Fraunhofer IEG

Network Expansion and Design Optimization of District Heating Systems utilizing Open Data

Energy Innovation Summit 2024 - Optimization Strategies for the Energy Transition

Maximilian Sporleder
14.03.24

Table of Content

 © Fraunhofer IEG

Fraunhofer IEG

Motivation

- **Moving away from fossil fuels and phasing out coal**
- **Accelerating the decarbonization process in the heating sector**
- **Utilzing district heating networks in the decarbonization process**

Foto: Frank Hilbert

Network expansion will be a key factor in the energy transition

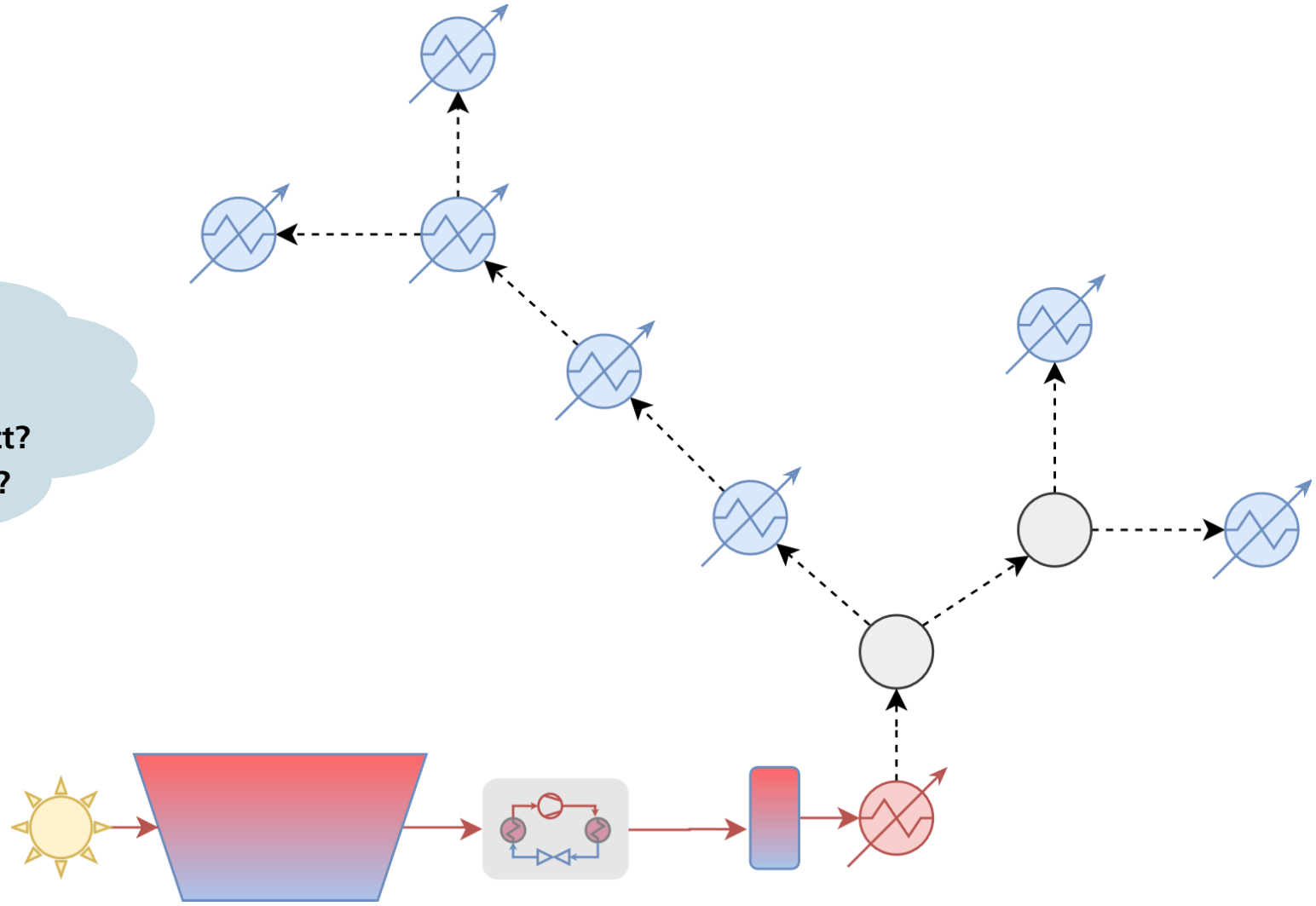
Electrification of the heating sector integrating heat pumps as central supply systems and using seasonal storage facilities

© Fraunhofer IEG

Motivation

Supplying a City District

How can we supply a city district with renewable energy? What would be the buildings to connect? What is the design of the system?



© Fraunhofer IEG

Fraunhofer IEG

Introduction

Use Case and Workflow

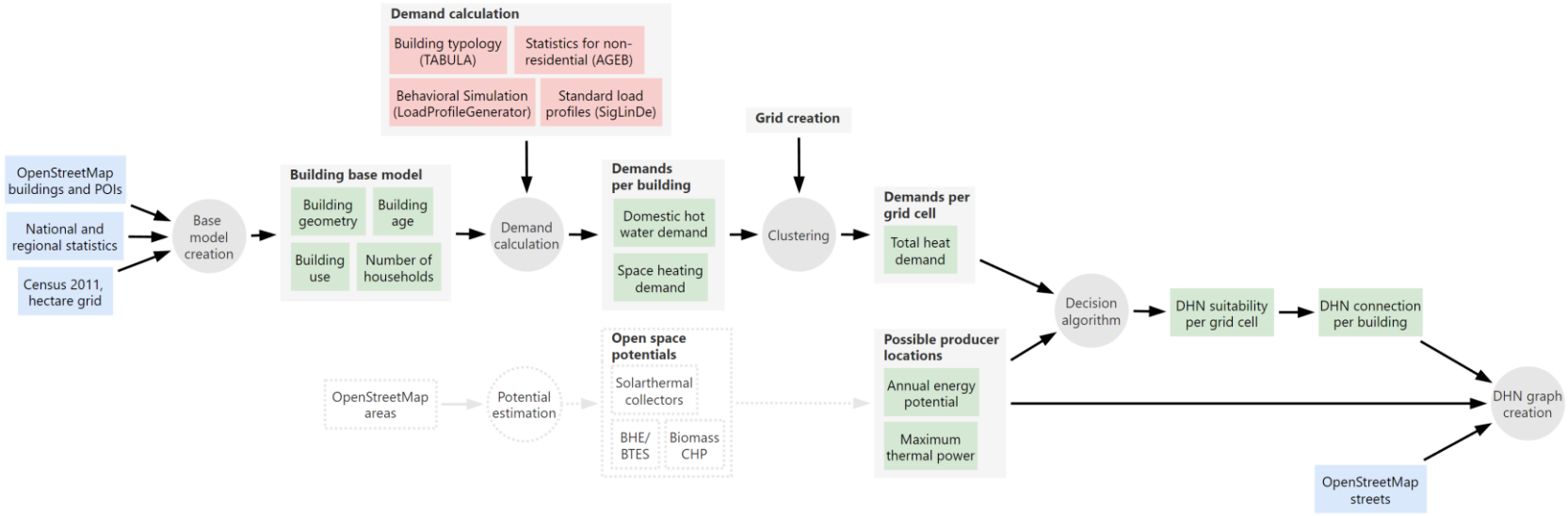
Two-stage workflow

- Preparatory workflow: Calculate demands and find a network graph
- Optimization: Find a cost-optimal supply system

Use Case

- Located in the West of Frankfurt
- Ca. 700 buildings, mainly residential

© Google, GeoBasis-DE/BKG



 © Fraunhofer IEG

Fraunhofer IEG

Demand estimation

Create base models and apply established demand models

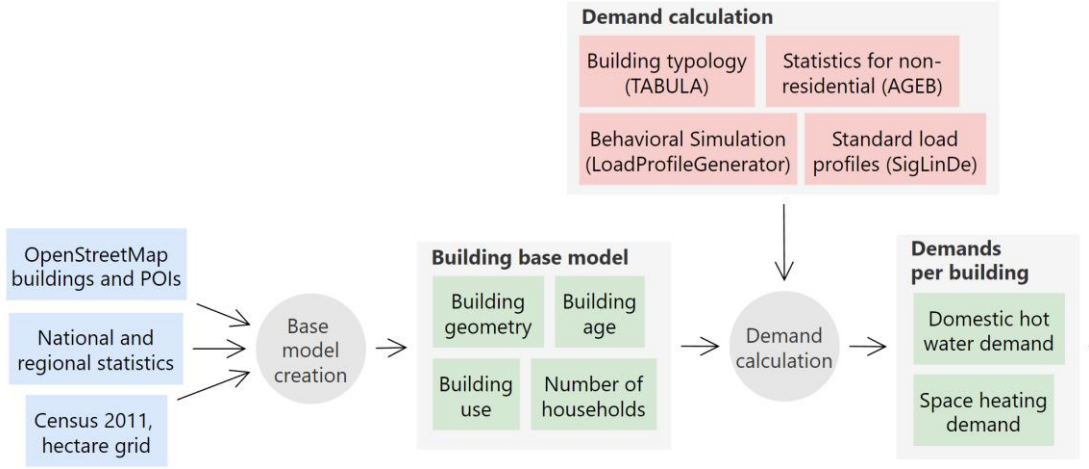
Base model creation per building

- Use Open Data to create core information
  - OpenStreetMap
  - LoD1 models (availability/license depending on State)
  - Census data on building use, households etc. per 100x100 m² grid cell

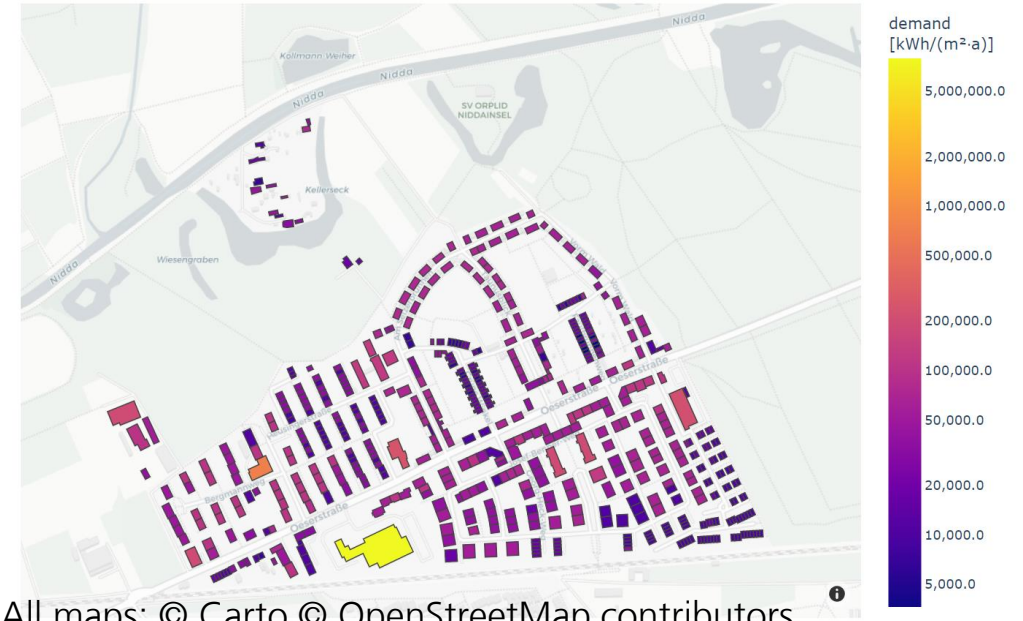
- Data enrichment by
  - additional statistics
  - heuristics and plausibility checks

Demand calculation per building

- Assume TRY climate time series (DWD)
- Residential buildings:
  Tabula building typology with standard load profiles
- Commercial and public buildings:
  national AGEB statistics with standard load profiles



demand (heat)

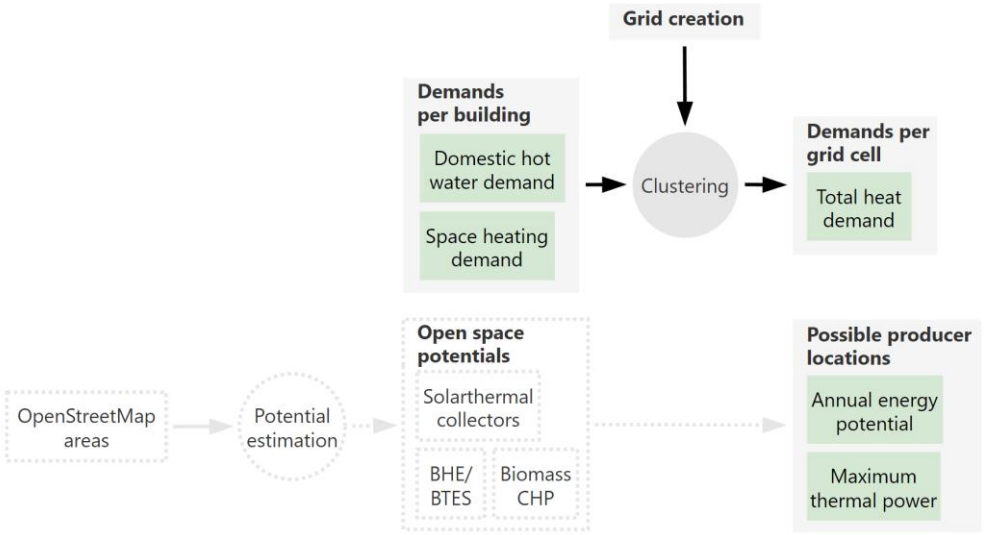


All maps: © Carto © OpenStreetMap contributors

 © Fraunhofer IEG

Fraunhofer IEG

Potential estimation and Clustering



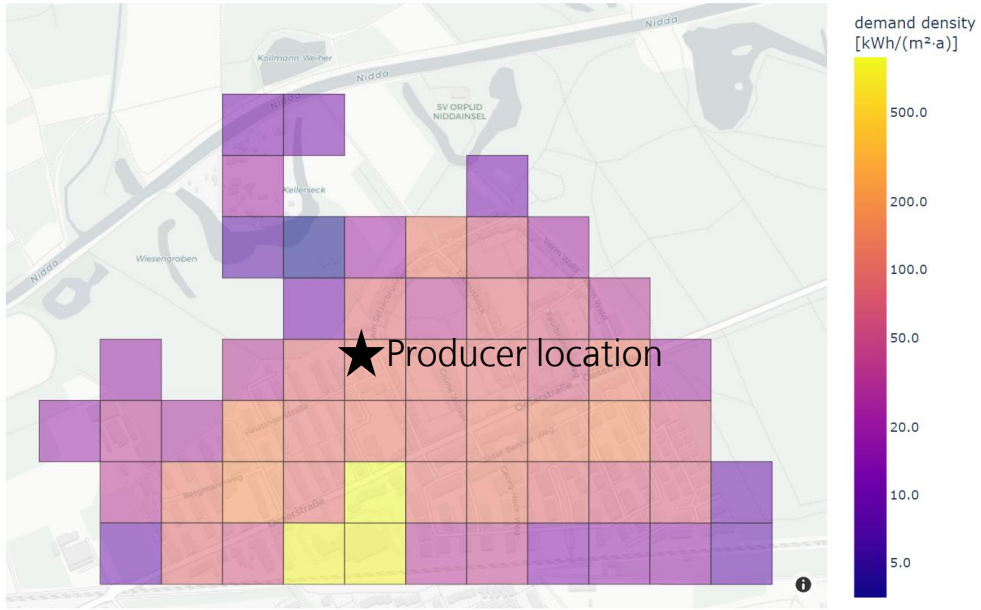
Estimate potential

- Potential can be estimated by analyzing OpenStreetMap data (open space, lakes and rivers, exclusion criteria)
- In this case: Assume a producer at a given location
  - maximum thermal power of 3 MW
  - Maximum annual energy of 10 GWh

Estimate DHN suitability

- As a pre-stage to optimization, decide which regions are worth connecting
- Square grid of 100x100 m²
- Per grid cell, calculate for all contained buildings
  - total heat demand
  - maximum thermal power

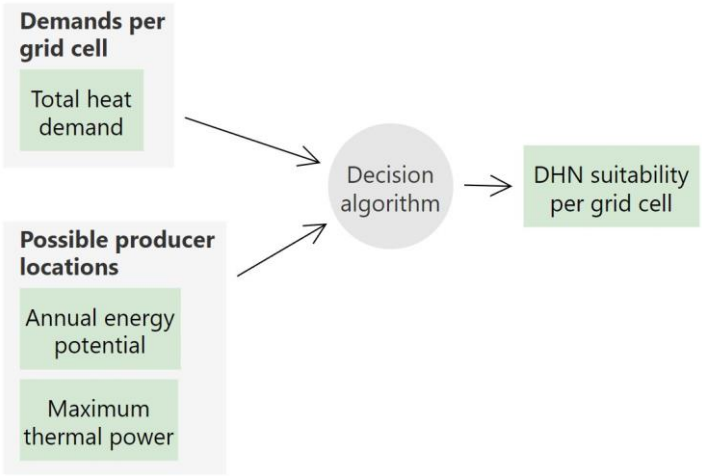
demand density (heat)



 © Fraunhofer IEG

Fraunhofer IEG

Expansion Algorithm

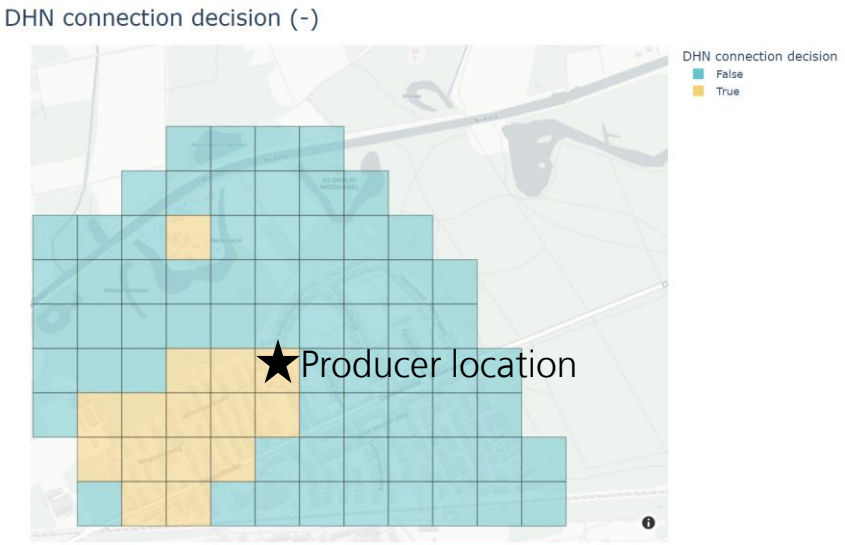


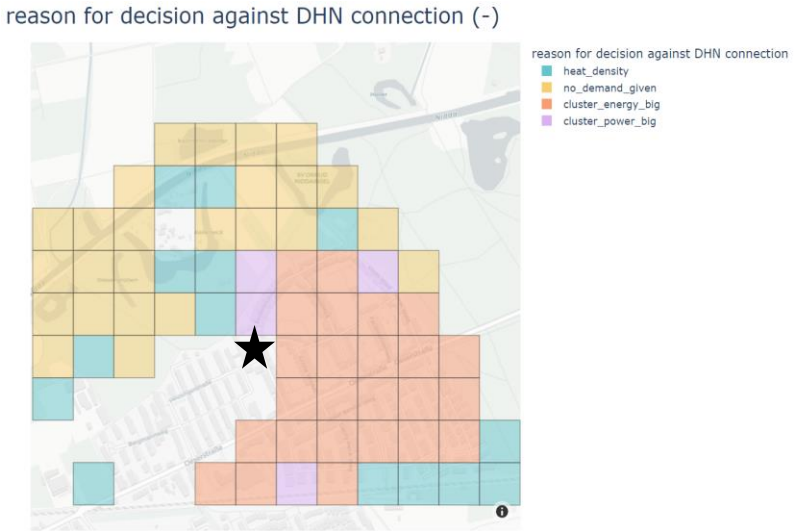
Algorithm description (rule-based)

- Inputs: Cluster, Producer
- Algorithm
  - Sort clusters from closest to farthest from producer
  - If producer's energy and producer's max. heat flow is sufficient: connect and subtract cluster's energy and max. heat flow from the producer
  - Continue until the producer's energy is empty
- Min. energy density 15 kWh/m²
- Max. distance 5 km
- Connection rate 70 %

Result

- Most parts of the district have been ruled out by heuristics
- Single remote cell with positive connection decision

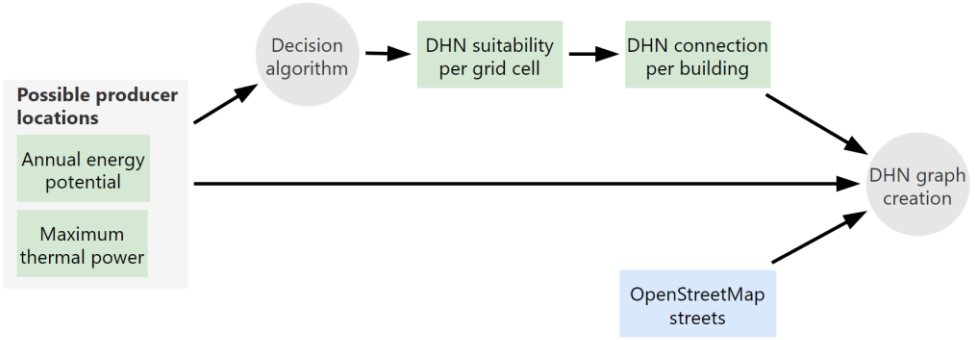




 © Fraunhofer IEG

Fraunhofer IEG

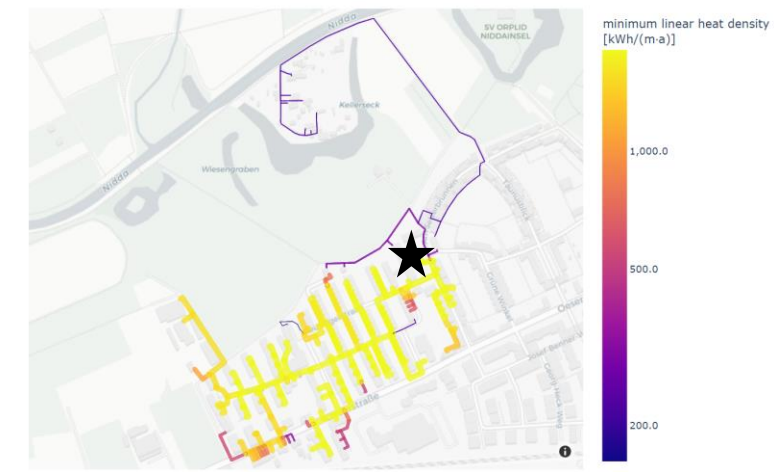
DHN graph creation



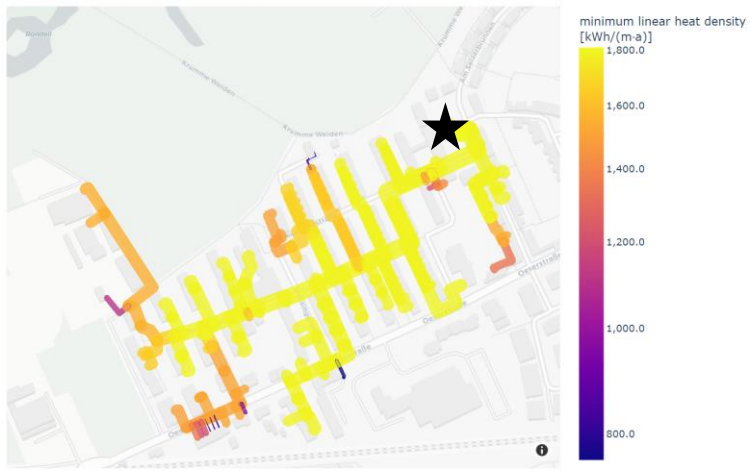
- Create street graph from OpenStreetMap
- For clusters with positive decision: Assign each building to closest street
- Create subgraph as minimum spanning tree containing all producers and connected buildings
- Prune network by all parts that are connected to the producers by any line with downstream linear heat densities of less than 700 kWh/(m·a)

net exergy flow (-)

minimum linear heat density (-)



minimum linear heat density (-)

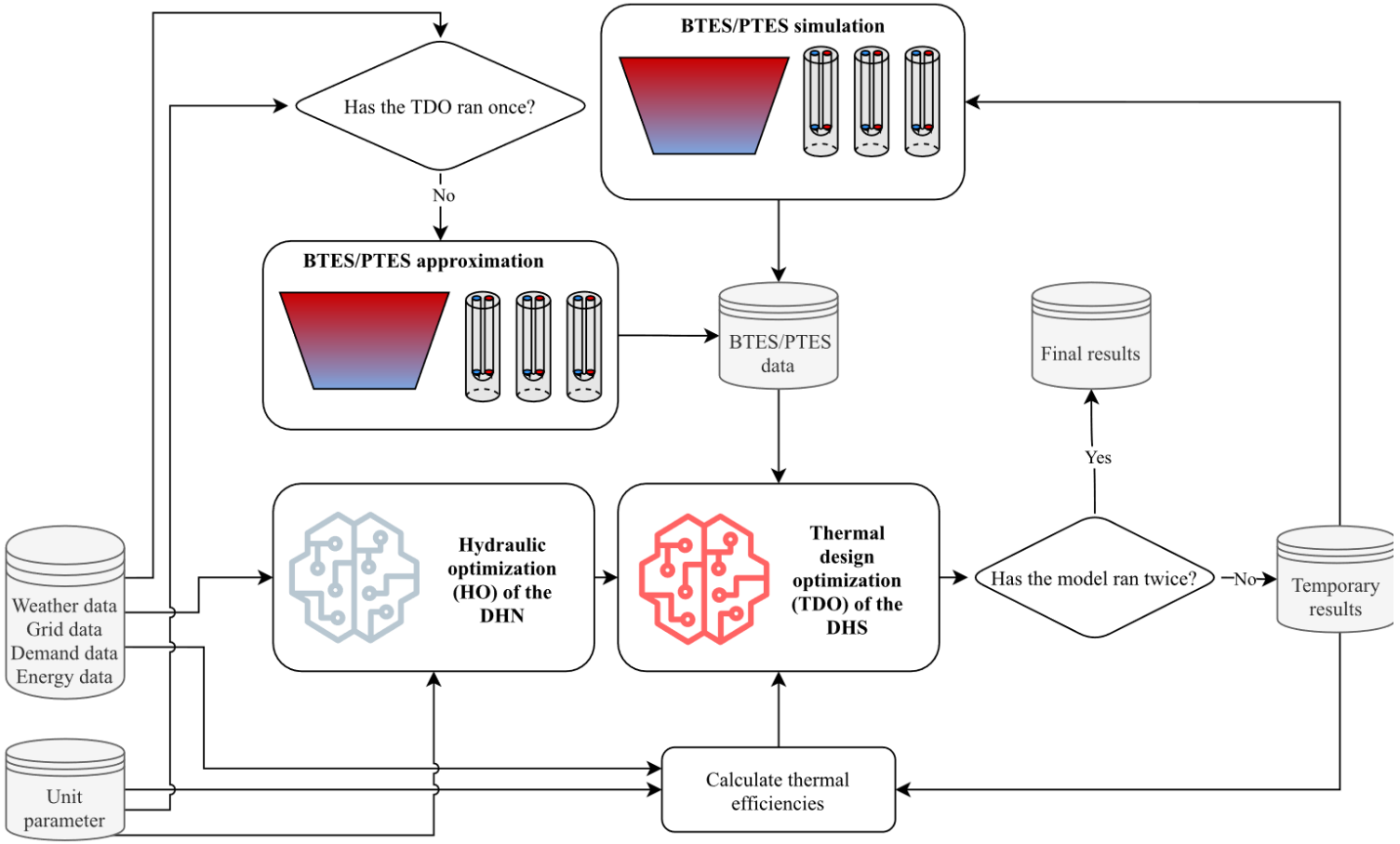


 © Fraunhofer IEG

Fraunhofer IEG

Method

Focus: Design not Controll



Optimization Metrics

- Optimization horizon: 1 year
- Timestep: Variable, but for larger systems one day

Key simplifications

- Separate thermal and hydraulic calculation
- Run the thermal design optimization twice and adjust thermal efficiencies (COPs)
- Separate optimization from the seasonal storage simulation

© Fraunhofer IEG

Method

Most important equations for the network

Objective Function

Annuity method applied

$$\min\left(\sum_{a\in Z^{\mathrm{conv}}\cup Z^{\mathrm{stor}}\cup Z^{\mathrm{transfer}}\cup Z^{\mathrm{add\_equip}}} C_a^{\mathrm{inv}} + \Delta t \sum_{t\in Z^{\mathrm{time}}} opex_t^{\mathrm{var}} + opex^{\mathrm{fix}}\right)\alpha$$

Energy Balance Pipes

Mass flow becomes here a parameter

$$c_{\mathrm{p}} m_a \frac{T_{a,t-1}^{\mathrm{out}} - T_{a,t}^{\mathrm{out}}}{\Delta t} + \dot{m}_{a,t} c_{\mathrm{p}}\left(T_{a,t}^{\mathrm{in}} - T_{a,t}^{\mathrm{out}}\right) - U_a A_a^{\mathrm{m}}\left(T_{a,t}^{\mathrm{out}} - T_t^{\mathrm{soil}}\right) = 0 \quad for\ a \in Z^{\mathrm{pipes}}, t\ \in Z^{\mathrm{time}}$$

Energy Storage — *Thermal in-/output* — *Thermal losses*

$$\sum_{a\in Z^{\mathrm{pro}}} \dot{Q}_{a,t}^{\mathrm{pro}}\ \mu^{\mathrm{pro}} \geq \sum_{\mathrm{a}\in Z^{\mathrm{con}}} \frac{\dot{Q}_{a,t}^{\mathrm{con}}}{\mu^{\mathrm{con}}} + \sum_{a\in Z^{\mathrm{pipes}}} \left(U_a A_a^{\mathrm{m}}\left(T_{a,t}^{\mathrm{out}} - T_t^{\mathrm{soil}}\right) - c_{\mathrm{p}} m_a \frac{T_{a,t-1}^{\mathrm{out}} - T_{a,t}^{\mathrm{out}}}{\Delta t}\right) \qquad for\ t \in Z^{\mathrm{time}}, a \in Z^{\mathrm{pro}}$$

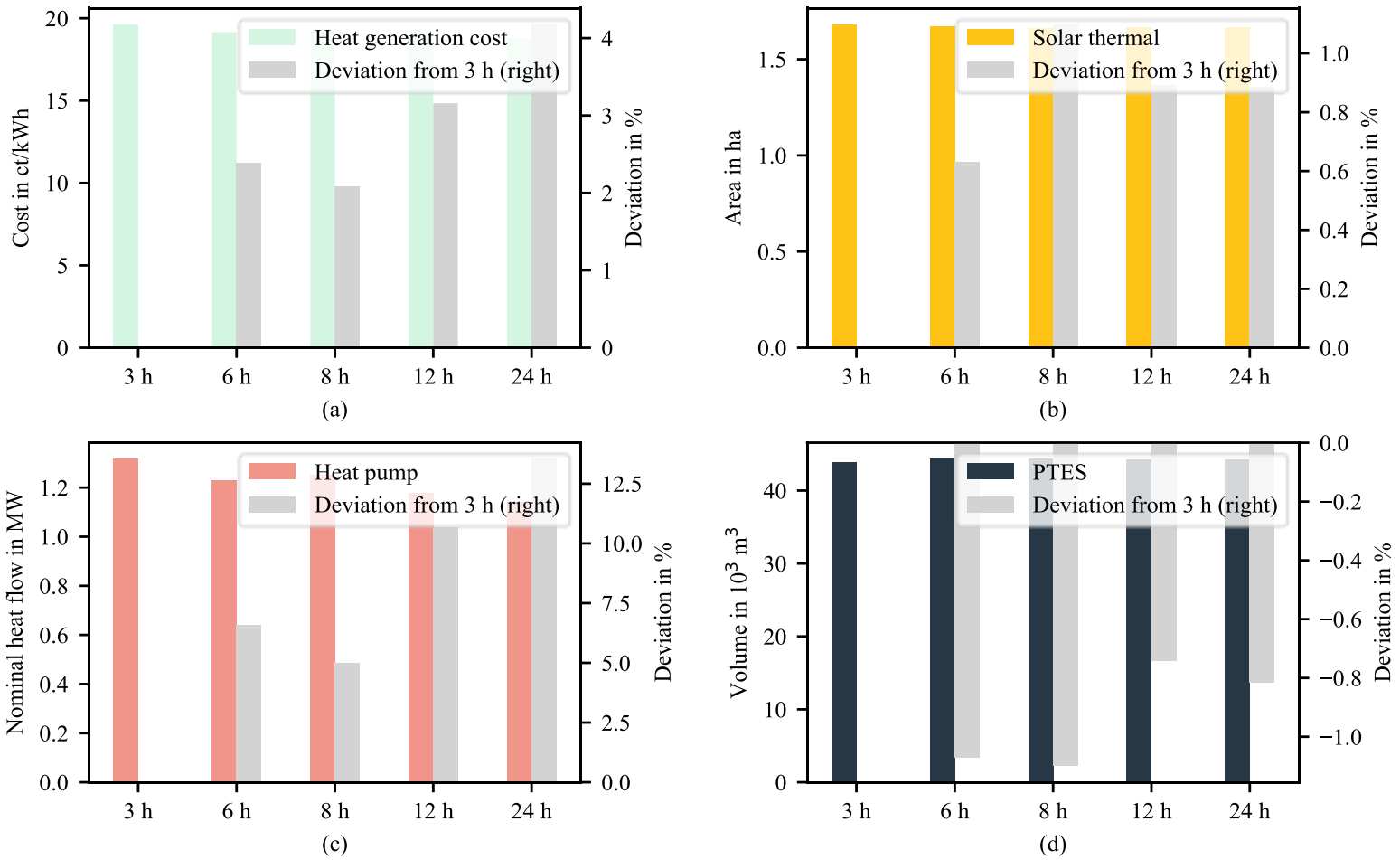
Energy Balance over the System

Equation is basically unnecessary because each consumer and producer is modelled individually

© Fraunhofer IEG

Method

Problem: High timestep



a) Cost Influence

- The costs vary up to 4 %
- The variation is mainly caused by the capex

b) Solar Thermal Device

- The deviation is very low (< 1 %)
- The extracted heat via solar thermal energy stays the same

c) The Heat Pump

- The deviation is the dimension is relatively high (~ 12.5 %)

d) The PTES (Storage)

- The deviation is neglectable

Introduction of a peak shaving factor depending on the max. heat demand for 1 h timestep vs. 24 h timestep

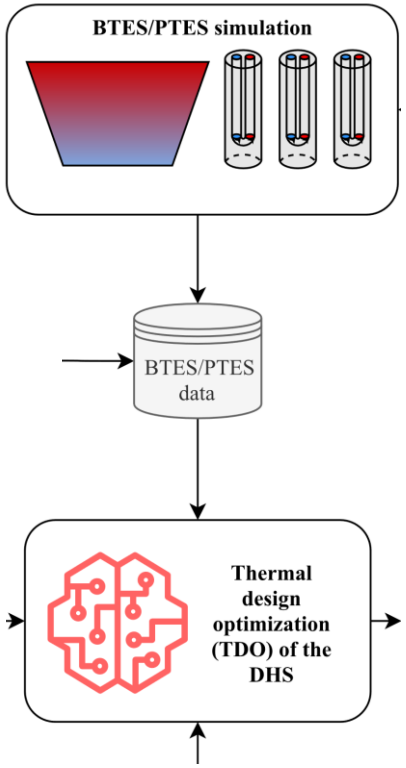
© Fraunhofer IEG

Method

Pit Thermal Energy Storage

Optimization model

- Has SOS2-constraints for
  - the surface areas: bottom, top, side
  - capex
  - depend on the volume
- The top and bottom temperature are parameters inside the optimization
- Heat losses depend on the top, bottom temperature and the surface areas
- Output: Charging and discharging curves for one year



Simulation model

- Takes the surface areas and volume and builds a realistic geometric model of the PTES
- The charging and discharging curves are given into the simulation
- Output: Top and bottom temperature of the storage

Optimization model second run

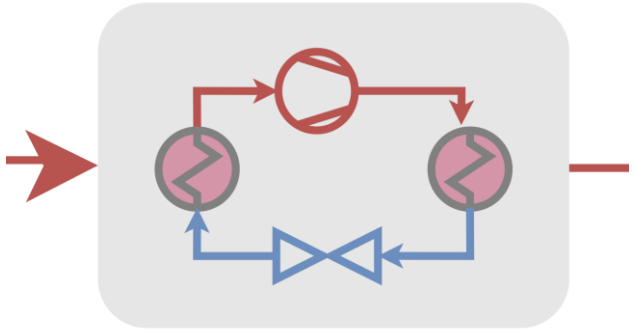
- If the top temperature is high enough, the storage discharges the energy directly into the network
- If the top temperature is not high enough, a heat pump lifts the fluid's temperature

© Fraunhofer IEG

Method

Second stage of heat pumps

How many stages does my heat pump need and does it influence the capex?



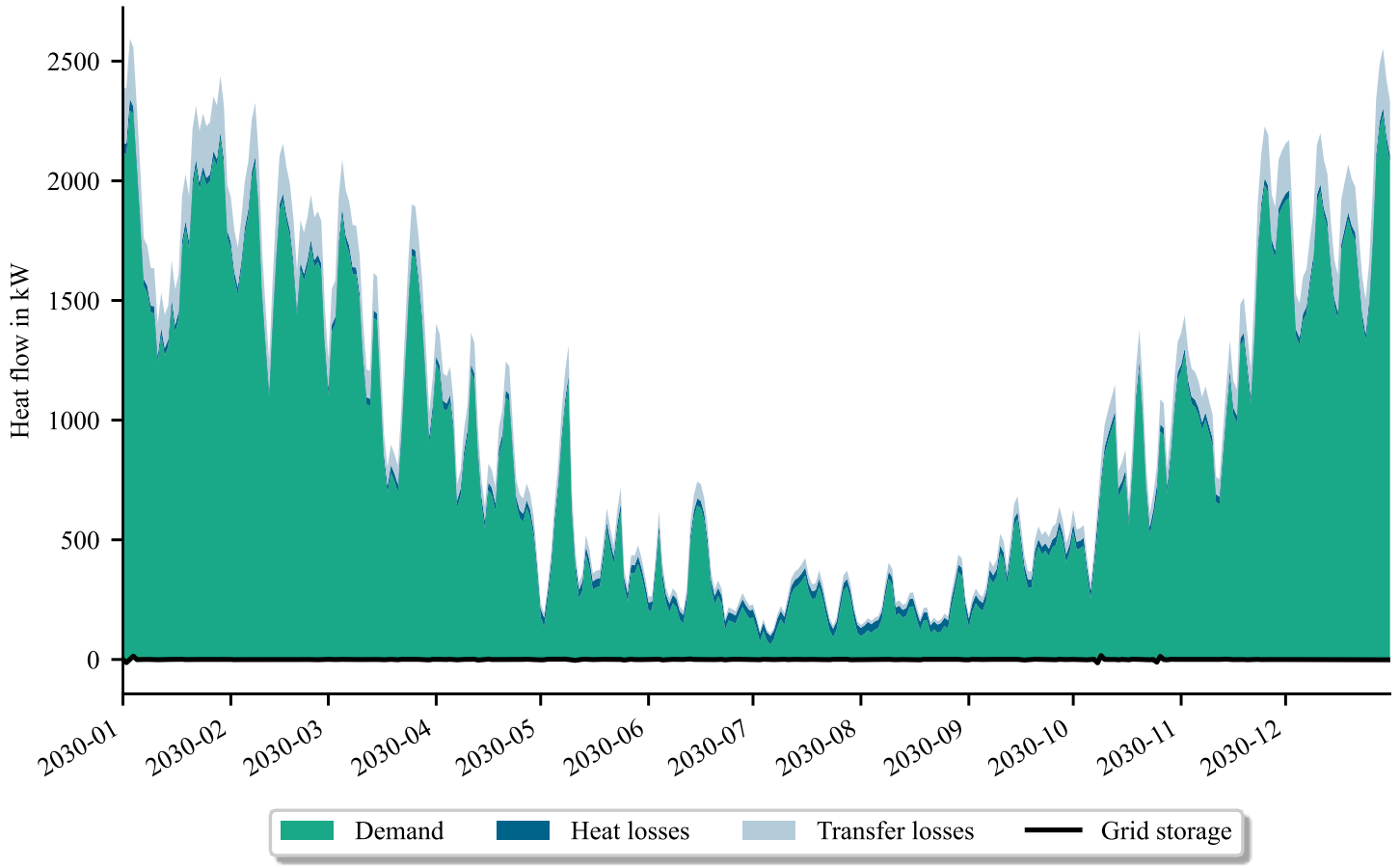
$$\sum_{t \in \tau^{\text{critical}}} u_{i,t} \leq \gamma_i n(\tau) \quad for\ i \in Z^{\text{heat pump}}$$

- The critical times occur when the temperature delta between sink and source exceeds 75 K
- If the heat pump is turned on at these times the capex increase by 60 %

© Fraunhofer IEG

Results Case Study

Demand – ca. 8 GWh

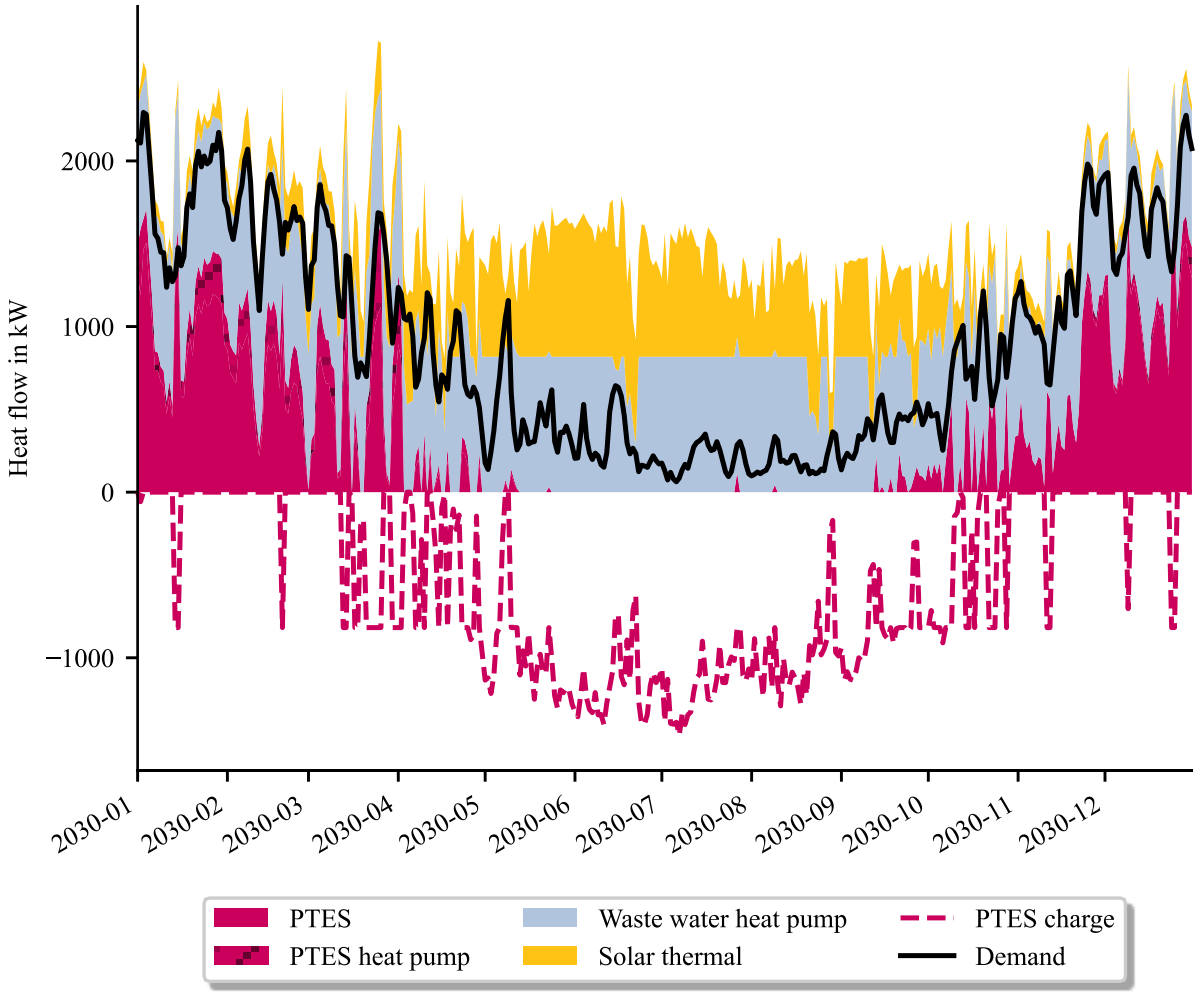


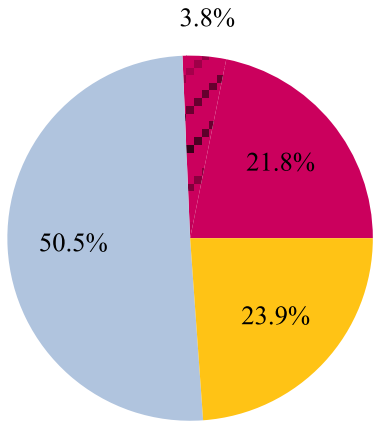
 © Fraunhofer IEG

Fraunhofer IEG

Results Case Study

Central Supply System





© Fraunhofer IEG

Fraunhofer IEG

Results Case Study

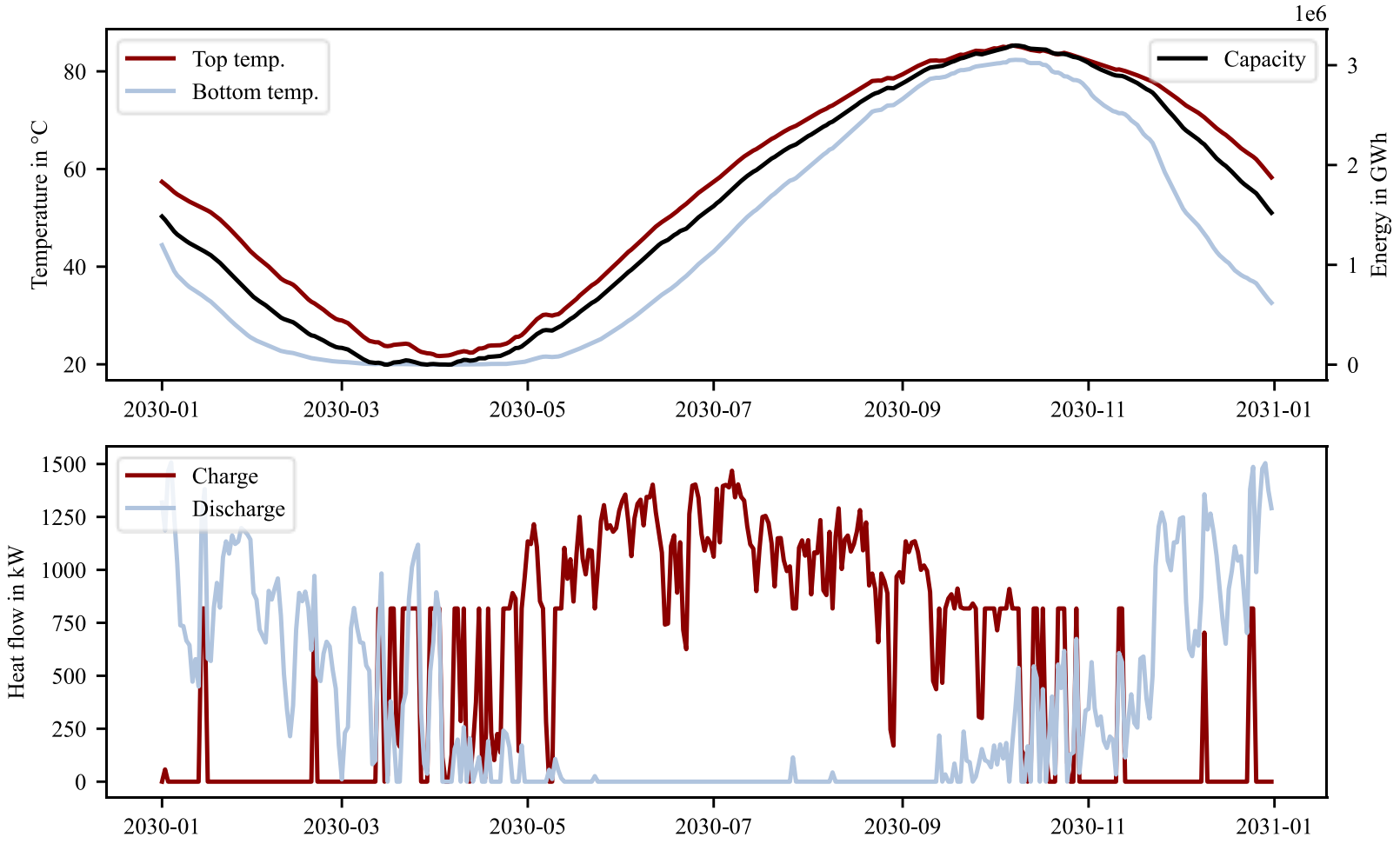
Central Supply System – 18 ct/kWh

Name	Energy [MWh]	Capex [k€]	Dimension	Space [m²]
Buffer tank	0	0	0	0
PV	796	413	3,469 m^2	10,407
PTES	3,012	1,651	45,116 m^3	6,533
PTES heat pump	3,117	2,295	2.1 MW	313
Solar thermal	3,293	1,428	7,475 m^2	22,425
Waste water heat pump	6,063	2,339	1 MW	300
Total	17,182	8,126		40,000 (almost six football fields)

© Fraunhofer IEG

Results Case Study

Pit Thermal Energy Storage



 © Fraunhofer IEG

Fraunhofer IEG

Conclusion and Outlook

Main Take-Aways

Optimization approach

- Combine simulation and optimization
- Increase timesteps and work with a factor to adjust design
- Hierarchical model

Problems

- Computational time
- Large timesteps
- Simplifications of the physical system

Future

- Further increase technical accuracy through combining simulation and optimization
- Reduce computational time
- Increase number of scenarios → decreasing uncertainties
- Improve DHN optimization algorithm

© Fraunhofer IEG

Thank You for Your Attention

Maximilian Sporleder, M.Sc.
Research Associate
Heat Grids 4.0

Fraunhofer IEG
Institution for Energy Infrastructures and Geothermal Systems
Breslauer Straße 48 | 76139 Karlsruhe | Germany
I E maximilian.sporleder@ieg.fraunhofer.de

Open-Source Gitlab Repository