IEWT 2021

Das Energiesystem nach Corona: Irreversible Strukturänderungen - Wie?

8. – 10. September 2021 | Karlsplatz & Online | TU Wien

IEWT 2021

Das Energiesystem nach Corona: Irreversible Strukturänderungen - Wie?

12. Internationale Energiewirtschaftstagung an der TU Wien

8. – 10. September 2021
Wien, Österreich

Tagungsort: TU Wien & Virtuell

TU Wien Logo und IEWT Logo
Berücksichtigung verschiedener Siedlungsmuster in der Entwicklung von lokalen Energiegemeinschaften mit Peer-to-Peer Handel

Theresia Perger
TU Wien
Energy Economics Group (EEG)
IEWT Vienna 2021, 08.09.-10.09.2021
perger@eeg.tuwien.ac.at

This project has received funding from the European Unions Horizon 2020 research and innovation program under grant agreement No. 835896
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
  - Low entry barriers: No closed systems, but part of the distribution network
  - Dynamic participation
- **Research question:**
  - Dynamic participation in peer-to-peer trading communities depending on different settlement patterns
Motivation and Scope

**Scope:**
- Optimizing energy communities within different settlement patterns 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 within different settlement patterns

Modeling Approach

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

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

- „Benchmarks“:
  \[ \Delta costs_i = costs_i - costs_{i,old}, \]
  \[ \Delta emissions_i = emissions_i - emissions_{i,old}. \]
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:
    \[ CE = \sum_{i \in I_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i \]
  • \( \Delta costs_i \) 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

\[
\begin{align*}
\min & \quad \left\{ \text{load}_i, PV_i, b_i, Q_i, t \right\} \\
\text{subject to:} & \\
& b_i \cdot \text{load}_i^{\min} \leq \text{load}_i \leq b_i \cdot \text{load}_i^{\max} \quad \forall i \in I_{new} \\
& b_i \cdot PV_i^{\min} \leq PV_i \leq b_i \cdot PV_i^{\max} \quad \forall i \in I_{new} \\
& \sum_{i \in I_{new}} b_i = n
\end{align*}
\]
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

\[
\begin{align*}
\max_{Q_{i,t}} \sum_{t \in T} \sum_{i \in I} p_{i}^{\text{out}} q_{i,t}^{\text{out}} - \sum_{t \in T} \sum_{i \in I} p_{i}^{\text{in}} q_{i,t}^{\text{in}} + \sum_{t \in T} \sum_{i \in I} w_{i} q_{i,t}^{\text{share}} \\
\text{subject to:}
\end{align*}
\]

- \[q_{i,t}^{\text{in}} + p_{i}^{\text{out}} + \sum_{j \in I} q_{j,t}^{\text{share}} - q_{i,t}^{\text{load}} = 0 \quad (\lambda_{i,t}^{\text{load}}) \quad \forall i \in I_{\text{odd}}, t\]
- \[q_{i,t}^{\text{out}} + q_{i,t}^{\text{in}} + \sum_{j \in I} q_{j,t}^{\text{share}} - q_{i,t}^{PV} = 0 \quad (\lambda_{i,t}^{PV}) \quad \forall i \in I_{\text{odd}}, t\]
- \[q_{i,t}^{\text{in}} + q_{i,t}^{\text{out}} + \sum_{j \in I} q_{j,t}^{\text{share}} - \text{load}_{i,t}^{\text{load}} = 0 \quad (\lambda_{i,t}^{\text{load}}) \quad \forall i \in I_{\text{new}}, t\]
- \[q_{i,t}^{\text{out}} + q_{i,t}^{\text{in}} + \sum_{j \in I} q_{j,t}^{\text{share}} - PV_{i,t} q_{i,t}^{PV} = 0 \quad (\lambda_{i,t}^{PV}) \quad \forall i \in I_{\text{new}}, t\]
- \[\text{SoC}_{i,t-1} + q_{i,t}^{\text{in}} \cdot \eta^{B} - q_{i,t}^{\text{out}} \cdot \eta^{B} - \text{SoC}_{i,t} = 0 \quad (\lambda_{i,t}^{\text{SoC}}) \quad \forall i, t > t_{0}\]
- \[\text{SoC}_{i,t=t_{0}} + q_{i,t_{0}}^{\text{in}} \cdot \eta^{B} - q_{i,t_{0}}^{\text{out}} \cdot \eta^{B} - \text{SoC}_{i,t_{0}} = 0 \quad (\lambda_{i,t_{0}}^{\text{SoC}}) \quad \forall i, t = t_{0}\]
- \[\text{SoC}_{i,t} - \text{SoC}_{i}^{\text{max}} \leq 0 \quad (\mu_{i,t}^{\text{SoC}}) \quad \forall i, t\]
- \[q_{i,t}^{\text{in}} - q_{i,t}^{\text{max}} \leq 0 \quad (\mu_{i,t}^{\text{in}}) \quad \forall i, t\]
- \[q_{i,t}^{\text{out}} - q_{i,t}^{\text{max}} \leq 0 \quad (\mu_{i,t}^{\text{out}}) \quad \forall i, t\]
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 – Settlement patterns

Characteristics of the different settlement patterns:

1. City areas (high population density)
   - Multi-apartment buildings
     - Assuming voluntary participation of tenants
     - Aggregation of tenants’ load profiles
     - Possibly with different types of businesses in the buildings (shops on the first floor, offices, …)
     - Limited rooftop area for PV systems

2. Suburban areas (medium density)
   - Mix of multi-apartment buildings and single family houses
   - Some businesses included (e.g. shops, bakery, …)

3. Rural areas (low population density)
   - Mostly single family houses
   - Sufficient rooftop area available
Case study:

- Model implemented in Python using Pyomo
- Small community set-up consisting of 10 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:
  - Apartment building: \( PV = 5 \, kW_{peak}, load = 39000 \frac{kWh}{yr} \)
  - Single house: \( PV = 3 \, kW_{peak}, load = 1400 \frac{kWh}{yr} \)

---

Comparison of peer-to-peer trading with 10 members:

- Annual results: *electricity trades with the peers*
- Different settlement patterns: city – suburban – rural

### City

<table>
<thead>
<tr>
<th>AB 1</th>
<th>AB 2</th>
<th>AB 3</th>
<th>AB 4</th>
<th>AB 5</th>
<th>SH 6</th>
<th>SH 7</th>
<th>SH 8</th>
<th>SH 9</th>
<th>SH 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Suburban area

<table>
<thead>
<tr>
<th>AB 1</th>
<th>AB 2</th>
<th>AB 3</th>
<th>AB 4</th>
<th>AB 5</th>
<th>SH 6</th>
<th>SH 7</th>
<th>SH 8</th>
<th>SH 9</th>
<th>SH 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Rural area

<table>
<thead>
<tr>
<th>SH 1</th>
<th>SH 2</th>
<th>SH 3</th>
<th>SH 4</th>
<th>SH 5</th>
<th>SH 6</th>
<th>SH 7</th>
<th>SH 8</th>
<th>SH 9</th>
<th>SH 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Comparison of peer-to-peer trading with 10 members:

- Annual results: self-consumption/trading with community/trading with grid
- Different settlement patterns: city – suburban – rural
Results – Comparison of settlement patterns

Comparison of peer-to-peer trading with 10 members:

- Annual results: self-consumption/trading with community/trading with grid
- Different settlement patterns: city – suburban – rural
Results – Rural area

All prosumers want to minimize their individual costs:

\[ \alpha_i = 1, \forall i \in I_{old} \]

Results:

- Apartment building
- Opportunity to sell to the new prosumer (high demand, no PV installed) and lower annual costs

Sankey diagram of PV generation
Results – City area

All prosumers want to minimize their individual emissions:

\[ \alpha_i = 0, \forall i \in I_{old} \]

Results:

- Single house
- Emissions decrease, some costs increase
Influence of the willingness-to-pay:

<table>
<thead>
<tr>
<th></th>
<th>Minimize ind. emissions</th>
<th>Minimize ind. costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AB</td>
<td>SH</td>
</tr>
<tr>
<td>City</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Suburban area</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Rural area</td>
<td>✓</td>
<td>✓</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

Future outlook:
• Analysis of the effects on the DSO and the community manager
• Behavior of prosumers in urban areas vs. rural areas
Thank you for your attention!

GitHub

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

open ENergy TRansition ANalyses for a low-Carbon Economy

https://openentrance.eu/

This project has received funding from the European Unions Horizon 2020 research and innovation program under grant agreement No. 835896
Appendix

City – Average hourly electricity demand values

![Graph showing average hourly electricity demand values for different locations in the city.](image)
Appendix

Suburban area – Average hourly electricity demand values
Appendix

Rural area – Average hourly electricity demand values
Prosumers’ data: City area