An optimization approach to control the energy flows in renewable energy communities

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Abstract

Energy communities are new concepts in the European legislation, where it is possible to produce, store and also sell (renewable) energy via the public grid. Participants of such communities can then sell a surplus of Photovoltaic energy to their neighbors and all players can then economically benefit from this energy exchange. This exchange must be coordinated within the energy community and can be seen as a typical optimization task in order to minimize the costs of all players respectively to maximize the benefit of every participant.

Key-words: Energy communities, optimization, photovoltaics, storage systems, optimal power flow

1. Introduction

An energy community is a new concept in the European legislation ("winter package") and will be an essential parts of the new energy distribution system [*EE-RL 2018*]. Within these communities, renewable energy will be exchanged beyond household or company borders and every participant of such a community is allowed to produce, sell, buy or store energy. This paper shows a method to coordinate the energy flows within such a community in order to maximize the benefit of each participant and to distribute the savings of the partners in an energy community in a fair way.

To establish energy communities, possible participants would like to benefit from this energy cooperation. These advantages are almost always linked to monetary benefits. Such a benefit in general can be a reduced or even waived grid charges for exchanged energy or simply a reduced purchase price for (renewable) excess power from e.g. a photovoltaic plant from the neighbour.

In the future, the energy exchange in energy communities must be controlled in order to maximize the benefit for the participants. The control of optimal power flow within such an energy community is typically a static and straightforward task. The consideration of storage units changes the problem into a dynamical one [*Steinmaurer*].

For measurement purposes and energy billing, the purchased and supplied electrical energy is discretized in time intervals of 15min. Therefor it makes sense to consider the problem of energy flow coordination in an energy community as a discrete optimization task.

2. Participants of energy communities

2.1 Definition of energy flows in an energy community

In this work, each participant of a renewable energy community has the following properties, according to Figure 1. The states x_1 ... x_8 are power values of this player in the community and describe the energy flow situation. State x_5 refers to the state of charge of the storage unit. Arrows indicate possible energy flow directions,like load and PV production, costs for energy purchase (x_1) as well as remuneration for feed-in (x_2) are assumed to be known.

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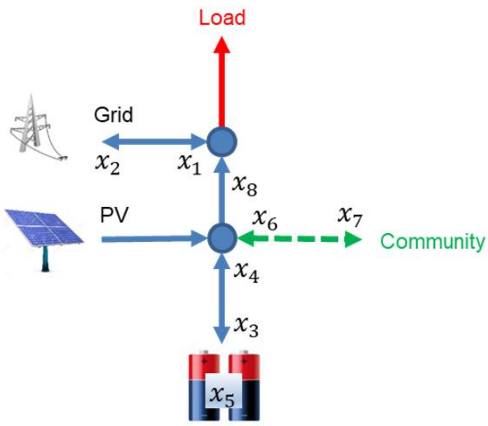

Figure 1: Structure of energy flow optimization of one single participant in an energy community. States xi consider power flow at every time instant

Every Energy community consist of N participants with properties of Figure 1. Renewable energy is considered to be exchanged via the public grid - but with different fees and costs (so the states x_6 and x_7 are necessary).

The energy exchange will be calculated at discrete time instants $m, m = 1, \ldots, M$.

The usage of Figure 1 directly leads to the following energy balance equations for each participant n and at every time instant m with a discretization interval time T

$$x_{1,n,m} - x_{2,n,m} + x_{8,n,m} = P_{load,n,m} \quad \text{(eq. 1)}$$

$$-x_{3,n,m} + x_{4,n,m} + x_{6,n,m} - x_{7,n,m} + x_{8,n,m} = P_{PV,n,m} \quad \text{(eq. 2)}$$

The change of the charge level $(x_{5,n,m} - x_{5,n,m-1})$ of the storage of a participant n between time instant m and $(m-1)$ can be calculated as

$$-\eta_{ch,n} x_{3,n,m} + \frac{1}{\eta_{dis,n}} x_{4,n,m} + T(x_{5,n,m} - x_{5,n,m-1}) = 0 \quad \text{(eq. 3)}$$

whereas $\eta_{ch,n}$, $\eta_{dis,n}$ are charging respectively discharging efficiencies of the storage unit of participant n and T the duration of the discrete time instants.

Within the energy community it is necessary, that the sum of the exchanged energy of all participants is balanced at every time instant m, i.e.

$$\sum_{n=1}^{N} x_{6,n,m} - x_{7,n,m} = 0, \quad m = 1..M \quad \text{(eq. 4)}$$

The costs for participant n in the time instant m can be calculated as

$$\tilde{c}_{n,m} = c_{1,n} x_{1,n,m} - c_{2,n} x_{2,n,m} + c_{6,n} x_{6,n,m} - c_{7,n} x_{7,n,m} \quad \text{(eq. 5)}$$

whereas

$c_{1,n}$ costs for grid purchase of particiant n

$c_{2,n}$ feed-in tariff of particiant n

$c_{6,n}$; $c_{7,n}$ costs respectively feed-in tariff for the community exchange

All this aspects lead in general to an enormous number of equations, so it makes sense to group and simplify the formal description.

3. Formulation of a linear optimization task

The 8 states for participant n in the time instant m can be collected in an vector $\tilde{\boldsymbol{x}}_{n,m}$

$$\tilde{\boldsymbol{x}}_{n,m}^T = [x_{1,n,m} \quad x_{2,n,m} \quad x_{3,n,m} \quad x_{4,n,m} \quad x_{5,n,m} \quad x_{6,n,m} \quad x_{7,n,m} \quad x_{8,n,m}] \qquad \text{(eq. 6)}$$

In order to simplify the description, (eq.1) to (eq.3) are then

$$\tilde{\boldsymbol{A}}_{n,m}\, \tilde{\boldsymbol{x}}_{n,m}^T = \tilde{\boldsymbol{b}}_{n,m} \qquad \text{(eq. 7)}$$

$$\tilde{\boldsymbol{A}}_{n,m} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & -1 & 1 & 0 & 1 & -1 & 1 \\ 0 & 0 & -\eta_{ch,n} & \frac{1}{\eta_{dis,n}} & T & 0 & 0 & 0 \end{bmatrix} \qquad \text{(eq. 8)}$$

$$\tilde{\boldsymbol{b}}^{\boldsymbol{T}}{}_{n,m} = [P_{load,n,m} \quad P_{PV,n,m} \quad 0] \qquad \text{(eq. 9)}$$

The costs for participant n in the time instant m depend only on the states 1, 2, 6 and 7

$$\tilde{\boldsymbol{c}}_n\, \tilde{\boldsymbol{x}}_{n,m}^T \qquad \text{(eq. 10)}$$

with

$$\tilde{\boldsymbol{c}}_n = [c_{1,n} \quad -c_{2,n} \quad 0 \quad 0 \quad 0 \quad c_{6,n} \quad -c_{7,n} \quad 0] \qquad \text{(eq. 11)}$$

The problem of this energy flow coordination is to find an optimal state vector $\boldsymbol{x}$

$$\boldsymbol{x} = [\,[\tilde{\boldsymbol{x}}_{1,1}^T \quad \dots \quad \tilde{\boldsymbol{x}}_{n,1}^T] \quad [\tilde{\boldsymbol{x}}_{1,2}^T \quad \dots \quad \tilde{\boldsymbol{x}}_{n,2}^T] \quad \dots \quad [\tilde{\boldsymbol{x}}_{1,m}^T \quad \dots \quad \tilde{\boldsymbol{x}}_{n,m}^T]\,] \qquad \text{(eq. 12)}$$

to minimize $\boldsymbol{c}^T\boldsymbol{x}$ with

$$\boldsymbol{c} = [\,[\tilde{c}_{1,1} \quad \dots \quad \tilde{c}_{n,1}] \quad [\tilde{c}_{1,2} \quad \dots \quad \tilde{c}_{n,2}] \quad \dots \quad [\tilde{c}_{1,m} \quad \dots \quad \tilde{c}_{n,m}]\,] \qquad \text{(eq. 13)}$$

and fulfilling the boundary conditions. The overall energy flow coordination problem considering all time instants an every participating partner leads then to an a linear programming procedure []

$$\min_{\boldsymbol{x}} \boldsymbol{c}^T\boldsymbol{x} \qquad \text{(eq. 14)}$$

$$\boldsymbol{A}_{eq}\boldsymbol{x} = \boldsymbol{b}_{eq}$$

$$\boldsymbol{x}_{lb} \le \boldsymbol{x} \le \boldsymbol{x}_{ub}$$

considering equality constraints $\boldsymbol{A}_{eq}\boldsymbol{x} = \boldsymbol{b}_{eq}$ ((eq. 1) to (eq. 4)) and inequality constraints $\boldsymbol{x}_{lb} \le \boldsymbol{x} \le \boldsymbol{x}_{ub}$ (e.g. maximum and minimum power, storage limitations, …).

4. Test cases

The objective function to be minimized for this task ($\boldsymbol{c}^T\boldsymbol{x}$) is the sum of all costs of each participant in the considered time interval (power purchase costs, reduced by feed-in remuneration). Within this work a sampling time of 1 h is used.

In order to test the optimization task and examine the resulting energy flows, test cases with participants with different properties (with or without PV, storage existing or not, load profiles, tariff situation, ..:) are examined for a sunny day with significant PV production. The individual parameters of 4 candidates (participant P1 – P4) to attend an energy community are listed up in Tab. 1. The monetary difference between $c_{6,n}$ and $c_{7,n}$ is used to cover fees for using the public grid.

The last line of Tab.1 shows the costs of each participant without attendance at the community for this exemplary single day, which are the result of purchased and supplied energy, considering the associated costs. The Fig 1 show the load and PV production data for this day. The overall costs of all participants sum up to 271.33 €.

Tab. 1: Parameters of participants of an energy community

Participant		**P1**	**P2**	**P3**	**P4**
Grid Purchase costs $c_{1,n}$	$\frac{€Cent}{kWh}$	10.5	10.5	12	15
Grid Feed-in tariff $c_{2,n}$	$\frac{€Cent}{kWh}$	5			
Community purchase $c_{6,n}$	$\frac{€Cent}{kWh}$	8			
Community feed-in $c_{7,n}$	$\frac{€Cent}{kWh}$	7			
Storage size	kWh	-	-	100	-
Costs on exemplary day	€	103.95	34.15	14.73	118.50
Summed Costs	€	271.33			

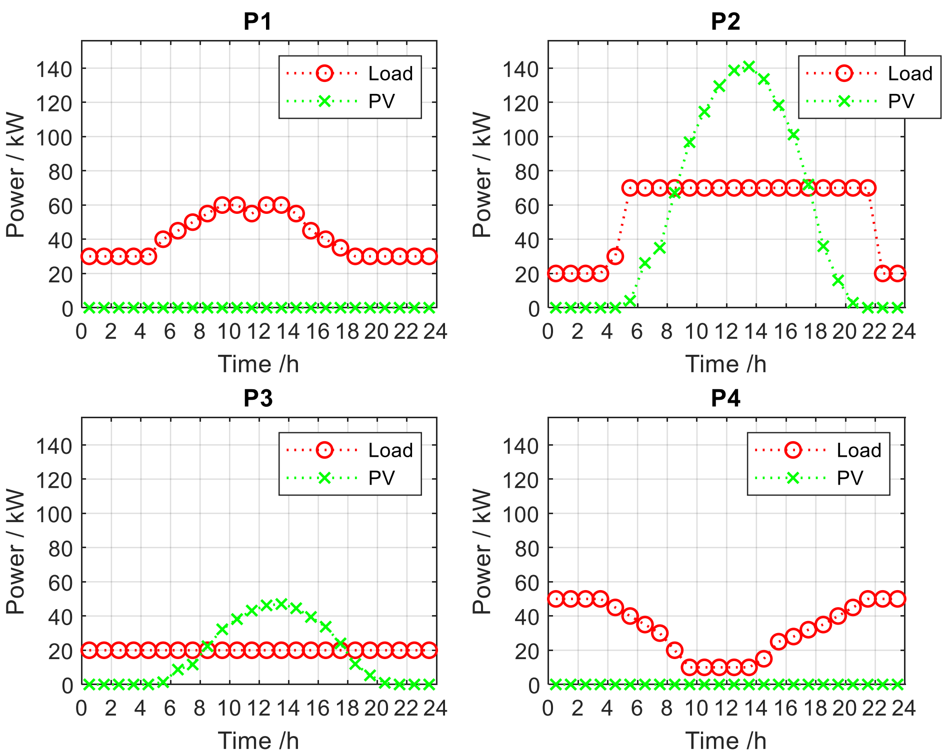

Fig. 1: Load and PV power of participants P1 to P4 on the exemplary day

4.1 Case 1: Energy community with P1 and P2

The first case study combines the participants P1 and P2, which form a quite reasonable community: P1 is a pure consumer and P2 offers energy excess from the photovoltaic plant during this sunny day. P1 pays 8 €Cent/kWh for the purchased energy (which is less than from the grid) and P2 sells the energy at a higher price than the feed-in tariff. The resulting optimized time history of this simply energy exchange is shown in Fig. 2, where the third subplot shows, that excess energy from P2 is sold to P1. Since no storage unit is built in, the state of charge (SOC) is equal to zero. The problem of this test case is converted into a linear optimization task (eq. 14) and solved with the standard software MATLAB.

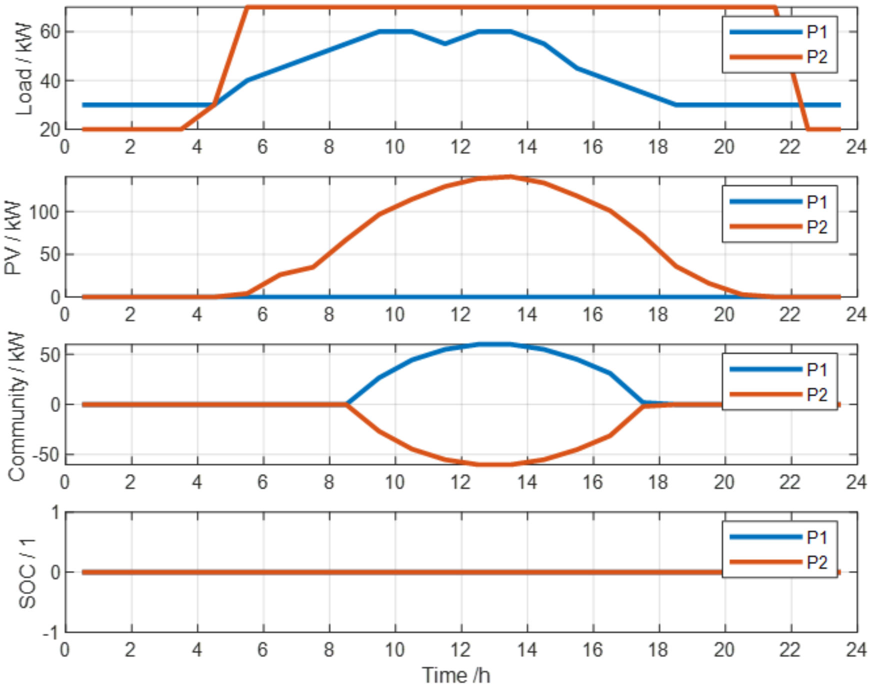

Fig. 2: First: Load profile of P1 and P2; Second: PV production; Third: Exchanged energy in the community, Fourth: State of Charge

4.2 Case 2: Energy community with P1, P2 and P3

The second case study combines the participants P1, P2 and P3, where in contrast to case study 1 with P3 an additional PV-energy provider with an integrated storage unit is part of the community. The necessary additional boundary condition for the charge level of the store of P3 is set to 50% at the beginning and at the end of the exemplary day to yield comparable results. The solution of the optimization procedure (eq. 14) results in a time behaviour according to Fig. 3

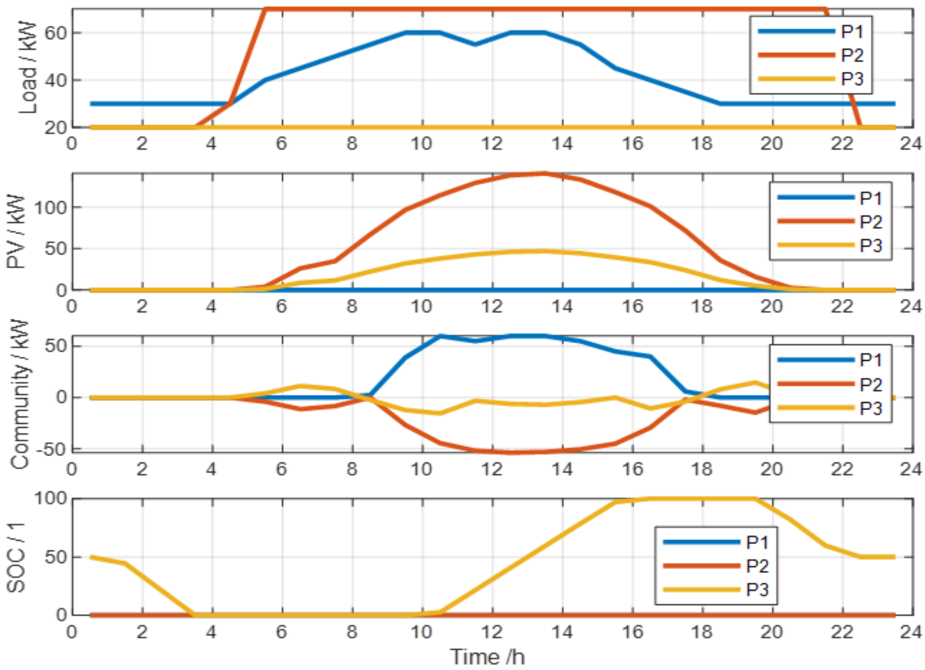

Fig. 3: Results of the optimization of an energy community with P1, P2 and P3

4.3 Case 3: Energy community with P1, P2, P3 and P4

In the third test case, an additional pure consumer (P4) was included. The combination of all four participants yields to an optimized time behaviour of Fig. 4.

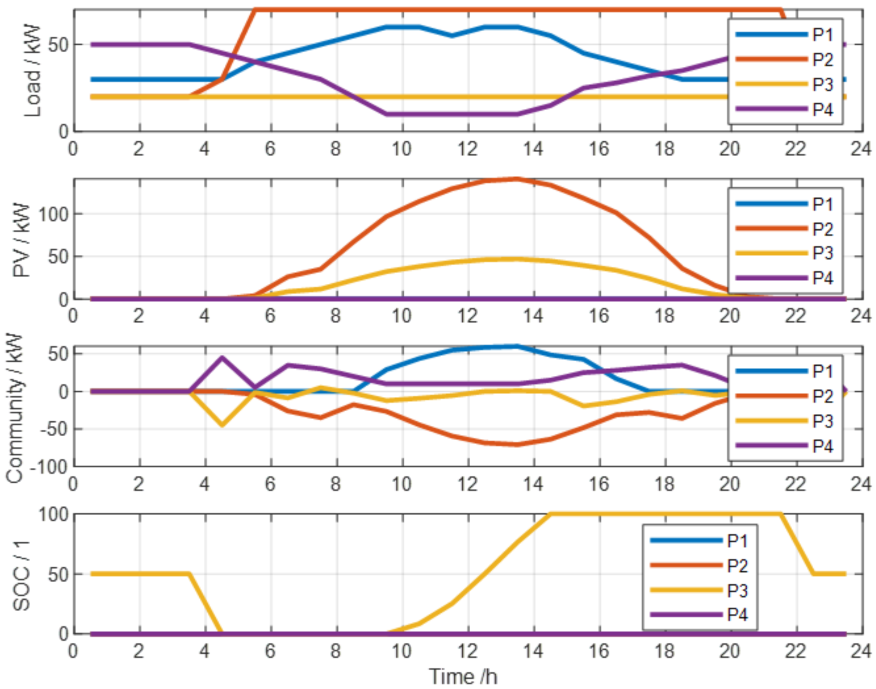

Fig. 4: Results of the optimization of an energy community with four participants

4.4 Analysis of the test cases

The goal of each optimization procedure according to (eq. 14) is the minimization of the sum of costs (also considering revenues for selling energy to the grid or to community partners), such that boundary conditions are satisfied. The reduction of individual costs for each participant is not a primary objective. Tab. 2 shows the resulting costs and the changes of costs (“savings”) for the test cases. It is obvious, that the savings for the community are growing (to be precise: do not decrease) with an increasing number of participants, but the individual savings of the attendees are not balanced. The worst case happens for P3 in the optimized energy community with four participants, where P3 has a disadvantage of 3.78€ for attending the community.

Tab. 2: Results cost for each participant in every test case and the saving in comparison to the individual costs without being part of an energy community

			P1	P2	P3	P4	Sum
Individual cost without energy community		€	103.95	34.15	14.73	118.50	271.33
Test Case 1 P1&P2	Savings through community	€	9.48	7.59	-	-	17.07
Test Case P1&P2&P3	Savings through community	€	10.57	5.41	3.28	-	19.25
Test Case 3 P1&P2&P3&P4	Savings through community	€	10.56	5.41	**-3.78**	27.31	34.99

5. Consequences of the test cases results

Analysing the resulting cost structure of the optimized energy communities offers the situation that the overall costs are minimized. The major drawback of this optimization results is, that not every participant in this community benefit in the same extend. It can happen, that someone even pays more for the energy (P3 in test case 3) as without the community and others benefit above average. Such an unfair distribution of economic savings will not lead to a long-term collaboration within the renewable energy community.

In order to find a fair distribution of the community benefits, two possible solutions are presented.

5.1 Limitation of individual benefits of the participants

To avoid economic drawbacks of participants in the energy community, an additional boundary condition can be integrated into the optimization task: each participant must at least benefit to a specified extend. This lead to an optimization task with an additional inequality boundary conditions (eq. 15). Tab 3 shows the results with this additional “minimum savings” for the test cases 3 of chapter 4.3 with all four participants.

$$\min_{\boldsymbol{x}} \boldsymbol{c}^T \boldsymbol{x} \qquad \text{(eq. 15)}$$

$$\boldsymbol{A}_{eq}\boldsymbol{x} = \boldsymbol{b}_{eq}$$

$$\boldsymbol{A}_{ineq}x \leq \boldsymbol{b}_{ineq}$$

$$\boldsymbol{x}_{lb} \leq \boldsymbol{x} \leq \boldsymbol{x}_{ub}$$

Tab. 3: Consideration of limiting the individual benefits of participants,
***) No solution found for minimum savings of 10€**

		Minimum savings	**P1**	**P2**	**P3**	**P4**	**Sum of savings**
Savings	€	Not considered	10.56	5.41	-3.78	27.31	34.99
Savings	€	≥ 0 (no individual losses)	8.87	2.58	0	22.03	33.49
Savings	€	≥ 3	8.87	3	3	16.48	31.35
Saving*)	€	≥ 10	-	-	-	-	-

5.2 Assessment of the individual contribution to the energy community
The results of chapter 5.1 show, that the limitation of drawbacks or the demand for an minimum benefits reduces the overall savings of the community. In order to gain the maximum benefits, an operation without limitations (like in test case 3) can be carried out and then the community savings are distributed among the participants. This leads to the problem of determining the importance of each participants with respect to the community. Should everyone get the same share of the savings?

To assess the contribution of each participant, the following procedure is used:

1) Run the optimization without limiting the benefits (like test case 3 in chapter 4.3)

2) Exclude single partners from the community and calculate the resulting optimal costs of this reduced community.

The achieved savings (Tab. 4) can be used as an indicator for the importance of each participant. For the test case 3 from chapter 4.3 it turns out, that excluding P2 reduces the savings from 34.99€ to 10.04€ - P2 is the most important participant on this day in the considered renewable energy community.

Tab. 4: Assessment of the individual contribution to the energy community

	Savings	**Resulting Assessment**
Community without **P1**	19.04 €	
Community without **P2**	10.04 €	P2 is the MSP – most significant participant
Community without **P3**	29.79 €	P3 is the LSP – least significant participant
Community without **P4**	19.25 €	
Community with **all participants**	34.99 €	

6. Acknowledgments

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7. References

EE-RL 2018: Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

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