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Mapping the Energy Future -Voyage in Uncharted Territory-

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To all participants at the venue

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Closing Plenary

A STOCHASTIC APPROACH TO DYNAMIC PARTICIPATION IN ENERGY 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 participation
- Trading and sharing of PV generation within a certain framework: Energy communities and peer-to-peer trading
- When energy communities are more established in the future
- Search for optimal technology vs. optimal participants
- How to design or assign contracts in energy communities
- Previous work within my thesis:
  - Peer-to-peer trading under consideration of the prosumers' willingness-to-pay [1] →LP
  - Dynamic participation in local energy communities [2] → Bi-level

[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.
[2] Perger T and Auer H. Dynamic participation in local energy communities with peer-to-peer trading [version 1; peer review: 1 approved]. Open Research Europe 2022, **2**:5 (https://doi.org/10.12688/openreseurope.14332.1)

Research question and framework

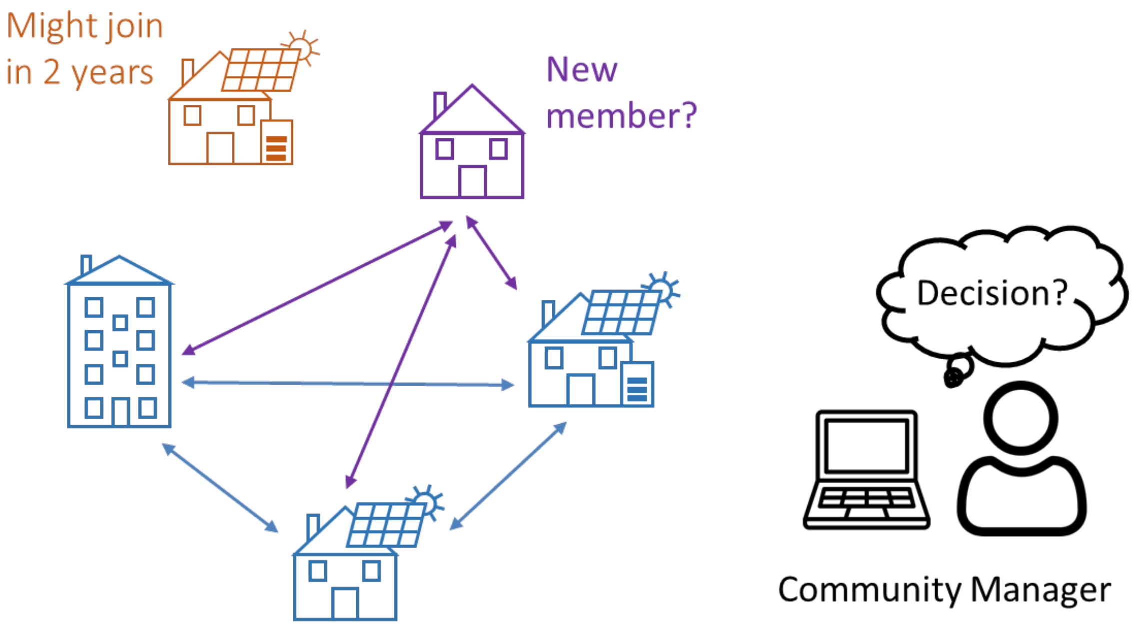
- Research Question:

We want to find out if having knowledge about the future development of prosumers in energy communities can help a community manager to <u>make better decisions selecting new participants</u>.

- Framework:
  - Voluntary participation
  - Low entry barriers: Prosumer can join or leave easily
  - PV sharing beyond the meter

- Method:

A stochastic dynamic program is developed to select participants with a look-ahead policy (planning over a certain time horizon).



Stochastic dynamic programming in general

- Dynamic programming is a mathematical method to solve sequential (multi-level) decision processes.
- The quality of a decision is not only measured by its current impact, but by its influence on the whole process.
  - Example: Chess game
- Components:
  - Control (decision) variables
  - State variables
  - Transition function (system dynamic)
  - Objective function
- Deterministic vs. stochastic dynamic programming
- Policy: function to determine decisions given available information in a state (*mapping* from state to action)
- How to choose a policy class?

Method

Planning horizon
$n \in N$

Scenarios
$\omega \in \Omega$

Portfolio of prosumers
$i \in I$

Contract assignment:

$$\min \; F_1 + \sum_{\omega \in \Omega} p(\omega) \cdot \sum_{n=2}^{N} F_n(\omega)$$

$$\text{s.t.} \quad x_{n,i}(\omega) = x_{n-1,i}(\omega) - b_{n-1,i}(\omega) + s_{n,i}(\omega) u_{n,i}(\omega)$$

Optimal allocation within the community

$$\max CW(Q_{i,t}(\omega))$$

$$\text{s.t.} \quad q^{G_{in}} + q^{B_{out}} + \sum q^{share} = b \cdot q^{load}$$

$$q^{G_{out}} + q^{B_{in}} + \sum q^{share} = b \cdot q^{PV}$$

$$SoC_t = SoC_{t-1} + q^{B_{in}} \eta - \frac{q^{B_{out}}}{\eta}$$

Method

Upper-level problem ("*leader*"):

- Transition function: $x_{n,i}(\omega) = x_{n-1,i}(\omega) - b_{n-1,i}(\omega) + s_{n,i}(\omega)u_{n,i}(\omega)$
- Exogenous information:
  - Deterministic for n=1: $s_{1,i}$
  - Stochastic for n>1: $s_{n,i}(\omega)$
  - Note that $x_{n,i}(\omega) = 0$ if $s_{n,i}(\omega) = 0$
- Emissions of prosumer *i* per year *n* and scenario ω: $emissions_{n,i}(\omega) = \sum_{t \in \mathcal{T}} e_t q_{i,t,n}^{G_{in}}(\omega)$
- As part of the objective function:

$$F_n(\omega) = \sum_{i \in \mathcal{I}} (emissions_{n,i}(\omega) - b_{n,i}(\omega) emissions_{out,i}) \cdot s_{n,i}(\omega) \cdot b_{0,i}$$

- Including the planning horizon and scenarios:

$$\min_{x_{n,i}(\omega), u_{n,i}(\omega), b_{n,i}(\omega), Q_{i,t,n}(\omega)} \quad F_1 + \sum_{\omega \in \Omega} \sum_{n=2}^{N} p(\omega) F_n(\omega)$$

Method

- Lower-level problem ("*follower*"):
  - Maximizing the community welfare, given the parameters selected in the upper problem
- Two parts in community welfare *CW*:
  - 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

$$\max_{Q_{i,t,n}(\omega)} \sum_{n\in\mathcal{N},\omega\in\Omega} \sum_{t\in\mathcal{T},i\in\mathcal{I}} \left(p_{t,n}^{G_{out}} q_{i,t,n}^{G_{out}}(\omega) - p_{t,n}^{G_{in}} q_{i,t,n}^{G_{in}}(\omega) + \sum_{j\in\mathcal{I}} wtp_{i,j,t} q_{i,j,t,n}^{share}(\omega) \right) \tag{13a}$$

$$\text{subject to:} \tag{13b}$$

$$q_{i,t,n}^{G_{in}}(\omega) + q_{i,t,n}^{B_{out}}(\omega) + \sum_{j\in\mathcal{I}} q_{j,i,t,n}^{share}(\omega) - b_{n,i}(\omega) q_{i,t}^{load} = 0 \qquad (\lambda_{i,t,n}^{load}(\omega)) \quad \forall i,t,n \tag{13c}$$

$$q_{i,t,n}^{G_{out}}(\omega) + q_{i,t,n}^{B_{in}}(\omega) + \sum_{j\in\mathcal{I}} q_{i,j,t,n}^{share}(\omega) - b_{n,i}(\omega) q_{i,t}^{PV} = 0 \qquad (\lambda_{i,t,n}^{PV}(\omega)) \quad \forall i,t,n \tag{13d}$$

$$SoC_{i,t-1,n}(\omega) + q_{i,t,n}^{B_{in}}(\omega)\cdot\eta^B - q_{i,t,n}^{B_{out}}(\omega)/\eta^B - SoC_{i,t,n}(\omega) = 0 \qquad (\lambda_{i,t,n}^{SoC}(\omega)) \quad \forall i, t > t_0, n \tag{13e}$$

$$SoC_{i,t=t_{end},n}(\omega) + q_{i,t0,n}^{B_{in}}(\omega)\cdot\eta^B - q_{i,t0,n}^{B_{out}}(\omega)/\eta^B - SoC_{i,t_0,n}(\omega) = 0 \qquad (\lambda_{i,t_0,n}^{SoC}(\omega)) \quad \forall i, t = t_0, n \tag{13f}$$

$$SoC_{i,t=t_{end},n}(\omega) - SoC_{init} = 0 \qquad (\lambda_{i,t_{end},n}^{SoC_{init}}(\omega)) \quad \forall i, t = t_{end}, n \tag{13g}$$

$$SoC_{i,t,n}(\omega) - b_{n,i} SoC_i^{max} \leq 0 \qquad (\mu_{i,t,n}^{SoC^{max}}(\omega)) \quad \forall i,t,n \tag{13h}$$

$$q_{i,t,n}^{B_{in}}(\omega) - b_{n,i} q_i^{B^{max}} \leq 0 \qquad (\mu_{i,t,n}^{B_{in}^{max}}(\omega)) \quad \forall i,t,n \tag{13i}$$

$$q_{i,t,n}^{B_{out}}(\omega) - b_{n,i} q_i^{B^{max}} \leq 0 \qquad (\mu_{i,t,n}^{B_{out}^{max}}(\omega)) \quad \forall i,t,n \tag{13j}$$

Method

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

Data and assumptions

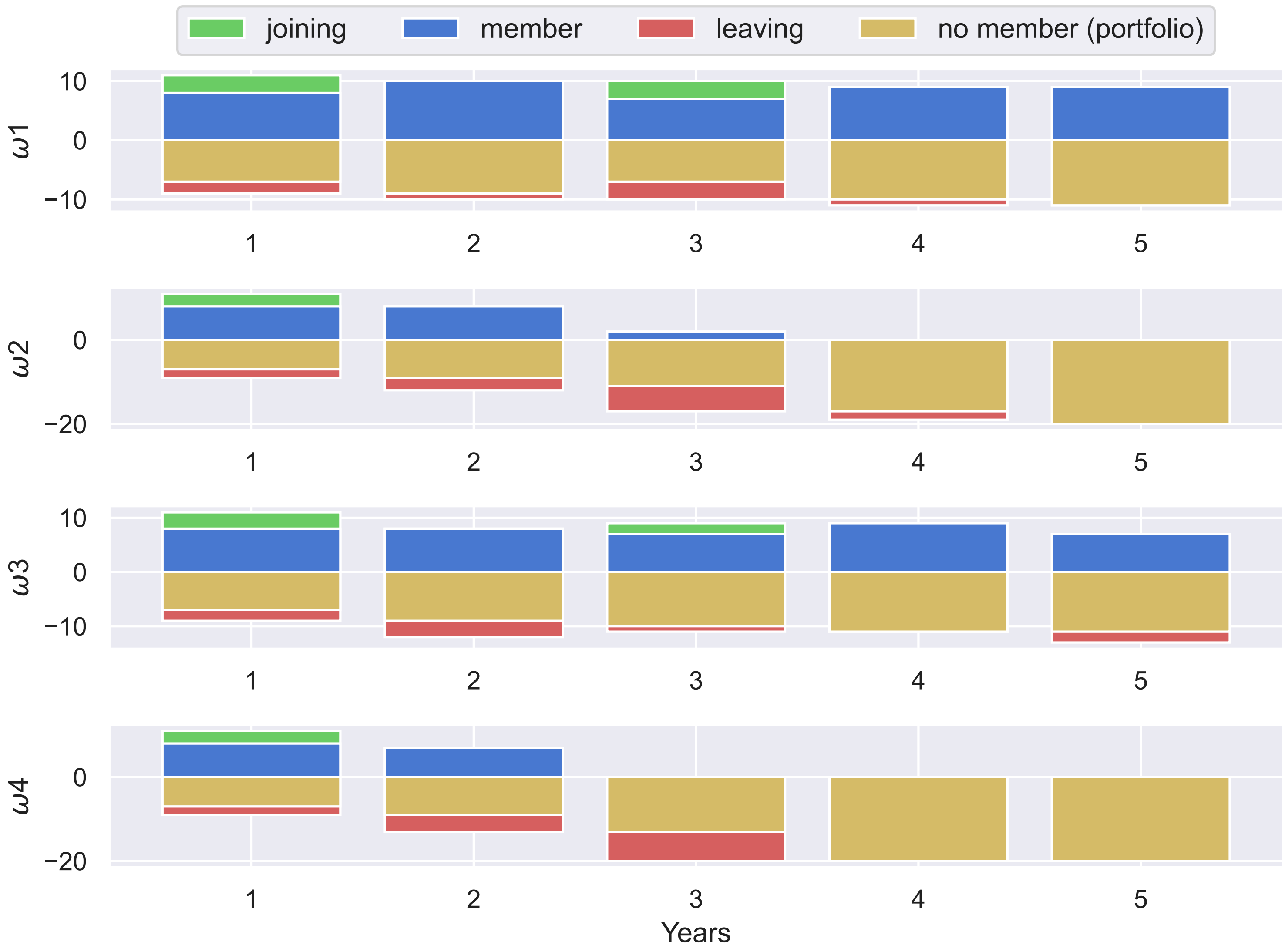
- Model implemented in *Python* using *Pyomo* [1] and *Gurobi* as solver
- Portfolio of 20 prosumers consisting of ten single houses (SH), eight small apartment buildings (SAB), and two small businesses (SME)
  - SH: PV systems with up to 5 kWpeak installed
  - SAB and SME: PV systems with up to 8 kWpeak installed
  - Some prosumer have BESS included
- Initial set-up: 5 SH, 4 SAB, 1 SME
- Electricity demand data and PV production data from open-source tools ([2] and [3])
- Annual hourly data is clustered into 3 representative days using a Python module [4]

[1] https://pyomo.readthedocs.io/en/stable/; [2] https://www.loadprofilegenerator.de;
[3] https://www.renewables.ninja/; [4] https://scikit-learn.org/stable/modules/generated/sklearn.cluster.KMeans.html

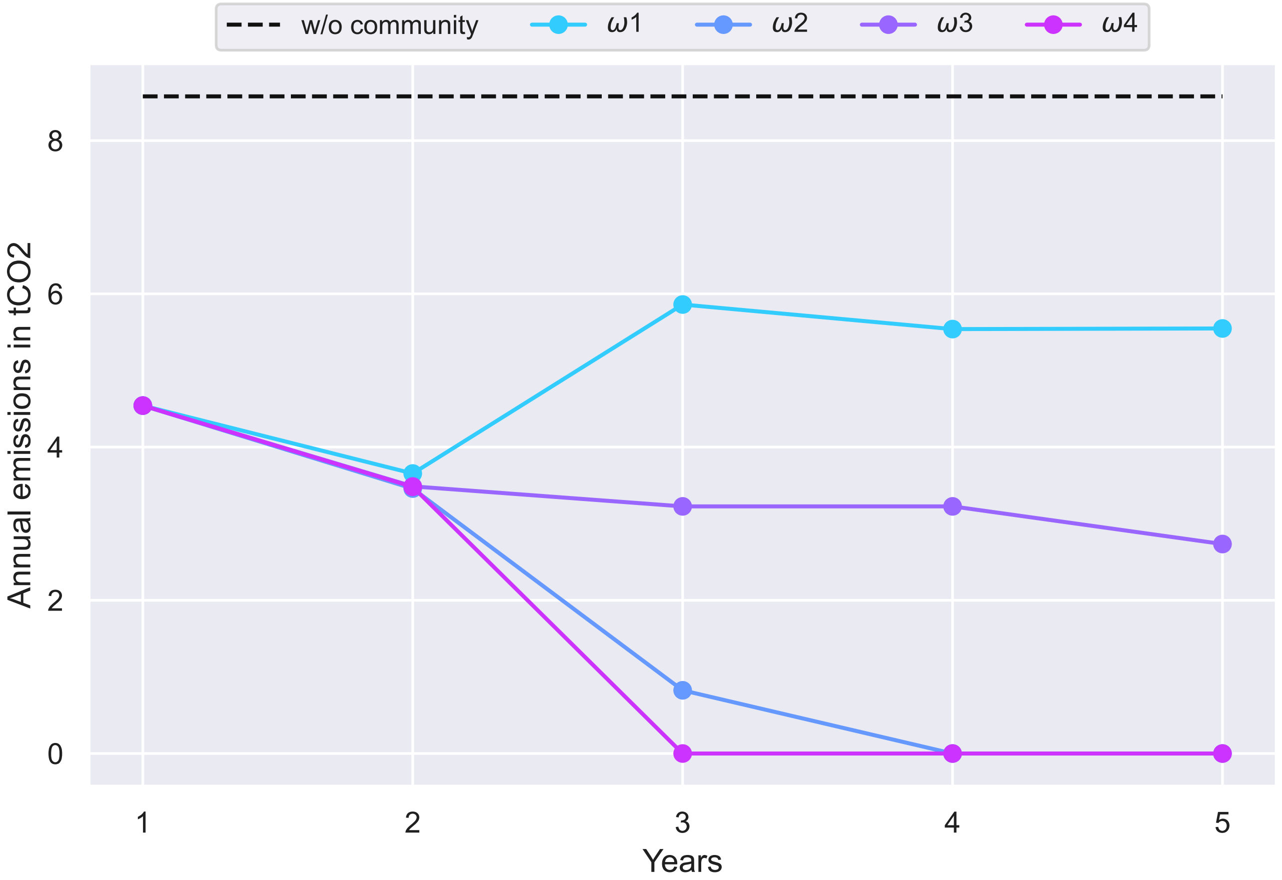
Scenarios

- Finite set of scenarios to represent possible developments within energy communities.
- Considering a high number of possible prosumers and their decisions as well as a time horizon of a few years, in general one would end up with a very large scenario tree.
- Due to the high computational efforts of stochastic programming, we do not aim at using the full scenario tree for our research. Instead, a relatively small set of completely different scenarios is developed to represent the wide spectrum of possibilities.
- The use case that will be shown in the results section considers three prosumer types: single houses (SH), apartment buildings (SAB), and small businesses (SME). At the beginning, 5 SHs, 4 SABs, and 1 SME are present in the community.
- From there, four different scenarios are considered:
  - ω_1: additional SABs might want to join in the upcoming years
  - ω_2: the SABs might want to phase-out in the upcoming years
  - ω_3: additional SHs might want to join in the upcoming years
  - ω_4: the SHs might want to phase-out in the upcoming years

Results: Acceptance/dropping out per scenario



Results: Emissions per scenario



Conclusions

Findings and limitations of this work:

- Objective function minimizes individual emission balances instead of costs
  - Peer-to-peer trading includes preference to save emissions
  - Environmental incentives play a particularly important role for participants of energy communities
  - This analysis focuses entirely on environmental interests
- Rejection of potential participants
  - Energy community should be a small, socially tangible entity of manageable size
  - Boundaries are consciously drawn
- Scenario selection can be crucial if wrong assumptions are made
- How to implement in practice?
  - Forecast of electricity demand of future participants difficult

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Energy Economics Group

Thank you for your attention!

GitHub

https://github.com/tperger/PARTICIPATE

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

Energy community model FRESH:COM

About the (open-source) model:

- Linear optimization model FRESH:COM [4] maximizing the community welfare of a **local energy community by peer-to-peer trading**
  - Community welfare:

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

- Allocation mechanism: Peer-to-peer trading under the consideration of each prosumer's *individual willingness-to-pay*:

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

- Members: Private households and SMEs
  - Photovoltaic (PV) and Battery Energy Storage Systems(BESS)

[4] T. Perger, FRESH:COM, https://github.com/tperger/FRESH-COM