Optimizing the integration of renewable energy sources, energy efficiency, and flexibility solutions in a multi-network pharmaceutical industry

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Supplementary Material A

Input data for the Python energy system simulation model.

The formula used for computing the annual cost of a technology is as follows:

$$C_{tech} = \left(\mathrm{CAPEX} \cdot \frac{i \cdot (1+i)^L}{(1+i)^L - 1} + \mathrm{OM}_{fix} \right) \Phi + \mathrm{OM}_{var} \cdot \Psi$$

where Φ, Ψ are quantities, expressed as power capacity or energy capacity, according to the specific technology. The discount rate (i) is considered 0.02. Table 1 presents the characteristics of every technology considered in the study.

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Technology	**Efficiency (HHV-based) [%]**	**CAPEX (including installation cost)**	**Lifetime L [year]**	**Fixed operational cost $\mathbf{OM}_{fix}$**	**Variable operational cost $\mathbf{OM}_{var}$**	**Land specific use**	**Source**	**Note**
Natural gas boilers	0.93	55 k€/MW	25	1925 €/MW	1.05 €/MWh	N.A.	[1]	Technology data for Generation of Electricity and District Heating
Biomass boilers	0.76	675 k€/MW	25	32000 €/MW	3.08 €/MWh	N.A.	[1]	Technology data for Generation of Electricity and District Heating
Hydrogen boilers	0.93	60 k€/MW	25	2021 €/MW	1.1 €/MWh	N.A.	[1]	Derived from natural gas boilers
Natural gas CCHP	EE 0.4, steam 0.13, hot water 0.22, chiller 0.7	1025 k€/MW	25	9525 €/MW	5.25 €/MWh	N.A.	[1]	Technology data for Generation of Electricity and District Heating
Hydrogen CCHP	EE 0.4, steam 0.13, hot water 0.22, chiller 0.7	1275 k€/MW	25	9525 €/MW	5.25 €/MWh	N.A.	[1]	Derived from natural gas CCHP
Combined heat and cooling heat pump	Total efficiency 3.3	1170 k€/MW	25	2000 €/MW	2.69 €/MWh	N.A.	[1]	Technology Data for Industrial Process Heat

PV system	Hourly derived from SAM	970 k€/MW	30	10600 €/MW	0	4880 m^2/MW	[1]	Technology data for Generation of Electricity and District Heating
Linear Fresnel reflectors	Hourly derived from Bolognese	562 k€/MW	25	3936 €/MW	0	2806 m^2/MW	[2], [3]	
High temperature heat pump	Total efficiency 2.0	1630 k€/MW	25	2000 €/MW	3.4 €/MWh	N.A.	[1]	Technology Data for Industrial Process Heat
Alkaline water electolyzer	0.786	700 k€/MW	25	33000 €/MW	0	N.A.	[1]	Technology Data for Renewable Fuels
Battery energy storage system	Charge / discharge 0.97, self-discharge 4.2e-5	1042 k€/MWh	25	540 €/MW	0	26.25 m^2/MWh	[1]	Technology Data for Energy Storage
H2 storage tank	Charge 0.88	570 k€/MWh	25	600 €/MW	0	5 m^2/MWh	[1]	Technology Data for Energy Storage
Thermal energy storage	Charge / discharge 0.98, self-discharge 12e-5	4 k€/MWh	40	8.6 €/MW	0	8 m^2/MWh	[1]	Technology Data for Energy Storage

Table 1: Technical and financial parameters of investigated technologies.

The following formula is adopted for the calculation of energy vector cost:

$$C_{import} = \sum_{h=1}^{8784} \Big(\big((1+\alpha) * C_{REF,h} + \beta \big) * Q_h \Big) + \sum \gamma * P_i + C_{fix}$$

where Q is the energy quantity imported and P_i is the power quantity related to a specific period. In Table 2 the parameters are summarized. In Table 3 are resumed the parameters used in this study.

Commodity	C_{REF} **[€ / MWh]**	α **[-]**	β **[€ / MWh]**	C_{fix} **[€ / month]**	γ **[€ / MW/ month]**	**Source**
Electricity	PUN (time dependent)	0.238	26	N.A.	2751	PUN average from GME [4]. Other data provided by the industrial site
Natural gas	40	N.A.	7	17000	N.A.	C_{REF} forecasted by [5]. Other data provided by the industrial site
Biomass	37.33	N.A.	N.A.	N.A.	N.A.	[6]

Table 2: Cost parameters of energy vectors

Other costs and remuneration factors are resumed in Table 3.

	Value	**Source**
EUA of EU ETS	100 [€/ton]	[7]
DHN heat export	23.31 [€/MWh]	Derived from natural gas and EUA costs[7]
TEE from high efficiency cogeneration	250 €/TEP	[4]
Cost of rental roof	6.15 €/m^2	[8]
Cost of rental land	0.6 €/m^2	[10]

Table 3: Economic parameters considered.

National grid energy mix considered and energy vector emission factors are resumed in Table 4 and Table 5.

	Value [tonCO_2 /MWh]	Source
Coal	0.341	[9]
Oil	0.267	[9]
Ngas	0.202	[9]

Table 4: CO_2 emission factors.

	Value [-]	Source
Coal	0	[9]
Oil	0.0193	[9]
Ngas	0.4425	[9]
RES and Nuclear	0.5381	[9]
Efficiency	0.51	[9]

Table 5: National grid energy mix and efficiency.

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