Energy Communities and Peer-to-peer Electricity Markets

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1 Introduction

The goal of this assignment is to investigate novel concepts related to electricity markets for energy communities (also referred to as energy collectives), going towards a peer-to-peer setup. This assignment starts from some basic considerations about agents involved and their costs functions, as well as basics of market clearing to eventually go towards alternative formulation and implementation for these novel types of electricity markets.

In practice, the objectives to be achieved at the end of the assignment are to be able to:

- Understand the concepts of centralized pool markets, community markets and peer-to-peer markets
- Formulate the clearing and negotiation mechanisms for such markets in the form of optimization problems
- Implement those and solve them with “classical” solvers and with distributed optimization approaches

- Perform simulations for a range of conditions to appraise the impact of consumer preferences on market outcomes

For those highly motivated, an extension with a full peer-to-peer electricity market can be discussed.

2 Test case for the assignment

We use here a simplified version of the test case described in [1], where agents are placed on an IEEE 14-bus system. In the present case, the network is not considered in practice though, in order to lighten the implementation aspects and to focus on the market aspects instead. A summary of the agents and of their characteristics is given in Table 1. Each of the agents is either producer (P) or consumer (C) with some renewable power generation. They may hence be seen as prosumers. Their minimum and maximum consumption levels are given by $\mathrm{P}_{\mathrm{max}}$ and $\mathrm{P}_{\mathrm{min}}$. The reason for that convention is that production is seen as positive and consumption as negative. The level of power generation for these prosumers is given in the column $\mathrm{P}_{\mathrm{ren}}$, say, from solar panels. Finally, the various agents are seen as having quadratic cost function. Therefore, for participation in the market one is to consider their marginal cost functions which are assumed linear, i.e., $c(x) = ax + b$, with the a and b parameters given in the last 2 columns of the table.

While those agents are those taking part of the community, we consider a single connection to the rest of the world, in the form of an external agent (e.g., a retailer) that provide a service to that community. This agent is willing to buy any extra generated energy at a price of 40 €/MWh, while selling to the community any missing unit of energy at a price of 70 €/MWh.

3 Part 1: Formulate and implement a centralized pool-based market

Conventional wholesale markets take today the form of pool-based markets, for which each market participants make offers for production and consumption, which are cleared in a centralized manner based on a social welfare maximization principle. As a reference case prior to further development, we aim here to see what would be the outcome of a centralized pool-based

Table 1: Description of the test case for implementing and simulating pool-based, community-based and peer-to-peer electricity markets.

Agent	Type	Energy	P_{min} [MW]	P_{max} [MWh]	P_{ren} [MWh]	a (€/MWh^2)	b (€/MWh)
1	C	-	-21.7	0	0	4	130
2	C	-	-94.2	0	0	1	120
3	C	-	-47.8	0	0	2	135
4	C	-	-7.6	0	14.9	10	125
5	C	-	-11.2	0	9	8	140
6	C	-	-29.5	0	10	4	145
7	C	-	-9	0	18.5	9	150
8	C	-	-3.5	0	2	15	135
9	C	-	-6.1	0	7	18	140
10	C	-	-13.5	0	5	7	125
11	C	-	-14.9	0	5	6	120
12	P	Gas	0	20	0	7	25
13	P	Coal	0	50	0	2	10
14	P	Gas	0	10	0	8	20

market clearing if that was the system in use for our community setup. If needing to go through basics of wholesale electricity markets, one is referred to [3].

To formulate and implement this centralized pool-based market clearing, one needs to:

1. Write the cost functions of the various players, both consumers and producers. We will assume that all agents will readily offer based on their marginal cost functions in the market

2. Consequently write the objective function of the optimization problem that will be used for clearing. [*Hint*: social welfare in that frame is defined as the difference between consumer payments and producer costs]

3. Formulate the market equilibrium constraint as an equality constraint. [*Hint*: at all time, consumption is to be equal to production]

4. Translate the potential range of production and consumption of the various agents into a set of inequality constraints.

5. Obtain the final quadratic program by associating the objective function with all equality and inequality constraints.

6. Solve with a QP solver in e.g. MOSEK, Python, Matlab, R, etc.

7. Obtain the schedule of the various agents as primal solution variables, as well as the market price from the dual variable associated to the balance equation (equality constraint)

8. Under a uniform pricing scheme, deduce payments and revenues of all agents. [*Hint*: any unit of energy consumed is bought at the market price, any unit of energy supplied is paid at the market price]

4 Part 2: Formulate and implement a community-based market

Recently various proposals have been made to rethink electricity markets. One of those has gained momentum as supported at the EU level by the Clean Energy package and through novel regulation in e.g. France, based on the concept of collective self-consumption. The basic idea is that as a community one may have both production and consumption means, while the rest of the system only sees this community as a single agent. In practice, that also means that this community has freedom to decide upon how to exchange and price energy within the community, re-distribute grid costs, etc. The work to be done in this part is based on [4] which we advise to read carefully. The resulting community-based market is to rely on the same test case as in the above.

To formulate and implement these community-based markets with various alternative flavours, one needs to:

1. Rethink the objective function of the centralized pool-based market so as to account for all cost functions of the community agents involved, by augmenting it with a function that represents the perceived cost (/revenue) from interaction with the outside world. [*Hint*: The general form of that problem is given in Section II.A. of [4]. Assume market-based optimization as given in Eq. (4) with $\lambda_{DA} = 40$ and $\tau = 30$.]

2. Instead of using the single balance equation of the pool-based case, formulate a set of equality constraints defining imports (1d), exports (1e), community balance (1c) and agents' balance (1b) as in Problem (1) of [4]

3. Translate the potential range of production and consumption of the various agents into a set of inequality constraints, similarly to the case of the pool-based market

4. Obtain the resulting quadratic program by associating the objective functions with all equality and inequality constraints.

5. Solve it with a QP solver in e.g. MOSEK, Python, Matlab, R, etc.

6. Obtain the schedule of the various agents as primal solution variables, as well as the market price from the dual variable associated to the balance equation

7. Deduce payments and revenues of all agents. [*Hint*: any unit of energy consumed is bought at the community market price, any unit of energy supplied is paid at the community market price]

8. Compare the community-based with the pool-based market outcomes. What happens if agent 7 has $P_{\text{ren}} = 0$? Compare the new market outcomes.

5 Part 3: Solve a community-based markets with distributed optimization

Eventually, if going towards more decentralized views and peer-to-peer electricity markets, one expect that market clearing should not be solved in a centralized manner. This means that each and every agent is to solve his/her own optimization problem, under some form of coordination. In the case of energy collectives, this may take the form of a community manager, consisting of a fusion node for all agents of the community. While a wealth of distributed optimization techniques could be considered, emphasis is placed here on the Alternating Direction Method of Multipliers (ADMM), which has been widely used over the last decade and which naturally fits our problem setup, as done in [4].

To solve a community-based market in a distributed optimization framework, one needs to:

1. Read carefully Section IV of [4]. [*Hint*: consider weighting the community power balance constraint by $\frac{1}{n}$, as in Section IV.B of [4], and a fixed penalty parameter $\rho \in [1, 50]$]

2. Formulate the augmented Lagrangian of Eq. (15) as in [4] for the market-based and community-based cases

3. Deduce the x-update, z-update and y-update for the ADMM solution approach for the two cases

4. Starting from a feasible point (i.e., respecting the equality and inequality constraints), iterate over k to get the ADMM solution approach to converge

5. Verify that the results obtained are consistent with those obtained in Part 2.

6 Part 4: Introduce common and individual preferences

When part of an energy collective, members can jointly agree on how to value social contracts within the community. These social contracts can relate to common agreements on how to interface with the outside world as well as how to distribute costs and revenues to the community members. Here we will consider that the community wants to reduce imported energy from the outside world, in favour of local match of generation and consumption. This translates as an extra cost on top of the import price τ_{aut}, that the community is willing to pay to increase autonomy.

1. Consider that agent 7 has $P_{\text{ren}} = 0$ and that $\gamma_{\text{imp}} = \lambda_{DA} + \tau + \tau_{\text{aut}}$ as given by Eq. (6) of [4]. Varying τ_{aut}, investigate how preferences can impact market outcomes.

2. *Optional: express preferences at individual level.*
   Consider adding to the objective function of each agent the function $h_j(q_j, \alpha_j, \beta_j)$ as in Section II.B of [4]. What kind of preferences could be represented by means of h? What if these preferences are heterogeneous among community members?

7 Lessons Learned – Reflection

While going through your readings, problem formulation, as well as implementation, you must have encountered a number of issues. Please describe these issues and explain how you manage to solve them eventually. As one should not only focus on issues, think also of all the new concepts and methods learned through this assignment, discuss them, and explain how those may be relevant for your own research/work.

References

[1] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, E. Sorin (2018) Peer-to-peer and community-based markets: A comprehensive review. *Under review*, available at: `http://pierrepinson.com/docs/Sousaetal2018.pdf`

[2] T. Sousa, T. Soares, P. Pinson, F. Moret, T. Baroche, E. Sorin (2018) The P2P-IEEE 14-bus system. Available at zenodo.org: `doi:10.5281/zenodo.1220935`

[3] P. Pinson (2018). Renewables in Electricity Markets - Lecture 1: Day-ahead Markets. *Online course material*, Available at: `pierrepinson.com/31761/Lectures/31761-Lecture1.pdf`

[4] F. Moret, P. Pinson (2018). Energy collectives: a community and fairness based approach to future electricity markets. *IEEE Transactions on Power Systems*, available online and at: `pierrepinson.com/docs/MoretPinson2018.pdf`