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LoT-NET

Benefits of including thermal energy stores on the levelised cost of heat of district heating networks

Miguel Angel Pans Castillo

Philip Eames

VERITATE SCIENTIA LABORE

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Summary and objectives

i. A novel model was used to simulate how an existing district heating (DH) network for Holywell Park, Loughborough University (Loughborough, UK) could be transitioned to low/zero carbon heat. A simulation which includes HPs and ETSTCs to both provide heat for buildings and charge a potential centralised seasonal thermal energy storage (STES) system was performed.

ii. Both a) real historic half-hourly CO_2 emissions per kWh of electricity and b) real historic half-hourly heat demands for Holywell Park for the year 2021 are used in the simulations.

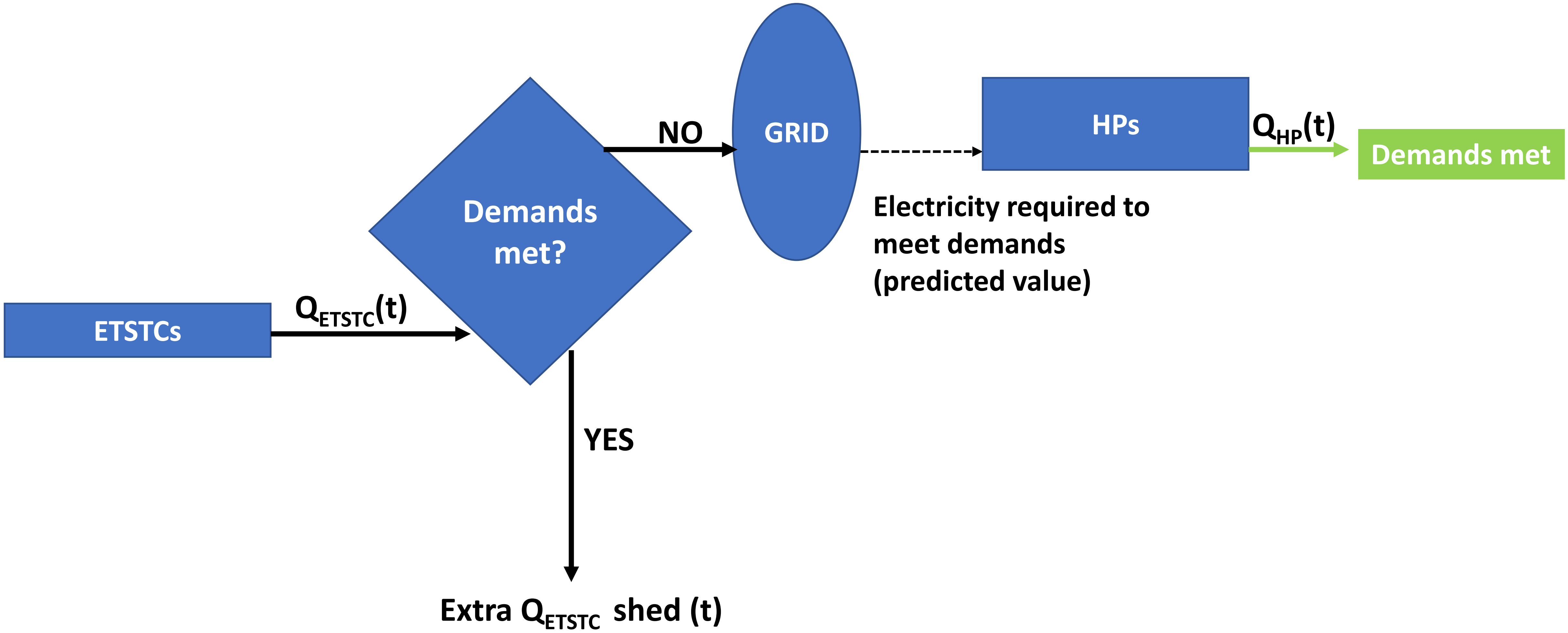
iii. HPs can only be used to charge STES systems at those times when the CO_2 emissions associated with grid electricity are 0.

iv. A parametric analysis was used to investigate the effect of the 1) the volume of STES system and 2) maximum amount of zero-emissions electricity available to charge STES ($MAE_{CO2 = 0, STES}$) on a) the annual CO_2 emissions, b) the DH system efficiency (η_{DH}), c) the levelised cost of heat (LCOH) for 23 years.

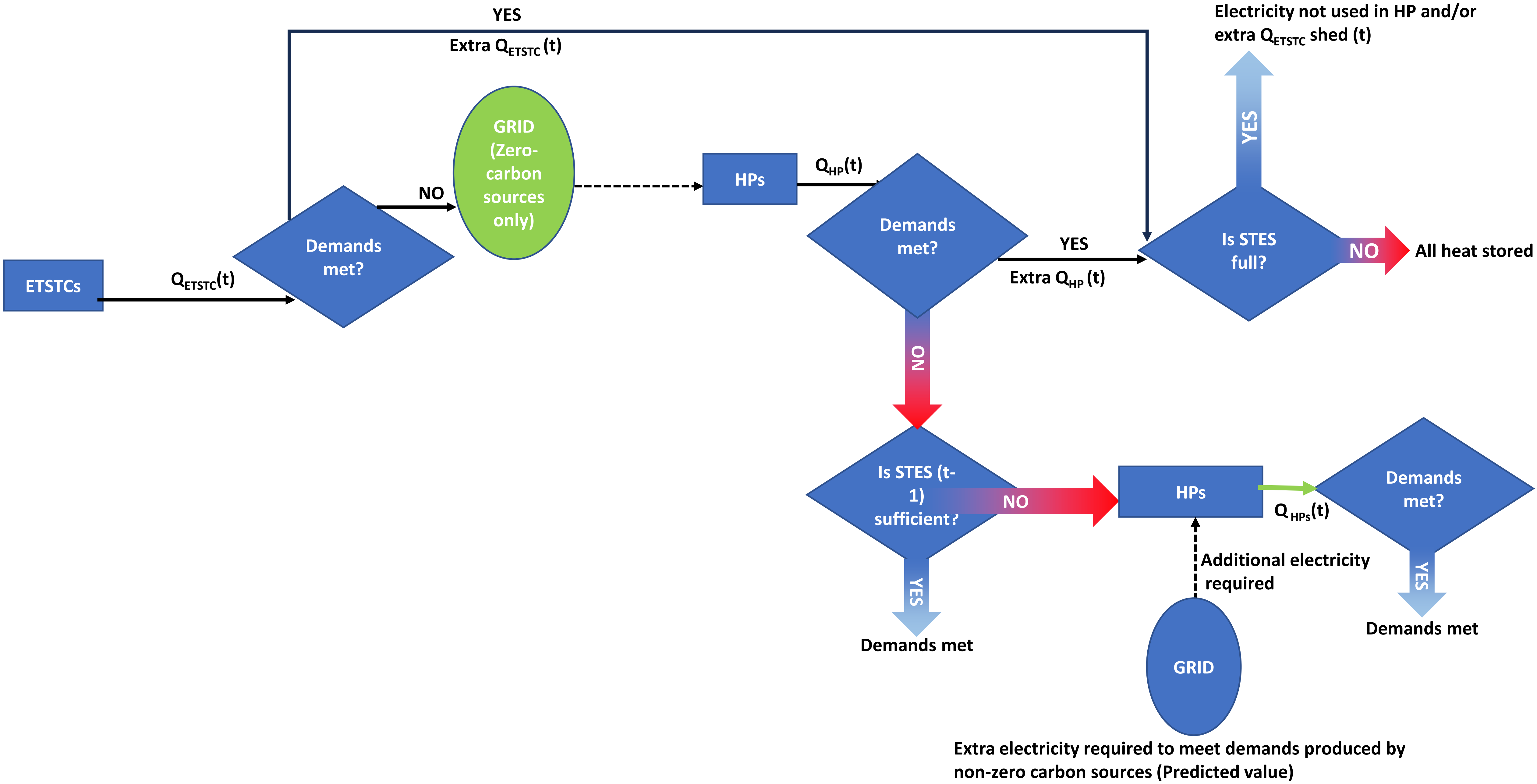
Existing DH system with added low-carbon heat sources and STES

Total length of the DH network pipes (m)	812
Total floor area (m^2)	57714

Methodology: Flow diagram of the process followed when NOT using STES (Baseline scenario, Scenario 1)



Methodology: Flow diagram of the process followed when using STES (Scenario 2)



Key parameters specified for the simulation.

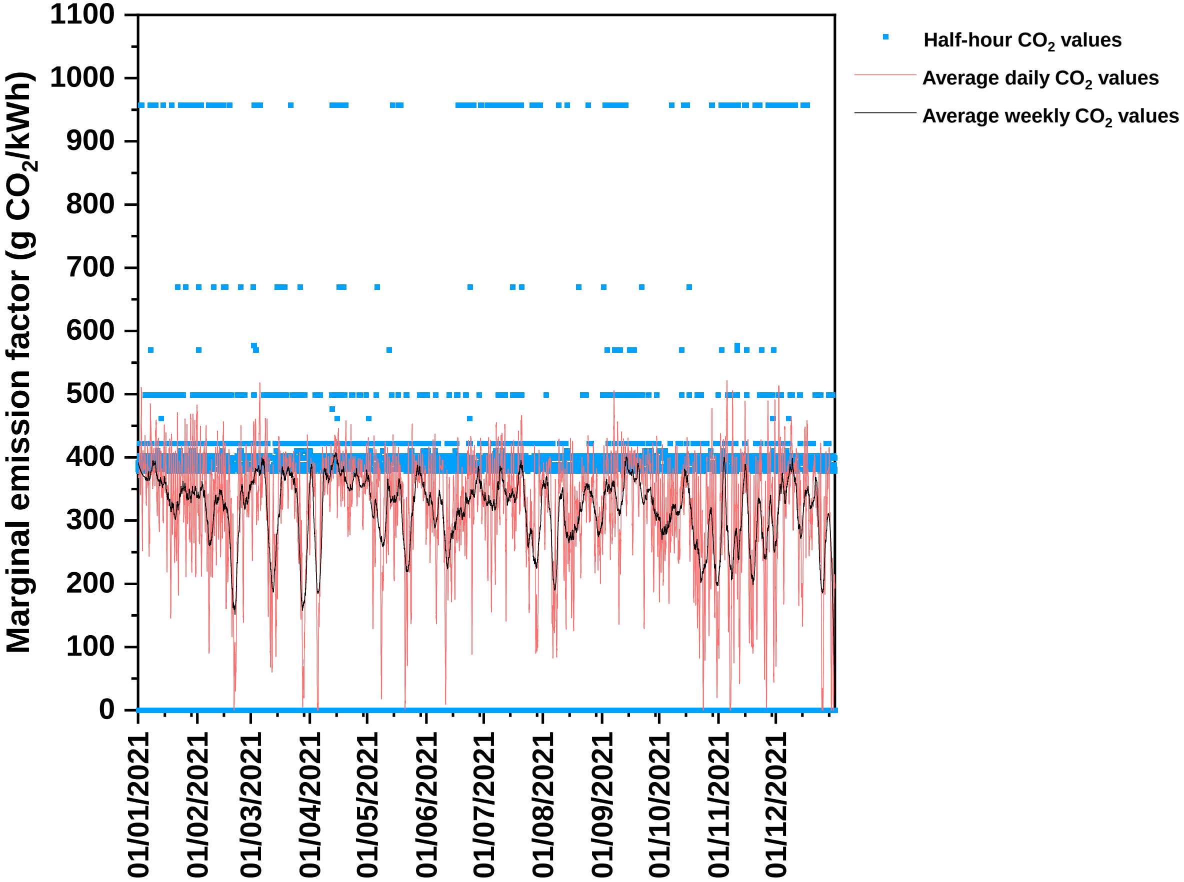
Location and time	
Area/town	Holywell Park, Loughborough University, Loughborough, (UK)
Time-period simulated	23 years (from 01/01/2000 00:00 to 31/12/2022 23:30)

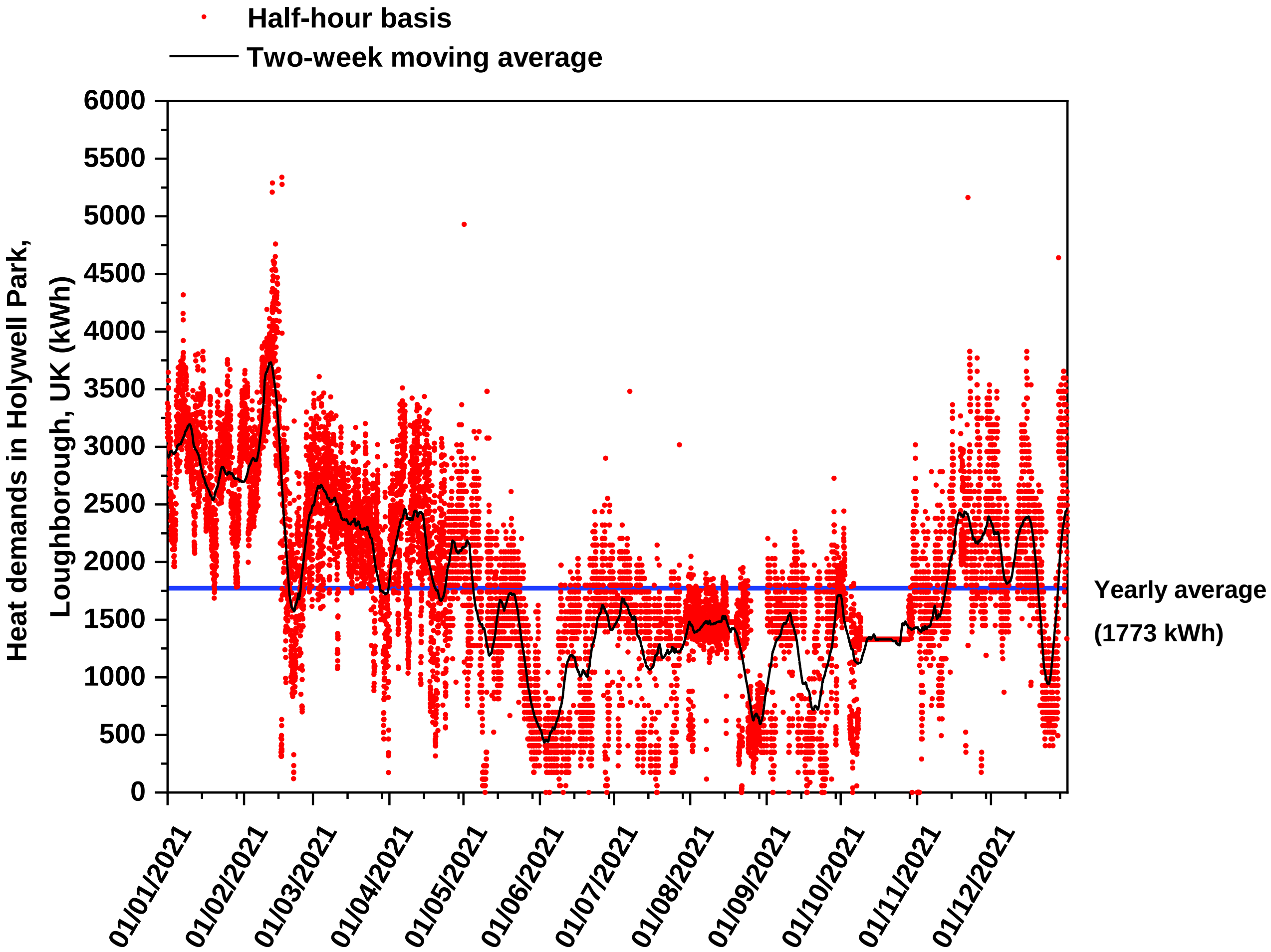
STES system main parameters	
$T_{charging\ STES}$ (°C)	60
$Volume_{STES}$ (m^3)	50000, 75000
Initial assumed heat stored in STES (% of the maximum storage capacity)	0%

Heat and electricity main parameters	
Maximum half-hourly zero-carbon electricity available for use in HPs to charge STES ($MAE_{CO2 = 0\ STES}$, kWh per half hour)	500, 800 , 1200, 1500
Half-hourly electricity required by HPs to fully meet demands (kWh per half hour)	Predicted
Specified area of ETSTC per dwelling (m^2)	10000, 15000, 18000, 20000
HPs	
%ASHP	50%
%GSHP	50%
Heat Capacity per unit (kW)	250

Historic CO_2 emissions per kWh of grid electricity for the North West region of the UK, 2021 (7% transmission and distribution loss included) and heat demands for Holywell Park, Loughborough University, Loughborough, UK.

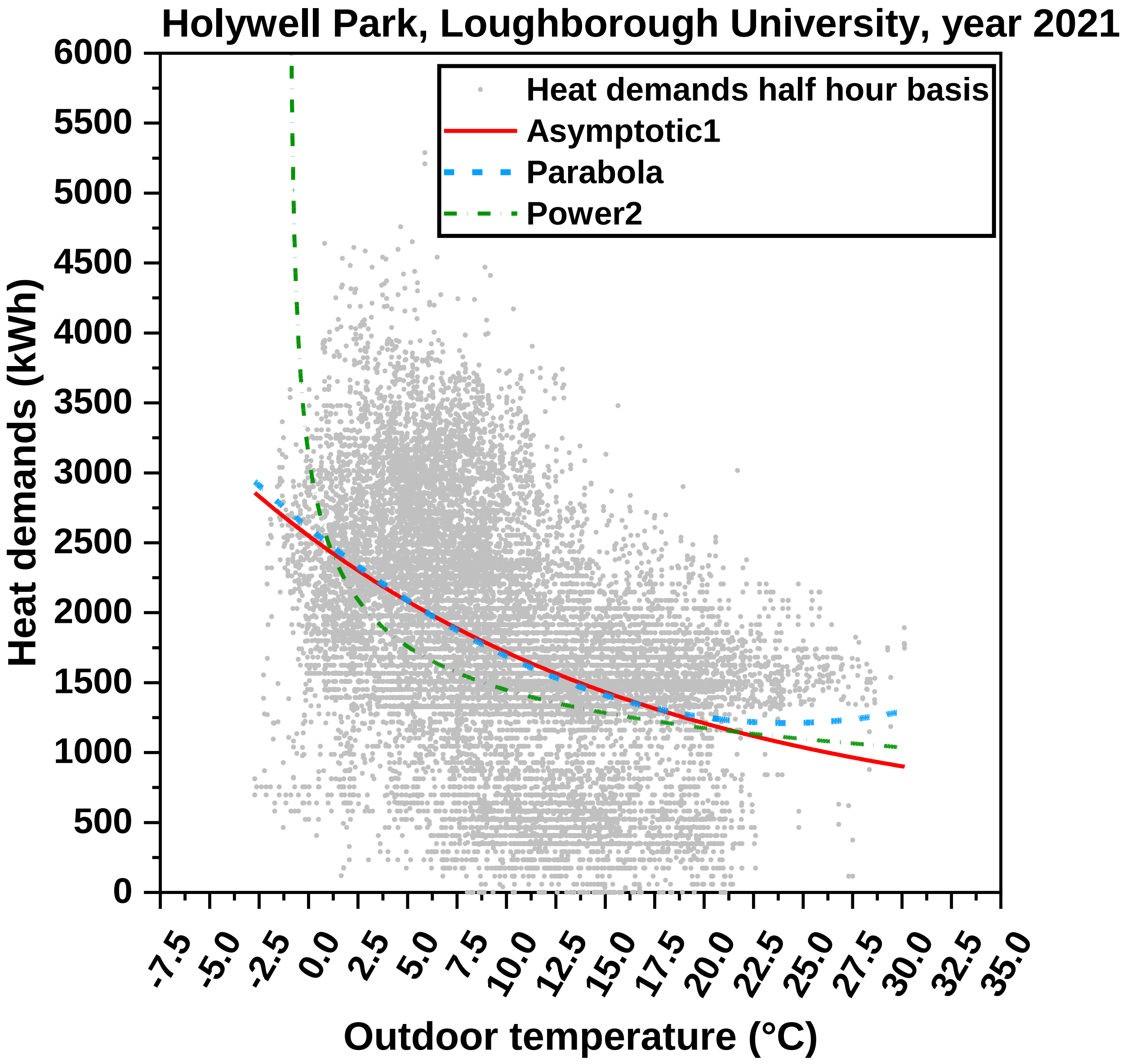
Source: SSE Energy Solutions





Source: Loughborough University

Correlation between the outdoor temperature and the heat demands for Holywell Park, Loughborough University, UK, for the year 2021.



Calculation of Levelised Cost Of Heat (LCOH)

$$LCOH = \frac{Inv + \sum_{t=1}^{n} \frac{(OC\&M)_t}{(1-r)^t}}{\sum_{t=1}^{n} \frac{H_t}{(1-r)^t}}$$

Where:

- ✓ **Inv = investment cost, which includes cost of STES, HPs and ETSTCs (£)**
- ✓ **OC_t = Operational cost in the year *t*, i.e. cost of electricity needed to operate the heat pumps (£)**
- ✓ **M_t = Maintenance cost of STES, HPs and ETSTC in year *t* (£)**
- ✓ **r = discount rate (assumed 5%)**
- ✓ **H_t = total heat produced by ETSTC and HPs in year *t* (kWh per half hour, includes the heat used to meet demands and the heat that is charged to the STES).**
- ✓ **n = number of years (23 years)**

Calculation of Levelised Cost Of Heat (LCOH): Investment and maintenance cost for the different parts of the DH system

	Capital cost
ETSTC (£/m²)	170
STES (£/m³)(Guelpa and Verda, 2019)	50

Cost heat pumps[1] (M£) = a + b MW_{th}	
ASHPs (M£)	a =0.1883 b = 0.6774
GSHPs (M£)	a =0.5054 b = 0.6398

	Maintenance cost per year
ETSTC (£/m²/year)[2]	13
HPs (% of the operating cost)[3]	20%
STES (% of the investment cost)[4]	1%
Salary of operator per year (£)[3]	12,300

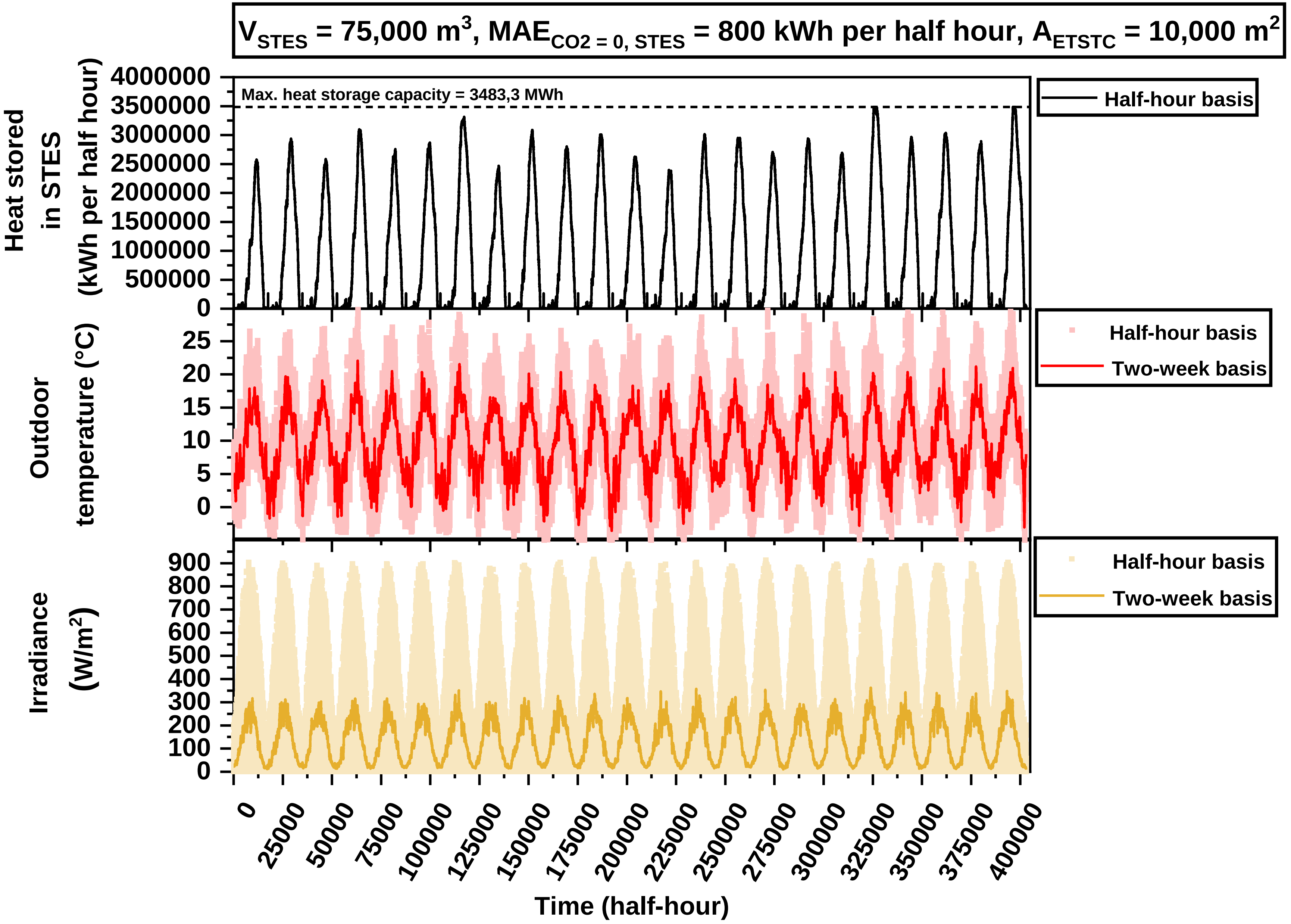
[1] Pieper, H., Ommen, T., Buhler, F., Lava Paaske, B., Elmegaard, B., & Brix Markussen, W. (2018). Allocation of investment costs for large-scale heat pumps supplying district heating. Energy Procedia, 147, 358–367. https://doi.org/10.1016/J.EGYPRO.2018.07.104

[2] Launay, S., Kadoch, B., Le Métayer, O., & Parrado, C. (2019). Analysis strategy for multi-criteria optimization: Application to inter-seasonal solar heat storage for residential building needs. Energy, 171, 419–434. https://doi.org/10.1016/J.ENERGY.2018.12.181

[3] Kim, M. H., Kim, D., Heo, J., & Lee, D. W. (2019). Techno-economic analysis of hybrid renewable energy system with solar district heating for net zero energy community. Energy, 187, 115916. https://doi.org/10.1016/J.ENERGY.2019.115916

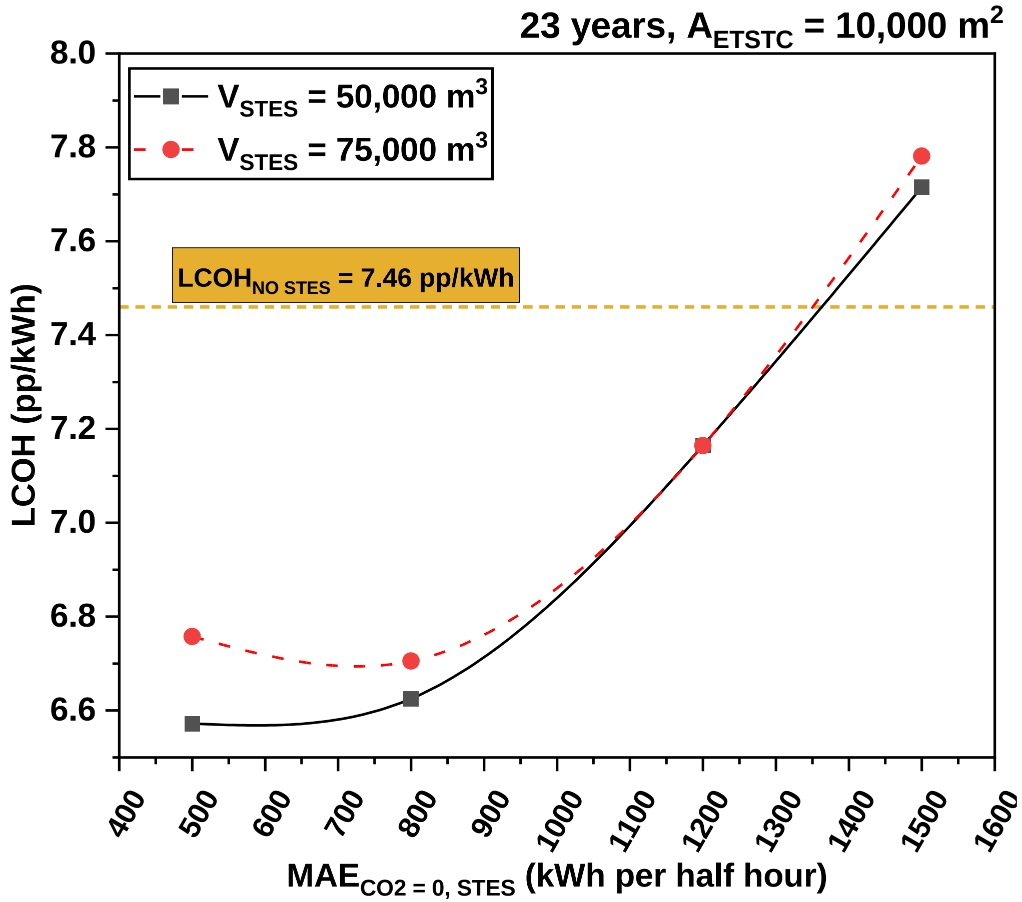
[4] Yang, T., Liu, W., Kramer, G. J., & Sun, Q. (2021). Seasonal thermal energy storage: A techno-economic literature review. Renewable and Sustainable Energy Reviews, 139, 110732. https://doi.org/10.1016/J.RSER.2021.110732

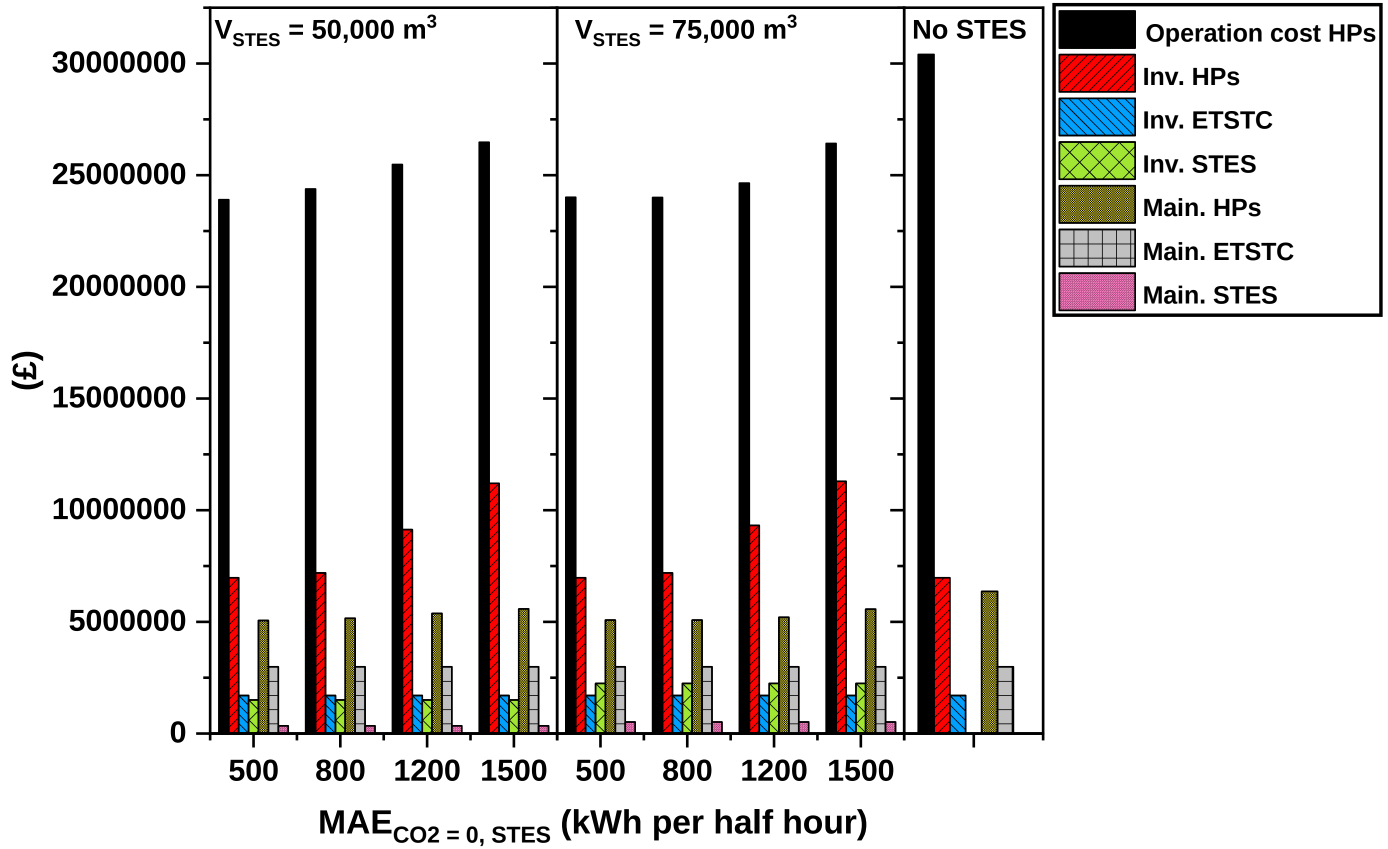
Results: Example of heat stored in STES, outdoor temperature and irradiance vs. time



Effect of maximum amount of zero-emissions electricity available to charge the seasonal thermal energy storage system on levelised cost of heat, η_{DH} and CO_2 emissions reduction

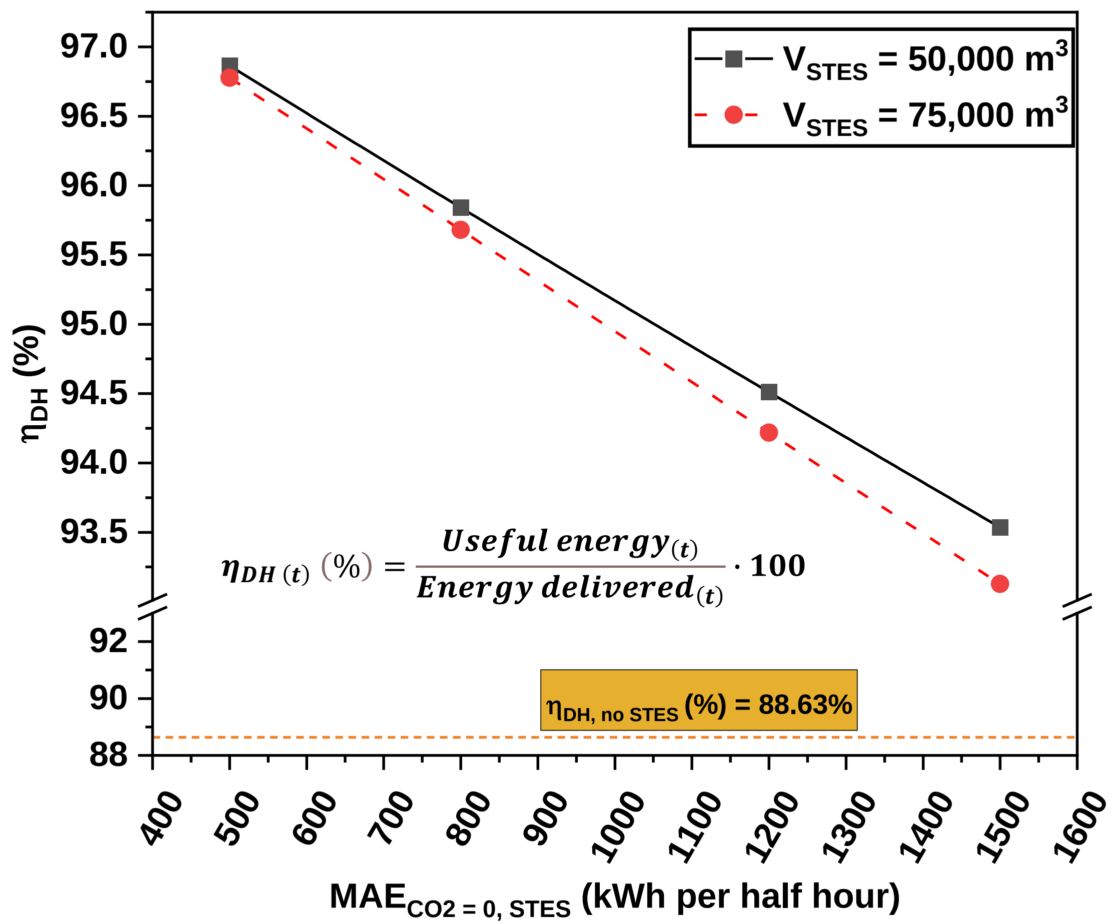
Results: effect of V_{STES} and $MAE_{CO2 = 0, STES}$ on LCOH for A_{ETSTC} = 10,000 m^2

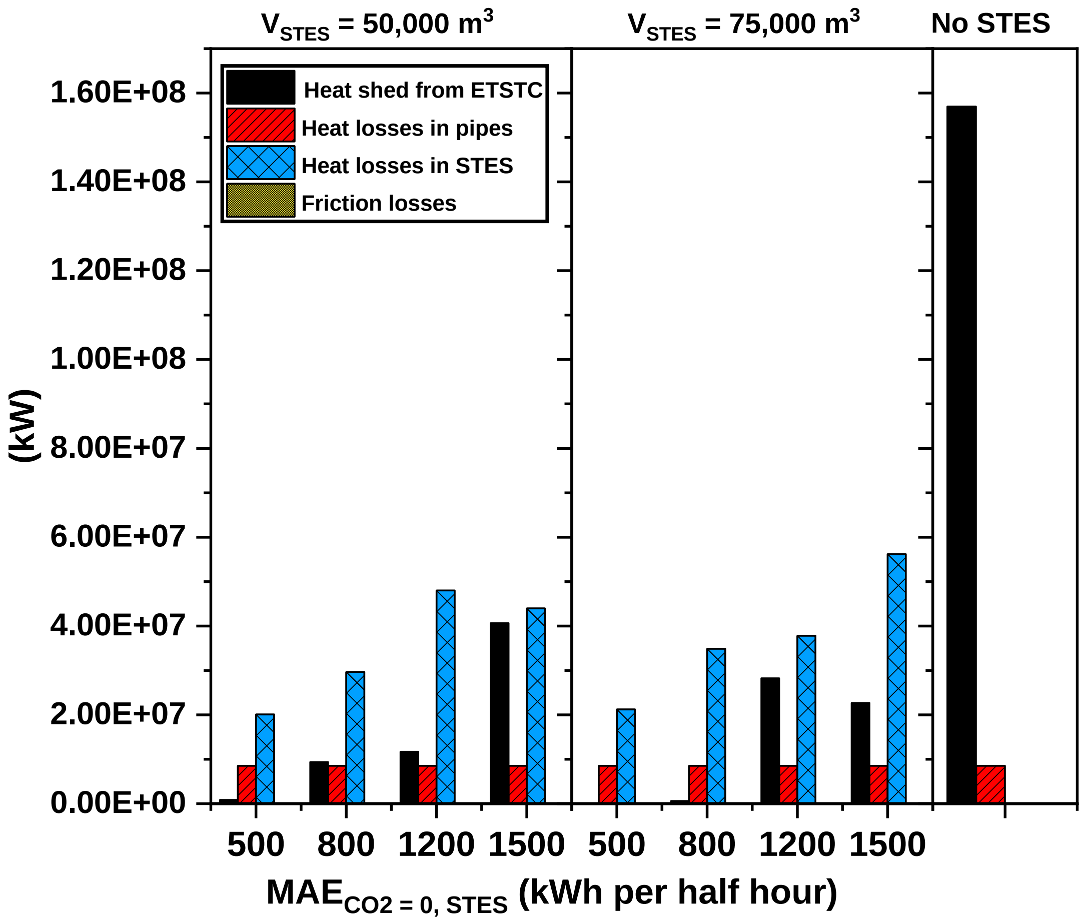




- Similar LCOH values obtained when using STES for $MAE_{CO2 = 0, STES}$ up to ~ 800 kWh per half hour. Values substantially lower than the LCOH value obtained when not using STES of 50,000 and 75,000 m^3.
- For $MAE_{CO2 = 0, STES}$ up to > 800 kWh per half hour LCOH increases due mainly to the increase in the operational cost related to HPs, investment and maintenance of HPs
- For $MAE_{CO2 = 0, STES}$ = 1500 kWh per half hour the LCOH obtained when using STES is greater than LCOH obtained when not using STES.

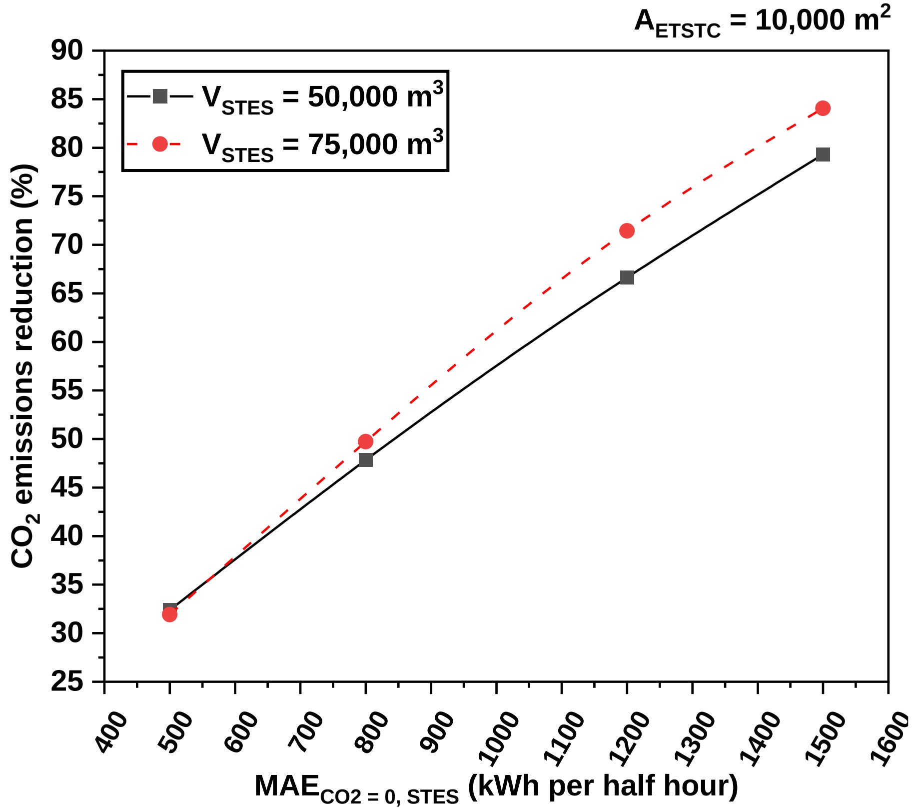
Results: effect of V_{STES} and $MAE_{CO2 = 0, STES}$ on η_{DH} for A_{ETSTC} = 10,000 m²





- Predicted η_{DH} obtained with STES decreases with increasing $MAE_{CO2 = 0,STES}$ due to higher heat losses from the STES and increased heat shed from ETSTCs.
- η_{DH} obtained with STES considerably higher than the η_{DH} obtained when not using STES, for all $MAE_{CO2 = 0,STES}$ values, due to the higher heat shed from ETSTC when not using STES.

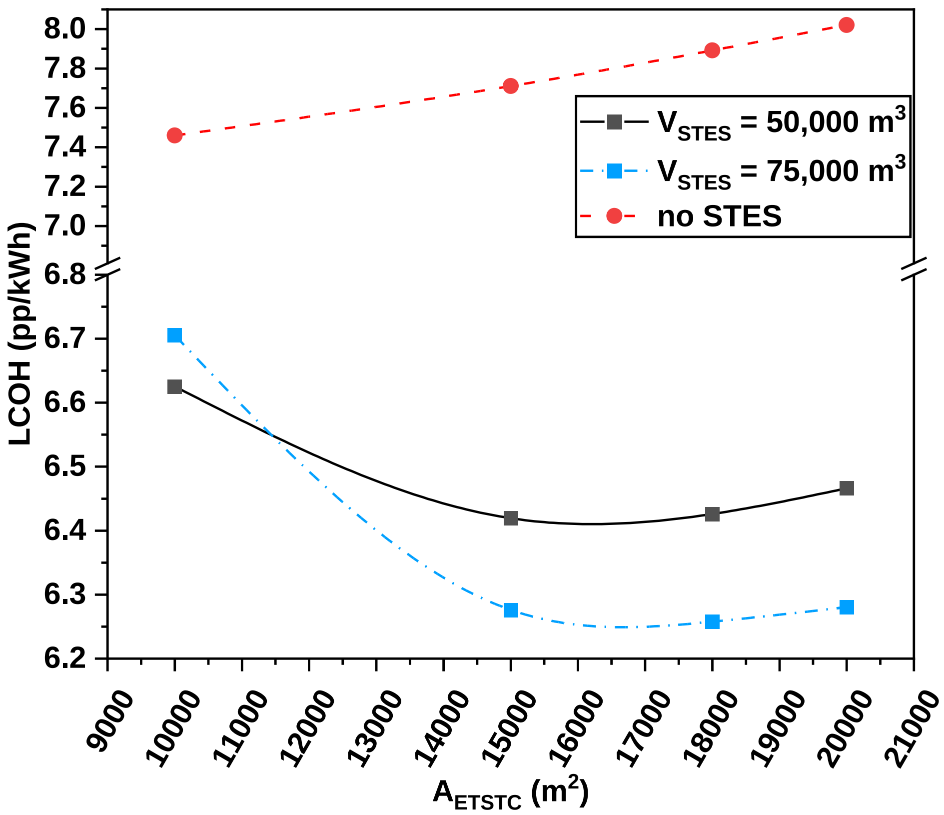
Results: effect of V_{STES} and $MAE_{CO2\,=\,0,\,STES}$ on CO_2 emissions reduction for A_{ETSTC} = 10,000 m²

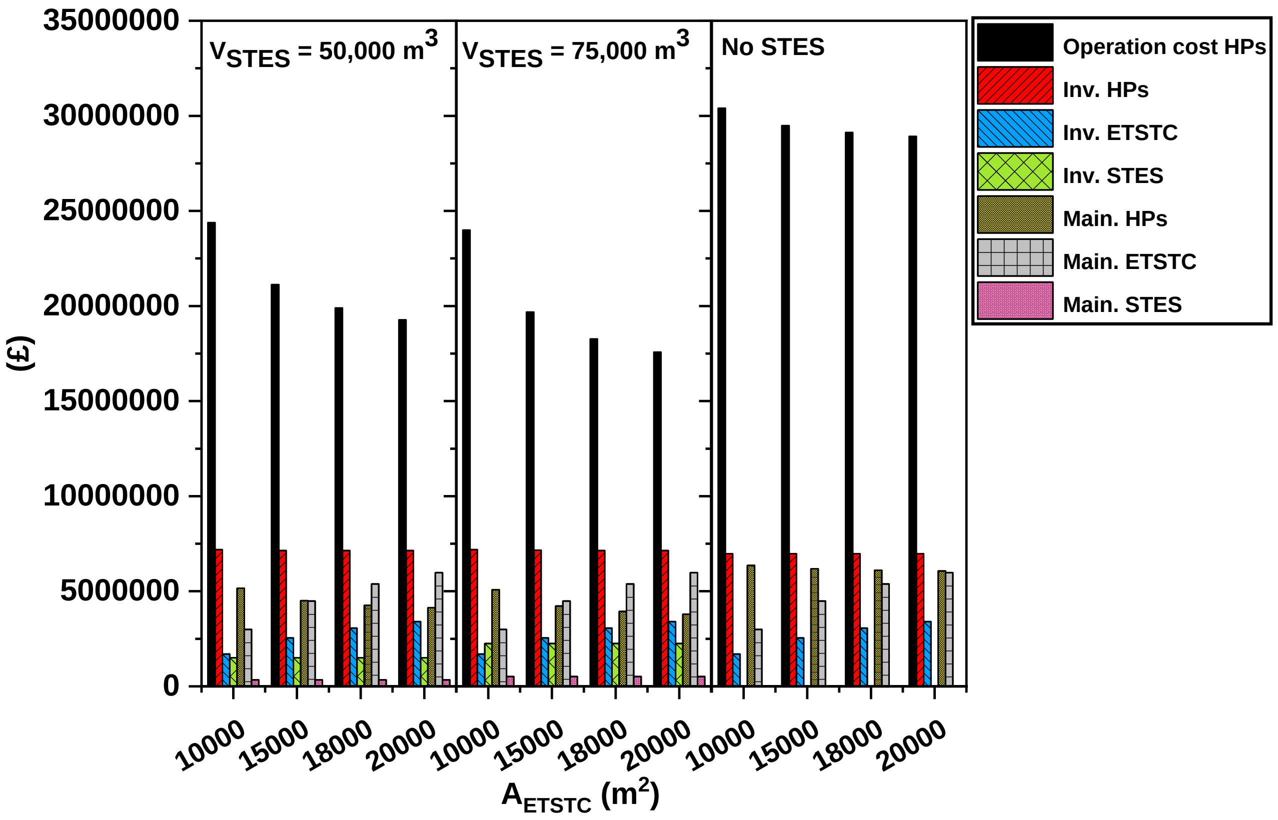


- CO_2 emissions reduction increase with $MAE_{CO2\,=\,0,STES}$ due to greater heat stored in STES.
- Similar CO_2 emissions obtained for V_{STES} = 50,000 and 75,000 m^3, for values of $MAE_{CO2\,=\,0,STES}$ up to 800 kWh per half hour.
- For $MAE_{CO2\,=\,0,STES}$ > 800 kWh per half hour greater CO_2 emissions reduction were predicted for V_{STES} = 75,000 m^3 due to the higher amount of heat stored in STES.
- A maximum CO_2 emissions reduction of ca. 85% was predicted for the simulations performed.

Effect of the total area of evacuated-tube solar thermal collectors (A_{ETSTC}) on levelized cost of heat, district heating system efficiency and CO_2 emissions reduction

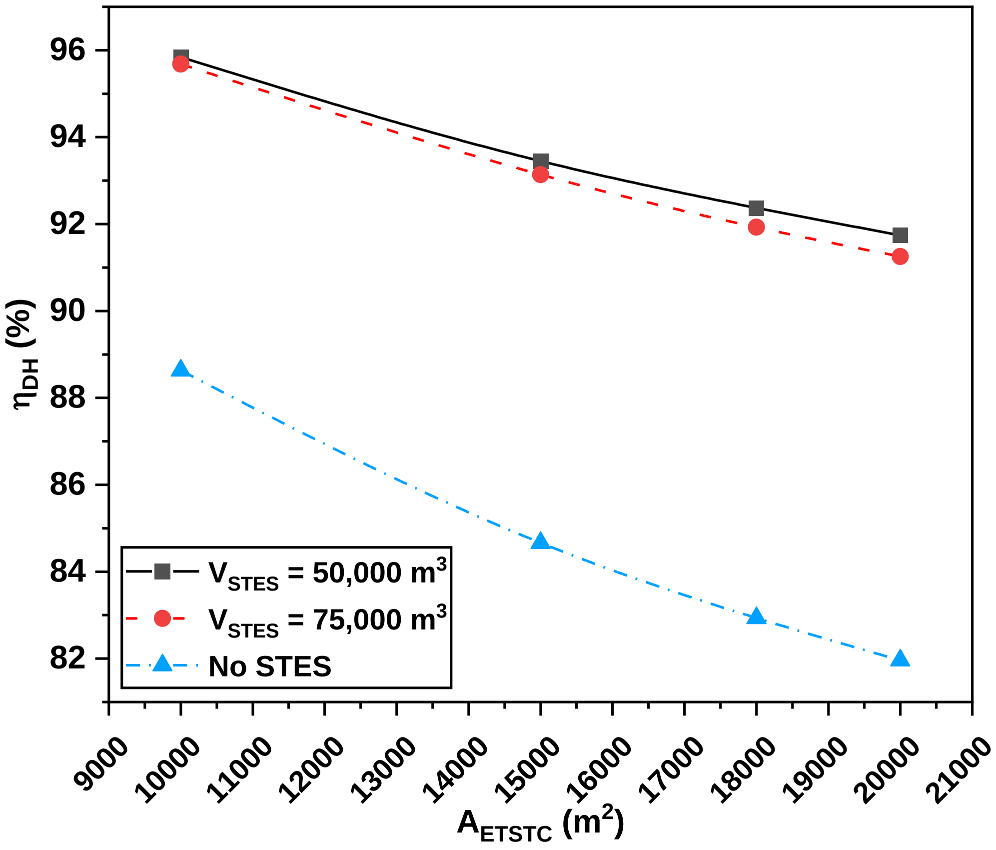
Results: effect of A_{ETSTC} on LCOH, for V_{STES} = 50,000 and 75,000 m^3 and $MAE_{CO2 = 0, STES}$ = 800 kWh per half hour.

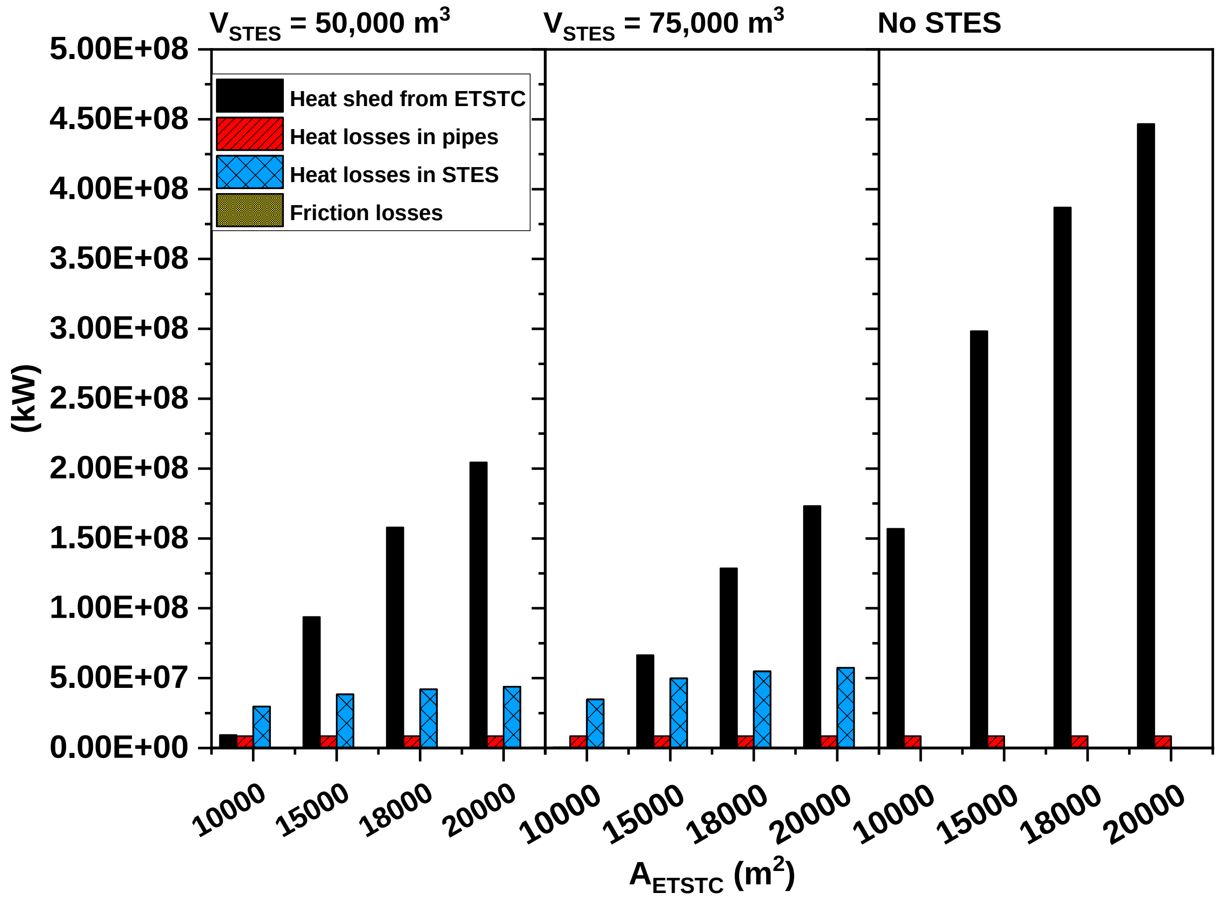




- Predicted LCOH values decreased with A_{ETSTC} up to 15,000 – 18,000 m^2, due to the lower cost required for HP operation which counteracts the increase in the cost of the ETSTC.
- For A_{ETSTC} = 18,000 – 20,000 m^2 predicted LCOH increases due mainly to the small decrease in the cost required for HP operation and increase in ETSTC costs. A minimum number of heat pumps are required to fully meet demands in this DH system, independently of A_{ETSTC}.
- For $A_{ETSTC} \geq$ 15,000 m^2 the increase of V_{STES} from 50,000 to 75,000 m^3 significantly reduces the LCOH due to the higher storage capacity of STES, which leads to lower operational cost associated with HPs.

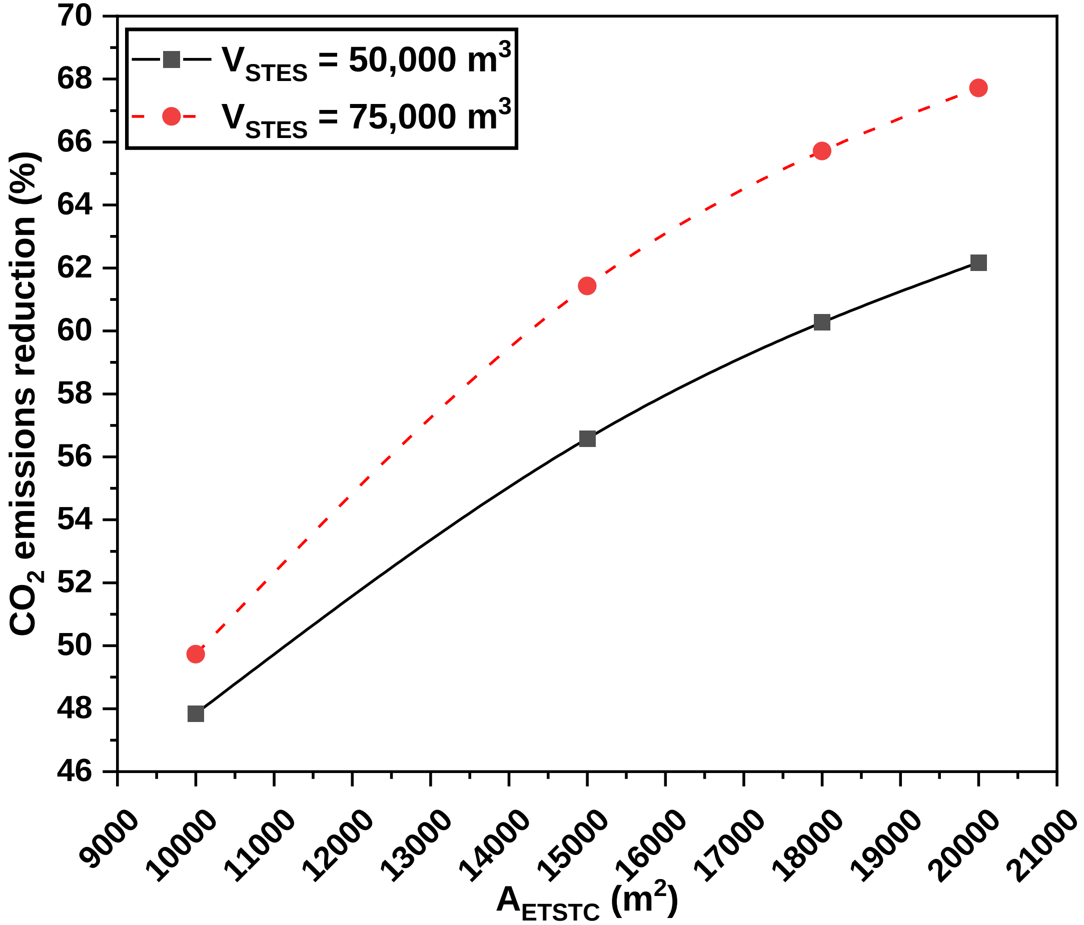
Results: effect of A_{ETSTC} on η_{DH}, for V_{STES} = 50,000 m^3 and $MAE_{CO2=0, STES}$ = 800 kWh per half hour





- η_{DH} predicted with STES decreases with increased A_{ETSTC} mainly due to increasing heat from ETSTCs being shed.
- η_{DH} predicted with STES is considerably higher than the η_{DH} predicted when not using STES, for all A_{ETSTC} values, due to the high level of heat shed from the ETSTC when there is no STES.

Results: effect of A_{ETSTC} on CO_2 emissions reduction, for V_{STES} = 50,000 m^3 and $MAE_{CO2 = 0, STES}$ = 800 kWh per half hour



- Predicted CO_2 emissions reductions increase with increasing area A_{ETSTC} due to reduced use of HPs using non-zero emissions electricity to meet demands.
- Higher CO_2 emissions reductions were achieved with V_{STES} = 75,000 m^3 due to the greater storage capacity which allows more heat from ETSTC to be used.

Results summary

A_{ETSTC} (m^2)	V_{STES} (m^3)	$MAE_{CO2 = 0, STES}$ (kWh per half hour)	η_{DH} with STES (%)	η_{DH} without STES (%)	CO_2 reduction (%)	LCOH with STES (pp/kWh)	LCOH NO STES (pp/kWh)
Effect of $MAE_{CO2 = 0, STES}$							
10000	50000	500	96.86%	88.63%	32.39%	6.57	7.46
10000	50000	800	95.84%	88.63%	47.84%	6.63	7.46
10000	50000	1200	94.51%	88.63%	66.64%	7.16	7.46
10000	50000	1500	93.54%	88.63%	79.30%	7.72	7.46
10000	75000	500	96.78%	88.63%	31.92%	6.76	7.46
10000	75000	800	95.68%	88.63%	49.73%	6.71	7.46
10000	75000	1200	94.22%	88.63%	71.43%	7.16	7.46
10000	75000	1500	93.13%	88.63%	84.06%	7.78	7.46
Effect of A_{ETSTC}							
10000	50000	800	95.84%	88.63%	47.84%	6.63	7.46
15000	50000	800	93.45%	84.66%	56.58%	6.42	7.71
18000	50000	800	92.37%	82.93%	60.27%	6.43	7.89
20000	50000	800	91.74%	81.96%	62.17%	6.47	8.02
10000	75000	800	95.68%	88.63%	49.73%	6.71	7.46
15000	75000	800	93.14%	84.70%	61.43%	6.27	7.70
18000	75000	800	91.93%	82.93%	65.71%	6.26	7.89
20000	75000	800	91.25%	81.96%	67.72%	6.28	8.02

For A_{ETSTC} = 18,000 m^2, V_{STES} = 75,000 m^3 and $MAE_{CO2 = 0, STES}$ = 800 kWh per half hour:

η_{DH} = 91.93%, CO_2 reduction = 65.71% and LCOH = 6.26 pp/kWh.

Conclusions

Effect of maximum amount of zero-emissions electricity available in a half hour period to charge STES:

- ✓ For Holywell park a $MAE_{CO2 = 0, STES}$ value of 800 kWh per half hour leads to the minimum LCOH. Using more than 800 kWh per half hour increases the operational cost, investment and maintenance of HPs, which increases LCOH.
- ✓ For the modelled system η_{DH} obtained with STES decreases with increasing $MAE_{CO2 = 0,STES}$ due to greater heat losses from the STES and heat shed from ETSTCs.
- ✓ Predicted CO_2 emissions reductions increase with $MAE_{CO2 = 0,STES}$ due to greater amount of heat stored in the STES.

Effect of the area of evacuated-tube solar thermal collectors:

- ✓ An increase in A_{ETSTC} up to 15,000 – 18,000 m^2 decreases LCOH values, due to the lower cost associated with HP operation.
- ✓ η_{DH} predicted with STES decreases with increased A_{ETSTC} mainly due to increasing heat from ETSTCs being shed
- ✓ Predicted CO_2 emissions reductions increase with increasing area A_{ETSTC} due to reduced use of HPs using non-zero emissions electricity to meet demands.

Conclusions

The use of STES:

- ✓ reduces the LCOH by up to 1.74 pp/kWh, due mainly to the reduced operational and maintenance cost of HPs.
- ✓ predicted η_{DH} increases by up to ca. 10%, due mainly to the decreased heat shed from ETSTC.
- ✓ reduces predicted CO_2 emissions by up to 84%.

A η_{DH} = 91.93%, CO_2 reduction = 65.71% and LCOH = 6.26 pp/kWh can be obtained for A_{ETSTC} = 18,000 m^2,V_{STES} = 75,000 m^3 and $MAE_{CO2 = 0, STES}$ = 800 kWh per half hour.

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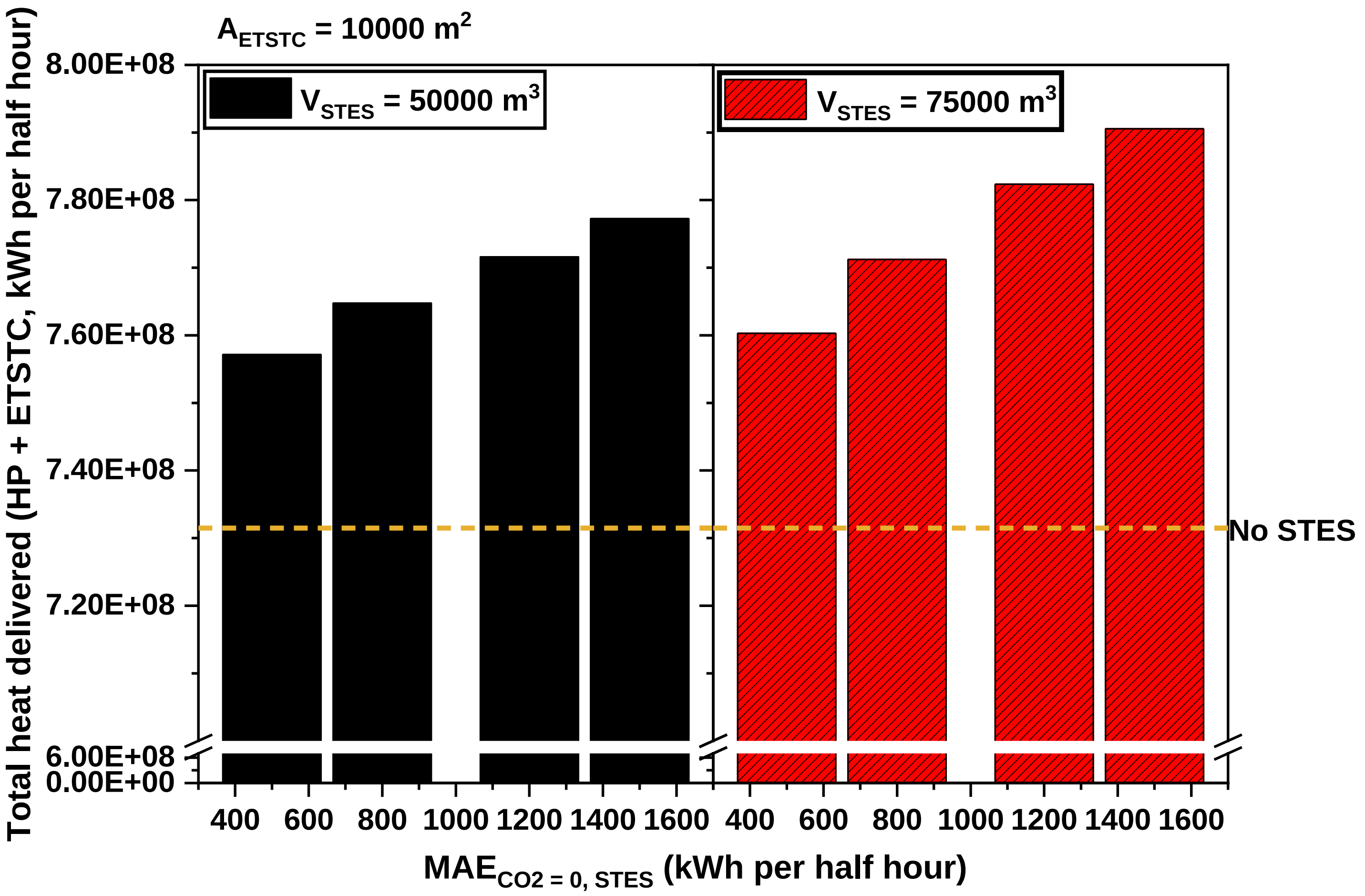
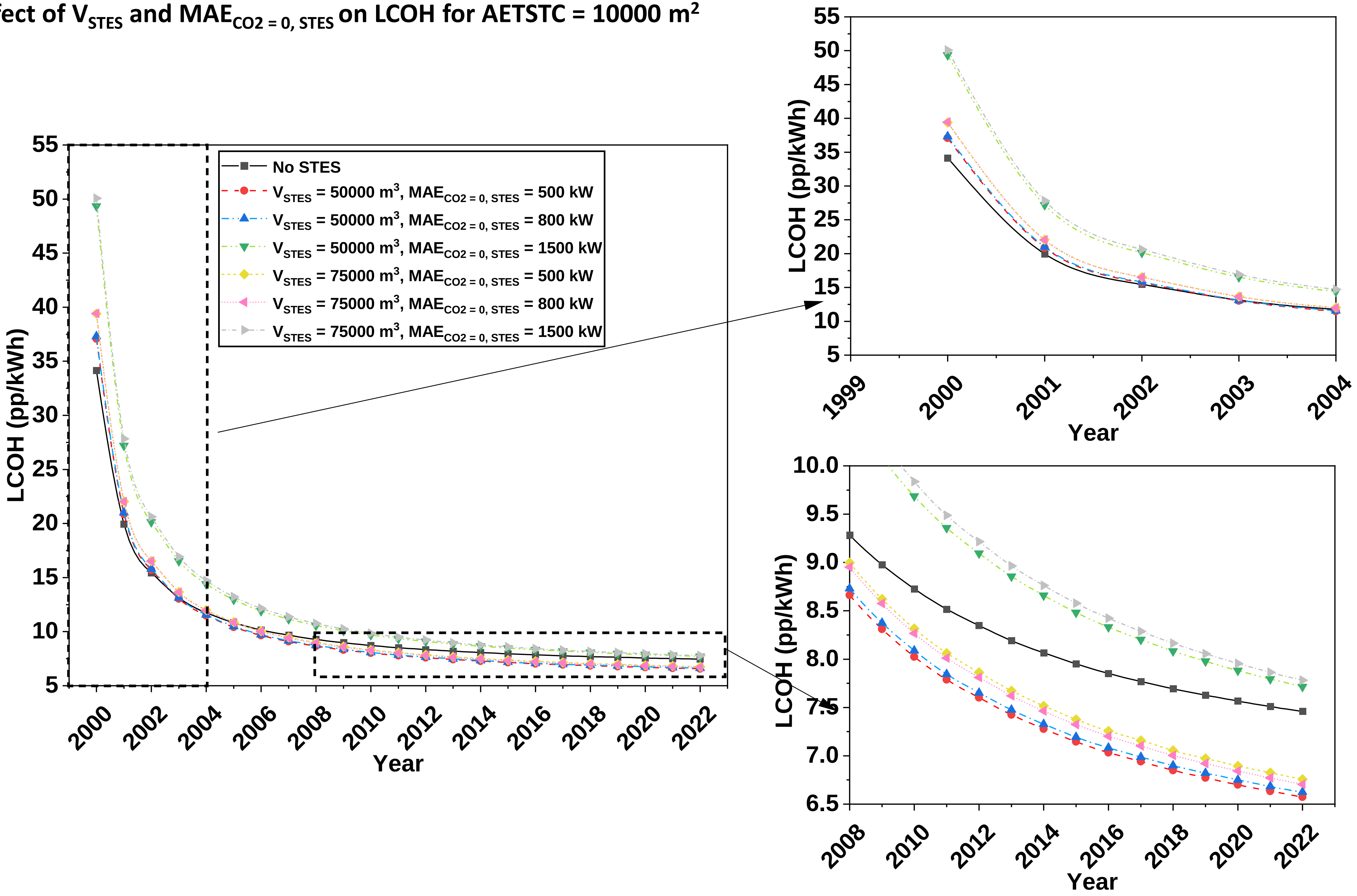
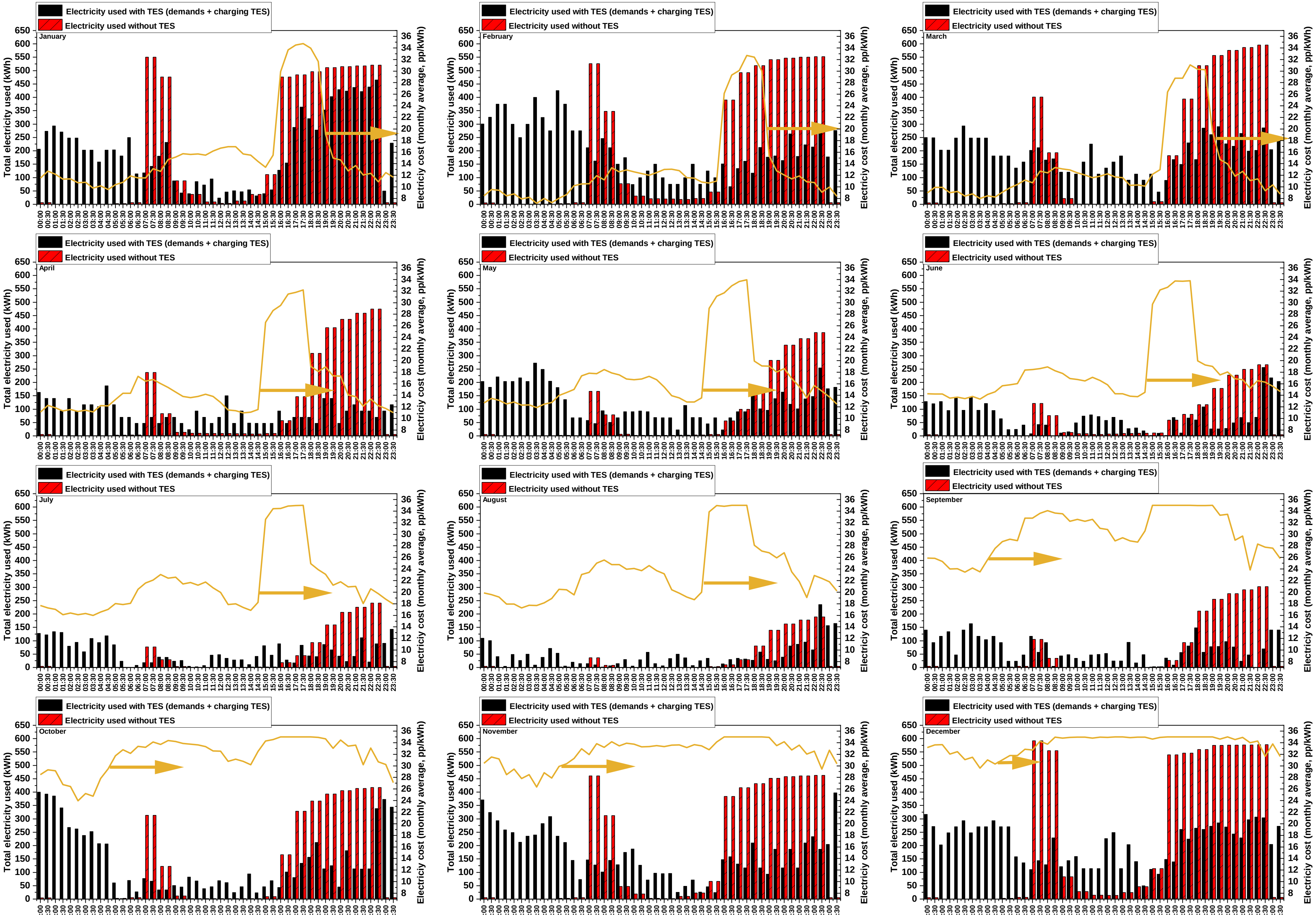


A_{ETSTC} = 10000 m^2
V_{STES} = 50000 m^3
V_{STES} = 75000 m^3
No STES
Total heat delivered (HP + ETSTC, kWh per half hour)
8.00E+08
7.80E+08
7.60E+08
7.40E+08
7.20E+08
6.00E+08
0.00E+00
400 600 800 1000 1200 1400 1600
400 600 800 1000 1200 1400 1600
$MAE_{CO2 = 0, STES}$ (kWh per half hour)

Results: effect of V_{STES} and $MAE_{CO2 = 0, STES}$ on LCOH for AETSTC = 10000 m^2





Electricity used with TES (demands + charging TES)
Electricity used without TES
Total electricity used (kWh)
Electriciy cost (monthly average, pp/kWh)
January
February
March
April
May
June
July
August
September
October
November
December