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A MILP Model for the Design Optimization of Energy Communities#

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ABSTRACT

Energy communities are considered a key element in the transition towards more sustainable energy systems. Indeed, the final consumers are encouraged to form communities to share the locally produced renewable electricity. In such a prospective, this work proposes a novel Mixed Integer Linear Programming formulation for the design optimization of energy communities: given a set of buildings/prosumers of a district, the model allows optimizing the number of energy communities and the selection of prosumers/buildings to be included in each community with the objective of maximizing the economic or energy benefit for the whole district. The proposed model is applied to a case study of a district with 40 prosumers and results are critically analyzed.

Keywords: energy communities, energy district, smart energy system, MILP.

1. INTRODUCTION

In 2019 the European Commission updated its energy policy framework with the publication of the Clean Energy Package, initially proposed in 2016. The package consists of a set of four Regulations and four Directives aimed to facilitate the transition away from fossil fuels towards clean energy. The European Union (EU) targets for 2030 are:

i. 40 % reduction in greenhouse gases emissions compared to 1990 levels
ii. 32 % share for the renewable energy sources (RES) in the energy mix
iii. 32.5 % improvement in energy efficiency.

A key element in this transition towards a more sustainable energy sector is represented by the energy community, two definitions of which are present in the Clean Energy Package: "renewable energy community (REC)", mentioned in the Renewable Energy Directive 2018/2001 [1], and "citizen energy community (CEC)", mentioned in the Electricity Market Directive 2019/944 [2]. With the introduction of this new subject, each Member State is asked to transpose the two directives into national laws, to promote and facilitate the energy community development.

Focusing on the "renewable energy community" (simply "energy community" in the following), the term refers to a group of natural persons, small and/or medium-size enterprises, and/or local authorities, including municipalities, which provide local RES production to primarily serve the community, storing and/or exporting the energy produced in excess. This means that, with the creation of an energy community, we are also witnessing the creation of an energy market internal to the community itself, as each member can potentially buy energy from other members, as well as sell his own produced energy to them.

This decentralized energy production has many benefits, such as the utilization of local energy sources, increased local security of energy supply, shorter transport distances and, consequently, reduced energy transmission losses. Such decentralization also fosters community development and cohesion by providing income sources [1]. Energy communities would bring not only environmental and economic benefits, but also social ones. One of the most important social innovations is represented by the shift of the consumer role [3]: with the installation of RES indeed, such as photovoltaic (PV) panels, the traditional passive consumer becomes "prosumer" of energy [4], so an active participant in the electricity system and, thus, more autonomous and independent of the centralized energy supply.

Due to the high complexity in the design and operation of energy communities, that should deal with the internal energy market created, as well as the different energy fluxes that are established (between the members of the community and between the community and the external electrical grid), new optimization models and methodologies need to be developed. Some of them have already been published in the open literature. Ref. [5] proposed a model of microgrid that allows the aggregation of final users in energy community. The suggested model has been called "Power Sharing Model (PSM)" because it permits the full self-consumption by the users of the local energy generated by renewables. Ref. [6] analyzes different energy strategies and incentives applied to an energy community have been analyzed. The results have shown that an incentive on the shared energy promotes an optimal portfolio sized on the users demands, while a direct incentive on the produced energy leads to an oversized production capacity. Moreover, the installation of an energy storage system always increases the Net Present Value (NPV) of the community. Ref. [7] introduced a methodology to address the design and management of energy community initiatives. The model has been applied to a small/medium condominium and it is divided into two steps: first, design and operation of energy assets (e.g., boilers, PV) are optimized to obtain the best cash flow for the condominium; then, revenues deriving from the energy sharing within the condominium itself are distributed among the members, exploiting the solution based on the Shapley value. From the analysis it has resulted that: (i) the electrification brings to cost saving, linked for instance to the exploitation of the local electricity generation from the installed PV; (ii) the use of Shapley value-based income distribution pushes the final users' consumption in periods with high PV generation, provided that the users are willing to shift their electrical loads. Both the works in [6] and [7] are based on the Italian regulatory framework.

In all the above-mentioned optimization models, the prosumers for the considered energy community are already known, i.e., the prosumers taking part to the community are fixed a priori. But a common problem arising in urban districts is determining which prosumers/users should be included in the community and how many communities should be formed in order to maximize the economic/energy benefit. The answer to these two questions depends on different factors: the different energy sources installed and/or which can be installed in each building, the energy demand and production profiles of the prosumers/users, and the selling/purchasing price of the electricity. Indeed, in absence of demand side management programs, forming a community leads to economic advantages if at least one the following conditions is met:

1) the electricity selling price is lower than the electricity purchase price from the main grid. If this condition is not met, it is more advantageous to directly sell the excess electricity to the main grid rather than sharing with the community (or selling to a user of the community)
2) the net energy demand profiles (energy demand minus renewable production profiles) of the prosumers/users are not synchronous and there are time periods where a prosumer is generating an excess of electricity (negative net energy demand) and another one needs electricity. In this case, the excess electricity is transferred from one prosumer to the other reducing the electricity purchased (at high price) from the grid
3) if new energy production/storage units can be installed (e.g., batteries, fuel cells, etc.), there is a scale effect on costs and efficiency favoring the installation of a large community-shared unit rather than installing multiple smaller units.

Thus, to determine the optimal design of energy communities and selecting the prosumers to be included, it is necessary to take into account the expected yearly operation of the prosumers and the electricity purchase/selling prices. This work proposes an efficient MILP model which, given an urban district (set of prosumers and users), optimizes the number of energy communities to be formed and the selection of prosumers/users for each community.

To the best of our knowledge, it is the first model addressing such class of problems including the details of the expected yearly operations.

2. METHODOLOGY

2.1 Problem statement

The optimization problem can be summarized as follows:

given the following inputs:

- typical hourly demand profiles and intermittent renewable (PV) production profiles of the prosumers in the district area
- typical hourly demand profiles of the users in the district area
- typical/forecasted hourly profiles of both selling and purchasing prices of the electricity
- maximum number of communities that can be formed or maximum number of prosumers/users in each community
- set of the energy technologies which can be installed in each prosumer/user (e.g., PV panels) and in each community (as a community-shared technology, like BESS), with their minimum and

maximum capacity, investment and operating costs, and efficiency

determine the optimal number of energy communities, list of users and prosumers in each community, and energy technologies to be installed (in each prosumer/user or in the community). It is important to note that some prosumers and users might remain stand-alone if their participation to a community is suboptimal. The objective function considered in this work is the Net Present Value (objective function):

$$\mathrm{NPV} = -\mathrm{inv}_0 + \sum_{i=1}^{T_{inv}} \frac{\mathrm{CF}}{(1+r)^i} \tag{1}$$

where:

- inv_0 is the initial investment cost (i.e., at year 0) that need to be sustained, related for instance to the installation of PV panels and BESS
- CF is the annual cash flow, related to the O&M cost of the different technologies, the revenues/cost due to the electricity sold/purchased to/from the grid, and the eventual incentive on the self-consumed/shared energy within the formed energy community
- T_{inv} is the investment lifetime
- r is the discount rate.

Figure 1 shows the energy community optimization problem. It shows that some prosumers/users might not be included in any community and remain stand-alone. In addition, PV and BESS can be installed by all prosumers/users while the community can install a shared BESS. Moreover, each community has an internal electricity exchange "node". The excess or the deficit is exported/taken from the electric grid. In this model, communities cannot directly exchange electricity, but they are connected only to the main electricity grid.

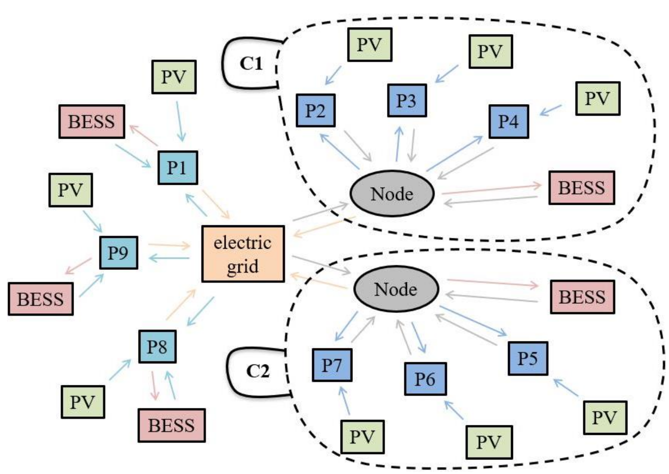

Fig. 1 Scheme of the optimization problem.

The variables of the problem can be classified in three groups:

- binary variables $z_{i,j}$ for the clustering of prosumers/users *i* in the communities *j* (if $z_{i,j} = 0$ for all *j* the prosumer/user *i* remains stand-alone, otherwise it belongs to the *j*-th community)
- binary variables $z_{i,k}$ and $z_{j,k}$ denoting the installation of energy storage unit *k* in the stand-alone prosumer *i* or in the community *j*
- continuous variables related to the BESS SOCs and the electric power exchanged between each prosumer, the community nodes, and the main grid.

The constraints of the problem can be grouped in the following categories:

- energy balance of the community *j* (e.g., energy fluxes among the different prosumers within the community)
- energy balance for each prosumer and user *i*
- State of Charge (SOC) evolution of the prosumer's BESSs and community shared BESSs
- technical limit (max SOC, max discharge/charge power) of the BESSs
- logical constraints related to the selection of users/prosumers in each community
- logical constraints linking the binary variables for the clustering of the prosumers/users in the communities and the installation binary variables with the operational variables of the installable energy production/storage units.

2.2 Clustering algorithm

When facing with a design optimization problem for the installation and sizing of energy systems, the operations across the whole lifetime should be taken into account to have an accurate estimate of operating costs/revenues and operating issues. To limit the computational time, a limited set of representative operating days, referred to as "typical days", must be selected. However, determining them is not straightforward and appropriate clustering algorithms should be used. The most used clustering algorithms are k-means, k-medoids, k-centers, and several works already compared them [8][9].

In this study, we use the "k-MILP" clustering algorithm [10] because it allows determining also the extreme (atypical) operating days. Since the clustering algorithm has to identify typical and atypical days to represent the different energy demand/production profiles of all prosumers/users, the accuracy considerably depends on the number of typical and atypical days set at input. However, the increase in the number of extreme days (as well as typical ones) leads to an exponential increase in the computational time.

In order to find a solution to the trade-off between accuracy and computational time required to solve the MILP community design problem, we set the number of typical days to 12 and atypical days to 2. We also set a constraint in the k-MILP clustering model that one of the selected extreme days corresponds to the maximum of electricity demand of the district area. The maximum error in approximating the load duration curve of the district has been set to 12%.

3. CASE STUDY

The optimization model described above has been applied to a case study in which 40 possible prosumers are considered, comprising:

- 1 university campus (open Monday to Friday, 8:00-18:00)
- 1 school (open Monday to Friday, 8:00-18:00)
- 1 hospital (open all days, 24h/day)
- 2 industries: one of them works on one slot per day, while the other one works on three slots per day (8 hours each). Both the industries are closed during weekend, requiring low electrical energy supply
- 35 residential buildings (electrical demands from SIRAM and [11]).

To deeply understand the benefits coming from the formation of the energy community, different cases have been analyzed, listed below:

- "Stand-alone, Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings cannot install the PV; all prosumers and users are stand-alone (no community)
- "Opt. Comm., Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings cannot install the PV; the energy community (number and participants) is optimized
- "10-limit Comm., Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings cannot install the PV; only a single energy community with up to 10 buildings can be formed
- "Stand-alone, Opt. Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings can install the PV (up to a maximum surface equal to that available on the rooftop); stand-alone buildings considered, i.e., the energy communities cannot be formed
- "Opt. Comm., Opt. Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings can install the PV (up to a maximum surface equal to that available on the rooftop); the energy community (number and participants) is optimized
- "10-limit Comm., Opt. Small PV": 20 buildings have already a fixed installed area of the PV (equal to the surface available on the rooftop); the remaining 20 buildings can install the PV (up to a maximum surface equal to that available on the rooftop); only a single energy community can be formed with up to 10 buildings.

To investigate the economic and energy effects of BESSs, all the above-mentioned cases have been analyzed both with and without the possibility of installing BESSs, "BESS" and "no BESS", respectively (thus obtaining 12 cases in total).

Moreover, except for the case "10-limit Comm.", the above-mentioned cases have been tested assuming a different value for the PV area, i.e.:

- for the buildings with an already installed PV, it has been assumed equal to the surface that is necessary to satisfy the yearly demand, with net-zero yearly export/import of electricity
- for the buildings that can install the PV, the maximum possible PV surface is set equal to that necessary to satisfy the yearly demand, with net-zero yearly export/import of electricity.

These last cases, referred to as "Large PV", have been analyzed to understand the effect of the available PV surface on the economic advantage of forming communities.

The purchasing and selling prices of the electricity for all the above-mentioned cases have been taken from [12] ("Servizio elettrico nazionale") and [13] ("Gestore dei Mercati Energetici", Prezzo Unico Nazionale, PUN), respectively, considering the year 2019.

Finally, the cases with "Small PV", except for "10-limit Comm.", have been repeated both with and without the possibility of installing the BESS considering higher prices, i.e., the purchasing and selling prices of electricity in 2021.

The cases analyzed in this work are summarized in Table 1.

Regarding the considered costs (investment, operating and maintenance) for PV and BESS, they are reported below:

- PV investment cost: 1357 €/kWp [14]
- PV operating and maintenance (O&M): 17.8 €/kWp/year [14]
- BESS investment cost: 400 €/kWh
- BESS operating and maintenance (O&M) throughout: 0.01 €/kWh.

The investment lifetime and the interest rate have been assumed equal to 10 years and 8%, respectively.

The optimization has been performed with Pyomo optimization modelling library [15], using the MILP solver Gurobi [16]. The imposed relative gap (i.e., the relative difference between the best found solution and the lower bound) is equal to 0.5%.

Table 1. Summary table of analyzed cases.

2019 Elec. Prices	Small PV	Opt. Small PV	Large PV	Opt. Large PV
no BESS	Stand-alone, Opt. Comm., 10-limit Comm.	Stand-alone, Opt. Comm., 10-limit Comm.	Stand-alone, Opt. Comm.	Stand-alone, Opt. Comm.
BESS	Stand-alone, Opt. Comm., 10-limit Comm.	Stand-alone, Opt. Comm., 10-limit Comm.	Stand-alone, Opt. Comm.	Stand-alone, Opt. Comm.
2021 Elec. Prices	**Small PV**	**Opt. Small PV**	**Large PV**	**Opt. Large PV**
no BESS	Stand-alone, Opt. Comm.	Stand-alone, Opt. Comm.	n.a.	n.a.
BESS	Stand-alone, Opt. Comm.	Stand-alone, Opt. Comm.	n.a.	n.a.

4. RESULTS AND DISCUSSION

In this section the results of the optimization are reported and discussed in detail, starting from those related to the cases "Small PV, no BESS, 2019" and "Opt. Small PV, no BESS, 2019". These results are reported in Table 2.

As it can be seen, the formation of the energy community is always advantageous, even when 20 buildings are not allowed to install the PV, with economic savings up to 5.45% with respect to the stand-alone configuration. Moreover, when the energy community is allowed to be formed, it is formed with a number of buildings equal to the maximum possible (i.e., 40 in the cases "Opt. Comm." and 10 in the cases "10-limit Comm."). The benefit of doing this comes from the possibility of sharing electrical energy among the buildings/prosumers within the community. This advantage can be seen looking at the significant increase in the yearly self-consumed energy, which reduces both the grid exported and imported electricity. In the "10-limit Comm., Small PV" case, the formed energy community comprises 10 prosumers (i.e., all of them have already the installed PV). Thus, all the 20 buildings that cannot install the PV do not take part to the community. This occurs because within the community there is also an industry which features a large electric demand in the peak sun hours. Thus, the optimizer selects only prosumers (houses with PV installed) to reduce the grid-imported electricity for the industry. Focusing on the cases "Opt. Small PV", the optimization of the stand-alone configuration ("Stand-alone, Opt. Small PV") has resulted in the installation of a smaller PV surface than the maximum possible. Indeed, the installation of a too large PV surface would have brought to both higher investment and operating and maintenance costs, without any further benefit, as the stand-alone prosumers cannot share the electricity among them. The reasoning is completely different when the community is allowed to be formed ("Opt. Comm., Opt. Small PV"), because in this case all the 40 prosumers of the community can share energy between them, indeed, the optimization has resulted in the maximization of the PV surface for those who have not an already installed PV, bringing to an economic saving equal to 11.5% over the stand-alone configuration. This significant benefit is also underlined by the much higher self-consumed energy. Finally, in the case "10-limit Comm., Opt. Small PV", all the buildings that have not an already installed PV and take part to the community, install the maximum possible surface, while the remaining stand-alone ones do not saturate the PV surface (for the same reasons previously explained). This resulted in an economic saving by 3.36% with respect to the stand-alone configuration.

What just said occurred even for the cases in which the BESS is allowed to be installed, whose results are shown in Table 3. The optimization of both the stand-alone configurations ("Stand-alone, Small PV", "Stand-alone, Opt. Small PV") has brought to the installation of a certain BESS capacity for some prosumers, due to the overproduction from PV, aiming at reutilizing the stored energy later in the day. On the other side, when the energy community is allowed to be formed ("Opt. Comm., Small PV" and "Opt. Comm., Opt. Small PV"), no

Table 2. Optimization results: "Small PV, no BESS, 2019", "Opt. Small PV, no BESS, 2019".

	Stand-alone, Small PV, no BESS, 2019	**Opt. Comm., Small PV, no BESS, 2019**	**diff [%]**	**10-limit Comm., Small PV, no BESS, 2019**	**diff [%]**
Net Present Value [€]	-22416336	-21194912	5.45	-21677377	3.3
Yearly self-consumed energy [kWh]	2908482.68	4609585.47	58.49	3946982.26	35.71
Yearly exported energy [kWh]	1807649.82	106547.03	-94.11	769150.25	-57.46
Yearly imported energy [kWh]	21307106.04	19606003.25	-7.99	20268606.46	-4.88
	Stand-alone, Opt. Small PV, no BESS, 2019	**Opt. Comm., Opt. Small PV, no BESS, 2019**	**diff [%]**	**10-limit Comm., Opt. Small PV, no BESS, 2019**	**diff [%]**
Net Present Value [€]	-22210903	-19657096	11.5	-21465591	3.36
Yearly self-consumed energy [kWh]	3426988.08	7916793.94	131.02	4625878.61	34.99
Yearly exported energy [kWh]	2113296.06	770818.56	-63.53	1462964.21	-30.78
Yearly imported energy [kWh]	20788600.63	16298794.78	-21.6	19589710.11	-5.77

Table 3. Optimization results: "Small PV, BESS, 2019", "Opt. Small PV, BESS, 2019".

	Stand-alone, Small PV, BESS, 2019	**Opt. Comm., Small PV, BESS, 2019**	**diff [%]**	**10-limit Comm., Small PV, BESS, 2019**	**diff [%]**
Net Present Value [€]	-22414302	-21194912	5.45	-21675442	3.3
Yearly self-consumed energy [kWh]	2929864.85	4609585.47	57.34	3965520.52	35.35
Yearly exported energy [kWh]	1783144.85	106547.03	-94.03	747922.82	-58.06
Yearly imported energy [kWh]	21285724.39	19606003.25	-7.9	20250068.19	-4.87
Installed BESS capacity [kWh]	28.01	0	-	23.87	-14.79
	Stand-alone, Opt. Small PV, BESS, 2019	**Opt. Comm., Opt. Small PV, BESS, 2019**	**diff [%]**	**10-limit Comm., Opt. Small PV, BESS, 2019**	**diff [%]**
Net Present Value [€]	-22207321	-19657096	11.49	-21462025	3.36
Yearly self-consumed energy [kWh]	3470045.04	7916793.94	128.15	4668553.38	34.54
Yearly exported energy [kWh]	2069121.83	770818.56	-62.75	1419842.7	-31.38
Yearly imported energy [kWh]	20745543.67	16298794.78	-21.44	19547035.33	-5.78
Installed BESS capacity [kWh]	55.33	0	-	54.52	-1.47

BESS has been installed within the community. This means that the cost related to the installation of the BESS to store energy during the hours of overproduction from PV would be higher than the cost related to the electricity import from the electrical grid when there is no availability of energy production from PV. The same outputs resulted from the optimization of the two cases in which up to 10 buildings/prosumers can take part to the community (“10-limit Comm., Small PV”, “10-limit Comm. Opt. Small PV”). Indeed, on the one hand, no BEES has been installed within the community, while on the other hand, a certain storage capacity has been installed by some stand-alone prosumers experiencing an overproduction. However, the installed BESS capacities are small compared to the overall demand of the buildings. As consequence, approximately the same economic savings as those without the possibility of installing the BESS have been obtained.

The optimization assuming a PV surface capable of satisfying the yearly demand of the buildings, instead, has brought to different results, reported in Table 4, without the possibility of installing the BESS (“Large PV, no BESS, 2019”, “Opt. Large PV, no BESS, 2019”). The economic savings coming from the formation of the energy community, indeed, are lower than those obtained in the “Small PV” cases, above all when the buildings that do not have an already installed PV are allowed to install it. In the “Stand-alone, Opt. Large PV” case, the optimization has brought to the installation of a certain PV area for those buildings that did not have it, but this area, as occurred previously, has not been saturated. Moreover, a higher NPV than before has been obtained, as well as for the “Stand-alone, Large PV" case, due to the much larger PV surface already installed, which allows to satisfy a higher portion of the electrical demand. In the two cases in which the energy community can be formed (“Opt. Comm., Large PV”, “Opt. Comm. Opt. Large PV”), all the buildings take part to the community but, when the 20 buildings without a previously installed PV are allowed to install it (“Opt. Comm., Opt. Large PV”), no further PV surface is installed. This means that the already available PV surface is sufficient to cover the electrical demand of the entire community during the hours of production from PV. This brings to the same values in terms of NPV, self-consumed, exported, and imported energy as those of the “Opt. Comm, Large PV” case. These aspects resulted in lower economic savings (by 5.11% and 3.27%) with respect to the stand-alone layouts than the “Small PV” cases.

What just said has occurred also for the case in which the BESS is allowed to be installed, whose results are shown in Table 5. While a certain BESS capacity has been installed by the prosumers in both the stand-alone cases (“Stand-alone, Large PV”, “Stand-alone, Opt. Large PV”) to store electrical energy during the PV overproduction hours, no BESS has been installed in the cases in which the energy community has been formed (“Opt. Comm., Large PV”, “Opt. Comm., Opt. Large PV”), which comprises all the 40 buildings/prosumers, in both the cases present in the table. This has occurred for the same reason explained previously, that is the cost related to the community BESS installation is higher than the cost related to the electricity purchase from the grid during the hours in which there is not enough production from PV. As a result, the possibility of installing the BESS in the community does not bring to any advantage in terms of NPV (relative to the stand-alone cases) with respect to the case when the BESS is not allowed to be installed.

The last analysis has been performed considering again “Small PV”, and “2021”, so the electricity prices taken from 2021. The results for the case without the possibility of installing the BESS (“Small PV, no BESS, 2021”, “Opt. Small PV, no BESS, 2021”) are reported in Table 6. First of all, the obtained NPVs are much lower than those obtained with the electricity prices from 2019. This is due to the higher electricity prices considered in this last analysis. Considering the case in which the buildings that do not have the PV cannot install it (“Opt. Comm., Small PV”), the optimization has brought to the formation of the energy community, comprising all the 40 buildings. Moreover, approximately the same economic saving as that with the prices from 2019 (Table 2) has been obtained. This is because in the calculation of the percentage difference between the obtained NPVs what is important is not the numerical value of the electricity purchase and selling prices, but the ratio among them, that in this case is almost the same as that of the year 2019 (“almost” and not “exactly equal” because this factor is calculated considering the yearly mean PUN of 2021 and 2019, not the instantaneous one). On the other hand, the percentage differences in terms of self-consumed, exported, and imported energy are the same, because the optimized system layout is the same (same buildings, same demands, same PV). Considering the case in which the buildings without PV can install it (“Opt. Small PV”), instead, a larger economic saving has been obtained. In the “Stand-alone, Opt. Small PV” case, the PV surface has been saturated. This is because of the high price at which the electricity is sold to the grid. On the other side, the optimization of the “Opt. Comm., Opt. Small PV” case has brought to the same results (except for the NPV) as those with the prices from 2019. This has ensured an economic saving equal to 14.07%.

Table 4. Optimization results: "Large PV, no BESS, 2019", "Opt. Large PV, no BESS, 2019".

	Stand-alone, Large PV, no BESS, 2019	**Opt. Comm., Large PV, no BESS, 2019**	**diff [%]**
Net Present Value [€]	-10802208	-10251179	5.11
Yearly self-consumed energy [kWh]	10471080.84	11246584.9	7.41
Yearly exported energy [kWh]	13783243.95	13007739.9	-5.63
Yearly imported energy [kWh]	13744507.87	12969003.82	-5.65
	Stand-alone, Opt. Large PV, no BESS, 2019	**Opt. Comm., Opt. Large PV, no BESS, 2019**	**diff [%]**
Net Present Value [€]	-10597227	-10251179	3.27
Yearly self-consumed energy [kWh]	10987284.55	11246584.9	2.37
Yearly exported energy [kWh]	14085169.72	13007739.9	-7.65
Yearly imported energy [kWh]	13228304.17	12969003.82	-1.97

Table 5. Optimization results: "Large PV, BESS, 2019", "Opt. Large PV, BESS, 2019".

	Stand-alone, Large PV, BESS, 2019	**Opt. Comm., Large PV, BESS, 2019**	**diff [%]**
Net Present Value [€]	-10799638	-10251179	5.08
Yearly self-consumed energy [kWh]	10502616.34	11246584.9	7.09
Yearly exported energy [kWh]	13747013.7	13007739.9	-5.38
Yearly imported energy [kWh]	13712972.38	12969003.82	-5.43
Installed BESS capacity [kWh]	42.03	0	-
	Stand-alone, Opt. Large PV, BESS, 2019	**Opt. Comm., Opt. Large PV, BESS, 2019**	**diff [%]**
Net Present Value [€]	-10592656.69	-10251179	3.23
Yearly self-consumed energy [kWh]	11042797.05	11246584.9	1.85
Yearly exported energy [kWh]	14032990.68	13007739.9	-7.31
Yearly imported energy [kWh]	13172791.66	12969003.82	-1.55
Installed BESS capacity [kWh]	69.35	0	-

Finally, Table 7 shows the results for the cases in which the BESS is allowed to be installed. In the "Stand-alone, Small PV" case the BESS has been installed by some prosumers which are in overproduction during the PV energy generation hours. Moreover, as it can be observed, the installed BESS capacity is larger than the value of the corresponding case with the prices from 2019, due to the higher electricity purchase cost, that pushes the prosumers to store more energy rather than buying it from the grid. On the other side, with the possibility of forming an energy community ("Opt. Comm., Small PV"), the optimization does not bring to the installation of the BESS, as the energy in excess from some prosumers is shared within the community itself. This resulted in an economic saving equal to 4.9%. When the remaining 20 buildings are left free to install the PV,

Table 6. Optimization results: "Small PV, no BESS, 2021", "Opt. Small PV, no BESS, 2021".

	Stand-alone, Small PV, no BESS, 2021	**Opt. Comm., Small PV, no BESS, 2021**	**diff [%]**
Net Present Value [€]	-53494327	-50568479	5.47
Yearly self-consumed energy [kWh]	2908482.68	4609585.47	58.49
Yearly exported energy [kWh]	1807649.82	106547.03	-94.11
Yearly imported energy [kWh]	21307106.04	19606003.25	-7.99
	Stand-alone, Opt. Small PV, no BESS, 2021	**Opt. Comm., Opt. Small PV, no BESS, 2021**	**diff [%]**
Net Present Value [€]	-50895411	-43737142	14.07
Yearly self-consumed energy [kWh]	3685806.32	7916793.94	114.8
Yearly exported energy [kWh]	5001806.18	770818.56	-84.59
Yearly imported energy [kWh]	20529782.4	16298794.78	-20.61

Table 7. Optimization results: "Small PV, BESS, 2021", "Opt. Small PV, BESS, 2021".

	Stand-alone, Small PV, BESS, 2021	**Opt. Comm., Small PV, BESS, 2021**	**diff [%]**
Net Present Value [€]	-53170603	-50568479	4.9
Yearly self-consumed energy [kWh]	3495931.63	4609585.47	31.86
Yearly exported energy [kWh]	1035770.62	106547.03	-89.72
Yearly imported energy [kWh]	20719657.1	19606003.25	-5.38
Installed BESS capacity [kWh]	1222.07	0	-
	Stand-alone, Opt. Small PV, BESS, 2021	**Opt. Comm., Opt. Small PV, BESS, 2021**	**diff [%]**
Net Present Value [€]	-50257073	-43710457	13.03
Yearly self-consumed energy [kWh]	4857966.92	7971103.88	64.09
Yearly exported energy [kWh]	3440863.2	710471.38	-79.36
Yearly imported energy [kWh]	19357621.8	16244484.83	-16.09
Installed BESS capacity [kWh]	2456.47	155.77	-93.66

the surface has been again saturated in both cases ("Stand-alone, Opt. Small PV" and "Opt. Comm., Opt. Small PV"). Regarding the BESS, this time it has been installed not only for the stand-alone buildings case ("Stand-alone, Opt. Small PV"), but even in the case when the energy community (comprising all the 40 prosumers) has been formed ("Opt. Comm., Opt. Small PV"). This is due to the higher electricity purchasing cost, which drives even the energy community to install a battery to store the electrical energy produced in excess and use it later in the day, rather than buying it at a high price during the hours in which there is not availability of PV production.

5. CONCLUSIONS

This work proposes a novel MILP formulation for the design optimization of energy communities. To investigate and understand the benefits coming from the aggregation of different prosumers and/or users belonging to a district area into an energy community, the proposed model is applied to a case study of a district with 40 prosumers/users, and the results have been compared with the reference case in which the prosumers/users are stand-alone. The optimization has shown that the formation of the energy community is always advantageous with respect to the stand-alone configuration, even when the number of prosumers/users within the community is limited. This benefit comes from the possibility of sharing energy between the buildings within the community, resulting in an increased self-consumed energy, increased economically optimal PV capacity installation, and reduced electricity purchased/sold from/to the electrical grid. These aspects have ensured economic benefits for the district area, up to approximately 14%.

However, the economic savings are strongly case dependent. Indeed, based on the results of this works, it is possible to conclude that the formation of the energy community brings to very significant benefits (>10%) when the following conditions simultaneously hold:

- during some hours of the day some prosumers are in the condition of overproduction from the installed PV, while other prosumers/users require additional electrical energy to satisfy their demand. This way, with the formation of the community, the prosumers that are in overproduction can share the energy in excess with the ones requiring it
- there is a large area available for installing the PV, to produce more energy and satisfy the demand of the entire district, minimizing the electricity purchased at high price from the grid.

On the other side, the possibility of installing the BESS has not brought to significant benefits (over the stand-alone configuration) with respect to the case in which the BESS cannot be installed. However, future works should consider also the effect of scale effects on the capital cost of the community-shared BESS as well as the possibility of integrating other energy technologies, demand side management and district heating networks.

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