# Supplementary Figures

Chart, line chart

Description automatically generatedFig. 5 Two clustering quality indicators of different number of typical days (a); Heating demand error in load duration curve for the anchor building (b)

paper_figs/demand.pdf

Fig. 6 Simulated energy demand (heating and electricity) for all buildings (stacked) in the district corresponding to the 13 typical days (colors represent the different buildings in the district)

paper_figs/pipecost.pdf

Fig. 12 Linear cost curve over pipe capacity

# Appendix

## Appendix A.

In this appendix, the formulations of the constraints for other generation technologies (CHP, PV, ST, Gas Boiler, Biomass Boiler, GSHP) and storage technologies (battery and thermal storage) in the optimization model are given.

**Solar technologies:**

Solar technologies considered in the model include both PV panels and solar thermal panels. The installed capacities are represented as the installed area and at each building i. The upper bound of the total installed capacity of solar technologies is limited by the available roof area, shown in Eq.A.1.

Output power from the PV panels at every timestep is calculated as:

Output power from the Solar Thermal panels at every timestep is calculated as:

**Storage technologies:**

Storage technologies include battery storage and thermal storage. The operational constraints are set up for storage technologies concerning their state of charge (SOC), standby, discharging, and charging performances. In this model, storage technologies are considered only for daily storage usage. Therefore, the energy stored at the beginning of the day should equal to the state at the end of the day for each typical day. To achieve this, the state of charge in the storage technology represented in Eq.A.4 applies to the first time step of the day, and Eq.A.5 applies for the rest of the timesteps of the day.

**Dispatchable conversion technologies:**

The dispatchable conversion technologies include boilers (gas boilers and biomass boilers), CHP, and GSHP. For each technology, there is a lower bound for the installed capacity. The operations of the technologies are assumed by a linear curve. Detailed values used for the technical specifications are given in Table B. 1 in Appendix B. A minimum load constraint is set as 15% for the boilers. This is formulated by using a binary variable ( ) to guarantee the operations of the boilers within the bound of the minimum load requirement, as shown in Eq.A.6-9.

The input of each energy carriers (natural gas, biomass) to the D-MES is calculated according to the operational performance of each conversion technologies as :

Appendix B.

In this appendix, all values used for the technical parameters, costs, and emission data in the optimization models (a-d) are given.

*Table B. 1 Investment costs and technical specifications of energy conversion technologies.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Energy Conversion technology | Fixed Investment cost  (CHF)[a] | Linear Investment cost (CHF/kW)  [a] | Efficiency (%)|COP  [b] | Lifetime (year)  [b] | Minimum load (%) | Minimum Capacity  (kW|m2) |
| Gas Boiler | 27600 | 620 | 90 | 25 | 15 | 20 |
| Biomass Boiler | 27800 | 860 | 85 | 25 | 15 | 20 |
| CHP | 43450 | 3100 | 25% HER: 2 | 20 | - | 20 |
| GSHP | 20000 | 2380 | COP:4 | 20 | - | 20 |
| ST panels | 4000 | 1000 | 45 | 25 | - | 1 |
| PV panels | 900 | 400 | 15 | 30 | - | 1 |

a:(M.Jakob, S. Kallio, W. Otto, C.Nägeli, R. Bolliger, 2015) b: (Morvaj et al., 2016)

*Table B. 2 Investment costs and technical specifications of storage technologies* (Mavromatidis, 2017)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Storage Technologies | Fixed Investment cost (CHF)[a] | Linear Investment cost (CHF/kWh)[a] | Lifetime (year)  [b] | Standby loss (%/hour)  [b] | Charging & Discharging efficiency (%) [b] |
| Battery | 2000 | 600 | 10 | 0.1 | 90/90 |
| TES | 1685 | 12.5 | 30 | 0.1 | 99/99 |

*Table B. 3 Fuel price, electricity price and carbon emissions for each energy carrier* (Mavromatidis, 2017)

|  |  |  |
| --- | --- | --- |
| Energy carrier | Price (CHF/kWh) | CO2 (kg CO2-eq/kWh) |
| Natural Gas | 0.12 | 0.198 |
| Biomass | 0.127 | 0 |
| Electricity | 0.237| Feed-in tariff 0.0798 | 0.0095 |

Appendix C:

This appendix includes information and parameters related to the thermal network's assumptions. In the DHN simulation model, the thermal transfer coefficient is approximated as a linear function depends on the pipe diameter based on extrapolated data from Liu et al. (Liu et al., 2015) as :. The pipe roughness is 0.4 mm. Ground temperature is assumed as constant at 10 °C. In the MILP optimization model (b-d), the new derived thermal loss coefficient, and *a=0.172 x 10-3* and *b=7.69x10-8 .*

*Table C. 1 Data for Piping costs according to the design diameter used in the DHN simulation model* (Nussbaumer and Thalmann, 2016)

|  |  |  |  |
| --- | --- | --- | --- |
| Nominal Diameter (mm) | Piping cost (€/m) | Trench cost (€/m) | Total costs (€/m) |
| 20 | 226 | 83 | 308 |
| 25 | 231 | 83 | 313 |
| 32 | 257 | 83 | 340 |
| 40 | 272 | 83 | 355 |
| 50 | 293 | 107 | 400 |
| 65 | 335 | 107 | 442 |
| 80 | 376 | 124 | 500 |
| 100 | 504 | 140 | 645 |
| 125 | 640 | 157 | 798 |
| 150 | 791 | 165 | 956 |
| 200 | 960 | 182 | 1141 |
| 250 | 1363 | 207 | 1569 |

(Exchange rate 1.13 is used to convert Euros into Swiss Francs.)

*Table C. 2 Data for Piping costs and lifetime used in the optimization model (a-d)*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Model (a) (Morvaj et al., 2016) | Model (b-d) | | Model (a-d) (Morvaj et al., 2016) |
| District Heating Network | Fixed Investment cost (CHF/m) | Fixed Investment cost (CHF/m) | Linear Investment cost (CHF/kW/m) | Lifetime  (year) |
| Pipe capacity < 657 kW | 400 | 327 | 0.189 | 40 |
| Pipe capacity > 657 kW | 400 | 392 | 0.089 | 40 |

# References:

Liu, X., Jenkins, N., Wu, J., and Bagdanavicius, A. (2015). Combined analysis of electricity and heat networks. *Appl. Energy* 61, 155–159. doi:10.1016/j.egypro.2014.11.928.

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Morvaj, B., Evins, R., and Carmeliet, J. (2016). Optimising urban energy systems: Simultaneous system sizing, operation and district heating network layout. *Energy* 116, 619–636. doi:10.1016/j.energy.2016.09.139.

Nussbaumer, T., and Thalmann, S. (2016). Influence of system design on heat distribution costs in district heating. *Energy* 101, 496–505. doi:10.1016/j.energy.2016.02.062.