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Dynamic Participation in Peer-to-Peer Electricity Trading Mechanisms in Local Communities

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Motivation and Scope

• Photovoltaic (PV) systems: Decentralized electricity production and *prosumers*
• From individual self-consumption to collective self-consumption to active participants
• Trading and sharing of PV within a certain framework: Energy communities and Peer-to-Peer Trading
• Clean Energy Package (CEP) legal instruments:
  • Member states to enable the entrance of active participants into the market
  • Definition of peer-to-peer trading
• Framework:
  • Voluntary participation and consideration of individual willingness-to-pay
  • PV sharing beyond the meter
  • Low entry barriers: No closed systems, but part of the distribution network
**Motivation and Scope**

**Scope:**
- Optimizing energy communities over several years:
  - Considering phase-in/phase-out of prosumers
  - Assuming that local energy markets are more established in the future
  - Operating model of existing prosumers who want to participate in a local energy community

**About the model:**
- Linear optimization model FRESH:COM [1] maximizing the social welfare of a **local energy community**
- Allocation mechanism: Peer-to-peer trading under the consideration of each prosumer's *individual willingness-to-pay*
- Members: Private households and SMEs
  - Photovoltaic (PV) and Battery Energy Storage Systems (BESS)

**Contribution:**
- Extension of FRESH:COM to optimize *dynamic participation* in peer-to-peer trading communities

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Modeling Approach

- **Social welfare:**
  \[
  SW = \sum_{t \in T, i \in I} p_t^{G_{out}} q_{i,t}^{G_{out}} - \sum_{t \in T, i \in I} p_t^{G_{in}} q_{i,t}^{G_{in}} + \sum_{t \in T, j \in J} w t p_{i,j,t} q_{i,j,t}^{\text{share}}.
  \]

- **Willingness-to-pay:**
  \[
  w t p_{i,j,t} = p_t^{G_{in}} + w_j (1 - d_{i,j}) \cdot c_t.
  \]

- **“Benchmarks“:**
  \[
  \Delta costs_i = \frac{costs_i - costs_{i,old}}{|costs_{i,old}|}
  \]
  \[
  \Delta emissions_i = \frac{emissions_i - emissions_{i,old}}{emissions_{i,old}}
  \]
Modeling Approach – Bi-level problem

- Upper level problem ("leader"):  
  - Selecting the optimal electricity demand and PV capacity of new prosumers to fulfill certain requirements set by the original community members  
  - Minimizing the cost-emission function CE:

\[
CE = \sum_{i \in L_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i
\]

- \( \Delta costs_i \) and \( \Delta emissions_i \) are the changes of annual costs and emissions of prosumer \( i \), respectively.  
- \( \alpha_i \in [0,1] \) is individual weighting factor of prosumer \( i \)  
- \( b_i \in (0,1) \) are binary decision variables

\[
\min_{\{load_i, PV_i, b_i, Q_i, t\}} \sum_{i \in L_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i
\]

subject to:

\[
\begin{align*}
    b_i \cdot load_i^{\min} &\leq load_i \leq b_i \cdot load_i^{\max} \quad \forall i \in I_{new} \\
    b_i \cdot PV_i^{\min} &\leq PV_i \leq b_i \cdot PV_i^{\max} \quad \forall i \in I_{new} \\
    \sum_{i \in L_{new}} b_i &= n
\end{align*}
\]
Modeling Approach – Bi-level problem

• Lower level problem ("follower"):  
  • Maximizing the social welfare of the community, given the new prosumers' parameters selected in the upper problem

• Two parts in social welfare SW:  
  • Maximizes the overall self-consumption of the community and  
  • Optimally distributes PV generation between the prosumers (peer-to-peer trading)

• Constraints:  
  • Covering electricity demand and PV generation  
  • Battery storage operation
How is the bi-level problem solved?

- Transformation of the lower level problem with its corresponding KKT conditions ("Karush-Kuhn-Tucker"):  
- Mathematical program with equilibrium constraints (MPEC)  
- The equilibrium problem of the follower is parametrized by the leader’s decisions variables  
- Formulation of a set of complementarity conditions  
- Big-M transformation
Modeling Approach – Data and assumptions

Case study:

- Model implemented in **Python** using **Pyomo**
- Small community set-up consisting of 6 prosumer + new prosumer
- Electricity demand: Modular households or houses from **Load Profile Generator** [1]
- PV generation: PV modules with different orientations (location: Vienna) from **renewables.ninja** [2]

- Annual hourly data is clustered in representative time periods using Python module **sklearn.cluster.Kmeans** [3]
- New prosumer (household and business):
  - Standardized load profile (H0 for households, G0 for business)
  - $P_{PV}^{min} = 0$, $P_{PV}^{max} = 5 \text{ kW}_{peak}$
  - $load^{min} = 2000 \text{ kWh}_{yr}$, $load^{max} = 8000 \text{ kWh}_{yr}$
  - $w_{new} = 50 \text{ EUR/tCO}_2$

Results – New prosumer household

All prosumers want to minimize their individual emissions:
\[ \alpha_i = 0, \forall i \in I_{old} \]

Results:

- \( PV = 5 \, kW_{peak} \)
- \( load = 2000 \, \frac{kWh}{yr} \)
- The new prosumer is a competition to certain prosumers due to the high installed PV capacity
- Costs increase for some prosumers
- Emissions decrease

Sankey diagram of electricity demand
All prosumers want to minimize their individual costs:
\[ \alpha_i = 1, \forall i \in I_{old} \]

Results:

- \( PV = 0 \ kW_{peak} \)
- \( load = 8000 \ \frac{kWh}{yr} \)
- Opportunity to sell to the new prosumer (high demand, no PV installed) and lower annual costs

Sankey diagram of PV generation
Results – Household vs. business

Minimizing individual emissions

✓ H0 with $PV = 5 \ kW_{peak}, \ load = 2000 \ \frac{kWh}{yr}$

Minimizing individual costs

✓ G0 with $PV = 0 \ kW_{peak}, \ load = 8000 \ \frac{kWh}{yr}$
Sensitivity Analysis

Influence of the willingness-to-pay:
• \( w_i = 0 \) EUR/tCO\(_2\) or \( w_i = 100 \) EUR/tCO\(_2\)

<table>
<thead>
<tr>
<th></th>
<th>H0 (( w_i = 0 ))</th>
<th>H0 (( w_i = 100 ))</th>
<th>H0 (( w_i = 0 ))</th>
<th>G0 (( w_i = 100 ))</th>
<th>G0 (( w_i = 0 ))</th>
<th>H0 (( w_i = 100 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ind. emissions</td>
<td></td>
<td></td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>–</td>
</tr>
<tr>
<td>ind. costs</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
<td>–</td>
<td>✓</td>
</tr>
</tbody>
</table>

Fairness indicators:
• Quality of service:

\[
QoS = \frac{\left(\sum_{j \in \mathcal{I}} q_j\right)^2}{n \cdot \sum_{j \in \mathcal{I}} q_j^3}
\]

\[
q_j = \sum_{t \in \mathcal{T}, \, i \neq j \in \mathcal{I}} \left(q_{j, i, t}^{\text{share}} + q_{j, i, t}^{\text{share}}\right)
\]

<table>
<thead>
<tr>
<th></th>
<th>QoS (H0 with ( w_i = 50 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>old community</td>
<td>0.674</td>
</tr>
<tr>
<td>ind. emissions</td>
<td>0.657</td>
</tr>
<tr>
<td>ind. costs</td>
<td>0.815</td>
</tr>
</tbody>
</table>
Conclusions

Findings:
• The model is able to choose between potential prosumer
• Balancing the needs of environmental- and profit-oriented members
• Aiming for a diverse set-up of actors
• Ultimately, the energy community has to be able to attract suitable potential new members to guarantee its performance over the years
• Larger communities are not as “sensitive” to changes as smaller communities → certain duration of contract essential

Future outlook:
• Analysis of different settlement patterns
• Analysis of the effects on the DSO and the community manager
Thank you for your attention!

GitHub

https://github.com/tperger/FRESH-COM

open ENergy TRansition ANalyses for a low-Carbon Economy

https://openentrance.eu/

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