

Supplementary material

Supplementary S1: Technology data input

Table S1. Assumed costs and technical data for the production and storage technologies included in the model. Based on [1].

Technology	Lifetime [years]	Investment cost [EUR/kW]	Variable OM-cost [EUR/MWh]	Fixed OM- cost [EUR/kW]	Start- up time [h]
Production technologies					
Solar PV (PV)*	40	525	1.1	6.8	0
Gas turbine biogas (GT_BG)	25	520	4	18	0
Combined-cycle gas turbine biogas (CCGT_BG)	25	800	4	26	4
Electric boiler (EB)	20	60	1	0	0
Heat pump (HP)	25	830	1.7	2	0
Heat only-boiler biomass (HOB_bio)	20	400	3.8	36.1	4
Heat only-boiler biogas (HOB_BG)	25	50	1	1.7	4
Combined heat and power biomass (CHP_Bio)	25	3200	4.6	129	12
Electric arc furnace (EAF)	40	1294	0	38.8	0
Electrolyzer	25	500	0	1.5	0
Storage technologies					
Lithium Ion battery storage (Lilon-bat)	25	75	0	0	-
Lithium Ion battery discharge capacity (Lilon- cap)	25	60	0	0.5	-
Tank thermal energy storage (TTES)	25	8	0	0.009	-
Direct reduced iron storage (DRI-storage)	40	0.1**	0	0	-
Hydrogen storage (H2- storage)	30	11	0	0	-

*Production profiles for solar PV are taken from [2] and [3] for each individual city, based on hourly weather data for Year 2019.

** Assumed value

Supplementary S2: City data input

Table S2. Assumed data for the modeled cities for Year 2050.

	Gothenburg	Stockholm	Luleå	Malmö	Norrköping	Skellefteå
<i>City ID</i>	GBG	STH	LUL	MMO	NRP	SKT
<i>Electrification drivers</i>	Hydrogen, Battery factory	Data centers, transport	EAf, data centers	Transport, electrification of current industry	Hydrogen, electrification of current industry	Data centers, Battery factory
<i>Added constant electricity demand (GW)</i>	0.3	0.1	0.2	0.1	0.2	0.3
<i>Added annual hydrogen demand (GWh_H2)</i>	1,156	0	0	0	578	0
<i>Added average flexible industrial electricity demand (GW)</i>	0	0	0.3	0	0	0
<i>Total average added industrial electricity demand (GW)</i>	0.5	0.1	0.5	0.1	0.3	0.3
<i>Increase in annual electricity demand compared to Year 2019 (%)</i>	131	47	559	74	177	272
<i>Number of EVs (thousands)</i>	198	360	40	134	86	42
<i>Waste heat (% of total heat demand)</i>	15	0	10	0	0	20
<i>Electricity-to-heat ratio</i>	3.37	1.44	6.45	1.99	5.42	7.88
<i>Flexible share of load (%)</i>	19	3	49	3	19	1
<i>Electricity import capacity at high import level (GW)</i>	1.52	1.66	0.74	0.63	0.77	0.62

Supplementary S3: Sensitivity analysis of tax on power-to-heat

Due to limitation in length of the publication, the sensitivity analysis on including tax on power-to-heat is included in the Appendix.

To test the robustness of HPs as the dominant heat source, the impact of including a tax on power-to-heat was included. Figure S1 presents the impacts of three tax levels (0, 30 and 60 EUR/MWh) imposed on power-to-heat production for the High electricity import scenario, with the resulting normalized installed capacity of TES indicated by black circles. The figure shows that a tax of up to 30 EUR/MWh, comparable to the Swedish level as of Year 2022 of approximately 35 EUR/MWh, has limited effects on the production sources. In this case, some of the power-to-heat generated through EBs and HPs is substituted by bio-based alternatives, such as HOBs or CHP. However, HPs remain the dominant technology for bulk heat production in all the modeled cities.

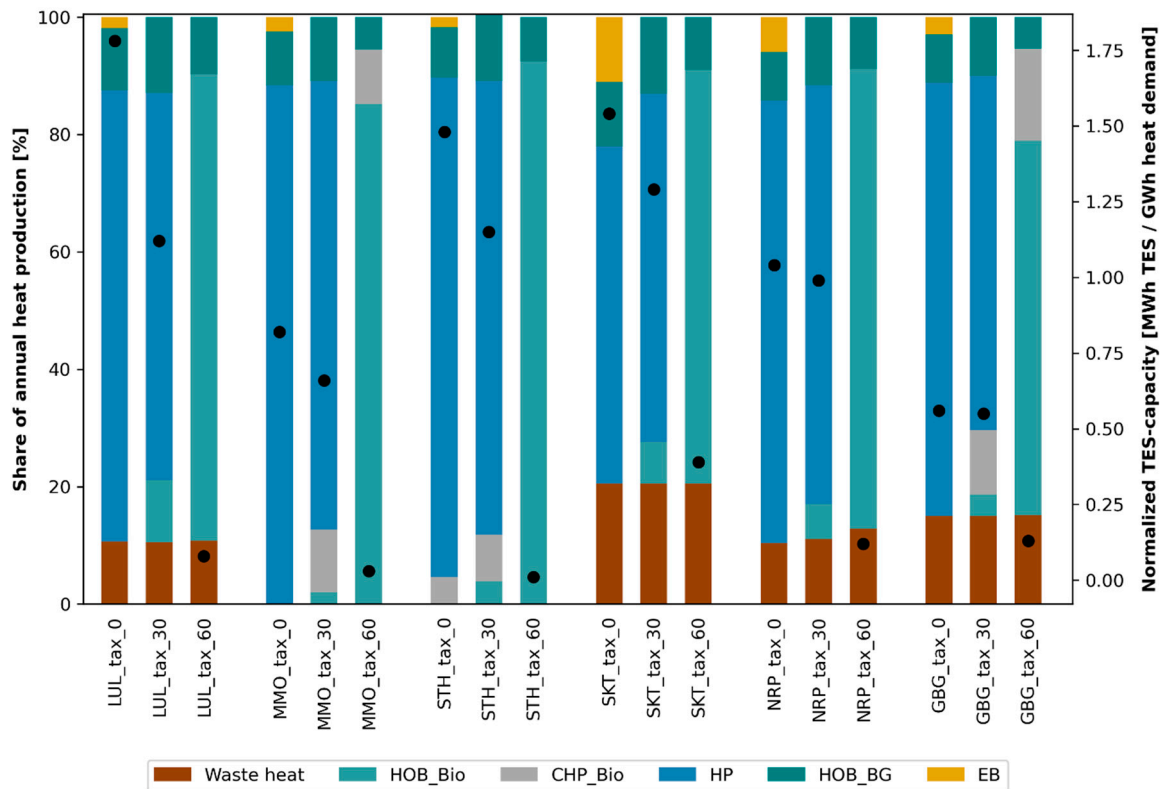


Figure S1. Shares of heat production from the different production sources for three levels of taxes imposed on power-to-heat in the modeled cities. The black circular markers indicate the optimal normalized TES capacity for each model run (right-hand y-axis).

For a tax level of 60 EUR/MWh, however, the optimal technology combination for heat supply undergoes a significant transformation, in that power-to-heat technologies are completely abandoned in favor of bio-based alternatives, particularly HOBs fueled by solid biofuels. Figure S1 also shows that the optimal installed capacity of TES decreases with higher taxation levels. This is in contrast to the high TES capacity observed for the technology combination referred to as Heat_CHP, where the majority of the heat is supplied by CHP. This difference can be attributed to two factors. First, TES enables CHP systems to respond more effectively to changes in electricity prices, which is not observed for bio-based HOB units. Second, the operational flexibility of bio-based HOBs is higher compared to CHP systems. Consequently, the value of TES as a tool to maintain more-consistent production levels from HOBs fueled by solid biofuels is lower compared to a system that has a higher penetration of CHP.

References in Appendix

- [1] Danish Energy Agency, "Technology Data," 2023. <https://ens.dk/en/our-services/projections-and-models/technology-data>
- [2] I. Staffell and S. Pfenninger, "Using bias-corrected reanalysis to simulate current and future wind power output," *Energy*, vol. 114, pp. 1224–1239, 2016, doi: 10.1016/j.energy.2016.08.068.
- [3] S. Pfenninger and I. Staffell, "Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data," *Energy*, vol. 114, pp. 1251–1265, 2016, doi: 10.1016/j.energy.2016.08.060.