Dynamic Simulation Model of a Renewable Energy Community for Small Municipalities

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Abstract: The presented paper describes the dynamic simulation model developed to predict the real time operation of a Renewable Energy Community based on PV panels coupled with energy storage systems. The dynamic model is able to evaluate the self-consumed energy of the community as well as the energy delivered to the grid considering a real electric load of the community. The model is able to evaluate in detail the economic feasibility of the plant, according to a comprehensive economic analysis, based on the Italian regulation. TRNSYS software is used to model the included energy components. The model is applied to a suitable case study, the municipality of Foiano di Val Fortore, located in the south of Italy. The main results of the presented analysis highlight that the photovoltaic panels lead to a reduction of the primary energy consumption of the renewable energy community by 32%. Due to incentives the achieved simple payback is extremely low. In fact, when the energy storage system is not considered, the achieved simple payback is equal to 4.0 years. When the PV panels are coupled with the energy storage system, the simple payback reaches the value of 13.5 years.

1 INTRODUCTION

The European Union (EU) is actively promoting the energy transition process, focusing on substantial reduction of greenhouse gas (GHG) emissions, improvement of energy efficiency, and increase of energy share from renewable energy sources (RESs) (F. Calise, Vicidomini, Cappiello, & D'Accadia, 2021). In line with the EU long-term strategy for achieving climate neutrality by 2050, significant changes should be implemented both in the production and final consumption stages (Gianaroli et al., 2024).

In this regard, global renewable energy capacity has increased over the recent years, accounting for 43% to the end of 2023 (F. Calise, Cappiello, Dentice d'Accadia, & Vicidomini, 2020), mainly due to growing of solar and wind-based plants. On the other side, energy sharing emerges as a key factor of the decarbonization effort within the framework of the circular economy, intending to provide the entire population with environmental, economic and social benefits (Sajjad Ahmed & Măgurean, 2024).

Following the focus on the active role of end-user in the energy transition, EU encourages energy-sharing models, such as Renewable Energy Communities (RECs) (Lowitzsch, Hoicka, & van Tulder, 2020). Introduced by the Renewable Energy Directive (RED II) in EU legislation, RECs enhance the gathering of local users to better align energy demand with generation locally, thus alleviating the strain on power grids (PG) (Volpato et al., 2024). REC members, private citizens, local authorities or small and medium enterprises, can hold the role of consumers, producers or both, becoming prosumers (Esposito et al., 2024). Optimal design of the

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configuration, in terms of selected technologies and members, contributes to the maximization of associate advantages (Laurini, Bonvini, & Bracco, 2024). Furthermore, the inclusion of charging points for electric mobility, as REC's points of delivery, allows to meet flexible management in order to minimize the electric energy import and export to the PG (Velkovski, Gjorgievski, Markovski, Cundeva, & Markovska, 2024) simultaneously offering additional services to citizens.

The immediate benefits of energy sharing are in primary energy saving and reduction of environmental impact related to REC's members consumptions. In addition, economic incentives are also recognised on shared energy as determined by the regulation context of some EU states, such as Italy. Other countries, as France, Germany and Spain, provide feed-in tariffs for electricity sold to the PG (Belloni, Fioriti, & Poli, 2024). Finally, the use of locally available RESs enhances the acceptability of plants and boosts the direct economic impact on the territory, also through the development of short supply chains, with implications for employment. Energy justice can also be addressed, by including vulnerable end-users with an energy poverty mitigation aim (Campagna, Rancilio, Radaelli, & Merlo, 2024).

In this framework, the following paper addresses the evaluation of the economic feasibility of a specific REC implementing the dynamic simulation approach for the evaluation of the shared renewable energy by a detailed economic analysis based on the Italian regulation context.

2 METHOD

In this section the layout of the investigated renewable energy community (REC) and the dynamic simulation model developed to assess the energy performance of the PV plant in terms of self-consumed energy and energy delivered to the grid, as well as the economic feasibility of the plant, is described.

2.1 Layout

The layout is very simple and is based on a PV field connected to a system inverter/regulator, managing the load of the community and the power production of the solar field. However, in order to better understand the performance of such REC, several scenarios were investigated, namely:

- scenario A1: PV field without electric energy storage system (ESS);
- scenario A2: PV field with ESS.

2.2 System Model

TRNSYS 18 was adopted to develop the dynamic simulation model of the examined REC layouts. TRNSYS is a reference and valid tool for the academic community. The software is based on built-in components, experimentally validated (Bordignon, Emmi, Zarrella, & De Carli, 2021; Francesco L. Cappiello, 2024; Francesco Liberato Cappiello & Erhart, 2021; Klein et al., 2006; Testasecca, Catrini, Beccali, & Piacentino, 2023), providing high accuracy and reliability of the returned results in terms of dynamic energy performance of solar systems (Bordignon et al., 2021; Francesco L. Cappiello, 2024; Francesco Liberato Cappiello & Erhart, 2021; Klein et al., 2006; Testasecca et al., 2023). The energy components of TRNSYS are defined as Types and are based on detailed and comprehensive models. In this work, in order to simulate the presented scenarios, the following types are adopted.

Photovoltaic Field Model. Type 94 simulates the PV field of the REC using the so-called "four parameters" model (Buonomano, Calise, d'Accadia, & Vicidomini, 2018).

Lithium-Ion Battery Model. Type 47 simulates the lithium-ion ESS according to the Shepherd model. Note that his model is natively designed for mimicking the performance of lead acid battery. However, in this case the main parameters of the type are customized in order to fit the performance of a lithium-ion battery (Francesco Calise, Cappiello, Cartenì, Dentice d'Accadia, & Vicidomini, 2019). The model evaluates the discharging efficiency according to battery conditions. Further details are available in ref (Francesco Calise et al., 2019).

Regulator/Inverter Model. Type 48 models the regulator/inverter for the optimal management of the current exchanged among PV arrays, ESS, inverter and community. Type 48 is used to mimic the performance of a regulator/inverter converting the DC into AC, before providing it to the electric grid when the state of charge reaches the maximum value or to the charging stations.

In the A1 and A2 scenarios, two distinct models have been developed. These dynamic models are designed to mimic the performance of the PV field and storage system. They also assess the energy shared within the

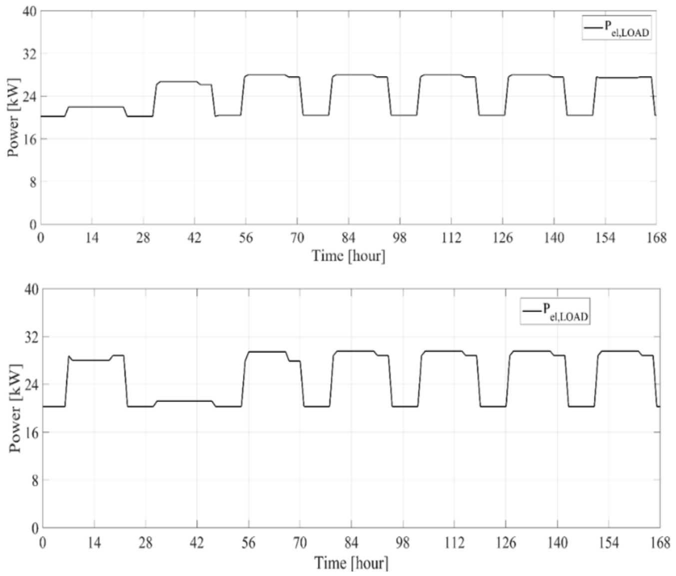

Figure 1: Daily load for a typical summer day (below) and a typical winter day (above).

Table 1: Main economic assumptions.

Parameter	Description	Value	Unit
J_{PV}	Photovoltaic specific cost	$1.400 \cdot (P_{el,PV,rated})^{-0.075}$ XX	€
J_{LIB}	Lithium-ion battery specific cost	200.0 (Shabbir Ahmed et al., 2018; F. Calise, Cappiello, Cimmino, & Vicidomini, 2023)	€/kWh
m_{Ord}	Ordinary maintenance	3.0	%/year
m_{extr}	Extraordinary maintenance (10th year)	20.0	%
j_{toGrid}	Electricity exporting price	0.060(*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government)	€/kWh
$j_{fromGrid}$	Electricity purchasing cost	0.210 (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government)	€/kWh
j_{feed}	Feed in tariff due to REC policy (related to self-consumed energy)	0.120 (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government)	€/kWh
$j_{feed(arera)}$	Feed in tariff due to ARERA	0.008 (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government)	€/kWh
$J_{inc,cap}$	Incentive due to REC policy (related to capital cost)	40.0 (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government)	%

community and the PV energy production in relation to the energy demand of the REC. For both scenarios, an economic analysis was developed. In order to perform the analysis, the scenarios were compared with the reference system (RS), where the load is totally balanced by the electric energy withdrawn from the grid.

Concerning the proposed systems (A1 and A2), according to REC policy, only a virtual electricity self-consumption is considered (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government). This means that the total PV energy production is delivered to the grid, and the load of the REC is balanced withdrawing the electricity from the grid.

Then the self-consumed energy is assessed as the difference between the PV energy production and the community energy demand. The main economic factors considered were: i) the unit cost of electricity withdrawn from the grid $j_{fromGrid}$; ii) the REC ordinary management, maintenance and administration costs m_{Ord}; iii) the selling of the renewable electricity j_{toGrid}; iv) the feed in tariff j_{feed} according to the Italian regulation and the feed in tariff due to ARERA $j_{feed(ARERA)}$ (*https://www.mase.gov.it/comunicati/energia-mase-pubblicato-decreto-cer*, Italian Government). Note that for both scenarios, the economic analysis is developed by means a suitable cash flow able to evaluate the following economic indexes: the simple payback period (*SPB*), the net present value (*NPV*) and the profit index (*PI*), assuming a lifetime of 20 years and a discount rate of 5%. To evaluate the economic feasibility of the considered scenarios, the capital costs of the PV field (scenario A1 and A2) and energy storage system (scenario A2) are evaluated considered the nominal capacity of the components, P_{PV} [kW] and Cap_{LIB} [kWh].

$$J_{TOT} = J_{PV} + J_{LIB} = 1400\left(P_{PV}\right)^{-0{,}075} + 200\left(Cap_{LIB}\right) \tag{1}$$

For each year, the yearly economic saving ΔC, difference between the operating cost of the reference and proposed system, is evaluated according two incentive regulations, namely: ΔC_{jfeed} and $\Delta C_{INC,CC}$. This last economic saving considers the feed in tariff j_{feed} reduced by half, because an incentive according to the REC regulation, equal to 40% of the capital cost, is expected.

$$\Delta C_{jfeed} = \left(E_{el,fromGRID} j_{fromGRID}\right)_{RS} - \begin{bmatrix} E_{el,fromGRID} j_{fromGRID} + m_{Ord} \\ -E_{el,toGRID} j_{toGRID} - E_{el,\mathrm{self}}\left(j_{feed(ARERA)} + j_{feed}\right) \end{bmatrix}_{PS} \tag{2}$$

$$\Delta C_{INC,CC} = \left(E_{el,fromGRID} j_{fromGRID}\right)_{RS} - \begin{bmatrix} E_{el,fromGRID} j_{fromGRID} + m_{Ord} \\ -E_{el,toGRID} j_{toGRID} - E_{el,\mathrm{self}}\left(j_{feed(ARERA)} + \dfrac{j_{feed}}{2}\right) \end{bmatrix}_{PS} \tag{3}$$

3 CASE STUDY

The case study selected for this research consist of the municipality of Foiano di Val Fortore (F. Calise, Cappiello, Cimmino, Dentice d'Accadia, & Vicidomini, 2024) located in the south of Italy. In particular, such small municipality includes 1 325 inhabitants (F. Calise et al., 2023). Figure 1 displays the assumed load of the whole municipality: ranging around 24 kW.

In the reference system the municipality load is balanced by means of the electricity withdrawn from the grid.

The proposed system 1 (A1) relies on the foundation of a renewable energy community, where a diffuse photovoltaic installation is performed. In particular, an overall PV capacity of 50 kW is installed. Note that since the diffuse photovoltaic field installation only a virtual electricity self-consume is considered. This concept is described in the previous section.

The proposed system 2 (A2) is equal to the proposed system 1, i.e. it is considered a renewable energy community relying on diffuse photovoltaic field installation. Note that in this case an overall PV capacity of 50 kW is considered. Moreover, such arrangement also includes a district electricity energy lithium-ion battery of 20 kWh. Also, in this case the virtual electricity self-consumption is considered. Table 1 summarizes the main cost figures and assumption regarding the economic analysis. The PV plant is shutdown 2 days per month, due to maintenance. This assumption is performed for both the proposed systems. Note that an yearly degradation by 2% through the whole life time of the PV field is considered.

4 RESULTS

This section deals with the results achieved by this work. Table 2 summarizes the yearly results. As expected, the installation of the PV fields leads to a significant reduction of the primary energy consumption of the municipality. In particular, a reduction by 32 % of the primary energy of the municipality is achieved for SP1 (see *PES* Table 2).

Table 2: Yearly results for A1.

Parameter	RS	PS	Unit
	Value		
$E_{el,fromGRID}$	216.57	158.19	MWh/y
$E_{el,toGRID}$	-	11.61	MWh/y
$E_{el,PV}$	-	71.42	MWh/y
$E_{el,self}$	-	58.38	MWh/y
PE	470.81	318.66	MWh/y
$E_{el,self}/E_{el,LOAD}$	-	26.96	%
$E_{el,self}/E_{el,PV}$	-	81.74	%
ΔPE	-	152.15	MWh/y
PES	-	32.32	%
SPB (feed)	-	5.30	years
NPV (feed)	-	56.10	k€
PI (feed)	-	1.10	-
SPB (feed+inc)	-	4.00	years
NPV (feed+inc)	-	52.20	k€
PI (feed+inc)	-	1.70	-

Note that the self-consumed energy ($E_{el,self}/E_{el,LOAD}$) balances almost 27.0% of the load of the municipality, Table 2. This result is due to the fact that the power production occurs only during the central part of the day balancing only a limited part of the district daily load (see Figure 2). Note that the district is able to self-consume the majority of the PV production, i.e. $E_{el,self}/E_{el,PV}$ almost equal to 87%, Table 2. These results are quite expected. From the economic point of view, the REC policy is able to make this investment profitable. The scenario, where only the feed in tariffs are considered, leads to simple payback of 5.30 years, with a NPV of 56 k€. The scenario, where both the feed in tariff and the capital cost incentives are considered, achieve the better results with a limited payback period of 4.0 years and NPV of 52.2 k€. Then, the policy combining the reduced feed in tariff with the capital cost incentive is the better solution.

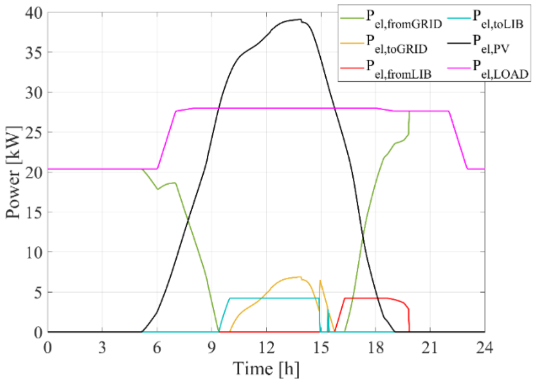

Figure 2: Dynamic results for A1.

The proposed system 2 (A2) is able to furterly reduce the primary energy consumption of the district due to the electric energy storage system. In fact, for A2 the REC is able to reduce the primary energy consumption by 31%, see *PES* Table 3. Note that the battery increases by 3% the self-consumed energy ratio ($E_{el,self}/E_{el,LOAD}$), which passes from (26% in A1 Table 2) to 29% in A2 Table 3. This slight enhancement is mainly due to the battery limited capacity. In fact, because the high capital cost of such technology a small battery is installed. The result is furtherly confirmed by Figure 3. In fact, the battery is able to handle only a limited amount of the excess of renewable electricity, i.e. 4.22 kW out of 10.91 kW, Figure 3.

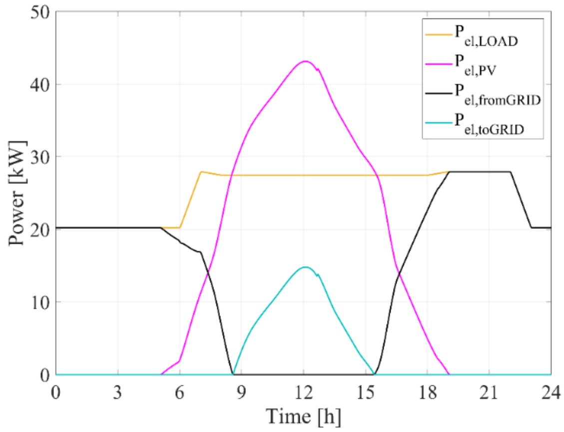

Figure 3: Dynamic results for A2.

Table 3: Yearly results for A2.

Parameter	RS	PS	Unit
	Value		
$E_{el,fromGRID}$	216.57	153.73	MWh/y
$E_{el,toGRID}$	-	4.45	MWh/y
$E_{el,PV}$	-	71.42	MWh/y
$E_{el,self}$	-	62.85	MWh/y
$E_{el,fromLIB}$	-	6.96	MWh/y
$E_{el,toLIB}$	-	4.84	MWh/y
$E_{el,fromLIB}/E_{el,LOAD}$	-	3.21	%
$E_{el,toLIB}/E_{el,PV}$	-	6.77	%
$E_{el,self}/E_{el,LOAD}$	-	29.02	%
$E_{el,self}/E_{el,PV}$	-	88.00	%
PE	470.81	324.52	MWh/y
ΔPE	-	146.29	MWh/y
PES	-	31.07	%
SPB (inc)	-	12.40	years
NPV (inc)	-	2.97	k€
PI (inc)	-	0.05	-
SPB (inc+inc,cap)	-	13.50	years
NPV (inc+inc,cap)	-	0.01	k€
PI (inc+inc,cap)	-	0.00	-

The battery adoption leads to a worsening of the economic performance if compared with A1 (i.e. the layout without the battery). This result is related with the fact that the battery has a very high specific cost, leading to average economic results. In other words, the increase in the capital cost is not balanced by the reduction of the operative cost due to the increased self-consumed energy. As for A2, the better policy relies on the full feed in tariffs policy without any incentive on the investment. This result is mainly due to the fact that the policy regarding the feed in tariff is able to maximize the revenue due to the increase in the self-consumed energy because the battery adoption.

5 CONCLUSIONS

This paper deals with the analyses of the energy performance and economic performance of a renewable energy community. The simulation model of the renewable energy community is developed in TRNSYS environment. The small town of Foiano di Val Fortore is selected as suitable case study. In particular, it is supposed to found a renewable energy community relying on diffuse photovoltaic installation. For this reason, in this case the virtual electricity self-consumption is considered. According to this policy all the electricity produced by the photovoltaic field is exported to the grid, the load of the district is balanced by the electricity withdrawn from the district. The self-consumed energy is considered equal to the difference between the electricity delivered to the grid and withdrawn from the grid. Note that the assessment of the self-consumed energy is crucial in the framework of the renewable energy community, since the feed in tariff rewards the electricity self-consumed. Two scenarios are considered, one based on the renewable energy community relying only on the diffuse photovoltaic installation. The second one is based on an energy community adopting the diffuse photovoltaic installation and a lithium-ion battery.

The main findings of this research are condensed below.

- The photovoltaic adoption leads to a reduction of the primary energy consumption of the renewable energy community by 32%.
- The self-consumed energy balances 26% of municipality load for the scenario relying only on photovoltaic. The self-consumed energy matches almost 29% of the load of the municipality for the scenario adopting photovoltaic and battery.
- The renewable energy community policy is useful in making such investments very profitable. In fact, due to incentives the achieved simple payback is extremely limited. The first scenario achieves a simple payback of 4.0 years and the second scenario reaches a simple payback of 13.5 years.

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