Large-scale heat pump integration model: A case study of Tallinn district heating

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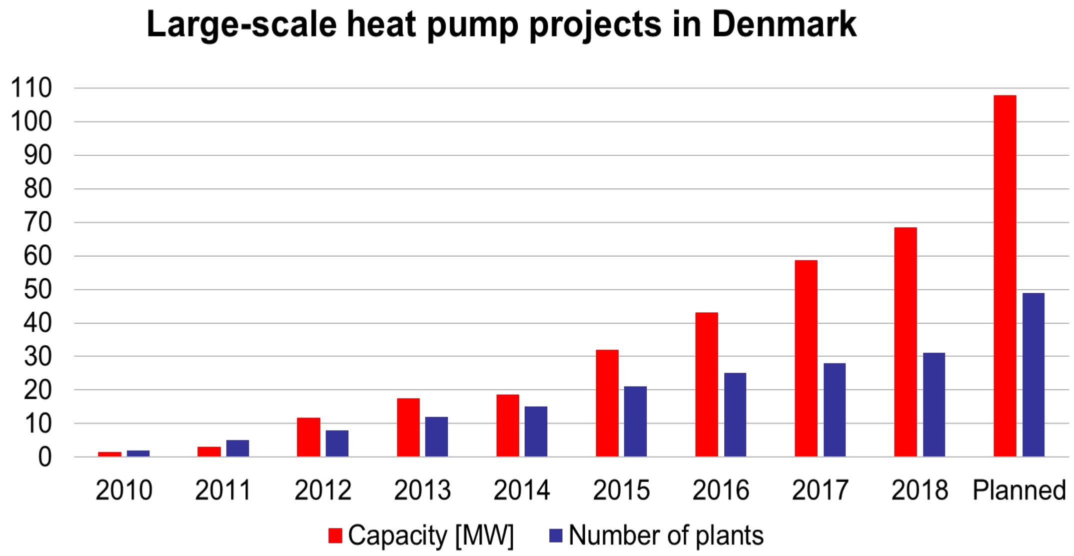
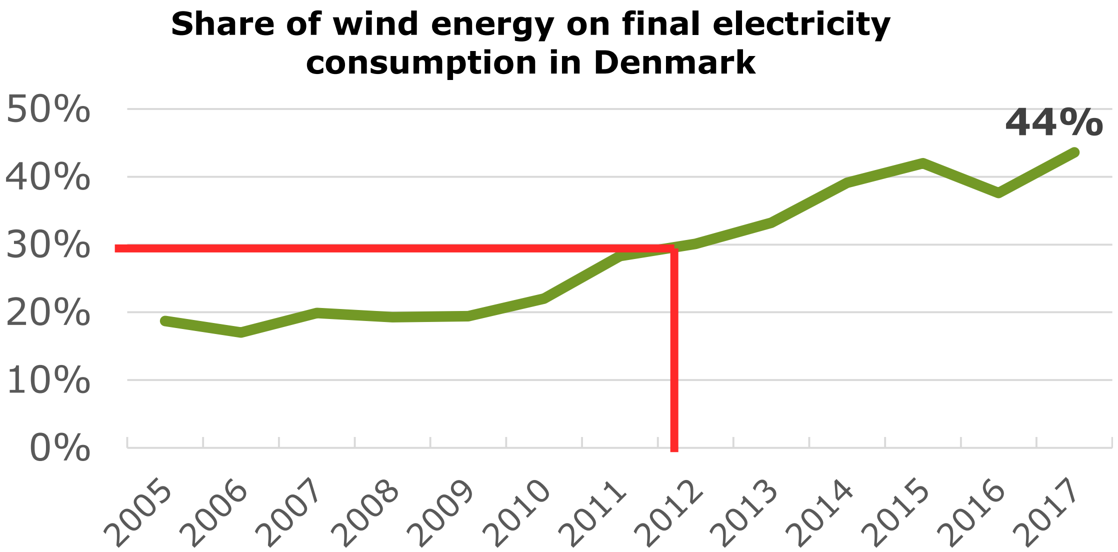
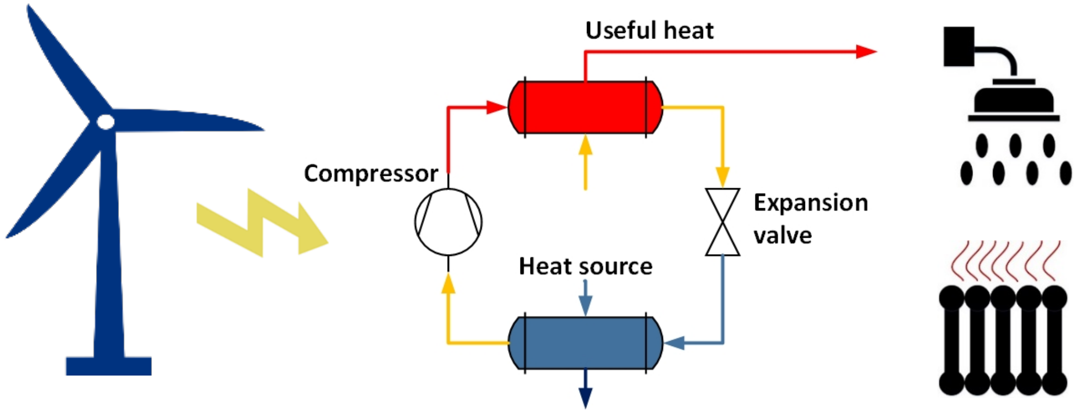
I. Introduction





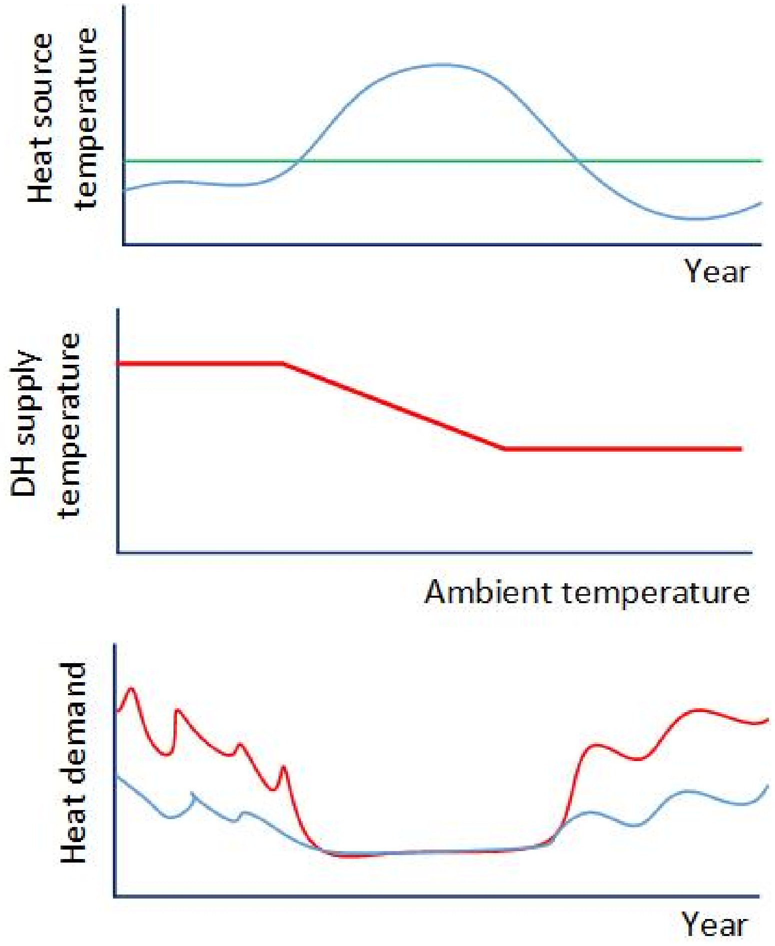


- Heat pumps part of ”Smart Energy Systems”
- Balance intermittent power generation
- Use surplus electricity
- Use existing storage capacity in DH networks

I. Introduction

Energy planning tools:

- Variety of technologies included (boiler, CHP,…)
- Considering investments and O&M costs
- Hourly calculations for full year
- Simulation or optimization models
- Limitations on HP:
  - Constant COP or varying COP with constant Lorenz efficiency
  - Same investment costs for HPs
  - Only few heat sources



<u>Aim of this study:</u>

- Reduce these limitations for large-scale HPs
- More realistic representation → more realistic solution

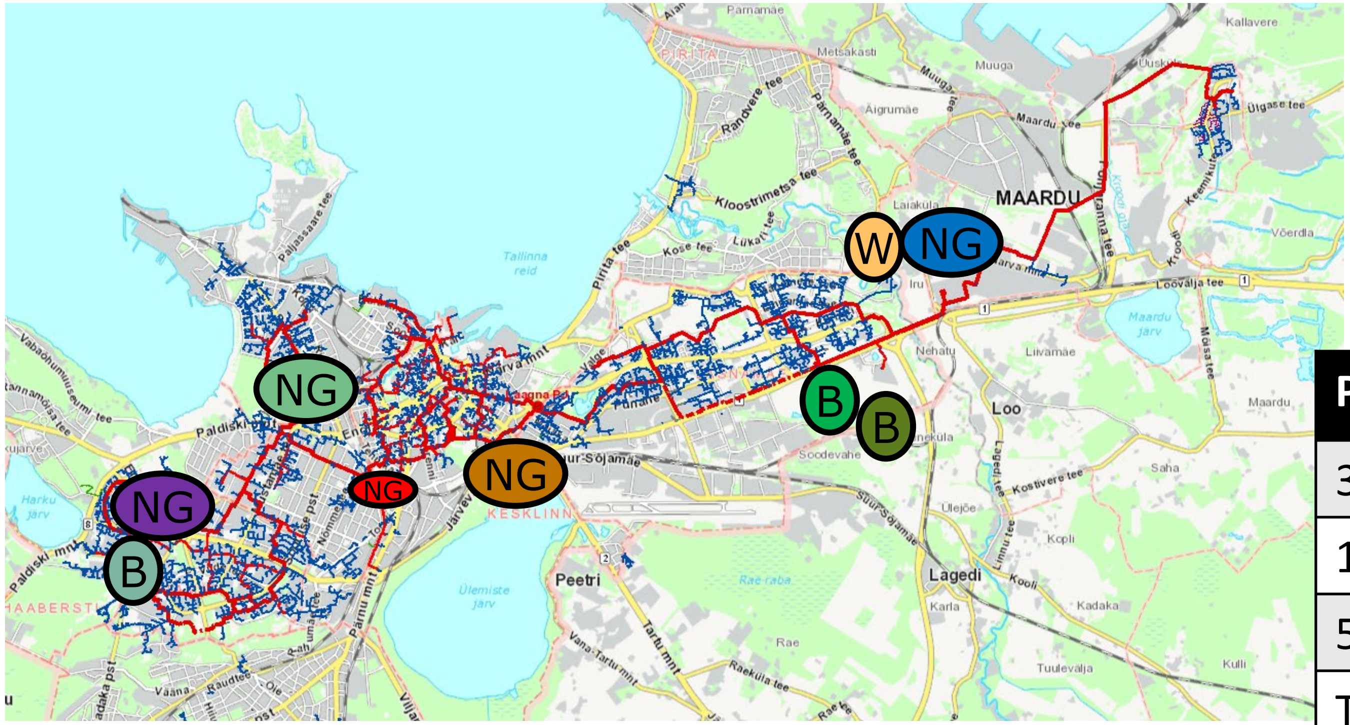
II. Model

- GAMS, optimization using mixed integer linear programming
  - minimize investment and O&M costs [1]
  - Seasonal variation of heat source and heat sink temperatures
  - Capacity limitations
  - Hourly calculations for one year
- Model determines:
  - Best suitable heat sources
  - Optimal HP capacities
  - Technical, economic and environmental parameters

- $\mathrm{COP} = \mathrm{COP}_L \dfrac{1+\frac{\Delta\bar{T}_{r,H}+\Delta\bar{T}_{\mathrm{pp}}}{\bar{T}_H}}{1+\frac{\Delta\bar{T}_{r,H}+\Delta\bar{T}_{r,C}+2\Delta\bar{T}_{\mathrm{pp}}}{\Delta\bar{T}_{\mathrm{lift}}}} \eta_{\mathrm{is},c}\left(1-\frac{w_{\mathrm{is},e}}{w_{\mathrm{is},c}}\right)+1-\eta_{\mathrm{is},c}-f_Q$
  - Red: fitted based on linear approximation
  - Paper link on reference slide [2]

Par.	Value used
f_Q	0.05
$\eta_{\mathrm{is},c}$	0.80
$\Delta\bar{T}_{\mathrm{pp}}$	5 K
$\Delta\bar{T}_{r,C}$	$0.5(T_{C,i}-T_{C,o})$
$\bar{T}_H$	$\dfrac{T_{H,o}-T_{H,i}}{\ln(T_{H,o}-T_{H,i})}$
$\Delta\bar{T}_{\mathrm{lift}}$	$\bar{T}_H-\bar{T}_C$
COP_L	Lorenz COP

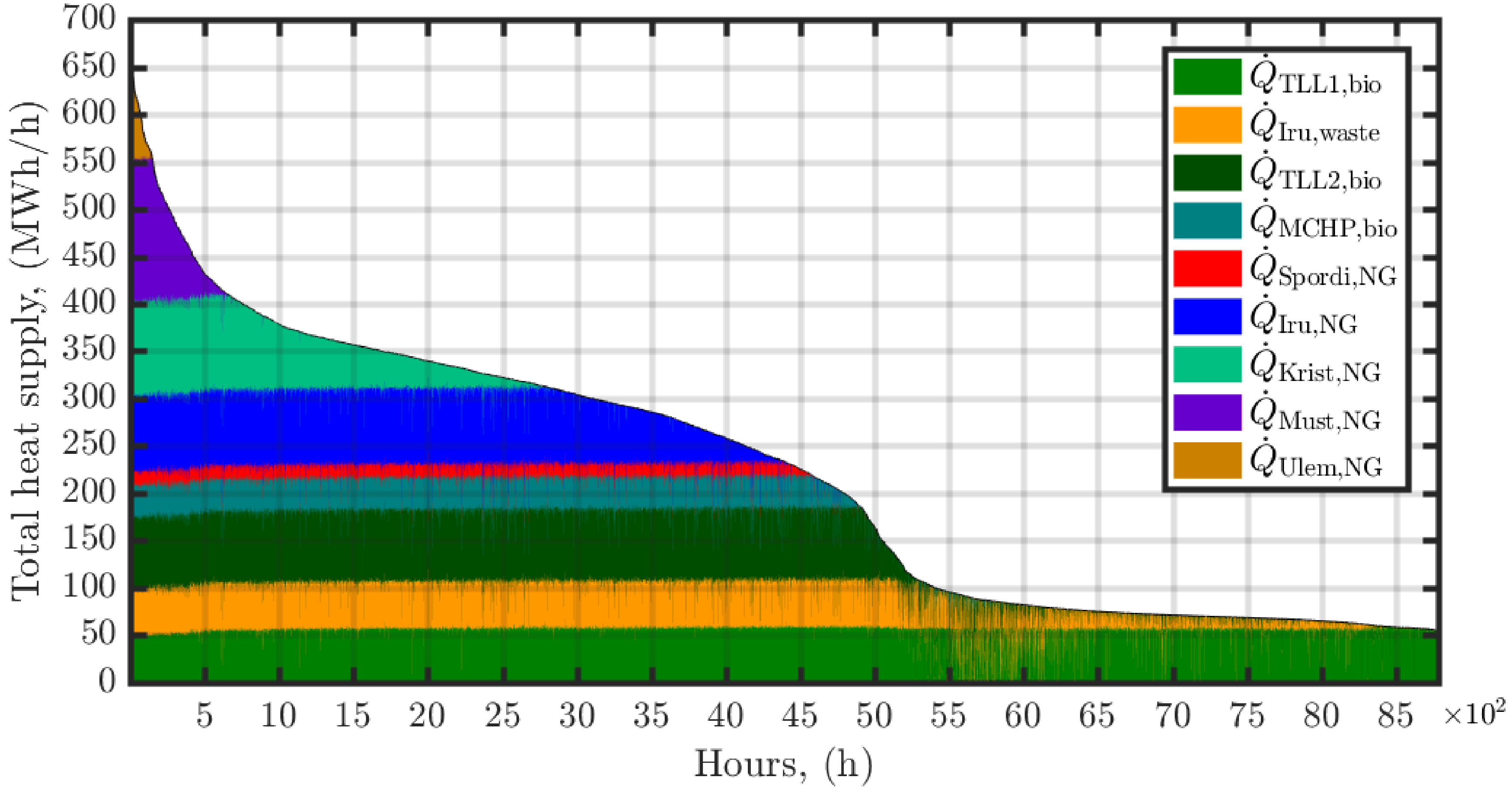
II. Case study: DH network of Tallinn



- Tallinn: 400,000 inhabitants
- B: Biomass
- W: Waste incineration
- NG: Natural gas

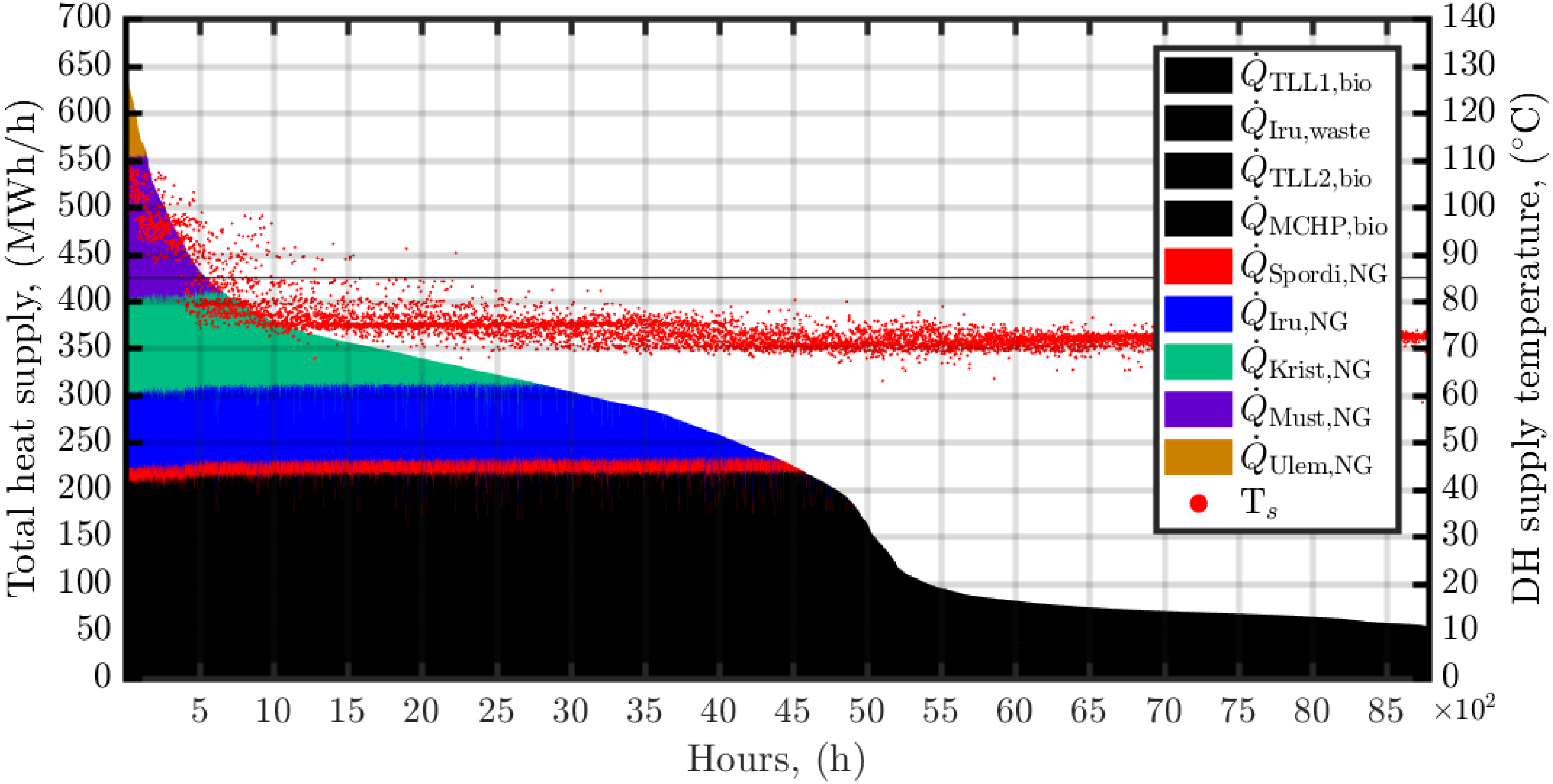
Production units	Parameter	Share in 2017
3 x biomass CHP	170 MW	35%
1 x waste incineration	50 MW	15%
5 x NG boiler houses	>500 MW	50%
Total production	1970 GWh	
Pipe length	438 km	
# of buildings supplied	3873	
Heat loss	14.5%	
Avg. supply/return temp.	77/51 °C	

II. Load duration curve



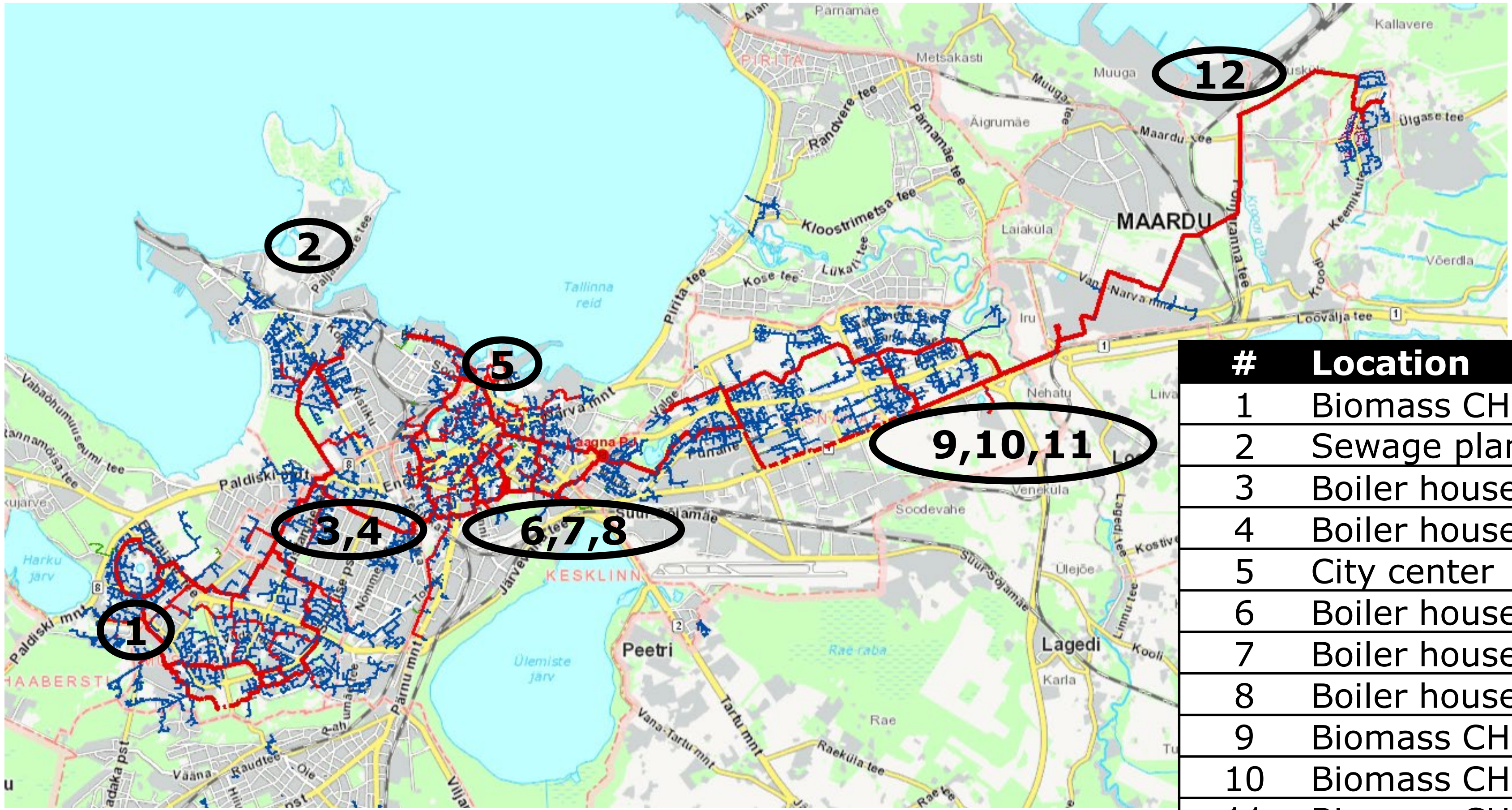
- Peak demand (2016): 660 MW
- 220 MW from non-fossil fuels

II. Potential heat supply for HPs



- Supply temperature up to 110 ° C
- Temperature limit for ammonia HPs: 85 ° C
- Max. 4000 (4500) h of potential heat supply
- Number of full load hours depends on HP capacity

II. Possible HP locations



#	Distance DH
2	2.5 km
5	0.2 km
6	0.3 km
9	0.6 km
12	2.0 km
13	0.1 km

#	Location	Heat source	Limit
1	Biomass CHP*	Groundwater	2 MW
2	Sewage plant	Sewage water	4000 – 14000 m3/h
3	Boiler house	Ambient air	10 MW
4	Boiler house	Groundwater	1 MW
5	City center	Seawater	No limit
6	Boiler house	Lake water	27000 m3/h
7	Boiler house	Groundwater	1 MW
8	Boiler house	Ambient air	10 MW
9	Biomass CHP*	River water	6000-25000 m3/h
10	Biomass CHP*	Ambient air	24 MW
11	Biomass CHP*	Groundwater	6 MW
12	Maardu**	Seawater	Local heat demand
13	100 m from DH	Groundwater	6 MW each

*Distribution costs avoided

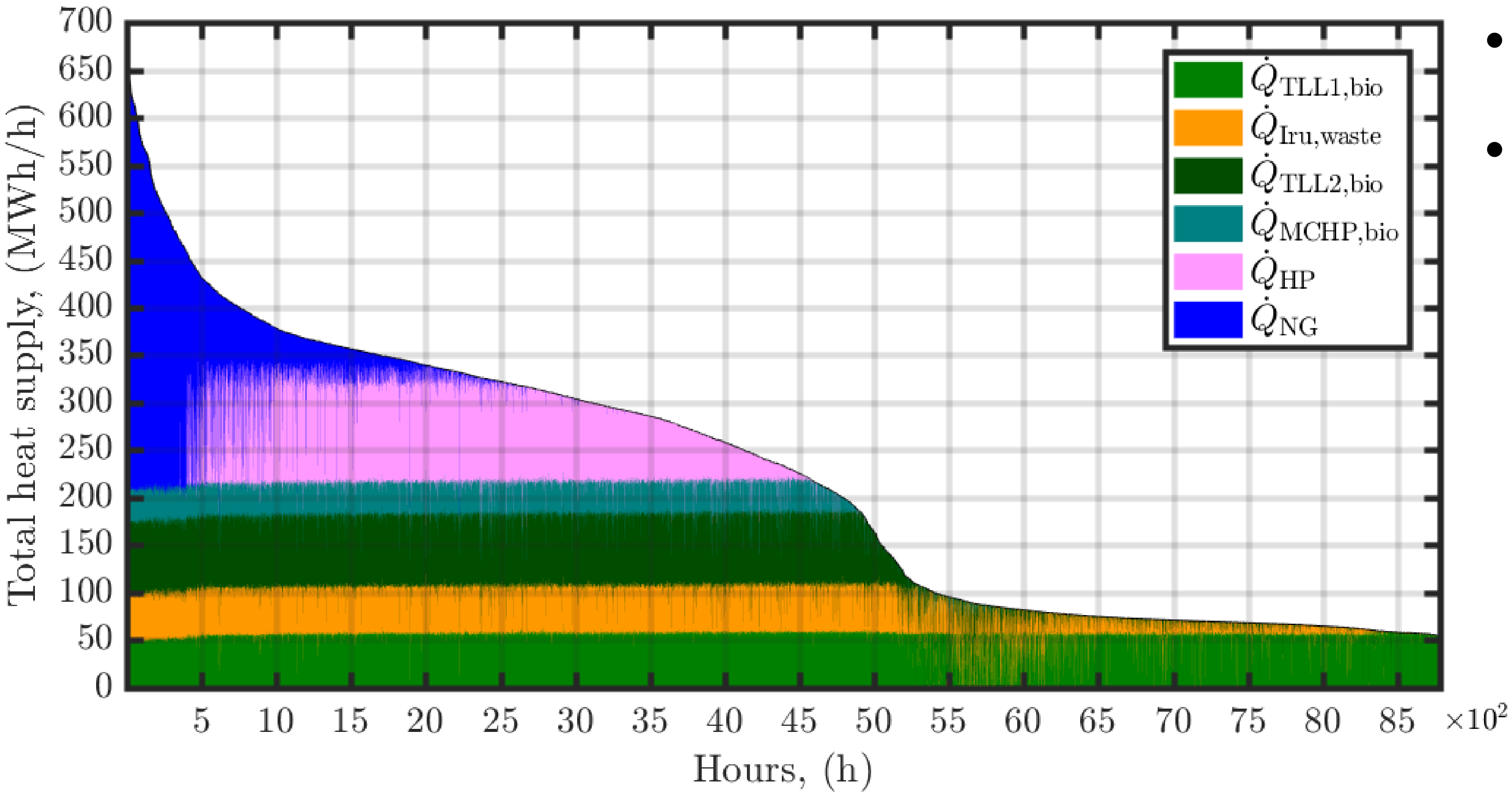
**Heat loss of 13 km transmission pipe avoided

III. Results

Parameter	Unit	#3	#6	#10	#11	#12	Total	Denmark [3]
Source		Sew	Lake	Air	GW	Sea	Mix	
Q_{HP}	MW	45	43	24	6	12	130	
SCOP	-	3.4	3.2	2.9	3.2	3.3	3.2	3.5 – 4.5
FLH	h	3356	2263	1838	2846	2797	2638	3000 - 6000
$Cost_{HP,inv+el}$	€/MWh_h	30.2	34.8	39.3	33.5	35.4	33.3	42 - 49
$Cost_{HP,el}$	€/MWh_h	16.4	18.3	17.8	15.5	17.5	17.2	25 - 32
$Cost_{el}$	€/MWh_{el}	53.5	56.0	48.9*	47.4*	54.8	53.4	90 - 100
NPV	M€	33	15	4	3	9**	64	
PBT_{simple}	yrs	6.4	8.2	10.4	8.1	6.5**	7.5	4 – 8
$CO2_{ratio}$	-	1.32	1.39	1.53	1.39	1.37	1.38	0.29

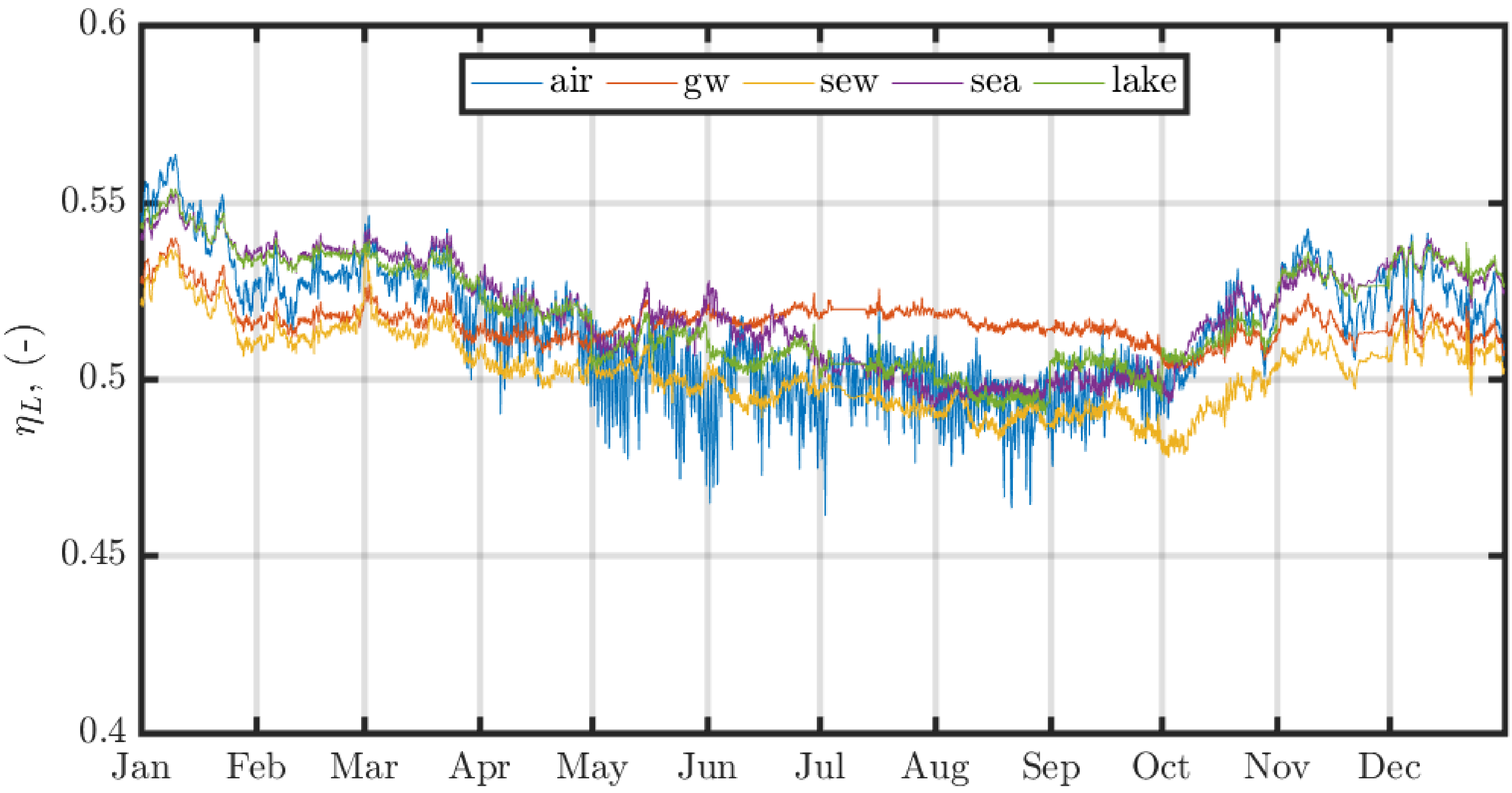
*Distribution costs avoided **Heat loss of 13 km transmission pipe avoided

III.Load duration curve with HPs



- 344 GWh HP operation (17%)
- Share of NG reduced from 50% to 33%

III.Lorenz efficiency



- Lorenz efficiency
  - varies during the year
  - differs between heat sources

IV.Discussion

- Limited applicability of HPs due to existing biomass CHP and waste incineration

- Solution considers different benefits:
  - No distribution costs (air, groundwater)
  - Reduction of heat loss (seawater)
  - Reduction of part of the investment (building, land, evaporator)

- Sustainability of HPs depends on electricity mix
  - 0.95 $tonCO_2/MWh_{el}$ in Estonia (for energy generation: 75% oil shale)
    - 2009: 1.19 $tonCO_2/MWh_{el}$
    - Needed for HPs: <0.69 $tonCO_2/MWh_{el}$
  - 0.2 $tonCO_2/MWh_{el}$ in Denmark

V. Conclusion

It was found:

- Optimal HP capacities, heat sources and HP operation
- Best economic solution: 130 MW HP capacity
- Heat sources: sewage water, lake water, groundwater, ambient air and seawater

- Sustainability of HPs depends on electricity mix

Thank you for your attention

Questions?

References

Investment costs of large-scale heat pumps:

- [1] Pieper, H., Ommen, T., Bühler, F., Lava Paaske, B., Elmegaard, B., & Markussen, W. B. (2018). Allocation of investment costs for large-scale heat pumps supplying district heating. Energy Procedia, 147, 358-367. DOI: 10.1016/j.egypro.2018.07.104 http://orbit.dtu.dk/en/publications/allocation-of-investment-costs-for-largescale-heat-pumps-supplying-district-heating(33c64aca-8cb6-44eb-b5f9-cddb66de1905).html

COP estimation:

- [2] Jensen, J. K., Ommen, T., Reinholdt, L., Markussen, W. B., & Elmegaard, B. (2018). Heat pump COP, part 2: Generalized COP estimation of heat pump processes. In Proceedings of the13th IIR-Gustav Lorentzen Conference on Natural Refrigerants International Institute of Refrigeration. DOI: 10.18462/iir.gl.2018.1386 http://orbit.dtu.dk/en/publications/heat-pump-cop-part-2-generalized-cop-estimation-of-heat-pump-processes(c792e113-61ba-4f66-ad2b-fefc0fc7f418).html

Danish examples of large-scale HPs:

- [3] Danish Energy Agency. Inspirationskatalog for store varmepumpeprojekter i fjernvarmesystemet, 2017. https://ens.dk/sites/ens.dk/files/Varme/inspirationskatalog_for_store_varmepumper.pdf

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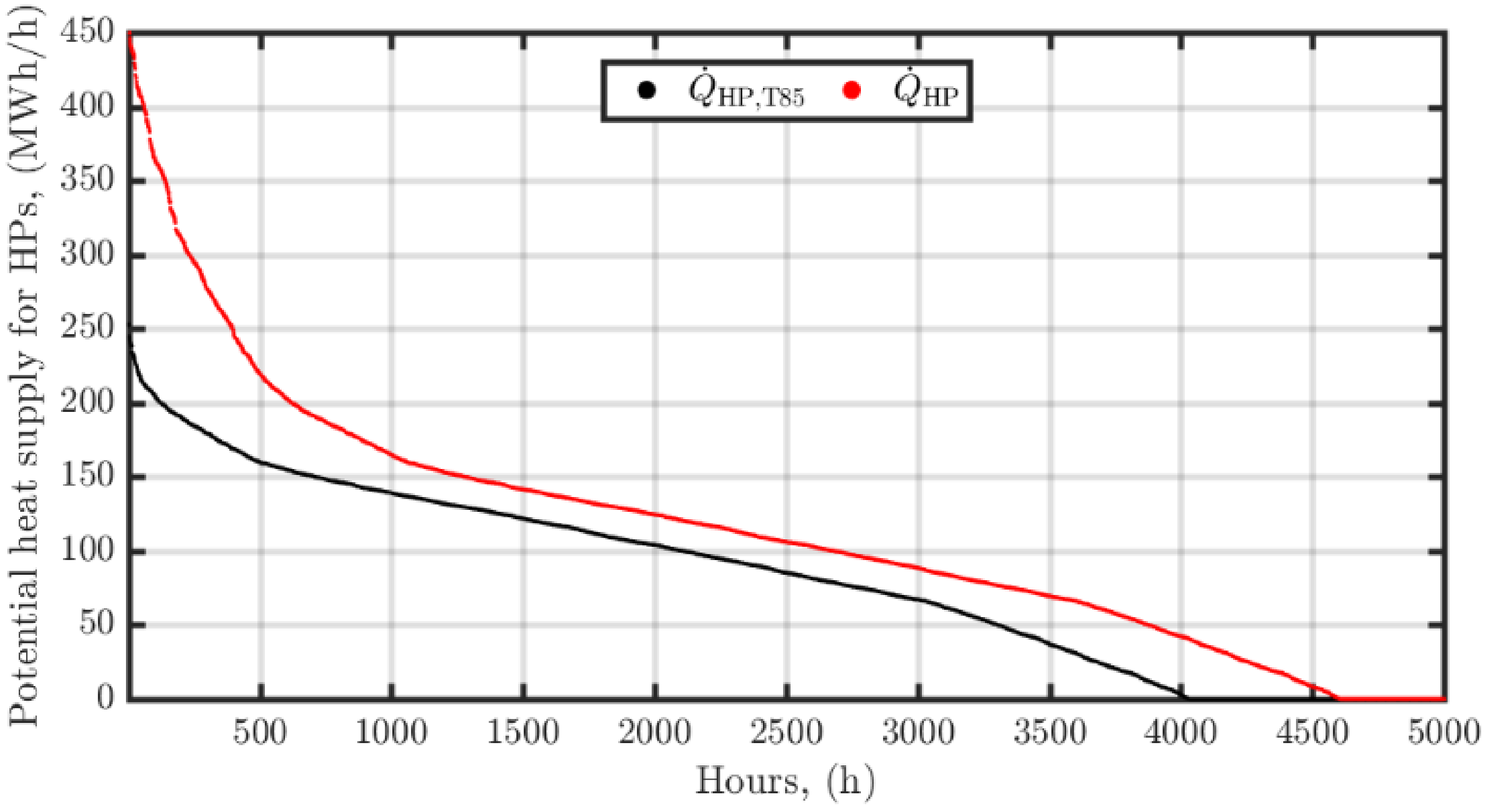
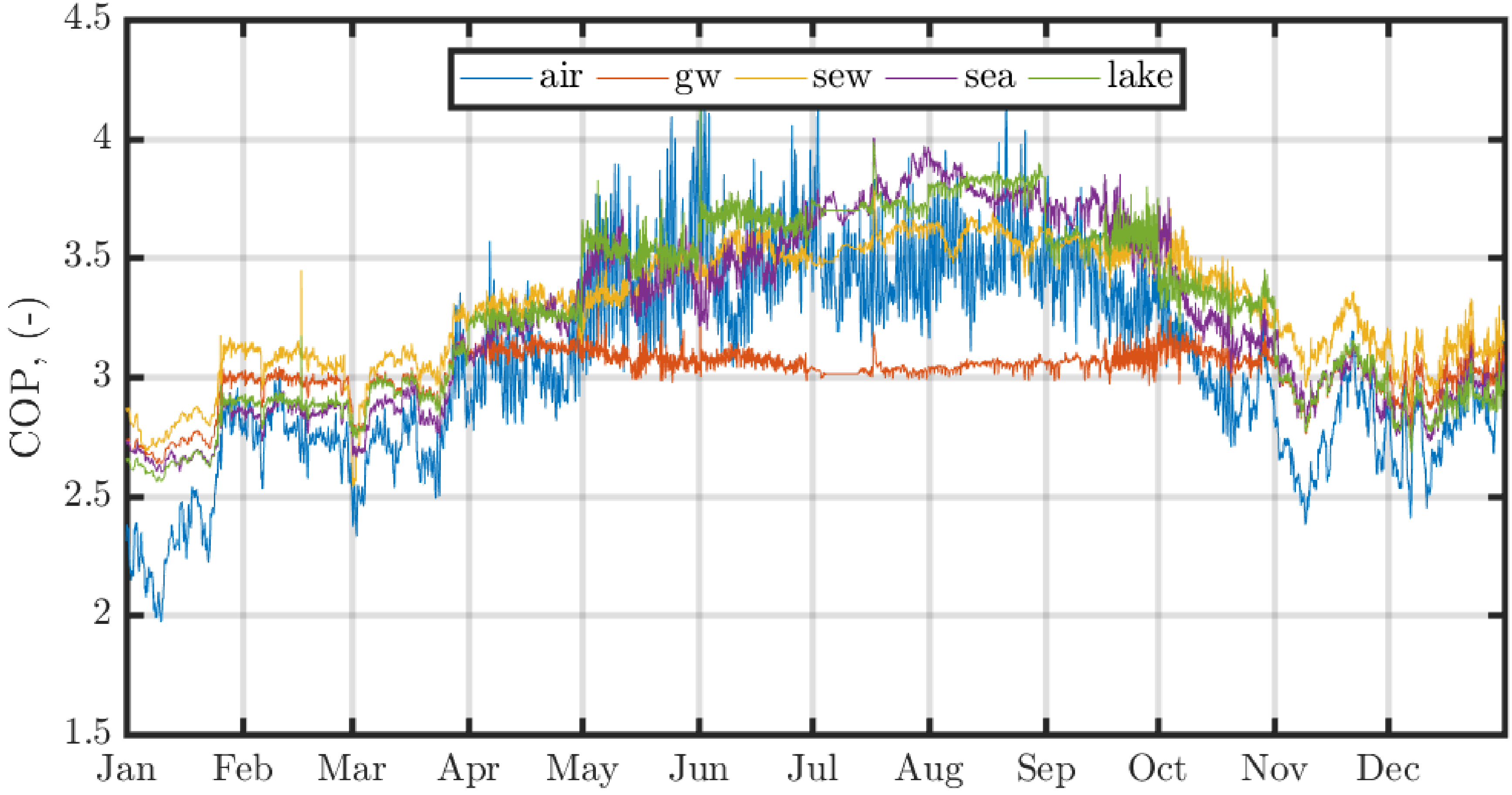
II. Potential heat supply for HPs



- Max. 4000 (4500) h of potential heat supply
- Number of full load hours depends on HP capacity

III.COP of HPs



III. Sensitivity analysis: electricity price +30%

Parameter	Unit	#3	#6	#10	#11	#12	Total	Total change	
Source		Sew	Lake	Air	GW	Sea	Mix	Rel.	Abs.
Q_{HP}(Input)	MW	45	43	24	6	12	130		
SCOP	-	3.4	3.2	2.9	3.2	3.3	3.2		
FLH	h	3356	2261	1840	2849	2804	2640		
$Cost_{HP,inv+el}$	€/MWh_h	33.2	38.1	42.8	36.6	38.6	36.5	+9.6%	+3.2
$Cost_{HP,el}$	€/MWh_h	19.4	21.6	21.4	18.6	20.7	20.4	+18.6%	+3.2
$Cost_{el}$	€/MWh_{el}	63.6	66.4	59.3*	57.5*	65.0	63.6	+19.1%	+10.2
NPV	M€	27	11	2	2	8**	50	-21.9%	-14
PBT_{simple}	yrs	7.1	9.2	11.9	9.0	7.1**	8.3	+10.7%	+0.8
$CO2_{ratio}$	-	1.32	1.39	1.53	1.39	1.37	1.38		

*Distribution costs avoided **Heat loss of 13 km transmission pipe avoided