TECHNISCHE
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Energy
Economics
Group

Berücksichtigung verschiedener Siedlungsmuster in der Entwicklung von lokalen Energiegemeinschaften mit Peer-to-Peer Handel

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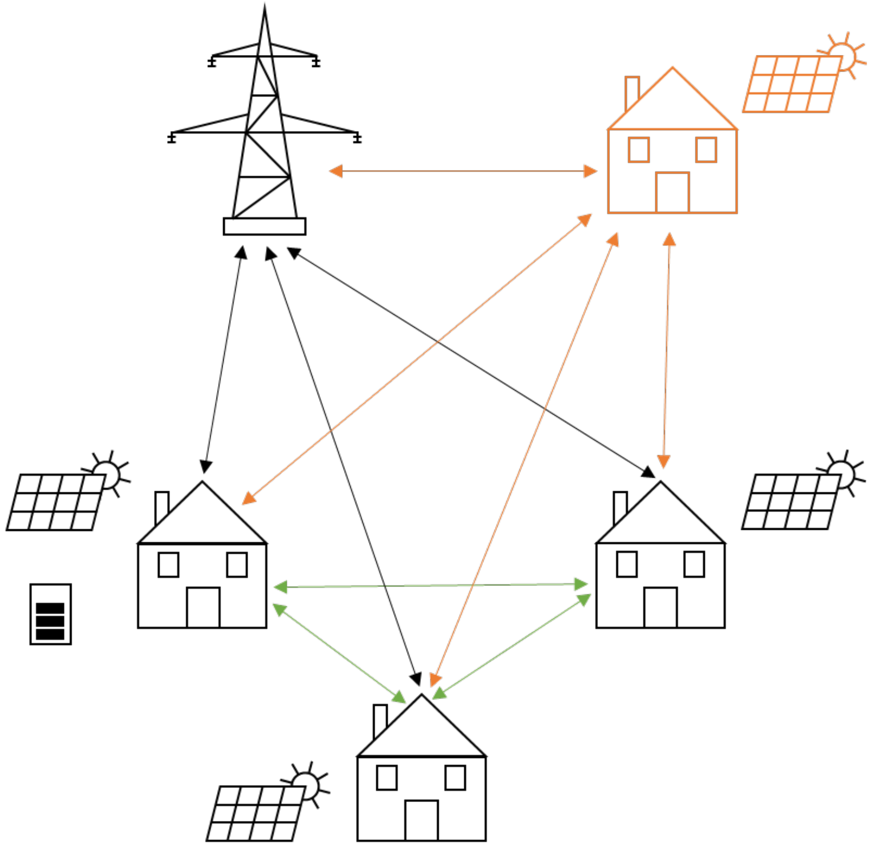
Motivation and Scope

- 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
  - 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:

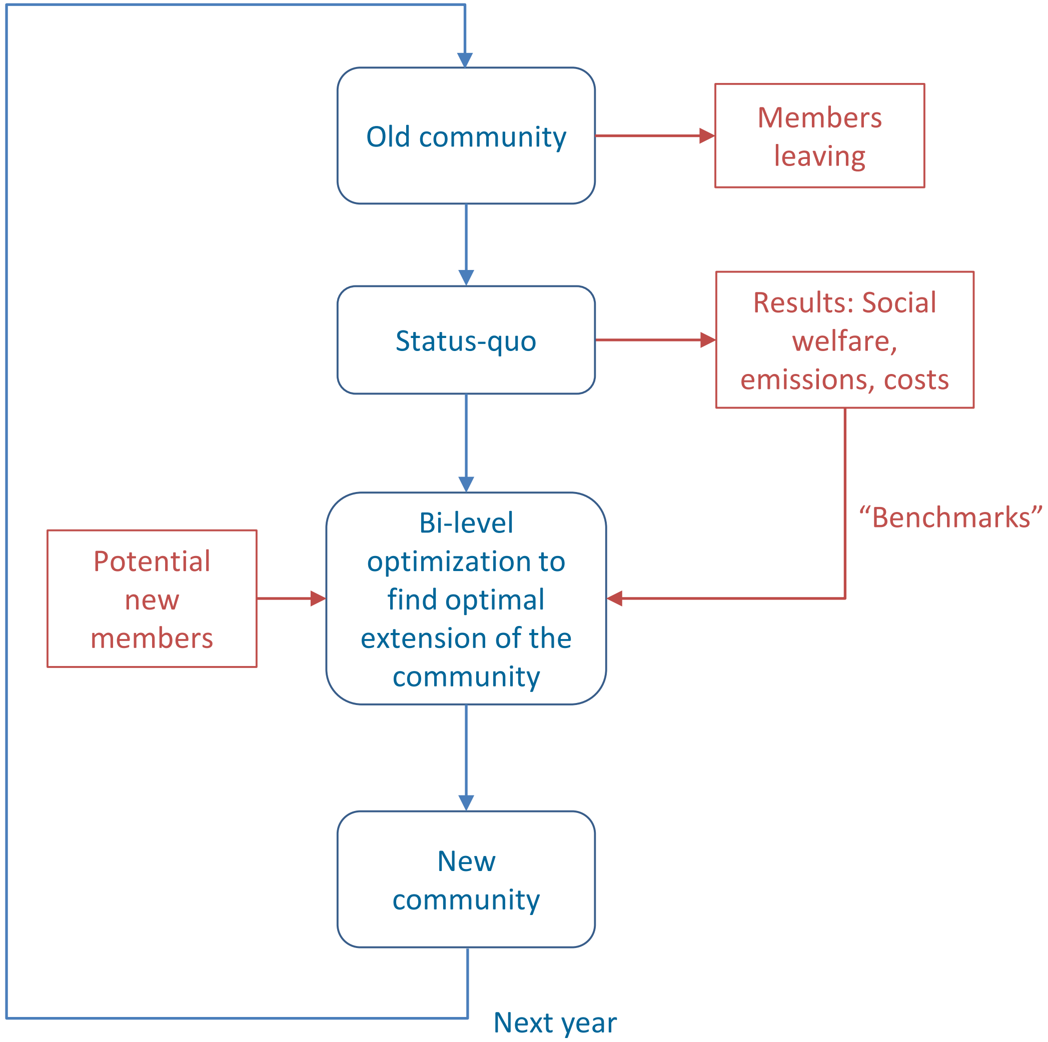
- Linear optimization model FRESH:COM [1] maximizing the social welfare of a **local energy community**
- Allocation mechanism: Peer-to-peer trading under the consideration of each prosumer’s *individual willingness-to-pay*
- Members: Private households and SMEs
  - Photovoltaic (PV) and Battery Energy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

Contribution:

- Extension of FRESH:COM to optimize *dynamic participation* in peer-to-peer trading communities within different settlement patterns

[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


Old community

Members leaving

Status-quo

Results: Social welfare, emissions, costs

“Benchmarks”

Potential new members

Bi-level optimization to find optimal extension of the community

New community

Next year

- Social welfare:

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

- Willingness-to-pay:

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

- „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:

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

  - $\Delta costs_i$ 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

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

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 – Settlement patterns

Characteristics of the different settlement patterns:

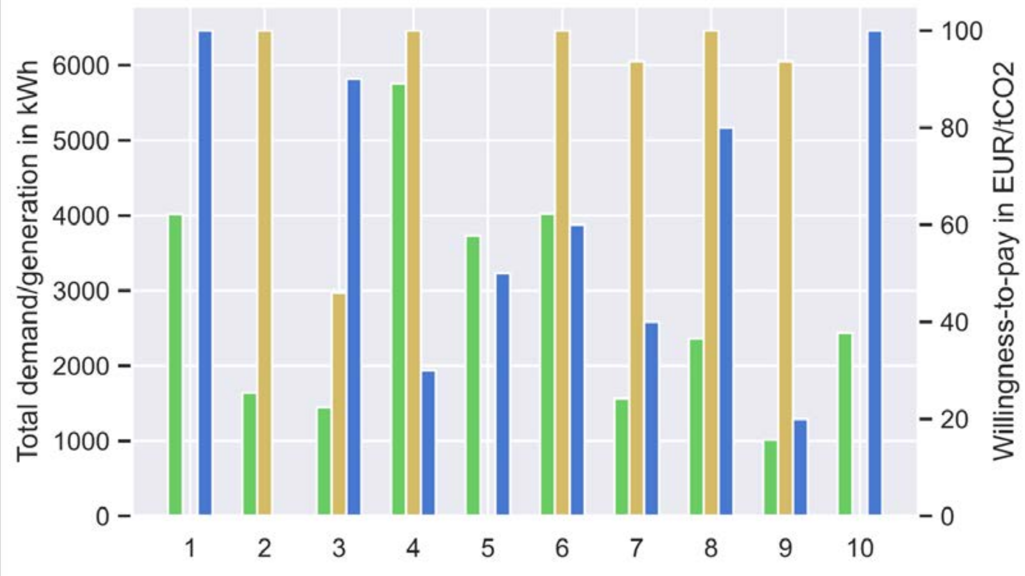
1. City areas (high population density)
    - Multi-apartment buildings
        - Assuming voluntary participation of tenants
        - Aggregation of tenants' load profiles
        - Possibly with different types of businesses in the buildings (shops on the first floor, offices, …)
        - Limited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

Modeling Approach – Data and assumptions

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: $PV = 3\ kW_{peak}, load = 1400 \frac{kWh}{yr}$

Prosumer data (rural area): electricity demand (green), PV generation (yellow), willingness-to-pay (blue)



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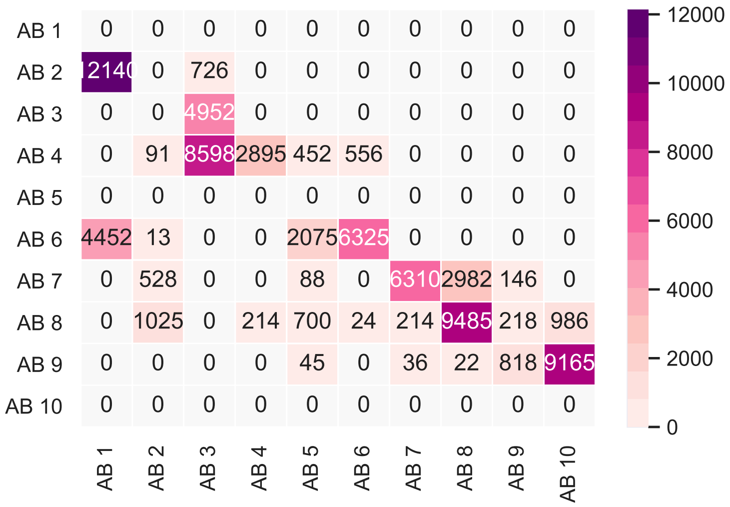
[1] https://www.loadprofilegenerator.de; [2] https://www.renewables.ninja/; [3] https://scikit-learn.org/stable/modules/generated/sklearn.cluster.KMeans.html

Results – Comparison of settlement patterns

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

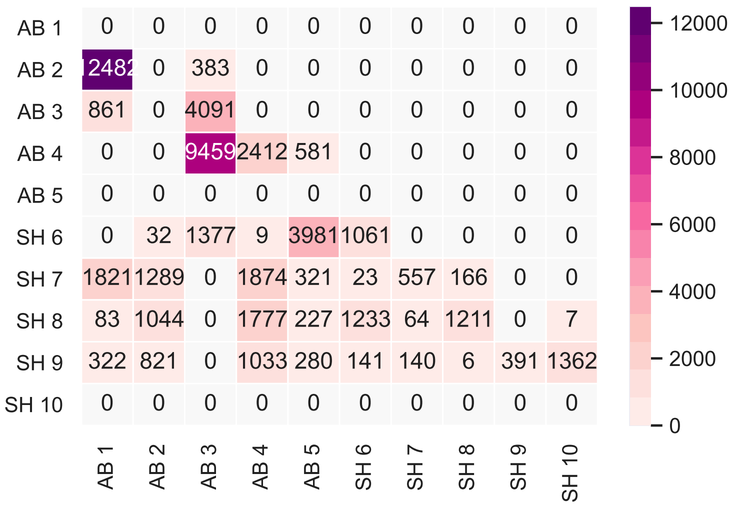
- Annual results: **electricity trades with the peers**
- Different settlement patterns: city – suburban – rural

City



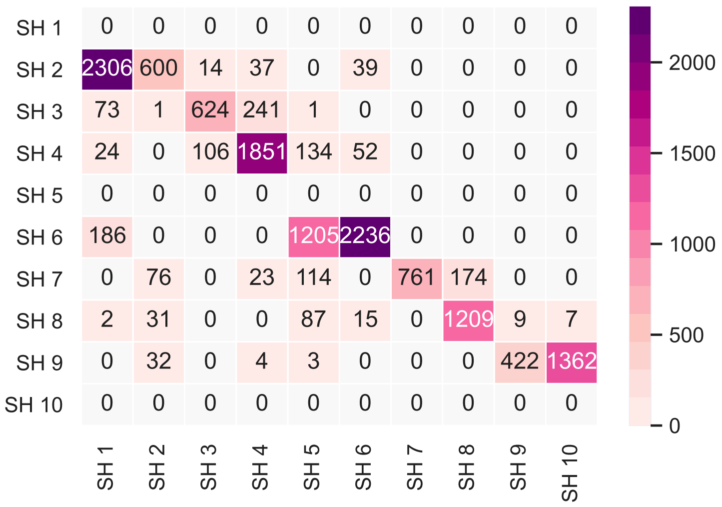
	AB 1	AB 2	AB 3	AB 4	AB 5	AB 6	AB 7	AB 8	AB 9	AB 10
AB 1	0	0	0	0	0	0	0	0	0	0
AB 2	12140	0	726	0	0	0	0	0	0	0
AB 3	0	0	4952	0	0	0	0	0	0	0
AB 4	0	91	8598	2895	452	556	0	0	0	0
AB 5	0	0	0	0	0	0	0	0	0	0
AB 6	4452	13	0	0	2075	6325	0	0	0	0
AB 7	0	528	0	0	88	0	6310	2982	146	0
AB 8	0	1025	0	214	700	24	214	9485	218	986
AB 9	0	0	0	0	45	0	36	22	818	9165
AB 10	0	0	0	0	0	0	0	0	0	0

Suburban area



	AB 1	AB 2	AB 3	AB 4	AB 5	SH 6	SH 7	SH 8	SH 9	SH 10
AB 1	0	0	0	0	0	0	0	0	0	0
AB 2	12482	0	383	0	0	0	0	0	0	0
AB 3	861	0	4091	0	0	0	0	0	0	0
AB 4	0	0	9459	2412	581	0	0	0	0	0
AB 5	0	0	0	0	0	0	0	0	0	0
SH 6	0	32	1377	9	3981	1061	0	0	0	0
SH 7	1821	1289	0	1874	321	23	557	166	0	0
SH 8	83	1044	0	1777	227	1233	64	1211	0	7
SH 9	322	821	0	1033	280	141	140	6	391	1362
SH 10	0	0	0	0	0	0	0	0	0	0

Rural area



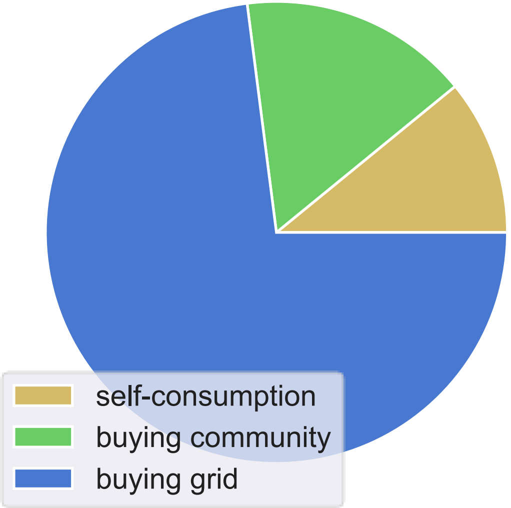
	SH 1	SH 2	SH 3	SH 4	SH 5	SH 6	SH 7	SH 8	SH 9	SH 10
SH 1	0	0	0	0	0	0	0	0	0	0
SH 2	2306	600	14	37	0	39	0	0	0	0
SH 3	73	1	624	241	1	0	0	0	0	0
SH 4	24	0	106	1851	134	52	0	0	0	0
SH 5	0	0	0	0	0	0	0	0	0	0
SH 6	186	0	0	0	1205	2236	0	0	0	0
SH 7	0	76	0	23	114	0	761	174	0	0
SH 8	2	31	0	0	87	15	0	1209	9	7
SH 9	0	32	0	4	3	0	0	0	422	1362
SH 10	0	0	0	0	0	0	0	0	0	0

Results – Comparison of settlement patterns

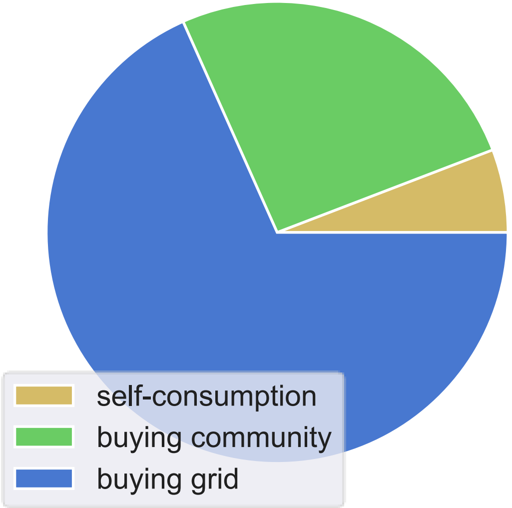
Comparison of peer-to-peer trading with 10 members:

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

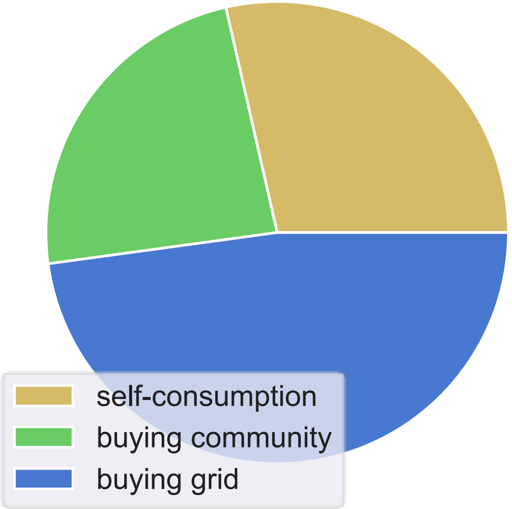
City



Suburban area



Rural area



Results – Comparison of settlement patterns

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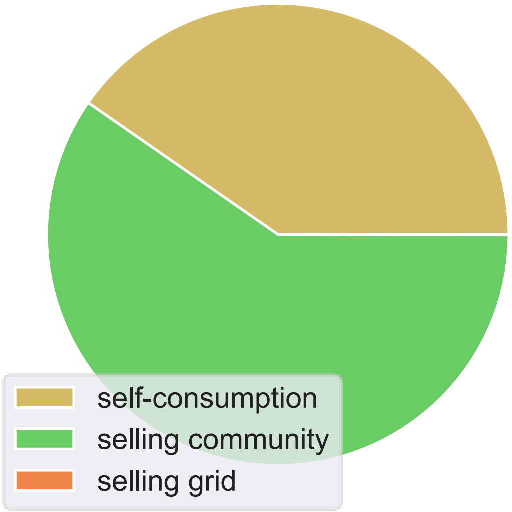
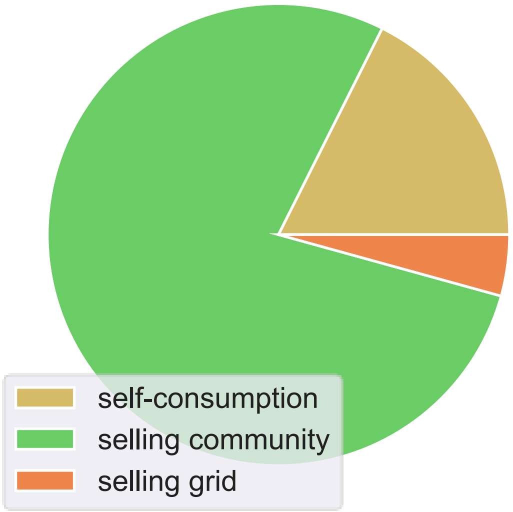
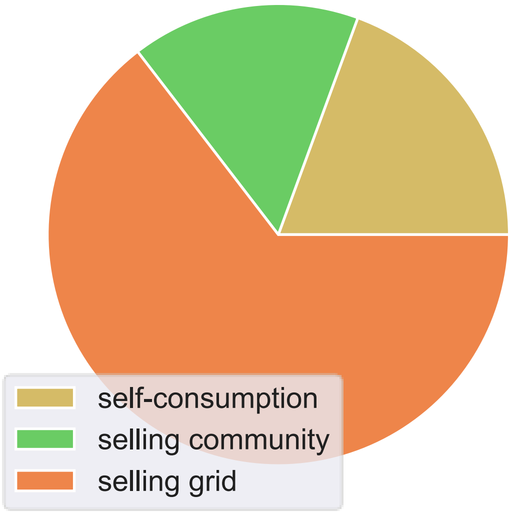


Suburban area



Rural area



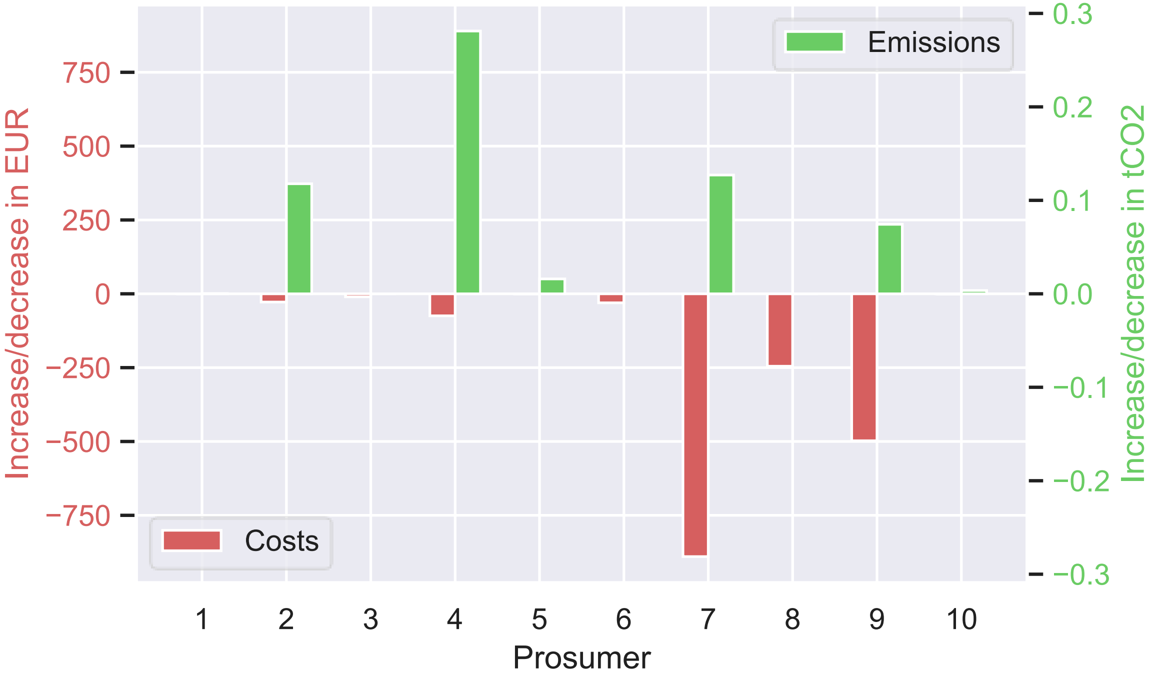
Results – Rural area

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

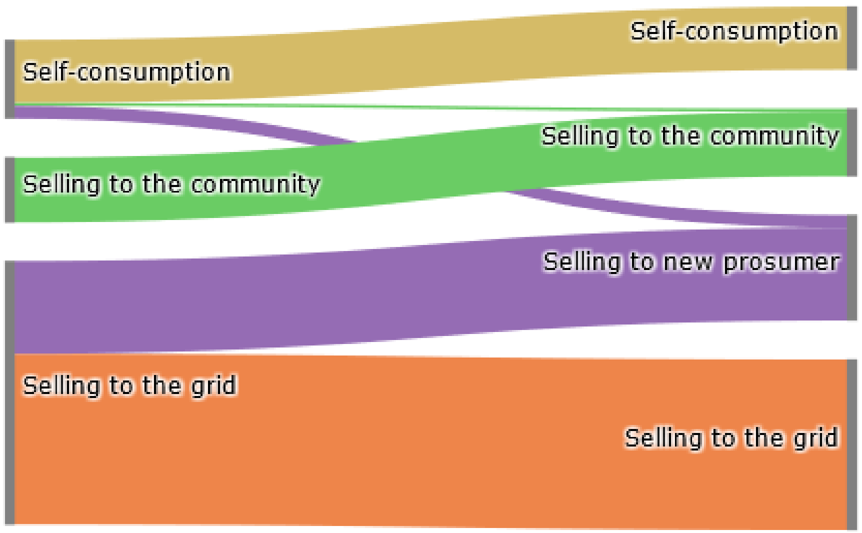
$$\alpha_i = 1, \forall i \in I_{old}$$

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

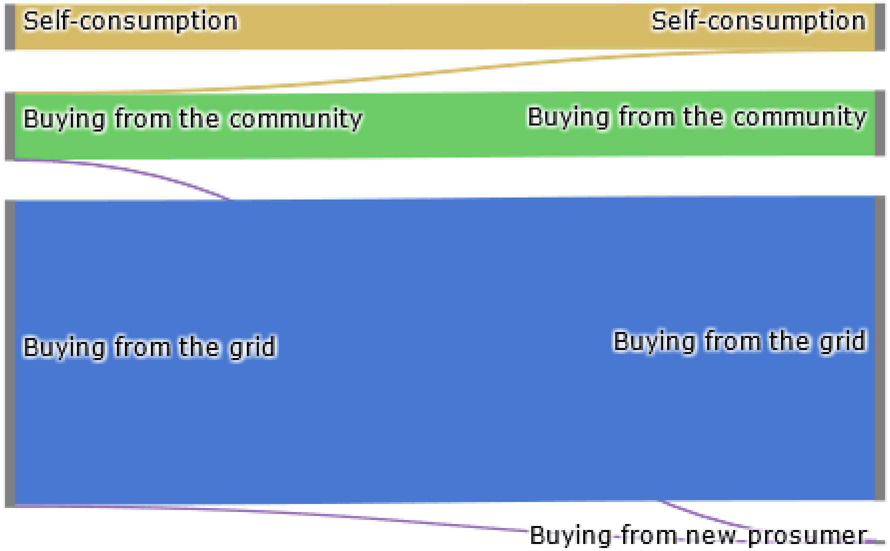
All prosumers want to minimize their individual emissions:

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

Results:

- ✓ Single house
- ✓ Emissions decrease, some costs increase

Sankey diagram of electricity demand



Results – Apartment building vs. single house

Influence of the willingness-to-pay:

	Minimize ind. emissions		Minimize ind. costs	
	AB	SH	AB	SH
City		✓	✓	
Suburban area		✓		✓
Rural area		✓	✓	

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!

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

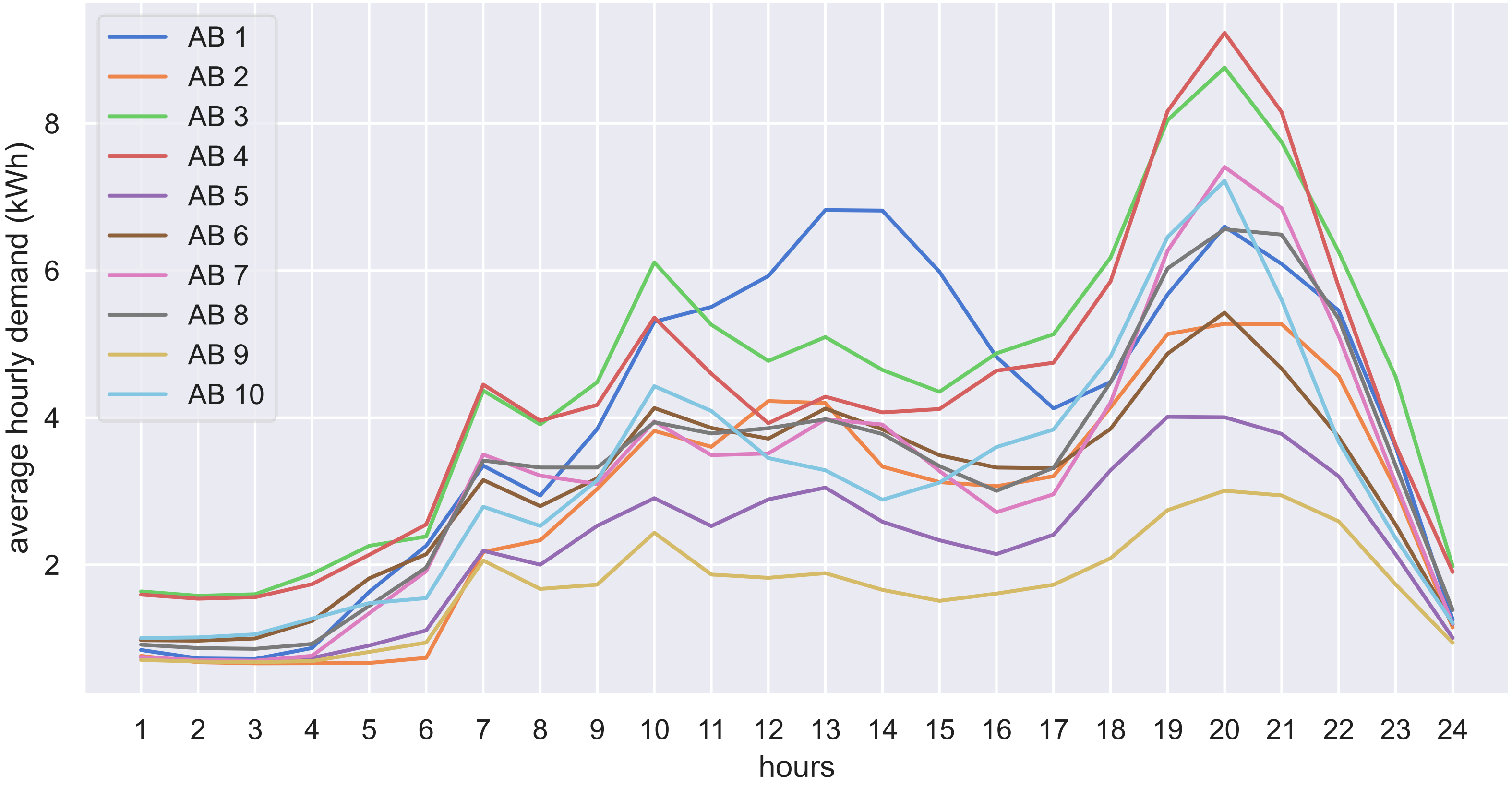
open ENergy TRansition ANalyses for a
low-Carbon Economy

https://openentrance.eu/

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

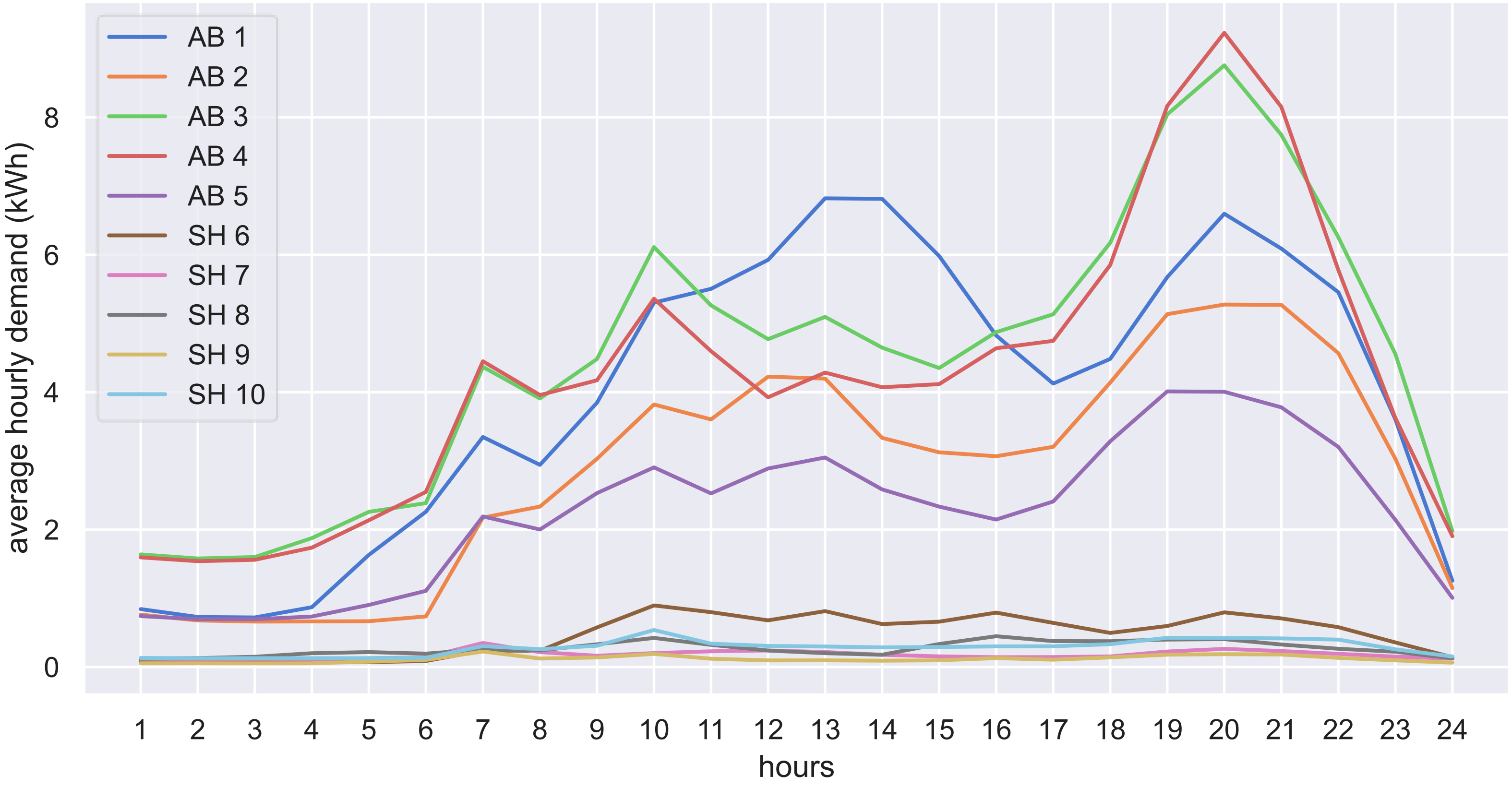
Appendix

City – Average hourly electricity demand values



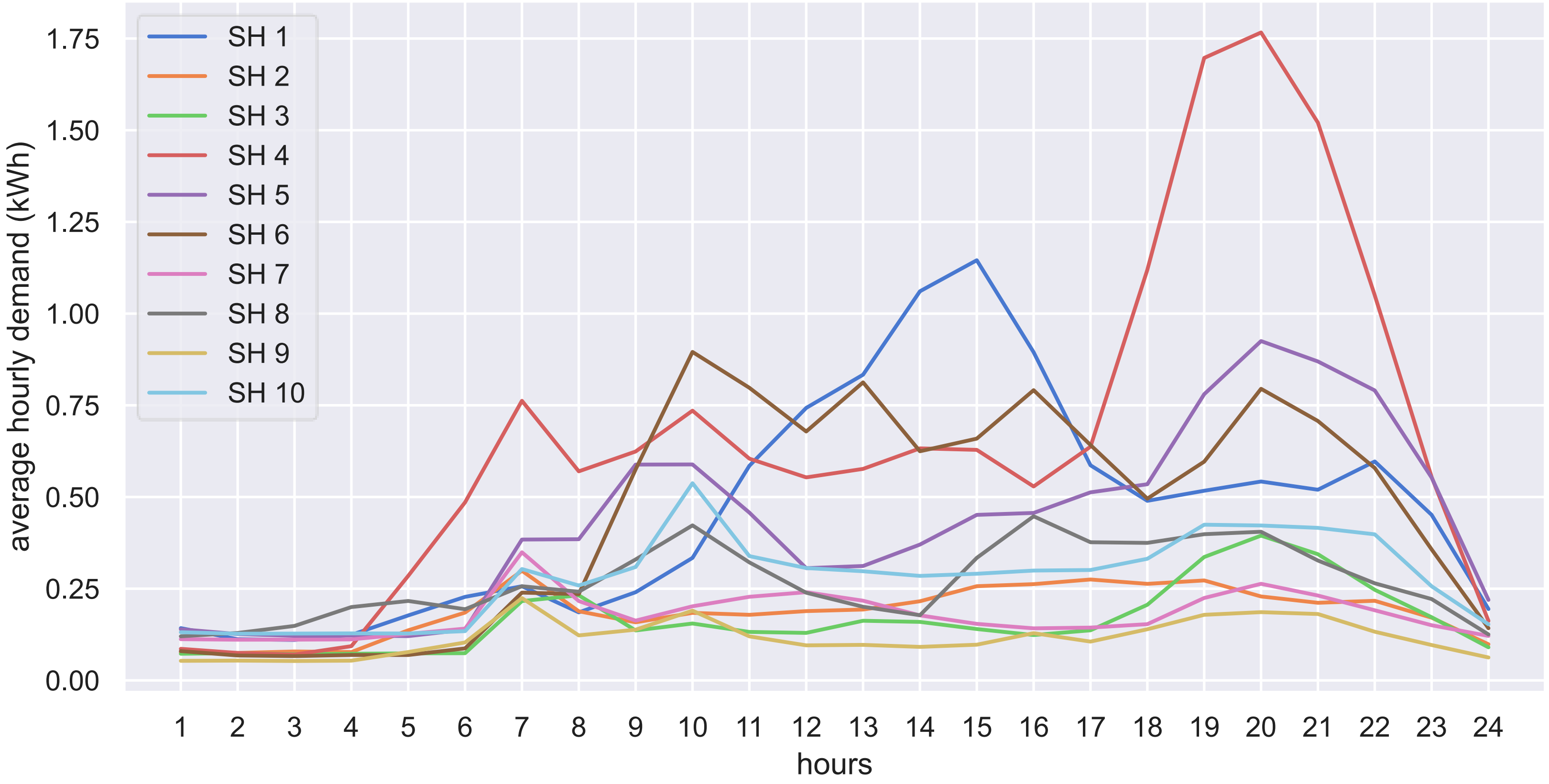
Appendix

Suburban area – Average hourly electricity demand values



Appendix

Rural area – Average hourly electricity demand values



Appendix

Prosumers‘ data: City area