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

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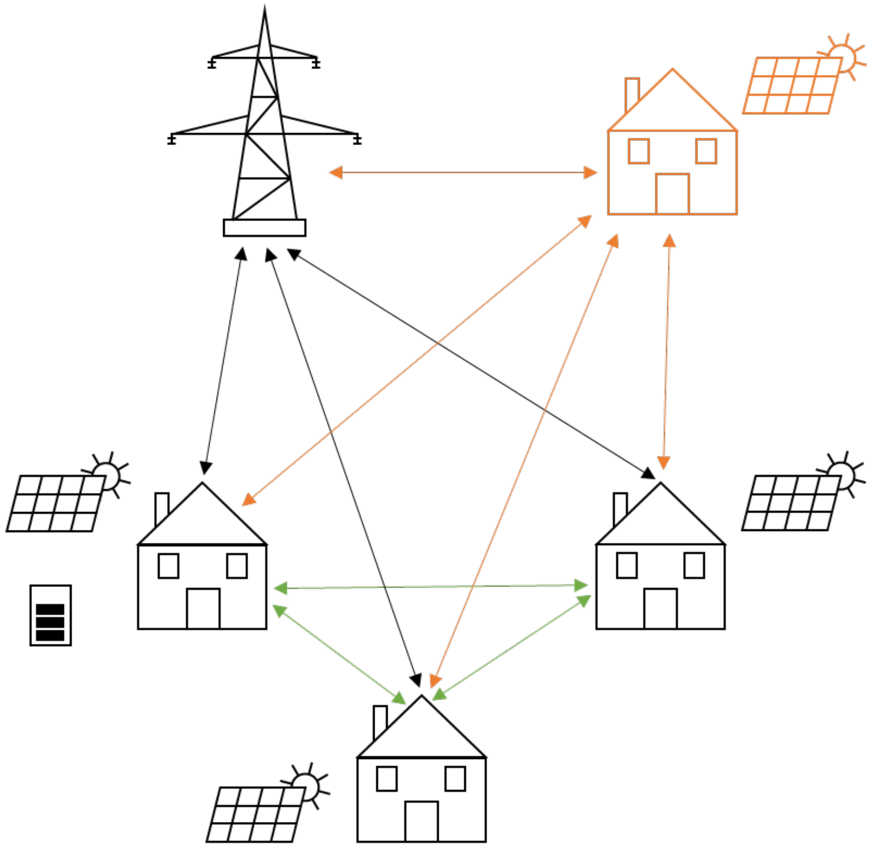
Motivation and Scope

- 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:

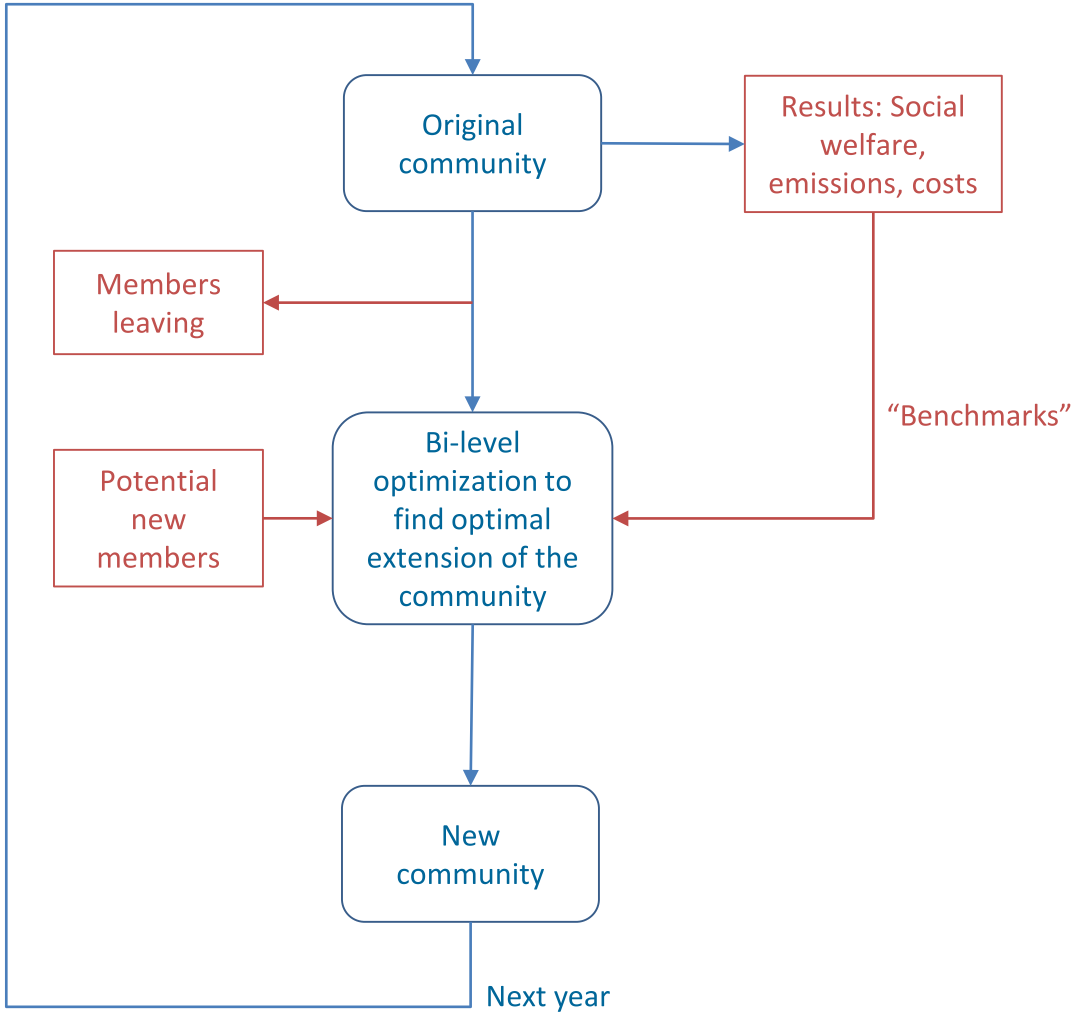
- Linear optimization model FRESH:COM [1] maximizing the social welfare of a **local energy community**
- Allocation mechanism: Peer-to-peer trading under the consideration of each prosumer's *individual willingness-to-pay*
- Members: Private households and SMEs
  - Photovoltaic (PV) and Battery Energy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

Contribution:

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

[1] T. Perger et al., PV sharing in local communities: Peer-to-peer trading under consideration of the prosumers' willingness-to-pay, Sustainable Cities and Society, Volume 66, 2021, https://doi.org/10.1016/j.scs.2020.102634.

Modeling Approach



- Social welfare:

$$SW = \underbrace{\sum_{t\in\mathcal{T}, i\in\mathcal{I}} p_t^{Gout} q_{i,t}^{Gout} - \sum_{t\in\mathcal{T}, i\in\mathcal{I}} p_t^{Gin} q_{i,t}^{Gin}}_{\mathrm{I}} + \underbrace{\sum_{t\in\mathcal{T}, i,j\in\mathcal{I}} wtp_{i,j,t} q_{i,j,t}^{share}}_{\mathrm{II}}.$$

- Willingness-to-pay:

$$wtp_{i,j,t} = p_t^{Gin} + w_j (1 - d_{i,j}) \cdot e_t.$$

- „Benchmarks“:

$$\Delta costs_i = \frac{costs_i - costs_{i,old}}{\mid costs_{i,old} \mid}$$

$$\Delta emissions_i = \frac{emissions_i - emissions_{i,old}}{emissions_{i,old}}$$

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:

$$CE = \sum_{i \in \mathcal{I}_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i$$

  - $\Delta costs_i$ 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

$$\min_{\{load_i, PV_i, b_i, Q_{i,t}\}} \sum_{i \in \mathcal{I}_{old}} \alpha_i \Delta costs_i + (1 - \alpha_i) \Delta emissions_i$$

subject to:

$$b_i \cdot load_i^{min} \leq load_i \leq b_i \cdot load_i^{max} \quad \forall i \in \mathcal{I}_{new}$$

$$b_i \cdot PV_i^{min} \leq PV_i \leq b_i \cdot PV_i^{max} \quad \forall i \in \mathcal{I}_{new}$$

$$\sum_{i \in \mathcal{I}_{new}} b_i = n$$

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

$$\max_{Q_{i,t}} \sum_{t\in\mathcal{T},i\in\mathcal{I}} p_t^{G_{out}} q_{i,t}^{G_{out}} - \sum_{t\in\mathcal{T},i\in\mathcal{I}} p_t^{G_{in}} q_{i,t}^{G_{in}} + \sum_{t\in\mathcal{T},i,j\in\mathcal{I}} wtp_{i,j,t} q_{i,j,t}^{share}$$

subject to:

$$q_{i,t}^{G_{in}} + q_{i,t}^{B_{out}} + \sum_{j\in\mathcal{I}} q_{j,i,t}^{share} - q_{i,t}^{load} = 0 \qquad (\lambda_{i,t}^{load}) \quad \forall i \in \mathcal{I}_{old}, t$$

$$q_{i,t}^{G_{out}} + q_{i,t}^{B_{in}} + \sum_{j\in\mathcal{I}} q_{i,j,t}^{share} - q_{i,t}^{PV} = 0 \qquad (\lambda_{i,t}^{PV}) \quad \forall i \in \mathcal{I}_{old}, t$$

$$q_{i,t}^{G_{in}} + q_{i,t}^{B_{out}} + \sum_{j\in\mathcal{I}} q_{j,i,t}^{share} - load_i q_{i,t}^{load} = 0 \qquad (\lambda_{i,t}^{load}) \quad \forall i \in \mathcal{I}_{new}, t$$

$$q_{i,t}^{G_{out}} + q_{i,t}^{B_{in}} + \sum_{j\in\mathcal{I}} q_{i,j,t}^{share} - PV_i q_{i,t}^{PV} = 0 \qquad (\lambda_{i,t}^{PV}) \quad \forall i \in \mathcal{I}_{new}, t$$

$$SoC_{i,t-1} + q_{i,t}^{B_{in}} \cdot \eta^B - q_{i,t}^{B_{out}}/\eta^B - SoC_{i,t} = 0 \qquad (\lambda_{i,t}^{SoC}) \quad \forall i, t > t_0$$

$$SoC_{i,t=t_{end}} + q_{i,t_0}^{B_{in}} \cdot \eta^B - q_{i,t_0}^{B_{out}}/\eta^B - SoC_{i,t_0} = 0 \qquad (\lambda_{i,t_0}^{SoC}) \quad \forall i, t = t_0$$

$$SoC_{i,t} - SoC_i^{max} \leq 0 \qquad (\mu_{i,t}^{SoC^{max}}) \quad \forall i, t$$

$$q_{i,t}^{B_{in}} - q_i^{B^{max}} \leq 0 \qquad (\mu_{i,t}^{B_{in}^{max}}) \quad \forall i, t$$

$$q_{i,t}^{B_{out}} - q_i^{B^{max}} \leq 0 \qquad (\mu_{i,t}^{B_{out}^{max}}) \quad \forall i, t$$

Modeling Approach – Bi-level problem

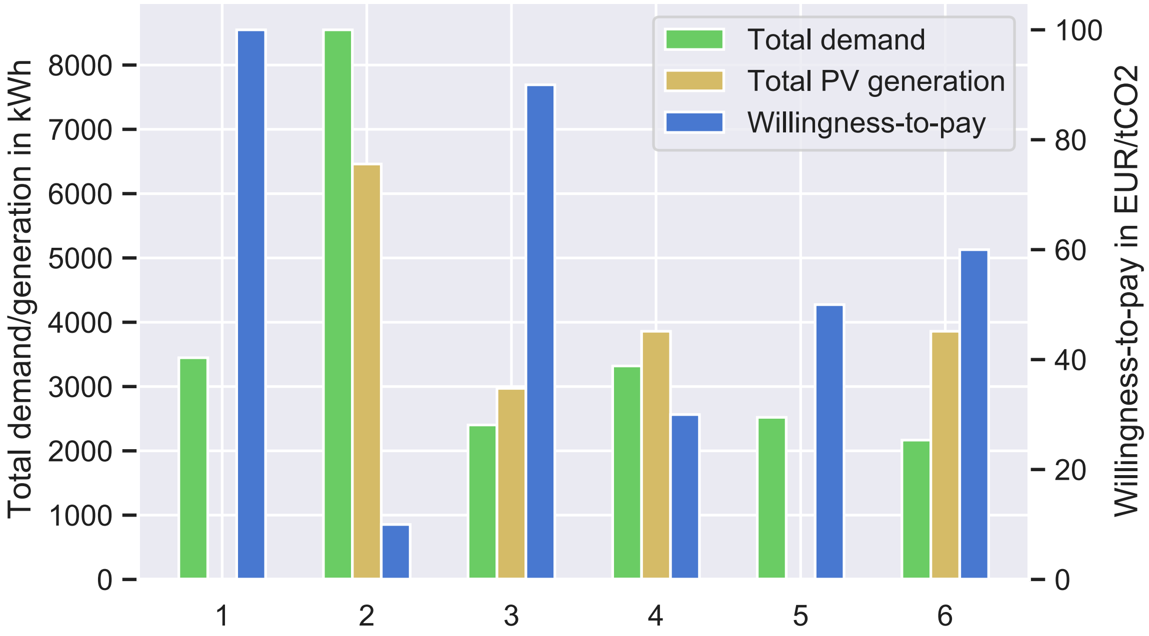
How is the bi-level problem solved?

- 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)
  - $PV^{min} = 0, PV^{max} = 5\ kW_{peak}$
  - $load^{min} = 2000 \frac{kWh}{yr}, load^{max} = 8000 \frac{kWh}{yr}$
  - $w_{new} = 50\ EUR/tCO_2$



Results – New prosumer household

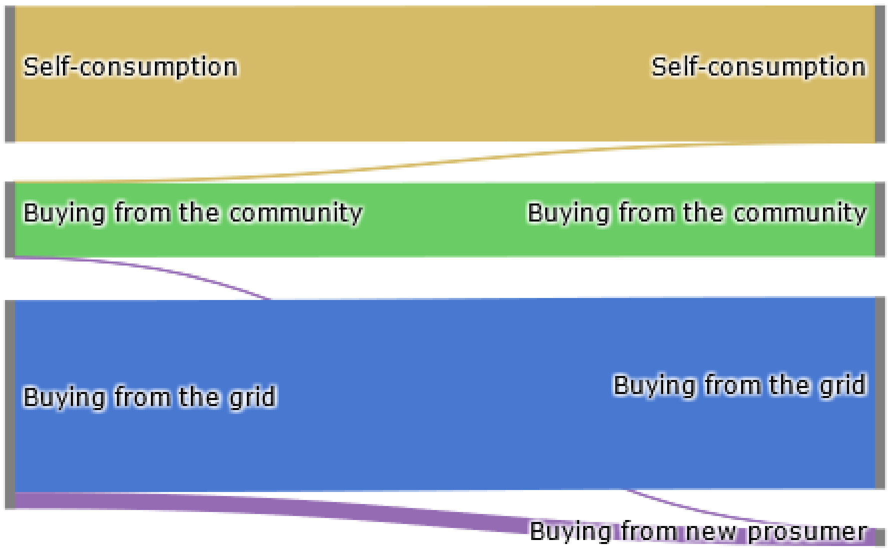
All prosumers want to minimize their individual <u>emissions</u>:

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

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



Results – New prosumer household

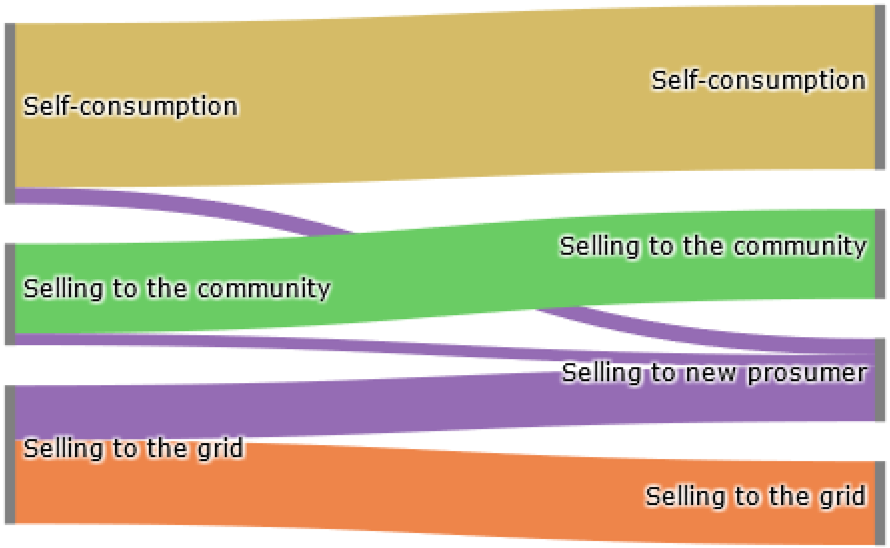
All prosumers want to minimize their individual costs:

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

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

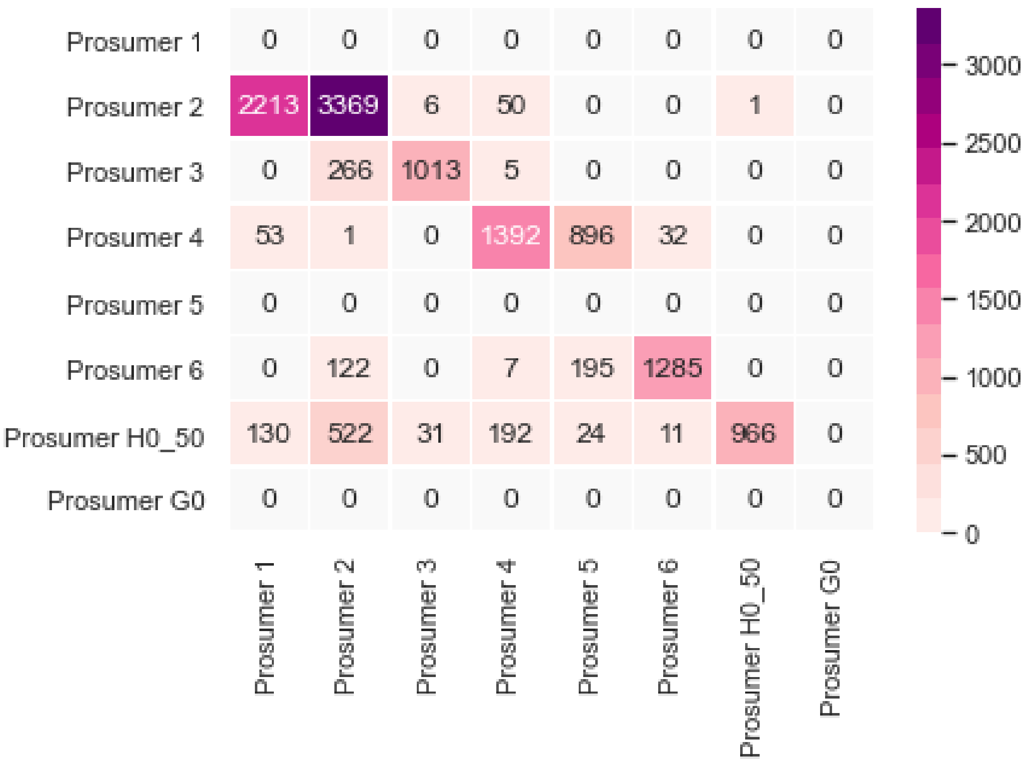
Sankey diagram of PV generation



Results – Household vs. business

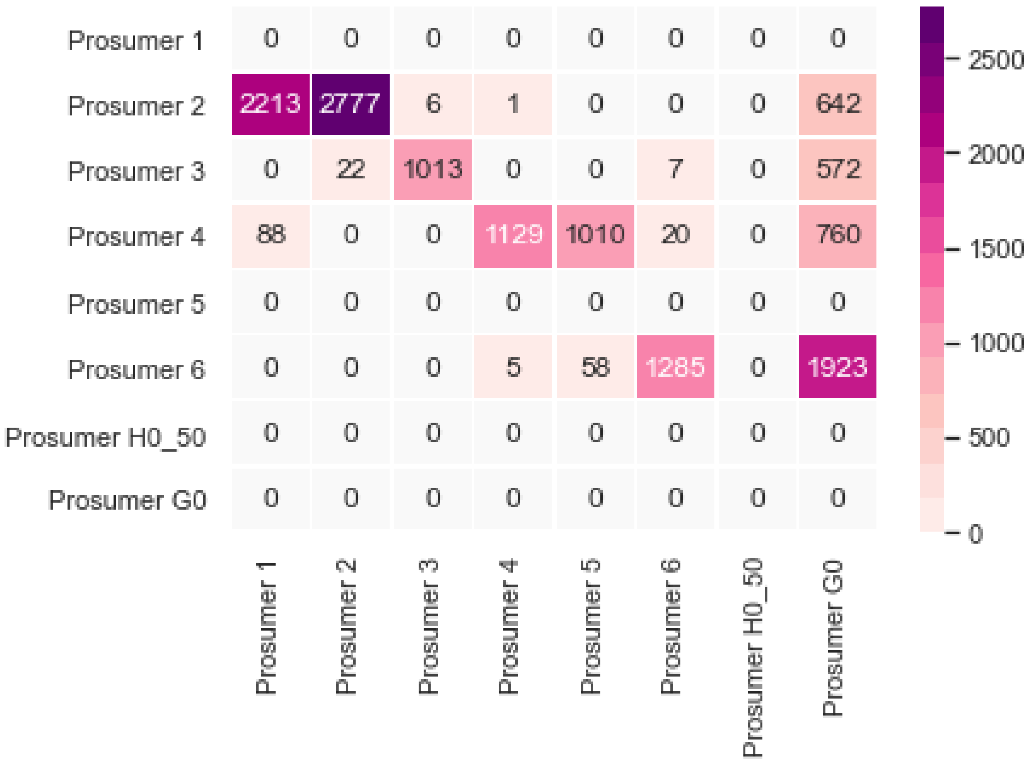
Minimizing individual emissions

✓ 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:

- $w_i = 0 \text{ EUR/tCO}_2$ or $w_i = 100 \text{ EUR/tCO}_2$

	H0 ($w_i = 0$)	H0 ($w_i = 100$)	H0 ($w_i = 0$)	G0 ($w_i = 100$)	G0 ($w_i = 0$)	H0 ($w_i = 100$)
ind. emissions	✓	-	✓	-	✓	-
ind. costs	-	✓	-	✓	-	✓

Fairness indicators:

- Quality of service:

$$QoS = \frac{(\sum_{j \in \mathcal{I}} q_j)^2}{n \cdot \sum_{j \in \mathcal{I}} q_j^2}$$

$$q_j = \sum_{t \in \mathcal{T}, i \neq j \in \mathcal{I}} (q_{i,j,t}^{share} + q_{j,i,t}^{share})$$

	QoS (H0 with $w_i = 50$)
old community	0.674
ind. emissions	0.657
ind. costs	0.815

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!

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

open ENergy TRansition ANalyses for a low-Carbon Economy

https://openentrance.eu/

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