers, users and renewable energy sources, they will naturally include more complex generation and sharing scenarios, involving for example not just the electric loads but also heat generation and thermal energy storage. In the following the energy, financial and environmental performance of a REC is analysed. The case study includes a mix of production characterized by the integration of photovoltaic and biomass plants for cogeneration, several residential and commercial users and is in a city of Lazio Region, Italy. First, a territorial analysis is carried out to identify the energy demand and the availability spaces to install distributed generation plants. Second, the mix of consumers, the size of photovoltaic systems and combined power and heat fuelled by biomass is selected following a multi-objective optimization strategy. All calculations were run on pyRES, an in-house Python code for time-dependent energy systems simulations with resolution up to 15 minutes. Modelling of biomass was developed for this work and validated against available experimental data and TRNSYS results. Energy, economic and environmental performance indices highlighting the impact on shared energy, CO_2 emissions, capital and operating expenditure have been defined for the comparison between different configuration analysed. Results show that with a biomass cogenerator prosumers have minor economic interest in being part of a REC as the incentives are proportional to shared energy. Increasing their share of the REC revenue, on the contrary, reduces the appeal to normal users, resulting in a difficult balance.

KEYWORDS
Renewable Energy Communities, Biomass Cogeneration, Photovoltaics, Electric and Thermal Loads, Energy and Financial Performance, Environmental Impact, pyRES.

INTRODUCTION

RECs in EU and Italy

The European Union has introduced RECs with the RED II and IEM directives, as a tool for member states to achieve the energy transition goals defined in the CEP - Clean Energy Package [1]-[2]. The first phase of introduction of RECs in the Italian legislation is documented in [3] and can be summarized as follows:

- incentives to renewable energy in a REC were proportional to the amount of self-consumption rather than renewable production;
- a REC should be made of at least a prosumer and a consumer and be a non-profit legal entity;
- members should be under the same secondary MV-LV unit substation;
- power plants could have a maximum nominal capacity of 200 kW.

The definitive reception of RED II (Legislative Decree of 8 November 2021[4]):

- extended the maximum size of the single plant to 1 MW;
- and moved the boundary to the MV-HV transformation cabin.

Under these conditions, RECs represent an opportunity to integrate various renewable sources and energy vectors, although only the electricity-sharing modalities are defined by laws. The virtual regulatory model identified by ARERA (Resolution 318/2020 [5]) allows to use the existing electrical grid to exchange electricity between generation and consumption units, avoiding the physical connection of community members. The electric energy balance of the REC is calculated hourly by GSE based on the already installed meters and is the major factor in economic incentives to the REC. The current incentive mechanism is based on the Decree of the Ministry of Economic Development of 16 September 2020, which defines and incentivizes shared energy for a period of twenty years, with recognition by GSE of €118.37/MWh (as of beginning of 2023) [6]. On the contrary, other energy vectors, such as heat, require the realization of new infrastructures and may require more complex forms of incentives [7]. The Italian legislation is now on the verge of publishing the implementing decree that should provide a complete and definitive regulatory framework and cover all renewable technologies: from photovoltaic to wind, hydro, geothermal and biomass. It is recognized that the future development of RECs is linked to entrepreneurial initiatives of local entities or small and medium-sized companies, and energy production should come from local resources [8]-[10]. The National Recovery and Resilience Plan (PNRR) [11] has allocated approximately 2.2 billion euros for RECs implemented in municipalities with less than 5,000 inhabitants, which would be added to the incentives provided by the ministry and regulated by the GSE. In this context, biomass can be one of the local resources that, especially in mountainous areas, can form the basis of energy and heat production in RECs [12][20]. Moreover, the Ministerial Decree of August 4, 2011 [21] defines the methods of incentivizing electricity produced in high-efficiency cogeneration. These incentives can be combined with those of the REC when the cogeneration plant is powered by renewable sources.

RECs with Combined Heat and Power loads

In a typical scenario with electric and thermal loads to satisfy several strategies can be followed, from the electrification of heat generation to cogeneration. The latter is of particular interest when dealing with local availability of biomasses. For example, Tiwary et al, [14] studied the use of solid biowaste as a source of power and how to couple it with wind turbines, PVs, biogas generators and BESS in Gateshead (UK) and Sofia (BG). They performed computations with HOMER concluding that the biowaste of the two communities could cover between 60% and 65% of the energy demand, offering a stable basis to build up with solar and wind. Mahzouni, [15] reported on the experience carried out in St. Peter (DE), where a local community decided to build an energy co-operative for a biomass heating district plant. He concluded that the role of institutional entrepreneurship was the key for the success of the operation, that is now seen as an example from neighbouring communities. He also highlighted that the same conditions do not apply to any generic communities but only to those with similar conditions. Yana et al, [16] provide a review of experience in Indonesia with local communities developing biomass waste powered RECs. With a potential close to 50 GW, Indonesia is in fact a possible key player in the development of RECs. Di Silvestre et al. [17] discussed the role of RECs in Italy, providing an analysis of RECs, emphasizing their primary features and their relevance to power system aspects. They also focussed on the integration of the new REC model with the phase-out of coal and in general with the topic of clean energy transition. Aste et al. [18] discussed the case of a nearly zero energy district in Milan (IT) with a combination of low-energy building design, small-size wood biomass, groundwater heat pumps and PV systems. The core of the operation is a biomass boiler coupled with a twin-screw heat expander. They concluded that the key aspect for the success of the operation is the selection of temperature levels to ensure a low interaction with the energy grid as especially during wintertime the PV production is scarce. Paletto et al. [19] discussed the role of biomass power plants to increase the social acceptance of RES. They concluded that the size of the biomass energy plant (< 1 MW or >1 MW) and the feedstock used (forest or sawmill woodchip) are two main variables that influence the environmental impact. Perea-Moreno et al. in [20] discussed the role of biomass in worldwide research trends, highlighting an overall increase in the subject.

Aims of the work

This works aims at designing and analysing a REC that includes two renewable energy sources based on local resources, at investigating the technical and economic challenges associated with customizing a REC and the synergies can be created in the territory. One of the two sources is dispatchable and can be controlled to match the energy demand. Both electricity and heat consumptions are taken into consideration. The selection of energy sources, prosumers and consumers is based on the specific territorial context. The case study is a small municipality in Lazio, located in a mountainous are with a few hundred small and medium enterprises (SMEs), characterized by woods and multiple biomass supply sources. Given the presence of activities requiring both electricity and heat, the proximity of suitable areas for the construction of storage warehouses, and the availability of more than one biomass supply source, the municipality is well suited for the biomass energy production.

METHODOLOGY

The REC analysis is carried out using pyRES, an open-source tool developed in Python by the Authors; pyRES is specifically designed to manage assembling process of RECs. The tool is based on the oriented object programming which allows to develop single module for each component of the real systems, [3]. pyRES is structured on four blocks:

• *Input data*: is the phase of acquisition of technical specification of the systems, fixed and variable costs, users' electric consumptions and data concerning weather.

• *Input pre-processing*: input data is cleaned and users' electric consumptions are used to generate demand curves.

• *System modelling and simulation*: A digital twin of the REC is built in pyRES by assembling elementary modules including production plants, batteries, load curves and auxiliary components (pumps, gas storage, inverter, biogasification system). Elementary modules are assembled to build the members of the REC. Each consumer is associated with an energy demand curve. Each prosumer, which is a user physically connected to a renewable energy production plant, is simulated by combining a demand curve with a production curve of a renewable energy system. Every prosumer self-produces energy and exports the excess into the national grid. The REC is built by integrating consumers, prosumers, and renewable plants.

• *Output formulation*: the aims and desired impacts of the REC are translated into the objective functions of an optimization problem. The economic goals are represented using a cost function that includes the investment, operation and maintenance costs over the lifetime. The technical energy goals are represented by the self-consumption. Given a community with a number of consumers, prosumers, and renewable plants of the REC, equals n_{con} , n_{pro} , n_{plant} respectively, for each time step t of a reference period T, and for each prosumer j, the selfconsumption is equal to the minimum value between the renewable production $\left(P_j^t\right)$ and the demand (D_j^t) . Additionally, for each prosumer the exported energy $(Export_j^t)$ and energy imported $(Import_j^t)$ from the network are calculated. The shared energy (SH_{REC}^t) is calculated as the minimum value between the sum of the renewable production from REC plants (P_m^t) and the total export from all prosumers, and the sum of consumer demand and the total import from all prosumers. These definitions are represented by the following compact formulation:

$$SC_j^t = \min\left(P_j^t; D_j^t\right) \qquad \forall\, j \in \left(1, n_{pro}\right), \forall\, t \in (1, T) \tag{1}$$

$$Export_j^t = P_j^t - SC_j^t \quad \forall\, j \in \left(1, n_{pro}\right), \forall\, t \in (1, T) \tag{2}$$

$$Import_j^t = D_j^t - SC_j^t \quad \forall\, j \in \left(1, n_{pro}\right), \forall\, t \in (1, T) \tag{3}$$

$$SH_{REC}^t = \min\left(\sum_j^{n_{pro}} Export_j^t + \sum_m^{n_{plant}} P_m^t ; \sum_k^{n_{con}} D_k^t + \sum_j^{n_{pro}} Import_j^t\right) \forall\, t \in (1, T) \tag{4}$$

Based on self-consumption of each prosumer and the shared energy, the savings on the energy bill and the incentives are then calculated. The output of pyRES is a dynamic analysis of energy performance with a temporal resolution of up to 15 minutes, and the economic analysis of the digital twin. Results of the analysis provide precise details about how the REC perform over time and what economic benefits are associated with different design and operation choices. In this work, the digital twin development involves several phases: First, a territorial analysis is carried out to identify the energy demand, the potential number of consumers and prosumers and the availability of renewable sources. Second, the demand curves of each user are built based on real consumption data or through an audit energy when real consumptions aren't available. Third, the type of renewable production systems is selected for each prosumer and the production curves are estimated. Finally, a multi-objective optimisation problem is designed for sizing of the systems and selecting the best combinations of REC members. The aim is to identify the consumers who contribute the most to consuming shared energy and generating incentives. To achieve this, all potential consumers are defined, and a genetic algorithm of NSGA-II type is used to compare all possible combinations of consumers [22]. Since the thermal consumptions are also taken into account, modules for biomass gasification system, gas compressor, gas storage and the combined heat and power (CHP) have been developed and integrated into pyRES components. Furthermore, a controller has been developed to optimize the CHP operations of the system.

Biomass gasification and syngas treatment

The biomass gasification module in pyRES is designed to estimate the electricity consumption, heat production, and syngas production per kilogram of biomass. To simplify the description of the thermo-chemical process involved in transforming biomass into syngas, the module relies on manufacturer specifications (Table 1) rather than on the thermal-chemical equations. Assuming that input biomass and output syngas properties at a specific working point are provided by the manufacturer, the module calculates the syngas production per kilogram of biomass. The advantages of this model include simple equations, short computation times and experimental activities aren't necessary. However, this module is only valid under the assumption that the gasifier consistently operates at the same specific working point. The model does not consider the dependence of the thermos-chemical performance on the specific characteristics of the input biomass or the environmental conditions. Results were validated using experimental data obtained from literature sources [23][24].

Table 1. Main parameters of biomass gasifier from technical data sheet.

	Specification
Electric power [kWel]	68
Thermal power [kWth]	144
Fuel	Natural wood chips (DIN ISO 17225-1)
Fuel consumption [kg/h]	55.1
Syngas composition [Vol%]	CO(17-20%), H2(13-16%), CH4(1-5%), CO2(7-12%) CnHn(0,1-0,5%), N2(resto)
Lower heat value [kJ/kg]	4.5

Compressor and gas tank

Both modules simulating the thermodynamic processes associate with compression and storage stages under the hypothesis of an ideal gas (R, ρ_0). Based on the ideal gas law, the compressor module calculates the power required (P) for compressing of n mole of syngas from the initial pressure P_1 at final pressure P_2 (4). The input variables are the temperature (T_1) and pressure (P_1) conditions of the input gas and the number of compressors in parallel ($n_{parallel}$). The compression process is multi-stage and is approximated by a polytropic transformation of coefficient γ. Based on P estimates the electricity consumption associated with the compression process. The gas tank module is based on the inlet ($V_{input} * \rho_0$) and outlet ($V_{output} * \rho_0$) mass balance (5). The module estimates the gas level within the tank (V) and determines the potential gas waste when the tank reaches its maximum capacity. Results were validated against those calculated by TRNSYS Type 167 and Type 164 [25].

$$P = \frac{n_{parallel} * n}{3600} * \frac{(\gamma * R * T_1)}{(\gamma - 1) * \left(1 - \frac{P_1}{P_2}\right)^{\frac{(\gamma-1)}{\gamma}}} \tag{4}$$

$$V * \rho_0 = V_{input} * \rho_0 + V * \rho_{in} - V_{output} * \rho_0 \tag{5}$$

CHP and controller

The CHP module simulates a generator set. The module is based on the characteristic curve that indicates the fuel consumption for each power regime, which can be found directly on the manufacturer's technical data sheet. Based on this curve the following function is estimated:

$$fuel_{cons} = F(P/P_{rated}) \tag{6}$$

where P_{rated} is the rated power, P is the produced power and $fuel_{cons}$ is the fuel consumption. The model calculates the electrical efficiency and thermal losses. The consumption of auxiliary components for each operating regime is calculated as fraction of the produced power. In the case of combined heat and power, it also calculates the heat recovery efficiency and thermal production. The module can simulate more than one generator set at the same time and is integrated with a controller to match the electrical or thermal load. CHP can operate in two modes, one mode follows the electrical demand, and the second mode follows the thermal demand. The controller set the production and the optimal number of active engines. The characteristic curve is specific for each fuel[25], the characteristic curve in case of syngas is shown in Figure 1 . Results were validated against those calculated by TRNSYS Type 120 and Type 102 [25].

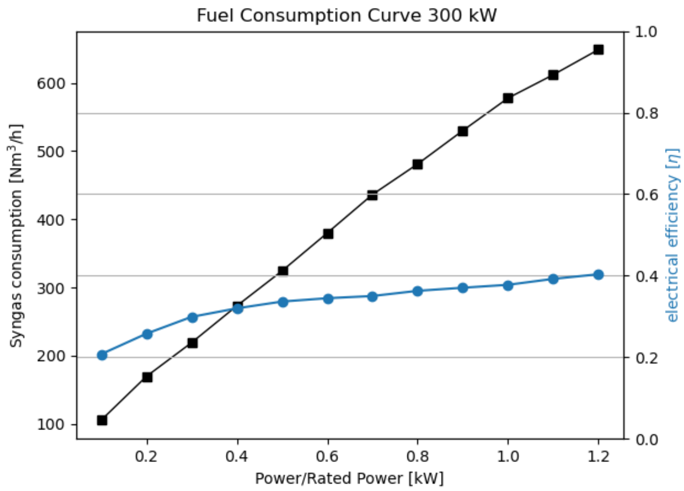

Figure 1. Fuel consumption curve of a 300 kW cogenerator

Integration controller for PV and CHP System

The controller (Figure 2) ensures the integration of photovoltaic power (PV_{prod}) with the power generated by a CHP system. The CHP system consists of a group of engines with nominal, maximum, and minimum power equal to P_n, P_{max}, and P_{min} respectively. When the photovoltaic production cannot match the demand (D), the controller calculates the number of engines (n) to activate and the power (P) of each engine to meet the residual demand not satisfied by photovoltaic production. If n exceeds the maximum limit (n_{max}), the controller increases the power P and if necessary, sets it to the maximum (P_{max}). If there is still an unsatisfied demand, the controller imports power from the national grid. Conversely, if n falls below the minimum (n_{min}), the controller decreases the power P, and if necessary, sets it to the minimum (P_{min}). If there is still surplus production, the controller exports power to the national electricity grid. When the demand (D) is completely satisfied by photovoltaic the controller sets the number of engines and the power supplied by each to the minimum level (n_{min}, P_{min}). The presence of a minimum number of always operating engines ensures a constant production of heat, which guarantees the stability of the thermal load.

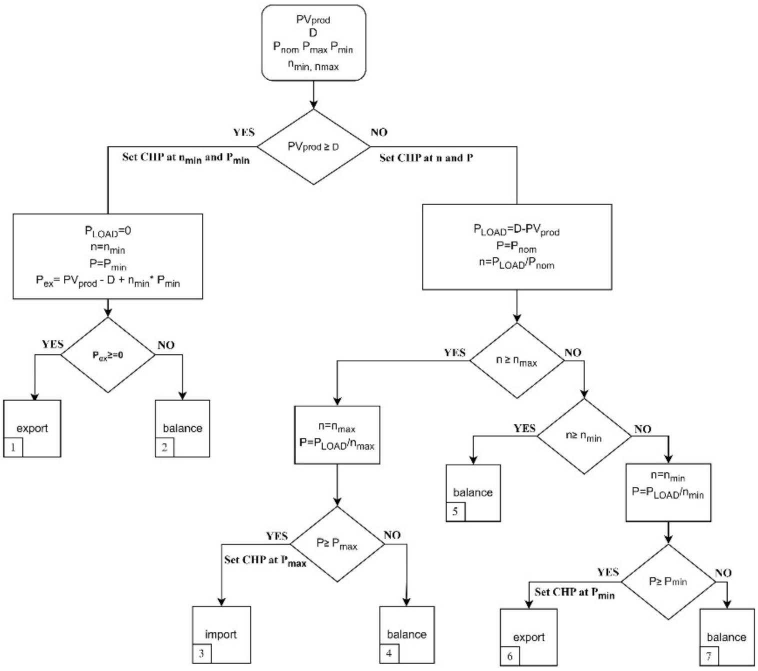

Figure 2. CHP and PV control logic scheme.

CASE STUDY

The case study concerns a municipality located in the Lazio Region with approximately 11,000 inhabitants. A preliminary analysis was conducted to identify the key factors that could impact the development and establishment of RECs. The municipality covers an area of about 16 km^2, has a population density of 670 inhabitants/km^2, 4700 families, and an average household size of 2.36 members. The main economic sectors are services and industrial sectors, with a few hundred of SMEs [26] . The northern area of the municipality is occupied by woods, mainly consisting of chestnut trees, which involves periodic cutting. The land-use maps are used to identify agroforestry resources, and an approximate estimate shows a productivity of 24,057 tons per year from residual biomass. The solar resource potential is obtained from PVGIS [27] and corresponds to an average hourly radiation of 150 W/m^2. The energy demand is characterized by collecting and summing the consumptions of 50 residential users, a school, and a small and medium enterprise (SME) as summarized in Table 2Table **1**. The total electricity consumption of residential users is 196 MWh/year, with an average consumption of 3.9 MWh/year per single user, and the contractual power ranging from 3 to 6 kW. The school has 1000 students and available space for photovoltaic systems with a maximum nominal power of 60 kW. The SME is an industrial laundry for hotels and restaurants with approximately 40 employees and an average production of 4,500 tons/year of washed and ironed products. The thermal load is mainly due to needs for hot water and steam in the washing, drying, and ironing phases. The machines operate for an average of 3500 hours, equivalent to 40% of the total hours per year. In the current configuration, the thermal load is satisfied by five methane gas boilers with an efficiency of 0.91.

Table 2. Characterization of the members of the REC

Description	Space [m^2]	Potential PV size [kW]	Electricity		Heat	
			Consumption [MWh/year]	Peak power [kW]	Hot Water [MWh_{th}/year]	Peak power [kW_{th}]
Residents	-	-	196	3-6	-	-
School	2500	60	180	58	-	500
SME	40000	1000	898	200	5873	1900

Based on the energy demand, a REC in which the school and the SME act as prosumers is analysed in pyRES, Figure 3.

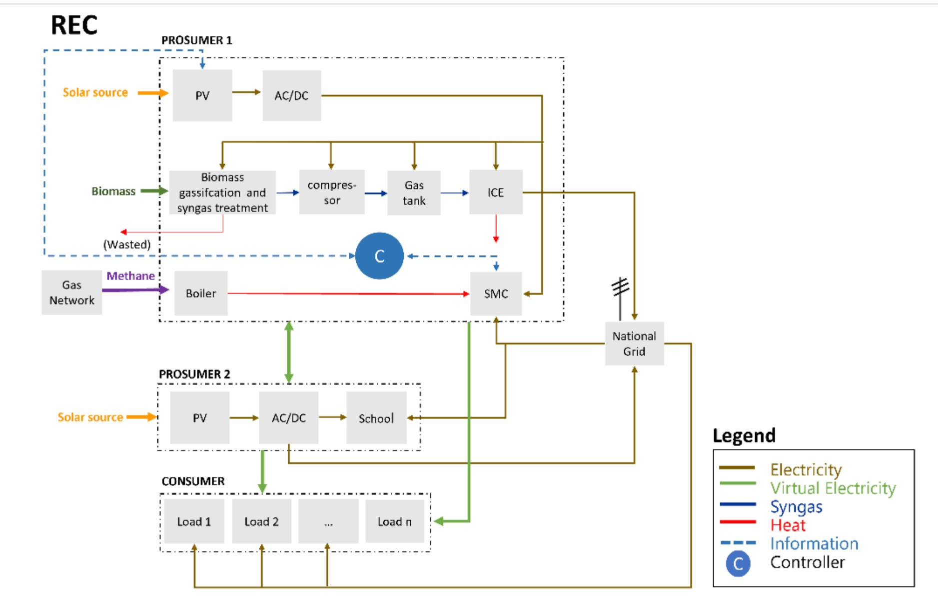

Figure 3. REC model in pyRES

The integration between boilers and a biofuel-powered CHP system to self-produce heat is evaluated for the SME, which is labelled as Prosumer1. The new configuration exploit wood chip to produce syngas through a gasification process. The syngas is then compressed and stored in a gas tank to feed the CHP system. A controller guarantees the track of the electrical load and the optimal operations of the CHP system to access the high-efficiency cogeneration incentives [21].The introduction of a PV to self-produce electricity is evaluated to the school, which is labelled as Prosumer2. The establishment of the REC allows to share the prosumers surplus of electricity with community members via a virtual connection; on the contrary, sharing of heat is not possible due to the absence of a district heating network.

Optimal sizing of prosumers power plants

For Prosumer 1, the process of identifying the size of the plants involved a multi-objective optimization problem, which included the following steps:

- *Setting the Independent Variables*: independent variables are PV power and CHP power.
- *Definition of Range of Variables:* the photovoltaic power ranges between 0 and 500 kW. The maximum value was determined considering the availability of spaces, a utilization factor of 0.4 (which accounts for safety access spaces, shading, and maintenance activities). The CHP power varies discretely from 0 to 300 kW. Within the demand range, the CHP power can assume one of the six configurations indicated in Table 3. Each configuration has a specific gassification system, while the syngas tank size remains the same for all configurations.
- *Selection of Objective Functions:* objectives of the problem are to maximize the Net Present Value (NPV) of the investment and minimize the initial investment. Additionally, there is a constraint on the initial investment, which is approximately 500,000 €.
- *Problem Formulation:* from pyRES modules it is possible to calculate the energy metabolism of the prosumer. Once the annual self-consumption, export, and import values have been calculated, savings on the bill and revenues from energy sales can be determined. By comparing revenues with costs and repeating the analysis for all years of the investment, the cash flow is calculated. The initial investment and NPV are calculated based on the photovoltaic power and the cogeneration power. Integrating the pyRES modules with an NSG-II type genetic algorithm, the analysis is repeated for all values of the independent variables within the defined intervals. Finally, the algorithm selects only those solutions that maximize the objectives.

Table 3. Potential sizes for CHP and biomass tanks

Variable	Configuration					
	1	2	3	4	5	6
CHP [kW]	19	35	50	100	200	300
CHP [kWth]	28	51	73	146	292	438
Biomass consumption [kg/h]	20	40	45	90	180	250
Tank [m^3]	10					

For Prosumer 2, the PV system is sized based on peak demand.

Optimization of the REC

The best mix of consumers of the REC is determined in a multi-objective optimization analysis with the NSGA-II genetic algorithm. The objective functions are the NPV of the REC and the revenue for each consumer. The REC cash flow is calculated under the assumption that the investment and maintenance costs of the systems are paid from the prosumers, that also receive revenues from energy sold, while incentives from shared energy are split 50/50 between prosumers and consumers. The optimal configuration is determined by comparing 2^{50} possible combinations, where 50 corresponds to the maximum number of potential consumers. Reference parameters for economic performance calculations are summarized in Table 4.

Table 4. Economic parameters.

	Investment time horizon [years]	20
	Discount rate [%]	3
Annual production decay	PV [‰]	6
	BiomassSystem [‰]	4
Initial cost	PV [€/kW]	1500
	Biomass systems [€/kW]	4100
O&M	O&M PV cost [€/kW/year]	40
	Replacement inverter after 10 years [€/kW]	140
	Biomass systems [€/kWh]	0.025
Resource cost	PUN [€/MWh]	235
	Wood chips [€/ton]	75
	Gas [€/Sm3]	0.75
Taxes	PV management cost (GSE) [€/kW/year]	0.65
	Taxes on energy sold [%]	20
	REC management costs [€/POD/year]	4
Incentives	PV Bonus50%	
	High efficiency cogeneration [€/MWh energy produced in high efficiency]	250
	REC configuration [€/MWh energy shared]	118

RESULTS

The results of the optimization problem designed to identify the best combination of solar panels and CHP in the configuration of Prosumer 1 are shown in Figure 4. Considering the limit of €500,000 on the initial investment, the combination that maximizes the NPV corresponds to 80 kW of photovoltaics and 100 kWel of CHP.

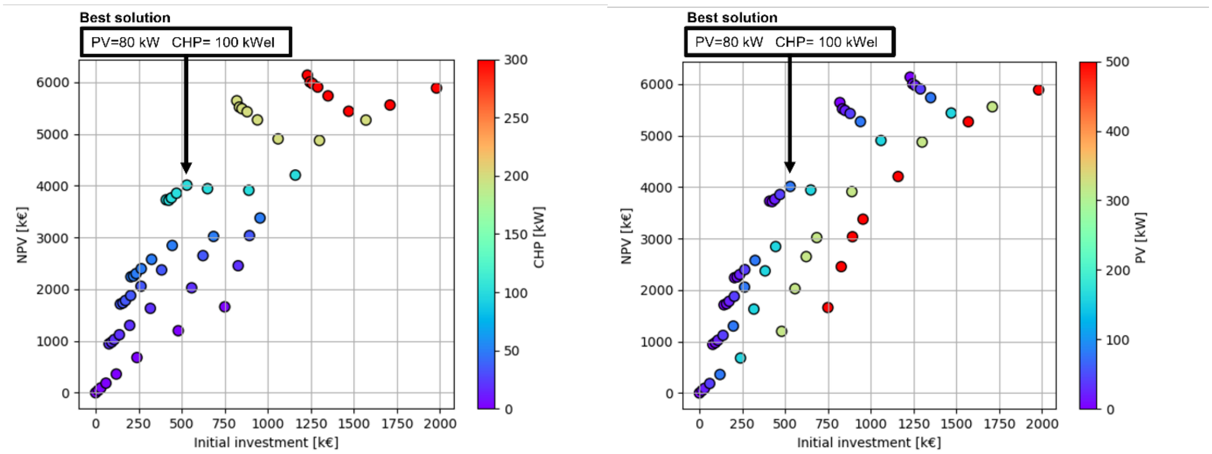

Figure 4. Optimisation analysis for sizing of Prosumer 1.

For this solution, the electricity and heat demand and production for a typical operating day are shown in Figure 5. The hours of lack of photovoltaic production randomly correspond to the hours when the demand reaches its minimum value. This makes the SME user suitable for the integration with the solar source. During these hours, the demand is covered by the CHP, which produces an excess of production that is exported to the grid. Export to the grid also occurs at 12 noon when photovoltaic production is maximum. During the remaining hours, the combined production from photovoltaics and CHP does not meet the demand, resulting in import from the grid. The heat generated in combination with electricity is fully absorbed throughout the day, ensuring that the CHP meets the high-efficiency cogeneration conditions and qualifies for incentives for over 90% of the hours in a year.

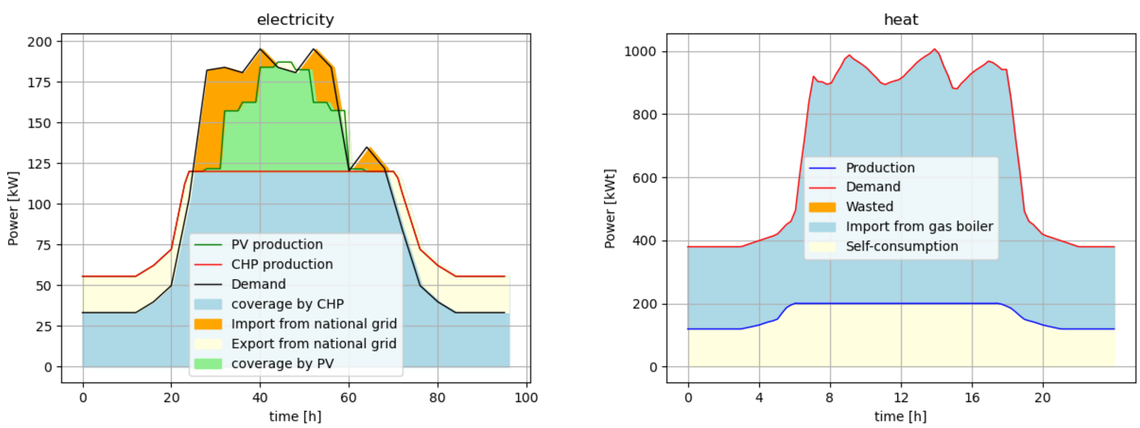

Figure 5. Production and demand of electricity (right) and heat (left) for Prosumer 1 in a typical working day with PV=80 kW and CHP=100 kWel.

PyRES allows to calculate the energy metabolism for all days of the year and monthly energy flows. By observing Figure 6, the electricity production and demand result balanced: self-consumption never falls below 85% of production, and export never exceeds 14%. On the other hand, cogeneration heat production never exceeds 25% of the demand. This behaviour is consistent throughout the year and is not affected by the seasonality of the photovoltaic production since the CHP production adapts to the photovoltaic production to meet the remaining unsatisfied demand.

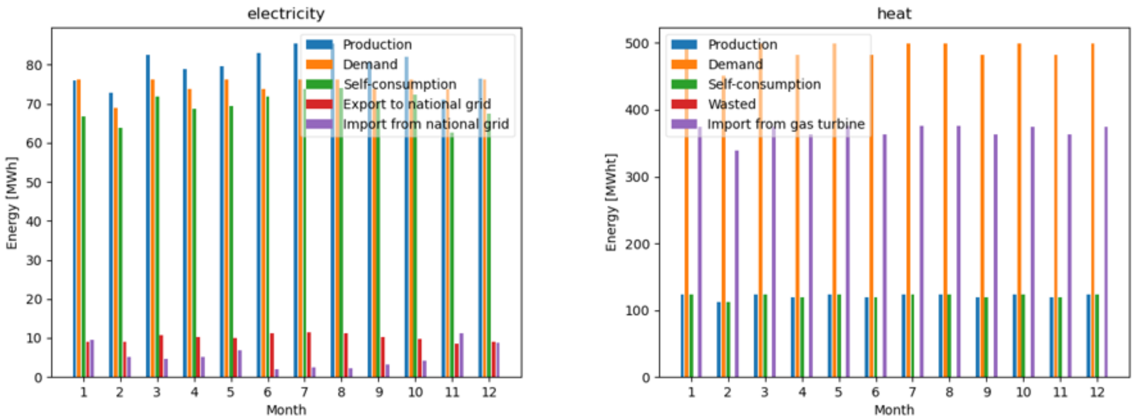

Figure 6. Monthly electricity (right) and heat (left) fluxes of Prosumer 1 with PV=80 kW and CHP=100 kWel.

The summary of annual energy performance for all vectors and resources in the examined configuration is reported in Table 5.

Table 5. Annual Energy perfomance of Prosumer 1 with PV=80 kW and CHP=100 kWel.

Resource/Vector		
Wood chips	Demand [ton/year]	788
Syngas	Production [Nm^3/year]	1807108
	Demand [Nm^3/year]	1643125
	Surplus [Nm^3/year]	163159
Electricity	PV Production [MWh/year]	150
	CHP Production [MWh/year]	803
	Demand [MWh/year]	899
	Self-consumption [MWh/year]	833
	Import from national grid [MWh/year]	65
	Export to national grid [MWh/year]	120
Heat	Production [MWh/year]	1456
	Demand [MWh/year]	5874
	Wasted [MWh/year]	0
	From boiler [MWh/year]	4417

The annual demand for wood chips amounts to 788 tons, corresponding to a syngas production of approximately 1.8 million Nm^3 and providing full coverage of the demand. The output syngas has a calorific value of 4500 kJ/kg and a density of 1.1 kg/Nm3. The combined production of PV and CHP covers 93% of the demand, with 87% of the production used for self-consumption and the remaining 13% exported to the grid. It should be noted that even though it is a small percentage, in absolute terms due to the well-sized system, it amounts to 120 MWh/year, making the prosumer a candidate for sharing in a REC. 25% of the heat demand is covered by cogeneration heat, which still needs to be integrated with production from boilers fuelled by natural gas. The calculation of energy flows allows to calculate costs and revenues associated with this configuration (Figure 7). Under the assumption that the analysed year represents a reference for the entire investment duration, it is possible to calculate the cash flow.

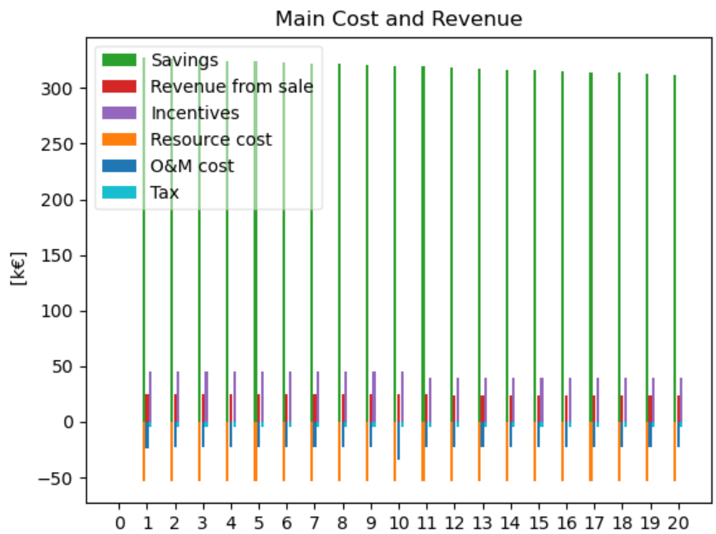

Figure 7. Main costs and revenues of Prosumer 1 with PV=80 kW and CHP=100 kWel

Savings on gas and electricity bills represent the main revenues and are approximately six times the costs for purchasing wood chips. The sum of cogeneration incentives and incentives for the purchase of the photovoltaic system represent represents the second part of the revenues. The last part is derived from energy sales. The list of costs includes purchasing of wood chips, maintenance costs for the gasification, CHP and PV system. The balance is positive, resulting in an NPV of 4 000 000 € and a PBP of 2 years. As for Prosumer 2, the system was sized based on the school's peak demand which it equals to 60 kW.

Analysing the energy flows for four weeks of the year (Figure 8), it is evident that, excluding public holidays, the daily demand profile of Prosumer 2 matches well with the production profile of the PVs. However, the typical seasonality of school energy demand is opposite to that of PV energy production, which reaches its maximum during the summer months when demand is at its lowest.

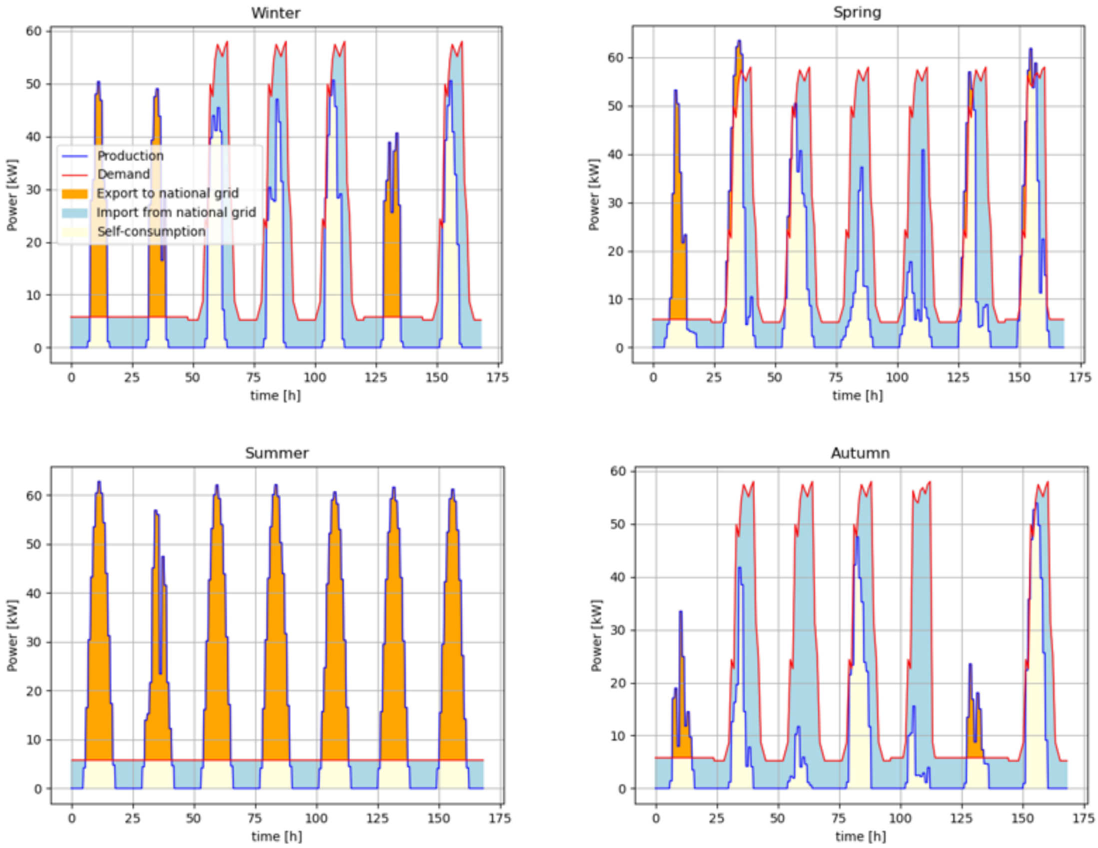

Figure 8. Production and demand of electricity for Prosumer 1 in a typical week for each season with PV=60 kW.

By analysing the monthly flows in Figure 9, in August the export to national grid becomes 11 times larger compared to January, and self-consumption is approximately halved. The coverage reaches the maximum in May, where production is 80% of the demand, and the minimum in November, when the production is only 25% of the demand.

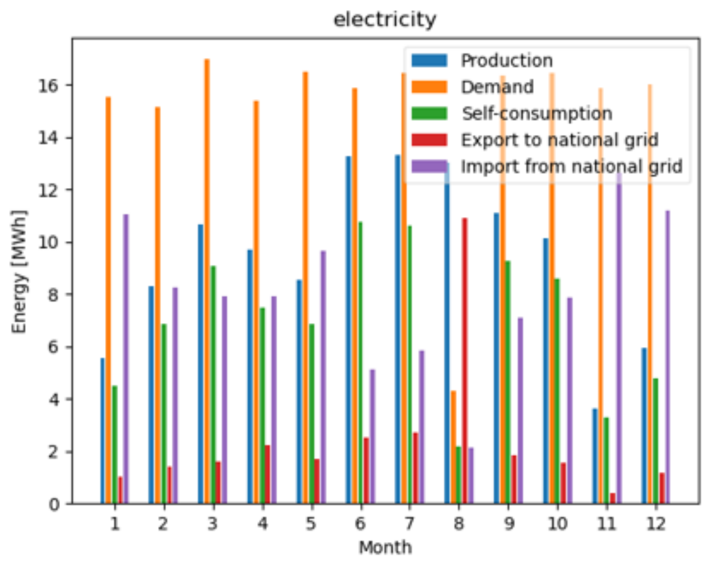

Figure 9. Monthly electricity fluxes of Prosumer 2 with PV=60 kW.

The main cost and revenue items for Prosumer 2 are shown in Figure 10. Savings on electricity expenses are the main source of revenue, amounting to approximately €20,000 per year compared to the €6,000 per year generated from electricity sales. This demonstrates how maximizing self-consumption brings both economic and energy benefits. The last revenue item consists of the Bonus50% incentives, which are only available for the first 10 years of the investment. Maintenance costs take the first place, reaching a peak of €11,000 in the tenth year due to inverter replacement. Finally, there are taxes on revenue from energy sales. The balance is positive, resulting in a NPV of €250,000 and a PBP of 4 years.

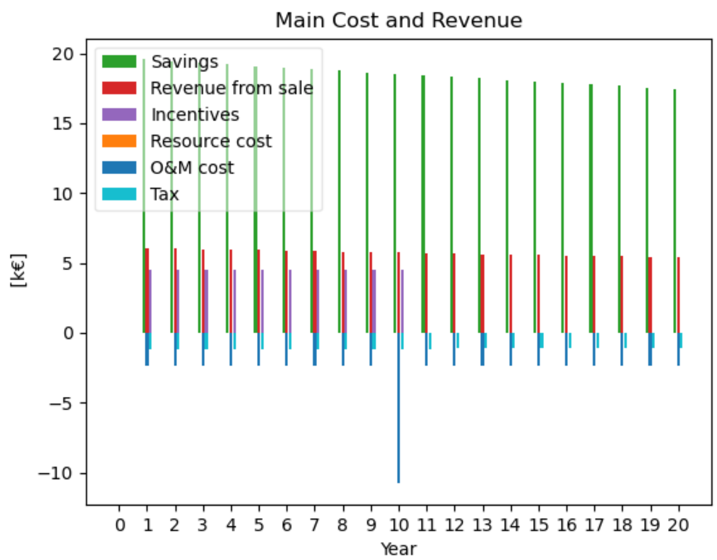

Figure 10. Main costs and revenues of Prosumer 1 with PV=80 kW and CHP=100 kWel

Both prosumers present an excess of production available to share with a REC. The best combinations are identified and represented in the Pareto front of

Figure 11. As the number of consumers increases, NPV increases because the probability to absorb the surplus of prosumers and to generate energy shared increases, on the other hand the revenue for each consumer decreases. The choice of the best mix depends on the purpose of the REC. If the community aims to generate a common fund and use it for social interventions, it is advisable to include all available consumers. Otherwise, if the goal is to divide the incentives among the members, finding the best combination becomes essential. In the optimal solutions, the total number of consumers ranges from 15 to 33. The selected combination corresponds to a NPV of €30,400 and a revenue of €65/year for each of the 23 members.

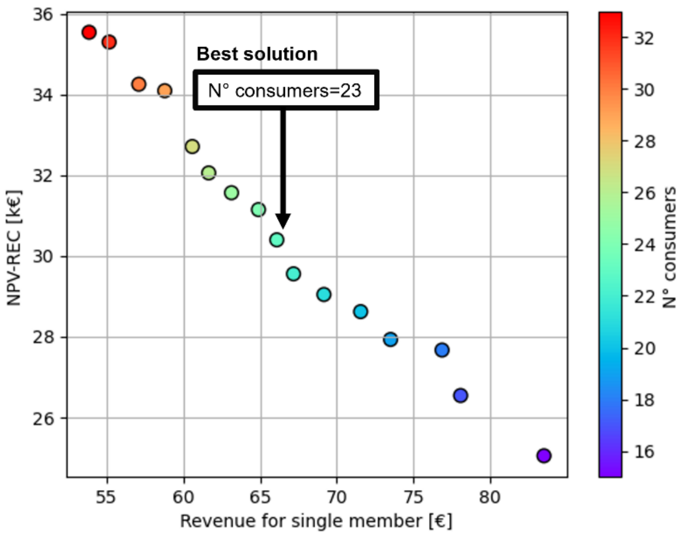

Figure 11. Pareto front of the optimal REC considering a maximum of 50 potential members.

Analysing the energy flows for four weeks of the year (Figure 12), the excess of prosumers, ranges from 20 to 80 kW while the peak of the total demand ranges from 17 to 165 kW. The excess of prosumers satisfies almost 100% of the demand during the summer months when the import from the power grid is almost zero. In the other months, the excess is unable to meet the demand peaks, and the electricity continues to be imported from the national grid. However, an average shared power of 15 kW is guaranteed in all months, and the complete absorption of prosumers' excess is ensured for 30% of the hours of the year.

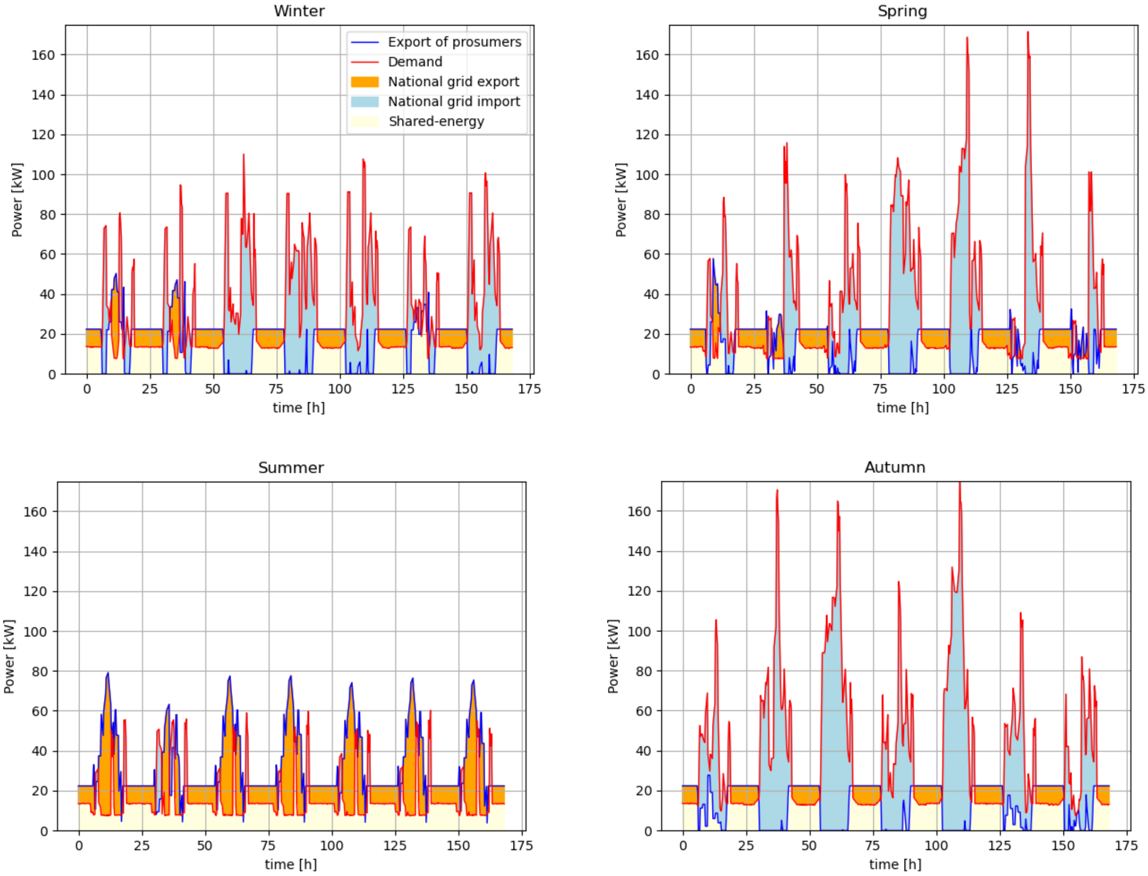

Figure 12. Export of prosumers and demand for the REC with 25 members in a typical week for each season.

From the analysis of the monthly flows in Figure 13, the REC guarantees a minimum of 5 MWh of shared energy in all months of the year.

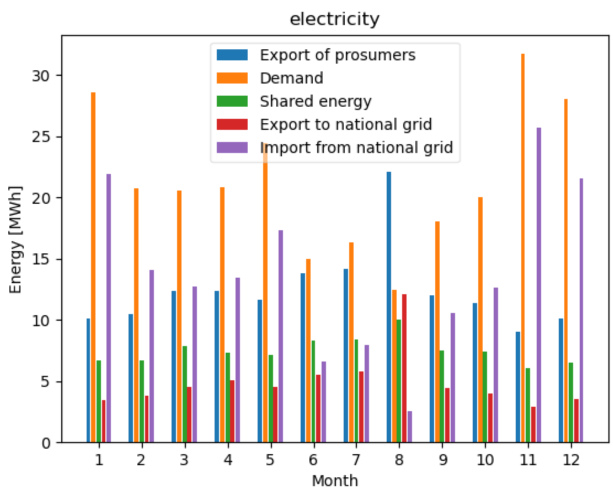

Figure 13. Energy perfomance of REC (resolution of a month).

Table 6 summarizes the energy and economic performance of the REC, which has a total of 25 members, including 23 consumers and two prosumers. Sixty percent of the export of the two prosumers is converted into shared energy which contributes to satisfying the 30% of the consumers demand. The aggregation of the REC generates €30,400 and a revenue of approximately €65 per year for each consumer. Based on the proposed financial model for sharing of REC incentives, Prosumers earn a total of €78,000.

Table 6. Summary of REC energy and economic performance

	Prosumer1	Prosumer2	REC
Production [MWh/year]	953	113	0
Demand [MWh/year]	899	181	256
Self-consumption [MWh/year]	833	84	-
Export to national grid [MWh/year]	120	29	0
Import from national grid [MWh/year]	65	97	166
Shared energy [MWh/year]	-	-	90
Initial investment [k€]	530	90	0
NPV [k€]	4010	250	30.4
PBP [years]	2	4	
Revenue from REC in 20 years [k€]	78	78	
Consumer revenue in 20 years [k€]	-	-	1.3
[tCO_{2eq}/year]	717	85	-

CONCLUSIONS

The new directive for RECs in Italy is mainly focused on incentives on shared electricity within members. However, especially in communities with wide availability of biomasses, incentives on the systems can play a major role in the aggregation of members of the community and in general in the reduction of carbon emissions. Starting from real data for electric and thermal loads, a REC was assembled around two prosumers, an industrial laundry with combined heat and power fueled by biomass, and a school with PV panels. Both prosumers have a significant amount of surplus of production and thus makes sense to assemble a community around them. The best mix of members for the REC was selected with the double aim of maximizing the NPV and revenues for members. This study examines the economic impact of the REC on member consumers and prosumers with different systems sizes and initial investments. The aggregation of the REC results in a positive economic benefit as it generates a cash flow which would not exist otherwise, without requiring an initial investment. However, when considering prosumers with power peak exceeding 100 kW and a biomass fueled cogenerator, the incentive mechanism based on shared energy results not appealing from an economic point of view. They could be more interested by a revenue scheme that allow them to recover part of the cashflow of the REC, but this inevitably results in the REC being less attractive for simple members.

ACKNOWLEDGMENT

This research is supported by the Ministry of University and Research (MUR) as part of the European Union program NextGenerationEU, PNRR - M4C2 - ECS_00000024 “Rome Technopole” in Flagship Project 1 “Clean energy transition and circular economy: materials, bioenergy, green chemistry, green hydrogen and alternative fuels, renewable energy communities, isolated energy systems and smaller islands" and by Regione Lazio under agreement with Department of Mechanical and Aerospace Engineering of Sapienza University of Rome on research and support to Renewable Energy Communities.

NOMENCLATURE

NPV	Net Positive Value	[€]
REC	Renewable Energy Community	

REFERENCES

[1] EU Directive 2018/2001 on the Promotion of the Use of Energy from Renewable Sources. 2018

[2] EU Directive 2019/944 on Common Rules for the Internal Market for Electricity and Amending Directive 2012/27/EU.

[3] Corsini, A., Delibra, G., Pizzuti, I., & Tajalli-Ardekani, E. (2023). Challenges of renewable energy communities on small Mediterranean islands: A case study on Ponza island. *Renewable Energy*, 118986. https://doi.org/10.1016/J.RENENE.2023.118986

[4] Decreto legislativo “ 8/11/2021 n. 199, Attuazione della direttiva (UE) 2018/2001 del Parlamento europeo e del Consiglio, dell’11 dicembre 2018, sulla promozione dell’uso dell’energia da fonti rinnovabili".

[5] ARERA. Delibera 4/10/2020—318/2020/R/EEL.

[6] Decreto ministeriale “16/09/2020, Individuazione della tariffa incentivante per la remunerazione degli impianti a fonti rinnovabili inseriti nelle configurazioni sperimentali di autoconsumo collettivo e comunità energetiche rinnovabili.”

[7] Hoicka, Christina E., et al. "Implementing a just renewable energy transition: Policy advice for transposing the new European rules for renewable energy communities." Energy Policy 156 (2021): 112435.

[8] Mutani, Guglielmina, Simone Beltramino, and Anna Forte. "A clean energy atlas for energy communities in Piedmont Region (Italy)." International Journal of Design & Nature and Ecodynamics 15.3 (2020): 343-353.

[9] Butturi, M. A., et al. "Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis." Applied Energy 255 (2019): 113825.

[10] Taghizadeh-Hesary, Farhad, and Naoyuki Yoshino. "Sustainable solutions for green financing and investment in renewable energy projects." Energies 13.4 (2020): 788.

[11] https://www.governo.it/sites/governo.it/files/PNRR.pdf (accessed 16 April 2022)

[12] Malik, Prashant, Mamta Awasthi, and Sunanda Sinha. "Biomass-based gaseous fuel for hybrid renewable energy systems: an overview and future research opportunities." International Journal of Energy Research 45.3 (2021): 3464-3494.

[13] Ceglia, Francesca, et al. "Biomass-Based Renewable Energy Community: Economic Analysis of a Real Case Study." Energies 15.15 (2022): 5655.

[14] Tiwary, A., Spasova, S., & Williams, I. D. (2019). A community-scale hybrid energy system integrating biomass for localised solid waste and renewable energy solution: Evaluations in

UK and Bulgaria. *Renewable Energy*, *139*, 960–967. https://doi.org/10.1016/J.RENENE.2019.02.129
[15] Mahzouni, A. (2019). The role of institutional entrepreneurship in emerging energy communities: The town of St. Peter in Germany. *Renewable and Sustainable Energy Reviews*, *107*, 297–308. https://doi.org/10.1016/J.RSER.2019.03.011
[16] Yana, S., Nizar, M., Irhamni, & Mulyati, D. (2022). Biomass waste as a renewable energy in developing bio-based economies in Indonesia: A review. *Renewable and Sustainable Energy Reviews*, *160*, 112268. https://doi.org/10.1016/J.RSER.2022.112268
[17] Di Silvestre, M. L., Ippolito, M. G., Sanseverino, E. R., Sciumè, G., & Vasile, A. (2021). Energy self-consumers and renewable energy communities in Italy: New actors of the electric power systems. *Renewable and Sustainable Energy Reviews*, *151*, 111565. https://doi.org/10.1016/J.RSER.2021.111565
[18] Aste, N., Caputo, P., del Pero, C., Ferla, G., Huerto-Cardenas, H. E., Leonforte, F., & Miglioli, A. (2020). A renewable energy scenario for a new low carbon settlement in northern Italy: Biomass district heating coupled with heat pump and solar photovoltaic system. *Energy*, *206*, 118091. https://doi.org/10.1016/J.ENERGY.2020.118091
[19] Paletto, A., Bernardi, S., Pieratti, E., Teston, F., & Romagnoli, M. (2017). *Assessment of environmental impact of biomass power plants to increase the social acceptance of renewable energy technologies*. https://doi.org/10.1016/j.heliyon.2019.e02070
[20] Perea-Moreno M-A, Samerón-Manzano E, Perea-Moreno A-J. Biomass as Renewable Energy: Worldwide Research Trends. *Sustainability*. 2019; 11(3):863. https://doi.org/10.3390/su11030863
[21] Decreto interministeriale 4 agosto 2011 - Promozione della cogenerazione
[22] Deb, Kalyanmoy, et al. "A fast and elitist multiobjective genetic algorithm: NSGAII." IEEE transactions on evolutionary computation 6.2 (2002): 182-197
[23] Sharma, Shweta, and Pratik N. Sheth. "Air–steam biomass gasification: experiments, modeling and simulation." Energy conversion and management 110 (2016): 307-318.
[24] Baruah, Dipal, and D. C. Baruah. "Modeling of biomass gasification: A review." Renewable and Sustainable Energy Reviews 39 (2014): 806-815.
[25] TRNSYS 18 User Manual – Standard Component Library Overview.
[26] Data ISTAT 31 dicembre 2020.
[27] PVGIS-Geographical Assessment of Solar Resource and Performance of Photovoltaic Technology. Available online: http://re.jrc.ec.europa.eu/pvgis/ (accessed on 16 April 2022)