MANGOever formulation

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In the following, we detail the formulation of the MANGOever (MANGO for **e**lectric **v**ehicles and **e**nergy **r**etrofits) model. It extends the existing MANGO model suite introduced by Mavromatidis and Petkov [1] and Pektov et al. [2]. The model is formulated as a Mixed-Integer Linear Program (MILP). It is developed in Python using the open-source `Pyomo` modeling language [3, 4], and can be solved using MILP solvers like Gurobi [5].

1 Sets

Table 1 presents an overview of all the model sets and subsets over which the parameters, variables and constraints of the model are indexed. The sets reflect the temporal and spatial dimensions of the model, the considered energy carriers, energy technologies and retrofitting packages as well as all aspects related to the integration of electric vehicles (EVs).

Table 1: MANGOever model sets and indices

Set	*Index*	*Description*
$\mathcal{P}$	p	Periods considered in the model horizon
$\mathcal{Y}$	y	Calendar years considered in the model horizon
$\mathcal{D}$	d	Set of representative days considered for each period
$\mathcal{CD}$	cd	Set of calendar days of a full calendar year
$\mathcal{T}$	t	Time steps considered for each representative day
$\mathcal{W} \subseteq \mathcal{P}$	w	Investment stages
$\mathcal{L}$	l	Energy system locations
$\mathcal{L}_b \subseteq \mathcal{L}$	l_b	Building sites
$\mathcal{L}_o \subseteq \mathcal{L}$	l_o	Other/Public sites
$\mathcal{EV}$	ev	Electric vehicles
$\mathcal{U}$	u	Charging location strategies
$\mathcal{K}$	k	Charging locations
$\mathcal{I}$	i	Charging sessions
$\mathcal{EC}$	ec	All energy carriers in the energy system
$\mathcal{EC}_i \subseteq \mathcal{EC}$	ec_i	Energy carriers that can be imported by the sites
$\mathcal{EC}_e \subseteq \mathcal{EC}$	ec_e	Energy carriers that can be exported from the sites
$\mathcal{EC}_d \subseteq \mathcal{EC}$	ec_d	Energy carriers for which demands are established
$\mathcal{EC}_{ev} \subseteq \mathcal{EC}$	ec_{ev}	Energy carriers for which the EVs have demand
$\mathcal{H}$	h	Retrofitting demand packages
$\mathcal{C}$	c	Energy conversion technologies
$\mathcal{C}_d \subseteq \mathcal{C}$	c_d	Dispatchable energy conversion technologies
$\mathcal{C}_r \subseteq \mathcal{C}$	c_r	Renewable conversion technologies
$\mathcal{C}_{ex} \subseteq \mathcal{S}$	s_{ex}	Existing conversion technologies
$\mathcal{S}$	s	Energy storage technologies
$\mathcal{S}_{ex} \subseteq \mathcal{S}$	s_{ex}	Existing storage technologies

2 Parameters

The model requires various technical, environmental, economic, and miscellaneous parameters, which are provided in Tables 2, 3, 4, 5, 6 and 7.

Table 2: Temporal model parameters

Parameter	*Unit*	*Description*
$nd_{p,d}$	[day]	The number of days that each typical day d corresponds to in period p
ny_p	[year]	Number of years each period p represents
$cd2td_{p,cd}$	[day]	Parameter to match each calendar day cd of a full year to a typical day d
$y2p_y$	[year]	Parameter to match each each calendar year to a model period
y_p^{real}	[year]	First, actual calendar year of each model period
$dem_{ec_d,l,p,d,t}$	[kWh]	Energy demand for energy carrier ec_d, at location l, in period p, day d and time step t
$dem^{EV}_{ec_{ev},ev,u,k,p,d,t}$	[kWh]	Charging energy demand of energy carrier ec_ev, for EV ev, in charging strategy u, in charging location k, in period p, day d and time step t for the unmanaged charging scenarios
$dem_{ev,u,k,p,d,i}$	[kWh]	Charging energy demand of EV ev, for charging strategy u, in charging location k, in period p, day d and charging session i for the managed charging scenarios
$t^a_{ev,u,k,p,d,i}$	[h]	Arrival time of EV ev, for charging strategy u, in charging location k, in period p, day d and charging session i for the managed charging scenarios
$t^d_{ev,u,k,p,d,i}$	[h]	Departure time of EV ev, for charging strategy u, in charging location k, in period p, day d and charging session i for the managed charging scenarios

Table 3: Model parameters for conversion technologies

Parameter	*Unit*	*Description*
$cpl_{c,l}$	[0/1]	Defines if a technology c can be installed at location l
cap_c^{min}	[kW]	Minimum possible newly installed capacity for a technology c
cap_c^{max}	[kW]	maximum possible newly installed capacity for a technology c
cl_c	[years]	Lifetime of conversion technology c in calendar years
cl_c^p	[periods]	Lifetime of conversion technology c in model periods p
$ecc^{disp}_{c_d,ec,ec'}$	[0/1]	Input-output coupling of energy carriers ec, ec' for dispatchable technology c_d
$\eta^{disp}_{c_d,ec,ec'}$	[%]	Conversion factor for dispatch technology t_d between energy carrier ec and ec'
$rcc_{r,ec}$	[0/1]	Output energy carriers ec for renewable technology t_d
$rcap^{max}_{r,l,p}$	[kWh]	Maximum allowable total capacity for the installation of each renewable technology r at each site l and period p
$sol^{rad}_{l,p,d,t}$	[kWh/m^2]	Incoming solar radiation patterns at energy system location l, in period p, day d, and time step h
$\eta^{sol,ntr}_{r_s,ec}$	[%]	Efficiency of solar renewable supply technology r_s
$excap^{tech}_{t_{ex},ec,l}$	[kW]	Installed capacity of an existing conversion technology c and energy carrier ec at a site l in the beginning of the model horizon

Table 4: Model parameters for storage technologies

Parameter	*Unit*	*Description*
$stc_{s,ec}$	[0/1]	Storage technology coupling parameter describing the energy carrier ec stored in storage technology s
$spl_{s,l}$	[0/1]	Defines if a storage technology s can be installed at location l
sl_s	[years]	Lifetime of storage technology s in calendar years
sl_s^p	[periods]	Lifetime of storage technology s in model periods p
$q_s^{ch,max}$	[kW]	maximum charging rate of a storage technology s
$q_s^{dis,max}$	[kW]	maximum discharging rate of a storage technology s
η_s^{self}	[%]	Self-discharge losses of a storage technology s
η_s^{ch}	[%]	Charging efficiency of a storage technology s
η_s^{dis}	[%]	Discharging efficiency of a storage technology s
cap_s^{min}	[kWh]	Minimum possible newly installed capacity for a storage technology s
cap_s^{max}	[kWh]	maximum possible newly installed capacity for a storage technology s
$cap_{s,l}^{max}$	[kWh]	maximum allowable total energy storage capacity per technology s at location l
$excap_{s_{ex},ec,l}^{stor}$	[kWh]	Installed storage capacity and energy carrier ec at a site l the beginning of the modeling period

Table 5: Model parameters for electric mobility.

Parameter	*Unit*	*Description*
chr_k^{max}	[kW]	Maximum charging rate at charging location k
chl	[years]	Lifetime of EV charger in calendar years
chl^p	[periods]	Lifetime of EV charger in model periods

3 Decision variables

Table 6: Economic model parameters

Parameter	*Unit*	*Description*
$i_{ec_i,p,d,t}$	[CHF/kWh]	Price for importing energy carrier ec_i, in period p, on day d, in time step t
$e_{ec_e,p}$	[CHF/kWh]	Compensation for exporting energy carrier ec_e, in period p
$fc^{conv}_{c,w}$	[CHF]	Fixed cost for the installation of conversion technology c, in investment stage w
$lc^{conv}_{c,w}$	[CHF/kW]	Linear, capacity-dependent cost for the installation of conversion technology c, in investment stage w
$fc^{stor}_{s,w}$	[CHF]	Fixed cost for the installation of storage technology s, in investment stage w
$lc^{stor}_{s,w}$	[CHF/kWh]	Linear, capacity-dependent cost for the installation of storage technology s, in investment stage w
om^{conv}_{c}	[-]	Parameter used to calculate the annual maintenance cost for conversion technology c as a fraction of its total investment cost
om^{stor}_{s}	[-]	Parameter used to calculate the annual maintenance cost for storage technology s as a fraction of its total investment cost
$cslvg_{c,w}$	[-]	Salvage percentage of initial investment cost for conversion technology c that was installed in stage w and has not reached the end of its lifetime at the end of the model horizon (Defined for: $\{w \geq \max_{p \in \mathcal{P}}(p) + 1 - cl_c\}$)
$sslvg_{s,w}$	[-]	Salvage percentage of initial investment cost for storage technology s - same formula applies as for $cslvg_{c,w}$
lc^{ret}_{w}	[CHF/kWh]	Linear retrofitting cost per kWh saved in one year
$rslvg_{g,w}$	[-]	Salvage percentage of initial investment cost for a retrofitting intervention - same formula applies as for $cslvg_{c,w}$
$fc^{ch}_{k,w}$	[CHF]	Fixed cost for the installation of an EV charger in location type k, in investment stage w
$lcoch_{k,p}$	[CHF/kWh]	Levelized cost of charging per kWh in charging location type k, in investment stage w
$chslvg_{w}$	[-]	Salvage percentage of initial investment cost for an EV charger - same formula applies as for $cslvg_{c,w}$
r	[%]	Discount rate

Table 7: Environmental and miscellaneous model parameters

Parameter	*Unit*	*Description*
$ef_{ec_i,y}$	[kgCO$_2$//kWh]	Carbon emission factor for imported energy carrier ec in year y
ϵ	-	Epsilon value for the multi-objective epsilon-constrained optimization
$bigM$	-	"Big M" - Sufficiently large value

Table 8: Decision variables pertaining to energy system operation

Variable	*Unit*	*Description*
$PIN^{disp}_{c_d,ec,l,p,d,t}$	kMWh]	Input energy to dispatch technology c_d, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$POUT^{disp}_{c_d,ec,l,p,d,t}$	[kWh]	Output energy from dispatch technology c_d, installed at energy system location l, and operating in period p, day d, and time step h
$POUT^{re}_{r,ec,l,p,d,t}$	[kWh]	Output energy from renewable energy technology r, installed at energy system location l, and operating in period p, day d, and time step t
$P^{imp}_{ec_i,l,p,d,t}$	[kWh]	Import of energy carrier ec_i, at energy system location l, in period p, day d, and time step t
$P^{exp}_{ec_e,l,p,d,t}$	[kWh]	Exported energy of energy carrier ec_e, at energy system location l, in period p, day d, and time step t
$Q^{ch}_{s,ec,l,p,d,h}$	[kWh]	Charging energy for storage technology s, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step h
$Q^{dis}_{s,ec,l,p,d,h}$	[kWh]	Discharging energy for non-tracked storage technology s, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step h
$SoC_{s,ec,l,p,d,h}$	[kWh]	Intra-day state of charge of storage technology s, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step h
$SoC^{interday}_{s,ec,l,p,cd}$	[kWh]	Inter-day state of charge of storage technology s, for energy carrier ec, installed at energy system location l, and operating in period p, calendar day cd
$SoC^{min}_{s,ec,l,p,d}$	[kWh]	Minimum intra-day state of charge of storage technology s, installed at energy system location l and operating in period p and day d
$SoC^{max}_{s,ec,l,p,d}$	[kWh]	Maximum intra-day state of charge of storage technology s, installed at energy system location l and operating in period p and day d
$chr_{ec_{ev},ev,k,p,d,t}$	[kW]	Charging rate of electric vehicle ev, at charging location k, in period p, day d, and time step t
$chr^{strategy}_{ec_{ev},ev,u,k,p,d,t}$	[kW]	Helper variable that describes the charging rate per charging infrastructure strategy u for electric vehicle ev, at charging location k, in period p, day d, and time step t

Table 9: Decision variables pertaining to the system design

Variable	*Unit*	*Description*
$Y^{conv}_{c,l,w}$	[-]	Binary variable denoting the installation of new capacity of conversion technology c, at location l, in investment stage w
$Y^{stor}_{s,l,w_{cs}}$	[-]	Binary variable denoting the installation of new capacity of storage technology s, at location l, in investment stage w_{cs}
$NCAP^{conv}_{c,l,w}$	[kW, m^2]	New capacity of conversion technology c, installed at location l, in investment stage w
$NCAP^{stor}_{s,l,w}$	[kWh]	New capacity of storage technology s, installed at location l, in investment stage w
$TCAP^{conv}_{t,ec,l,p}$	[kW]	Total capacity of conversion technology t, for energy carrier ec, in period p, at location l
$TCAP^{stor}_{t,ec,l,p}$	[kW]	Total capacity of conversion technology t, for energy carrier ec, in period p, at location l
$Y^{retdem,new}_{h,l_b,w}$	[-]	Binary variable denoting a new retrofitting level h, at location l, in stage w
$Y^{retdem}_{h,l_b,p}$	[-]	Binary variable denoting the active retrofitting level h, at location l, in period p
$Y^{evdem}_{ev,u,p}$	[-]	Binary variable denoting the active charging location strategy u, for EV ev, in period p
$Y^{EVcharger}_{l,ev,p}$	[-]	Binary variable denoting whether an EV charging station is available in location l, for EV ev, in period p
$Y^{EVcharger,new}_{l,ev,w}$	[-]	Binary variable denoting the installation of a new EV charging station in location l, for EV ev, in investment stage w

Table 10: Economic decision model variables on (nominal) energy system cost and emission performance

Variable	*Unit*	*Description*
$T^{syst,cost}$	[CHF]	Total lifetime energy system cost
T^{CO_2}	[CO_2]	Total lifetime energy system CO_2 emissions
$C^{imp}_{l,y}$	[CHF]	Total cost due to energy carrier imports at location l, in year y
$R^{exp}_{l,y}$	[CHF]	Total revenue due to energy carrier exports at location l, in year y
$C^{maint}_{l,y}$	[CHF]	Total maintenance cost for all conversion and storage technologies installed at location l, in year y
$C^{conv,inv}_{l,w}$	[CHF]	Total investment cost for conversion technologies at location l, in investment stage w
$C^{stor,inv}_{l,w}$	[CHF]	Total investment cost for storage technologies at location l, in investment stage w
$C^{ret,inv}_{l,w}$	[CHF]	Total investment cost for retrofit interventions at location l, in investment stage w
$C^{char,inv}_{l,w}$	[CHF]	Total investment cost for the installation of EV charging infrastructure at location l, in investment stage w
R^{slvg}_{l}	[CHF]	Salvage value of all technologies at location l not reaching the end of their lifetime at the end of the model horizon

4 Objective functions

The following details the two objective functions implemented in the MANGOever model.

4.1 Equation 1

Definition of the total system cost model objective function:

$$\begin{aligned}
T^{syst,cost} = &\sum_{l\in\mathcal{L}}\sum_{w\in\mathcal{W}}\left(C^{conv,inv}_{l,w} + C^{stor,inv}_{l,w} + C^{ret,inv}_{l,w} + C^{char,inv}_{l,w}\right)\cdot\frac{1}{(1+r)^{w-1}} \\
&+\sum_{l\in\mathcal{L}}\sum_{y\in\mathcal{Y}}\left(C^{imp}_{l,y} + C^{maint}_{l,y} - R^{exp}_{l,y}\right)\cdot\frac{1}{(1+r)^{y}} \\
&-\sum_{l\in\mathcal{L}} R^{slvg}_{l}\cdot\frac{1}{(1+r)^{|\mathcal{Y}|+1}}
\end{aligned} \tag{1}$$

4.2 Equation 2

Definition of the total system carbon model objective function:

$$T^{CO_2} = \sum_{y\in\mathcal{Y}}\sum_{d\in\mathcal{D}}\sum_{t\in\mathcal{T}} P^{imp}_{ec_i,l,y2p_y,d,t}\cdot ef_{ec_i,y}\cdot nd_{y2p_y,d}\ \forall\ ec_i\in\mathcal{EC}_i, l\in\mathcal{L}, y\in\mathcal{Y} \tag{2}$$

5 Constraints

The following section lists all constraints that comprise the MANGOever model. They define the optimization's possible solution space and represent various technical and economic relations in the integrated energy system.

5.1 Equation 3

Input-output relationship for dispatchable technologies:

$$\begin{aligned}
POUT^{disp}_{t_d,ec',l,p,d,t} = PIN^{disp}_{c_d,ec,l,p,d,t}\cdot\eta^{disp}_{t_d,ec,ec'}\ , \\
\forall\ c_d\in\mathcal{C}_d,\ ec,ec'\in\mathcal{EC},\ l\in\mathcal{L},\ p\in\mathcal{P},\ d\in\mathcal{D},\ t\in\mathcal{T}\ | \\
\{cpl_{c_d,l}=1\ ,\ ecc^{disp}_{c_d,ec,ec'}=1\}
\end{aligned} \tag{3}$$

5.2 Equation 4

Constraint for the calculation of the energy output by solar technologies:

$$\begin{aligned}
&POUT^{sol}_{r_s,ec,l,p,d,t} = sol^{rad}_{l,p,d,t}\cdot\frac{TCAP^{tech}_{r_s,ec,l,p}}{\eta^{sol,ntr}_{r_s,ec}}\cdot\eta^{sol}_{r_s,ec}\ , \\
&\forall\ r_s\in\mathcal{R}_s,\ ec\in\mathcal{EC},\ l\in\mathcal{L},\ p\in\mathcal{P},\ d\in\mathcal{D},\ h\in\mathcal{H}\ |\ \{tpl_{r_s,l}=1\ ,\ rcc_{r_s,ec}=1\}
\end{aligned} \tag{4}$$

5.3 Equation 5

Energy balance for the building energy system including conversion, storage, and export flows for the uncontrolled and controlled charging cases:

$$
\begin{aligned}
&\begin{cases} P^{imp}_{ec,l,p,d,h} & , ec \in \mathcal{EC}_i \\ 0 & , ec \notin \mathcal{EC}_i \end{cases} \\
&+ \sum_{\substack{c_d \in \mathcal{C}_d \\ cpl_{c_d,l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_d,ec',ec}=1}} POUT^{disp}_{c_d,ec,l,p,d,t} \\
&- \sum_{\substack{c_d \in \mathcal{C}_d \\ cpl_{c_d,l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_d,ec,ec'}=1}} PIN^{disp}_{c_d,ec,l,p,d,t} \\
&+ \sum_{\substack{r \in \mathcal{R} \\ tpl_{r,l}=1 \\ rcc_{r,ec}=1}} POUT^{re}_{r,ec,l,p,d,h} \\
&+ \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1 \\ stc_{s,ec}=1}} (Q^{dis}_{s,ec,l,p,d,t} - Q^{ch}_{s,ec,l,p,d,t}) \\
&- \begin{cases} P^{exp}_{ec,l,p,d,t} & , ec \in \mathcal{EC}_e \\ 0 & , ec \notin \mathcal{EC}_e \end{cases} \\
&= \begin{cases} dem_{ec_d,h,l,p,d,t} \cdot Y^{retdem}_{h,l_d,p} & \\ 0 & , ec \notin \mathcal{EC}_d \end{cases} \\
\text{for uncontrolled charging: } &+ \begin{cases} \sum_{ev \in \mathcal{EV}} \sum_{u \in \mathcal{U}} dem^{EV}_{ec_{ev},ev,u,k,p,d,t} \cdot Y^{evdem}_{ev,u,p} & \\ 0 & , ec \notin \mathcal{EC}_{ev} \end{cases} \\
\text{for controlled charging: } &+ \begin{cases} \sum_{ev \in \mathcal{EV}} \sum_{u \in \mathcal{U}} chr_{ec_{ev},ev,k,p,d,t} & \\ 0 & , ec \notin \mathcal{EC}_{ev} \end{cases} \\
&\forall\ ec \in \mathcal{EC},\ l \in \mathcal{L}_b,\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{k = \text{Home}\}
\end{aligned} \tag{5}
$$

5.4 Equation 6

Energy balance for the public site for the uncontrolled and controlled charging cases:

$$
\begin{aligned}
&\begin{cases} P^{imp}_{ec,l,p,d,t} & , ec \in \mathcal{EC}_i \\ 0 & , ec \notin \mathcal{EC}_i \end{cases} = \\
\text{for uncontrolled charging: } &\begin{cases} \sum_{ev \in \mathcal{EV}} \sum_{u \in \mathcal{U}} dem^{EV}_{ec_{ev},ev,u,k,p,d,t} \cdot Y^{evdem}_{ev,u,p} & \\ 0 & , ec \notin \mathcal{EC}_{ev} \end{cases} \\
\text{for controlled charging: } &\begin{cases} \sum_{ev \in \mathcal{EV}} \sum_{u \in \mathcal{U}} chr_{ev,k,p,d,t} & \\ 0 & , ec \notin \mathcal{EC}_{ev} \end{cases} \\
&\forall\ ec \in \mathcal{EC},\ l \in \mathcal{L}_o,\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} | \ \{k = \text{Public}\}
\end{aligned} \tag{6}
$$

5.5 Equation 7

Constraint to ensure that electricity is only exported to the grid when there is electricity generation from solar PV:

$$
\begin{aligned}
&P^{exp}_{ec_e,l,p,d,t} = POUT^{sol}_{c_r,ec,l,p,d,t} \\
&\forall ec_e \in \mathcal{EC}_e,\ l \in \mathcal{L},\ p \in \mathcal{P}\ ,\ d \in \mathcal{D}\ ,\ t \in \mathcal{T} \mid \{cpl_{c_r,l} = 1\ ,\ rcc_{r,ec} = 1\}
\end{aligned} \tag{7}
$$

5.6 Equation 8

Constraint ensuring that only a single retrofit demand profile is active in each period:

$$\sum_{h\in\mathcal{H}} Y^{retdem}_{h,l_b,p} = 1 \qquad \forall\ l_b \in \mathcal{L}_b\ ,\ p \in \mathcal{P} \tag{8}$$

5.7 Equation 9

Constraint that tracks the installation of a new retrofitting level:

$$Y^{retdem}_{h,l_b,p} = \sum_{\substack{w\in\mathcal{W}\\ p\geq w}} Y^{retdem,new}_{h,l_b,w} \qquad \forall\ h \in \mathcal{H}\ ,\ l_b \in \mathcal{L}_b\ ,\ p \in \mathcal{P} \tag{9}$$

5.8 Equation 10

Constraint to keep track of the total available capacity per technology at each energy site and period:

$$\begin{aligned} TCAP^{conv}_{c,ec',l,p} = \sum_{\substack{w\in\mathcal{W}\\ p\geq w\\ p\leq w+cl^p_c-1}} NCAP^{conv}_{c,ec',l,w} \\ \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ | \\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1) \end{aligned} \tag{10}$$

5.9 Equation 11

Constraint defining the relationship of different capacities of multi-output technologies:

$$\begin{aligned} NCAP^{conv}_{c_d,ec'_1,l,w} \cdot \eta^{disp}_{c_d,ec,ec'_2} = NCAP^{conv}_{c_d,ec'_2,l,w} \cdot \eta^{disp}_{c_d,ec,ec'_1} \\ \forall\ c_d \in \mathcal{C}_d,\ ec, ec'_1, ec'_2 \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \\ |\ \{cpl_{c_d,l} = 1\ ,\ ecc^{disp}_{c_d,ec,ec'_1} = 1,\ ecc^{disp}_{c_d,ec,ec'_2} = 1,\ ec'_1 \neq ec'_2\} \end{aligned} \tag{11}$$

5.10 Equation 12

Constraint setting an upper limit to the total renewable capacity per technology at each site:

$$\sum_{\substack{ec\in\mathcal{EC}\\ rcc_{r,ec}=1}} TCAP^{conv}_{r,ec,l,p} \leq rcap^{max}_{r,l,p} \qquad \forall\ r \in \mathcal{R},\ l \in \mathcal{L},\ p \in \mathcal{P},\ |\ cpl_{r,l} = 1 \tag{12}$$

5.11 Equation 13

Constraint setting the capacity for existing conversion technologies:

$$\begin{aligned} NCAP^{tech}_{c_{ex},ec',l,1} = excap^{tech}_{c_{ex},ec',l} \qquad \forall\ c_{ex} \in \mathcal{C}_{ex},\ ec' \in \mathcal{EC},\ l \in \mathcal{L}\ | \\ \{\ cpl_{t_{ex},l} = 1 \wedge ((c_{ex} \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c_{ex},ec,ec'} = 1)\ \vee rcc_{c_{ex},ec'} = 1)\} \end{aligned} \tag{13}$$

5.12 Equation 14

Constraint preventing the re-installation of existing conversion technologies:

$$\text{If } w \neq 1 : ncap^{tech}_{c_{ex},ec,l,w} <= 0 \qquad \forall\ c_{ex} \in \mathcal{C}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W}\ |\ cpl_{c_{ex},l} = 1 \tag{14}$$

5.13 Equation 15

Constraint preventing capacity violation for the conversion technologies of the energy system:

$$POUT^{disp,ntr}_{c_d,ec',l,p,d,t} \leq TCAP^{conv,ntr}_{c_d,ec',l,p} \qquad \forall\ c_d \in \mathcal{C}_d,\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{\ cpl_{c_d,l} = 1\ , \exists\ ec\ \in \mathcal{EC} \mid ecc_{c_d,ec,ec'} = 1\} \tag{15}$$

5.14 Equation 16

Maximum possible conversion technology capacity per technology considered:

$$NCAP^{conv}_{c,ec',l,w} \leq cap^{max}_c \cdot Y^{conv}_{c,l,w} \qquad \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1)\} \tag{16}$$

5.15 Equation 17

Minimum possible conversion technology capacity per technology considered:

$$NCAP^{conv}_{c,ec',l,w} \geq cap^{min}_c \cdot Y^{conv}_{c,l,w} \qquad \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1)\} \tag{17}$$

5.16 Equation 18

Constraint for the formulation of the fixed cost in the objective function:

$$NCAP^{tech}_{c,ec',l,w} \leq bigM \cdot Y^{tech}_{c,l,w} \qquad \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1)\} \tag{18}$$

5.17 Equation 19

Constraint to keep track of the total available capacity per storage technology at each energy site and period:

$$TCAP^{stor}_{s,ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + sl^p_s - 1}} NCAP^{stor}_{s,ec,l,w} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{19}$$

5.18 Equation 20

Intra-day energy balance for the storage modules considering incoming and outgoing energy flows:

$$SoC_{s,ec,l,p,d,t} = \begin{cases} \eta^{ch}_s \cdot Q^{ch}_{s,ec,l,p,d,t} - \frac{1}{\eta^{dis}_s} \cdot Q^{dis}_{s,ec,l,p,d,t} & , t = 1 \\ \eta^{ch}_s \cdot Q^{ch}_{s,ec,l,p,d,t} - \frac{1}{\eta^{dis}_s} \cdot Q^{dis}_{s,ec,l,p,d,t} | & \\ +(1 - \eta^{self}_s) \cdot SoC_{s,ec,l,p,d,t-1} & , t \neq 1 \end{cases} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{\ spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{20}$$

5.19 Equation 21

Constraint for the maximum allowable charging rate of the storage technologies:

$$Q^{ch}_{s,ec,l,p,d,t} \leq q^{ch,max}_s \cdot TCAP^{stor}_{s,ec,l,p} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{21}$$

5.20 Equation 22

Constraint for the maximum allowable discharging rate of the storage technologies:

$$Q^{dis}_{s,ec,l,p,d,t} \leq q^{dis,max}_{s} \cdot TCAP^{stor}_{s,ec,l,p} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{22}$$

5.21 Equation 23

Constraint to capture the minimum intra-day state-of-charge for a storage technology:

$$SoC^{min}_{s,ec,l,p,d} \leq SoC_{s,ec,l,p,d,t} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{23}$$

5.22 Equation 24

Constraint to capture the maximum intra-day state-of-charge for a storage technology:

$$SoC^{max}_{s,ec,l,p,d} \geq SoC_{s,ec,l,p,d,t} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{24}$$

5.23 Equation 25

Constraint connecting the inter-day state-of-charge of a storage technology:

$$SoC^{interday}_{s,ec,l,p,cd} = \begin{cases} 0 & , p = 1 \wedge cd = 1 \\ SoC^{interday}_{s,ec,l,p-1,max(cd)} \cdot (1 - \eta^{self}_{s})^{max(t)} & \\ \;+SoC_{s,ec,l,p-1,cd2td_{p-1,max(cd)},max(t)} & , p \neq 1 \wedge cd = 1 \\ SoC^{interday}_{s,ec,l,p,cd-1} \cdot (1 - \eta^{self}_{s})^{max(t)} & \\ \;+SoC_{s,ec,l,p,cd2td_{p,cd-1},max(t)} & , cd \neq 1 \end{cases}$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{25}$$

5.24 Equation 26

Constraint for non-violation of the capacity of a storage technology:

$$SoC^{interday}_{s,ec,l,p,cd} + SoC^{max}_{s,ec,l,p,cd2td_{p,cd}} \leq TCAP^{stor}_{s,ec,l,p}$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{26}$$

5.25 Equation 27

Constraint to enforce non-negativity for the state-of-charge of a storage technology:

$$SoC^{interday}_{s,ec,l,p,cd} \cdot (1 - \eta^{self}_{s})^{max(t)} + SoC^{min}_{s,ec,l,p,cd2td_{p,cd}} \geq 0$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{27}$$

5.26 Equation 28

Minimum possible storage technology capacity per technology considered:

$$NCAP^{stor}_{s,ec,l,w} \geq cap^{min}_{s} \cdot Y^{stor}_{s,l,w} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{28}$$

5.27 Equation 29

Maximum possible storage technology capacity per technology considered:

$$NCAP^{stor}_{s,ec,l,w} \leq cap^{max}_{s} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{29}$$

5.28 Equation 30

Constraint enforcing the maximum allowable storage capacity per type of storage technology:

$$TCAP^{stor}_{s,ec,l,p} \leq cap^{max}_{s,l} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{30}$$

5.29 Equation 31

Constraint for the formulation of the fixed cost in the objective function:

$$NCAP^{stor}_{s,ec,l,w} \leq bigM \cdot Y^{stor}_{s,l,w} \qquad \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{31}$$

5.30 Equation 32

Constraint setting the capacity for existing storage technologies:

$$NCAP^{stor}_{s_{ex},ec,l,1} = excap^{stor}_{s_{ex},ec,l} \qquad \forall\ s_{ex} \in \mathcal{S}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L} \mid \{spl_{s_{ex},l} = 1,\ stc_{s_{ex},ec} = 1\} \tag{32}$$

5.31 Equation 33

Constraint limiting the possibility of reinvesting in existing storage technologies:

$$\text{If } w \neq 1 : Y^{stor}_{s_{ex},l,w} = 0 \qquad \forall\ s_{ex} \in \mathcal{S}_{ex},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W} \mid \{spl_{s_{ex},l} = 1\} \tag{33}$$

5.32 Equation 34

Definition of the expense for importing energy from external sources (e.g. electricity grid) at building sites:

$$C^{imp}_{l,y} = \sum_{ec_i \in \mathcal{EC}_i} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P^{imp}_{ec_i,l,y2p_y,d,t} \cdot p_{ec_i,y} \cdot nd_{y2p_y,d} \qquad \forall\ l \in \mathcal{L}_b,\ y \in \mathcal{Y} \tag{34}$$

5.33 Constraint 35

Definition of the income due to electricity exports component of the total energy system cost at each site:

$$R^{exp}_{l,y} = \sum_{ec_e \in \mathcal{EC}_e} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P^{exp}_{ec_e,l,y2p_y,d,t} \cdot p_{ec_e,y} \cdot nd_{y2p_y,d} \qquad \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \tag{35}$$

5.34 Equation 36

Definition of the maintenance cost component of the total energy system cost for each site:

$$\begin{aligned} C_{l,y}^{main} = & \sum_{\substack{c \in \mathcal{C} \\ cpl_{t,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ | \\ ecc^{disp}_{t,ec,ec'}=1) \\ \vee rcc_{t,ec'}=1)}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y_w^{real} \\ y \leq y_w^{real}+cl_c-1}} (fc_{c,ec',w}^{tech} \cdot Y_{c,l,w}^{tech} + lc_{c,ec',w}^{tech} \cdot NCAP_{c,ec',l,w}^{tech}) \cdot om_c^{tech} \\ & + \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1}} \sum_{\substack{ec \in \mathcal{EC} \\ stc_{s,ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y_w^{real} \\ y \leq y_w^{real}+cl_s-1}} (fc_{s,ec,w}^{stor} \cdot Y_{s,l,w}^{stor} + lc_{s,ec,w}^{stor} \cdot NCAP_{s,ec,l,w}^{stor}) \cdot om_s^{stor} \\ & \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \end{aligned} \tag{36}$$

5.35 Equation 37

Definition of the investment expenditure for the purchase of technologies at each candidate site:

$$\begin{aligned} C_{l,w}^{conv,inv} = & \sum_{\substack{c \in \mathcal{C} \\ cpl_{c,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ | \\ ecc^{disp}_{c,ec,ec'}=1) \\ \vee rcc_{c,ec'}=1)}} fc_{c,ec',w}^{conv} \cdot Y_{c,l,w}^{conv} + lc_{c,ec',w}^{conv} \cdot NCAP_{c,ec',l,w}^{conv} \\ & \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \end{aligned} \tag{37}$$

5.36 Equation 38

Definition of the investment expenditure for the purchase of storage technologies at each candidate site:

$$C_{l,w}^{stor,inv} = \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1}} \sum_{\substack{ec \in \mathcal{EC} \\ stc_{s,ec}=1}} fc_{s,ec,w}^{stor} \cdot Y_{s,l,w}^{stor} + lc_{s,ec,w}^{stor} \cdot NCAP_{s,ec,l,w}^{stor}\ \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{38}$$

5.37 Equation 39

Definition of the investment expenditure for retrofitting interventions at each building site:

$$\begin{aligned} C_{l,w}^{ret} = & \sum_{h \in \mathcal{H}} Y_{h,l,w}^{ret,new} \cdot \sum_{\substack{y \in \mathcal{Y} \\ y=w}} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} [(dem_{Heat,noret,l,p,d,t} - dem_{Heat,h,l,p,d,t}) \cdot nd_{y,d}] \cdot lc_w^{ret} \\ & \forall\ l \in \mathcal{L}_b,\ w \in \mathcal{W} \end{aligned} \tag{39}$$

5.38 Equation 40

Definition of the investment expenditure for home electric vehicle chargers at each building site:

$$\begin{aligned} C_{l,w}^{char} = & \sum_{substackevin\mathcal{EV}} Y_{l,ev,w}^{EVcharger} \cdot fc_{k,w}^{ch} \\ & \forall\ l \in \mathcal{L}_b,\ w \in \mathcal{W} \mid \{k = Home\} \end{aligned} \tag{40}$$

5.39 Equation 41

Definition of the electric vehicle charging costs at the public site:

$$\begin{aligned} C_{l,y}^{imp} = & \sum_{ec_ev \in \mathcal{EC}_{ev}} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P_{ec_{ev},l,y2p_y,d,t}^{imp} \cdot (p_{ec_ev,y} + lcoch_{k,y}) \cdot nd_{y2p_y,d} \\ & \forall\ l \in \mathcal{L}_b,\ y \in \mathcal{Y} \mid \{k = Public\} \end{aligned} \tag{41}$$

5.40 Equation 42

Definition of the salvage value term at the end of the horizon for each energy site:

$$
\begin{aligned}
R_l^{slvg} = \\
&\sum_{\substack{c \in \mathcal{C} \\ cpl_{c,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((c \in \mathcal{C}_d \wedge \exists \ ec \in \mathcal{EC} \ | \\ ecc^{disp}_{c,ec,ec'}=1) \\ \vee rcc_{c,ec'}=1)}} \sum_{\substack{w \in \mathcal{W} \\ w \geq max(p)+1-cl_c^p}} (fc^{conv}_{c,ec',w} \cdot Y^{conv}_{c,l,w} + lc^{conv}_{t,ec',w} \cdot NCAP^{conv}_{t,ec',l,w}) \cdot cslvg_{c,w} \\
&+ \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1}} \sum_{\substack{ec \in \mathcal{EC} \\ stc_{s,ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ w \geq max(p)+1-sl_s^p}} (fc^{stor}_{s,ec,w} \cdot Y^{stor}_{s,l,w} + lc^{stor}_{s,ec,w} \cdot NCAP^{stor}_{s,ec,l,w}) \cdot sslvg_{s,w} \\
&+ \sum_{h \in \mathcal{H}} \sum_{\substack{w \in \mathcal{W} \\ w \geq max(p)+1-rl^p}} Y^{ret,new}_{h,l,w} \cdot \sum_{\substack{y \in \mathcal{Y} \\ y=w}} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} [(dem_{Heat,noret,l,p,d,t} - dem_{Heat,h,l,p,d,t}) \cdot nd_{y,d}] \cdot lc^{ret}_w \\
&+ \sum_{substackevin\mathcal{EV}} \sum_{\substack{w \in \mathcal{W} \\ w \geq max(p)+1-evl_e^p v}} (Y^{EVcharger}_{l,ev,w} \cdot fc^{ch}_{k,w}) \cdot evslvg_w \\
&\forall \ l \in \mathcal{L}
\end{aligned}
\tag{42}
$$

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