Characteristics of natural heat sources for heat pumps and their impact in energy planning

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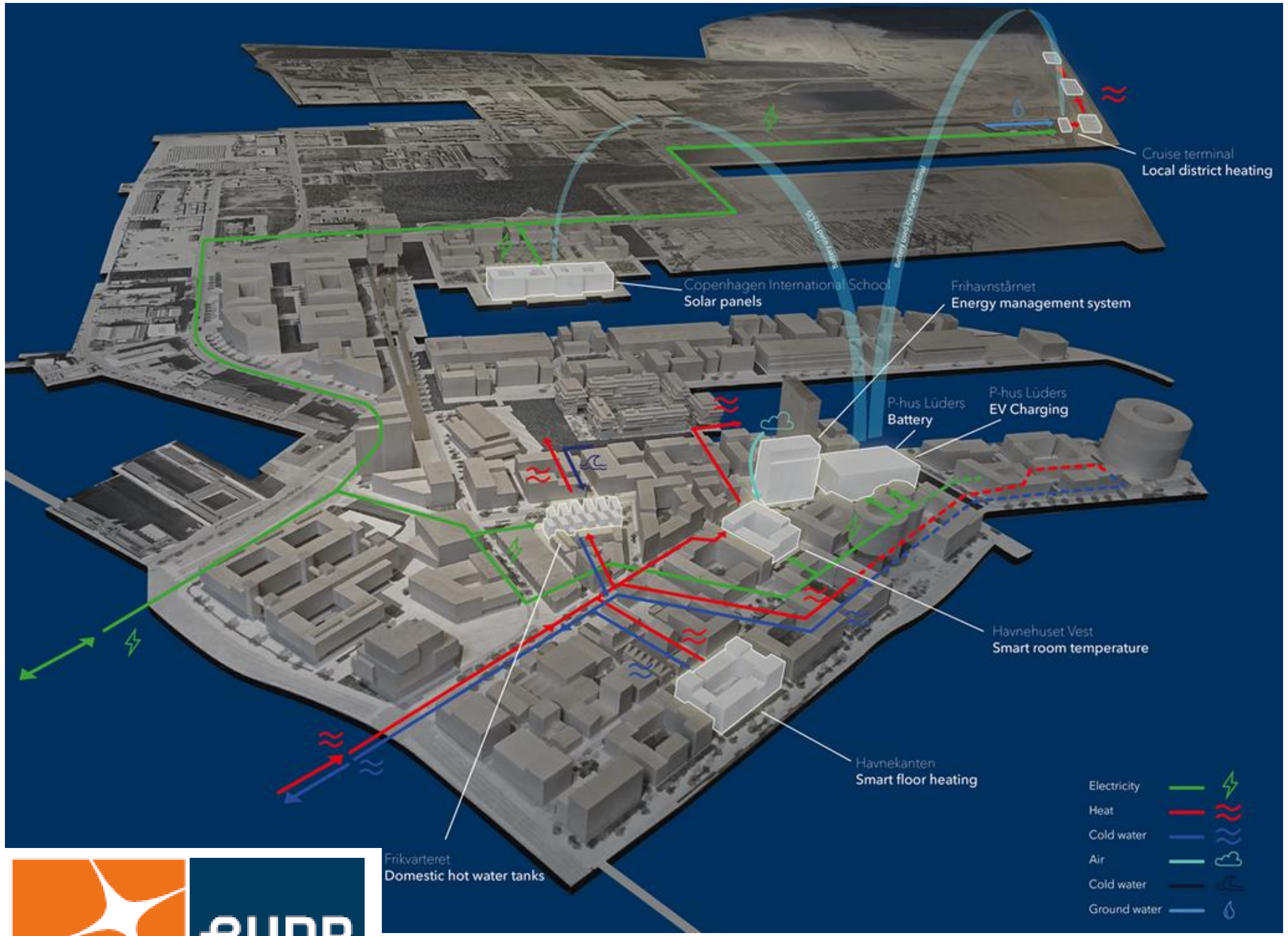
I. Nordhavn: one of the largest development districts in Europe

Transform old harbour area outside of Copenhagen until 2060 to accommodate:

- 40,000 inhabitants
- 40,000 jobs
- 3.5 mio m^2 floor area
- During 5 development stages

I. EnergyLab Nordhavn

- Develop new methods and solutions
  for design and operation of the future
  cost-effective integrated energy system
  based on Nordhavn as a living lab
- Budget: 19 Mio. € (11 Mio. € from EUDP)
- April 2015 until October 2019
- 9 PhDs, 4 Postdocs
- http://energylabnordhavn.weebly.com/



I. EnergyLab Nordhavn

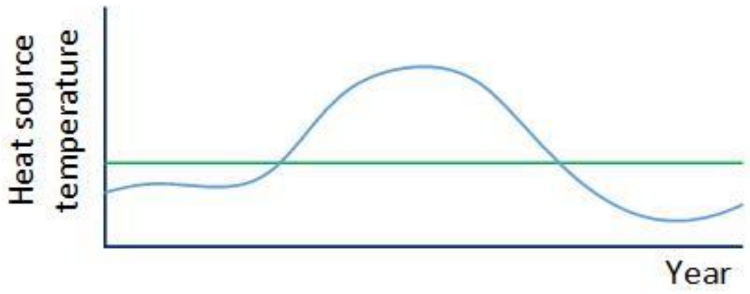
Integration of energy systems to allow:
- Fuel shift
- Peak shaving (thermal and electrical)
- Integration of renewables
- Cost-effective energy supply

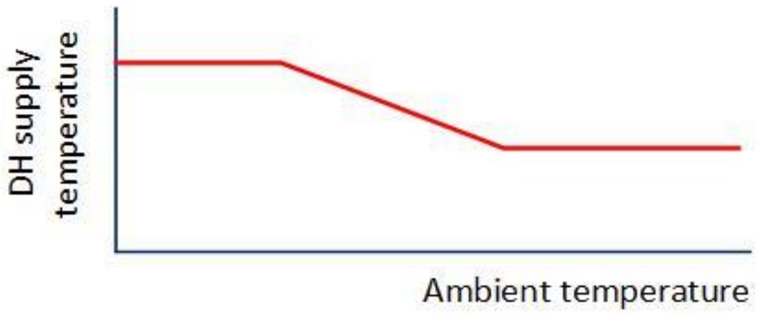
Demonstrations:
- FlexHeat: 0.8 MW_{th} groundwater HP
- HeatBooster substations for ULTDH
- Smart building control
- Electric battery: 630 kW_{el}
- Smart EV charging stations (up to 150 kW)
- Copenhagen International School (CIS)
- Data Management System
- …

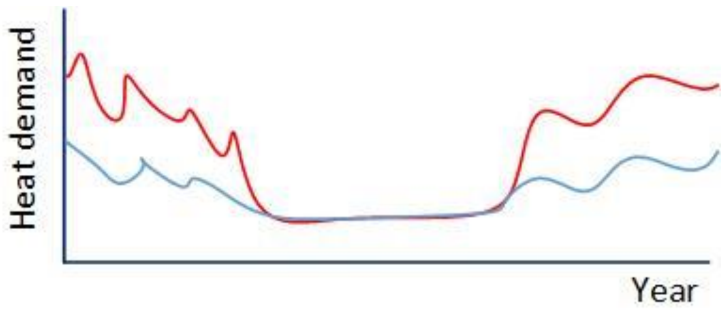
Showroom in Nordhavn

I. HP limitations in energy planning tools

- Simplified representation of HP:
  - Constant COP
  - Constant Lorenz/Carnot efficiency







- Analysis of seasonal temperature variations and availability of heat sources
- Integration of heat source characteristics in energy planning tool

II. Heat sources for Nordhavn

- Identified heat sources:
  - Ambient air
  - Groundwater
  - Sewage water
  - Seawater

- Disregarded heat sources:
  - Drinking water
  - Shallow geothermal energy
  - Solar energy
  - Industrial waste heat

II.Ambient air

- Danish Design Reference Year (DRY) for coastal parts of Sealand
- DTU weather station in Lyngby
- Weather service for Nordhavn
- Weather station at CIS in Nordhavn

- Examples of HPs:
  - Ringkøbing, 4.4 MW ->
  - Tønder, 4.4 MW
  - Sig, 0.8 MW
- Space limitation in cities
- Noise issues
- De-frosting
- Recirculation

II. Groundwater

- FlexHeat in Nordhavn
  - 2 drillings 110 m deep
  - Temperature: 10 ℃ to 11 ℃
- Examples of HPs:
  - Broager, 4 MW
  - Rye, 2 MW
  - Farstrup-Kølby, 0.8 MW
  - Dronninglund, 3 MW
- Existing HPs and reports about pumping:
  - HP capacity limit around 5 MW

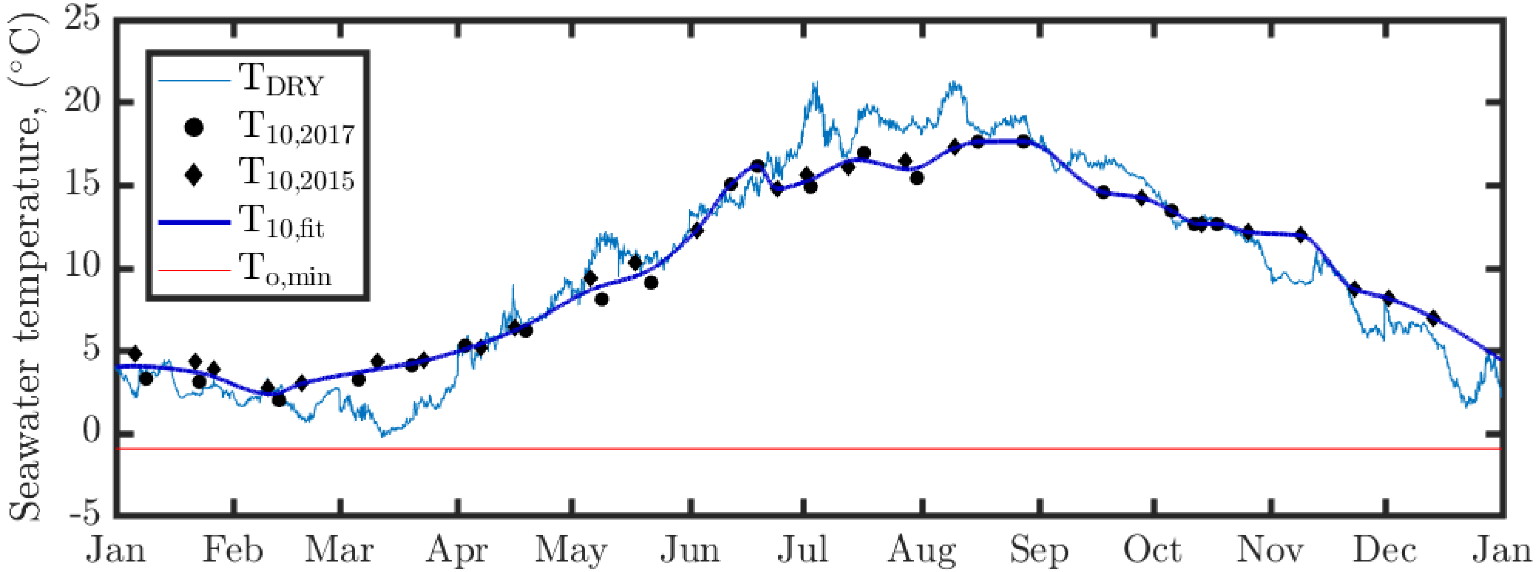
Temporary reduction of groundwater level for 50 m^3/h

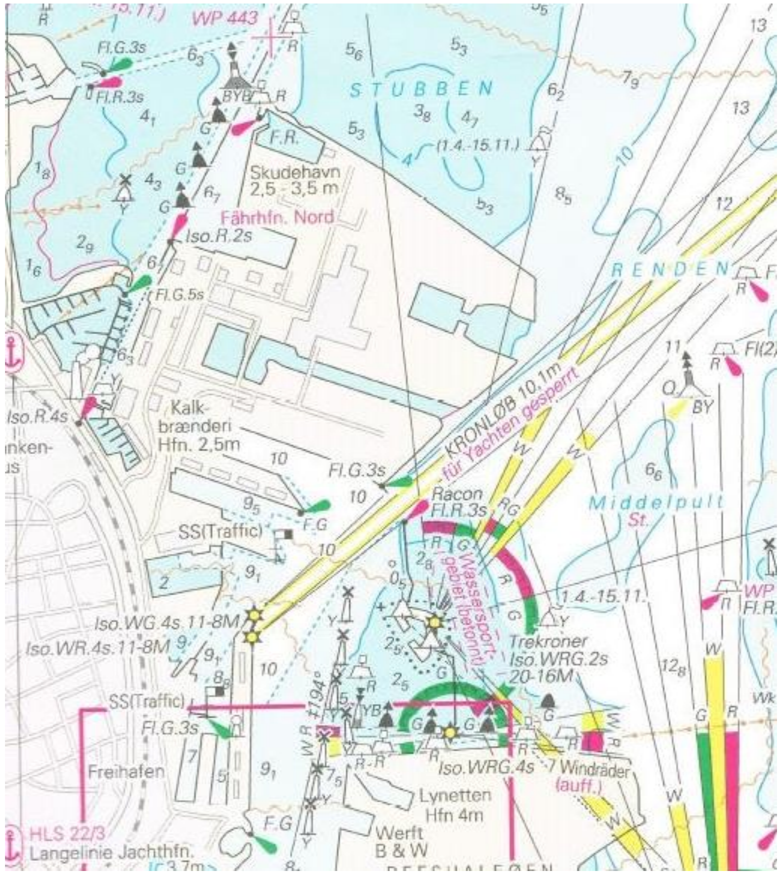
II. Sewage water

- Sewage water treatment plant Lynetten
  - 2 km south of Nordhavn
  - Measurements of temperature and flow
- Biological treatment sensitive to temperature changes
- Treated sewage water let out to sea
- Examples of HPs:
  - Rødkærsbro, 1.6 MW
  - Kalundborg, 10 MW
  - Malmo, 40 MW
  - Copenhagen, SVAF, 5 MW ->

II.Seawater

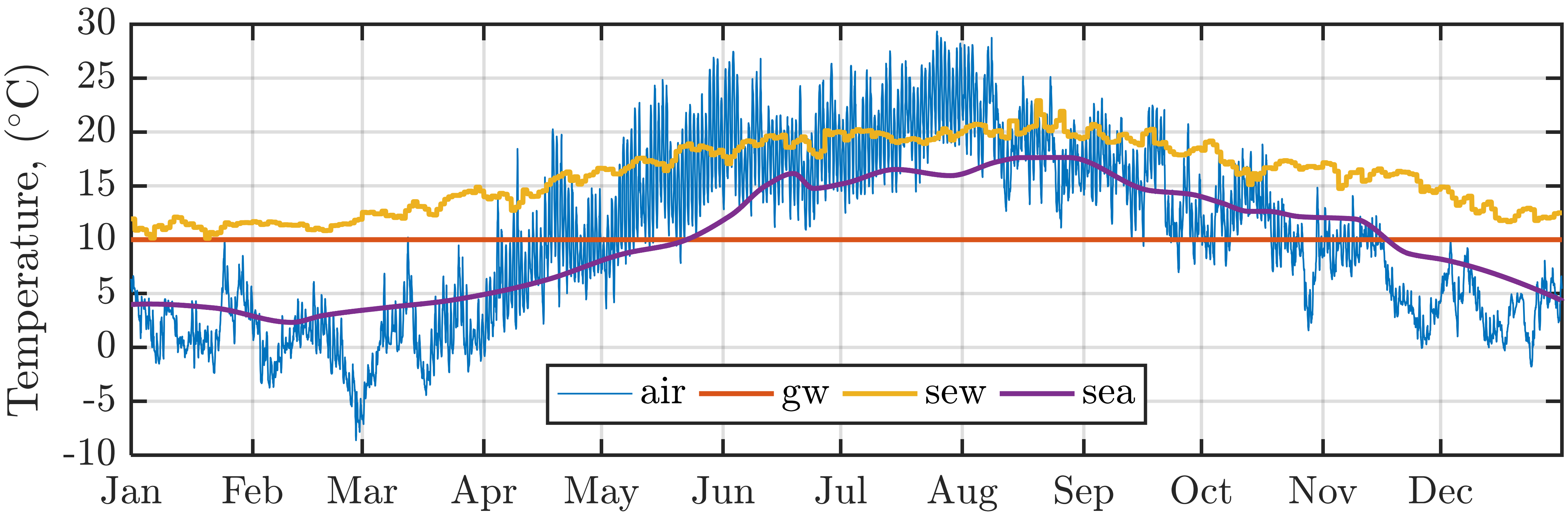
- Measurements outside Nordhavn from National database
- Comparison with surface water from DRY
- Problem of freezing





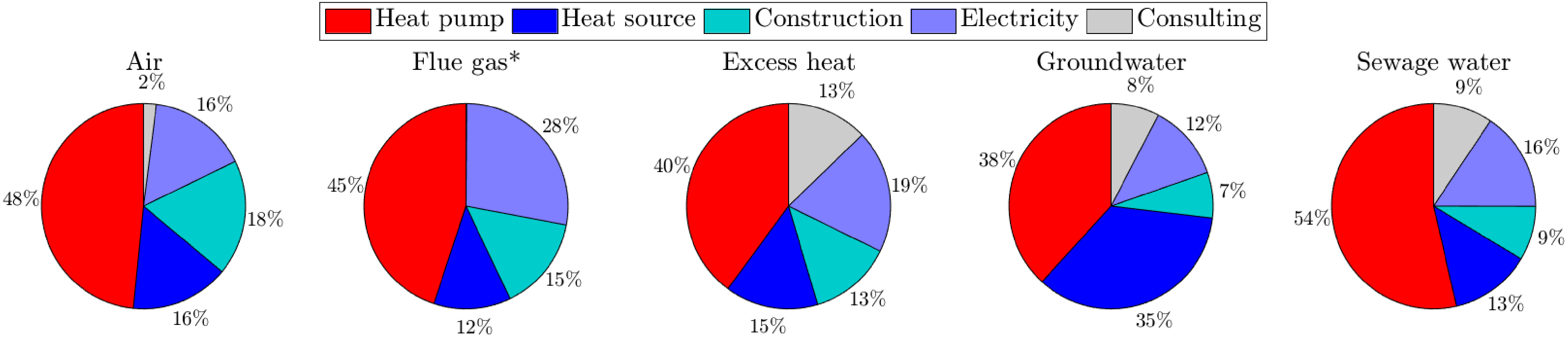
II. Heat source temperatures

- Ambient air (air), groundwater (gw), sewage water (sew) and seawater (sea)



II. Investment costs of large-scale HPs

- 26 existing and 3 planned HP projects, 12 offers of HP units
- Investments grouped into 5 categories
- Differentiated by heat source



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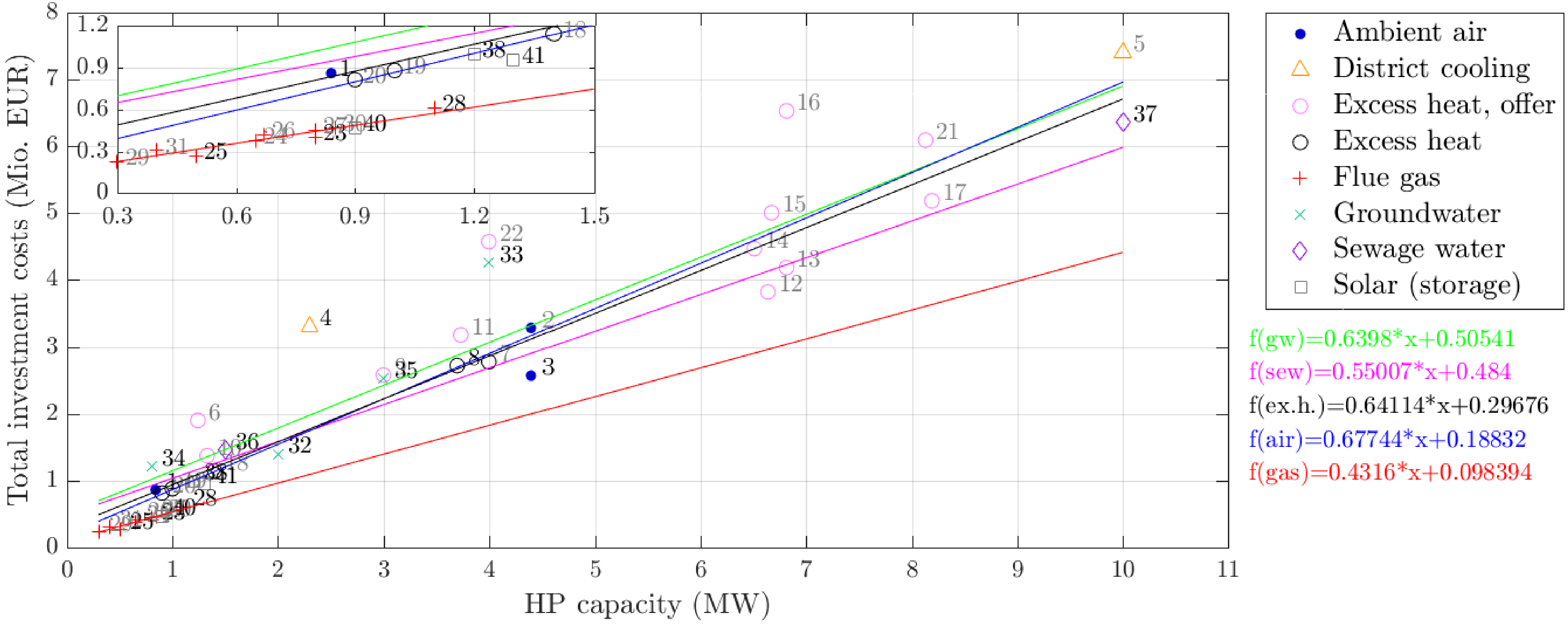
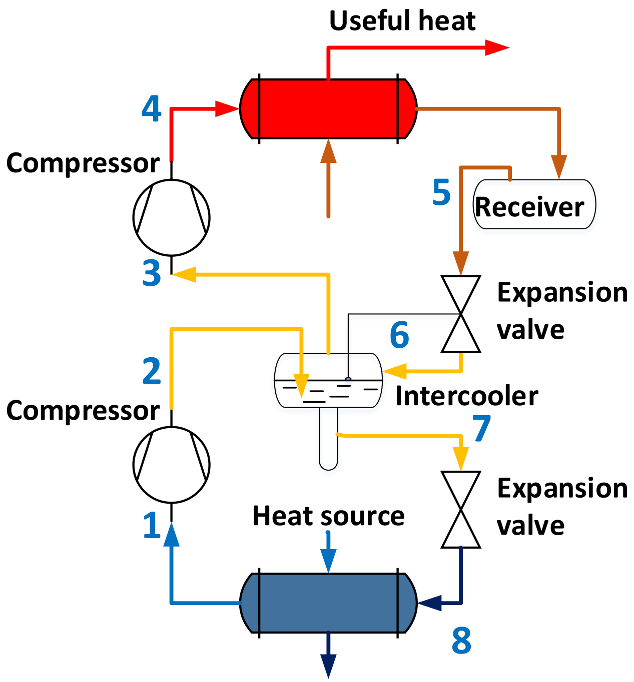
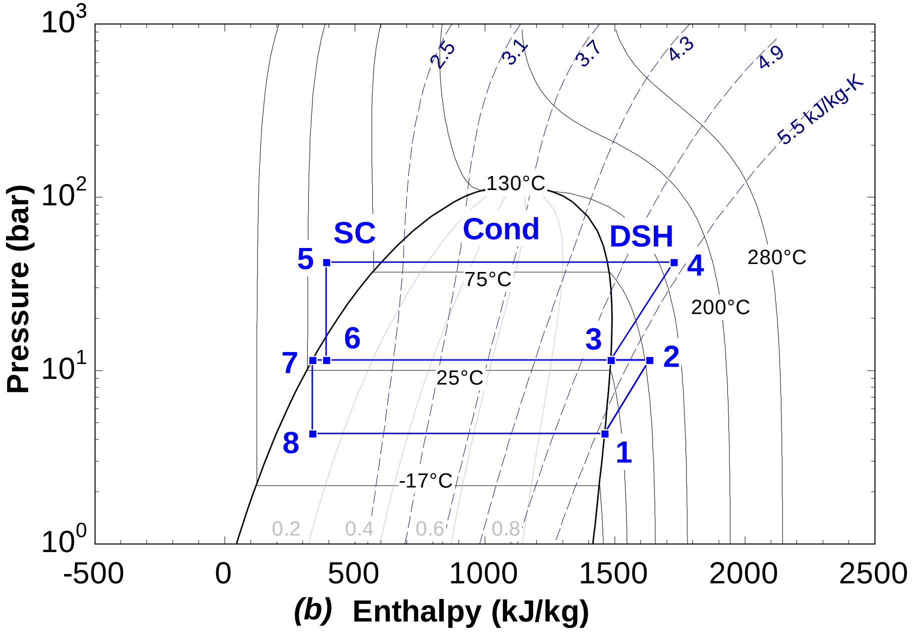
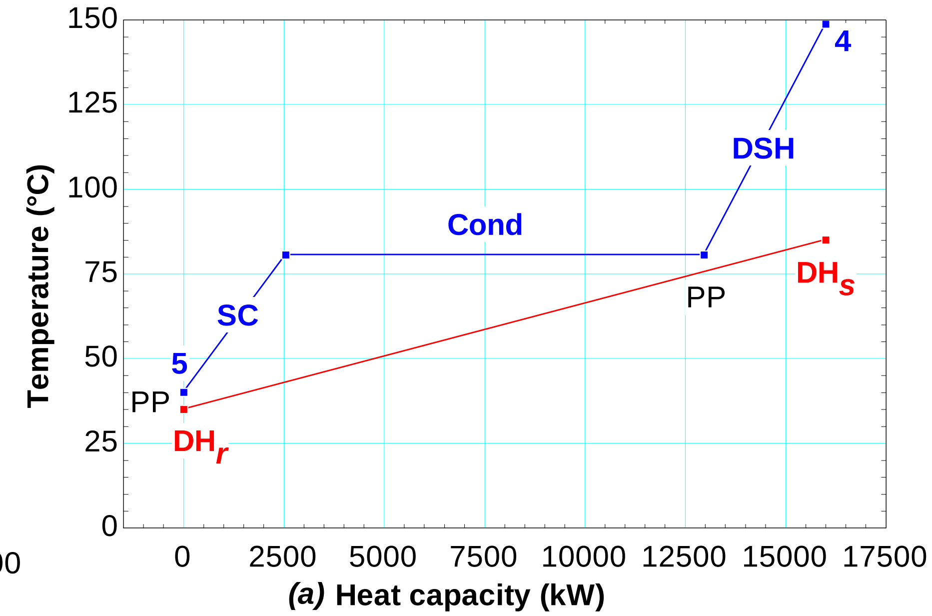


II. Thermodynamic HP model

- Engineering Equation Solver (EES)
- Calculation of state points
- 2-stage heat pump with open intercooler and ammonia as refrigerant
- Comparison with COP estimation methods







II. Developed energy planning tool

- GAMS and CPLEX solver
- Mixed-integer linear programming
- Identifying the most economical
  - Heat pump capacities
  - Heat sources to use for each hour
  - Storage capacity and hourly operation
- Considering
  - Heat source characteristics
  - Distance of heat source
  - Annualized investments
  - O&M costs
  - Full-load operation of heat pumps

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*************************************************************
*Storage equations
charge(t) .. St_char(t) =l= st_char_rate;
discharge(t) .. St_dis(t) =l= st_char_rate;
Max_storage(t) .. St_lev(t) =l= st_c_max*u_st;
storage_cap(t) .. st_c =g= St_lev(t);
storage_init(t)$(ord(t)=1) .. St_lev(t) =e= st_c_init
storage(t)$(ord(t)>1) .. St_lev(t) =e= St_lev(t-1)+St
storage_end(t)$(ord(t)=%te%) .. St_lev(t) =e= st_c_in
storage_vol .. st_V =e= st_c/(rho_DH*cp_DH*(T_s_d-T_r

*************************************************************

check_Q_sink(p,t) .. Q_sink_d_check(p)=g=Q_sink(p,t);
check_Q_hs(p,t) .. Q_hs_check(p)=g=Q_hs(p,t);

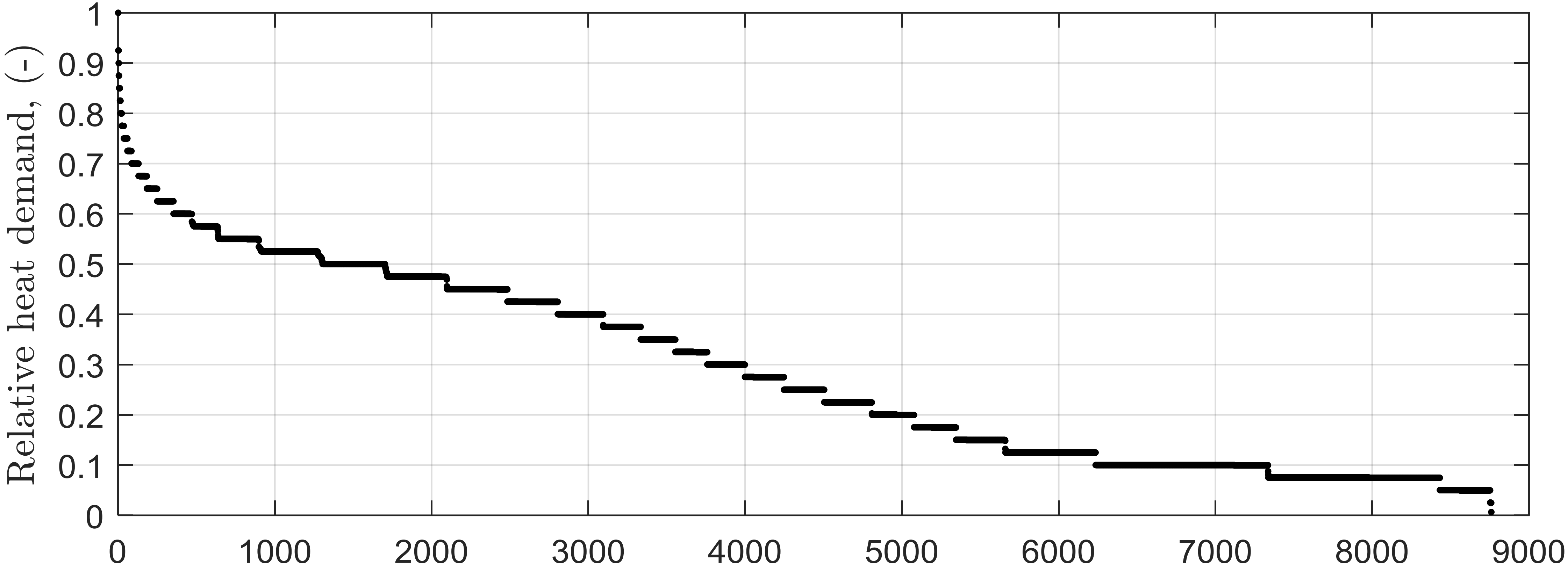
*production
supply(p,t) .. Q_hs(p,t) =l= Q_sink(p,t) ;
supply_max(p,t) .. Q_hs(p,t) =l= Q_sink_d(p) ;

demand(t) .. sum(p, Q_hs(p,t)) =e= d(t)+St_char(t)-St
* -Q_hs('sew',t)*l_DH

power(p,t) .. P_hs(p,t) =e= Q_hs(p,t)/COP(p,t);
supply_tot(p) .. Q_tot(p) =e= sum(t, Q_hs(p,t))/conv;
power_tot(p) .. P_tot(p) =e= sum(t, P_hs(p,t)/conv);
power_max(p,t) .. P_max(p) =g= P_hs(p,t);
```

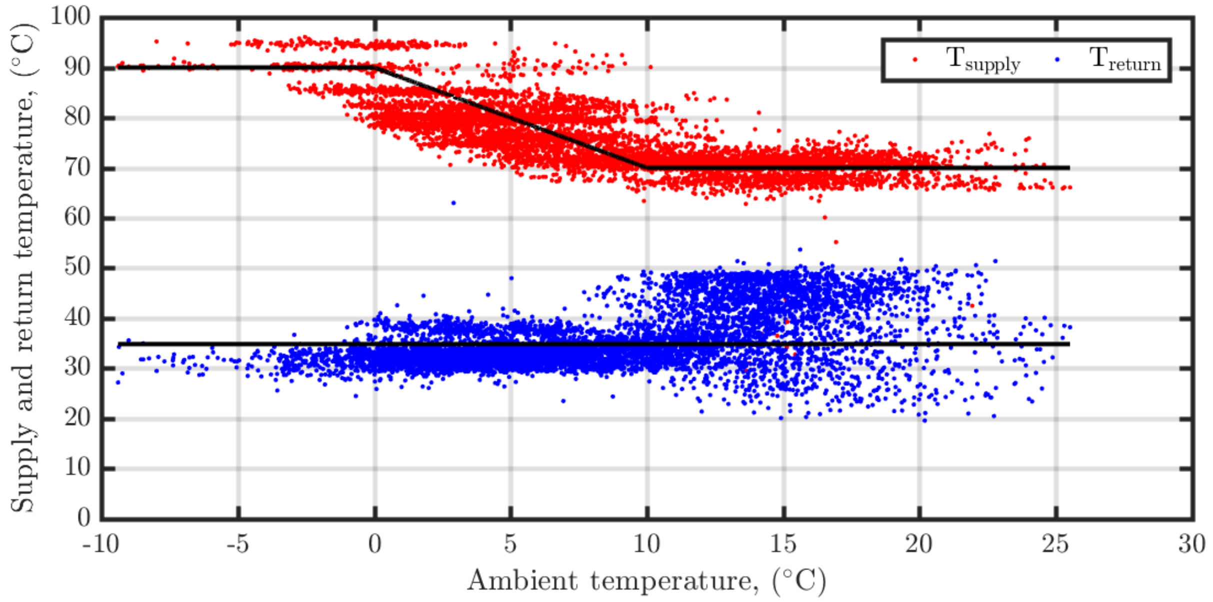
II. Heat demand for optimization

- Measurements of DH supply for existing part of Nordhavn in 2018
- Relative heat demand * 20 MW -> 51 GWh annually

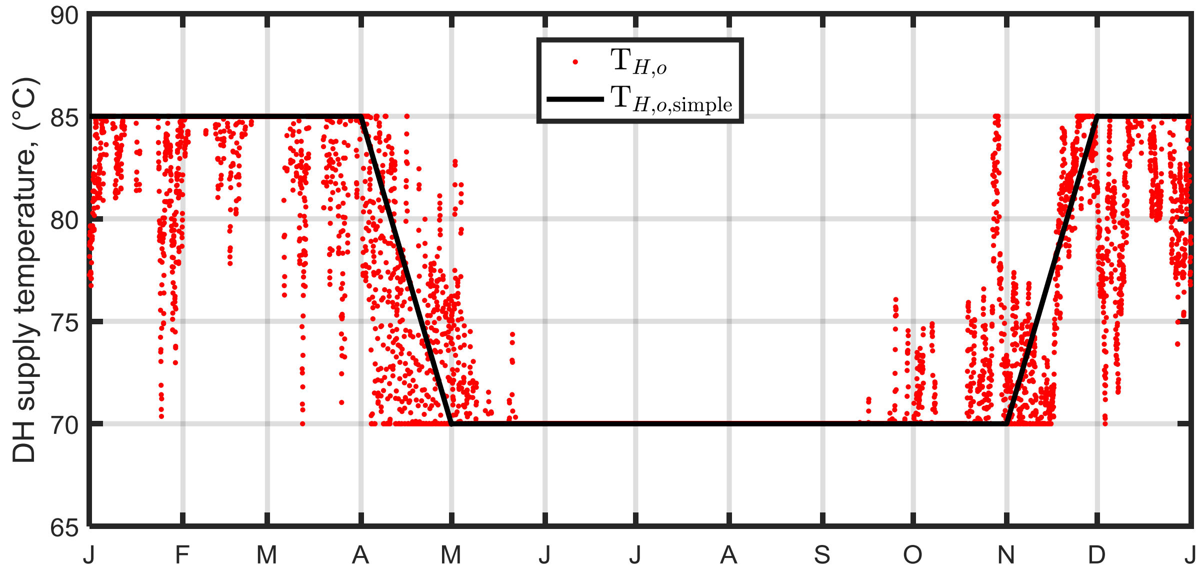


II. District heating temperatures

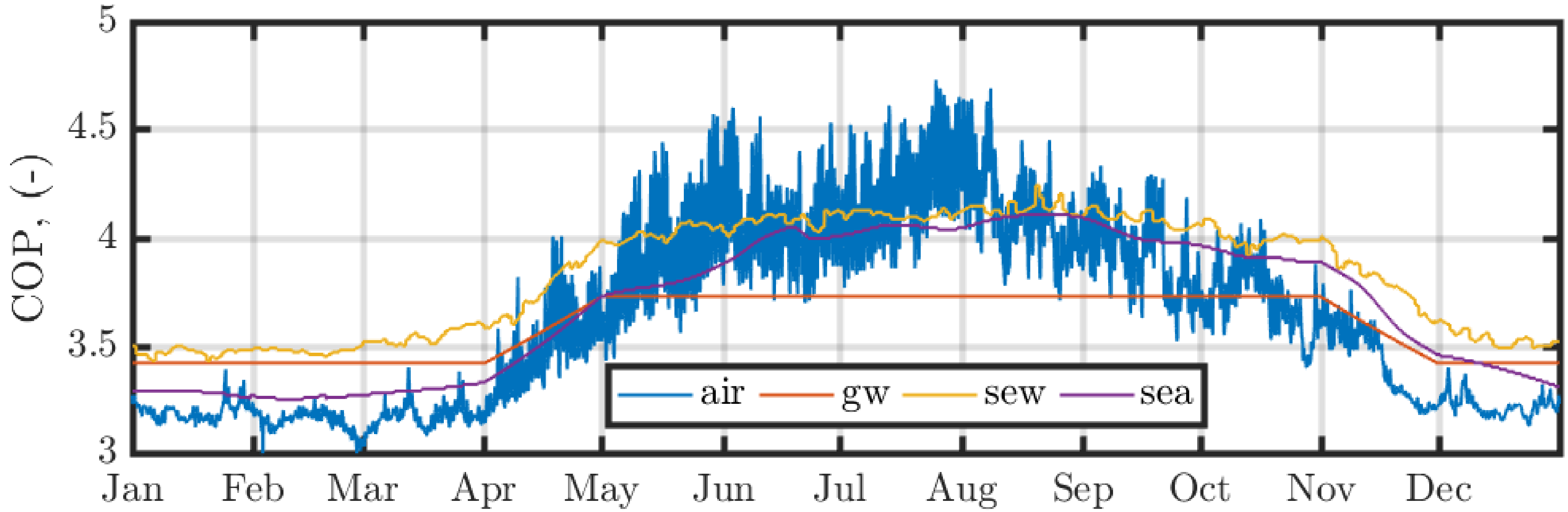
- Measurements of DH temperatures for a building in Nordhavn



- Simplification



III.Hourly COPs



Parameter	Sea	Sew	Air	GW
Seasonal COP	3.48	3.67	3.35	3.51

III. Results of optimization

1 €/MWh$_{th}$ -> 50,000 €/yr

Comparison (Sewage water, Ambient air, Ground water, Denmark [3])

Parameter	Unit	Sea water	Sewage water	Ambient air	Ground water	Denmark [3]	Sea/GW/air
HP capacity	MW	15.4	16.3	16.8	15.4		10.0/5.0/0.4
Storage capacity	MW	32.2	32.9	29.6	32.3		33.0
Seasonal COP	-	3.4	3.4	3.3	3.5	3.5 – 4.5	3.5
Levelized cost of heat	€/MWh$_{th}$	**45.2**	**46.8**	**47.5**	**44.5**	42 - 49	**45.7**
O&M costs	€/MWh$_{th}$	31.7	31.8	33.0	31.5	25 - 32	31.4
CO_2 emissions	kg/MWh$_{th}$	67.0	66.8	69.5	65.9		66.1

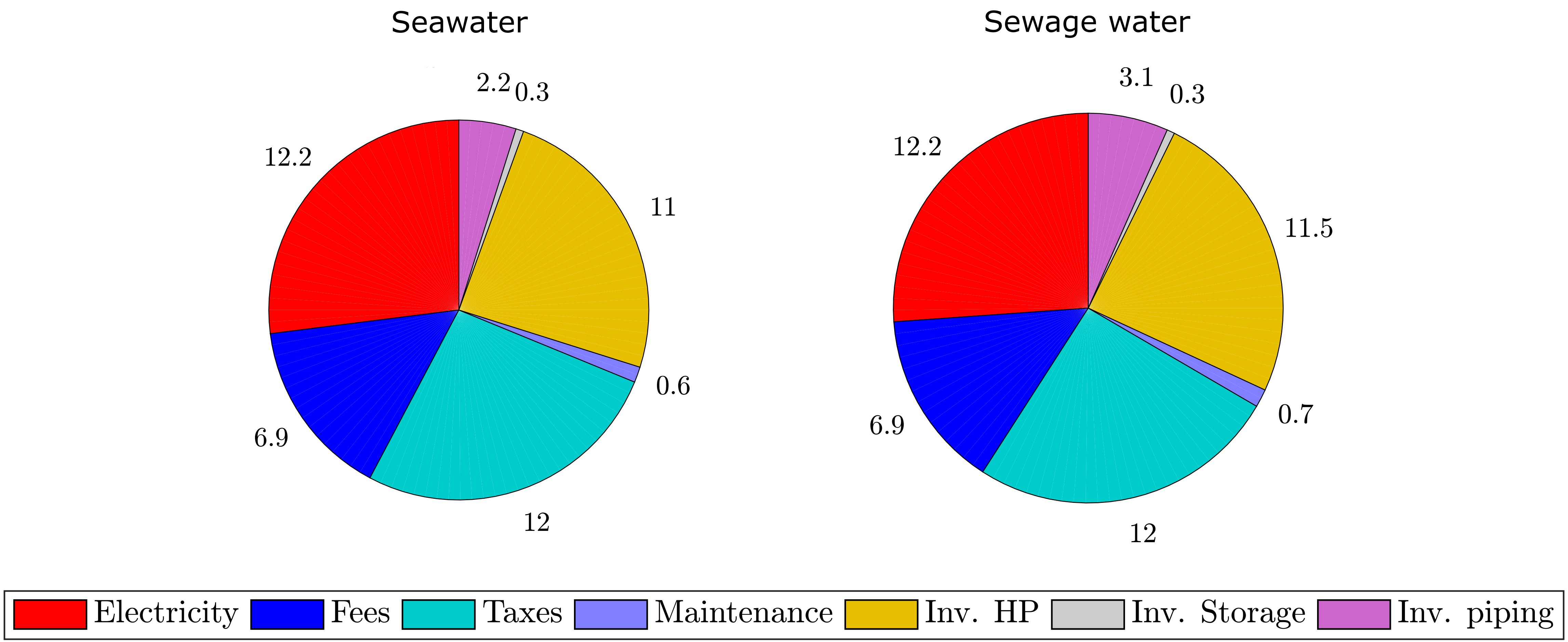
0.2 km piping

2.0 km piping

5% pipe heat loss

Seawater HP limit: 10 MW
Groundwater HP limit: 5 MW

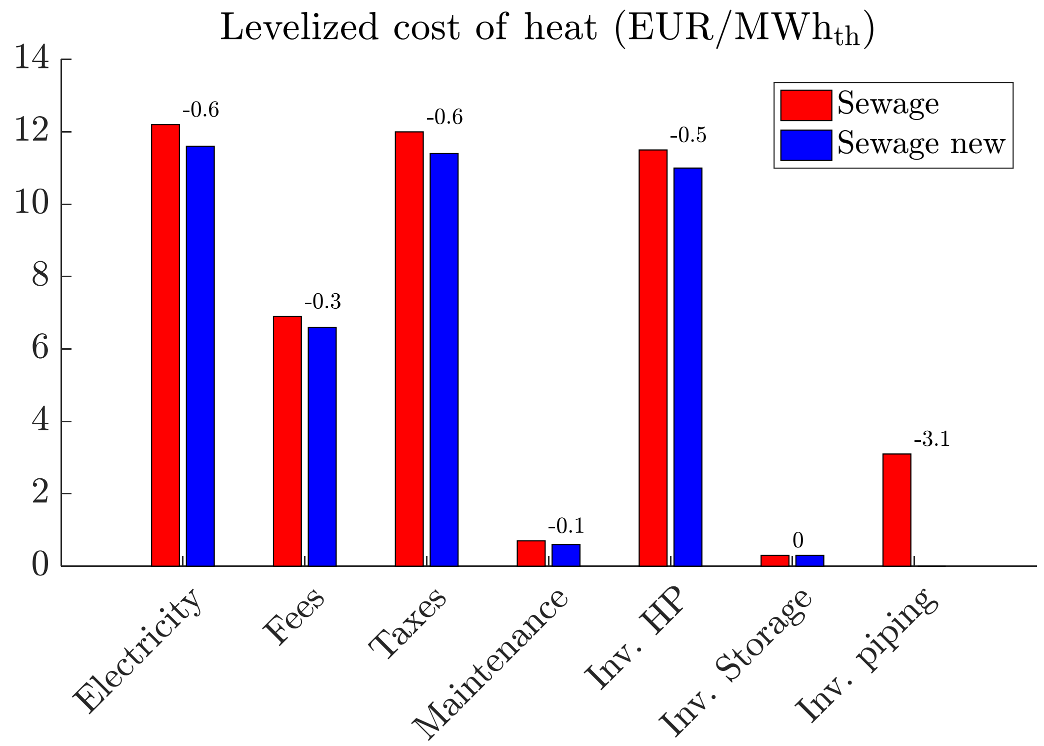
III. Levelized costs of heat



III. Results, if no distance to heat sources

Parameter	Unit	Sewage water	Difference
HP capacity	MW	15.5	–0.8
Storage capacity	MW	28.8	–4.1
Seasonal COP	-	3.6	+0.2
Levelized cost of heat	€/MWh_{th}	**41.6**	**–5.2**
O&M costs	€/MWh_{th}	30.2	–1.6
CO_2 emissions	kg/MWh_{th}	63.4	–3.4

LCOH of seawater HP: 43



IV.Discussion

- No part-load operation of HP in developed model
- No auxiliary electricity consumption (pumps, fans)
- Investment costs of DH network not considered
- Lifetime of 25 years, discount rate of 4 %
- Limited to certain HP design and ammonia as refrigerant
  - Comparison with COP estimation methods on-going
- Case study of Nordhavn
  - Tool applicable to any case
  - Impact of pipe length
- Optimum based on several heat sources possible
  - Can be better than the 2. best heat source

V. Conclusion

- COP varies considerably during the year
- Seawater is the most suitable heat source
  - Then follow: Sewage water, ambient air and groundwater
- HP capacity 80 % of hourly peak demand
- Storage capacity 160 % of hourly peak demand (564 m^3)
- No electric peak load boiler

Thank you for your attention

Questions?

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