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Optimization of solar and ground source based district heating system using bottom-up technology modelling

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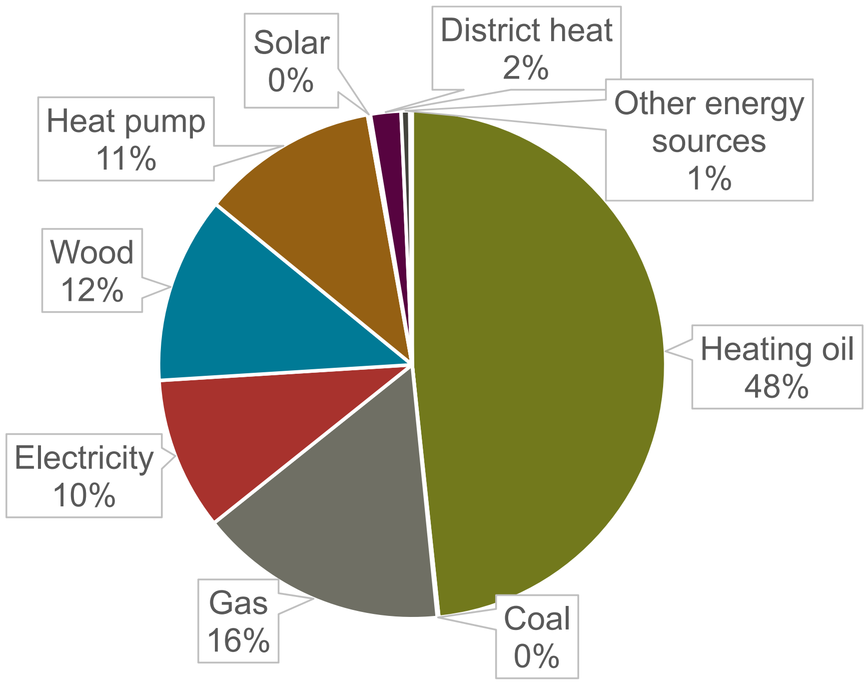
Swiss building stock



Distribution of energy sources used for heating in buildings

*Data source: Swiss Federal Statistical Office (2013)

Contribution to total CO_2 emissions

40%

Swiss energy strategy 2050

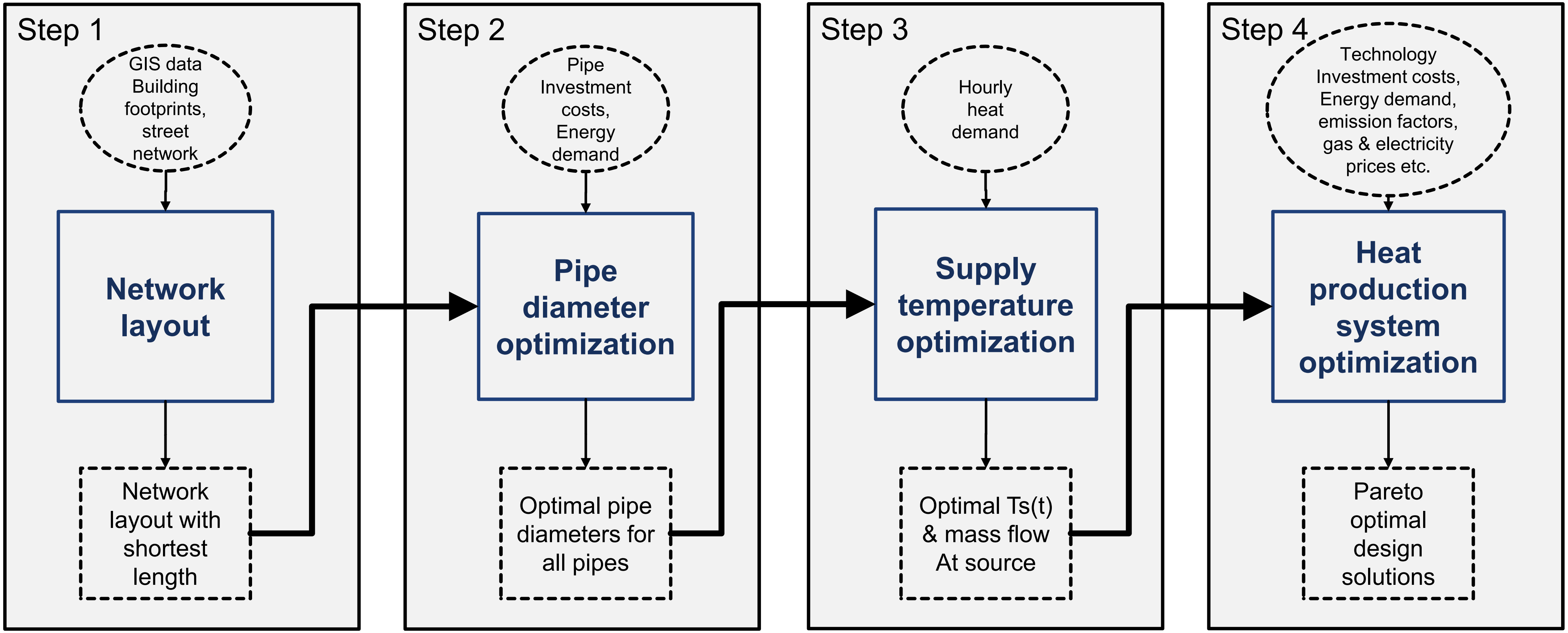
- Political basis for Switzerland’s energy transition
- Lays down several pathways to decarbonisation
  - Building integrated renewable energy systems
    - Example: Solar PV/T, ground source heat pumps (GSHPs)
  - Renewable energy based district heating system
  - Energy efficiency measures
    - Example: Building envelope retrofitting

Energy systems side

Energy demand side

Aim: To optimize a district heating system based on solar thermal energy and ground source heat using bottom up technology models

Modelling framework: Overview

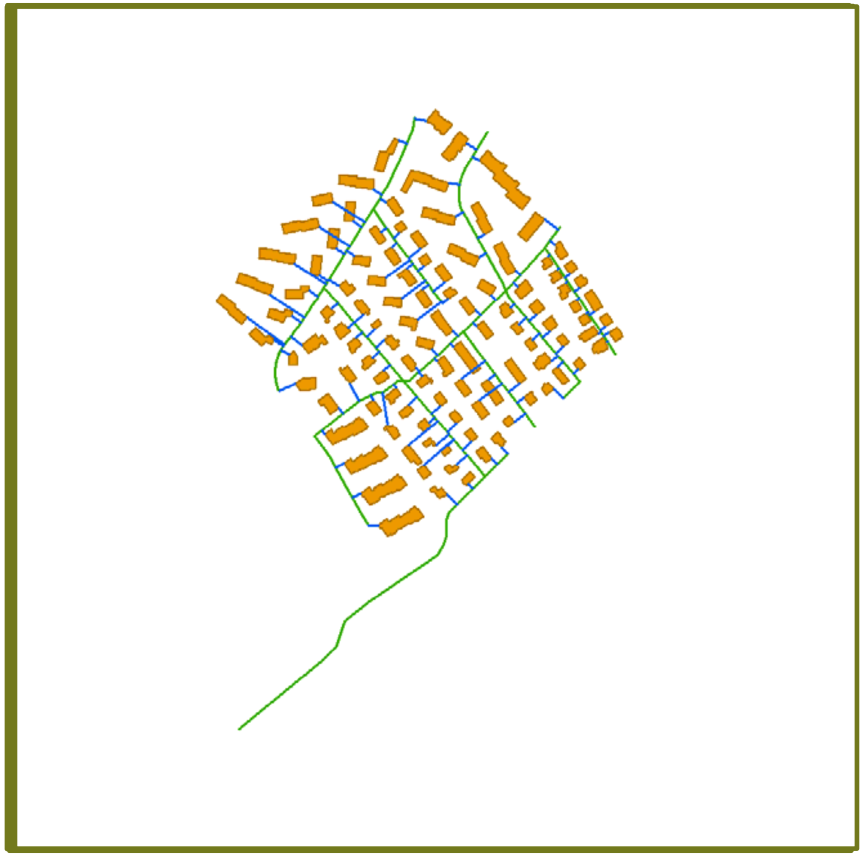


Step 1: Network layout

INPUT DATA:
1. Building footprints
2. Digital elevation model
3. Street network

GIS workflow

Network consisting of Nodes as points Edges as polylines



-XY coordinates are added
-Elevation is added to all pipes

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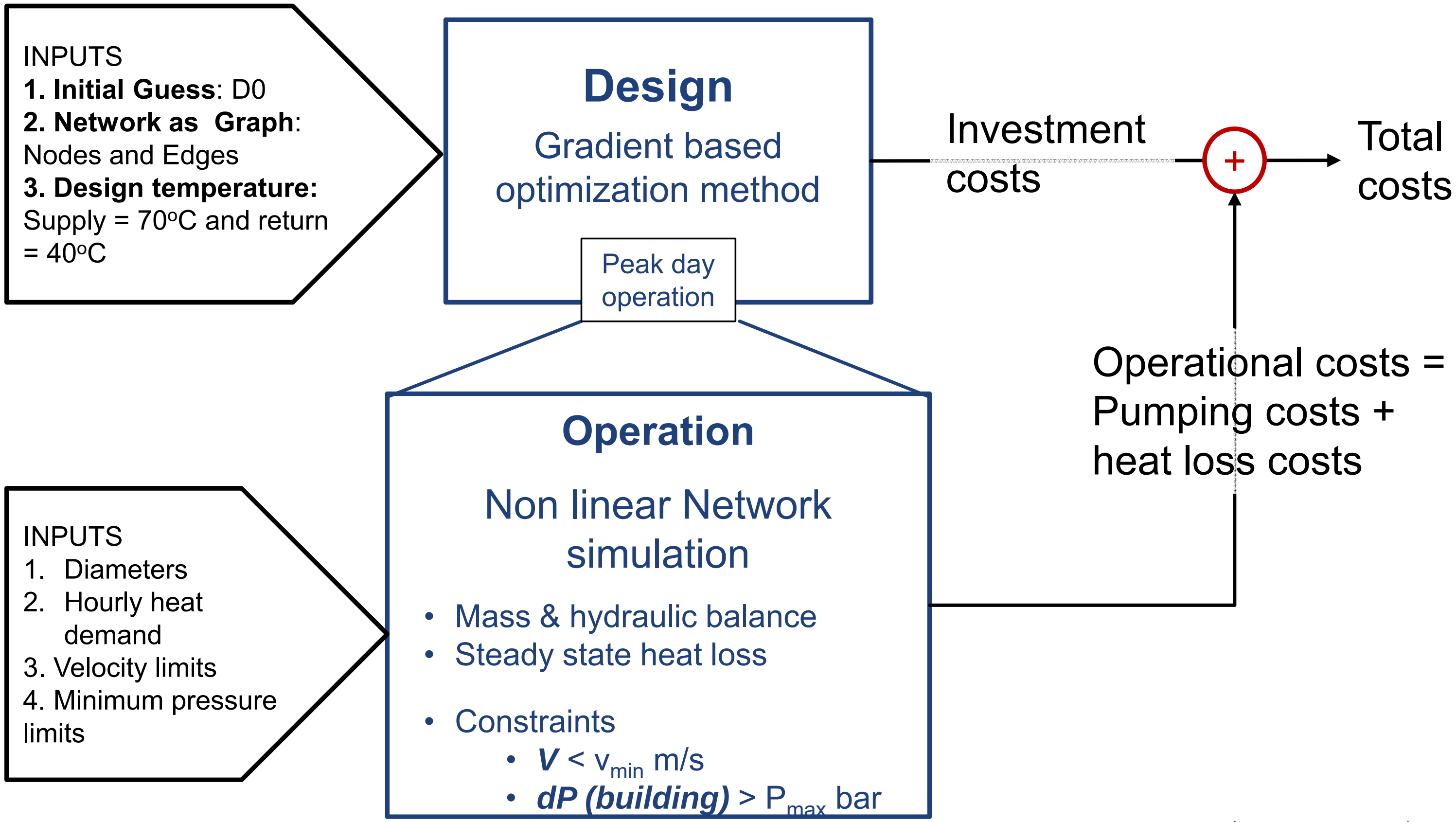
Step 2: Optimization of pipe diameters

- **Objective function**: Total costs
- **Subject to constraints**:
  - Velocity limits
  - Minimum pressure at customer
  - Minimum temperature at customer



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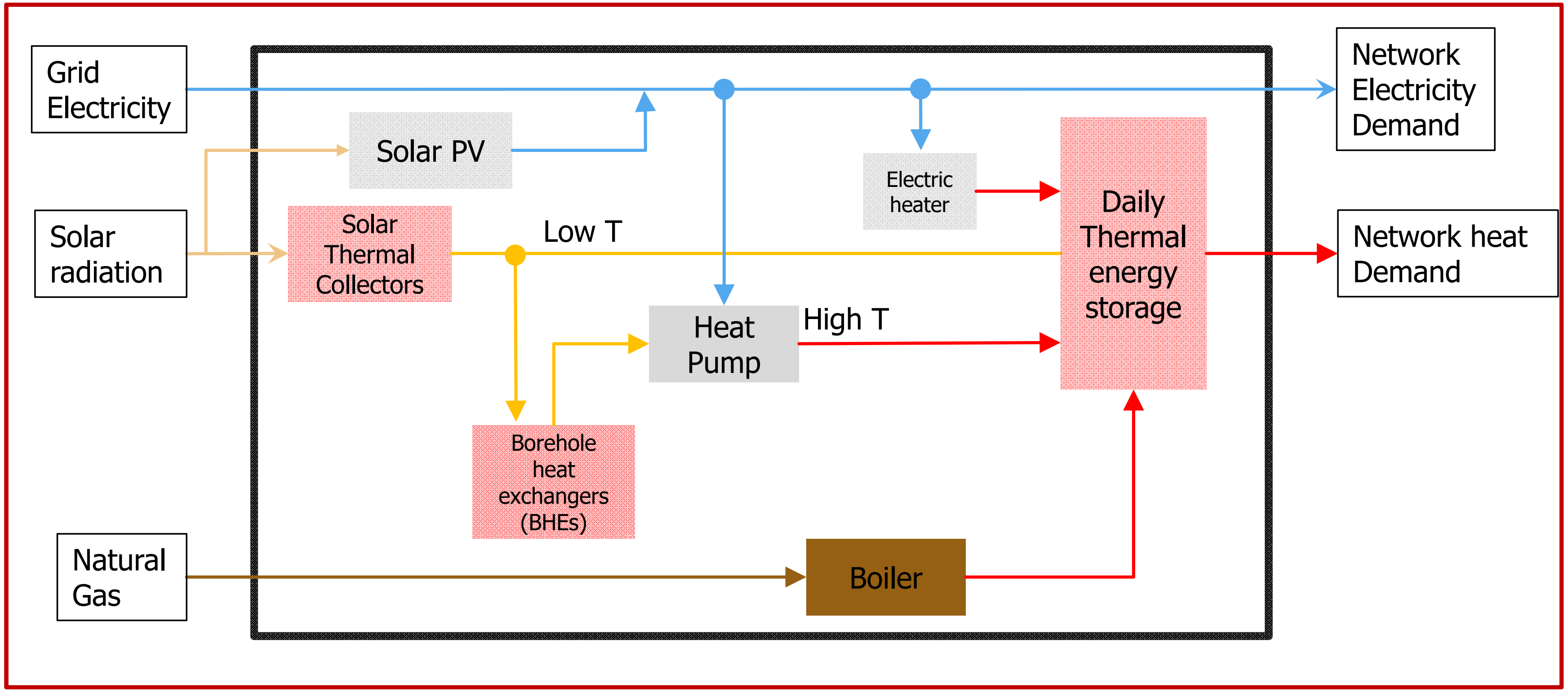
Step 3: Supply temperature optimization

- The network design including pipe diameters is fixed
- Hourly heating demand as input
- Same optimization scheme
  - Minimisation of operation costs = Pumping + heat losses
  - optimization variable is the supply temperature at source, $\mathbf{T_s}$
- 8760 variables, for each hour of the year
- Optimal $\mathbf{T_s}(t)$ and associated mass flow, $\dot{\mathbf{m}}(t)$ for given hourly heating demand

Step 4: Heat production system optimization

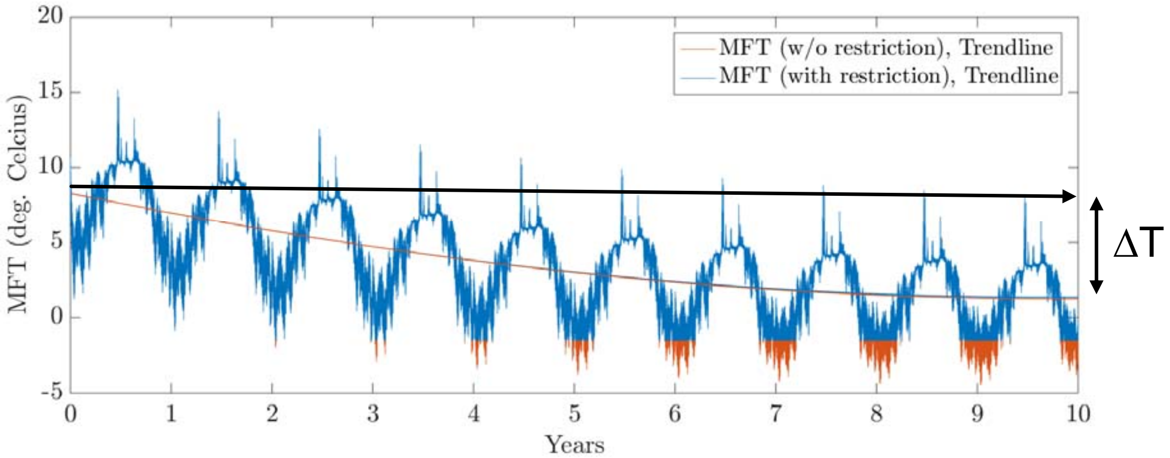


$$\mathbf{Q}(t) = \dot{m}(t) C_p (\boldsymbol{T_s}(\boldsymbol{t}) - T_R)$$

Optimal mass flow from Step 3

Optimal supply temperature from Step 3

Ground source heat pumps (GSHPs)



Long term evolution of mean fluid temperature within a BHE

Miglani S., Orehounig K., Carmeliet J., A methodology to calculate long-term shallow geothermal energy potential for an urban neighborhood, Energy and Buildings (2017) (Submitted)

- **Borehole Heat Exchanger (BHE)**
  - Vertically drilled U-tubes
  - Circulating fluid exchanges heat
  - Heat pump source side
- **Short term operation:**
  - When HP switched on ground cools
  - Lower COP and higher operating costs
  - When HP off or on part load ground regenerates naturally
- **Long term operation**
  - Annual heat imbalance leads to long term ground cooling
- Solar regeneration can help
- Bottom up modelling is important

BHE modelling: g-functions

- g-functions also known as thermal response function
- Represent the temperature response of the ground to a heat pulse

$$T_b - T_0 = \frac{Q}{2\pi kL} g\left(\frac{t}{t_s}, \frac{r_b}{L}, Borhole\ field\ geometry\right)$$

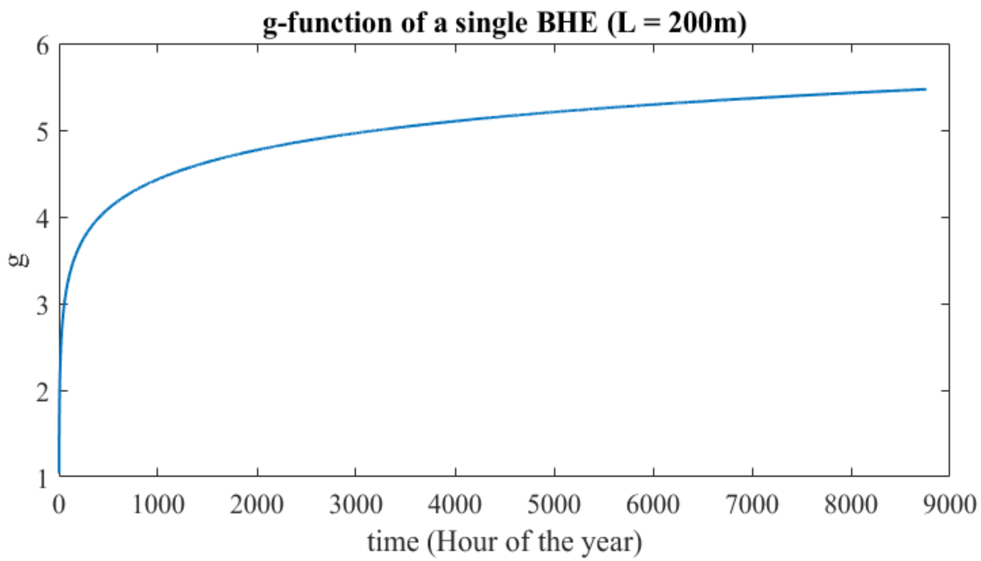
g Function

-Dimensionless

-Fixed for given geometry of field

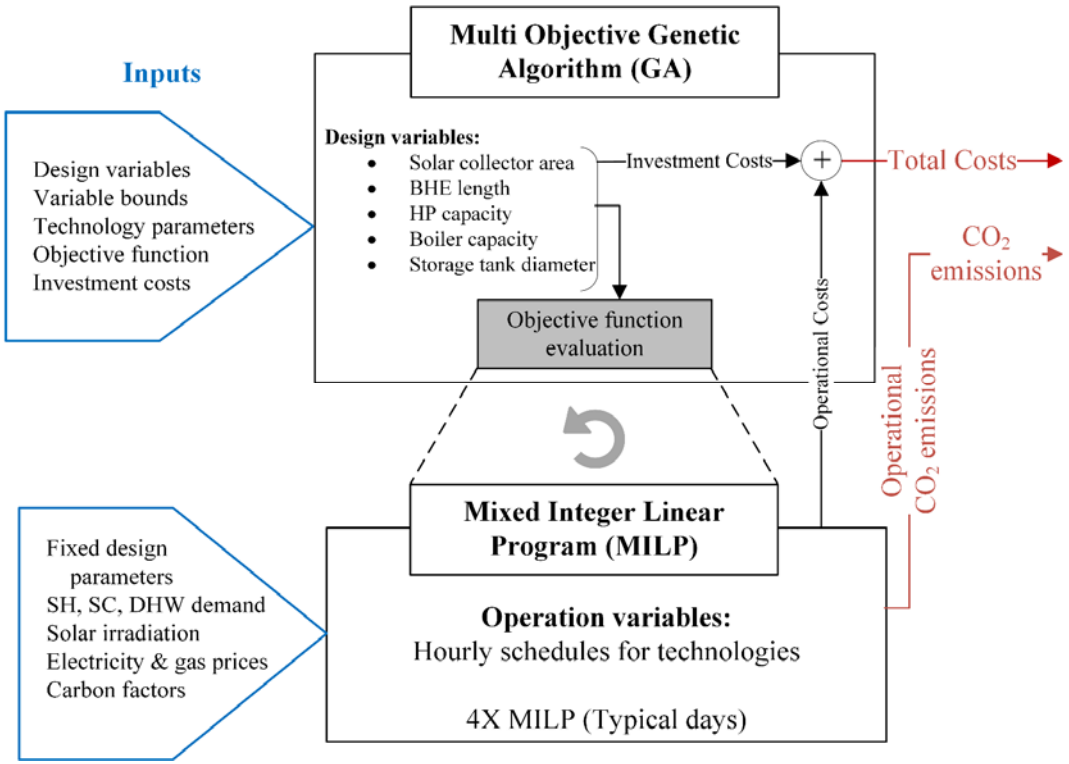
-Time dependent

-Calculated at a given radius from the BHE



g-function for a single BHE (L=200m)

Step 4: Heat production system optimization



MILP

- $\boldsymbol{Operating\ costs} = {}^{\cdot grid,elec}_{HP,t} \cdot p_{elec} + {}^{\cdot grid,gas}_{GB,t} \cdot p_{gas}$

- ***Subject to***:
  - Technology specific constraints
    - Based on their respective mathematical models
  - Energy / mass balance constraints
  - Operational constraints
    - E.g. Minimum temperature of heat delivery, capacity limits, heat pump operational temperature limits

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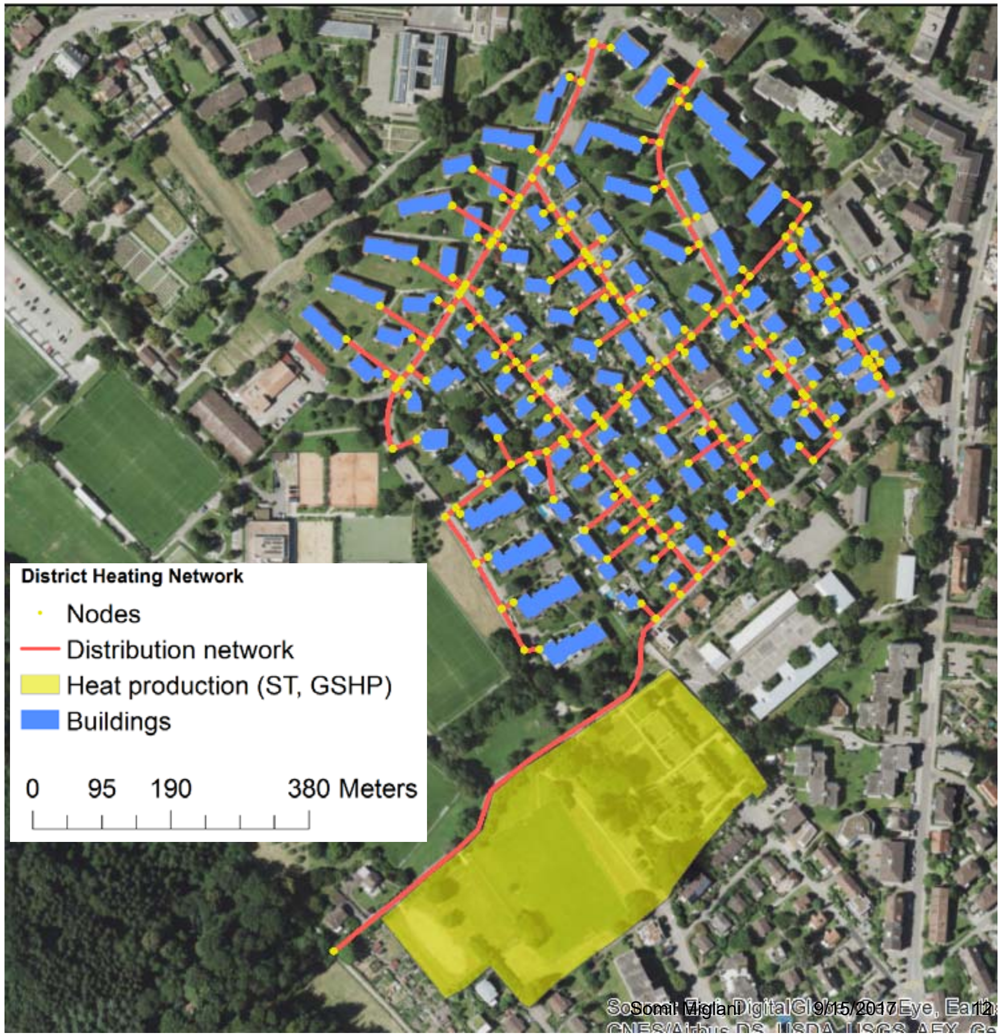
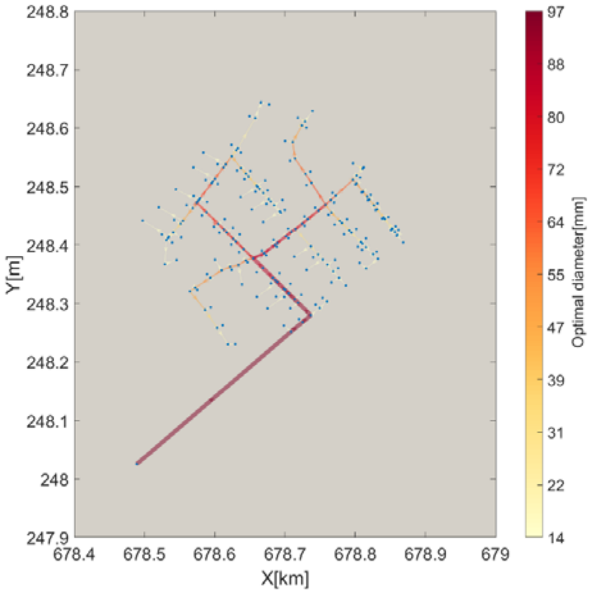
Case Study: Altstetten, Zurich

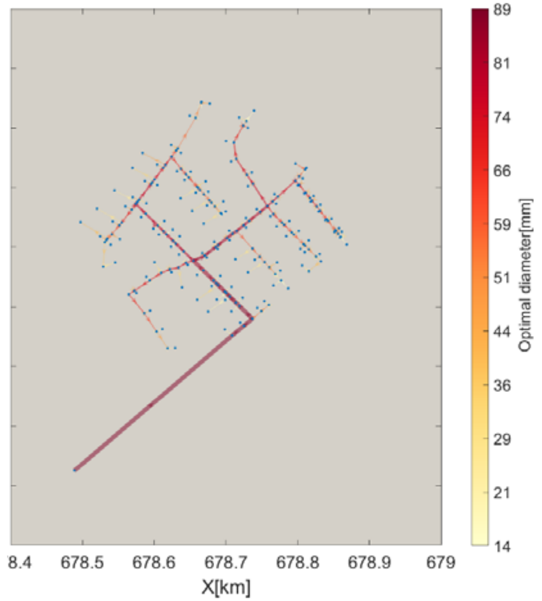
- Suburban area in Zurich, Switzerland
- 170 Buildings

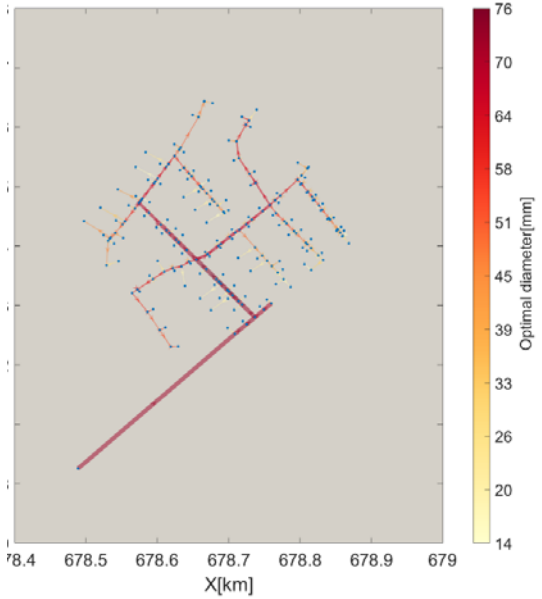
- Envelope retrofitting scenarios
  - No retrofit
  - Window retrofit
  - Façade retrofit= walls + windows
  - Whole building retrofit = windows + walls + roof + floor

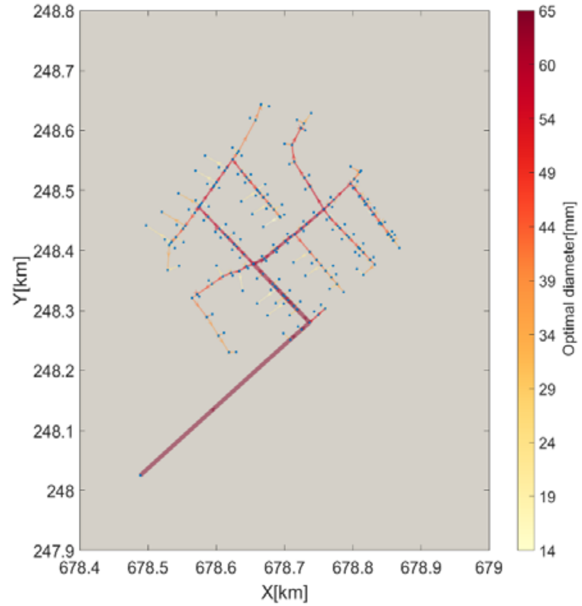


Results: Optimal diameter









Retrofit Scenario: No retrofitting	Window Retrofitting	Façade retrofitting	Whole building retrofitting
Investment costs = 1.49 mCHF	1.40 mCHF	1.35 mCHF	1.2 mCHF
Linear heat density= 3.71 MWh/m	3.02 MWh/m	1.61 MWh/m	0.96 MWh/m

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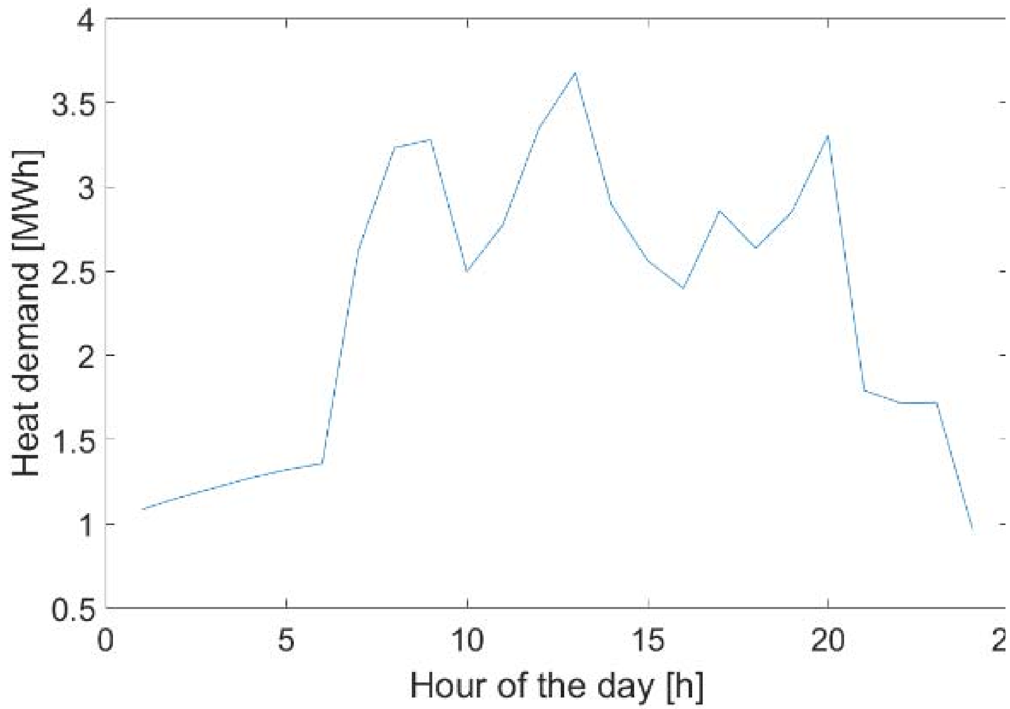
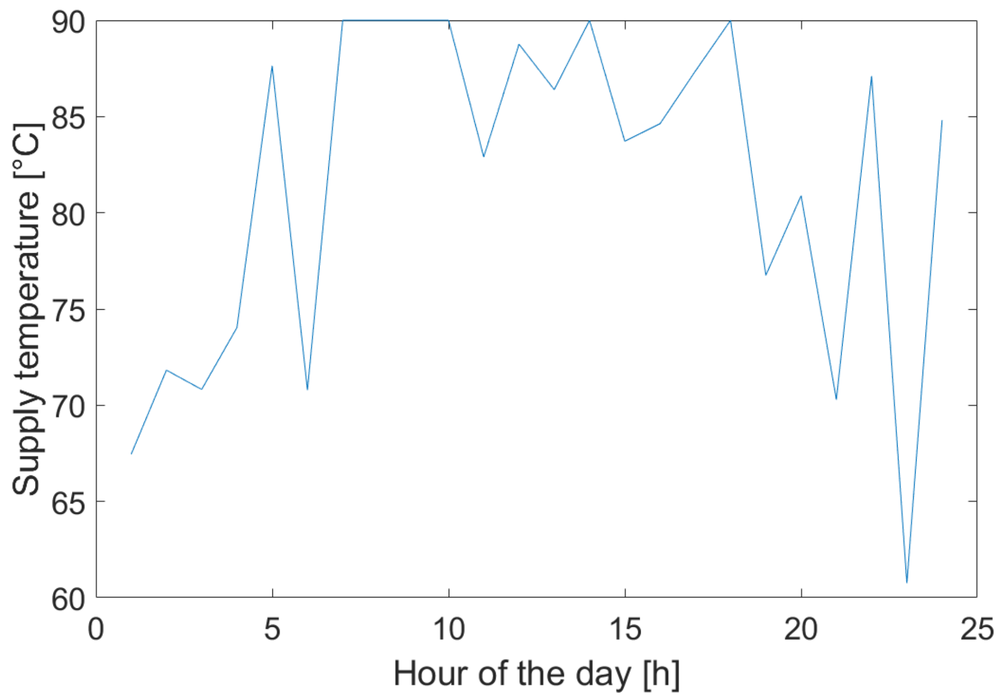
Results: Optimal supply temperature



Peak day heat demand



Optimal supply temperature

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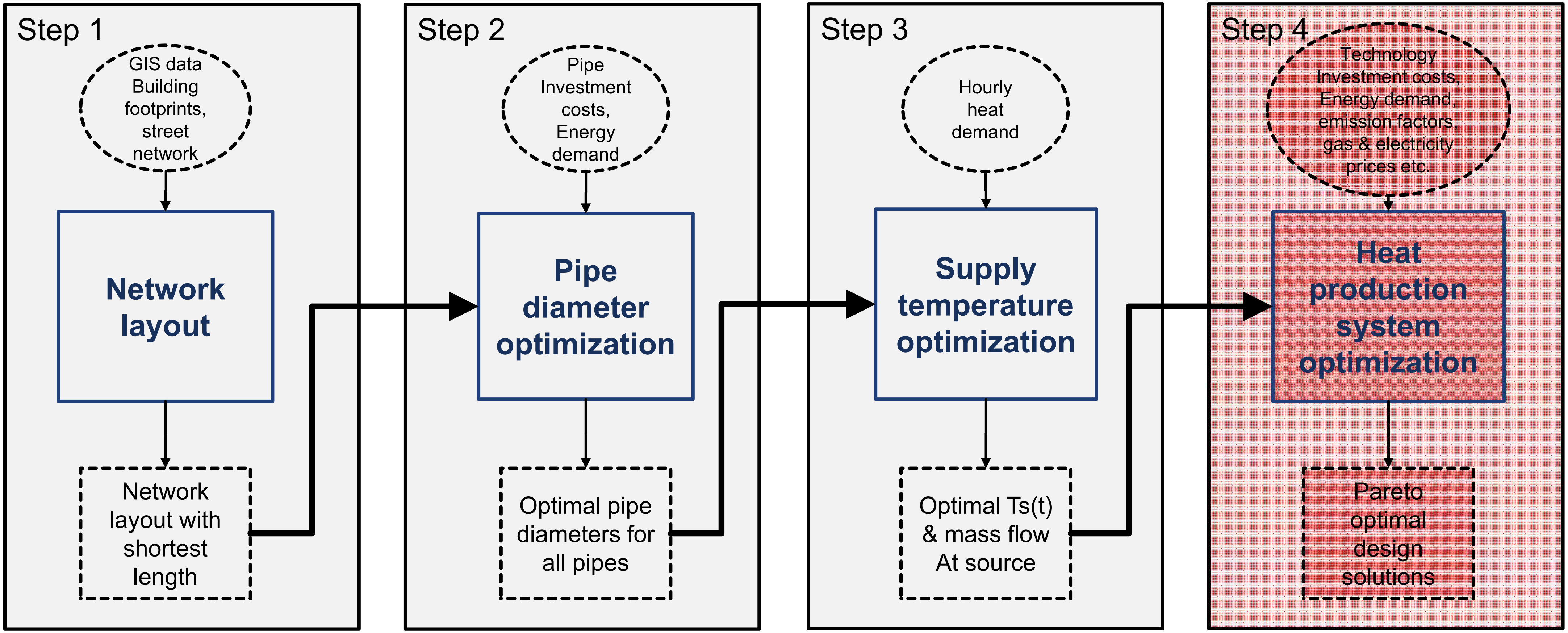
Conclusion

- A holistic approach to DH optimization is presented
- Technologies such as BHEs, ST collectors, heat pump, thermal storage etc. are modelled in a bottom up fashion
- Allows modelling of the ground not only as source but as storage
- Solar regeneration and design for long term sustainable operation can be incorporated
- Pareto optimal design solutions can be obtained that highlight the tradeoff between total costs and CO2 emissions

Modelling framework: Current/future research



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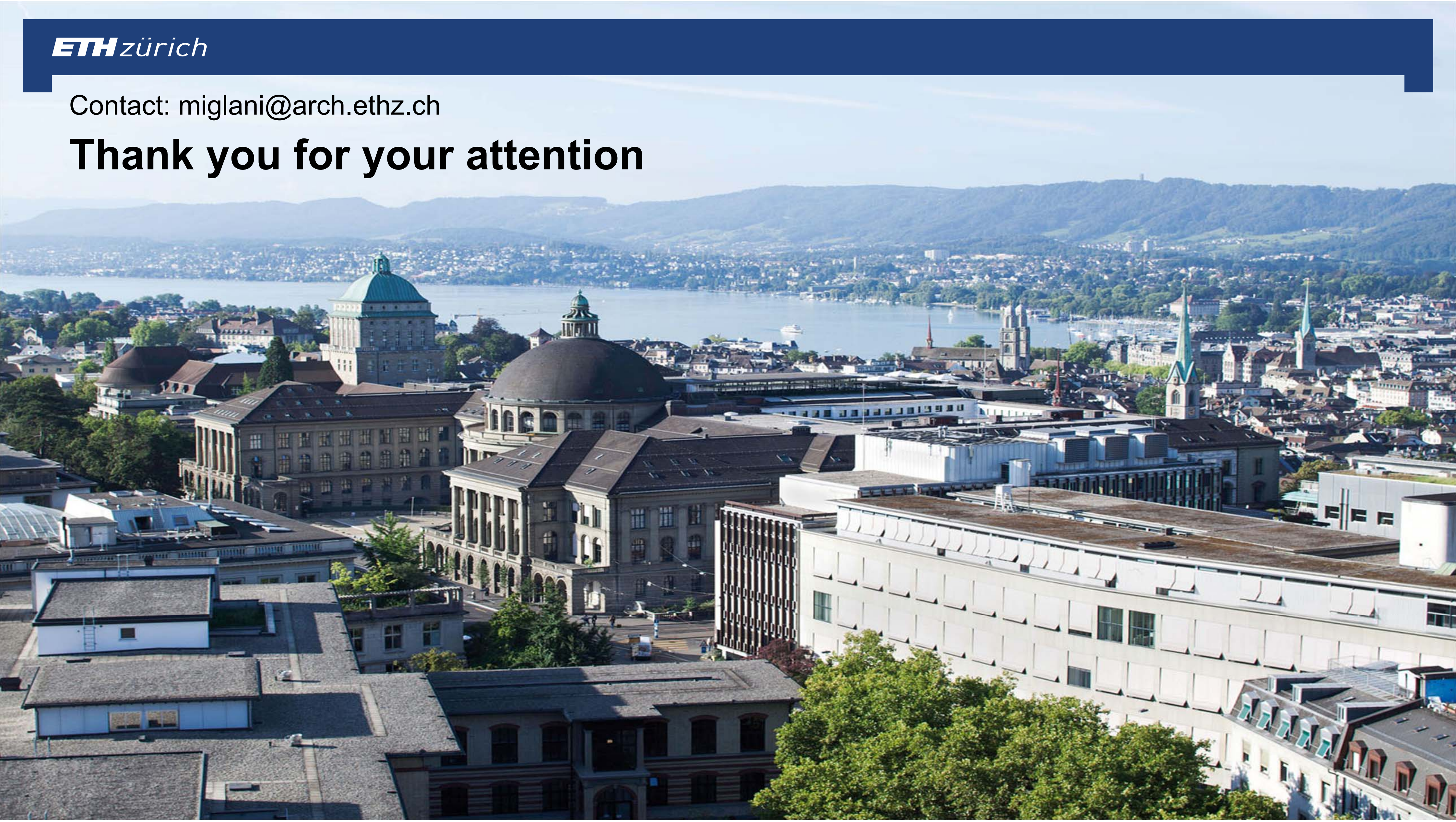
Thank you for your attention

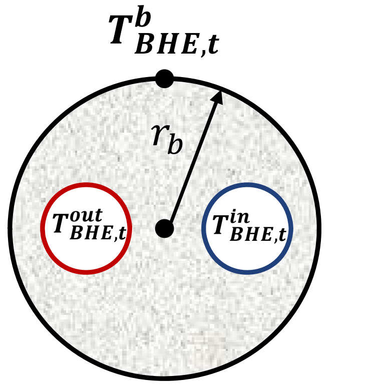


BHE model

Borehole wall temperature: $\boldsymbol{T^{b}_{BHE,t}} - T_o = \sum_{i=1}^{t} \frac{(\dot{}_{BHE,i} - \dot{}_{BHE,i-1})}{2\pi k L} g(\frac{t-i-1}{t_s}, \frac{r_b}{L})$

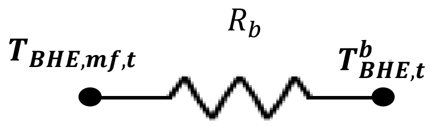
Mean fluid temperature: $\boldsymbol{T^{mf}_{BHE,t}} = \boldsymbol{T^{b}_{BHE,t}} - \frac{\dot{q}_{BHE,t} \cdot R_b}{L}$

$$\boldsymbol{T_{BHE,mf,t}} = \frac{\boldsymbol{T^{out}_{BHE,t}} + \boldsymbol{T^{in}_{BHE,t}}}{2}$$



Heat extraction: $\dot{}_{BHE,t} = \dot{}_{BHE} C(\boldsymbol{T^{out}_{BHE,t}} - \boldsymbol{T^{in}_{BHE,t}})$

Min. inlet temperature: $\boldsymbol{T^{in}_{BHE,t}} \geq T^{in,min}_{BHE}(-5^oC)$



Heat pump model

Source side Inlet temperature — Load side Inlet temperature — Source side \`Mass flow — Load side Mass flow

Heat Load:

$$\frac{\dot{q}_{HP,l,t}}{\dot{q}_{ref}} = a_1 + a_2\left(\frac{T^{S,in}_{HP,l,t}}{T_{ref}}\right) + a_3\left(\frac{T^{L,in}_{HP,t}}{T_{ref}}\right) + a_4\left(\frac{\dot{m}^{S}_{HP}}{\dot{m}_{S,ref}}\right) + a_5\left(\frac{\dot{m}^{L}_{HP,l,t}}{\dot{m}_{L,ref}}\right)$$

Power consumption:

$$\frac{\dot{p}_{HP,l,t}}{\dot{p}_{ref}} = b_1 + b_2\left(\frac{T^{S,in}_{HP,l,t}}{T_{ref}}\right) + b_3\left(\frac{T^{L,in}_{HP,t}}{T_{ref}}\right) + b_4\left(\frac{\dot{m}_{HP,S}}{\dot{m}_{S,ref}}\right) + b_5\left(\frac{\dot{m}^{L}_{HP,l,t}}{\dot{m}_{L,ref}}\right)$$

Energy balance:

$$\dot{p}_{HP,t} = \dot{q}_{HP,t} - \dot{q}_{BHE,t}$$

Load side mass flow:

$$\dot{q}_{HP,l,t} = \dot{m}^{L}_{HP,l,t}.C.(10K))$$

Connection with BHE:

$$T^{S,in}_{HP,t} = T^{out}_{BHE,t}$$

Operation range:

$$y_{HP,l,t}\,.\,T^{S,in,min}_{HP}(20^{o}C) \leq T^{S,in}_{HP,l,t} \leq y_{HP,l,t}\,.\,T^{S,in,max}_{HP}\,(80^{o}C)$$

Solar regeneration :

$$\dot{q}_{BHE} = \dot{q}^{S}_{HP} - \dot{q}_{Solar}$$