MANGOpol formulation

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May 28, 2025

This supplementary document provides the full mathematical formulation of the MANGOpol framework in Aliana et al. (2025), including both the Policy Mix Designer (PMD) and the Energy System Planner (ESP).

While the main manuscript presents a simplified overview of the model to aid clarity, this document offers a more detailed and transparent representation of the model structure, variables, and constraints. It reflects the full implementation used in the case study, including technical elements omitted or simplified in the paper.

Although MANGOpol supports a flexible multi-site structure, enabling the representation of spatially distributed energy systems and inter-site exchanges, the case study applies a simplified two-site setup. Specifically, "Site 1" contains all energy demands and most technologies, while "Site 2" is a demandless node used to represent the district heating network. This setup allows us to model heat flows between the two sites and capture investment and operational decisions related to district heating infrastructure. The formulation presented here is general and supports more complex spatial configurations for future applications.

1 Energy System Planner

In this section, the details of the Energy System Planner (ESP) module of MANGOpol are presented. The ESP is heavily based on the MANGO suit of models [1, 2, 3] with some modifications to include the policy dimension of MANGOpol. The ESP is formulated as a Mixed-Integer Linear Program (MILP), it is developed in Python using the Pyomo modelling language [4], and can be solved using MILP solvers like Gurobi [5].

1.1 Sets, parameters and variables

This section shows the different sets, parameters and variables that are used in the ESP of MANGOpol.

Table 1 presents a summary of all model sets along with their description and also defines subsets for the energy carrier set, $\mathcal{EC}$ and the technology set, $\mathcal{T}$, which are then used to index the rest of parameters and variables shown in this section.

Table 1: MANGO 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
$\mathcal{H}$	h	Time steps considered for each representative day
$\mathcal{W} \subseteq \mathcal{P}$	w	Investment stages
$\mathcal{L}$	l	Energy system locations
$\mathcal{EC}$	ec	All energy carriers in the energy system
$\mathcal{EC}_i \subseteq \mathcal{EC}$	ec_i	Energy carriers that can be imported by the energy system
$\mathcal{EC}_x \subseteq \mathcal{EC}$	ec_x	Energy carriers that can be exchanged between energy system locations
$\mathcal{EC}_d \subseteq \mathcal{EC}$	ec_d	Energy carriers for which demands are established
$\mathcal{T}$	t	Energy conversion and storage technologies
$\mathcal{T}_d \subseteq \mathcal{T}$	t_d	Subset of dispatchable energy conversion technologies
$\mathcal{T}_{ex} \subseteq \mathcal{T}_d$	t_{ex}	Subset of existing energy conversion technologies
$\mathcal{R} \subseteq \mathcal{T}$	r	Renewable energy supply technologies
$\mathcal{R}_{sol} \subseteq \mathcal{R}$	r_{sol}	Solar energy supply technologies
$\mathcal{R}_{win} \subseteq \mathcal{R}$	r_{win}	Wind energy supply technologies
$\mathcal{R}_{gr}$	r_{gr}	Group of renewable energy supply technologies
$\mathcal{R}_{grm} \subseteq \mathcal{R}_{gr}$	r_{grm}	Members of a group of renewable energy supply technologies
$\mathcal{S} \subseteq \mathcal{T}$	s	Energy storage technologies

Table 2: Temporal MANGO 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
$dem_{ec_d,l,p,d,h}$	[MW]	Energy demand for energy carrier ec_d, at location l, in period p, day d and time step h

Table 3: MANGO model parameters for conversion technologies

Parameter	*Unit*	*Description*
$tpl_{t,l}$	[0/1]	Defines if a technology t can be installed at location l
cap_t^{min}	[MW]	Minimum possible newly installed capacity for a technology c
cap_t^{max}	[MW]	maximum possible newly installed capacity for a technology c
cl_t	[years]	Lifetime of technology t in calendar years
cl_t^p	[periods]	Lifetime of technology t in model periods p
$ecc_{t_d,ec,ec'}^{disp}$	[0/1]	Input-output coupling of energy carriers ec, ec' for dispatchable technology t_d
$\eta_{d,ec,ec',w}^{disp}$	[%]	Conversion factor for dispatch technology t_d between energy carrier ec and ec'
$excap_{t_{ex},ec,l}^{tech}$	[MW]	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: MANGO model parameters for renewable conversion technologies

Parameter	*Unit*	*Description*
$rcc_{r,ec}$	[0/1]	Output energy carriers ec for renewable technology t_d
$rcap^{max}_{r,l,p}$	[MWh]	maximum allowable total capacity for the installation of each renewable technology r at each site l and period p
$rcap^{max,gr}_{r_{gr},l,p}$	[MWh]	maximum allowable total capacity for the installation of each renewable technology group r_{gr} at each site l and period p
$sol^{rad}_{l,p,d,h}$	[MWh/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
$ws_{l,p,d,h}$	$[m/s]$	Wind speed at location l, in period p, day d and time step h
$ws^{rate}_{r_w}$	$[m/s]$	Rated wind speed for a wind technology
$ws^{cutin}_{r_w}$	$[m/s]$	Cut-in wind speed for a wind technology
$ws^{cutout}_{r_w}$	$[m/s]$	Cut-out wind speed for a wind technology

Table 5: MANGOelec 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^p_s	[periods]	Lifetime of storage technology s in model periods p
$q^{ch,max}_s$	[MW]	maximum charging rate of a storage technology s
$q^{dis,max}_s$	[MW]	maximum discharging rate of a storage technology s
η^{self}_s	[%]	Self-discharge losses of a storage technology s
η^{ch}_s	[%]	Charging efficiency of a storage technology s
η^{dis}_s	[%]	Discharging efficiency of a storage technology s
cap^{min}_s	[MWh]	Minimum possible newly installed capacity for a storage technology s
cap^{max}_s	[MWh]	maximum possible newly installed capacity for a storage technology s
$cap^{max}_{s,l}$	[MWh]	maximum allowable total energy storage capacity per technology s at location l
$excap^{stor}_{s_{ex},ec,l}$	[MWh]	Installed storage capacity and energy carrier ec at a site l the beginning of the modeling period
$dexcap^{stor}_{s_{ex},ec,l,p}$	[MWh]	Existing capacity of a conversion technology s_{ex} that is at its end of life

Table 6: MANGO model parameters for energy exchange and demand reduction

Parameter	*Unit*	*Description*
$\eta^{net}_{ec_x}$	[%]	Losses per kilometer of network connection transferring energy carrier ec_x
$x_{l,l'}$	[km]	Distance between two locations
$linepl_{ec_x,l,l'}$	[0/1]	Defines if an interconnection for an energy carrier ec_x can be installed between location l and l'
$excap^{line}_{ec_x,l,l'}$	[MW]	Initial capacity for the exchange of an energy carrier ec_x between two locations l and l'
$excap^{imp}_{ex_i,l}$	[MW]	Initial capacity for the import of an energy carrier ec_i at location l
$C^{Demred}_{ec_d,p}$	[EUR]	Cost of reduction of demand of energy carrier ec_d at period p
$Demred^{max}_{ec_d,p}$	[%]	maximum percentage of reduction of demand of energy carrier ec_d at period p

Table 7: Economic MANGO model parameters

Parameter	*Unit*	*Description*
$p_{ec_i,y}$	[EUR/MWh]	Price for importing energy carrier ec_i, in year y
$fc^{tech}_{t,ec,p}$	[EUR]	Fixed cost for the installation of technology t, in period p
$lc^{tech}_{t,ec,w}$	[EUR/MW]	Linear, capacity-dependent cost for the installation of technology t, in period p
$fc^{stor}_{s,ec,w}$	[EUR]	Fixed cost for the installation of storage technology s, in period p
$lc^{stor}_{s,ec,w}$	[EUR/MWh]	Linear, capacity-dependent cost for the installation of storage technology s, in period p
$fc^{exc}_{ec_x,w}$	[EUR]	Fixed cost for the expansion of exchange capacities between two sites for an energy carrier ec_x, in period p
$lc^{exc}_{ec_x,w}$	[EUR/MWh]	Linear, capacity-dependent cost for the expansion of exchange capacities between two sites for an energy carrier ec_x, in period p
$fc^{imp}_{ec_i,w}$	[EUR]	Fixed cost for the expansion of import capacities for an energy carrier ec_i, in period p
$lc^{imp}_{ec_i,w}$	[EUR/MWh]	Linear, capacity-dependent cost for the expansion of import capacities for an energy carrier ec_i, in period p
om_t	[%]	Parameter used to calculate the annual maintenance cost for technology t as a fraction of its total investment cost
$cslvg_{t,p}$	[%]	Salvage percentage of initial investment cost for technology t that was installed in period p and has not reached the end of its lifetime at the end of the model horizon (Defined for: $\{p \geq \max_{y \in \mathcal{Y}}(y) + 1 - cl_t\}$)
$carb_{ec_i,y}$	[tCO_2/MWh]	Carbon emission factor for imported energy carrier ec_i in year y
r	[%]	Discount rate

Table 8: Policy MANGOpol model parameters

Parameter	*Unit*	*Description*
$Sub_{t,p}$	[%]	Percentage of investment cost subsidised for technology t, in period p
$Sub_{ec_x,p}$	[%]	Percentage of investment cost subsidised for the expansion of the exchange network of carrier ec_x, in period p
$Sub_{ec_i,p}$	[%]	Percentage of investment cost subsidised for the expansion of the import network of carrier ec_x, in period p
$CO2tax_p$	[EUR/tCO_2]	Carbon tax in period p
$BanInst$	[period]	Period p from which the instalment of technology t is banned
$BanOp_t$	[period]	Period p from which the operation of technology t is banned
$SubDem_{ec_d,p}$	[%]	Percentage of investment cost subsidised for reducing the demand of energy carrier ec_d, in period p
$ExpLim_{t,p}$	[%]	Expansion of technology installation limits of technology t at period p
$C^{ExpLim}_{ec,p}$	[EUR/MW]	Cost of the expansion of technology installation limits of technology t at period p

Table 9: Environmental and miscellaneous MANGO model parameters

Parameter	*Unit*	*Description*
ϵ	-	Epsilon value for the multi-objective epsilon-constrained optimization
$bigM$	-	"Big M" - Sufficiently large value

Table 10: MANGO model decision variables

Variable	*Unit*	*Description*
$PIN^{disp}_{t_d,ec,l,p,d,h}$	[MWh]	Input energy to dispatch technology $t_{d,ntr}$, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step h
$POUT^{disp}_{t_{d,ntr},ec,l,p,d,h}$	[MWh]	Output energy from dispatch technology $t_{d,ntr}$, installed at energy system location l, and operating in period p, day d, and time step h
$POUT^{re}_{ec,l,p,d,h}$	[MWh]	Output energy from non-tracked dispatch technology $t_{d,ntr}$, installed at energy system location l, and operating in period p, day d, and time step h
$P^{imp}_{ec_i,l,p,d,h}$	[MWh]	Import of energy carrier ec_i, at energy system location l, in period p, day d, and time step h
$P^{exc}_{ec_x,l,l',p,d,h}$	[MWh]	Exchanged energy of energy carrier ec_x, from location l to location l', in period p, day d, and time step h (Defined for: $\{l \neq l'\}$)
$Y^{t}_{t,l,w}$	-	Binary variable denoting the installation of new capacity of conversion technology t, at location l, in investment stage w
$NCAP^{tech}_{t,ec,l,w}$	[MW]	New capacity of conversion technology t, for energy carrier ec, installed at location l, in investment stage w
$TCAP^{tech}_{t,ec,l,p}$	[MW]	Total capacity of non-tracked conversion technology t, for energy carrier ec, in period p, at location l
$NCAP^{imp}_{ec_i,l,w}$	[MW]	New impport capacity for energy carrier ec_i to location l, in investment stage w
$Y^{imp}_{ec_i,l,w}$	-	Binary variable denoting the installation of new import capacities for energy carrier ec_i to location l, in investment stage w
$TCAP^{imp}_{ec_i,l,w}$	[MW]	Total available capacity for the import of energy carrier ec_i to location l, in investment stage w
$NCAP^{exc}_{ec_x,l,l',w}$	[MW]	New exchange capacity for energy carrier ec_e between location l and l', in investment stage w
$Y^{exc}_{ec_x,l,l',w}$	-	Binary variable denoting the connection to exchange energy carrier ec_x, between energy system locations l, l', in investment stage w (Defined for: $\{l \neq l'\}$)
$TCAP^{exc}_{ec_x,l,l',p}$	[MW]	Total available capacity for the exchange of energy carrier ec_e between location l and l', in period p
$Y^{stor}_{s,l,w}$	-	Binary variable denoting the installation of new capacity of storage technology s, at location l, in investment stage w
$NCAP^{stor}_{s,ec,l,w}$	[MW]	New capacity of storage technology s, for energy carrier ec, installed at location l, in investment stage w
$TCAP^{stor}_{s,ec,l,p}$	[MW]	Total capacity of storage technology s, for energy carrier ec, in period p, at location l
$NPOW^{stor}_{s,ec,l,w}$	[MW]	New power of storage technology s, for energy carrier ec, installed at location l, in investment stage w
$TPOW^{stor}_{s,ec,l,p}$	[MW]	Total capacity of storage technology s, for energy carrier ec, in period p, at location l
$Demred_{ec_d,p}$	[%]	Percentage of demand reduced for energy carrier ec_d, in period p, day d and time step h, after applying the demand reduction measures
$Dem^{new}_{ec_d,l,p,d,h}$	[MW]	Updated energy demand for energy carrier ec_d, at location l, in period p, day d and time step h, after applying the demand reduction measures

Table 11: MANGOelec model decision variables for storage

Variable	*Unit*	*Description*
$Q^{ch}_{s,ec,l,p,d,h}$	[MWh]	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
$Q^{dis}_{s,ec,l,p,d,h}$	[MWh]	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
$SoC_{s,ec,l,p,d,h}$	[MWh]	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
$SoC^{interday}_{s,ec,l,p,cd}$	[MWh]	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
$SoC^{min}_{s,ec,l,p,d}$	[MWh]	Minimum intra-day state of charge of storage technology s, installed at energy system location l and operating in period p and day d

Table 12: Economic MANGOpol model variables on (nominal) energy system cost and emission performance

Variable	*Unit*	*Description*
T^{sys}	[EUR]	Total lifetime energy system cost
T^{soc}	[EUR]	Total lifetime societal expenditure
T^{pol}	[EUR]	Total lifetime policy cost
T^{em}	[CO_2]	Total lifetime energy system CO_2 emissions
$T^{imp}_{l,y}$	[EUR]	Total cost due to energy carrier imports at location l, in year y
$T^{main}_{l,y}$	[EUR]	Total maintenance cost for all conversion and storage technologies installed at location l, in year y
$T^{tech,inv}_{l,w}$	[EUR]	Total investment cost for conversion technologies at location l, in investment stage w
$T^{stor,inv}_{l,w}$	[EUR]	Total investment cost for storage technologies at location l, in investment stage w
$T^{exc,inv}_{l,w}$	[EUR]	Total investment cost for network expansions between location l and l', in investment stage w
$T^{imp,inv}_{l,w}$	[EUR]	Total investment cost for import network expansions, in investment stage w
$T^{exp,inv}_{l,w}$	[EUR]	Total investment cost for export network expansions, in investment stage w
R^{slvg}_{l}	[EUR]	Salvage value of all conversion and storage technologies at location l not reaching the end of their lifetime at the end of the model horizon
T^{CO2tax}	[EUR]	Total revenue from CO2 taxes
T^{sub}	[EUR]	Cost of technology-specific subsidies in period p
T^{dem}	[EUR]	Cost of technology-specific subsidies in period p
T^{exp}	[EUR]	Cost of expansion of technology limits at location l, in period p

1.2 Equations and constraints

The following section lists all constraints present in the MANGO model used in the MANGOpol framework. They define the possible solution space of the optimization, representing various technical, economical and external relationships of an energy system.

1.2.1 Equation 1

Input-output relationship for dispatchable technologies:

$$\begin{aligned} POUT^{disp}_{t_d,ec',l,p,d,h} = PIN^{disp}_{c_d,ec,l,p,d,h} \cdot \eta^{disp}_{t_d,ec,ec'} \;, \\ \forall\ t_d \in \mathcal{T}_d,\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \\ \{tpl_{t_d,l} = 1 \;,\ ecc^{disp}_{t_d,ec,ec'} = 1\} \end{aligned} \tag{1}$$

1.2.2 Equation 2

Constraint limiting the possibility of operating a technology if it is banned:

$$\begin{aligned} \text{If } p \leq BanOp_t : POUT_{t_d,ec',l,p,d,h} = 0 \\ \forall\ t_d \in \mathcal{T}_d,\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \\ \{tpl_{t_d,l} = 1 \;,\ ecc^{disp}_{t_d,ec,ec'} = 1\} \end{aligned} \tag{2}$$

1.2.3 Equation 3

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

$$\begin{aligned} POUT^{sol}_{r_s,ec,l,p,d,t} = sol^{rad}_{l,p,d,t} \cdot \frac{TCAP^{tech}_{r_s,ec,l,p}}{\eta^{sol,ntr}_{r_s,ec}} \cdot \eta^{sol}_{r_s,ec} \;, \\ \forall\ r_s \in \mathcal{R}_s,\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{tpl_{r_s,l} = 1 \;,\ rcc_{r_s,ec} = 1\} \end{aligned} \tag{3}$$

1.2.4 Equation 4

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

$$POUT^{wind}_{r_w,ec,l,p,d,h} = \begin{cases} TCAP^{tech}_{r_w,ec,l,w,p,d,h} & , ws^{rate}_{r_w,w} \leq ws_{l,p,d,h} \leq ws^{cutout}_{r_w} \\ TCAP^{tech}_{r_w,ec,l,w,p,d,h} \cdot \frac{ws_{l,p,d,h} - ws^{cutin}_{r_w}}{ws^{rate}_{r_w} - ws^{cutin}_{r_w}} & , ws^{cutin}_{r_w,w} \leq ws_{l,p,d,h} \leq ws^{rate}_{r_w,w} \\ 0 & , ws_{l,p,d,h} < ws^{cutin}_{r_w,w} \vee ws_{l,p,d,h} > ws^{cutout}_{r_w} \end{cases} \tag{4}$$

$$\forall\ r_w \in \mathcal{R}_w,\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{tpl_{r_w,l} = 1 \;,\ rcc_{r_w,ec} = 1\}$$

1.2.5 Equation 5

Constraint setting the demand reduction measures bellow the maximum threshold:

$$Demred_{ec_d,p} \leq Demred^{max}_{ec_d,p} \forall\ ec_d \in \mathcal{EC},\ p \in \mathcal{P} \tag{5}$$

1.2.6 Equation 6

Constraint setting the updated demand after demand reduction policies

$$\begin{aligned} Dem^{new}_{ec_d,p,d,h} = Dem_{ec_d,p,d,h} \cdot (1 - Demred_{ec_d,p}) \\ \forall\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \end{aligned} \tag{6}$$

1.2.7 Equation 7

Constraint setting the share of DH demand covered by DH technologies.
Note: This constraint has been added in the MANGOpol case study to ensure that the district heating (DH) technologies (all located in Site 2) produce enough energy to satisfy the DH demand in Site 1, set at a minimum of 20% of total demand.

$$\begin{aligned} P^{exc}_{ec,l,l',p,d,h} = DH_p \cdot Dem^{new}_{ec_d,p,d,h} + P^{exc}_{ec,l',l,p,d,h} \cdot (1 - \eta^{net}_{ec} \cdot x_{l,l'}) \\ \forall\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \end{aligned} \tag{7}$$

1.2.8 Equation 8

Energy balance for each energy system including conversion, storage, losses, exchange and export flows:

$$\begin{aligned} \begin{cases} P^{imp}_{ec,l,p,d,h} & ,ec \in \mathcal{EC}_i \\ 0 & ,ec \notin \mathcal{EC}_i \end{cases} + \sum_{\substack{t_d \in \mathcal{T}_d \\ tpl_{t_d,l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{t_d,ec',ec}=1}} POUT^{disp}_{t_d,ec,l,p,d,h} \\ - \sum_{\substack{t_d \in \mathcal{T}_d \\ tpl_{t_d,l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{t_d,ec,ec'}=1}} PIN^{disp}_{t_d,ec,l,p,d,h} \\ + \sum_{\substack{r \in \mathcal{R} \\ tpl_{r,l}=1 \\ rcc_{r,ec}=1}} POUT^{re}_{r,ec,l,p,d,h} \\ + \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1 \\ stc_{s,ec}=1}} Q^{dis}_{s,ec,l,p,d,h} - Q^{ch}_{s,ec,l,p,d,h} \\ + \begin{cases} \sum\limits_{\substack{l' \in \mathcal{L} \\ l \neq l' \\ linepl_{ec,l,l'}=1}} P^{exc}_{ec,l',l,p,d,h} \cdot (1 - \eta^{net}_{ec} \cdot x_{l,l'}) - P^{exc}_{ec,l,l',p,d,h} & ,ec \in \mathcal{EC}_x \\ 0 & ,ec \notin \mathcal{EC}_x \end{cases} \\ = \begin{cases} dem^{new}_{ec_d,l,p,d,h} \\ 0 & ,ec \notin \mathcal{EC}_d \end{cases} \\ \forall\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \end{aligned} \tag{8}$$

1.2.9 Equation 9

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

$$\begin{aligned} TCAP^{conv}_{t,ec',l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + tl^p_t - 1}} NCAP^{conv}_{t,ec',l,w}\ \forall\ t \in \mathcal{T},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P} \mid \\ tpl_{t,l} = 1 \wedge ((t \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{t,ec,ec'} = 1)\ \vee rcc_{t,ec'} = 1) \end{aligned} \tag{9}$$

1.2.10 Equation 10

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

$$\begin{aligned} NCAP^{conv}_{t_d,ec'_1,l,w} \cdot \eta^{disp}_{t_d,ec,ec'_2} = NCAP^{conv}_{t_d,ec'_2,l,w} \cdot \eta^{disp}_{t_d,ec,ec'_1}, t_d \in \mathcal{T} \\ \forall\ t_d \in \mathcal{T}_d,\ ec, ec'_1, ec'_2 \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{tpl_{t_d,l} = 1\ ,\ ecc^{disp}_{t_d,ec,ec'_1} = 1,\ ecc^{disp}_{t_d,ec,ec'_2} = 1,\ ec'_1 \neq ec'_2\} \end{aligned} \tag{10}$$

1.2.11 Equation 11

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

$$\sum_{\substack{ec \in \mathcal{EC} \\ rcc_{r,ec}=1}} TCAP^{conv}_{r,ec,l,p} \leq rcap^{max}_{r,l,p} \\ \forall\ r \in \mathcal{R},\ l \in \mathcal{L},\ p \in \mathcal{P},\ \mid tpl_{r,l} = 1 \tag{11}$$

1.2.12 Equation 12

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

$$\sum_{\substack{t_{grm} \in \mathcal{T}_{grm} \cap \mathcal{T} \\ ec \in \mathcal{EC} \\ tpl_{t_{grm},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{t_{grm},ec',ec}=1}} TCAP^{conv,ntr}_{t_{grm},ec,l,p} \leq rcap^{max,gr}_{r_{gr},l,p} \\ \forall\ t_{gr} \in \mathcal{T}_{gr} \supseteq \mathcal{T}_{grm},\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{12}$$

1.2.13 Equation 13

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

$$\sum_{\substack{r_{grm} \in \mathcal{R}_{grm} \cap \mathcal{T} \\ ec \in \mathcal{EC} \\ tpl_{r_{grm},l}=1 \\ rcc_{r_{grm},ec}=1}} TCAP^{tech}_{r_{grm},ec,l,p} \leq rcap^{max,gr}_{r_{gr},l,p} \\ \forall\ r_{gr} \in \mathcal{R}_{gr} \supseteq \mathcal{R}_{grm},\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{13}$$

1.2.14 Equation 14

Constraint setting the capacity for existing conversion technologies:

$$NCAP^{tech}_{t_{ex},ec',l,1} = excap^{tech}_{t_{ex},ec',l} \qquad \forall\ t_{ex} \in \mathcal{T}_{ex},\ ec' \in \mathcal{EC},\ l \in \mathcal{L} \mid \\ \{\ tpl_{t_{ex},l} = 1 \wedge ((t_{ex} \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{t_{ex},ec,ec'} = 1)\ \vee rcc_{t_{ex},ec'} = 1)\} \tag{14}$$

1.2.15 Equation 15

Constraint preventing the re-installation of existing conversion technologies:

$$\text{If } w \neq 1 : ncap^{tech}_{t_{ex},ec,l,w} <= 0 \qquad \forall\ t_{ex} \in \mathcal{T}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W} \mid tpl_{t_{ex},l} = 1 \tag{15}$$

1.2.16 Equation 16

Constraint limiting the possibility of operating a technology if it is banned:

$$\text{If } p \leq BanInst_t : y_{t,l,p} = 0 \\ \forall\ t \in \sqcup,\ l \in \mathcal{L},\ p \in \mathcal{P}| \\ \{tpl_{t,l} = 1\} \tag{16}$$

1.2.17 Equation 17

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

$$POUT^{disp,ntr}_{t_d,ec',l,p,d,h} \leq TCAP^{conv,ntr}_{t_d,ec',l,p} \qquad \forall\ t_d \in \mathcal{T}_d,\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \\ \{\ tpl_{t_d,l} = 1\ , \exists\ ec\ \in \mathcal{EC} \mid ecc_{t_d,ec,ec'} = 1\} \tag{17}$$

1.2.18 Equation 18

Maximum possible conversion technology capacity per technology considered:

$$NCAP^{conv}_{t,ec',l,w} \leq cap^{max}_{t} \qquad \forall\, t \in \mathcal{T},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ tpl_{t,l} = 1 \wedge ((t \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{t,ec,ec'} = 1)\ \vee rcc_{t,ec'} = 1)\} \tag{18}$$

1.2.19 Equation 19

Minimum possible conversion technology capacity per technology considered:

$$NCAP^{conv}_{t,ec',l,w} \geq cap^{min}_{t} \qquad \forall\, t \in \mathcal{T},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ tpl_{t,l} = 1 \wedge ((t \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{t,ec,ec'} = 1)\ \vee rcc_{t,ec'} = 1)\} \tag{19}$$

1.2.20 Equation 20

Input-output relationship for dispatchable technologies:

$$POUT^{disp}_{t_d,ec',l,p,d,h} = PIN^{disp}_{t_d,ec,l,p,d,h} \cdot \eta^{tech}_{t_d,ec,ec'}\ , \quad \forall\ t_d \in \mathcal{T}_d,\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{tpl_{t_{d},l} = 1\ ,\ ecc^{disp}_{t_d,ec,ec'} = 1\} \tag{20}$$

1.2.21 Equation 21

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

$$NCAP^{tech}_{c,ec',l,w} \leq bigM \cdot Y^{tech}_{c,l,w} \qquad \forall\ t \in \mathcal{T},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ tpl_{t,l} = 1 \wedge ((t \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{t,ec,ec'} = 1)\ \vee rcc_{t,ec'} = 1)\} \tag{21}$$

1.2.22 Equation 22

Energy can only be exchanged between sites if their interconnection capacity allows it:

$$P^{exc}_{ec_x,l1,l2,p,d,h} \leq TCAP^{exc}_{ec_x,l1,l2,p} \qquad \forall\ ec_x \in \mathcal{EC}_x,\ l1, l2 \in \mathcal{L},\ p \in \mathcal{P}\ \ d \in \mathcal{D}\ \ h \in \mathcal{H} \mid \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{22}$$

1.2.23 Equation 23

Connections between sites have the same capacities:

$$NCAP^{exc}_{ec_x,l1,l2,w} = NCAP^{exc}_{ec_x,l2,l1,w} \qquad \forall\ ec_x \in \mathcal{EC}_x,\ l1, l2 \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{23}$$

1.2.24 Equation 24

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

$$NCAP^{exc}_{ec_x,l1,l2,w} \leq bigM \cdot Y^{exc}_{ec_x,l1,l2,w} \qquad \forall\ ec_{ex} \in \mathcal{EC}_{ex},\ l1, l2 \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{24}$$

1.2.25 Equation 25

Constraint to calculate the total available capacity for import considering initial capacity and expansion:

$$TCAP^{imp}_{ec_i,l,p} = excap^{imp}_{ec_i,l} + \sum_{\substack{w \in \mathcal{W} \\ w \leq p}} NCAP^{imp}_{ec_i,l,w} \qquad \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{25}$$

1.2.26 Equation 26

An energy carrier can only be imported if there is the capacity for import:

$$P^{imp}_{ec_i,l,p,d,t} \leq TCAP^{imp}_{ec_i,l,p} \qquad \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \tag{26}$$

1.2.27 Equation 27

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

$$NCAP^{imp}_{ec_i,l,w} \leq bigM \cdot Y^{imp}_{ec_i,l,w}\ \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{27}$$

1.2.28 Equation 28

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

$$\begin{aligned} TCAP^{stor}_{s,ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + sl^p_s - 1}} NCAP^{stor}_{s,ec,l,w} \\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{28}$$

1.2.29 Equation 29

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

$$\begin{aligned} TPOW^{stor}_{s,ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + sl^p_s - 1}} NPOW^{stor}_{s,ec,l,w} \\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{29}$$

1.2.30 Equation 30

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

$$\begin{aligned} SoC_{s,ec,l,p,d,h} = \begin{cases} \eta^{ch}_s \cdot Q^{ch}_{s,ec,l,p,d,h} - \frac{1}{\eta^{dis}_s} \cdot Q^{dis}_{s,ec,l,p,d,h} & ,t = 1 \\ \eta^{ch}_s \cdot Q^{ch}_{s,ec,l,p,d,h} - \frac{1}{\eta^{dis}_s} \cdot Q^{dis}_{s,ec,l,p,d,h} | & \\ +(1 - \eta^{self}_s) \cdot SoC_{s,ec,l,p,d,h-1} & ,t \neq 1 \end{cases} \\ \forall\ s_{\in}\mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{\ spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{30}$$

1.2.31 Equation 31

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

$$\begin{aligned} Q^{ch}_{s,ec,l,p,d,h} \leq q^{ch,max}_s \cdot TCAP^{stor}_{s,ec,l,p}\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H}| \\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{31}$$

1.2.32 Equation 32

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

$$\begin{aligned} Q^{dis}_{s,ec,l,p,d,h} \leq q^{dis,max}_s \cdot TCAP^{stor}_{s,ec,l,p}\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{32}$$

1.2.33 Equation 33

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

$$SoC^{min}_{s,ec,l,p,d} \leq SoC_{s,ec,l,p,d,h} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{33}$$

1.2.34 Equation 34

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

$$SoC^{max}_{s,ec,l,p,d} \geq SoC_{s,ec,l,p,d,h} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ h \in \mathcal{H} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{34}$$

1.2.35 Equation 35

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

$$SoC^{interday}_{s,ec,l,p,cd} = \begin{cases} 0 & ,p = 1 \wedge cd = 1 \\ SoC^{interday}_{s,ec,l,p-1,max(cd)} \cdot (1 - \eta^{self}_s)^{max(h)} & \\ \ +SoC_{s,ec,l,p-1,cd2td_{p-1,max(cd)},max(h)} & ,p \neq 1 \wedge cd = 1 \\ SoC^{interday}_{s,ec,l,p,cd-1} \cdot (1 - \eta^{self}_s)^{max(h)} & \\ \ +SoC_{s,ec,l,p,cd2td_{p,cd-1},max(h)} & ,cd \neq 1 \end{cases}$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{35}$$

1.2.36 Equation 36

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

$$SoC^{interday}_{s,ec,l,p,cd} + SoC^{max}_{s,ec,l,p,cd2td_{p,cd}} \leq TCAP^{stor}_{s,ec,l,p}$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{36}$$

1.2.37 Equation 37

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

$$SoC^{interday}_{s,ec,l,p,cd} \cdot (1 - \eta^{self}_s)^{max(h)} + SoC^{min}_{s,ec,l,p,cd2td_{p,cd}} \geq 0$$
$$\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{37}$$

1.2.38 Equation 38

Minimum possible storage technology capacity per technology considered:

$$NCAP^{stor}_{s,ec,l,w} \geq cap^{min}_s \cdot Y^{stor}_{s,l,w} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{38}$$

1.2.39 Equation 39

Maximum possible storage technology capacity per technology considered:

$$NCAP^{stor}_{s,ec,l,w} \leq cap^{max}_s\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{39}$$

1.2.40 Equation 40

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

$$\begin{aligned} &TCAP^{stor}_{s,ec,l,p} \leq cap^{max}_{s,l} \\ &\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC}\ ,\ l \in \mathcal{L}\ ,\ p \in \mathcal{P} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \end{aligned} \tag{40}$$

1.2.41 Equation 41

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

$$NCAP^{stor}_{s,ec,l,w} \leq bigM \cdot Y^{stor}_{s,l,w}\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{41}$$

1.2.42 Equation 42

Constraint setting the capacity for existing storage technologies:

$$NCAP^{stor}_{s_{ex},ec,l,1} = excap^{stor}_{s_{ex},ec,l}\ \forall\ s_{ex} \in \mathcal{S}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L} \mid \{spl_{s_{ex},l} = 1,\ stc_{s_{ex},ec} = 1\} \tag{42}$$

1.2.43 Equation 43

Constraint limiting the possibility of reinvesting in existing storage technologies:

$$\text{If } w \neq 1 : Y^{stor}_{s_{ex},l,w} = 0\ \forall\ s_{ex} \in \mathcal{S}_{ex},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W} \mid spl_{s_{ex},l} = 1 \tag{43}$$

1.2.44 Equation 44

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

$$T^{imp}_{l,y} = \sum_{ec_i \in \mathcal{EC}_i} \sum_{d \in \mathcal{D}} \sum_{h \in \mathcal{H}} P^{imp}_{ec_i,l,y2p_y,d,h} \cdot p_{ec_i,y} \cdot nd_{y2p_y,d}\ \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \tag{44}$$

1.2.45 Equation 45

Definition of the expense for importing energy from external sources (e.g. electricity grid) at each site per year:

$$T^{imp,disc}_{l,y} = T^{imp}_{l,y} \cdot \frac{1}{(1+r)^y}\ \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \tag{45}$$

1.2.46 Equation 46

Definition of the expense for importing energy from external sources (e.g. electricity grid) at each site per period:

$$T^{imp}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{imp}_{l,y}\ \forall\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{46}$$

1.2.47 Equation 47

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

$$T^{imp,disc}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{imp,disc}_{l,y}\ \forall\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{47}$$

1.2.48 Equation 48

Definition of the nominal cost per period for importing energy carriers at each site:

$$T^{imp}_{ec_i,l,y} = \sum_{d \in \mathcal{D}} \sum_{h \in \mathcal{H}} P^{imp}_{ec_i,l,y2p_y,d,h} \cdot p_{ec_i,y} \cdot nd_{y2p_y,d} \;\forall\; ec_i \in \mathcal{EC}_i,\; l \in \mathcal{L},\; y \in \mathcal{Y} \tag{48}$$

1.2.49 Equation 49

Definition of the discounted cost per period for importing energy carriers at each site:

$$T^{imp,disc}_{ec_i,l,y} = T^{imp}_{ec_i,l,y} \cdot \frac{1}{(1+r)^y} \;\forall\; ec_i \in \mathcal{EC}_i,\; \forall\; l \in \mathcal{L},\; y \in \mathcal{Y} \tag{49}$$

1.2.50 Equation 50

Definition of the nominal cost per period for importing energy carriers at each site:

$$T^{imp}_{ec_i,l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{imp}_{ec_i,l,y} \;\forall\; ec_i \in \mathcal{EC}_i,\; l \in \mathcal{L},\; p \in \mathcal{P} \tag{50}$$

1.2.51 Equation 51

Definition of the discounted cost per period for importing energy carriers at each site:

$$T^{imp,disc}_{ec_i,l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{imp,disc}_{ec_i,l,y} \;\forall\; ec_i \in \mathcal{EC}_i,\; l \in \mathcal{L},\; p \in \mathcal{P} \tag{51}$$

1.2.52 Equation 52

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

$$T^{main}_{l,y} = \sum_{\substack{t \in \mathcal{T} \\ cpl_{t,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((t \in \mathcal{T}_d \wedge \exists\; ec \in \mathcal{EC} \;|\; ecc^{disp}_{t,ec,ec'}=1) \;\vee rcc_{t,ec'}=1)}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y^{real}_w \\ y \leq y^{real}_w + cl_t - 1}} (fc^{tech}_{t,ec',w} \cdot Y^{tech}_{t,l,w} + lc^{tech}_{t,ec',w} \cdot NCAP^{tech}_{t,ec',l,w}) \cdot om^{tech}_t \;\forall\; l \in \mathcal{L},\; y \in \mathcal{Y} \tag{52}$$

1.2.53 Equation 53

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

$$T^{main,disc}_{l,y} = T^{main}_{l,y} \cdot \frac{1}{(1+r)^y} \;\forall\; l \in \mathcal{L},\; y \in \mathcal{Y} \tag{53}$$

1.2.54 Equation 54

Maintenance cost per period nmnl rule cost component of the total energy system cost for each site:

$$T^{main}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{main}_{l,y} \;\forall\; l \in \mathcal{L},\; p \in \mathcal{P} \tag{54}$$

1.2.55 Equation 55

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

$$T^{main,disc}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{main,disc}_{l,y} \;\forall\, l \in \mathcal{L},\; p \in \mathcal{P} \tag{55}$$

1.2.56 Equation 56

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

$$T^{tech,inv}_{l,w} = \sum_{\substack{t \in \mathcal{T} \\ tpl_{t,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((t \in \mathcal{T}_d \wedge \exists\ ec \in \mathcal{EC}\ | \\ ecc^{disp}_{t,ec,ec'}=1) \\ \vee rcc_{t,ec'}=1)}} fc^{tech}_{t,ec',w} \cdot Y^{tech}_{t,l,w} + lc^{tech}_{t,ec',w} \cdot (1 - Sub_{t,w}) \cdot NCAP^{conv}_{t,ec',l,w} \quad \forall\, l \in \mathcal{L},\; w \in \mathcal{W} \tag{56}$$

1.2.57 Equation 57

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

$$T^{tech,inv,disc}_{l,w} = T^{tech,inv}_{l,w} \cdot \frac{1}{(1+r)^{y^{real}_w - 1}} \;\;\forall\, l \in \mathcal{L},\; w \in \mathcal{W} \tag{57}$$

1.2.58 Equation 58

Definition of the investment expenditure for the interconnections between sites:

$$T^{exc,inv}_{l,w} = \sum_{ec_x \in \mathcal{EC}_x} \sum_{\substack{l' \in \mathcal{L} \\ l' \neq l \\ linepl_{ec_x,l,l'}=1}} (NCAP^{exc}_{ec_x,l,l',w} \cdot lc^{exc}_{ec_x,w} \cdot (1 - Sub_{ec_x,p}) + Y^{exc}_{ec_x,l,l',w} \cdot fc^{exc}_{ec_x,w}) \cdot x_{l,l'} \cdot 0.5 \;\forall\, l \in \mathcal{L},\; w \in \mathcal{W} \tag{58}$$

1.2.59 Equation 59

Definition of the investment expenditure for the interconnections between sites:

$$T^{exc,inv,disc}_{l,w} = T^{exc,inv}_{l,w} \cdot \frac{1}{(1+r)^{y^{real}_w - 1}} \;\;\forall\, l \in \mathcal{L},\; w \in \mathcal{W} \tag{59}$$

1.2.60 Equation 60

Definition of the expenditure to expand import capacities:

$$T^{imp,inv}_{l,w} = \sum_{ec_i \in \mathcal{EC}_i} NCAP^{imp}_{ec_i,l,w} \cdot lc^{imp}_{ec_i,w} \cdot (1 - Sub_{ec_i,w}) + Y^{imp}_{ec_i,l,w} \cdot fc^{imp}_{ec_i,w} \;\forall\, l \in \mathcal{L},\; w \in \mathcal{W} \tag{60}$$

1.2.61 Equation 61

Definition of the total energy system cost for each year of the modelled horizon:

$$T^{sys,disc}_{y} = \sum_{l \in \mathcal{L}} T^{disc}_{l,y} + T^{em}_{y} \cdot CO2tax_y \;\forall\, y \in \mathcal{Y} \tag{61}$$

1.2.62 Equation 62

Definition of the total energy system cost for each period of the modelled horizon:

$$T_p^{sys} = \sum_{l \in \mathcal{L}} T_{l,p} + T_p^{em} \cdot CO2tax_p \ \forall \ p \in \mathcal{P} \tag{62}$$

1.2.63 Equation 63

Definition of the total energy system cost for each period of the modelled horizon:

$$T_p^{sys,disc} = \sum_{l \in \mathcal{L}} T_p^{em} \cdot CO2tax_p \ \forall \ p \in \mathcal{P} \tag{63}$$

1.2.64 Equation 64

Definition of the total cost model objective function:

$$\begin{aligned} T^{sys} = & \\ & \sum_{l \in \mathcal{L}} \sum_{w \in \mathcal{W}} T_{l,w}^{tech,inv} + T_{l,w}^{exc,inv} + T_{l,w}^{imp,inv} + \\ & + \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} T_{l,p}^{imp} + T_{l,p}^{main} \\ & - \sum_{l \in \mathcal{L}} R_l^{slvg} \end{aligned} \tag{64}$$

1.2.65 Equation 65

Definition of the total carbon emissions per imported energy carrier, energy site and year:

$$T_{ec_i,l,y}^{em} = \sum_{d \in \mathcal{D}} \sum_{h \in \mathcal{H}} P_{ec_i,l,y2p_y,d,h}^{imp} \cdot carb_{ec_i,y} \cdot nd_{y2p_y,d} \ \forall \ ec_i \in \mathcal{EC}_i, l \in \mathcal{L}, y \in \mathcal{Y} \tag{65}$$

1.2.66 Equation 66

Definition of the total carbon emissions per imported energy carrier, energy site and period:

$$T_{ec_i,l,p}^{em} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T_{ec_i,l,y}^{em} \ \forall \ ec_i \in \mathcal{EC}_i, l \in \mathcal{L}, p \in \mathcal{P} \tag{66}$$

1.2.67 Equation 67

Definition of the total carbon emissions per imported energy carrier, energy site and period:

$$T_{l,y}^{em} = \sum_{ec_i \in \mathcal{EC}_i} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P_{ec_i,l,y2p_y,d,t}^{imp} \cdot carb_{ec_i,y} \cdot nd_{y2p_y,d} \ \forall \ l \in \mathcal{L}, y \in \mathcal{Y} \tag{67}$$

1.2.68 Equation 68

Definition of the total carbon emissions per energy site per period:

$$T_{l,p}^{em} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T_{l,y}^{em} \ \forall \ l \in \mathcal{L}, p \in \mathcal{P} \tag{68}$$

1.2.69 Equation 69

Definition of the total carbon emissions per site summed over all periods:

$$T_l^{em} = \sum_{p \in \mathcal{P}} T_{l,p}^{em} \ \forall \ l \in \mathcal{L} \tag{69}$$

1.2.70 Equation 70

Definition of the total carbon emissions per year summed over all energy sites:

$$T_y^{em} = \sum_{l \in \mathcal{L}} T_{l,y}^{em} \ \forall \ y \in \mathcal{Y} \tag{70}$$

1.2.71 Equation 71

Definition of the total carbon emissions per period summed over all energy sites:

$$T_p^{em} = \sum_{l \in \mathcal{L}} T_{l,p}^{em} \ \forall \ p \in \mathcal{P} \tag{71}$$

1.2.72 Equation 72

Definition of the total energy system carbon emissions summed across all sites and periods:

$$T^{em} = \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} T_{l,p}^{em} \tag{72}$$

1.2.73 Equation 73

Constraint used to calculate the total energy output per conversion technology, site and year:

$$POUT_{t,ec',l,y} = \begin{cases} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} POUT_{t,ec',l,y2p_y,d,h}^{disp} \cdot nd_{y2p_y,d} \ , t \in \mathcal{T}_d \\ \\ \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} POUT_{t,ec',l,y2p_y,d,h}^{re} \cdot nd_{y2p_y,d} \ , t \in \mathcal{R} \end{cases} \tag{73}$$
$$\forall \ t \in \mathcal{T}, \ ec' \in \mathcal{EC}, \ l \in \mathcal{L}, \ y \in \mathcal{Y} \mid tpl_{t,l} = 1 \land ((t \in \mathcal{T}_d \land \exists \ ec \in \mathcal{EC} \mid ecc_{t,ec,ec'}^{disp} = 1) \ \lor rcc_{t,ec'} = 1)$$

1.2.74 Equation 74

Constraint used to calculate the total energy output per conversion technology, site and period:

$$POUT_{t,ec',l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} POUT_{t,ec',l,y} \tag{74}$$
$$\forall \ t \in \mathcal{T}, \ ec' \in \mathcal{EC}, \ l \in \mathcal{L}, \ p \in \mathcal{P} \mid cpl_{t,l} = 1 \land ((t \in \mathcal{T}_d \land \exists \ ec \in \mathcal{EC} \mid ecc_{t,ec,ec'}^{disp} = 1) \ \lor rcc_{t,ec'} = 1)$$

1.2.75 Equation 75

Definition of the total carbon price revenue across all sites and periods:

$$T^{CO2tax} = \sum_{p \in \mathcal{P}} T_p^{CO_2} \cdot CO2tax_p \tag{75}$$

1.2.76 Equation 76

Definition of the total subsidy cost across all sites and periods:

$$T^{sub} = \sum_{t\in\mathcal{T}} \sum_{w\in\mathcal{W}} \left(\frac{lc^{tech}_{t,ec',w} \cdot Sub_{t,w} \cdot NCAP^{tech}_{t,ec,w,s,stg}}{(1+r)^{y^{real}_{w-1}}} \right) + \sum_{ec_i\in\mathcal{EC}} \sum_{w\in\mathcal{W}} \left(\frac{lc^{imp}_{ec_i,w} \cdot Sub_{ec_i,w} \cdot NCAP^{imp}_{ec_i,l,w}}{(1+r)^{y^{real}_{w-1}}} \right) + \sum_{ec_x\in\mathcal{EC}} \sum_{w\in\mathcal{W}} \sum_{l\in\mathcal{L}} \left(\frac{lc^{exc}_{ec_x,w} \cdot Sub_{ec_x,w} \cdot NCAP^{exc}_{ec_x,l,l',w}}{(1+r)^{y^{real}_{w-1}}} \right) \tag{76}$$

1.2.77 Equation 77

Definition of the total cost of demand reduction measures across all sites and periods:

$$T^{dem} = \sum_{ec_d\in\mathcal{EC}} \sum_{p\in\mathcal{P}} \sum_{l\in\mathcal{L}} \left(\frac{C^{Demred}_{ec_d,p} \cdot Demred_{ec_d,p} \cdot SubDem_{ec_d,p}}{(1+r)^{y^{real}_{p-1}}} \right) \tag{77}$$

1.2.78 Equation 78

Definition of the total cost of expanding technology limit across all sites and periods:

$$T^{exp} = \sum_{t\in\mathcal{T}} \sum_{p\in\mathcal{P}} \left(\frac{C^{ExpLim}_{ec,p} \cdot ExpLim_{t,p}}{(1+r)^{y^{real}_{p-1}}} \right) \tag{78}$$

1.2.79 Equation 79

Definition of the total policy cost:

$$T^{pol} = T^{sub} + T^{dem} + T^{exp} - T^{CO2tax} \tag{79}$$

1.2.80 Equation 80

Definition of the total societal expenditure:

$$T^{soc} = T^{pol} + T^{sys} \tag{80}$$

2 Policy Mix Designer

In this section, the main equations for the Policy Mix Designer (PMD) are presented. Note that to solve the multi-objective function of the PMD, the Non-dominated Sorting Genetic Algorithm II (NSGAII) is used [6], implemented through the Python library Pymoo [7].

2.1 Parameters and variables

This section shows the differents parameters and variables used in the PMD of MANGOpol. Note that the PMD used the same sets than the ESP, as presented in Table 1.

In terms of variables, the PMD has as decision variables the policy parameters that are inputs in the ESP, as seen in Table 14. Table 13 shows the parameters included in the PMD.

2.2 Equations and constraints

This section shows the different equations and constraints that govern the PMD module of the MANGOpol model.

Table 13: Policy Mix Designer parameters

Parameter	*Unit*	*Description*
$Sub^{max}_{p,t}$	[%]	Percentage of investment cost subsidised for technology t, in period p
$CO2tax^{Max}_{p}$	[EUR/tCO$_2$]	Carbon tax in period p
$SubDem^{Max}_{ec,p}$	[%]	Percentage of investment cost subsidised for reducing the demand of energy carrier ec_d, in period p
$ExpLim^{max}_{t,p}$	[%]	Expansion of technology installation limits of technology t at period p
N_{tar}	-	Number of targets that exist in an instrument type ins
N_{ins}	-	Number of instrument types present in the PMD

Table 14: Policy Mix Designer variables

Parameter	*Unit*	*Description*
$Sub_{t,p}$	[%]	Percentage of investment cost subsidised for technology t, in period p
$CO2tax_{p}$	[EUR/tCO$_2$]	Carbon tax in period p
$BanInst_t$	[period]	Period p from which the instalment of technology t is banned
$BanOp_t$	[period]	Period p from which the operation of technology t is banned
$SubDem_{ec,p}$	[%]	Percentage of investment cost subsidised for reducing the demand of energy carrier ec_d, in period p
$ExpLim_{t,p}$	[%]	Expansion of technology installation limits of technology t at period p
σ_{ph}	[%]	Policy homogeneity indicator
$\overline{\sigma}_{pc}$	[%]	Policy change indicator

2.2.1 Equation 81

Definition of the total technology-specific subsidy cost:

$$T^{sub} = \sum_{p,t} \left(Sub^{inv\_tech}_{p,t} \cdot T^{inv\_exc}_{p,t} \right) \tag{81}$$

2.2.2 Equation 82

Definition of the total CO_2 tax revenue:

$$T^{CO2tax} = \sum_{p} \left(CO2tax_p \cdot T^{Em}_{p} \right) \tag{82}$$

2.2.3 Equation 83

Definition of the total demand reduction subsidy cost:

$$T^{Dem} = \sum_{p} \left(SubDem_{ec,p} \cdot Demred_{ec,p} \right) \tag{83}$$

2.2.4 Equation 84

Definition of the total expansion of technology installation limits cost:

$$T^{exp} = \sum_{p} \left(ExpLim_{t,p} \cdot C^{ExpLim}_{t,p} \right) \tag{84}$$

2.2.5 Equation 85

Definition of the total policy cost:

$$\begin{aligned}
T^{pol} = & \underbrace{\sum_{p,t} \left(Sub_{p,t}^{Inv_Tech} \cdot T_{p,t}^{Inv_Exc} \right)}_{\text{Subsidy cost}} \\
& - \underbrace{\sum_{p} \left(CO2tax_{p} \cdot T_{p}^{Em} \right)}_{\text{Tax revenue}} \\
& + \underbrace{\sum_{p} \left(SubDem_{ec,p} \cdot Demred_{ec,p} \right)}_{\text{Dem. red. cost}} \\
& + \underbrace{\sum_{p} \left(ExpLim_{t,p} \cdot C_{t,p}^{ExpLim} \right)}_{\text{Exp. tech. limit cost}}
\end{aligned} \tag{85}$$

2.2.6 Equation 86

Definition of both objective functions of the PMD.

$$\begin{gathered} minT^{Em} \\ minT^{soc} \end{gathered} \tag{86}$$

2.2.7 Equation 87

Equations ensuring that all the policy variables output by the PMD are below their maximum values.

$$\begin{gathered} Sub_{t,p} \leq Sub_{t,p}^{\text{Max}} \quad ; \quad CO2tax_{p} \leq CO2tax_{p}^{\text{Max}} \\ SubDem_{ec,p} \leq SubDem_{ec,p}^{\text{Max}} \quad ; \quad ExpLim_{t,p} \leq ExpLim_{t,p}^{\text{Max}} \end{gathered} \tag{87}$$

2.3 Policymaker attitudes

This section presents the equations used for the three different policymaker attitudes evaluated in the first version of MANGOpol.

2.3.1 Equation 88

Definition of the objective function for the minimum government expenditure policymaker attitude.

$$\min T^{\text{pol}} = T^{\text{sub}} - T^{\text{CO2tax}} + T^{\text{dem}} + T^{\text{exp}} \tag{88}$$

2.3.2 Equations 89-92

Definition of the objective function to ensure a diverse policy mix as a policymaker attitude, included as the policy mix homogeneity indicator (σ_{ph}).

$$\overline{int}_{ins} = \frac{1}{N_{tar} \cdot N_{p}} \sum_{tar=1}^{N_{tar}} \sum_{p=1}^{N_{p}} \frac{x_{tar,p}}{x_{tar}^{Max}} \tag{89}$$

$$\overline{int} = \frac{1}{N_{ins}} \sum_{ins=1}^{N_{ins}} \overline{int}_{ins} \tag{90}$$

$$\sigma_{ph} = \sqrt{\frac{1}{N_{ins}} \sum_{ins=1}^{N_{ins}} \left(\overline{int}_{ins} - \overline{int} \right)^2} \tag{91}$$

$$\min_{x_{tar,p}} \sigma_{ph} \tag{92}$$

2.3.3 Equations 93-96

Definition of the objective function to secure a stable policy mix as a policymaker attitude, included as the policy change indicator ($\overline{\sigma}_{pc}$)

$$\sigma_{pc_{tar,ins}} = \sqrt{\frac{1}{N_p - 1} \sum_{p=1}^{N_p - 1} \left(\frac{x_{tar,p} - x_{tar,p+1}}{x_{tar}^{Max}} \right)^2} \tag{93}$$

$$\overline{\sigma}_{pc_{ins}} = \frac{1}{N_{tar}} \sum_{tar=1}^{N_{tar}} \sigma_{pc_{tar,ins}} \tag{94}$$

$$\overline{\sigma}_{pc} = \frac{1}{N_{ins}} \sum_{ins=1}^{N_{ins}} \overline{\sigma}_{pc_{ins}} \tag{95}$$

$$\min_{x_{tar,p}} \overline{\sigma}_{pc} \tag{96}$$

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