Optimal operation and fair profit allocation in community microgrids

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ABSTRACT

This work fits in the context of community migrogrids, where entities of a community can exchange energy and services among them without going through the usual channels of the public grid. We propose and analyze solutions methods to operate a community and to share the profit gained by the community between the entities forming the community, especially when the cost and revenues originate from different streams.

INTRODUCTION

This work fits in the context of energy communities, where entities of a community can exchange energy and services among them [1] without going through the usual channels of the public grid. It is practically motivated by the need arising from the pilot project MeryGrid [2], in which several companies and a storage system form a community microgrid. By community microgrid, we mean a special case of energy community that is a geographically limited power system made of several legal entities, each entity being a single-user microgrid with its own generation, consumption, storage, and level of flexibility. In this case, an operator manages the community in order to reach the highest economic efficiency by optimizing the energy flows and the interactions within the community and with the public grid, while satisfying the constraints set by the entities and constraints of the public grid (Figure 1). Leaving aside the (re)sizing and long term contracting questions, the operation of a microgrid can be divided in several phases, from day-ahead bidding to settlement. Although all these decision stages should be designed in a coherent way, this paper considers only the operational planning stage that optimizes decisions one day ahead with periods of 15 minutes given some prices, consumption and generation forecasts. The main focus of this paper is how to share the profit gained by the community between the entities forming the community, especially when the cost and revenues originate from different streams: an entity generates revenues from energy sales, either to the grid or to the community, and from ancillary services to the grid; energy purchases from the grid and from the community as well as peak penalties constitute the costs of an entity. The research questions addressed are, assuming we can solve the operational planning problem of an entity to optimality *(i)* how should we formulate the operational planning problem of the community and the mechanism that shares the profit gained by the community between the entities and the operator? *(ii)* How fair is the mechanism and how does it incentivize the entities to join or stay in a community?

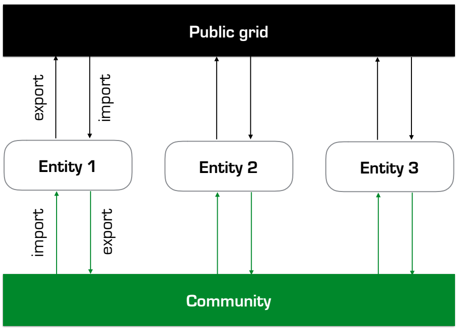


Figure 1: Community model

A way to price electricity and heat in local communities was proposed in [3], but only focused on the energy commodity. A fair economic settlement scheme for participants in a microgrid is proposed in [4], which considers the sizing problem but is limited to the electricity commodity. In a multi-TSO coordination context, [5] introduces a methodology and reviews some fairness notions that are of interest and are adapted to our problem in this paper. This topic is becoming of foremost importance with the rise of energy communities [6].

Starting from the operational planning problem of a single entity, we formulate the community operational planning problem of the operator. Then we propose and discuss three schemes to allocate the profit gained by this community-level optimization. Fairness is a subjective notion, but some indicators allow us to compare profit sharing mechanisms based on the solutions they lead to on a specific microgrid. Illustrative results are reported for a case inspired by the MeryGrid project [2].

MATHEMATICAL MODEL

Entities are indexed by the letter u and grouped in the set $\mathscr{U}$. The superscript SU denotes a quantity relative to an entity (a single-user) and the superscript MU denotes a quantity relative to the community (multi-user). The devices of an entity are modeled as follows. The devices consuming electricity fall in three categories: *inflexible demand* must be satisfied, hence can be seen as demand at maximum price; *flexible demand* must be satisfied as well but is specified as an amount of energy to be dispatched over the planning horizon; *sheddable demand* is not at maximum price and can be partially shed. On the generation side, devices fall in two categories: *steerable generation*, e.g. diesel generator, with a known fuel cost, rated power and efficiency, and *non-steerable generation* which is zero marginal cost but causes a loss of revenue if curtailed. Finally, *storage devices* are characterized by a rated power, energy capacity, charge and discharge efficiencies. The electrical network connecting the entities is not modelled. This paper does not make assumptions on the position of the entities within the public grid, but assumes a regulatory mechanism is available to allow metering flows that stay within the community and flows that are exchanged with the public grid.

The mathematical models we discuss next are mixed integer linear problems, but we do not totally detail them here for concision reasons.

Single-user optimization

Problem (1)–(3) is a condensed version of the problem a single-user not having access to the community could solve to plan its operations and maximize its profit over a time horizon of T time steps.

$$J^{\star,\mathrm{SU}} = \max_{a_u,x_u} J_u^{\mathrm{SU}}(a_u,x_u) \tag{1}$$

$$\text{s.t. } g_u(a_u,x_u) \leq 0 \tag{2}$$

$$h_u(a_u,x_u) \leq 0 \tag{3}$$

The decision variables of the problem are divided in two categories: the vector a_u collects the actions taken over the planning horizon, for instance the charge or discharge set points of a battery, and the vector x_u represents the state evolution of the system, for instance the state of charge of a battery. The objective (1) is to minimize the cost of electricity purchased from the external grid, of steerable generation, of curtailment, of shedding, and of the peak penalty, and to maximize incomes from sales of energy and services to the external grid. Constraints are divided in two sets: (2) collects all the constraints related to the devices of an entity, such as constraints defining the battery state of charge evolution and the load flexibility models, while (3) collects the energy balance constraints, the reserve levels definition, and the peak model, i.e. constraints related to interactions between the public grid and the entity.

Community optimization

We now turn to the problem of managing a community (cf. Figure 1). We optimize the energy flows and costs for each entity, but the operational plan is established for the community globally, satisfying the local constraints of all the entities. Each entity can now either exchange with the public grid or with the community, which is designed to offer several advantage to the community members:

- exchanges within the community are executed at a price that is more attractive than the public grid price;
- reserve is pooled over entities and is exchanged with the grid at the community level;
- the peak penalty is reduced, since the peak that is penalized is the peak of the community and not the entity peaks taken separately.

A fee γ_c applies on intra-community exchanges to remunerate the microgrid operator, Similarly, a fee γ_b on battery inflows and outflows remunerates the battery owners.

We denote by a'_u and x'_u the vectors of state and actions variables that are augmented to account for energy exchanges of an entity with the community, and by a_c the vector of community level decision variables. Problem (4)–(7) summarizes the community operational planning problem.

$$J^{\star,\mathrm{MU}} = \max_{a',x',a_c} J^{\mathrm{MU}}(a',a_c,x') \tag{4}$$

$$\text{s.t. } g_u(a'_u,x'_u) \qquad \forall u \in \mathscr{U} \tag{5}$$

$$h'_u(a'_u,x'_u) \leq 0 \qquad \forall u \in \mathscr{U} \tag{6}$$

$$h(a',a_c,x') \leq 0 \tag{7}$$

where $a' = (a'_1,\dots,a'_{|\mathscr{U}|})$ and $x' = (x'_1,\dots,x'_{|\mathscr{U}|})$ gather the actions and states of all the entities, respectively, (6) replaces (3) to account for the new exchange possibility of an entity within the community, and (7) constrains community level decisions.

Solving this optimization problem implicitly defines exchanges between entities of the community, but does not explicitly determine how the profit increase, defined as

$$P_{MU} = J^{\star,\mathrm{MU}} - \sum_{u\in\mathscr{U}} J_u^{\star,\mathrm{SU}} \geq 0,$$

is shared between the entities. Note that $P_MU \geq 0$ holds since γ_c and γ_b are known a priori, and in the worst case all entities behave as if they were alone without exchanges within the community. We thus now need to find a way to share P_{MU} among the entities, and to do this in a fair and transparent manner.

Notions of fairness and fairness indicators

Before entering in the details of the solution methods we propose, we first discuss the notions of fairness that are used as design principles, and can to some extent provide indicators assess the fairness of a profit sharing design [5].

1. **Freedom from envy** is considered as a necessary condition for fairness. It states, in summary, that all entities are treated equally, i.e. without using any entity specific information. In all approaches below, this is

treated by design since the same methodology is applied to everyone and we try as much as possible to lift indeterminacies that may lead to arbitrary decisions that could bias the results in favor of some entities.

2. **Efficiency** states that solutions obtained should be close to optimal, else an entity could claim a better solution exists and find the selected solution unfair.
3. **Accountability** states that more effort of an entity should result in more gain for that entity. This can be assessed for instance through a sensitivity analysis by loosening (resp. tightening) the constraints of an entity and assessing how his profit share increases (resp. decreases).
4. **Altruism**, in our interpretation, states that a member should have no interest in degrading the profit of another member (e.g. to increase his profit directly) if it changes nothing to his position. This notion is difficult to assess in practice but we try to apply some principles to tend towards an altruist design.

Method 1: Ex post profit sharing

A first idea is a two-stage approach that first solves (4)–(7), then determines an invoice per entity that shares P_{MU} and imposes no entity loses with respect to its lonely position. This is doable but has a main disadvantage: since the rule used to share the profit is not known by the optimization problem, the profit repartition is dependent on the particular solution found in the first stage. As there can be many equivalent solutions for the first stage, this can lead to unpredictable invoices that are unlikely to be accepted by community members.

Method 2: A priori profit sharing

The second method we propose merges the two stages of the first idea, and requires the definition of an a priori profit repartition rule. Table 1 lists the principles we have used. The first principle guarantees that invoices can easily be determined for each entity. The second principle, coupled with the first, guarantees that any contribution of an entity to any cost or revenue stream is accounted for (accountability). The third principle guarantees that an optimum is reachable, and in a reasonable amount of time (efficiency).

Table 1: A priori profit sharing principles.

1. The objective function is separable by entity
$$J^{\mathrm{MU}}(\cdot) = \sum_u J_u^{\mathrm{MU}}(\cdot).$$
2. Each cost or revenue stream is quantified.
3. The problem remains linear, or at least convex.
4. No entity suffers a profit degradation with respect to its selfish profit: $J_u^{\mathrm{MU}} \geq J_u^{\star,\mathrm{SU}}$.

The last principle cannot cause a decrease of P_{MU} with respect to the solution of (4)–(7) as we allow profit transfer between entities.

The algorithm proceeds as follows. Solve successively

1. problem (1)–(3) for each entity separately;
2. problem (4)–(7) for all entities, imposing also that each entity does not decrease the profit obtained in phase 1.

It is hard to determine the ”altruism level” of this method. We rather compare its results to the third method described below, which casts an alternative look at the problem.

Method 3: Equilibrium

The third method is inspired by [5] and attempts to get a solution that is as close as possible to an ”utopian repartition”, where each entity would make a profit as if the community were operated with the objective to maximize its selfish profit:

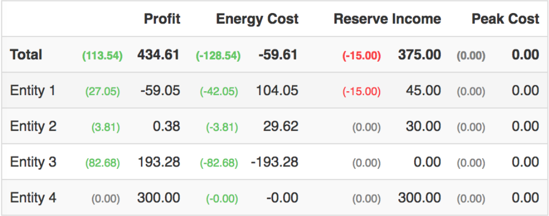
1. solve problem (4)–(7) for each entity, but with only the objective for the member considered. Hence replace (4) by $J_u^{\mathrm{MU}}(\cdot)$. This yields $J_u^{\star,\mathrm{utopian}}$, $\forall u \in \mathscr{U}$.
2. solve for a global equilibrium point, i.e. a solution that is as close as possible to the ”utopian” goal of phase 1. We replace (4) by
$$\min \sum_{u \in \mathscr{U}} w_u \left(J_u^{\mathrm{MU}} - J_u^{\star,\mathrm{utopian}} \right)^2 ,$$
where w_u scales entities positions to account for large entity size differences.

Phase 1 yields extreme solutions where the total profit may be heavily degraded in favor of one entity. Phase 2 attempts to find a solution that mitigates these extreme solutions. Comparing results of methods 2 and 3 provide some insight on their performance with respect to the altruism notion.

Illustrative results

We provide some illustrative results on a case inspired by the MeryGrid project [2], with four entities, among which the storage system. We have set $\gamma_c = \gamma_b = 0$ in this illustrative experiment. Similarly, we have considered no peak penalty. Other values will be studied during the project. Method 2 is implemented as follows. A community price is determined for each time step. The part of the profit of an entity related to energy exchanges is thus function of the product of this price and of the quantity exchanged, which yields non-linear terms. To linearize this, we introduce discrete price levels for community exchanges and use a reformulation similar to [4]. Only symmetrical reserve is valorized on the market. Reserve of entities can be

Table 2: Total profit and profit by entity with revenue stacking for method 2 vs. local optimization (i.e. phase 1 of method 2) indicated by green and red deltas.



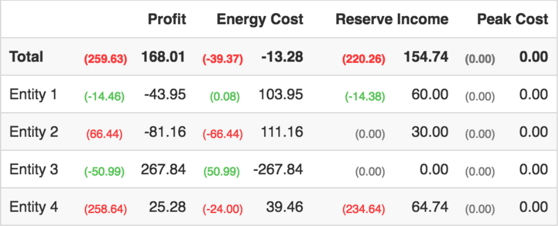
	Profit	Energy Cost	Reserve Income	Peak Cost
Total	(113.54) **434.61**	(-128.54) **-59.61**	(-15.00) **375.00**	(0.00) **0.00**
Entity 1	(27.05) -59.05	(-42.05) 104.05	(-15.00) 45.00	(0.00) 0.00
Entity 2	(3.81) 0.38	(-3.81) 29.62	(0.00) 30.00	(0.00) 0.00
Entity 3	(82.68) 193.28	(-82.68) -193.28	(0.00) 0.00	(0.00) 0.00
Entity 4	(0.00) 300.00	(-0.00) -0.00	(0.00) 300.00	(0.00) 0.00

Table 3: Total profit and profit by entity with revenue stacking for method 3, phase 2.

	Profit	Energy Cost	Reserve Income	Peak Cost
Total	**427.65**	**-52.65**	**375.00**	**0.00**
Entity 1	-58.41	104.03	45.62	0.00
Entity 2	-14.71	44.71	30.00	0.00
Entity 3	216.85	-216.85	0.00	0.00
Entity 4	283.92	15.46	299.38	0.00

combined to form symmetrical reserve, and any reserve is valorized in the community (accountability). The peak is defined at the community level, but ”virtual” entity peaks are computed to penalize each entity independently. However, the peak penalty is set to zero in this illustrative experiment. Table 2 summarizes results of method 2. The extra profit generated by the community is 113.54€. This thus leaves some room for increasing γ_c. In this case, entities gain some profit by exchanging energy through the community. On the other hand the storage system can only make profit by selling reserve to the market since $\gamma_b = 0$. It is thus not used for the community, and increasing γ_b would probably result in a profit increase for the community. Method 3 uses the same model as method 2. We have set $w_u = 1$ for all entities. Phase 1 is solved in two steps: first solve for an entity, then fix the solution for that entity, restore the global objective, and resolve. This tends to maintain an altruist mechanism. Table 3 shows the results of method 3, which achieves a total profit a little smaller than method 2. Table 4 illustrates phase 1 of method 3 for a particular entity.

Table 4: Total profit and profit by entity with revenue stacking for phase 1 of method 3, for entity 3 (green and red deltas are differences with respect to corresponding values in Table 3)



	Profit	Energy Cost	Reserve Income	Peak Cost
Total	(259.63) **168.01**	(-39.37) **-13.28**	(220.26) **154.74**	(0.00) **0.00**
Entity 1	(-14.46) -43.95	(0.08) 103.95	(-14.38) 60.00	(0.00) 0.00
Entity 2	(66.44) -81.16	(-66.44) 111.16	(0.00) 30.00	(0.00) 0.00
Entity 3	(-50.99) 267.84	(50.99) -267.84	(0.00) 0.00	(0.00) 0.00
Entity 4	(258.64) 25.28	(-24.00) 39.46	(234.64) 64.74	(0.00) 0.00

CONCLUSION AND FUTURE WORK

We have proposed ways to operate a community microgrid exploiting a complete set of revenue streams. Obviously, implementing this community model comes with technical challenges, that are currently under study in the MeryGrid project, and implies adaptations to the current regulatory framework. For instance (i) the market face meter of each entity has to be corrected to account for the flows that stay within the community, (ii) some components of the invoice may now be paid at the community level (e.g. the peak penalty). This work can be extended and complemented in several directions. For instance, it is certainly worth analyzing settlement principles to reconcile forecasting errors and other entity related behaviors.

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