Multi-Objective Optimization Framework for Integration of Distributed Energy Resources in Smart Communities

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***Abstract*—This paper studies a multi-objective optimization problem on the allocation problem of photovoltaic (PV) and battery energy storage systems (BESSs) in a community, whereby the aim is to find Pareto optimal solutions according to two different set of objective functions. These objective functions are minimizing the dependency of the whole community or each household on the national grid and minimizing the investment, operation, and maintenance costs of PV and BESS units. A Parallel Multi-Objective Multi-Verse Optimization (PMOMVO) algorithm is developed to obtain the Pareto optimal solutions for the problems. The optimization framework is used to determine all Pareto front solutions in a real community and the results are compared to the base case scenario of the community. The Pareto solutions show that by small investment in the BESS units, community can be less dependent on the national grid even with less PV panels installed in the community.**

***Index Terms*—Optimization, Energy storage, Parallel computation, Smart grids, PV allocation problem.**

I. Introduction

Electricity demand has increased over the past years and is predicted to grow continually in the future due to economic and population expansion [1]. Therefore, integrating renewable energy sources (RESs) to accommodate the growth of electricity demand attracts much attention. It is predicted that the amount of produced electrical power by RESs will be equal to amount of generated electricity by coal and natural gas in 2040 [2].

Electricity generated from sustainable energy sources at the households is a cost-effective and clean way to reduce the electricity from the grid. However, the technology of converting sustainable energy to electricity is constrained by weather-related factors such as sunlight and wind speed and this leads to fluctuation of production at households level and thereby small-scale battery energy storage systems (BESSs) are needed to provide energy at times that no renewable energy generators are available [3].

Equipping households with RES and BESS units may allow to create a self-consumption community (SCC). The most suitable generators for a SCC are PV panels, since they are simple and maintenance costs are low [4]. An important aspect for SCC has to have a reasonable payback period for the initial investment. From this perspective, SCCs for electricity are becoming more feasible nowadays for various reasons: reduced prices of PV modules, fast advances in BESS technologies and increasingly supportive energy policies [5].

The RESs utilization trend in local communities provides an excellent opportunity to develop a micro-grid based on the household electrical needs, these micro-grids may also be used to support the medium and high voltage electrical system. Knowing the optimal number of PV panels to be installed and the BESS capacity for different purposes are a challenge for the investors. On the one hand, a non-optimal solutions may result in a shortage of electrical power, especially in the island's communities. On the other hand, investment payback may get quite long and the solution may not be a best option.

Recently some related studies have been developed to investigate the potential of RES units integrated into the low voltage grid: The authors in [6] investigated local generation of households for various electricity tariffs in Norway. This work has an electricity market point of view and does not consider a technical point of view, such as grid impacts. In [7] for a low voltage distribution network in Slovenia, a technical analysis was conducted based on the assumption that 30 % of SCC penetration would be the most profitable scenario to minimize the exchange power to national grid while taking into account the electricity market problems. The study also shows that voltage and transformer loading issues arise with installing to much PV units. However, while the solution suggested significant BESS potential to improve energy flow control, it still lacked an economic perspective between the investment cost and payback benefits.

In [8], an investigation into the installed PV sizes in public buildings illustrated that the PV energy production and consumption match over time, so the given solution suggested no need for BESS. In [9], the impact of residential and commercial consumption on the SCC rates and curtailed energy was investigated. Different PV and BESS system sizes were used as the control parameters of the influence problem of 400 residential and 26 commercial communities in the Netherlands. The results show that commercial communities need more PV and BESS installation than residential systems. Furthermore, having BESS increases the self-consumption rate of the community. The generation and consumption match better in commercial than in residential networks. However, the study did not give an optimal sizing for PV and BESS units that solve the goals of the utilities and households.

Determining the optimal size for the PV systems and the BESS capacity for different households needs a robust optimization framework that finds near-optimal solutions and, at the same time, has a fast convergence behavior. Researchers [10], [11] have developed new optimization algorithms to solve energy management related Mixed-Integer Non-linear Programming problems. The optimization frameworks found in literature deliver a near-optimal solution using a single objective function formulated for the given problem.

In this work, a multi-objective optimization framework is proposed and developed to improve the convergence speed of the algorithm by paralleling optimization tasks. In detail, multi-objective functions are formulated for finding the optimal number of PV panels and optimal capacity and powers of the BESSs in a community. The objectives for the optimization process are formulated as minimizing the dependency of the community and the households on the electricity coming from the national grid while minimizing the investments to the units, the operation, and the maintenance cost. A parallel multi-objective multi-verse optimization (PMOMVO) algorithm has been developed to find all the Pareto optimal solutions for the formulated problem. The main contributions of this study are:

- new multi-objective formulation for minimizing the dependency of the community and the households on the electricity coming from the national grid while minimizing the costs of PV and BESS units;
- a multi-objective optimization framework based on parallel computing to speed up the optimization process;
- a method to determine the Pareto optimal solutions of the problem in different scenarios considering different objectives and investigating the performance of the communities for the solutions.

The remainder of the paper is organized as follows. The multi-objective formulation of the considered problem is described in Section II. Section III briefly describes the PMOMVO method and concentrates on the optimization framework for the proposed optimization problem. Section IV presents simulation results of test system applications. Finally, Section V concludes the paper.

II. Optimization problem

A general formulation for an n-dimensional multi-objective optimization problem given as follows:

$$\underset{w.r.t.\ \overrightarrow{x}}{\text{minimize}}\, F(\overrightarrow{x}) = \{f_1(\overrightarrow{x}), f_2(\overrightarrow{x}), ..., f_n(\overrightarrow{x})\} \tag{1}$$

$$\overrightarrow{x} = [x_1, x_2, ..., x_d]$$

$$\text{Subject to } \begin{cases} g_l(\overrightarrow{x}) \geq 0, l = 1, 2, ..., p \\ h_k(\overrightarrow{x}) = 0, k = 1, 2, ..., q \\ (\overrightarrow{x})^{lb} \leq \overrightarrow{x} \leq (\overrightarrow{x})^{ub} \end{cases}$$

where Pareto solutions can be found for the n individual objectives with respect to the d control variables ($\overrightarrow{x}$) of the problem. g and h are the inequality and equality constraints formulated for the problem. Note that $(\overrightarrow{x})^{lb}$ and $(\overrightarrow{x})^{ub}$ denote the lower and the upper bounds of the control variables in $\overrightarrow{x}$, respectively.

Considering the problem defined in this study, the control variables and the different objective functions formulated for the problem given as follow.

A. Control variables

The control variables for the problem are the number of PV panels and the capacity and power parameters of the BESSs ($\overrightarrow{x} = [\overrightarrow{N}_{\text{PV}}, \overrightarrow{E}, \overrightarrow{P}]$) where N_{PV} is the number of the PV panels, E denoted the capacity of BESSs, and P is power of the BESSs for the households in the community.

B. Objectives

The objectives for the problem comprise of functions for minimizing the dependency of the community and the household on the national grid and for minimizing annual investment, operation, and maintenance costs of the PVs and BESSs.

1) Households dependency on national grid: The goal is to have less dependency of the households on the electricity coming from the national grid. This can be modeled by minimizing the deviations of consumption profile (import/export with the national grid) in each house using the following formulation.

$$f_{HD} = \sum_{n=1}^{N_h} \sqrt{\sum_{t=1}^{N_T} (P_{n,t})^2} \tag{2}$$

$$P_{n,t} = (P_{n,t}^{\text{PV}} + P_{n,t}^{\text{BESS}} - P_{n,t}^{\text{Load}}) \tag{3}$$

where the terms P^{PV} denotes the active power of PV units, whereby $P^{\text{BESS}} > 0$ is discharging of the BESS, $P^{\text{BESS}} < 0$ represent the charging power of BESS, and P^{Load} denotes the active households' load of the community. Note that we use a discretization of time in N_T time intervals in this formulations.

2) Micro-grid Dependency on national grid's power: The goal of the objective is to minimize consumption profile deviations in the community using the following formulation:

$$f_{MD} = \sqrt{\sum_{t=1}^{N_T} \left(\sum_{n=1}^{N_h} P_{n,t} \right)^2} \tag{4}$$

3) Annual investment, operation and maintenance cost of PV panels and BESSs: Two objectives are used to minimize the annual costs of PV panels and BESS units for the community. The PV costs comprise installation, operation and maintenance costs of the units. They depend on the number of PV panels installed on the rooftops. Similarly, power and capacity-based costs are considered for BESS units to model the installation, operation and maintenance costs. BESS costs depend on both the capacity of the devices and the maximum charge/discharge power that the BESS can provide [12]. This objective is formulated as follows:

$$F_{\text{PV}} = \sum_{n=1}^{N_h} (\overline{IC}_{PV} \times C_{\tau_{PV}} + \overline{OM}_{PV}) \times N_{PV_n} \times S_{PV} \tag{5}$$

$$F_{\text{BESS}} = C_E + C_P \tag{6}$$

$$C_E = \sum_{n=1}^{N_h} (\overline{IC}_E \times C_{\tau_{BESS}} + \overline{OM}_v) \times E_n \tag{7}$$

$$C_P = \sum_{n=1}^{N_h} (\overline{IC}_P \times C_{\tau_{BESS}} + \overline{OM}_f) \times P_n \tag{8}$$

$$C_{\tau_x} = \frac{r(1+r)^{\tau_x}}{(1+r)^{\tau_x} - 1} \tag{9}$$

where $\overline{IC}$ denotes the marginal installation cost of the units and $\overline{OM}$ denotes the annual marginal operational and maintenance costs of the units. The value τ is the estimated lifetime of the units in years, N and S are the number of PV panels installed and the size of a each PV panel, respectively. E and P are the energy capacity and the maximum charge and discharge power of the BESSs. The fixed and the variable operation and maintenance costs of the BESSs are denoted with the sub-scripted letters f and v. Finally, C_τ is the capacity recovery factor of PV panels and BESS unit with an interest rate of r.

III. PMOMVO Algorithm and its Implementation

The Multi-Objective Multi-Verse Optimization (MOMVO) [13] is a recently developed optimization algorithm based on the theory of multi-verses in physics. The proposed algorithm is based on Pareto's optimal solution concepts and mimics the theoretical description of the interplay among universes using the concepts of white/black holes and wormholes. This study considers a MOMVO method and applies parallel computing techniques aiming to divide the optimization task between several processes while having efficient communication among them.

In this study, an introduced MOMVO method based on parallel computation called PMOMVO is used, where the optimization process divided between several agents (CPU cores). The PMOMVO implements a master-slave methodology, where one of the agents is the master and defines the communication strategy among the slave agents [11]. Besides, the slave agents are responsible for performing local optimization based on the best solutions provided by the master agent.

In the parallel method, the universe's number (number of the search solutions in optimization process) in each agent is equal to the universe's number in the base MOMVO algorithm. In the MOMVO algorithm, the Pareto solutions are stored in an external repository called the Archive set. Based on the communication between the agents in the PMOMVO algorithm, the Pareto solutions stored in each Archive set of agents are transferred to the master agent. Then, the non-dominated solutions from all the Pareto solutions are used to start the next iteration of the optimization process. Note that the maximum number of iterations in PMOMVO is the same as that in MOMVO. The optimization process is performed in the various slave agents individually; however, after each communication, the optimization process use on the best universes found by the slave agents and the non-dominated Archive set.

The communication rate (CR) among the agents is a main parameter that can affect the quality of the solutions. In every CR% of the iterations, the master request the Archive solutions among the other slaves and shares the best solutions with them. This process continues until the end of the computation process. Compared to the MOMVO algorithm, the computational time in PMOMVO can be estimated as time over the number of slaves. The PMOMVO process for finding Pareto optimal solutions is shown in Fig. 1 and the mathematical representation of the MOMVO process is taken from [13].

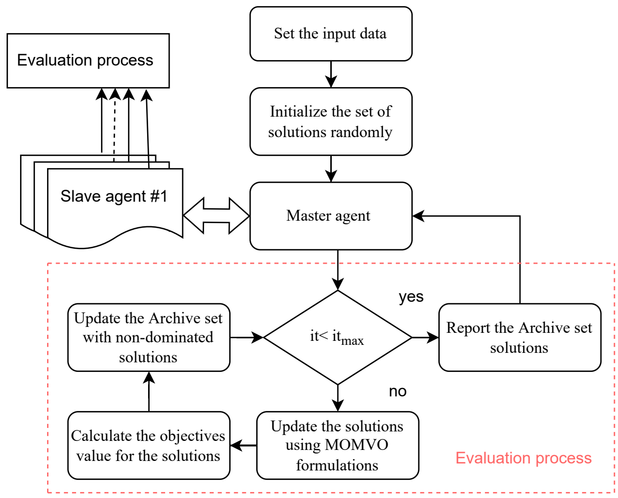

Fig. 1. The flowchart of the process.

IV. Simulation Results

A. Test system and PV data

The proposed optimization process is tested on data from the Aardehuizen community [14] in Olst, the Netherlands. The layout of the houses in the community is shown in Fig. 2. This community consists of 23 residential houses and one communing building. The main goal behind building this community is living responsibly with respect to the environment. In this regard, the houses are built using sustainable materials, and the goal is to satisfy their energy requirements using sustainable sources such as PV panels. However, a connection to the national electricity grid is still needed to balance the community's generation and consumption. Hereby, the aim is to minimize the dependency on the national grid.

The Aardehuizen community is modelled in the cyber-physical energy systems software DEMKit [15], [16], short for "Decentralized Energy Management Toolkit". DEMKit is capable of both executing an energy simulation as well as implementing optimization algorithms for the operation of different devices within an overall model. In the simulations executed for this paper, within DEMKit a demand side management approach called Profile Steering [17] is used for each solution generated by the PMOMVO algorithm to determine the objectives value of the solutions.

To generate energy load profiles for all households as input into DEMKit, we used the Artificial Load Profile Generator (ALPG) [18]. Information about the number of adults and children living in the community [19] combined with publicly available statistics [20] was used as input to the ALPG software to generate near-accurate energy usage data. Furthermore, components for modeling individual houses and operational control strategies are available in DEMKit and were used to find the general energy operation in the community. Note that a proper number of PV panels and capacity and powers of the BESS will be determined by PMOMVO and that the operation strategy in the community will be optimized using DEMKit. By combining these two methods, a complete smart grid model with near-optimal allocation of different devices can be created. For the calculations the parameters provided in Table I were used.

The PV panels with maximum range powers of 255W-270W are used for the simulation. The dimensiona of these panels are $1640 \times 990 \times 40$ millimeter [21] and the maximum number of PV panels is assumed on the basis of available rooftop area of the houses in the community. Among several potential battery technologies, a model based on lithium-ion BESS has been utilized due to its high energy efficiency, long cycle life and relatively high energy density with the parameters shown in Table I. For the optimization process, the upper capacity considered for the BESS units is assumed as 13.5 kWh, and the upper limit for the charging and discharging power that each BESS can provide is 11kW power.

TABLE I
BESS AND PV UNITS PARAMETERS. [22], [23].

PV			BESS		
parameter:	Value	Unit	parameter:	Value	Unit
τ_{PV}	30	year	τ_{BESS}	10	year
$\overline{IC}_{PV}$	1830	\$/kWh	$\overline{IC}_E$	160	\$/kWh
$\overline{OM}_{PV}$	18	\$/kW-yr	$\overline{IC}_P$	1800	\$/kWh
$\overline{OM}_f$	10	\$/kW-yr	$\overline{OM}_v$	0.03	\$/kWh-yr

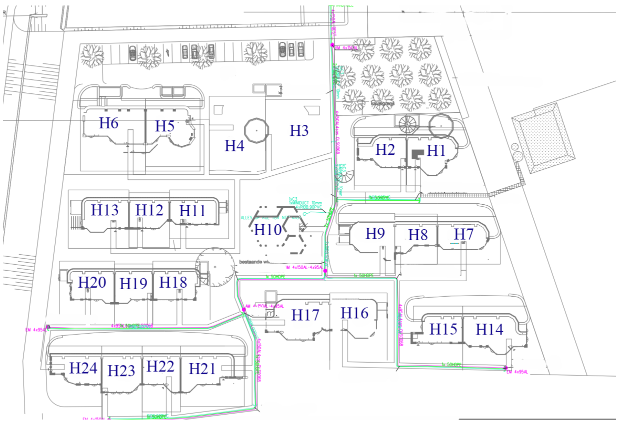

Fig. 2. The Aardehuizen micro-grid.

B. Solution results

1) Pareto optimal solutions: The non-dominated solutions found for the multi-objective minimization problem based on the objectives (2), (5), and (6) are shown in Fig. 3. Similarly, the Pareto solutions for the objective functions (4), (5), and (6) are shown in Fig. 4. Furthermore, the box plots of the number of PV panels for each house found by different Pareto solutions in the community are shown in Fig. 5 and Fig. 6.

The simulation results for different Pareto optimal solutions given in Fig. 4 show that the minimum and the maximum number of PV panels needed to be installed in the community are 203 and 330 PV panels. The minimum and maximum BESS capacity for Pareto solutions were found as 24.6 and 68.3 kWh. Similarly, the results for the Pareto solution in Fig. 3 show that between 210 to 315 PV panels and between 30.9 and 69.5 kWh BESS capacity are found in the Pareto front solutions of optimization problem. The minimum annual investment, operation, and maintenance cost for PVs and BESS was found as 15400 dollars for the Pareto solutions considering households' dependency on the national grid's electricity objective. In the solution, 283 PV panels and 29.1 kWh capacity of BESSs were used to maximize the self-production of the community. On the other hand, the maximum cost of the PVs and BESSs together was found to be 23750 dollars for a Pareto solution of Fig. 4. In the solution, the optimal parameters for the optimization problem were 210 PV panels and 69.5 kWh BESSs' capacity.

Determining the most suitable solution from the set of Pareto solutions for both sets of objective functions depends

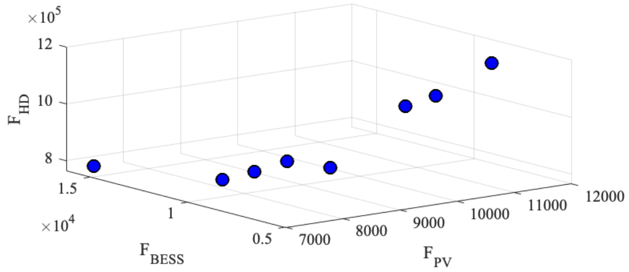

Fig. 3. Pareto optimal solutions considering the objectives (2), (5), and (6).

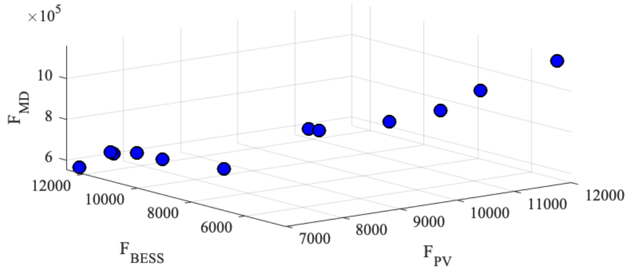

Fig. 4. Pareto optimal solutions considering the objectives (4), (5), and (6).

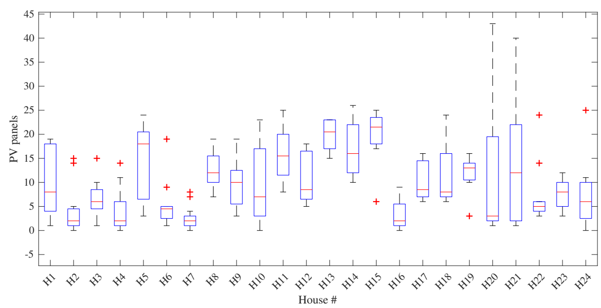

Fig. 5. Boxplot of the number of PV panels found for the Pareto solutions of Fig. 4

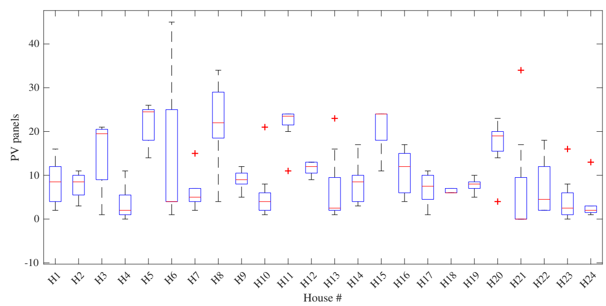

Fig. 6. Boxplot of the number of PV panels found for the Pareto solutions of Fig. 3.

on preference of the community members. Nevertheless, in the following we present a possible decision methodology, which is based on choosing a Pareto optimal solution with a minimum Euclidean distance to the origin in the three-dimensional space. The resulting candidate solution (CS) chosen from the Pareto solution sets is used to compare the benefits of PV and BESS installation compared to the current status of the community (base case) with 315 PV panels and no BESS installed. Besides the base case, also a solution from

TABLE II
THE RESULTS FOR CS, S1, AND BASE CASE SOLUTIONS.

	F_{HD}	F_{MD}	F_{PV}	F_{BESS}	PV panel #	BESS capacity [kWh]
base case	1195454	1170793	11224	0	315	0
S1	1181458		11224	6798	315	31.1
CS	799018		7910	10925	222	47.8

TABLE III
THE PARAMETERS OF PV AND BESS UNITS IN THE CS.

	CS			base case	S1		
	PV	BESS		PV	PV	BESS	
	N_{PV}	E	P	N_{PV}	N_{PV}	E	P
H1	12	215	215	12	12	217	217
H2	15	116	44	9	10	0	0
H3	1	0	0	14	20	390	390
H4	1	3589	1314	14	0	278	278
H5	19	159	159	10	25	442	442
H6	9	0	0	14	43	0	0
H7	0	9416	2674	14	7	284	284
H8	12	0	0	14	34	0	0
H9	13	0	0	11	12	530	530
H10	19	4840	4235	12	4	0	0
H11	13	607	607	5	24	3171	3171
H12	18	3746	1680	22	13	5268	2321
H13	20	0	0	14	2	237	237
H14	13	3071	2311	18	10	445	95
H15	25	2578	2128	16	24	3534	3534
H16	0	0	0	27	16	875	875
H17	14	0	0	0	9	2677	1502
H18	6	449	215	14	6	2320	795
H19	3	0	0	8	5	1027	253
H20	2	510	510	24	20	142	142
H21	40	493	314	14	0	0	0
H22	3	55	55	14	18	9269	5270
H23	9	1445	317	6	0	0	0
H24	2	664	664	9	1	0	0

the set of Pareto solutions with 315 PV panels (called S1) is used in the comparison. Table II shows the objective values and the PV and BESS parameters for the CS, S1, and base case solutions.

The CS, based on minimum Euclidean distance, has total PV and BESS cost of 18835 dollars per year, and the solution suggests installing 222 PV panels and BESS units with total caoacity of 47.8 kWh in the community. The PV and BESS parameters for the CS and S1 solutions were found by using PMOMVO for each house in the community and are shown in Table III together with the base case parameters. The dependency of the community from the grid is lower for the CS solution (33.1 % improvement in F_{HD} value) and uses even less PV panels as the other solutions.

Based on the results of Pareto solutions in Fig. 3, 315 PV panels is found while installing 31.1 kWh BESSs in S1 solution. The solution provides better peak shaving behavior by using the BESSs and lead to a power dependency on electricity from the national grid compared to the base case. The suggestion for the community with their current number of PV panels is to install a 31.1 kWh BESS units based on the BESS parameters shown in Table III. The community has to pay an extra of 6798 dollars per year, but on the other hand, the community moves towards a sustainable micro-grid, which is driven by the ideological beliefs of the Aardehuizen members rather than financial incentives.

Each of the three solutions (CS, S1, and base case) have been simulated using DEMKit. The total energy usage (P_t) of the community in three solutions for 365 days of the year are given in Fig. 7. The results show the impact of the BESS units in shaving the peak load and resulting in less dependency of the community and household on the national power grid.

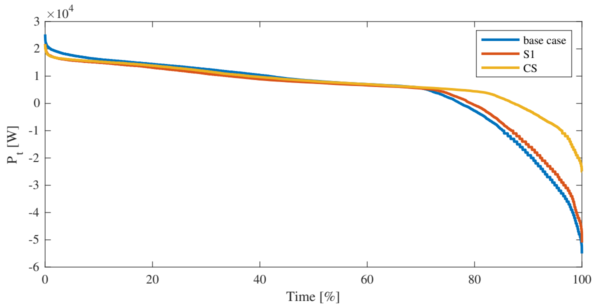

Fig. 7. The Load duration curves of the community for 365 days of simulation.

C. Pareto front solutions quality

To determine the presented results, the algorithms were coded in the programming language Python (DEMKit) and MATLAB 2021b (PMOMVO). The simulation results were obtained by running the algorithms on a PC with a 128GB RAM, Intel Intel Xeon E5-2630, 2.40 GHz processor configuration. The same MOMVO parameters as in [13] are considered for the fair comparison of the Pareto solution obtained with the CR values in the PMOMVO algorithm. For this purpose, the PMOMVO algorithm used 16 slaves with each 100 iterations for the optimization process. To validate the effect of the CR on the quality of the Pareto solutions, we applied the algorithm with communicating each 4, 5, 10, and 20 iterations of the agents and the best CR values based on the following indices are as follow.

The quality of the solutions obtained by the proposed algorithm with different CR value is measured and compared using different performance metrics, namely the spacing metric (SM), the C-index, and hyper-volume (HV) [12]. Based on the definition of the performance metrics [12], a smaller SM value corresponds to closely-distributed non-dominated solutions and better a quality Pareto front. C(set_1,set_2) value shows the percentage of solutions in set_2 that are dominated by the optimal solutions in set set_1. A smaller value for C(set_1,set_2) corresponds to a higher number of non-dominated solutions in the set. The HV index for the solutions in set_1 provides a clear idea of the convergence and diversity of the solutions. Higher values of HV indicate that the solutions are closer to the optimal Pareto front solutions.

The results of the SM, C-index, and HV are shown in Table IV and Table V. Based on the results for 20 individual runs, the results for SM and HV show that communication of master with slaves in each five iteration of the process provides better quality solutions. Besides, the C-index results show that the Pareto solutions in CR=5 are non-dominated solutions compare to the solutions found for other CR values. As the result, PMOMVO with five communications (CR=5) found better distributed non-dominated solutions.

V. CONCLUSION

In this paper, Pareto optimal solutions of a multi-objective formulation for the techno-economical goals of an energy community are determined using a parallelization methodology of a specific optimization algorithm. The objective functions minimize the micro-grid dependency on the overall grid, minimize the household's dependency on the electricity coming from the national grid, and minimize the annual

TABLE IV
THE PARETO SOLUTION QUALITY COMPARISON USING SM AND HV PERFORMANCE METRICS.

	CR	mean	std	min	max
SM	4	2.5034E+04	2.3089E+01	2.5079E+04	2.4993E+04
	5	**2.5028E+04**	1.1197E-11	2.5028E+04	2.5028E+04
	10	2.5031E+04	2.2756E+01	2.5082E+04	2.4998E+04
	20	2.5035E+04	2.7863E+01	2.5094E+04	2.4995E+04
HV	4	7.6546E-02	3.7230E-04	7.5848E-02	7.7183E-02
	5	**7.7259E-02**	2.8477E-17	7.7259E-02	7.7259E-02
	10	7.6477E-02	5.1440E-04	7.5497E-02	7.7259E-02
	20	7.6483E-02	3.6758E-04	7.5742E-02	7.7220E-02

TABLE V
THE PARETO SOLUTION QUALITY COMPARISON USING C-INDEX.

	mean	std	min	max
C(5,4)	0	0	0	0
C(4,5)	48	17	75	25
C(5,10)	0	0	0	0
C(10,5)	46	22	75	0
C(5,20)	0	0	0	0
C(20,5)	49	17	75	13

investment, operation, and maintenance cost of PV panels and BESSs. The results show that a solution can be found based on the minimum Euclidean distance to the origin which uses 29.5% fewer PV panels and BESS units can obtain less dependency on the national grid's electricity (33.1 % improvement) compared to the base case. Besides, a Pareto solution with the same number of PV panels and installing 31.1 kWh BESSs can reduce the household's dependency on the national grid. Finally, to validate the quality of the results found by the PMOMVO algorithm, the best CR is determined on the basis of the SM, C-index and HV performance metrics. Based on the results for the 16 agents, the optimization process with the communication rate of 5% was found as the best value that provided the non-dominated solutions. Future works cover the impact of different assets such as electric vehicles and heating devices on the Pareto optimal PV and BESS units.

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