Decentral Heat Storages in System-Beneficial District Heating Systems – an Integrated Optimization Approach

Johannes Röder [a*], Uwe Krien [a], Benedikt Meyer [a], Torben Stührmann [a], Edwin Zondervan [b]

[a] Department Resilient Energy Systems, University of Bremen

[b] Laboratory of Process Systems Engineering, University of Twente

* Correspondence: johannes.roeder@uni-Bremen.de

Powerd by

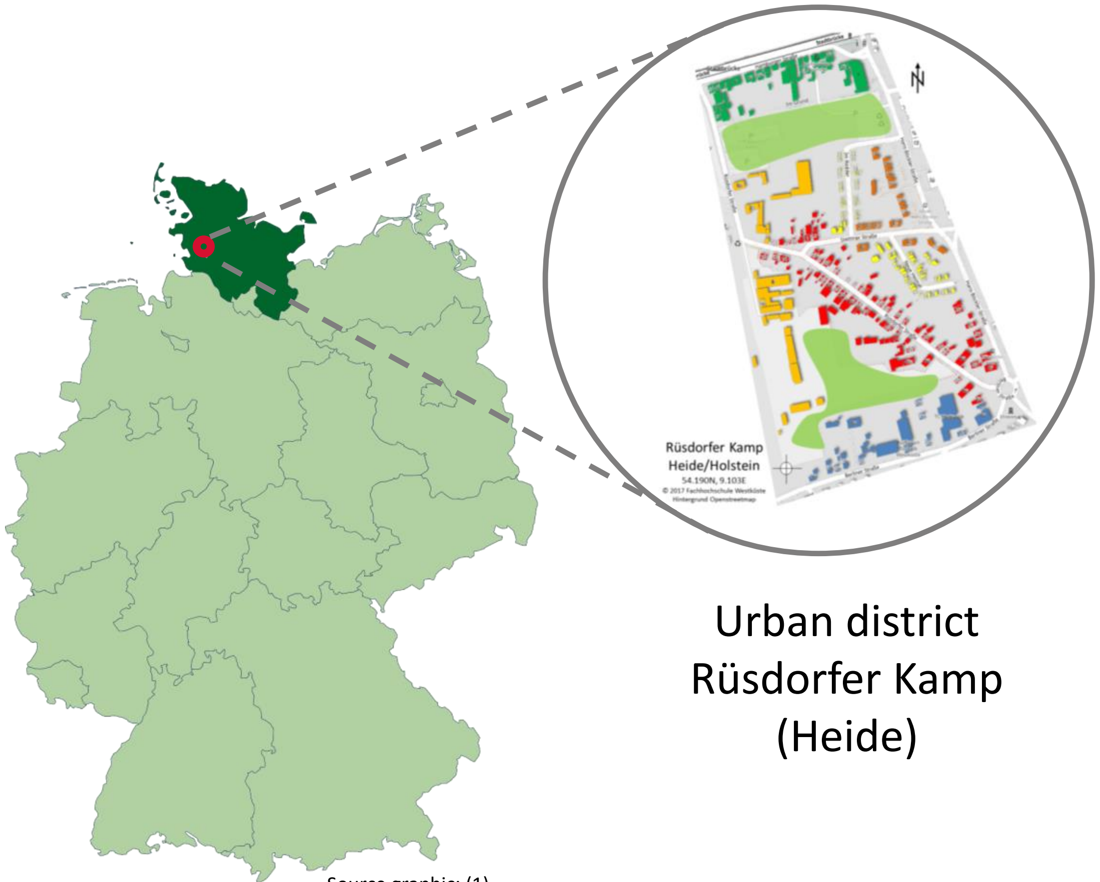
QUARREE 100

Research Project QUARREE100

- Resilient, scalable and transferable energy system solutions for built-up urban districts
- High share of renewable energies in all energy sectors
- Integration of urban districts in the overall energy system

➢ **Implementation of a district heating system (DHS)**

➢ **Option of distributed thermal energy storages (DTES) could be a promising solution for this district**



Urban district Rüsdorfer Kamp (Heide)

Source graphic: (1)

Bundesministerium für Bildung und Forschung
Bundesministerium für Wirtschaft und Energie
PtJ Projektträger Jülich Forschungszentrum Jülich

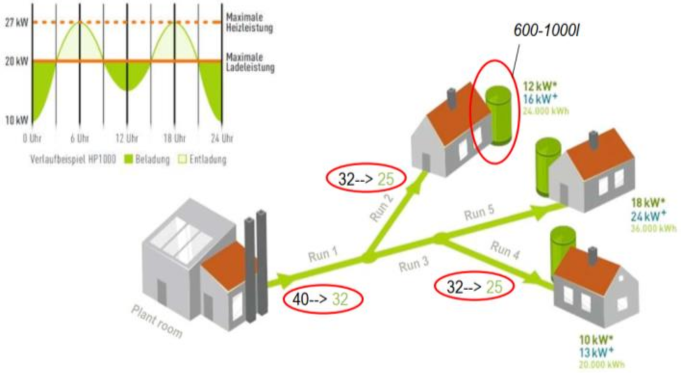
(1) https://de.wikipedia.org/wiki/Datei:Deutschland_Lage_von_Schleswig-Holstein.svg

Motivation and research question

- Benefits of distributed thermal energy storages (DTES) in DHS:
  - Optimization of overall DHS operation [1–4]
  - Avoidance of low mass flows in summer
  - Hot warm water storage in many cases reasonable anyway (e.g. multi-family houses)
  - Integration of renewable energies [4, 5]
  - Leaner piping network due to peak-shaving [1, 6, 12]

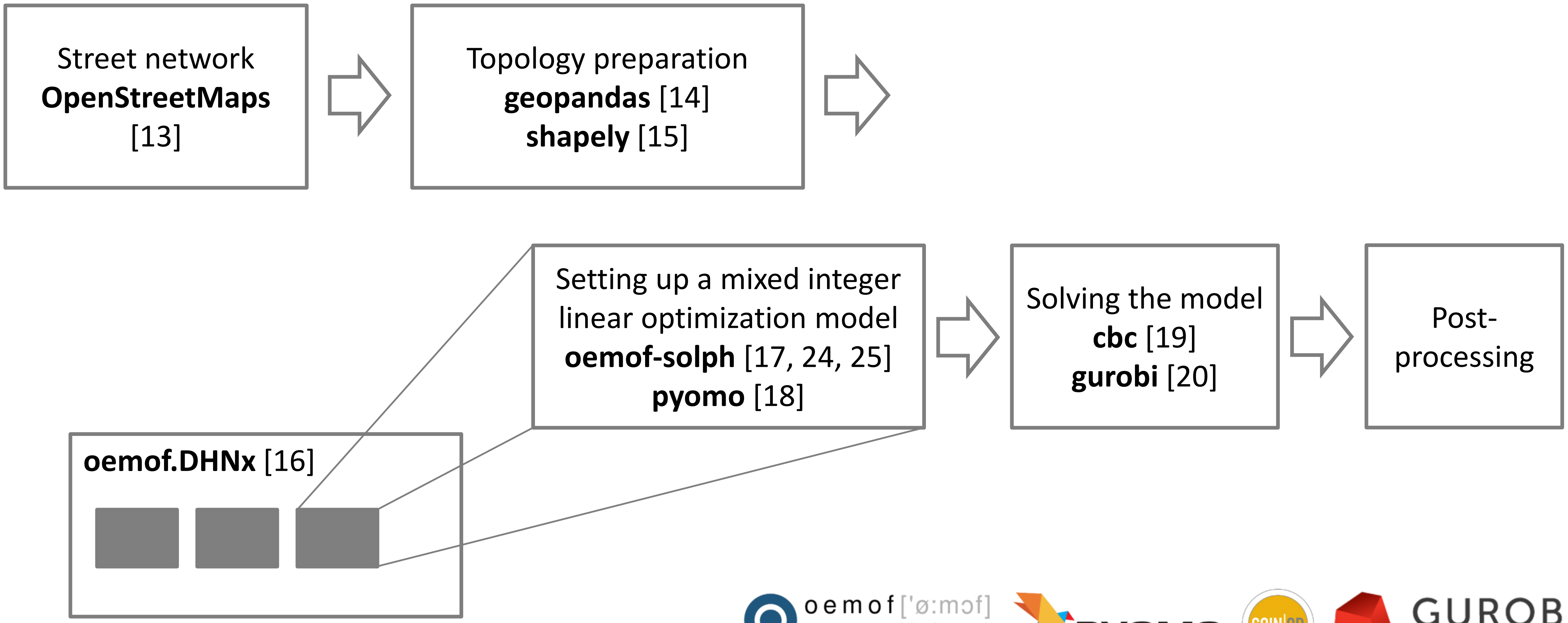
➢ **How to optimize the topology and the sizing of a district heating network with distributed thermal storages?**

- Existing planning tools for DH networks, e.g.:
  - THERMOS [7, 8]
  - Li et al. [9], Dorfner [10], Bordin et al. [11]



Source: ENERPIPE GmbH [12]

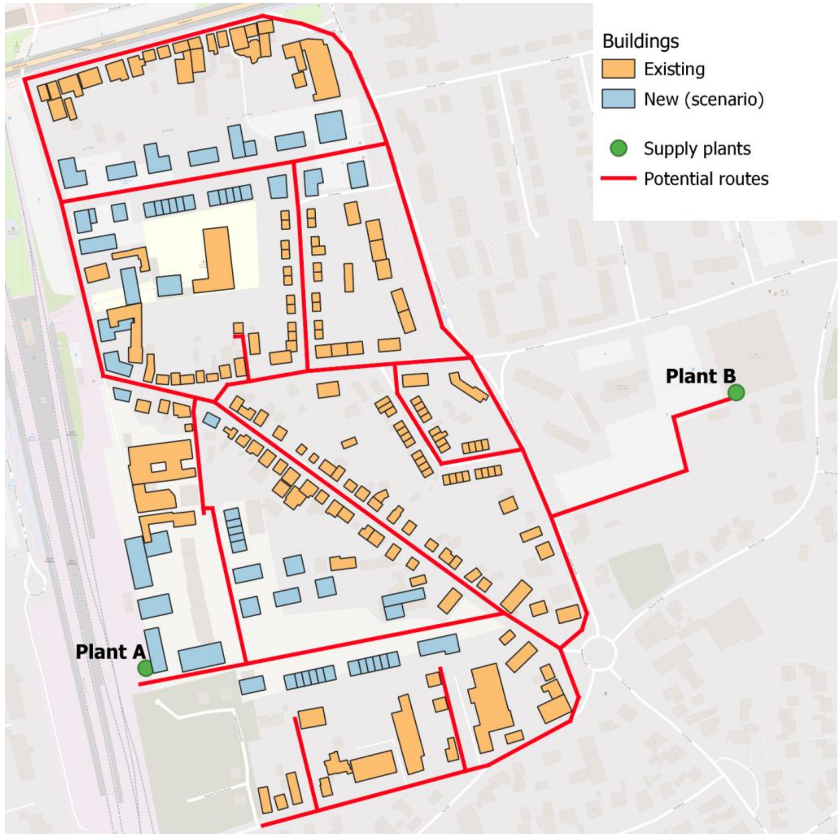
Modeling approach – Overview



Modeling approach – Topological input data

RESILIENT ENERGY SYSTEMS

LABORATORY OF PROCESS SYSTEMS ENGINEERING



Potential routes for piping network; Background map: [13]

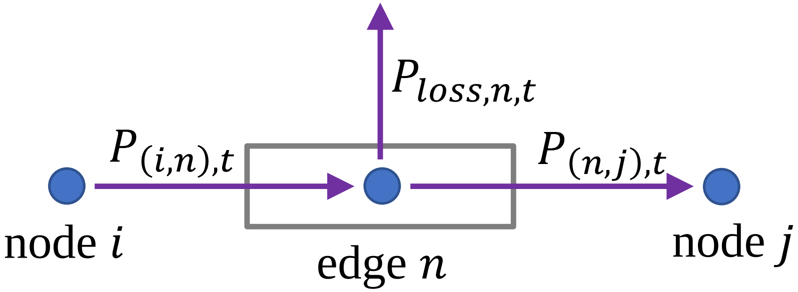
- Geometry preprocessing
- Assignment of IDs

Network after geometry processing; Background map: [13]

- ➢ Street network (e.g. from OpenStreetMaps [13]) serves as potential routes for the district heating network
- ➢ Detailed district heating system model (customers are represented individually)

Modeling approach – Mathematical background

District heating pipes [8, 21]



$$C_n = P_{(n,j),invest} \cdot c_{invest} + y_{(n,j)} \cdot c_{investfix}$$

$$P_{loss,n,t} = P_{(n,j),invest} \cdot f_{loss,t} + y_{(n,j)} \cdot f_{lossfix,t}$$

$$P_{(n,j),t} = P_{(i,n),t} - P_{loss,n,t}$$

$$P_{(i,n),invest} = P_{(n,j),invest}$$

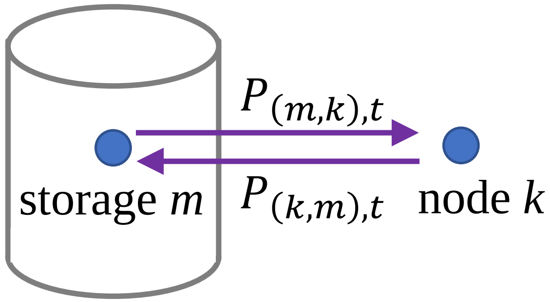
$$P_{(n,j),invest\,min} \cdot y_{(n,j)} \leq P_{(n,j),invest} \leq P_{(n,j),invest\,max} \cdot y_{(n,j)}$$

$$-P_{(i,n),invest} \leq P_{(i,n),t} \leq P_{(i,n),invest}$$

$$-P_{(n,j),invest} \leq P_{(n,j),t} \leq P_{(n,j),invest}$$

$$y_{(n,j)} \in \{0,1\}$$

Thermal storages [17]



$$W_{m,t} = W_{m,t-1} \cdot (1 - \delta_{m,t}) - P_{(m,k),t} \cdot \Delta t + P_{(k,m),t} \cdot \Delta t$$

$$W_{m,t_{last}} = W_{m,t_{zero}}$$

$$0 \leq W_{m,t} \leq W_{nom}$$

Objective function

$$\min! \sum_n C_n$$

Variables

C_n	€	Investment costs of DHS pipe n
$P_{(n,j),invest}$	kW	Capacity of DHS pipes
$P_{(n,j),t}$	kW	Heat flow at time step t
$y_{(n,j)}$	-	Investment decision variable (0 = no investment; 1 = investment)
$W_{m,t}$	kWh	Quantity of heat in storage at t

Parameters

c_{invest}	€/kW	Capacity dependent investment costs
$c_{investfix}$	€	Fix investment costs
f_{loss}	kW/kW	Capacity dependent heat loss
$f_{lossfix}$	kW	Fix heat loss
$P_{(n,j),invest\,min}$	kW	Minimum pipe capacity
$P_{(n,j),invest\,max}$	kW	Maximum pipe capacity
W_{nom}	kWh	Capacity of thermal energy storage
δ_m	-	Loss rate
Δt	0.25 h	Time step width

Modeling approach – Pipeline parameters

Max. pressure drop *[Pa/m]*
Roughness *[mm]*
Temperature level [°C]

→

Max. flow velocity *[m/s]*

Temperature spread *[K]*

→

Max. heat transport capacity *[kW]* for each nominal diameter

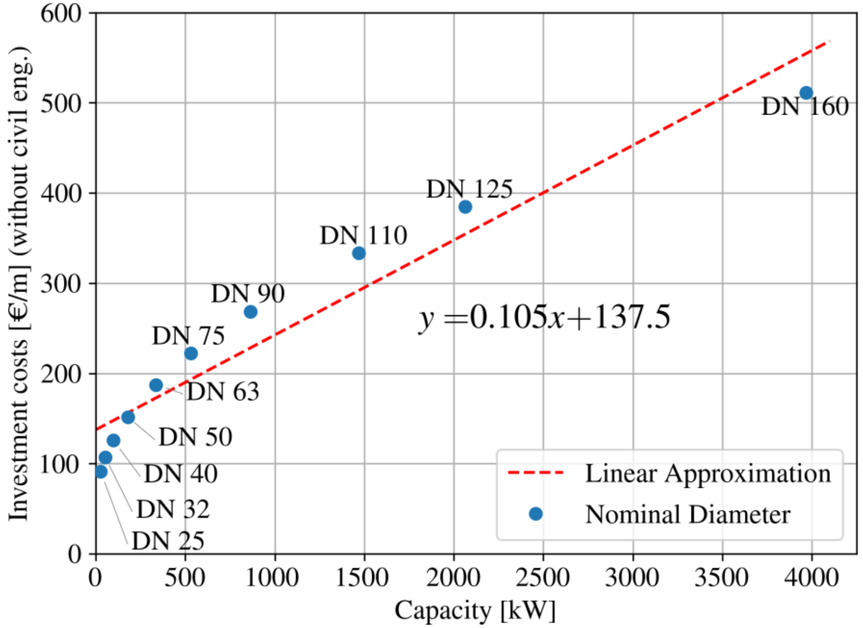
→

Specific costs per capacity *[€/(kW·m)]*

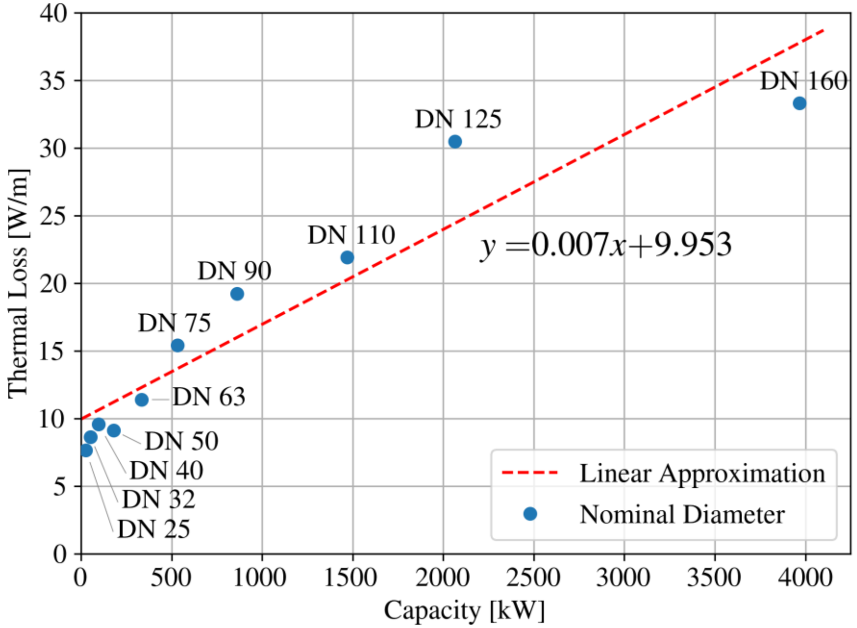
Specific heat loss per capacity *[W/(kW·m)]*

→

Linearization



Cost function for pipes: *50 €/m + (700 m^{-1} * DN)$^{1.3}$ €/m* [7]



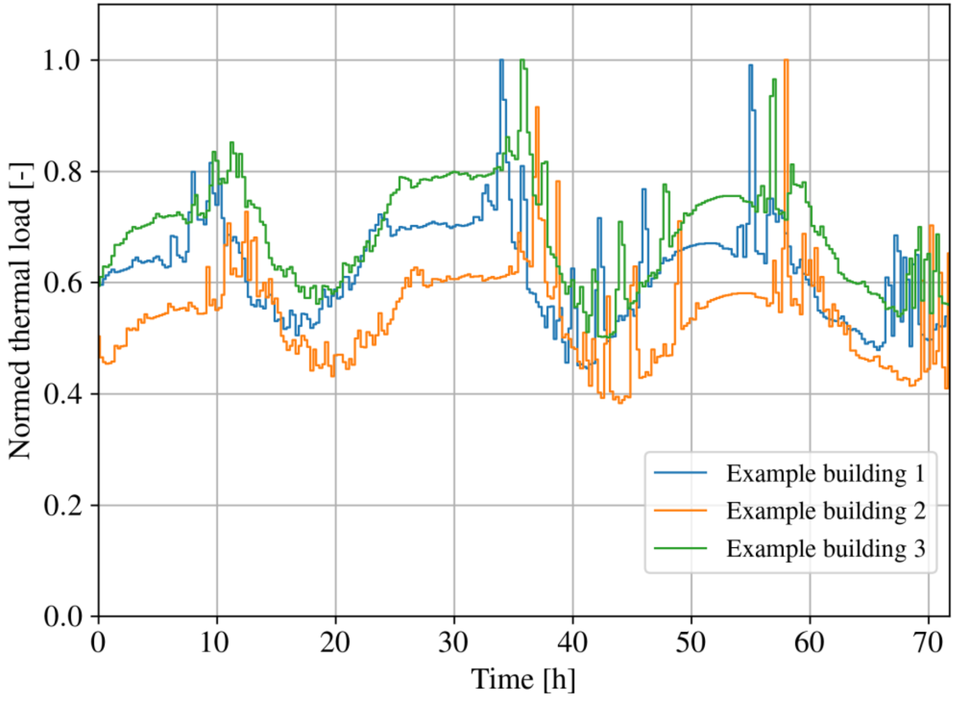
Heat losses based on manufacturer data [22]

Modeling approach – Simultaneity factor

RESILIENT ENERGY SYSTEMS

LABORATORY OF PROCESS SYSTEMS ENGINEERING

- Coldest period (3 days) in 1/4 hour time resolution as optimization period
- Heat demand data based on detailed building simulation with TRNSYS of different buildings types including a time shift randomly drawn from a normal distribution [23]



Exemplary normed demand time series

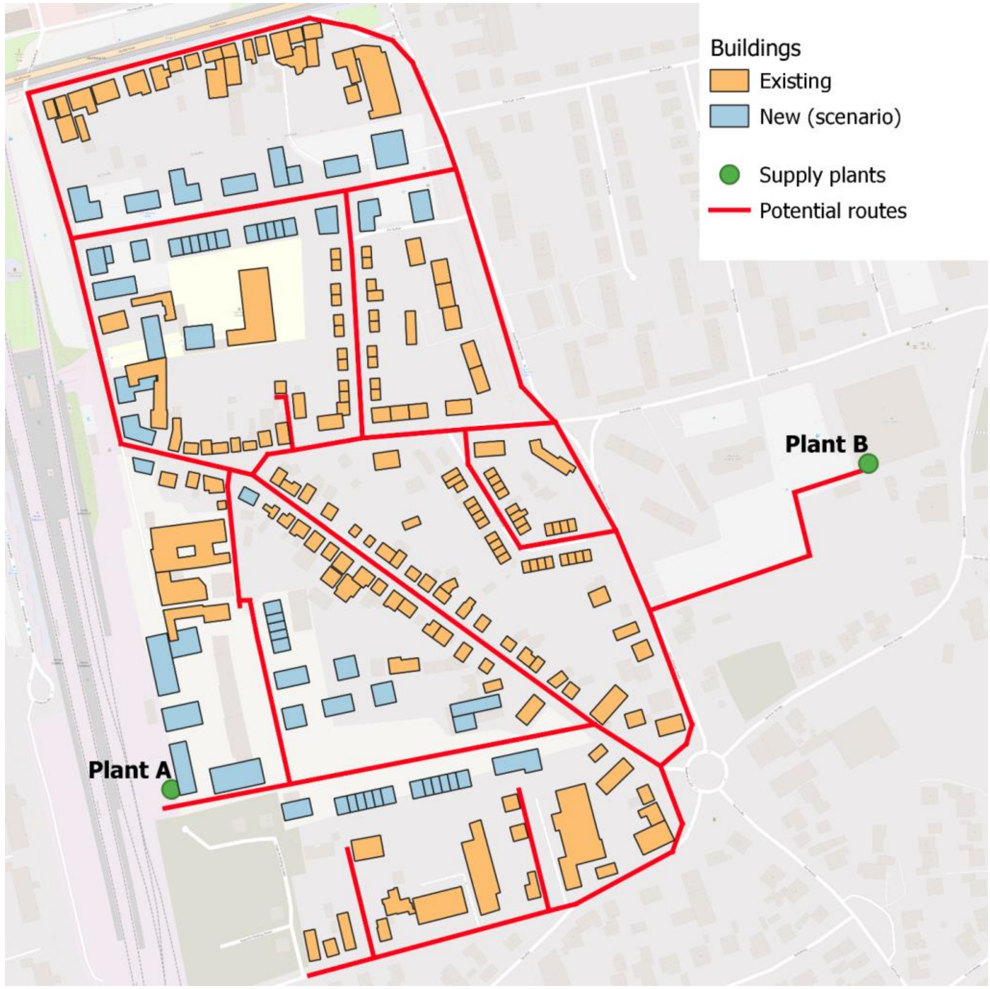
➢ **Aim: Imitating real diversified load**

Results – Comparison of pipeline network

RESILIENT ENERGY SYSTEMS
LABORATORY OF PROCESS SYSTEMS ENGINEERING

Optimization settings

Number of buildings	140
Total heat load	3.24 MW
Temperature spread	30 K
Max. pressure loss	100 Pa/m
Roughness	0.01 mm
Heat feed-in plants	2
Redundancy	100 %
Optimization period	2 x 72 h á 15 min
Size of DTES	1 m³ (35 kWh)



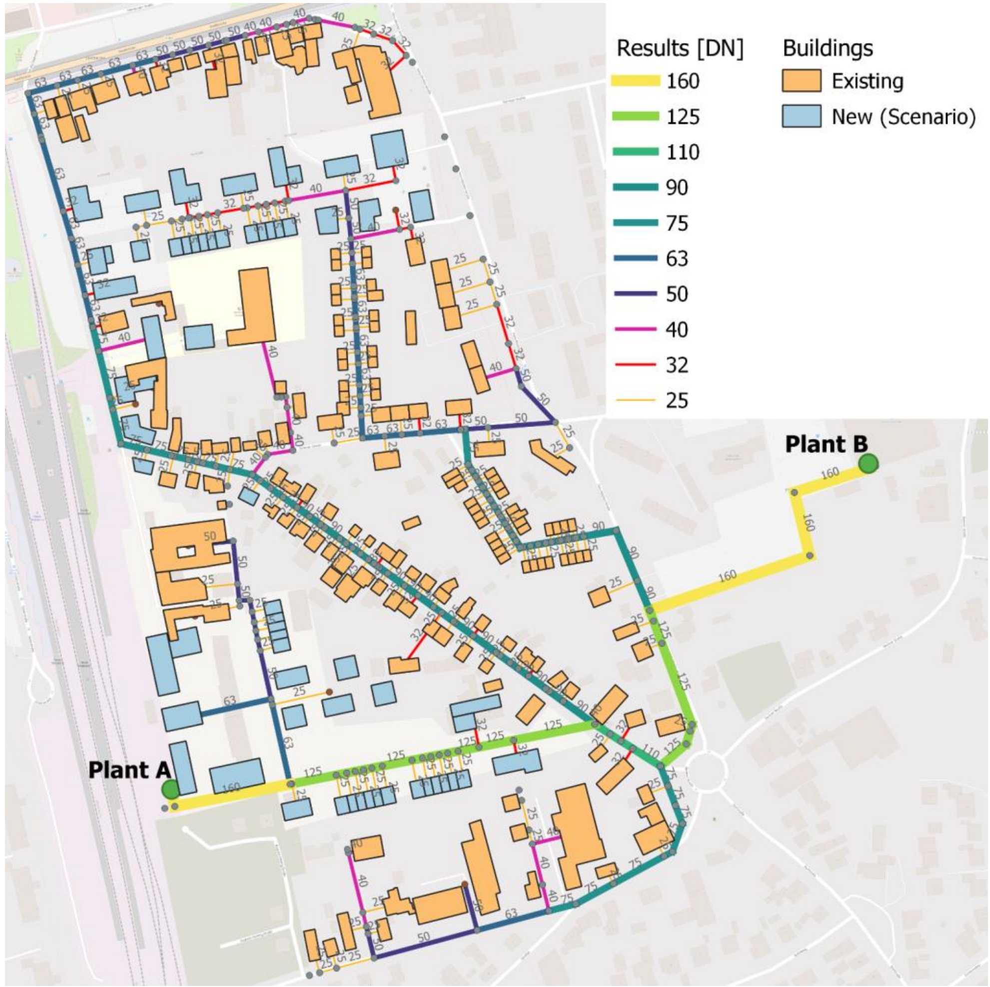
Results – Comparison of pipeline network

RESILIENT ENERGY SYSTEMS

LABORATORY OF PROCESS SYSTEMS ENGINEERING

Optimization settings

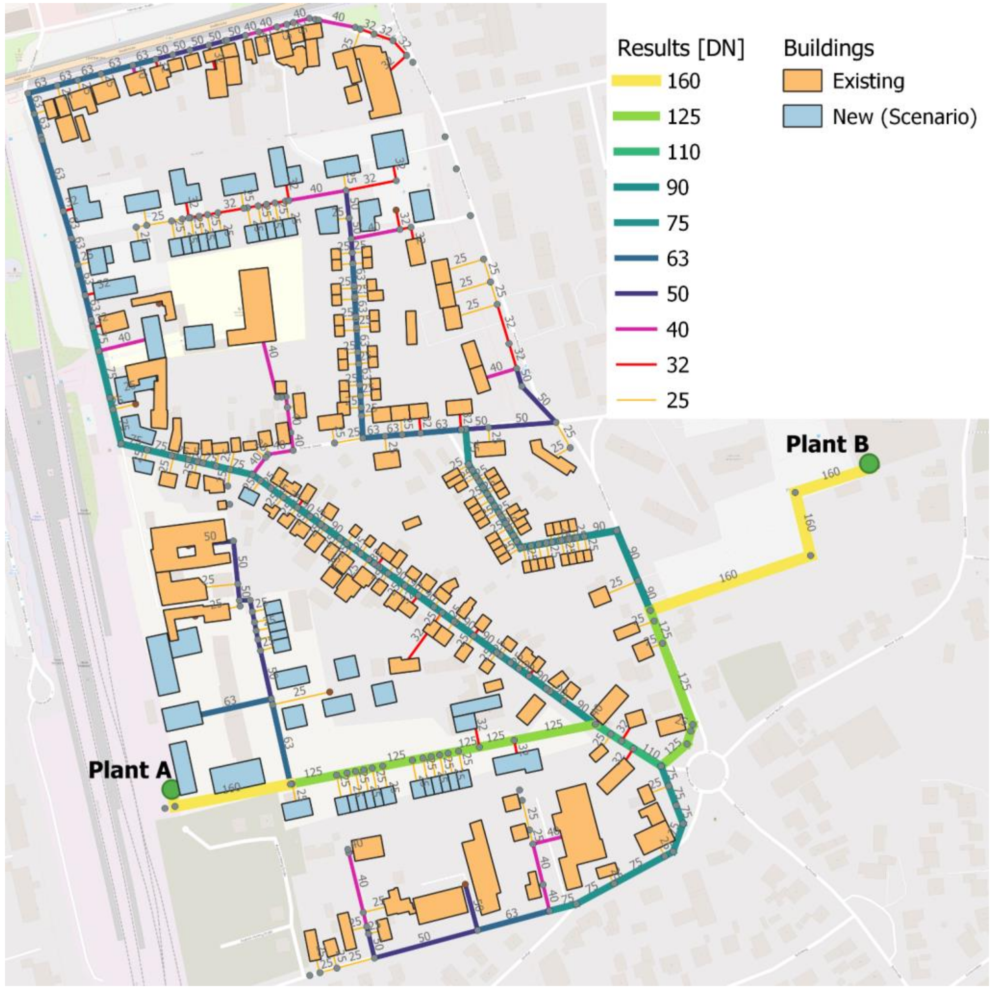
Number of buildings	140
Total heat load	3.24 MW
Temperature spread	30 K
Max. pressure loss	100 Pa/m
Roughness	0.01 mm
Heat feed-in plants	2
Redundancy	100 %
Optimization period	2 x 72 h á 15 min
Size of DTES	1 m³ (35 kWh)



No distributed heat storages

Results – Comparison of pipeline network

With distributed heat storages (1 m³)

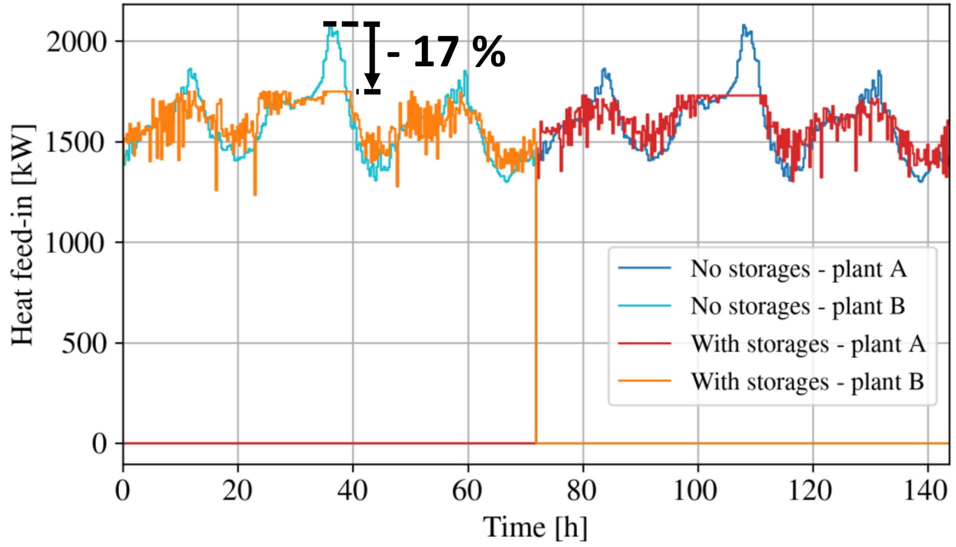


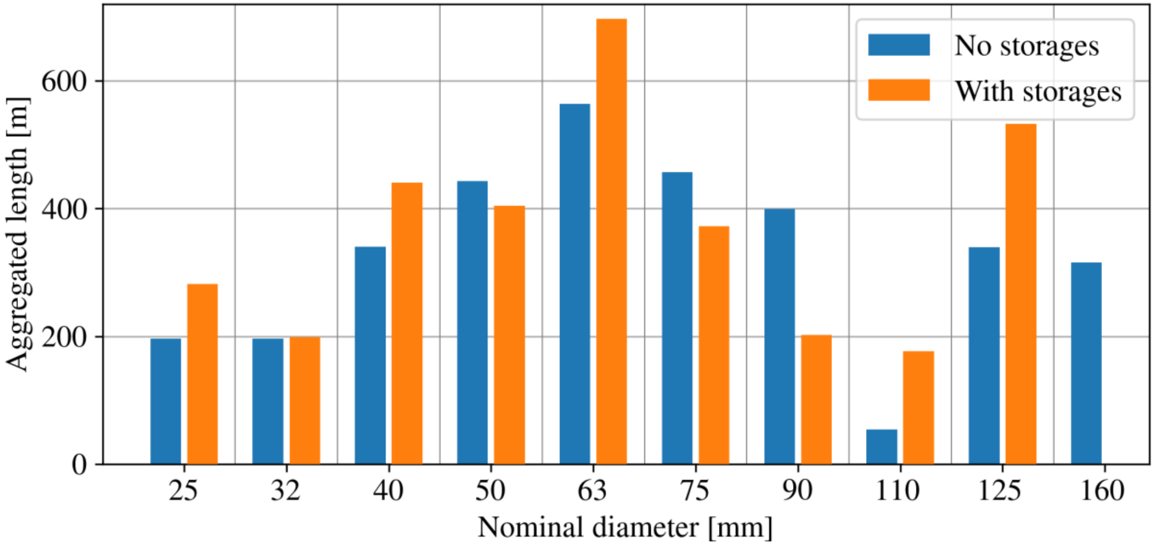
No distributed heat storages

Results – Investment costs and thermal loss

RESILIENT ENERGY SYSTEMS

LABORATORY OF PROCESS SYSTEMS ENGINEERING





Results of distribution lines	Costs[€] (without civil engineering)	Thermal loss power [kW]
No storages	773,716	53.7
With storages	695,326	49.5
Difference	**78,390**	**4.2**

- Reduction of thermal power loss by **4.2 kW (- 7.8 %)**
- Savings of investment costs of **78,390 €** (- **10.1 %**)
- Estimation of additional costs of storages:

  140 · 1,500 € = **210,000 €**

Summary and Outlook

RESILIENT ENERGY SYSTEMS
LABORATORY OF PROCESS SYSTEMS ENGINEERING

- Introduction of an optimization approach for DHS networks considering distributed thermal energy storages
- Results of case study
  - Distributed thermal heat storages enable a leaner piping system
    - ➢ **10.1 %** lower costs
    - ➢ **7.8 %** lower thermal power loss
  - Investment costs savings of distribution pipes do not offset investment costs of the energy storages

    (Benefits through savings in operating costs not included)
- Further analysis
  - Detailed assessment of operating costs

Open source modelling framework oemof

oemof ['ø:mɔf]

open energy modeling framework

https://oemof.org/

https://github.com/oemof/oemof-solph

https://github.com/oemof/DHNx

Thank you for your attention!

Partner Research Project QUARREE100

Funding Notes

This work was developed in the context of the research project "QUARREE 100 – Resiliente, integrierte und systemdienliche Energieversorgungssysteme im städtischen Bestandsquartier unter vollständiger Integration erneuerbarer Energien" (grant number: 03SBE113B). The authors thank the project executing organization Projektträger Jülich (PtJ), the Federal Ministry for Economic Affairs and Energy (BMWi) and the Federal Ministry of Education and Research (BMBF).

References

[1] VANDERMEULEN, Annelies ; VAN DER HEIJDE, Bram ; HELSEN, Lieve: Controlling district heating and cooling networks to unlock flexibility: A review. In: Energy 151 (2018), S. 103–115

[2] SCHUCHARDT, Georg K.: Integration of Decentralized Thermal Storages Within District Heating (DH) Networks. In: Environmental and Climate Technologies 18 (2016), Nr. 1, S. 5–16

[3] JOHANSSON, Christian ; WERNSTEDT, Fredrik ; DAVIDSSON, Paul: Distributed Thermal Storage Using Multi-Agent Systems. In: undefined (2012). URL https://www.semanticscholar.org/paper/Distributed-Thermal-Storage-Using-Multi-Agent-Johansson-Wernstedt/3fdcc2ebccfc02fda980c45c4f7a56150f7c9feb

[4] RAMM, Tobias ; HAMMEL, Carolina ; KLÄRNER, Michael ; KRUCK, Alfons ; SCHRAG, Tobias: Energy storage and integrated energy approach for district heating systems. In: Energy Procedia 135 (2017), S. 391–397

[5] DOMINKOVIĆ, D. F. ; GIANNIOU, P. ; MÜNSTER, M. ; HELLER, A. ; RODE, C.: Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization. In: Energy 153 (2018), S. 949–966

[6] GADD, H. ; WERNER, S.: Thermal energy storage systems for district heating and cooling. In: CABEZA, Luisa F. (Hrsg.): Advances in thermal energy storage systems : Methods and applications. Amsterdam : Elsevier Science, 2015 (Woodhead Publishing Series in Energy, 66), S. 467– 478

[7] THERMOS. URL https://www.thermos-project.eu/tool-resources/thermos-tool/

[8] KURIYAN, Kamal ; SHAH, Nilay: A combined spatial and technological model for the planning of district energy systems. International Journal of Sustainable Energy Planning and Management, Vol. 21 (2019) / International Journal of Sustainable Energy Planning and Management, Vol. 21 (2019) (2019)

[9] LI, Hongwei ; SVENDSEN, Svend: District Heating Network Design and Configuration Optimization with Genetic Algorithm. In: Journal of Sustainable Development of Energy, Water and Environment Systems 1 (2013), Nr. 4, S. 291–303

[10] DORFNER, Johannes ; HAMACHER, Thomas: Large-Scale District Heating Network Optimization. In: IEEE Transactions on Smart Grid 5 (2014), Nr. 4, S. 1884–1891

[11] BORDIN, Chiara ; GORDINI, Angelo ; VIGO, Daniele: An optimization approach for district heating strategic network design. In: European Journal of Operational Research 252 (2016), Nr. 1, S. 296–307

[12] ENERPIPE GMBH: Pufferspeichersysteme von ENERPIPE. URL https://enerpipe.de/uploaded/products/Waermeverluste_minimieren.pdf

References

[13] OPENSTREETMAP CONTRIBUTORS: Planet dump retrieved from https://planet.osm.org. URL https://www.openstreetmap.org

[14] GEOPANDAS DEVELOPERS: geopandas. URL https://geopandas.org/

[15] GILLIES, Sean ; OTHERS: Shapely: manipulation and analysis of geometric objects. 2007-. URL https://github.com/Toblerity/Shapely

[16] OEMOF DEVELOPER GROUP: DHNx : District heating system optimisation and simulation models, 2020. URL https://github.com/oemof/DHNx – Überprüfungsdatum 2020-07-20

[17] OEMOF DEVELOPER GROUP: oemof-solph - a model generator for energy systems - v0.4.1 : Zenodo, 2020. URL https://github.com/oemof/oemof-solph – Überprüfungsdatum 2020-07-20

[18] HART, William E. ; LAIRD, Carl D. ; WATSON, Jean-Paul. ; WOODRUFF, David L. ; HACKEBEIL, Gabriel A. ; NICHOLSON, Bethany L. ; SIIROLA, John D.: Pyomo -- Optimization Modeling in Python. 2nd ed. 2017. Cham : Springer International Publishing; Imprint: Springer, 2017 (Springer Optimization and Its Applications 67)

[19] JOHNJFORREST ; VIGERSKE, Stefan ; HAROLDO GAMBINI SANTOS ; RALPHS, Ted ; HAFER, Lou ; KRISTJANSSON, Bjarni ; JPFASANO ; EDWINSTRAVER ; LUBIN, Miles ; RLOUGEE ; JPGONCAL1 ; H-I-GASSMANN ; SALTZMAN, Matthew: coin-or/Cbc: Version 2.10.5 : Zenodo, 2020

[20] GUROBI OPTIMIZATION LLC: Gurobi Optimizer Reference Manual, 2020. URL http://www.gurobi.com

[21] DORFNER, Johannes: Open Source Modelling and Optimisation of Energy Infrastructure at Urban Scale. München, Technische Universität München. Dissertation. 2016

[22] ENERPIPE GMBH: Caldo PEX von ENERPIPE : Mit Sicherheit, mehr Wärme. URL https://www.enerpipe.de/produkte/pdl/?file=CaldoPEX_6S_ENERPE_06_2015_DE.pdf

[23] RÖDER, Johannes ; BEIER, David ; MEYER, Benedikt ; NETTELSTROTH, Joris ; STÜHRMANN, Torben ; ZONDERVAN, Edwin: Design of Renewable and System-Beneficial District Heating Systems Using a Dynamic Emission Factor for Grid-Sourced Electricity. In: Energies 13 (2020), Nr. 3, S. 619

[24] KRIEN, Uwe ; SCHÖNFELDT, Patrik ; LAUNER, Jann ; HILPERT, Simon ; KALDEMEYER, Cord ; PLEßMANN, Guido: oemof.solph—A model generator for linear and mixed-I nteger linear optimisation of energy systems. Software Impacts, 100028 (2020)

[25] HILPERT, S. ; KALDEMEYER, C. ; KRIEN, U. ; GÜNTHER, S. ; WINGENBACH, C. ; PLESSMANN, G.: The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling. In: Energy Strategy Reviews 22 (2018), S. 16–25