European Energy Research Alliance Joint Programme Smart Cities
International Journal of Sustainable Energy Planning and Management

Appendix/Supplementary material:

Interconnection of the electricity and heating sectors to support the energy transition in cities

Verena Heinisch [a*], Lisa Göransson [a], Mikael Odenberger [a], Filip Johnsson [a]

a Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden

Here the supplementary material to the research article "Interconnection of the electricity and heating sectors to support the energy transition in cities" is presented. The article has been published in the EERA Joint Programme on Smart Cities' Special issue on Tools, technologies and systems integration for the Smart and Sustainable Cities to come [1].

Please find the full article under:
http://dx.doi.org/10.5278/ijsepm.3328

[*] Corresponding author – e-mail *verena.heinisch@chalmers.se*

Appendix A Model description

This work presents a linear dispatch and investment optimisation model to analyse urban energy systems with an hourly time resolution. The objective is to minimise the total cost (consisting of annualised investments, fixed and variable O&M costs, and fuel costs), as expressed in Eq. (1). Electricity and heat balance equations [Eqs. (2) and (3)] ensure that the demand for electricity and heat in the city is met each hour. Heat pumps and electric boilers simultaneously consume electricity and produce heat, and are thereby part of the electricity and heat balances. CHP units produce electricity and heat, according to their power-to-heat ratios, as given in Eq. (4). While electricity can be imported from the national electricity grid, the amount is limited by the transmission capacity into the city, as shown in Eq. (5). Electricity generation and heat production is limited by the installed capacity as in Eqs. (6) and (7); a solar generation profile determines the output per installed capacity for solar PV. An urban emission target is set by Eq. (8). Storage technologies for electricity and heat can be utilised according to Eqs. (9)–(14). For thermal storage technologies, the C-factor limits how much energy can be charged and discharged per hour. Li-ion batteries can be fully charged and discharged each hour (i.e. C-factor of 1), while for flow batteries the charge and discharge per hour is limited to 50% of the installed capacity.

$$MIN \quad C^{tot} = \sum_{i\in I}\left(C_i^{inv} s_i + \sum_{t\in T}(C_i^{run} p_{i,t} + C_i^{run} q_{i,t})\right) + \sum_{t\in T} C_t^{el} w_t \tag{1}$$

$$D_t^{el} + \sum_{i\in I_{ElSt}} \frac{p_{i,t}^{ch}}{\eta_i} + \sum_{i\in I_{PtH}} \frac{q_{i,t}}{\eta_i} \leq \sum_{i\in I\setminus I_{ElSt}} p_{i,t} + w_t + \sum_{i\in I_{ElSt}} p_{i,t}^{dch} \tag{2}$$

$$D_t^{h} + \sum_{i\in I_{HSt}} \frac{q_{i,t}^{ch}}{\eta_i} \leq \sum_{i\in I\setminus I_{HSt}} q_{i,t} + \sum_{i\in I_{HSt}} q_{i,t}^{dch} + X_t \tag{3}$$

$$p_{i,t} = \alpha_i q_{i,t} \; \forall\, i \in I_{CHP} \tag{4}$$

$$w_t \leq M \tag{5}$$

$$p_{i,t} \leq (s_i + y_i) Z_{i,t} \; \forall\, i \in I_{el} \tag{6}$$

$$q_{i,t} \leq s_i + y_i \; \forall\, i \in I_h \tag{7}$$

$$\sum_{t\in T} \sum_{i\in I} p_{i,t} E_{i,t} \leq E^{lim} \tag{8}$$

$$sl_{i,t}^{ElSt} = sl_{i,(t-1)}^{ElSt} + q_{i,t}^{ch} - q_{i,t}^{dch} \tag{9}$$

$$p_{i,t}^{ch} \leq C_i^{f} s_i \; \forall\, i \in I_{ElSt} \tag{10}$$

$$p_{i,t}^{dch} \leq C_i^{f} s_i \; \forall\, i \in I_{ElSt} \tag{11}$$

$$sl_{i,t}^{HSt} = sl_{i,(t-1)}^{HSt} - L_i + q_{i,t}^{ch} - q_{i,t}^{dch} \tag{12}$$

$$q_{i,t}^{ch} \leq C_i^{f} s_i \; \forall\, i \in I_{HSt} \tag{13}$$

$$q_{i,t}^{dch} \leq C_i^{f} s_i \; \forall\, i \in I_{HSt} \tag{14}$$

Nomenclature:

T	The set of all time-steps
I	The set of all technologies in the urban energy system
I_{PtH}	Subset to I for all power-to-heat technologies, i.e., heat pumps and electric boilers
I_{ElSt}	Subset to I for all electricity storage technologies
I_{HSt}	Subset to I for all thermal storage technologies
I_{CHP}	Subset to I for all CHP units
I_{el}	Subset to I for all electricity generating units (incl. CHP)
I_h	Subset to I for all heat production units
C^{tot}	Total system costs to be minimised [€]
C_i^{inv}	CAPEX (annualised) including the fixed O&M costs for technology *i* [€/MW/year]
C_i^{run}	OPEX for each technology *i* (including fuel cost) [€/MWh]
C_t^{el}	Cost to import electricity to the city from the national grid [€/MWh]
s_i	Capacity of technology *i* invested in [MW(h)]
$p_{i,t}$	Electricity generation by technology *i* at time *t* [MWh/h]
$q_{i,t}$	Heat generation by technology *i* at time *t* [MWh/h]
w_t	Electricity imported to the city each hour [MWh/h]
D_t^{el}	Electricity demand per hour [MWh/h]
D_t^h	Heat demand per hour [MWh/h]
$p_{i,t}^{ch}$	Electricity charged to electricity storage units [MWh/h]
$p_{i,t}^{dch}$	Electricity discharged from electricity storage units [MWh/h]
η_i	Efficiency (or COP) for different technologies
$q_{i,t}^{ch}$	Heat charged to thermal storage units [MWh/h]
$q_{i,t}^{dch}$	Heat discharged from thermal storage units [MWh/h]
X_t	Heat production profile for industrial excess heat [MWh/h]
α_i	Power-to-heat ratio for CHP units
M	Transmission capacity limit for importing electricity [MW]
y_i	Existing capacity of technology *i* [MW]
$Z_{i,t}$	Generation profile for solar power (varies for solar power, equal to one for all other technologies)
$E_{i,t}$	Emissions resulting from the utilisation of the different technologies *i* [tonne_{CO2}/h]
E^{lim}	Limit imposed on emissions allowed in the urban energy system [tonne_{CO2}]
C_i^f	C-factor for charging and discharging thermal storage units and flow batteries
L_i	Losses from the thermal storage [MWh/h]

See Göransson et al. [2] for details on the implementation of thermal power plant cycling constraints and costs (implemented for the CHP plants in this model); these equations and variables have been omitted here for the sake of simplicity.

Appendix B Data and technology assumptions

Table A 1 gives the cost assumptions for the different electricity, heating, and storage technologies utilised in the modelling, as well as assumptions linked to life-time, efficiency, and power-to-heat ratios (for CHP plants). Table A 2 shows the cost assumptions, efficiencies, losses, and C-factors for the thermal storage technologies. For the annualised investment costs in the model, an interest rate of 5% is applied. Solar PV generation is based on MERRA data and a generation profile calculated with the model presented in [3]. The utilised solar profile results in 1,047 full-load hours for the City of Gothenburg.

Table A 1: Technology-related assumptions used in the model, (S, M and L correspond to small, medium and large units).

	Investment cost [€/kW_{el}]	Fixed O&M cost [€/kW]	Variable O&M cost [€/MWh]	Life-time [Years]	Efficiency [%]	Power-to-heat ratio
Electricity generation						
Solar PV *medium costs*	600	10	1.1	25	[a]	
Solar PV *low costs*	300	20	1.1	25	[a]	
Natural gas GT	390	7.92	0.4	30	37	
Biogas GT	378	7.92	0.7	30	37	
CHP					Electric	
CHP bio (S/L)	6000/3000	278/133/86	7.9/3.9	40	13.3/27.6	0.14/0.3
CHP biogas	1100	26	3	30	55	1.6
CHP gas	950	20	1.6	30	52.5	1.3
CHP waste (M/L)	760/6500	211/150	23.3/23.7	40	23.2/23.5	0.3
Heat production					Thermal	
Electric boiler	50	1.5	1	20	95	
Heat pump (S/M/L)	800/530/530	1.5/1/1	2/1.6/1.6	25	3 (COP)	
HOB bio (S/M/L)	590/540/490	29.3	1/0.85/0.7	25/20/20	115 [b]	
HOB biogas	50	1.7	1	25	104 [b]	
HOB gas	50	1.7	1	25	104 [b]	
HOB waste (M/L)	1550/1240	65.3/50.7	5.5/4.1	25	106 [b]	
HOB oil	400	2.5	1.5	20	90	
Electricity storage	[€/kWh]	[€/kW(h)]				
Li-ion batteries	150	0.5	-	15	90	
Flow batteries (energy)	50	-	-	30	70	
Flow batteries (capacity)	1100	54	-	30	100	

[a] For the PV generation, a solar profile based on the geographical area limits the output per kW installed for each hour,

[b] For the energy content in the fuel, the lower heating value has been used, which is matched with a higher value for the efficiency, Assumptions based on the IEA World Energy Outlook 2016 [4], as well as the Technology Data for Energy Storage provided by the Danish Energy Agency [5]

Table A 2: Assumptions made in relation to the different thermal storage systems, (M and L correspond to medium and large units).

Thermal storage	Investment cost [€/kWh]	Life-time [Years]	Efficiency [%]	C-factor	Loss [%/h]	Constant Loss [%/h]
Pit storage (M/L)	4/1.25	25	98	1/6	1/240	4.6/240
Pit with heat pump (M/L) [a]	0.857/0.268	25	98	1/6	1/240	-
Tank storage	26.5	25	98	1/168	1/240	4.6/240
Tank with heat pump [a]	5.7	25	98	1/168	1/240	-
Borehole storage	0.46	25	98	1/3,000	1/240	-

[a] Data only for storage, not the corresponding heat pump.

Table A 3 summarises the costs and emission levels for the modelling of the fuels, which can be utilised in the urban energy system.

Table A 3: Fuel cost assumptions

Fuel type	Fuel cost [€/MWh]	Emissions [$kgCO_{2\ equ}/MWh_{fuel}$]
Natural gas	34.27	207
Biomass (low/high)	20/40	0
Biogas (low/high)	48/77	0
Waste	1	132
Oil	66.18	264

In Figure A 1, the electricity price that is assumed to be paid on electricity imported to the urban energy system from the national grid is plotted. The electricity price curve assumption stems from a Northern European dispatch model and has been taken from a future scenario that includes an increased share of variable renewable electricity generation [6].

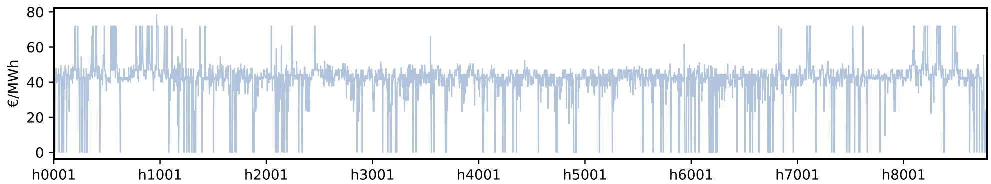

Figure A 1: Price (in €/MWh) for electricity imported to the city from the national electricity grid, as applied in the modelling. The price curve is derived from the results of a Northern European dispatch modelling [6], the x-axis shows all hours of the year.

The investigated district heating system currently includes CHP units that are fired by biomass and natural gas, as well as a small heat pump and HOBs fired by biomass, natural gas and oil. The biomass-fuelled units, as well as the heat pumps are operated in the cases presented in this work.

Figure A 2 shows the shares of the urban heating demand that can be supplied by waste heat in the modelling. At this point, no costs have been assigned for the utilization of waste heat. We assume a decrease in the amount of waste heat that is available in the city as compared to the current system, due to possible changes in the process designs of refineries, which are currently the main suppliers of waste heat. Both the future availability and price of waste heat are uncertain.

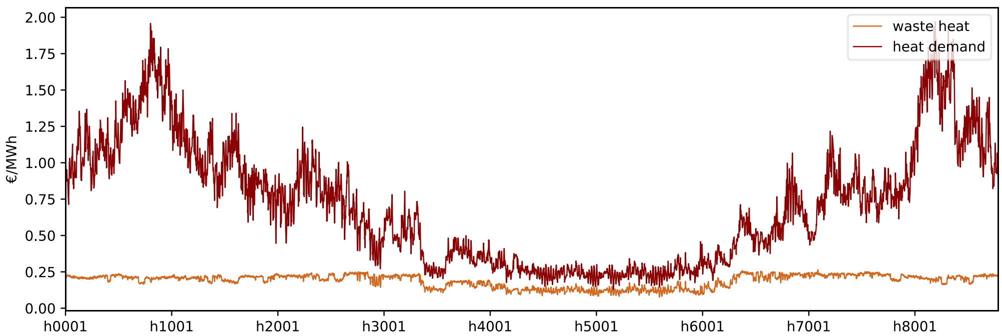

Figure A 2: Urban heat demand profile and waste heat production profile, as utilized in the modelling.

References in appendix:

[1] Østergaard PA, Maestoso PC. Tools, technologies and systems integration for the Smart and Sustainable Cities to come. Int J Sustain Energy Plan Manag 2019;24 2019. http://doi.org/10.5278/ijsepm.3450.
[2] Göransson L, Goop J, Odenberger M, Johnsson F. Impact of thermal plant cycling on the cost-optimal composition of a regional electricity generation system. Applied Energy 2017;197:230–40. http://doi.org/10.1016/j.apenergy.2017.04.018.
[3] Norwood Z, Nyholm E, Otanicar T, Johnsson F. A Geospatial Comparison of Distributed Solar Heat and Power in Europe and the US. PLOS ONE 2014;9:e112442. http://doi.org/10.1371/journal.pone.0112442.
[4] International Energy Agency. World energy Outlook 2016. Paris, France: 2016.
[5] Danish Energy Agency. Technology Data for Energy Storage. 2018.
[6] Taljegard M, Göransson L, Odenberger M, Johnsson F. Impacts of electric vehicles on the electricity generation portfolio – A Scandinavian-German case study. Applied Energy 2019;235:1637–50. http://doi.org/10.1016/j.apenergy.2018.10.133.