MANGO formulation

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The various temporal, spatial and technological dimensions outlined for the model in the preceding section form the sets that are used in MANGO to index the model parameters, variables, and constraints. 2 presents a summary of all model sets along with their description and also defines some useful subsets for the energy carrier set, $\mathcal{EC}$, the conversion technology set, $\mathcal{C}$ and the storage technology set, $\mathcal{S}$.

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 year
$\mathcal{CD}$	cd	Set of calendar days of a full calendar year
$\mathcal{T}$	t	Time steps considered for each 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
$\mathcal{EC}_e \subseteq \mathcal{EC}$	ec_e	Energy carriers that can be exported from 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
$\mathcal{C}$	c	Energy conversion technologies
$\mathcal{C}_{tr} \subseteq \mathcal{C}$	c_{tr}	Tracked energy conversion technologies
$\mathcal{C}_{ntr} \subseteq \mathcal{C}$	c_{ntr}	Non-tracked energy conversion technologies
$\mathcal{C}_d \subseteq \mathcal{C}$	c_d	Subset of dispatchable energy conversion technologies
$\mathcal{C}_b \subseteq \mathcal{C}_d$	c_b	Subset of baseload energy conversion technologies
$\mathcal{C}_{ccs} \subseteq \mathcal{C}_d$	c_{ccs}	Subset of dispatchable energy conversion technologies that support CCS technologies
$\mathcal{C}_{ex} \subseteq \mathcal{C}_d$	c_{ex}	Subset of existing energy conversion technologies
$\mathcal{R} \subseteq \mathcal{C}$	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
$\mathcal{R}_{ror} \subseteq \mathcal{R}$	r_{ror}	Run-of-river energy supply technologies
$\mathcal{R}_{dam} \subseteq \mathcal{R}$	r_{dam}	Hydro dam 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
$\mathcal{S}$	s	Energy storage technologies
$\mathcal{S}_{tr} \subseteq \mathcal{S}$	s_{tr}	Tracked energy storage technologies
$\mathcal{S}_{ntr} \subseteq \mathcal{S}$	s_{ntr}	Non-tracked energy storage technologies
$\mathcal{S}_{ex} \subseteq \mathcal{S}$	s_{ex}	Existing energy storage technologies

Table 2: MANGO model helper sets to improve formulation readability

Set combination	*Helper index*	*Description*
$\mathcal{C}_{d\_tr} = \mathcal{C}_d \cap \mathcal{C}_{tr}$	c_{d_tr}	Subset of tracked dispatchable energy conversion technologies
$\mathcal{C}_{d\_ntr} = \mathcal{C}_d \cap \mathcal{C}_{ntr}$	c_{d_ntr}	Subset of non-tracked dispatchable energy conversion technologies
$\mathcal{C}_{ccs\_ntr} = \mathcal{C}_{ccs} \cap \mathcal{C}_{ntr}$	c_{ccs_ntr}	Subset of non-tracked ccs energy conversion technologies
$\mathcal{C}_{d\_ex} = \mathcal{C}_d \cap \mathcal{C}_{ex}$	c_{d_ex}	Subset of existing dispatchable energy conversion technologies
$\mathcal{R}_{ex} = \mathcal{R} \cap \mathcal{C}_{ex}$	r_{ex}	Subset of existing renewable energy conversion technologies
$\mathcal{R}_{s\_tr} = \mathcal{R}_s \cap \mathcal{C}_{tr}$	r_{s_tr}	Subset of tracked and solar energy conversion technologies
$\mathcal{R}_{s\_ntr} = \mathcal{R}_s \cap \mathcal{C}_{ntr}$	r_{s_ntr}	Subset of non-tracked solar energy conversion technologies
$\mathcal{R}_{w\_tr} = \mathcal{R}_w \cap \mathcal{C}_{tr}$	r_{w_tr}	Subset of tracked wind energy conversion technologies
$\mathcal{R}_{w\_ntr} = \mathcal{R}_w \cap \mathcal{C}_{ntr}$	r_{w_ntr}	Subset of non-tracked wind energy conversion technologies
$\mathcal{R}_{r\_tr} = \mathcal{R}_{ror} \cap \mathcal{C}_{tr}$	r_{r_tr}	Subset of tracked hydro run-of-river energy conversion technologies
$\mathcal{R}_{r\_ntr} = \mathcal{R}_{ror} \cap \mathcal{C}_{ntr}$	r_{r_ntr}	Subset of non-tracked hydro run-of-river energy conversion technologies
$\mathcal{R}_{dam\_tr} = \mathcal{R}_{dam} \cap \mathcal{C}_{tr}$	r_{dam_tr}	Subset of tracked hydro dam energy conversion technologies
$\mathcal{R}_{dam\_ntr} = \mathcal{R}_{dam} \cap \mathcal{C}_{ntr}$	r_{dam_ntr}	Subset of non-tracked hydro dam energy conversion technologies
$\mathcal{R}_{dam\_ex} = \mathcal{R}_{dam} \cap \mathcal{C}_{ex}$	r_{dam_ex}	Subset of existing hydro dam energy conversion technologies

Table 3: Temporal MANGO model parameters

Parameter	*Model name*	*Unit*	*Description*
$nd_{p,d}$	`Number_of_days`	[day]	The number of days that each typical day d corresponds to
ny^p	`Years_per_period`	[year]	Number of years each period represents
$cd2td_{p,cd}$	`CD_to_TD`	[day]	Parameter to match each calendar day cd of a full year to a typical day d
$y2p_y$	`Y2P_match`	[year]	Parameter to match each each calendar year to a model period
y_p^{real}	`Real_years`	[year]	First, actual calendar year of each model period
y_w^{real}	`Real_investment_stages`	[year]	Calendar year that each model investment stage w corresponds to
$dem_{ec_d,l,p,d,t}$	`Energy_demand`	[MW]	Energy demand for energy carrier ec_d, at location l, in period p, day d and time step t

Table 4: MANGO model parameters for conversion technologies

Parameter	*Model name*	*Unit*	*Description*
$cpl_{c,l}$	`Conv_site_placement`	[0/1]	Defines if a conversion technology c can be installed at location l
cap_c^{min}	`Conv_minimum_cap_limit`	[MW]	Minimum possible newly installed capacity for a technology c
cap_c^{max}	`Conv_maximum_cap_limit`	[MW]	Maximum possible newly installed capacity for a technology c
cl_c	`Conv_lifetime`	[years]	Lifetime of conversion technology c in calendar years
cl_c^p	`Conv_lifetime_p`	[periods]	Lifetime of conversion technology c in model periods p
$cdeg^y_{c_{tr},ec}$	`Conv_degradation_coeff_per_year`		Degradation coefficient per calendar year for the conversion factor of tracked technology c_{tr} and energy carrier ec
$cdeg_{c_{tr},ec,w,p}$	`Conv_degradation_coeff`		Total degradation coefficient for the conversion factor of tracked technology c_{tr} and energy carrier ec depending on the installation stage w and the operation year y (Defined for: $\{p \geq w$ and $p \leq p + cl_c^p - 1\}$)
$ecc^{disp}_{c_d,ec,ec'}$	`Disp_tech_input_to_output_carrier_coupling`	[0/1]	Input-output coupling of energy carriers ec, ec' for dispatchable technology c_d
$\eta^{disp,tr}_{c_{d\_tr},ec,ec',w}$	`Conv_factor_tr`		Conversion factor for tracked dispatch technology c_{d_tr} between energy carrier ec and ec' installed in stage w
$\eta^{disp,ntr}_{c_{d\_ntr},ec,ec'}$	`Conv_factor_ntr`		Conversion factor for tracked dispatch technology c_{d_tr} between energy carrier ec and ec'
$excap^{conv}_{c_{ex},ec,l}$	`Conv_existing_capacity`	[MW]	Installed capacity of an existing conversion technology c and energy carrier ec at a site l in the beginning of the model horizon
$dexcap^{conv}_{c_{ex},ec,l,p}$	`Dead_cap_existing_conv_tech`	[MW]	Existing capacity of a conversion technology c_{ex} at location l that is at its end of life in period p
$\eta^{ccs}_{c_{ccs}}$	`CCS_penalty`		Efficiency decrease to account for an increase in self-consumption when using a carbon-capture technology c_{ccs}
$\eta^{leak}_{c_{ccs}}$	`CCS_leakage`		Percentage of non-captured carbon emissions for a carbon-capture technology c_{ccs}

Table 5: MANGO model parameters for renewable conversion technologies

Parameter	*Model name*	*Unit*	*Description*
$rcc_{r,ec}$	`Renewable_tech_to_carrier _coupling`	[0/1]	Output energy carriers ec for renewable technology c_d
$rcap^{max}_{r,l,p}$	`Renewable_max_total_capacity`	[MWh]	Maximum allowable total capacity for the installation of each renewable technology r at each site l and period p
$rcap^{max,gr}_{r_{gr},l,p}$	`Renewable_max_total_capacity _group`	[MWh]	Maximum allowable total capacity for the installation of each renewable technology group r_{gr} at each site l and period p
$sol^{rad}_{l,p,d,t}$	`Solar_rad`	[MWh/m^2]	Incoming solar radiation patterns at energy system location l, in period p, day d, and time step t
$\eta^{sol,tr}_{r_{s\_tr},ec,w}$	`Solar_efficiency_tr`		Efficiency of tracked solar renewable supply technology r_s per investment stage w
$\eta^{sol,ntr}_{r_{s\_ntr},ec}$	`Solar_efficiency_ntr`		Efficiency of non-tracked solar renewable supply technology r_s
$ws_{l,p,d,t}$	`Wind_speed`	$[m/s]$	Wind speed at location l, in period p, day d and time step t
$ws^{rate,tr}_{r_{w\_tr},w}$	`Wind_rated_speed_tr`	$[m/s]$	Rated wind speed for a tracked wind technology installed in stage w
$ws^{cutin,tr}_{r_{w\_tr},w}$	`Wind_cut_in_speed_tr`	$[m/s]$	Cut-in wind speed for a tracked wind technology installed in stage w
$ws^{cutout,tr}_{r_{w\_tr},w}$	`Wind_cut_out_speed_tr`	$[m/s]$	Cut-out wind speed for a tracked wind technology installed in stage w
$ws^{rate,ntr}_{r_{w\_ntr}}$	`Wind_rated_speed_ntr`	$[m/s]$	Rated wind speed for a non-tracked wind technology
$ws^{cutin,ntr}_{r_{w\_ntr}}$	`Wind_cut_in_speed_ntr`	$[m/s]$	Cut-in wind speed for a non-tracked wind technology
$ws^{cutout,ntr}_{r_{w\_ntr}}$	`Wind_cut_out_speed_ntr`	$[m/s]$	Cut-out wind speed for a non-tracked wind technology
$capf_{l,p,d,t}$	`Other_renew_cap_factor`		Capacity factor for other renewable power plants in location l, period p, day d, and time step t
$capf^{dam}_{l,p,d,t}$	`Hydro_dam_cap_factor`		Capacity factor for hydro dam plants
$\eta^{dam,tr}_{r_{dam\_tr},ec,w}$	`Hydro_dam_conv_efficiency_tr`		Efficiency of a tracked hydro dam technology installed in investment stage w
$\eta^{dam,ntr}_{r_{dam\_ntr},ec}$	`Hydro_dam_conv_efficiency_ntr`		Efficiency of a non-tracked hydro dam technology
$\eta^{self,dam,tr}_{r_{d\_tr},w}$	`Hydro_dam_stor_standing _losses_tr`		Self-discharging / standing losses of a tracked hydro dam technology
$\eta^{self,dam,ntr}_{r_{d\_ntr}}$	`Hydro_dam_stor_standing _losses_ntr`		Self-discharging / standing losses of a non-tracked hydro dam technology
$cap^{stor,conv,max}_{r_d}$	`Hydro_dam_stor_cap_per _conv_cap_max`	[MWh]	Maximum storage capacity per unit of generation capacity for a hydro dam technology
$excap^{dam}_{r_{dam\_ex},ec,l}$	`Hydro_dam_existing_stor _capacity`	[MWh]	Installed storage capacity of an existing hydro-dam technology and energy carrier ec at a site l the beginning of the modeling period
$dexcap^{dam}_{r_{dam\_ex},ec,l,p}$	`Dead_cap_existing_dam_tech`	[MWh]	Existing capacity of a storage technology $c_{ex} \cap r_d$ that is at its end of life

Table 6: MANGOelec model parameters for storage technologies

Parameter	*Model name*	*Unit*	*Description*
$stc_{s,ec}$	`Stor_tech_to_carrier _capacity_coupling`	[0/1]	Storage technology coupling parameter describing the energy carrier ec stored in storage technology s
$spl_{s,l}$	`Stor_site_placement`	[0/1]	Defines if a storage technology s can be installed at location l
sl_s	`Stor_lifetime`	[years]	Lifetime of storage technology s in calendar years
sl_s^p	`Stor_lifetime_p`	[periods]	Lifetime of storage technology s in model periods p
$\eta_{s_{tr},w}^{ch,tr}$	`Stor_charging_eff_tr`		Charging efficiency of a tracked storage technology s installed in stage w
$\eta_{s_{tr},w}^{dis,tr}$	`Stor_discharging_eff_tr`		Discharging efficiency of a tracked storage technology s installed in stage w
$\eta_{s_{tr},w}^{self,tr}$	`Stor_standing_losses_tr`		Self-discharge losses of a tracked storage technology s_{tr} installed in stage w
$q_{s_{tr},w}^{ch,max,tr}$	`Stor_max_charge_tr`		Maximum charging rate of a tracked storage technology s_{tr} installed in stage w
$q_{s_{tr},w}^{dis,max,tr}$	`Stor_max_discharge_tr`		Maximum discharging rate of a tracked storage technology s_{tr} installed in stage w
$q_{s_{ntr}}^{ch,max,ntr}$	`Stor_max_charge_ntr`		Maximum charging rate of a non-tracked storage technology s_{ntr}
$q_{s_{ntr}}^{dis,max,ntr}$	`Stor_max_discharge_ntr`		Maximum discharging rate of a non-tracked storage technology s_{ntr}
$\eta_{s_{ntr}}^{self,ntr}$	`Stor_standing_losses_ntr`		Self-discharge losses of a non-tracked storage technology s_{tr}
$\eta_{s_{ntr}}^{ch,ntr}$	`Stor_charging_eff_ntr`		Charging efficiency of a non-tracked storage technology s
$\eta_{s_{ntr}}^{dis,ntr}$	`Stor_discharging_eff_ntr`		Discharging efficiency of a non- tracked storage technology s
cap_s^{min}	`Stor_minimum_cap_limit`	[MWh]	Minimum possible newly installed capacity for a storage technology s
cap_s^{max}	`Stor_maximum_cap_limit`	[MWh]	Maximum possible newly installed capacity for a storage technology s
$cap_{s,l}^{max}$	`Stor_max_total_capacity`	[MWh]	Maximum allowable total energy storage capacity per technology s at location l
$excap_{s_{ex},ec,l}^{stor}$	`Stor_existing_capacity`	[MWh]	Installed storage capacity and energy carrier ec at a site l the beginning of the modeling period
$sdeg_{s_{tr},w,p}$	`Stor_degradation_coeff`		Total degradation coefficient for the the charging and discharging efficiencies of storage technology s depending on the installation stage w and the period p (Defined for: $\{p \geq w$ and $p \leq w + sl_s^p - 1\}$)
$sydeg_{s_{tr}}$	`Stor_degradation_coeff _capacity_per_year`		Yearly degradation coefficient for the conversion factor of tracked technology s_{tr}
$SoC_{r_{dam\_ex}}^{init}$	`Existing_hydro_dam_start_SoC`	[%]	Initial state-of-charge for existing hydro dam technologies - given in percentage terms of the total storage capacity
$dexcap_{s_{ex},ec,l,p}^{stor}$	`Dead_cap_existing_stor_tech`	[MWh]	Existing capacity of a conversion technology s_{ex} that is at its end of life

Table 7: MANGO model parameters for energy exchange, demand-side management and grid reserves

Parameter	*Model name*	*Unit*	*Description*
$\eta^{net}_{ec_x}$	`Exchange_network_losses`		Losses per kilometer of network connection transferring energy carrier ec_x
$x_{l,l'}$	`Distance_between_sites`	[km]	Distance between two locations
$linepl_{ec_x,l,l'}$	`Allowable_interconnections`	[0/1]	Defines if an interconnection for an energy carrier ec_x can be installed between location l and l'
$excap^{line}_{ec_x,l,l'}$	`Exchange_cap_init`	[MW]	Initial capacity for the exchange of an energy carrier ec_x between two locations l and l'
$excap^{imp}_{ex_i,l}$	`Import_cap_init`	[MW]	Initial capacity for the import of an energy carrier ec_i at location l
$excap^{exp}_{ex_e,l}$	`Export_cap_init`	[MW]	Initial capacity for the export of an energy carrier ec_e at location l
$dsm^{max}_{ec_d,p}$	`DSM_limit`	[MWh]	Maximum allowed volume of one demanded energy carrier ec_D that can be shifted in a period p
$dsm^{freq}_{ec_d}$	`DSM_freq`	[h]	Window of hours within a typical day for which demand-site management operations must be balanced
$rm_{ec_d,p}$	`Reserve_margin`		Reserve margin to offer backup power reserves in case of tertiary grid failures
$a^{disp}_{c_d,ec,p}$	`Availability_disp_tech`		Availability factor to the reserve margin of a dispatchable conversion technology c_d for energy carrier ec in period p
$a^{re}_{r,p}$	`Availability_stor_tech`		Availability factor to the reserve margin of a renewable technology c_d in period p
$a^{stor}_{s,ec,p}$	`Availability_renewable_tech`		Availability factor to the reserve margin of a storage technology c_d for energy carrier ec in period p
$a^{imp}_{ec,p}$	`Availability_import`		Availability factor to the reserve margin of import of energy carrier ec in period p

Table 8: Economic MANGO model parameters

Parameter	*Model name*	*Unit*	*Description*
$p_{ec_i,y}$	`Import_prices`	[EUR/MWh]	Price for importing energy carrier ec_i, in year y
$p_{ec_e,y}$	`Export_prices`	[EUR/MWh]	Compensation for exporting energy carrier ec_e, in year y
$fc^{conv}_{c,ec,w}$	`Conv_fixed_cost`	[EUR]	Fixed cost for the installation of conversion technology c, in investment stage w
$lc^{conv}_{c,ec,w}$	`Conv_linear_cost`	[EUR/kW]	Linear, capacity-dependent cost for the installation of conversion technology c, in investment stage w
$fc^{ccs}_{c_{ccs},ec,w}$	`Fixed_ccs_costs`	[EUR]	Fixed cost for the installation of a CCS technology c_{ccs}, in investment stage w
$lc^{ccs}_{c_{ccs},ec,w}$	`Linear_ccs_costs`	[EUR/kW]	Linear, capacity-dependent cost for the installation of a CCS technology c_{ccs}, in investment stage w
$fc^{dam}_{r_{dam},ec,w}$	`Hydro_dam_stor_fixed_cost`	[EUR]	Fixed cost for the installation of the storage capacity of a hydro dam technology r_{dam}, in investment stage w
$lc^{dam}_{r_{dam},ec,w}$	`Hydro_dam_stor_linear_cost`	[EUR/MWh]	Linear, capacity-dependent cost for the storage capacity of a hydro dam technology r_{dam}, in investment stage w
$fc^{stor}_{s,ec,w}$	`Stor_fixed_cost`	[EUR]	Fixed cost for the installation of storage technology s, in investment stage w
$lc^{stor}_{s,ec,w}$	`Stor_linear_cost`	[EUR/MWh]	Linear, capacity-dependent cost for the installation of storage technology s, in investment stage w
$fc^{exc}_{ec_x,w}$	`Exchange_cap_expansion _capacity_fixed_cost`	[EUR]	Fixed cost for the expansion of exchange capacities between two sites for an energy carrier ec_x, in investment stage w
$lc^{exc}_{ec_x,w}$	`Exchange_cap_expansion _capacity_linear_cost`	[EUR/MWh]	Linear, capacity-dependent cost for the expansion of exchange capacities between two sites for an energy carrier ec_x, in investment stage w
$fc^{imp}_{ec_i,w}$	`Import_cap_expansion _capacity_fixed_cost`	[EUR]	Fixed cost for the expansion of import capacities for an energy carrier ec_i, in investment stage w
$lc^{imp}_{ec_i,w}$	`Import_cap_expansion _capacity_linear_cost`	[EUR/MWh]	Linear, capacity-dependent cost for the expansion of import capacities for an energy carrier ec_i, in investment stage w
$fc^{exp}_{ec_e,w}$	`Export_cap_expansion _capacity_fixed_cost`	[EUR]	Fixed cost for the expansion of export capacities for an energy carrier ec_i, in investment stage w
$lc^{exp}_{ec_e,w}$	`Export_cap_expansion _capacity_linear_cost`	[EUR/MWh]	Linear, capacity-dependent cost for the expansion of export capacities for an energy carrier ec_i, in investment stage w
om^{conv}_c	`Conv_maintenance_cost_rate`		Parameter used to calculate the annual maintenance cost for conversion technology c as a fraction of its total investment cost
om^{stor}_s	`Stor_maintenance_cost_rate`		Parameter used to calculate the annual maintenance cost for storage technology s as a fraction of its total investment cost
$cslvg_{c,w}$	`Conv_early_retirement_salvage`		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: $\{w \geq \max_{y\in\mathcal{Y}}(y) + 1 - cl_c\}$)
$sslvg_{s,w}$	`Stor_early_retirement_salvage`		Salvage percentage of initial investment cost for storage technology s that was installed in stage w and has not reached the end of its lifetime at the end of the model horizon (Defined for: $\{w \geq \max_{y\in\mathcal{Y}}(y) + 1 - sl_s\}$)

Table 9: Economic MANGO model parameters 2.0

Parameter	*Model name*	*Unit*	*Description*
$dsmc^{pos}_{ec_d,y}$	`DSM_cost_pos`	[EUR/MWh]	Cost for increase in demand as part of demand-site management operations
$dsmc^{neg}_{ec_d,y}$	`DSM_cost_neg`	[EUR/MWh]	Cost for decrease in demand as part of demand-site management operations
$carb_{ec_i,y}$	`Import_carbon_factor`	[tCO_2/MWh]	Carbon emission factor for imported energy carrier ec_i in year y
$ctax_y$	`Carbon_tax`	[$kgCO_2$/EUR]	Carbon taxes per $kgCO_2$/EUR in year y
r	`Discount_rate`		Discount rate

Table 10: 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 11: MANGO model decision variables

Variable	*Model name*	*Unit*	*Description*
$PIN^{disp,tr}_{c_{d,tr},ec,l,w,p,d,t}$	`P_disp_inp_tr`	[MWh]	Input energy to tracked dispatch technology $c_{d,tr}$, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t (Defined for: $\{p \geq w$ and $y \leq p + cl^p_c - 1\}$)
$PIN^{disp,ntr}_{c_{d,ntr},ec,l,p,d,t}$	`P_disp_inp_ntr`	[MWh]	Input energy to non-tracked dispatch technology $c_{d,ntr}$, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$POUT^{disp,tr}_{c_{d,tr},ec,l,w,p,d,t}$	`P_disp_out_tr`	[MWh]	Output energy from tracked dispatch technology $c_{d,tr}$, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t (Defined for: $\{p \geq w$ and $y \leq p + cl^p_c - 1\}$)
$POUT^{disp,ntr}_{c_{d,ntr},ec,l,p,d,t}$	`P_disp_out_ntr`	[MWh]	Output energy from non-tracked dispatch technology $c_{d,ntr}$, installed at energy system location l, and operating in period p, day d, and time step t
$PIN^{ccs,ntr}_{c_{ccs,ntr},ec,l,p,d,t}$	`P_disp_ccs_inp_ntr`	[MWh]	Input energy to non-tracked CCS technology $c_{ccs,ntr}$, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$POUT^{ccs,ntr}_{c_{ccs,ntr},ec,l,p,d,t}$	`P_disp_ccs_out_ntr`	[MWh]	Output energy from non-tracked CCS technology $c_{ccs,ntr}$, installed at energy system location l, and operating in period p, day d, and time step t
$POUT^{base,tr}_{c_{b\_tr},ec,l,w,p}$	`Baseload_conv_tr`	[MWh]	Level of baseload operation for tracked baseload technology $c_b \cap c_{tr}$, installed at energy system location l, in investment stage w, and operating in period p (Defined for: $\{p \geq w$ and $y \leq p + cl^p_c - 1\}$)
$POUT^{base,ntr}_{c_{b\_ntr},ec,l,p}$	`Baseload_conv_ntr`	[MWh]	Level of baseload operation for non-tracked baseload technology $c_b \cap c_{ntr}$, installed at energy system location l, and operating in period p
$POUT^{re,tr}_{r_{tr},ec,l,w,p,d,t}$	`P_res_out_tr`	[MWh]	Output energy from tracked dispatch technology $c_{d,tr}$, for energy carrier ec, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t (Defined for: $\{p \geq w$ and $y \leq p + cl^p_c - 1\}$)
$POUT^{re,ntr}_{r_{ntr},ec,l,p,d,t}$	`P_res_out_ntr`	[MWh]	Output energy from non-tracked dispatch technology $c_{d,ntr}$, installed at energy system location l, and operating in period p, day d, and time step t
$P^{imp}_{ec_i,l,p,d,t}$	`P_import`	[MWh]	Import of energy carrier ec_i, at energy system location l, in period p, day d, and time step t
$P^{exp}_{ec_e,l,p,d,t}$	`P_export`	[MWh]	Exported energy of energy carrier ec_e, at energy system location l, in period p, day d, and time step t
$P^{exc}_{ec_x,l,l',p,d,t}$	`P_exchange`	[MWh]	Exchanged energy of energy carrier ec_x, from location l to location l', in period p, day d, and time step t (Defined for: $\{l \neq l'\}$)
$P^{curt}_{r,ec,l,p,d,t}$	`Curtailment`	[MWh]	Curtailed energy from renewable technology r and energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step t
$DSM^{pos}_{ec_d,l,p,d,t}$	`DSM_pos`	[MWh]	Increase in demand for energy carrier ec through demand-side management, at energy system location l, in period p, day d, and time step t
$DSM^{neg}_{ec_d,l,p,d,t}$	`DSM_neg`	[MWh]	Decrease in demand for energy carrier ec through demand-side management, at energy system location l, in period p, day d, and time step t

Table 12: MANGOelec model decision variables for storage

Variable	*Model name*	*Unit*	*Description*
$Q^{ch,tr}_{s_{tr},ec,l,w,p,d,t}$	`Qch_tr`	[MWh]	Charging energy for tracked storage technology s_{tr}, for energy carrier ec, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$Q^{dis,tr}_{s_{tr},ec,l,w,p,d,t}$	`Qdis_tr`	[MWh]	Discharging energy for tracked storage technology s_{tr}, for energy carrier ec, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$Q^{ch,ntr}_{s_{ntr},ec,l,p,d,t}$	`Qch_ntr`	[MWh]	Charging energy for non-tracked storage technology s_{ntr}, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step t
$Q^{dis,ntr}_{s_{ntr},ec,l,p,d,t}$	`Qdis_ntr`	[MWh]	Discharging energy for non-tracked storage technology s_{ntr}, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step t
$SoC^{tr}_{s_{tr},ec,l,w,p,d,t}$	`SoC_tr`	[MWh]	Intra-day state of charge of tracked storage technology s_{tr}, for energy carrier ec, installed at energy system location l, in investment stage w, and operating in period p, day d, and time step t
$SoC^{ntr}_{s_{ntr},ec,l,p,d,t}$	`SoC_ntr`	[MWh]	Intra-day state of charge of non-tracked storage technology s_{ntr}, for energy carrier ec, installed at energy system location l, and operating in period p, day d, and time step t
$SoC^{interday,tr}_{s_{tr},ec,l,w,p,cd}$	`SoC_inter_day_tr`	[MWh]	Inter-day state of charge of tracked storage technology s_{tr}, for energy carrier ec, installed at energy system location l, in investment stage w, and operating in period p, calendar day cd
$SoC^{interday,ntr}_{s_{ntr},ec,l,p,cd}$	`SoC_inter_day_ntr`	[MWh]	Inter-day state of charge of non-tracked storage technology s_{ntr}, for energy carrier ec, installed at energy system location l, and operating in period p, calendar day cd
$SoC^{min,tr}_{s_{tr},ec,l,w,p,d}$	`SoC_intra_day_min_tr`	[MWh]	Minimum intra-day state of charge of tracked storage technology s_{tr}, installed at energy system location l, in investment stage w, and operating in period p and day d
$SoC^{min,ntr}_{s_{ntr},ec,l,p,d}$	`SoC_intra_day_min_ntr`	[MWh]	Minimum intra-day state of charge of tracked storage technology s_{ntr}, installed at energy system location l and operating in period p and day d
$SoC^{max,tr}_{s_{tr},ec,l,w,p,d}$	`SoC_intra_day_max_tr`	[MWh]	Maximum Intra-day dam storage level per day for tracked storage technology s_{tr}, installed at energy system location l, in investment stage w, and operating in period p and day d
$SoC^{max,ntr}_{s_{ntr},ec,l,p,d}$	`SoC_intra_day_max_ntr`	[MWh]	Maximum Intra-day dam storage level per day for non-tracked storage technology s_{tr}, installed at energy system location l and operating in period p and day d
$SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,d,t}$	`Hydro_dam_stor_level_tr`	[MWh]	Intra-day dam storage level for tracked hydro dam technology r_{d_tr}, installed at energy system location l, in investment stage w, and operating in year y, day d, and time step t
$SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,d,t}$	`Hydro_dam_stor_level_ntr`	[MWh]	Intra-day dam storage level for non-tracked hydro dam technology r_{d_ntr}, installed at energy system location l and operating in year p, day d, and time step t
$SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd}$	`Hydro_dam_stor_level` `_inter_day_tr`	[MWh]	Inter-day dam storage level for tracked hydro dam technology r_{dam_tr}, installed at energy system location l, in investment stage w, and operating in year y and calendar day cd
$SoC^{interday,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd}$	`Hydro_dam_stor_level` `_inter_day_ntr`	[MWh]	Inter-day dam storage level for non-tracked hydro dam technology r_{d_ntr}, installed at energy system location l and operating in year p and calendar day cd
$SoC^{day,min,dam,tr}_{r_{dam\_tr},ec,l,w,p,d}$	`Hydro_dam_stor_level` `_intra_day_min_tr`	[MWh]	Minimum intra-day dam storage level per day for tracked hydro dam technology r_{d_tr}, installed at energy system location l, in investment stage w, and operating in period p and day d
$SoC^{day,min,dam,ntr}_{r_{dam\_ntr},ec,l,p,d}$	`Hydro_dam_stor_level` `_intra_day_min_ntr`	[MWh]	Minimum intra-day dam storage level per day for non-tracked hydro dam technology r_{dam_ntr}, installed at energy system location l and operating in period p and day d
$SoC^{day,max,dam,tr}_{r_{dam\_tr},ec,l,w,p,d}$	`Hydro_dam_stor_level` `_intra_day_max_tr`	[MWh]	Maximum intra-day dam storage level per day for tracked hydro dam technology r_{dam_tr}, installed at energy system location l, in investment stage w, and operating in period p and day d
$SoC^{day,max,dam,ntr}_{r_{dam\_ntr},ec,l,p,d}$	`Hydro_dam_stor_level` `_intra_day_max_ntr`	[MWh]	Maximum intra-day dam storage level per day for non-tracked hydro dam technology r_{dam_ntr}, installed at energy system location l and operating in period p and day d

Table 13: MANGO model decision variables

Variable	*Model name*	*Unit*	*Description*
$Y^{conv}_{c,l,w}$	`y_conv`		Binary variable denoting the installation of new capacity of conversion technology c, at location l, in investment stage w
$NCAP^{conv}_{c,ec,l,w}$	`ncap_conv`	[MW]	New capacity of conversion technology c, for energy carrier ec, installed at location l, in investment stage w
$TCAP^{conv,tr}_{c_{tr},ec,l,w,p}$	`tcap_conv_tr`	[MW]	Total capacity of tracked conversion technology c_{tr}, for energy carrier ec, in period p, at location l, installed in previous investment stage w
$TCAP^{conv,ntr}_{c_{ntr},ec,l,p}$	`tcap_conv_ntr`	[MW]	Total capacity of non-tracked conversion technology c_{ntr}, for energy carrier ec, in period p, at location l
$NCAP^{imp}_{ec_i,l,w}$	`ncap_imp`	[MW]	New impport capacity for energy carrier ec_i to location l, in investment stage w
$Y^{imp}_{ec_i,l,w}$	`y_imp`		Binary variable denoting the installation of new import capacities for energy carrier ec_i to location l, in investment stage w
$TCAP^{imp}_{ec_i,l,w}$	`tcap_imp`	[MW]	Total available capacity for the import of energy carrier ec_i to location l, in investment stage w
$NCAP^{exp}_{ec_e,l,p}$	`ncap_exp`	[MW]	New export capacity for energy carrier ec_e from location l, in investment stage w
$Y^{exp}_{ec_e,l,w}$	`y_exp`		Binary variable denoting the installation of new export capacities for energy carrier ec_e from location l, in investment stage w
$TCAP^{exp}_{ec_e,l,p}$	`tcap_exp`	[MW]	Total available capacity for the export of energy carrier ec_e from location l, in investment stage w
$NCAP^{exc}_{ec_x,l,l',w}$	`ncap_exc`	[MW]	New exchange capacity for energy carrier ec_e between location l and l', in investment stage w
$Y^{exc}_{ec_x,l,l',w}$	`y_exc`		Binary variable denoting the connection to exchange energy carrier ec_x, between energy system locations l, l', in investment stage w (Defined for: $\{l \neq l'\}$)
$TCAP^{exc}_{ec_x,l,l',p}$	`tcap_exc`	[MW]	Total available capacity for the exchange of energy carrier ec_e between location l and l', in period p
$NCAP^{dam,stor}_{r_d,ec,l,w}$	`ncap_hydro_dam_stor`	[MWh]	New capacity of storage level for hydro dam technology r_d and energy carrier ec, installed at location l, in investment stage w
$TCAP^{dam,tr}_{r_{d\_tr},ec,l,w,p}$	`tcap_hydro_dam_stor_tr`	[MW]	Total capacity of tracked storage level for hydro dam technology r_{dam_tr}, for energy carrier ec, in period p, at location l, installed in previous investment stage w
$TCAP^{dam,ntr}_{r_{dam\_ntr},ec,l,p}$	`tcap_hydro_dam_stor_ntr`	[MW]	Total capacity of non-tracked storage level for hydro dam technology r_{dam_tr}, for energy carrier ec, in period p, at location l
$Y^{ccs}_{c_{ccs},l,w}$	`y_ccs`		Binary variable denoting the installation of new capacity of CCS technology c_{ccs}, at location l, in investment stage w
$NCAP^{ccs}_{c_{ccs},ec,l,w}$	`ncap_ccs`	[MW]	New capacity of CCS technology c_{ccs}, for energy carrier ec, installed at location l, in investment stage w
$TCAP^{ccs,ntr}_{c_{ccs,ntr},ec,l,p}$	`tcap_ccs_ntr`	[MW]	Total capacity of non-tracked CCS technology $c_{ccs,ntr}$, for energy carrier ec, in period p, at location l
$Y^{stor}_{s,l,w}$	`y_stor`		Binary variable denoting the installation of new capacity of storage technology s, at location l, in investment stage w
$NCAP^{stor}_{s,ec,l,w}$	`ncap_stor`	[MW]	New capacity of storage technology s, for energy carrier ec, installed at location l, in investment stage w
$TCAP^{stor,tr}_{s_{tr},ec,l,w,p}$	`tcap_stor_tr`	[MW]	Total capacity of tracked storage technology s_{tr}, for energy carrier ec, in period p, at location l, installed in previous investment stage w
$TCAP^{stor,ntr}_{s_{ntr},ec,l,p}$	`tcap_stor_ntr`	[MW]	Total capacity of non-tracked storage technology s_{ntr}, for energy carrier ec, in period p, at location l
$NPOW^{stor}$	`npow_stor`	[MW]	New power of storage technology s, for energy car-

Table 14: Economic MANGO model variables on (nominal) energy system cost and emission performance

Variable	*Model name*	*Unit*	*Description*
T^{cost}	`Total_system_cost`	[EUR]	Total lifetime energy system cost
T^{CO_2}	`Total_system_carbon`	[tCO_2]	Total lifetime energy system CO_2 emissions
$C^{imp}_{l,y}$	`Import_cost_per_year_nmnl`	[EUR]	Total cost due to energy carrier imports at location l, in year y
$R^{exp}_{l,y}$	`Export_profit_per_year_nmnl`	[EUR]	Total revenue due to energy carrier exports at location l, in year y
$C^{main}_{l,y}$	`Maintenance_cost_per_year_nmnl`	[EUR]	Total maintenance cost for all conversion and storage technologies installed at location l, in year y
$C^{conv,inv}_{l,w}$	`Conv_investment_cost_nmnl`	[EUR]	Total investment cost for conversion technologies at location l, in investment stage w
$C^{ccs,inv}_{l,w}$	`CCS_investment_cost_nmnl`	[EUR]	Total investment cost for carbon capture and storage technologies at location l, in investment stage w
$C^{stor,inv}_{l,w}$	`Stor_investment_cost_nmnl`	[EUR]	Total investment cost for storage technologies at location l, in investment stage w
$C^{exc,inv}_{l,w}$	`Exchange_network_expansion _cost_nmnl`	[EUR]	Total investment cost for network expansions between location l and l', in investment stage w
$C^{imp,inv}_{l,w}$	`Import_capacity_expansion _cost_nmnl`	[EUR]	Total investment cost for import network expansions, in investment stage w
$C^{exp,inv}_{l,w}$	`Export_capacity_expansion _cost_nmnl`	[EUR]	Total investment cost for export network expansions, in investment stage w
R^{slvg}_{l}	`Salvage_at_end_of_horizon_nmnl`	[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
$C^{dsm}_{l,y}$	`DSM_cost_per_year_nmnl`	[EUR]	Cost for demand-side management operations, in year y
$CO2^{ccs}_{l,y}$	`Total_site_carbon_capture _per_year`	[EUR]	Emissions captured through all CCS technologies, at location l, in year y
$C^{CO2}_{l,y}$	`Carbon_tax_cost_per _year_nmnl`	[EUR]	CO2 taxes at location l, in year y
$C^{Curt}_{l,y}$	`Curtailment_cost_per _year_nmnl`	[EUR]	Cost for curtailing generated energy at location l, in year y

1 Objective function

2 Constraints on Input-output relationships for dispatchable tech

The following section lists all constraints present in the MANGO base model. They define the possible solution space of the optimization, representing various technical, economical and external relationships of an energy system. The constraints are split into a variety of subcategories which help the readability of the model.

2.1 Equation 1

Equation 1 defines the input-to-output relation for tracked, dispatchable technologies, while Equation 2 defines the same relationship for non-tracked, dispatchable technologies. The equations define the power output as the energy input times the conversion factor and the conversion degradation factor.
`Dispatchable_conv_tech_input_output_tr_rule`

$$\begin{aligned} POUT^{disp,tr}_{c_{d\_tr},ec',l,w,p,d,t} = PIN^{disp,tr}_{c_{d\_tr},ec,l,w,p,d,t} \cdot \eta^{conv,tr}_{c_{d\_tr},ec,ec',w} \cdot cdeg_{c_{d\_tr},ec',w,p} \ , \\ \forall\ c_{d\_tr} \in \mathcal{C}_{d\_tr},\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \\ \{p \geq w\ ,\ p \leq w + cl^{p}_{c_{d\_tr}} - 1\ ,\ cpl_{c_{d\_tr},l} = 1\ ,\ ecc^{disp}_{c_{d\_tr},ec,ec'} = 1\} \end{aligned} \tag{1}$$

2.2 Equation 2

Input-output relationship for non-tracked, dispatchable technologies:
`Dispatchable_conv_tech_input_output_ntr_rule`

$$\begin{aligned} POUT^{disp,ntr}_{c_{d\_ntr},ec',l,p,d,t} = PIN^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \cdot \eta^{disp,ntr}_{c_{d\_ntr},ec,ec'} \ , \\ \forall\ c_{d\_ntr} \in \mathcal{C}_{d\_ntr},\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \\ \{cpl_{c_{d\_ntr},l} = 1\ ,\ ecc^{disp}_{c_{d\_ntr},ec,ec'} = 1\} \end{aligned} \tag{2}$$

2.3 Equation 3

Input-output relationship for non-tracked, dispatchable CCS technologies:
`Dispatchable_CCS_conv_tech_input_output_ntr_rule`

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

3 Constraints on Input-output relationships for renewable tech

3.1 Equation 5

Constraint for the calculation of the energy output by tracked solar technologies: `Solar_output_tr_rule`

$$\begin{aligned} POUT^{re,tr}_{r_{s\_tr},ec,l,w,p,d,t} = sol^{rad}_{l,p,d,t} \cdot \frac{TCAP^{conv,tr}_{r_{s\_tr},ec,l,w,p}}{\eta^{sol,tr}_{r_{s\_tr},ec,w}} \cdot \eta^{sol,tr}_{r_{s\_tr},ec,w} \cdot cdeg_{r_{s\_tr},ec,w,p} \ , \\ \forall\ r_{s\_tr} \in \mathcal{R}_{s\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \\ \{p \geq w, p \leq w + cl^{p}_{r_{s\_tr}} - 1\ ,\ cpl_{r_{s\_tr},l} = 1\ ,\ rcc_{r_{s\_tr},ec} = 1\} \end{aligned} \tag{4}$$

3.2 Equation 5

Constraint for the calculation of the energy output by non-tracked solar technologies: `Solar_output_ntr_rule`

$$\begin{aligned} POUT^{re,ntr}_{r_{s\_ntr},ec,l,p,d,t} = sol^{rad}_{l,p,d,t} \cdot \frac{TCAP^{conv,ntr}_{r_{s\_ntr},ec,l,p}}{\eta^{sol,ntr}_{r_{s\_ntr},ec}} \cdot \eta^{sol,ntr}_{r_{s\_ntr},ec} \ , \\ \forall\ r_{s\_ntr} \in \mathcal{R}_{s\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{cpl_{r_{s\_ntr},l} = 1\ ,\ rcc_{r_{s\_ntr},ec} = 1\} \end{aligned} \tag{5}$$

3.3 Equation 6

Constraint for the calculation of the energy output by tracked wind technologies: `Wind_output_tr_rule`

$$POUT^{re,tr}_{r_{w\_tr},ec,l,w,p,d,t} = \begin{cases} TCAP^{conv,tr}_{r_{w\_tr},ec,l,w,p} \cdot cdeg_{r_{w\_tr},ec,w,p} & , ws^{rate,tr}_{r_{w\_tr},w} \leq ws_{l,p,d,t} \leq ws^{cutout,tr}_{r_{w\_tr}} \\ TCAP^{conv,tr}_{r_{w\_tr},ec,l,w,p} \cdot \frac{ws_{l,p,d,t} - ws^{cutin,tr}_{r_{w\_tr},w}}{ws^{rate,tr}_{r_{w\_tr},w} - ws^{cutin,tr}_{r_{w\_tr},w}} & , ws^{cutin,tr}_{r_{w\_tr},w} \leq ws_{l,p,d,t} \leq ws^{rate,tr}_{r_{w\_tr},w} \\ 0 & , ws_{l,p,d,t} < ws^{cutin,tr}_{r_{w\_tr},w} \vee ws_{l,p,d,t} > ws^{cutout,tr}_{r_{w\_tr}} \end{cases} \tag{6}$$

$$\forall\ r_{w\_tr} \in \mathcal{R}_{w\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ |$$
$$\{p \geq w \wedge p \leq cl^{p}_{r_{w\_tr}} - 1\ , cpl_{r_{w\_tr},l} = 1\ ,\ rcc_{r_{w\_tr},ec} = 1\}$$

3.4 Equation 7

Constraint for the calculation of the energy output by non-tracked wind technologies: `Wind_output_ntr_rule`

$$POUT^{wind,ntr}_{r_{w\_ntr},ec,l,p,d,t} = \begin{cases} TCAP^{conv,ntr}_{r_{w\_ntr},ec,l,w,p,d,t} & , ws^{rate,ntr}_{r_{w\_ntr},w} \leq ws_{l,p,d,t} \leq ws^{cutout,ntr}_{r_{w\_ntr}} \\ TCAP^{conv,ntr}_{r_{w\_ntr},ec,l,w,p,d,t} \cdot \frac{ws_{l,p,d,t} - ws^{cutin,ntr}_{r_{w\_ntr}}}{ws^{rate,ntr}_{r_{w\_ntr}} - ws^{cutin,ntr}_{r_{w\_ntr}}} & , ws^{cutin,ntr}_{r_{w\_ntr},w} \leq ws_{l,p,d,t} \leq ws^{rate,ntr}_{r_{w\_ntr},w} \\ 0 & , ws_{l,p,d,t} < ws^{cutin,ntr}_{r_{w\_ntr},w} \vee ws_{l,p,d,t} > ws^{cutout,ntr}_{r_{w\_ntr}} \end{cases} \tag{7}$$

$$\forall\ r_{w\_ntr} \in \mathcal{R}_{w\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ |\{cpl_{r_{w\_ntr},l} = 1\ ,\ rcc_{r_{w\_ntr},ec} = 1\}$$

3.5 Equation 8

Constraint for the calculation of the energy output by other tracked renewable technologies (e.g. Geothermal, RoR):`Other_renew_output_tr_rule`

$$\begin{aligned} &POUT^{re,tr}_{r_{r\_tr},ec,l,w,p,d,t} = capf_{l,p,d,t} \cdot TCAP^{conv,tr}_{r_{r\_tr},ec,l,w,p} \cdot cdeg_{r_{r\_tr},ec,w,p}\ , \\ &\quad \forall\ r_{r\_tr} \in \mathcal{R}_{r\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ &\qquad \{p \geq w \wedge p \leq w + cl^{p}_{r_{r\_tr}} - 1\ ,\ cpl_{r_{r\_tr},l} = 1\ ,\ rcc_{r_{r\_tr},ec} = 1\} \end{aligned} \tag{8}$$

3.6 Equation 9

Constraint for the calculation of the energy output by non-tracked hydro RoR technologies: `Other_renew_output_ntr_rule`

$$\begin{aligned} &POUT^{re,ntr}_{r_{r\_ntr},ec,l,p,d,t} = capf_{l,p,d,t} \cdot TCAP^{conv,ntr}_{r_{r\_ntr},ec,l,p}\ , \\ &\forall\ r_{r\_ntr} \in \mathcal{R}_{r\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ |\ \{\ cpl_{r_{r\_ntr},l} = 1\ ,\ rcc_{r_{r\_ntr},ec} = 1\} \end{aligned} \tag{9}$$

4 Hydro dam constraints

4.1 Equation 10

Energy balance for the tracked hydro dam storage technologies considering incoming and outgoing energy flows: `Hydro_dam_stor_balance_tr_rule`

$$\begin{aligned} SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,d,t} &= capf^{dam}_{l,p,d,t} \cdot TCAP^{dam,tr}_{r_{dam\_tr},ec,l,w,p} - \left(\frac{1}{\eta^{dam,tr}_{r_{dam\_tr},ec,w} \cdot cdeg_{r_{dam\_tr},ec,w,p}}\right) \cdot POUT^{re,tr}_{r_{dam\_tr},ec,l,w,p,d,t} + \\ &\begin{cases} 0 & , t = 1 \\ (1 - \eta^{self,dam,tr}_{r_{dam\_tr},w}) * SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,d,t-1}) & , t \neq 1 \end{cases}, \\ &\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ &\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\} \end{aligned} \tag{10}$$

4.2 Equation 11

Energy balance for the tracked hydro dam storage technologies considering incoming and outgoing energy flows: `Hydro_dam_stor_balance_ntr_rule`

$$
\begin{aligned}
SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,d,t} = capf^{dam}_{l,p,d,t} \cdot TCAP^{dam,ntr}_{r_{dam\_ntr},ec,l,p} - \left(\frac{1}{\eta^{dam,ntr}_{r_{dam\_ntr},ec}}\right) \cdot POUT^{re,ntr}_{r_{dam\_ntr},ec,l,p,d,t} + \\
\begin{cases} 0 & ,t = 1 \\ (1-\eta^{self,dam,ntr}_{r_{dam\_ntr}}) * SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,d,t-1}) & ,t \neq 1 \end{cases}, \\
\forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{\ cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned} \tag{11}
$$

4.3 Equation 12

Constraint limiting the output from tracked hydro dam plants according to their capacity: `Hydro_dam_conv_capacity_limit_tr_`

$$
\begin{aligned}
POUT^{re,tr}_{r_{dam\_tr},ec,l,w,p,d,t} \leq TCAP^{conv,tr}_{r_{dam\_tr},ec,l,w,p} \\
\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned} \tag{12}
$$

4.4 Equation 13

Constraint limiting the output from non-tracked hydro dam plants according to their capacity: `Hydro_dam_conv_capacity_limit_ntr_rule`

$$
\begin{aligned}
POUT^{re,ntr}_{r_{dam\_ntr},ec,l,p,d,t} \leq TCAP^{conv,ntr}_{r_{dam\_ntr},ec,l,p} \\
\forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned} \tag{13}
$$

4.5 Equation 14

Constraint to capture the minimum intra-day storage level for a tracked hydro dam technology: `Hydro_dam_stor_intra_day_min_tr_rule`

$$
\begin{aligned}
SoC^{day,min,dam,tr}_{r_{dam\_tr},ec,l,w,p,d} \leq SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,d,t} \\
\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned} \tag{14}
$$

4.6 Equation 15

Constraint to capture the maximum intra-day storage level for a tracked hydro dam technology: `Hydro_dam_stor_intra_day_max_tr_rule`

$$
\begin{aligned}
SoC^{day,max,dam,tr}_{r_{dam\_tr},ec,l,w,p,d} \geq SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,d,t} \\
\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned} \tag{15}
$$

4.7 Equation 16

Constraint to capture the minimum intra-day storage level for a non-tracked hydro dam technology: `Hydro_dam_stor_intra_day_min_ntr_rule`

$$
\begin{aligned}
SoC^{day,min,dam,ntr}_{r_{dam\_ntr},ec,l,p,d} \leq SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,d,t} \\
\forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
\{cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned} \tag{16}
$$

4.8 Equation 17

Constraint to capture the maximum intra-day storage level for a non-tracked hydro dam technology:
`Hydro_dam_stor_intra_day_max_ntr_rule`

$$
\begin{aligned}
SoC^{day,max,dam,ntr}_{r_{dam\_ntr},ec,l,p,d} \geq SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,d,t} \\
&\forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
&\{cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned} \tag{17}
$$

4.9 Equation 18

Constraint connecting the inter-day storage level of a tracked hydro dam technology:
`Hydro_dam_stor_inter_day_connection_tr_rule`

$$
SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd} =
\begin{cases}
0 & ,p = w \wedge cd = 1 \\
SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p-1,max(cd)} \cdot (1 - \eta^{self,dam,tr}_{r_{dam\_tr},w})^{max(t)} + SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p-1,cd2td_{p-1,max(cd)},max(t)} & ,p \neq w \wedge cd = 1 \\
SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd-1} \cdot (1 - \eta^{self,dam,tr}_{r_{dam\_ntr}})^{max(t)} + SoC^{day,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd2td_{p,cd-1},max(t)} & ,cd \neq 1
\end{cases} \tag{18}
$$

$$
\begin{aligned}
&\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
&\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned}
$$

4.10 Equation 19

Constraint connecting the inter-day storage level of a non-tracked hydro dam technology:
`Hydro_dam_stor_inter_day_connection_ntr_rule`

$$
SoC^{interday,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd} =
\begin{cases}
SoC^{init}_{r_{dam\_ntr}} \cdot TCAP^{dam,ntr}_{r_{dam\_ntr},ec,l,p} & ,p = 1 \wedge cd = 1 \wedge r_{dam\_ntr} \in \mathcal{R}_{dam\_ex} \\
0 & ,p = 1 \wedge cd = 1 \wedge r_{dam\_ntr} \notin \mathcal{R}_{dam\_ex} \\
SoC^{interday,dam,ntr}_{r_{dam\_ntr},ec,l,p-1,max(cd)} \cdot (1 - \eta^{self,dam,ntr}_{r_{dam\_ntr}})^{max(t)} \\
+SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p-1,cd2td_{p-1,max(cd)},max(t)} & ,p \neq 1 \wedge cd = 1 \\
SoC^{interday,dam,ntr}_{r_{dam\_tr},ec,l,p,cd-1} \cdot (1 - \eta^{self,dam,ntr}_{r_{dam\_tr}})^{max(t)} \\
+SoC^{day,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd2td_{p,cd-1},max(t)} & ,p \neq 1 \wedge cd \neq 1
\end{cases} \tag{19}
$$

$$
\begin{aligned}
&\forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD}\ | \\
&\{\ cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned}
$$

4.11 Equation 20

Constraint limiting the stored energy in tracked hydro dam plants according to the storage capacity:
`Hydro_dam_stor_capacity_limit_tr_rule`

$$
\begin{aligned}
SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd} + SoC^{day,max,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd2td_{p,cd}} \leq TCAP^{dam,tr}_{r_{dam\_tr},ec,l,w,p} \\
&\forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\
&\{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned} \tag{20}
$$

4.12 Equation 21

Constraint limiting the stored energy in the non-tracked hydro dam plants according to the storage capacity: `Hydro_dam_stor_capacity_limit_ntr_rule`

$$
\begin{aligned}
& SoC^{interday,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd} + SoC^{day,max,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd2td_{p,cd}} \leq TCAP^{dam,ntr}_{r_{dam\_ntr},ec,l,p} \\
& \qquad \forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \\
& \qquad \{cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned}
\tag{21}
$$

4.13 Equation 22

Constraint to enforce non-negativity for the storage level of a tracked hydro dam technology: `Hydro_dam_stor_inter_day_non_negativity_constr_tr_rule`

$$
\begin{aligned}
& SoC^{interday,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd} \cdot (1 - \eta^{self,dam,tr}_{r_{dam\_tr},w})^{max(t)} + SoC^{day,min,dam,tr}_{r_{dam\_tr},ec,l,w,p,cd2td_{p,cd}} \geq 0 \\
& \qquad \forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \\
& \qquad \{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1\}
\end{aligned}
\tag{22}
$$

4.14 Equation 23

Constraint to enforce non-negativity for the storage level of a non-tracked hydro dam technology: `Hydro_dam_stor_inter_day_non_negativity_constr_ntr_rule`

$$
\begin{aligned}
& SoC^{interday,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd} \cdot (1 - \eta^{self,dam,ntr}_{r_{dam\_ntr}})^{max(t)} + SoC^{day,min,dam,ntr}_{r_{dam\_ntr},ec,l,p,cd2td_{p,cd}} \geq 0 \\
& \forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{\ cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\}
\end{aligned}
\tag{23}
$$

4.15 Equation 24

Constraint governing the relationship between dam storage capacity and energy output for hydro dam technologies: `Hydro_dam_conv_stor_cap_relation_rule`

$$
\begin{aligned}
& NCAP^{dam,stor}_{r_{dam},ec,l,w} \leq cap^{stor,conv,max}_{r_{dam}} \cdot NCAP^{conv}_{r_{dam},ec,l,w} \\
& \forall\ r_{dam} \in \mathcal{R}_{dam},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ \mid \{\ cpl_{r_{dam},l} = 1\ ,\ rcc_{r_{dam},ec} = 1\}
\end{aligned}
\tag{24}
$$

5 Load balance and conversion contraints

5.1 Equation 25

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

$$
\begin{aligned}
&\begin{cases} P^{imp}_{ec,l,p,d,t} & , ec \in \mathcal{EC}_i \\ 0 & , ec \notin \mathcal{EC}_i \end{cases}
+ \sum_{\substack{c_{d\_tr} \in \mathcal{C}_{d\_tr} \\ cpl_{c_{d\_tr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_tr},ec',ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w+cl^{p}_{c_{d\_tr}}-1}} POUT^{disp,tr}_{c_{d\_tr},ec,l,w,p,d,t} \\
&+ \sum_{\substack{c_{d\_ntr} \in \mathcal{C}_{d\_ntr} \\ cpl_{c_{d\_ntr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_ntr},ec',ec}=1}} POUT^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \\
&+ \sum_{\substack{c_{d\_ntr} \in \mathcal{C}_{ccs\_ntr} \\ cpl_{c_{d\_ntr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_ntr},ec',ec}=1}} POUT^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \\
&- \sum_{\substack{c_{d\_tr} \in \mathcal{C}_{d\_tr} \\ cpl_{c_{d\_tr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_tr},ec,ec'}=1}} \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w+cl^{p}_{c_{d\_tr}}-1}} PIN^{disp,tr}_{c_{d\_tr},ec,l,w,p,d,t} \\
&- \sum_{\substack{c_{d\_ntr} \in \mathcal{C}_{d\_ntr} \\ cpl_{c_{d\_ntr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_ntr},ec,ec'}=1}} PIN^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \\
&- \sum_{\substack{c_{d\_ntr} \in \mathcal{C}_{ccs\_ntr} \\ cpl_{c_{d\_ntr},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{d\_ntr},ec,ec'}=1}} PIN^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \\
&+ \sum_{\substack{r_{tr} \in \mathcal{R}_{tr} \\ cpl_{r_{tr},l}=1 \\ rcc_{r_{tr},ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w+cl^{p}_{r_{tr}}-1}} POUT^{re,tr}_{r_{tr},ec,l,w,p,d,t} \\
&+ \sum_{\substack{r_{ntr} \in \mathcal{R}_{ntr} \\ cpl_{r_{ntr},l}=1 \\ rcc_{r_{ntr},ec}=1}} POUT^{re,ntr}_{r_{ntr},ec,l,p,d,t} \\
&+ \sum_{\substack{s_{tr} \in \mathcal{S}_{tr} \\ spl_{s_{tr},l}=1 \\ stc_{s_{tr},ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w+sl^{p}_{s_{tr}}-1}} Q^{dis,tr}_{s_{tr},ec,l,w,p,d,t} - Q^{ch,tr}_{s_{tr},ec,l,w,p,d,t} \\
&+ \sum_{\substack{s_{ntr} \in \mathcal{S}_{ntr} \\ spl_{s_{ntr},l}=1 \\ stc_{s_{ntr},ec}=1}} Q^{dis,ntr}_{s_{ntr},ec,l,p,d,t} - Q^{ch,ntr}_{s_{ntr},ec,l,p,d,t} \\
&+ \begin{cases} \sum\limits_{\substack{l' \in \mathcal{L} \\ l \neq l' \\ linepl_{ec,l,l'}=1}} P^{exc}_{ec,l',l,p,d,t} \cdot (1 - \eta^{net}_{ec} \cdot x_{l,l'}) - P^{exc}_{ec,l,l',p,d,t} & , ec \in \mathcal{EC}_x \\ 0 & , ec \notin \mathcal{EC}_x \end{cases} \\
&- \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,l,p,d,t} + dsm^{neg}_{ec,l,p,d,t} - dsm^{pos}_{ec,l,p,d,t} & , ec \in \mathcal{EC}_d \\ 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},\ t \in \mathcal{T}
\end{aligned}
\tag{25}
$$

5.2 Equation 26

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

$$\begin{aligned} TCAP^{conv,tr}_{c_{tr},ec',l,w,p} = NCAP^{conv}_{c_{tr},ec',l,w} \forall\ c_{tr} \in \mathcal{C}_{tr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ | \\ \{p \geq w\ ,\ p \leq w + cl^{p}_{c_{tr}} - 1\ ,\ cpl_{c_{tr},l} = 1\} \wedge ((c_{tr} \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c_{tr},ec,ec'} = 1)\ \vee rcc_{c_{tr},ec'} = 1) \end{aligned} \tag{26}$$

5.3 Equation 27

Constraint to keep track of the total available capacity per non-tracked technology at each energy site and period:
`tcap_balance_ntr_rule`

$$\begin{aligned} TCAP^{conv,ntr}_{c_{ntr},ec',l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + cl^{p}_{c_{ntr}} - 1}} NCAP^{conv}_{c_{ntr},ec',l,w}\ \forall\ c_{ntr} \in \mathcal{C}_{ntr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ | \\ cpl_{c_{ntr},l} = 1 \wedge ((c_{ntr} \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c_{ntr},ec,ec'} = 1)\ \vee rcc_{c_{ntr},ec'} = 1) \end{aligned} \tag{27}$$

5.4 Equation 28

Constraint to keep track of the total storage capacity per tracked hydro dam technology at each energy site and period:
`tcap_hydro_dam_stor_balance_tr_rule`

$$\begin{aligned} TCAP^{dam,tr}_{r_{dam\_tr},ec,l,w,p} = NCAP^{dam,stor}_{r_{dam\_tr},ec,l,w} \forall\ r_{dam\_tr} \in \mathcal{R}_{dam\_tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ | \\ \{p \geq w\ ,\ p \leq w + cl^{p}_{r_{dam\_tr}} - 1\ ,\ cpl_{r_{dam\_tr},l} = 1\ ,\ rcc_{r_{dam\_tr},ec} = 1 \end{aligned} \tag{28}$$

5.5 Equation 29

Constraint to keep track of the total available capacity per non-tracked technology at each energy site and period:
`tcap_hydro_dam_stor_balance_ntr_rule`

$$\begin{aligned} TCAP^{dam,ntr}_{r_{dam\_ntr},ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + cl^{p}_{r_{dam\_ntr}} - 1}} NCAP^{dam,stor}_{r_{dam\_ntr},ec,l,w} \\ \forall\ r_{dam\_ntr} \in \mathcal{R}_{dam\_ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ |\ \{\ cpl_{r_{dam\_ntr},l} = 1\ ,\ rcc_{r_{dam\_ntr},ec} = 1\} \end{aligned} \tag{29}$$

5.6 Equation 30

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

$$\begin{aligned} \begin{cases} NCAP^{conv}_{c_d,ec'_1,l,w} \cdot \eta^{disp,tr}_{c_d,ec,ec'_2,w} = NCAP^{conv}_{c_d,ec'_2,l,w} \cdot \eta^{disp,tr}_{c_d,ec,ec'_1,w} & , c_d \in \mathcal{C}_{tr} \\ NCAP^{conv}_{c_d,ec'_1,l,w} \cdot \eta^{disp,ntr}_{c_d,ec,ec'_2} = NCAP^{conv}_{c_d,ec'_2,l,w} \cdot \eta^{disp,ntr}_{c_d,ec,ec'_1} & , c_d \in \mathcal{C}_{ntr} \end{cases} \\ \forall\ c_d \in \mathcal{C}_d,\ ec, ec'_1, ec'_2 \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W}\ |\ \{cpl_{c_d,l} = 1\ ,\ ecc^{disp}_{c_d,ec,ec'_1} = 1,\ ecc^{disp}_{c_d,ec,ec'_2} = 1,\ ec'_1 \neq ec'_2\} \end{aligned} \tag{30}$$

5.7 Equation 31

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

$$
\begin{gathered}
\text{If } r \in \mathcal{C}_{tr}: \\
\sum_{\substack{ec \in \mathcal{EC} \\ rcc_{r,ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + cl_r^p - 1}} TCAP^{conv,tr}_{r,ec,l,w,p} \leq rcap^{max}_{r,l,p} \\
\text{If } r \in \mathcal{C}_{ntr}: \\
\sum_{\substack{ec \in \mathcal{EC} \\ rcc_{r,ec}=1}} TCAP^{conv,ntr}_{r,ec,l,p} \leq rcap^{max}_{r,l,p} \\
\forall\ r \in \mathcal{R},\ l \in \mathcal{L},\ p \in \mathcal{P},\ |\ cpl_{r,l} = 1
\end{gathered}
\tag{31}
$$

5.8 Equation 32

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

$$
\begin{gathered}
\sum_{\substack{c_{grm} \in \mathcal{C}_{grm} \cap \mathcal{C}_{tr} \\ ec \in \mathcal{EC} \\ p \geq w \\ p \leq w + cl^p_{c_{grm}} - 1 \\ cpl_{c_{grm},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{grm},ec',ec}=1}} TCAP^{conv,tr}_{c_{grm},ec,l,w,p} + \sum_{\substack{c_{grm} \in \mathcal{C}_{grm} \cap \mathcal{C}_{ntr} \\ ec \in \mathcal{EC} \\ cpl_{c_{grm},l}=1 \\ \exists\ ec' \in \mathcal{EC} | ecc^{disp}_{c_{grm},ec',ec}=1}} TCAP^{conv,ntr}_{c_{grm},ec,l,p} \leq rcap^{max,gr}_{r_{gr},l,p} \\
\forall\ c_{gr} \in \mathcal{C}_{gr} \supseteq \mathcal{C}_{grm},\ l \in \mathcal{L},\ p \in \mathcal{P}
\end{gathered}
\tag{32}
$$

5.9 Equation 33

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

$$
\begin{gathered}
\sum_{\substack{r_{grm} \in \mathcal{R}_{grm} \cap \mathcal{C}_{tr} \\ ec \in \mathcal{EC} \\ p \geq w \\ p \leq w + cl^p_{r_{grm}} - 1 \\ cpl_{r_{grm},l}=1 \\ rcc_{r_{grm},ec}=1}} TCAP^{conv,tr}_{r_{grm},ec,l,w,p} + \sum_{\substack{r_{grm} \in \mathcal{R}_{grm} \cap \mathcal{C}_{ntr} \\ ec \in \mathcal{EC} \\ cpl_{r_{grm},l}=1 \\ rcc_{r_{grm},ec}=1}} TCAP^{conv,ntr}_{r_{grm},ec,l,p} \leq rcap^{max,gr}_{r_{gr},l,p} \\
\forall\ r_{gr} \in \mathcal{R}_{gr} \supseteq \mathcal{R}_{grm},\ l \in \mathcal{L},\ p \in \mathcal{P}
\end{gathered}
\tag{33}
$$

5.10 Equation 34

Constraint setting the capacity for existing conversion technologies:
`Existing_conv_capacity_setting_rule`

$$
\begin{gathered}
NCAP^{conv}_{c_{ex},ec',l,1} = excap^{conv}_{c_{ex},ec',l} \qquad \forall\ c_{ex} \in \mathcal{C}_{ex},\ ec' \in \mathcal{EC},\ l \in \mathcal{L}\ | \\
\{\ cpl_{c_{ex},l} = 1 \wedge ((c_{ex} \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c_{ex},ec,ec'} = 1)\ \vee rcc_{c_{ex},ec'} = 1)\}
\end{gathered}
\tag{34}
$$

5.11 Equation 35

Constraint setting the storage capacity for existing hydro dam technologies:
`Existing_hydro_dam_stor_capacity_setting_rule`

$$
NCAP^{dam}_{r_{dam\_ex},ec',l,1} = excap^{dam}_{r_{dam\_ex},ec',l} \qquad \forall\ r_{dam\_ex} \in \mathcal{R}_{dam\_ex},\ ec' \in \mathcal{EC},\ l \in \mathcal{L}\ |\ rcc_{r_{dam\_ex},ec} = 1 \tag{35}
$$

5.12 Equation 36

Constraint preventing the re-installation of existing conversion technologies:
`Existing_conv_no_reinvestment_rule`

$$
\text{If } w \neq 1: ncap^{conv}_{c_{ex},ec,l,w} <= 0 \qquad \forall\ c_{ex} \in \mathcal{C}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W}\ |\ cpl_{c_{ex},l} = 1 \tag{36}
$$

5.13 Equation 37

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

$$POUT^{disp,tr}_{c_{d\_tr},ec',l,w,p,d,t} \leq TCAP^{conv,tr}_{c_{d\_tr},ec',l,w,p} \qquad \forall\ c_{d\_tr} \in \mathcal{C}_{d\_tr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P}, \\ d \in \mathcal{D}, t \in \mathcal{T}\ |\{p \geq w, p \leq w + cl^{p}_{c_{d\_tr}} - 1\ ,\ cpl_{c_{d\_tr},l} = 1\ , \exists\ ec\ \in \mathcal{EC}\ |\ ecc_{c_{d\_tr},ec,ec'} = 1\} \tag{37}$$

5.14 Equation 38

Constraint preventing capacity violation for the non-tracked conversion technologies of the energy system: `Capacity_constraint_ntr_rule`

$$POUT^{disp,ntr}_{c_{d\_ntr},ec',l,p,d,t} \leq TCAP^{conv,ntr}_{c_{d\_ntr},ec',l,p} \qquad \forall\ c_{d\_ntr} \in \mathcal{C}_{d\_ntr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ \{\ cpl_{c_{d\_ntr},l} = 1\ , \exists\ ec\ \in \mathcal{EC}\ |\ ecc_{c_{d\_ntr},ec,ec'} = 1\} \tag{38}$$

5.15 Equation 39

Constraint imposing steady operation per period for tracked, baseload technologies: `Baseload_operation_tr_rule`

$$POUT^{disp,tr}_{c_{b\_tr},ec',l,w,p,d,t} = POUT^{base,tr}_{c_{b\_tr},ec',l,w,p} \qquad \forall\ c_{b\_tr} \in \mathcal{C}_{b\_tr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D}, \\ t \in \mathcal{T}\ |\{p \geq w, p \leq w + cl^{p}_{c_{b\_tr}} - 1\ ,\ cpl_{c_{b\_tr},l} = 1\ , \exists\ ec\ \in \mathcal{EC}\ |\ ecc_{c_{b\_tr},ec,ec'} = 1\} \tag{39}$$

5.16 Equation 40

Constraint imposing steady operation per period for non-tracked, baseload technologies: `Baseload_operation_ntr_rule`

$$POUT^{disp,ntr}_{c_{b\_ntr},ec',l,p,d,t} = POUT^{base,ntr}_{c_{b\_ntr},ec',l,p} \qquad \forall\ c_{b\_ntr} \in \mathcal{C}_{b\_ntr},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ \{\ cpl_{c_{b\_ntr},l} = 1\ , \exists\ ec\ \in \mathcal{EC}\ |\ ecc^{disp}_{c_{b\_ntr},ec,ec'} = 1\} \tag{40}$$

5.17 Equation 41

Maximum possible conversion technology capacity per technology considered: `Conv_maximum_cap_limit_rule`

$$NCAP^{conv}_{c,ec',l,w} \leq cap^{max}_{c} \qquad \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W}\ | \\ \{\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_{d} \wedge \exists\ ec \in \mathcal{EC}\ |\ ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1)\} \tag{41}$$

5.18 Equation 42

Input-output relationship for non-tracked, dispatchable CCS technologies: `Dispatchable_CCS_conv_tech_input_output_ntr_rule`

$$POUT^{ccs,ntr}_{c_{ccs\_ntr},ec',l,p,d,t} = PIN^{ccs,ntr}_{c_{ccs\_ntr},ec,l,p,d,t} \cdot \eta^{conv,ntr}_{c_{ccs\_ntr},ec} \cdot (1 - \eta^{ccs}_{c_{ccs\_ntr}})\ , \\ \forall\ c_{ccs\_ntr} \in \mathcal{C}_{ccs} \cap \mathcal{C}_{ntr},\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ \{cpl_{c,l} = 1\ ,\ ecc^{disp}_{c_{ccs\_ntr},ec,ec'} = 1\} \tag{42}$$

5.19 Power output rule for tracked dispatch technologies

Input-output relationship for tracked, dispatchable technologies: `Dispatchable_conv_tech_input_output_tr_rule`

$$POUT^{disp,tr}_{c_{d\_tr},ec',l,w,p,d,t} = PIN^{disp,tr}_{c_{d\_tr},ec,l,w,p,d,t} \cdot \eta^{conv,tr}_{c_{d\_tr},ec,ec',w} \cdot cdeg_{c_{d\_tr},ec',w,p}\ , \\ \forall\ c_{d\_tr} \in \mathcal{C}_{d\_tr},\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ |\ \{cpl_{c_{d\_tr},l} = 1\ ,\ ecc^{disp}_{c_{d\_tr},ec,ec'} = 1\} \tag{43}$$

5.20 Power output rule for non-tracked dispatch technologies

Input-output relationship for non-tracked, dispatchable technologies: `Dispatchable_conv_tech_input_output_ntr_rule`

$$POUT^{disp,ntr}_{c_{d\_ntr},ec',l,p,d,t} = PIN^{disp,ntr}_{c_{d\_ntr},ec,l,p,d,t} \cdot \eta^{conv,ntr}_{c_{d\_ntr},ec,ec'} \ , \\ \forall\ c_{d\_ntr} \in \mathcal{C}_{d\_ntr},\ ec, ec' \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{cpl_{c_{d\_ntr},l} = 1\ ,\ ecc^{disp}_{c_{d\_ntr},ec,ec'} = 1\} \tag{44}$$

5.21 Non-tracked storage state of charge during the full year

Constraint connecting the inter-day state-of-charge of a non-tracked storage `Storage_inter_day_connection_ntr_rule`

5.22 Equation 45

Constraint for the formulation of the fixed cost in the objective function:
`Conv_fixed_cost_rule`
Disclaimer: This constraint has been deactivated in the current version of MANGOelec to reduce binary variables.

$$NCAP^{conv}_{c,ec',l,w} \leq bigM \cdot Y^{conv}_{c,l,w} \qquad \forall\ c \in \mathcal{C},\ ec' \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \\ \{\ cpl_{c,l} = 1 \wedge ((c \in \mathcal{C}_d \wedge \exists\ ec \in \mathcal{EC} \mid ecc^{disp}_{c,ec,ec'} = 1)\ \vee rcc_{c,ec'} = 1)\} \tag{45}$$

5.23 Equation 46

Constraint to calculate the total available capacity for export considering initial capacity and expansion:
`tcap_exc_balance_rule`

$$TCAP^{exc}_{ec_x,l1,l2,p} = excap^{line}_{ec_x,l1,l2} + \sum_{\substack{w\in\mathcal{W}\\ w\leq p}} NCAP^{exc}_{ec_x,l1,l2,w} \qquad \forall\ ec_x \in \mathcal{EC}_x,\ l1,l2 \in \mathcal{L},\ p \in \mathcal{P} \mid \\ \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{46}$$

5.24 Equation 47

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

$$P^{exc}_{ec_x,l1,l2,p,d,t} \leq TCAP^{exc}_{ec_x,l1,l2,p} \qquad \forall\ ec_x \in \mathcal{EC}_x,\ l1,l2 \in \mathcal{L},\ p \in \mathcal{P}\ \ d \in \mathcal{D}\ \ t \in \mathcal{T} \mid \\ \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{47}$$

5.25 Equation 48

Connections between sites have the same capacities:
`Bidirectional_connection_equal_capacities_rule`

$$NCAP^{exc}_{ec_x,l1,l2,w} = NCAP^{exc}_{ec_x,l2,l1,w} \qquad \forall\ ec_x \in \mathcal{EC}_x,\ l1,l2 \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{48}$$

5.26 Equation 49

Constraint for the formulation of the fixed cost in the objective function:
`Fixed_cost_exchange_rule`
Disclaimer: This constraint has been deactivated in the current version of MANGOelec to reduce binary variables.

$$NCAP^{exc}_{ec_x,l1,l2,w} \leq bigM \cdot Y^{exc}_{ec_x,l1,l2,w} \qquad \forall\ ec_{ex} \in \mathcal{EC}_{ex},\ l1,l2 \in \mathcal{L},\ w \in \mathcal{W} \mid \{\ l1 \neq l2, linepl_{ec_x,l1,l2} = 1\} \tag{49}$$

5.27 Equation 50

Constraint to calculate the total available capacity for export considering initial capacity and expansion:
`tcap_exp_balance_rule`

$$TCAP^{exp}_{ec_e,l,p} = excap^{exp}_{ec_e,l} + \sum_{\substack{w\in\mathcal{W}\\ w\leq p}} NCAP^{exc}_{ec_e,l1,l2,w} \qquad \forall\ ec_e \in \mathcal{EC}_e,\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{50}$$

5.28 Equation 51

An energy can only be exported if there is capacity for export:
`Export_limits_rule`

$$P^{exp}_{ec_e,l,p,d,t} \leq TCAP^{exp}_{ec_e,l,p} \qquad \forall\ ec_e \in \mathcal{EC}_e,\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \tag{51}$$

5.29 Equation 52

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

$$NCAP^{exp}_{ec_e,l,w} \leq bigM \cdot Y^{exp}_{ec_e,l,w} \qquad \forall\ ec_e \in \mathcal{EC}_e,\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{52}$$

5.30 Equation 53

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

$$TCAP^{imp}_{ec_i,l,p} = excap^{imp}_{ec_i,l} + \sum_{\substack{w \in \mathcal{W} \\ w \leq p}} NCAP^{imp}_{ec_i,l,w} \qquad \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{53}$$

5.31 Equation 54

An energy can only be imported if there is capacity for import:
`Import_limits_rule`

$$P^{imp}_{ec_i,l,p,d,t} \leq TCAP^{imp}_{ec_i,l,p} \qquad \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \tag{54}$$

5.32 Fixed cost import rule

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

$$NCAP^{imp}_{ec_i,l,w} \leq bigM \cdot Y^{imp}_{ec_i,l,w}\ \forall\ ec_i \in \mathcal{EC}_i,\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{55}$$

5.33 tcap_stor balance tr rule

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

$$\begin{aligned} TCAP^{stor,tr}_{s_{tr},ec,l,w,p} = NCAP^{stor}_{s_{tr},ec,l,w} \qquad & \forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P}\ | \\ & \{p \geq w, p \leq w + sl^p_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \end{aligned} \tag{56}$$

5.34 tcap_stor balance ntr rule

Constraint to keep track of the total available capacity per non-tracked storage technology at each energy site and period:
`tcap_stor_balance_ntr_rule`

$$\begin{gathered} TCAP^{stor,ntr}_{s_{ntr},ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + sl^p_{s_{ntr}} - 1}} NCAP^{stor}_{s_{ntr},ec,l,w} \\ \forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \end{gathered} \tag{57}$$

5.35 tpow_stor balance tr rule

Constraint to keep track of the total available power per tracked storage technology at each energy site and period:
`tpow_stor_balance_tr_rule`

$$\begin{aligned} TPOW^{stor,tr}_{s_{tr},ec,l,w,p} = NPOW^{stor}_{s_{tr},ec,l,w} \qquad & \forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P}\ | \\ & \{p \geq w, p \leq w + sl^p_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \end{aligned} \tag{58}$$

5.36 tpow_stor balance ntr rule

Constraint to keep track of the total available capacity per non-tracked storage technology at each energy site and period:
`tpow_stor_balance_ntr_rule`

$$TPOW^{stor,ntr}_{s_{ntr},ec,l,p} = \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w + sl^{p}_{s_{ntr}} - 1}} NPOW^{stor}_{s_{ntr},ec,l,w} \tag{59}$$
$$\forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P}\ \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\}$$

5.37 Equation 54

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

$$SoC^{tr}_{s_{tr},ec,l,w,p,d,t} = \begin{cases} \eta^{ch,tr}_{s_{tr},w} \cdot sdeg_{s_{tr},w,p} \cdot Q^{ch,tr}_{s_{tr},ec,l,w,p,d,t} - \frac{1}{\eta^{dis,tr}_{s_{tr},w} \cdot sdeg_{s_{tr},w,p}} \cdot Q^{dis,tr}_{s_{tr},ec,l,w,p,d,t} & ,t = 1 \\ \eta^{ch,tr}_{s_{tr},w} \cdot sdeg_{s_{tr},w,p} \cdot Q^{ch,tr}_{s_{tr},ec,l,w,p,d,t} - \frac{1}{\eta^{dis,tr}_{s_{tr},w} \cdot sdeg_{s_{tr},w,p}} \cdot Q^{dis,tr}_{s_{tr},ec,l,w,p,d,t} + & \\ (1 - \eta^{self,tr}_{s_{tr},w}) \cdot SoC^{tr}_{s_{tr},ec,l,w,p,d,t-1} & ,t \neq 1 \end{cases} \tag{60}$$
$$\forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\}$$

5.38 Equation 55

Intra-day energy balance for the non-tracked storage modules considering incoming and outgoing energy flows:
`Storage_balance_ntr_rule`

$$SoC^{ntr}_{s_{ntr},ec,l,p,d,t} = \begin{cases} \eta^{ch,ntr}_{s_{ntr}} \cdot Q^{ch,ntr}_{s_{ntr},ec,l,p,d,t} - \frac{1}{\eta^{dis,ntr}_{s_{ntr}}} \cdot Q^{dis,ntr}_{s_{ntr},ec,l,p,d,t} & ,t = 1 \\ \eta^{ch,ntr}_{s_{ntr}} \cdot Q^{ch,ntr}_{s_{ntr},ec,l,p,d,t} - \frac{1}{\eta^{dis,ntr}_{s_{ntr}}} \cdot Q^{dis,ntr}_{s_{ntr},ec,l,p,d,t} | & \\ +(1 - \eta^{self,ntr}_{s_{ntr}}) \cdot SoC^{ntr}_{s_{ntr},ec,l,p,d,t-1} & ,t \neq 1 \end{cases} \tag{61}$$
$$\forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ |\ \{\ spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\}$$

5.39 Equation 56

Constraint for the maximum allowable charging rate of the tracked storage technologies:
`Storage_charge_rate_constr_tr_rule`

$$Q^{ch,tr}_{s_{tr},ec,l,w,p,d,t} \leq q^{ch,max,tr}_{s_{tr},w} \cdot TCAP^{stor,tr}_{s_{tr},ec,l,w,p}\ \forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}\ | \\ \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \tag{62}$$

5.40 Equation 57

Constraint for the maximum allowable charging rate of the non-tracked storage technologies:
`Storage_charge_rate_constr_ntr_rule`

$$Q^{ch,ntr}_{s_{ntr},ec,l,p,d,t} \leq q^{ch,max,ntr}_{s_{ntr}} \cdot TCAP^{stor,ntr}_{s_{ntr},ec,l,p}\ \forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}| \\ \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{63}$$

5.41 Equation 58

Constraint for the maximum allowable discharging rate of the tracked storage technologies:
`Storage_discharge_rate_constr_tr_rule`

$$Q^{dis,tr}_{s_{tr},ec,l,w,p,d,t} \leq q^{dis,max,tr}_{s_{tr},w} \cdot TCAP^{stor,tr}_{s_{tr},ec,l,w,p}\ \forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T}| \\ \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1, spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \tag{64}$$

5.42 Equation 59

Constraint for the maximum allowable discharging rate of the non-tracked storage technologies:
`Storage_discharge_rate_constr_ntr_rule`

$$Q^{dis,ntr}_{s_{ntr},ec,l,p,d,t} \leq q^{dis,max,ntr}_{s_{ntr}} \cdot TCAP^{stor,ntr}_{s_{ntr},ec,l,p} \ \forall \ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{65}$$

5.43 Equation 60

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

$$SoC^{min,tr}_{s_{tr},ec,l,w,p,d} \leq SoC^{tr}_{s_{tr},ec,l,w,p,d,t} \ \forall \ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \tag{66}$$

5.44 Constraint 61

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

$$\begin{gathered} SoC^{max,tr}_{s_{tr},ec,l,w,p,d} \geq SoC^{tr}_{s_{tr},ec,l,w,p,d,t} \\ \forall \ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \\ \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \end{gathered} \tag{67}$$

5.45 Constraint 62

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

$$SoC^{min,ntr}_{s_{ntr},ec,l,p,d} \leq SoC^{ntr}_{s_{ntr},ec,l,p,d,t} \forall \ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{68}$$

5.46 Constraint 63

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

$$SoC^{max,ntr}_{s_{ntr},ec,l,p,d} \geq SoC^{ntr}_{s_{ntr},ec,l,p,d,t} \forall \ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ d \in \mathcal{D},\ t \in \mathcal{T} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{69}$$

5.47 Constraint 64

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

$$\begin{gathered} SoC^{interday,tr}_{s_{tr},ec,l,w,p,cd} = \begin{cases} 0 & , p = w \land cd = 1 \\ SoC^{interday,tr}_{s_{tr},ec,l,w,p-1,max(cd)} \cdot (1 - \eta^{self,tr}_{s_{tr},w})^{max(t)} \\ \ +SoC^{tr}_{s_{tr},ec,l,w,p-1,cd2td_{p-1,max(cd)},max(t)} & , p \neq w \land cd = 1 \\ SoC^{interday,tr}_{s_{tr},ec,l,w,p,cd-1} \cdot (1 - \eta^{self,tr}_{s_{tr},w})^{max(t)} \\ \ +SoC^{tr}_{s_{tr},ec,l,w,p,cd2td_{p,cd-1},max(t)} & , cd \neq 1 \end{cases} \\ \forall \ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \\ \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \end{gathered} \tag{70}$$

5.48 Constraint 65

Constraint connecting the inter-day state-of-charge of a non-tracked storage technology:
`Storage_inter_day_connection_ntr_rule`

$$SoC^{interday,ntr}_{s_{ntr},ec,l,p,cd} = \begin{cases} 0 & ,p = 1 \land cd = 1 \\ SoC^{interday,ntr}_{s_{ntr},ec,l,p-1,max(cd)} \cdot (1 - \eta^{self,ntr}_{s_{ntr}})^{max(t)} & \\ \quad +SoC^{ntr}_{s_{ntr},ec,l,p-1,cd2td_{p-1,max(cd)},max(t)} & ,p \neq 1 \land cd = 1 \\ SoC^{interday,ntr}_{s_{ntr},ec,l,p,cd-1} \cdot (1 - \eta^{self,ntr}_{s_{ntr}})^{max(t)} & \\ \quad +SoC^{ntr}_{s_{ntr},ec,l,p,cd2td_{p,cd-1},max(t)} & ,cd \neq 1 \end{cases}$$
$$\forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{71}$$

5.49 Constraint 66

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

$$SoC^{interday,tr}_{s_{tr},ec,l,w,p,cd} + SoC^{max,tr}_{s_{tr},ec,l,w,p,cd2td_{p,cd}} \leq TCAP^{stor,tr}_{s_{tr},ec,l,w,p}$$
$$\forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \tag{72}$$

5.50 Constraint 67

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

$$SoC^{interday,ntr}_{s_{ntr},ec,l,p,cd} + SoC^{max,ntr}_{s_{ntr},ec,l,p,cd2td_{p,cd}} \leq TCAP^{stor,ntr}_{s_{ntr},ec,l,p}$$
$$\forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{73}$$

5.51 Constraint 68

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

$$SoC^{interday,tr}_{s_{tr},ec,l,w,p,cd} \cdot (1 - \eta^{self,tr}_{s_{tr},w})^{max(t)} + SoC^{min,tr}_{s_{tr},ec,l,w,p,cd2td_{p,cd}} \geq 0$$
$$\forall\ s_{tr} \in \mathcal{S}_{tr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{p \geq w, p \leq w + sl^{p}_{s_{tr}} - 1\ ,\ spl_{s_{tr},l} = 1,\ stc_{s_{tr},ec} = 1\} \tag{74}$$

5.52 Constraint 69

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

$$SoC^{interday,ntr}_{s_{ntr},ec,l,p,cd} \cdot (1 - \eta^{self,ntr}_{s_{ntr}})^{max(t)} + SoC^{min,ntr}_{s_{ntr},ec,l,p,cd2td_{p,cd}} \geq 0$$
$$\forall\ s_{ntr} \in \mathcal{S}_{ntr},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ p \in \mathcal{P},\ cd \in \mathcal{CD} \mid \{spl_{s_{ntr},l} = 1,\ stc_{s_{ntr},ec} = 1\} \tag{75}$$

5.53 Constraint 70

Minimum possible storage technology capacity per technology considered:
`Storage_minimum_cap_limit_rule`

$$NCAP^{stor}_{s,ec,l,w} \geq cap^{min}_{s} \cdot Y^{stor}_{s,l,w} \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{76}$$

5.54 Constraint 71

Maximum possible storage technology capacity per technology considered:
`Storage_maximum_cap_limit_rule`

$$NCAP^{stor}_{s,ec,l,w} \leq cap^{max}_{s}\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{77}$$

5.55 Constraint 72

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

$$\begin{aligned}&\text{If } s \in \mathcal{S}_{tr}: \sum_{\substack{w \in \mathcal{W} \\ p \geq w \\ p \leq w+sl_s^p-1}} TCAP^{stor,tr}_{s,ec,l,w,p} \leq cap^{max}_{s,l} \\ &\text{If } s \notin \mathcal{S}_{tr}: TCAP^{stor,ntr}_{s,ec,l,p} \leq cap^{max}_{s,l} \\ &\forall\ s \in \mathcal{S},\ ec \in \mathcal{EC}\ ,\ l \in \mathcal{L}\ ,\ p \in \mathcal{P} \mid \{spl_{s,l} = 1,\ stc_{s,ec} = 1\}\end{aligned} \tag{78}$$

5.56 Constraint 73

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

$$NCAP^{stor}_{s,ec,l,w} \leq bigM \cdot Y^{stor}_{s,l,w}\ \forall\ s \in \mathcal{S},\ ec \in \mathcal{EC},\ l \in \mathcal{L},\ w \in \mathcal{W} \mid\ \{spl_{s,l} = 1,\ stc_{s,ec} = 1\} \tag{79}$$

5.57 Constraint 74

Constraint setting the capacity for existing storage technologies:
`Existing_stor_capacity_setting_rule`

$$NCAP^{stor}_{s_{ex},ec,l,1} = excap^{stor}_{s_{ex},ec,l}\ \forall\ s_{ex} \in \mathcal{S}_{ex},\ ec \in \mathcal{EC},\ l \in \mathcal{L} \mid \{spl_{s_{ex},l} = 1,\ stc_{s_{ex},ec} = 1\} \tag{80}$$

5.58 Constraint 75

Constraint limiting the possibility of reinvesting in existing storage technologies:
`Existing_stor_no_reinvestment_rule`

$$\text{If } w \neq 1: Y^{stor}_{s_{ex},l,w} = 0\ \forall\ s_{ex} \in \mathcal{S}_{ex},\ l \in \mathcal{L}\ ,\ w \in \mathcal{W} \mid spl_{s_{ex},l} = 1 \tag{81}$$

5.59 Constraint 76

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

$$C^{imp}_{l,y} = \sum_{ec_i \in \mathcal{EC}_i} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P^{imp}_{ec_i,l,y2p_y,d,t} \cdot p_{ec_i,y} \cdot nd_{y2p_y,d}\ \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \tag{82}$$

5.60 Constraint 77

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

$$C^{imp,disc}_{l,y} = C^{imp}_{l,y} \cdot \frac{1}{(1+r)^y}\ \forall\ l \in \mathcal{L},\ y \in \mathcal{Y} \tag{83}$$

5.61 Constraint 78

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

$$C^{imp}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1)\cdot ny^p+1 \\ y \leq p \cdot ny^p}} C^{imp}_{l,y}\ \forall\ l \in \mathcal{L},\ p \in \mathcal{P} \tag{84}$$

5.62 Constraint 79

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

$$C_{l,p}^{imp,disc} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} C_{l,y}^{imp,disc} \ \forall \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{85}$$

5.63 Constraint 80

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

$$C_{ec_i,l,y}^{imp} = \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P_{ec_i,l,y2p_y,d,t}^{imp} \cdot p_{ec_i,y} \cdot nd_{y2p_y,d} \ \forall \ ec_i \in \mathcal{EC}_i, \ l \in \mathcal{L}, \ y \in \mathcal{Y} \tag{86}$$

5.64 Constraint 81

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

$$C_{ec_i,l,y}^{imp,disc} = C_{ec_i,l,y}^{imp} \cdot \frac{1}{(1+r)^y} \ \forall \ ec_i \in \mathcal{EC}_i, \ \forall \ l \in \mathcal{L}, \ y \in \mathcal{Y} \tag{87}$$

5.65 Constraint 82

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

$$C_{ec_i,l,p}^{imp} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} C_{ec_i,l,y}^{imp} \ \forall \ ec_i \in \mathcal{EC}_i, \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{88}$$

5.66 Constraint 83

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

$$C_{ec_i,l,p}^{imp,disc} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} C_{ec_i,l,y}^{imp,disc} \ \forall \ ec_i \in \mathcal{EC}_i, \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{89}$$

5.67 Constraint 84

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

$$R_{l,y}^{exp} = \sum_{ec_e \in \mathcal{EC}_e} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P_{ec_e,l,y2p_y,d,t}^{exp} \cdot p_{ec_e,y} \cdot nd_{y2p_y,d} \ \forall \ l \in \mathcal{L}, \ y \in \mathcal{Y} \tag{90}$$

5.68 Constraint 85

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

$$R_{l,y}^{exp,disc} = R_{l,y}^{exp} \cdot \frac{1}{(1+r)^y} \ \forall \ l \in \mathcal{L}, \ y \in \mathcal{Y} \tag{91}$$

5.69 Constraint 86

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

$$R^{exp}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} R^{exp}_{l,y} \ \forall \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{92}$$

5.70 Constraint 87

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

$$R^{exp,disc}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} R^{exp,disc}_{l,y} \ \forall \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{93}$$

5.71 Constraint 88

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

$$\begin{aligned} C^{main}_{l,y} = & \sum_{\substack{c \in \mathcal{C} \\ cpl_{c,l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ ((c \in \mathcal{C}_d \wedge \exists \ ec \in \mathcal{EC} \ | \ ecc^{disp}_{c,ec,ec'}=1) \ \vee rcc_{c,ec'}=1)}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y^{real}_w \\ y \leq y^{real}_w + cl_c - 1}} (fc^{conv}_{c,ec',w} \cdot Y^{conv}_{c,l,w} + lc^{conv}_{c,ec',w} \cdot NCAP^{conv}_{c,ec',l,w}) \cdot om^{conv}_c \\ & + \sum_{\substack{r_{dam} \in \mathcal{R}_{dam} \\ cpl_{r_{dam},l}=1}} \sum_{\substack{ec' \in \mathcal{EC} \\ rcc_{r_{dam},ec'}=1}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y^{real}_w \\ y \leq y^{real}_w + cl_{r_{dam}} - 1}} (fc^{dam}_{r_{dam},ec',w} \cdot Y^{conv}_{r_{dam},l,w} + lc^{dam}_{r_{dam},ec',w} \cdot NCAP^{dam}_{r_{dam},ec',l,w}) \cdot om^{conv}_{r_{dam}} \\ & + \sum_{\substack{s \in \mathcal{S} \\ spl_{s,l}=1}} \sum_{\substack{ec \in \mathcal{EC} \\ stc_{s,ec}=1}} \sum_{\substack{w \in \mathcal{W} \\ y \geq y^{real}_w \\ y \leq y^{real}_w + cl_s - 1}} (fc^{stor}_{s,ec,w} \cdot Y^{stor}_{s,l,w} + lc^{stor}_{s,ec,w} \cdot NCAP^{stor}_{s,ec,l,w}) \cdot om^{stor}_s \\ & \forall \ l \in \mathcal{L}, \ y \in \mathcal{Y} \end{aligned} \tag{94}$$

5.72 Constraint 89

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

$$C^{main,disc}_{l,y} = C^{main}_{l,y} \cdot \frac{1}{(1+r)^y} \ \forall \ l \in \mathcal{L}, \ y \in \mathcal{Y} \tag{95}$$

5.73 Constraint 90

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

$$C^{main}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} C^{main}_{l,y} \ \forall \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{96}$$

5.74 Constraint 91

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

$$C^{main,disc}_{l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} C^{main,disc}_{l,y} \ \forall \ l \in \mathcal{L}, \ p \in \mathcal{P} \tag{97}$$

5.75 Constraint 92

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

$$
\begin{aligned}
&\mathrm{C}^{conv,inv}_{l,w} = \\
&\sum_{\substack{c\in\mathcal{C}\\ cpl_{c,l}=1}} \sum_{\substack{ec'\in\mathcal{EC}\\ ((c\in\mathcal{C}_d \wedge \exists\ ec\in\mathcal{EC}\ \mid\ ecc^{disp}_{c,ec,ec'}=1)\ \vee rcc_{c,ec'}=1)}} fc^{conv}_{c,ec',w}\cdot Y^{conv}_{c,l,w} + lc^{conv}_{c,ec',w}\cdot NCAP^{conv}_{c,ec',l,w} \\
&+ \sum_{\substack{r_{dam}\in\mathcal{R}_{dam}\\ cpl_{r_{dam},l}=1}} \sum_{\substack{ec'\in\mathcal{EC}\\ rcc_{r_{dam},ec'}=1}} fc^{dam}_{r_{dam},ec',w}\cdot Y^{conv}_{r_{dam},l,w} + lc^{dam}_{r_{dam},ec',w}\cdot NCAP^{dam}_{r_{dam},ec',l,w} \\
&\forall\ l\in\mathcal{L},\ w\in\mathcal{W}
\end{aligned}
$$

5.76 Constraint 93

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

$$C^{conv,inv,disc}_{l,w} = C^{conv,inv}_{l,w}\cdot\frac{1}{(1+r)^{y^{real}_w-1}}\ \ \forall\ l\in\mathcal{L},\ w\in\mathcal{W} \tag{98}$$

```
def Conv_investment_cost_disc_rule(m, s, stg):
    return m.Conv_investment_cost_disc[s, stg] == m.Conv_investment_cost_nmnl[
        s, stg
    ] / ((1 + m.Discount_rate) ** (m.Real_investment_stages[stg] - 1))

self.m.Conv_investment_cost_disc_def = pe.Constraint(
    self.m.Sites,
    self.m.Investment_stages,
    rule=Conv_investment_cost_disc_rule,
    doc="Definition of the investment expenditure for the purchase of conversion technologies at e
)
```

5.77 Constraint 94

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

$$C^{stor,inv}_{l,w} = \sum_{\substack{s\in\mathcal{S}\\ spl_{s,l}=1}}\sum_{\substack{ec\in\mathcal{EC}\\ stc_{s,ec}=1}} fc^{stor}_{s,ec,w}\cdot Y^{stor}_{s,l,w} + lc^{stor}_{s,ec,w}\cdot NCAP^{stor}_{s,ec,l,w}\ \forall\ l\in\mathcal{L},\ w\in\mathcal{W} \tag{99}$$

5.78 Constraint 95

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

$$C^{stor,inv,disc}_{l,w} = C^{stor,inv}_{l,w}\cdot\frac{1}{(1+r)^{y^{real}_w-1}}\ \ \forall\ l\in\mathcal{L},\ w\in\mathcal{W} \tag{100}$$

5.79 Constraint 96

Definition of the investment expenditure for the interconnections between sites:
`Exchange_network_expansion_cost_nmnl_rule`

$$C^{exc,inv}_{l,w} = \sum_{ec_x\in\mathcal{EC}_x}\sum_{\substack{l'\in\mathcal{L}\\ l'\neq l\\ linepl_{ec_x,l,l'}=1}} (NCAP^{exc}_{ec_x,l,l',w}\cdot lc^{exc}_{ec_x,w} + Y^{exc}_{ec_x,l,l',w}\cdot fc^{exc}_{ec_x,w})\cdot x_{l,l'}\cdot 0.5\ \forall\ l\in\mathcal{L},\ w\in\mathcal{W} \tag{101}$$

5.80 Constraint 97

Definition of the investment expenditure for the interconnections between sites:
`Exchange_network_expansion_cost_disc_rule`

$$C_{l,w}^{exc,inv,disc} = C_{l,w}^{exc,inv} \cdot \frac{1}{(1+r)^{y_w^{real}-1}} \ \ \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{102}$$

5.81 Constraint 98

Definition of the expenditure to expand export capacities:
`Export_capacity_expansion_cost_nmnl_rule`

$$C_{l,w}^{exp,inv} = \sum_{ec_e \in \mathcal{EC}_e} NCAP_{ec_e,l,w}^{exp} \cdot lc_{ec_e,w}^{exp} + Y_{ec_e,l,w}^{exp} \cdot fc_{ec_e,w}^{exp}\ \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{103}$$

5.82 Constraint 99

Definition of the expenditure to expand export capacities:
`Export_capacity_expansion_cost_disc_rule`

$$C_{l,w}^{exp,inv,disc} = C_{l,w}^{exp,inv} \cdot \frac{1}{(1+r)^{y_w^{real}-1}} \ \ \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{104}$$

5.83 Constraint 100

Definition of the expenditure to expand import capacities:
`Import_capacity_expansion_cost_nmnl_rule`

$$C_{l,w}^{imp,inv} = \sum_{ec_i \in \mathcal{EC}_i} NCAP_{ec_i,l,w}^{imp} \cdot lc_{ec_i,w}^{imp} + Y_{ec_i,l,w}^{imp} \cdot fc_{ec_i,w}^{imp}\ \forall\ l \in \mathcal{L},\ w \in \mathcal{W} \tag{105}$$

5.84 Constraint 111

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

$$T_y^{cost,disc} = \sum_{l \in \mathcal{L}} C_{l,y}^{disc}\ \forall\ y \in \mathcal{Y} \tag{106}$$

5.85 Constraint 112

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

$$T_p^{cost} = \sum_{l \in \mathcal{L}} C_{l,p}\ \forall\ p \in \mathcal{P} \tag{107}$$

5.86 Constraint 113

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

$$T_p^{cost,disc} = \sum_{l \in \mathcal{L}} C_{l,p}^{disc}\ \forall\ p \in \mathcal{P} \tag{108}$$

5.87 Constraint 114

Definition of the total cost model objective function:
`Total_system_cost_nmnl_rule`

$$\begin{aligned} T^{cost} = & \\ & \sum_{l \in \mathcal{L}} \sum_{w \in \mathcal{W}} C^{conv,inv}_{l,w} + C^{stor,inv}_{l,w} + C^{exc,inv}_{l,w} + C^{imp,inv}_{l,w} + C^{exp,inv}_{l,w} \\ & + \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} C^{imp}_{l,p} - R^{exp}_{l,p} + C^{main}_{l,p} \\ & - \sum_{l \in \mathcal{L}} R^{slvg}_{l} \end{aligned} \tag{109}$$

5.88 Constraint 115

Definition of the total cost model objective function:
`Total_system_cost_disc_rule`

$$\begin{aligned} T^{cost} = & \\ & \sum_{l \in \mathcal{L}} \sum_{w \in \mathcal{W}} C^{conv,inv,disc}_{l,w} + C^{stor,inv,disc}_{l,w} + C^{exc,inv,disc}_{l,w} + C^{imp,inv,disc}_{l,w} + C^{exp,inv,disc}_{l,w} \\ & + \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} C^{imp,disc}_{l,p} - R^{exp,disc}_{l,p} + C^{main,disc}_{l,p} \\ & - \sum_{l \in \mathcal{L}} R^{slvg,disc}_{l} \end{aligned} \tag{110}$$

5.89 Constraint 116

Definition of the total cost model objective function:
`Total_system_cost_def`

$$\begin{aligned} T^{cost} = & \\ & \sum_{l \in \mathcal{L}} \sum_{w \in \mathcal{W}} C^{conv,inv,disc}_{l,w} + C^{stor,inv,disc}_{l,w} + C^{exc,inv,disc}_{l,w} + C^{imp,inv,disc}_{l,w} + C^{exp,inv,disc}_{l,w} \\ & + \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} C^{imp,disc}_{l,p} - R^{exp,disc}_{l,p} + C^{main,disc}_{l,p} \\ & - \sum_{l \in \mathcal{L}} R^{slvg,disc}_{l} \end{aligned} \tag{111}$$

5.90 Constraint 117

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

$$T^{CO_2}_{ec_i,l,y} = \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P^{imp}_{ec_i,l,y2p_y,d,t} \cdot carb_{ec_i,y} \cdot nd_{y2p_y,d} \; \forall \; ec_i \in \mathcal{EC}_i, l \in \mathcal{L}, y \in \mathcal{Y} \tag{112}$$

5.91 Constraint 118

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

$$T^{CO_2}_{ec_i,l,p} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T^{CO_2}_{ec_i,l,y} \; \forall \; ec_i \in \mathcal{EC}_i, l \in \mathcal{L}, p \in \mathcal{P} \tag{113}$$

5.92 Constraint 119

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

$$T_{l,y}^{CO_2} = \sum_{ec_i \in \mathcal{EC}_i} \sum_{d \in \mathcal{D}} \sum_{t \in \mathcal{T}} P_{ec_i,l,y2p_y,d,t}^{imp} \cdot carb_{ec_i,y} \cdot nd_{y2p_y,d} \;\forall\; l \in \mathcal{L}, y \in \mathcal{Y} \tag{114}$$

5.93 Constraint 120

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

$$T_{l,p}^{CO_2} = \sum_{\substack{y \in \mathcal{Y} \\ y \geq (p-1) \cdot ny^p + 1 \\ y \leq p \cdot ny^p}} T_{l,y}^{CO_2} \;\forall\; l \in \mathcal{L}, p \in \mathcal{P} \tag{115}$$

5.94 Constraint 121

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

$$T_l^{CO_2} = \sum_{p \in \mathcal{P}} T_{l,p}^{CO_2} \;\forall\; l \in \mathcal{L} \tag{116}$$

5.95 Constraint 122

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

$$T_y^{CO_2} = \sum_{l \in \mathcal{L}} T_{l,y}^{CO_2} \;\forall\; y \in \mathcal{Y} \tag{117}$$

5.96 Constraint 123

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

$$T_p^{CO_2} = \sum_{l \in \mathcal{L}} T_{l,p}^{CO_2} \;\forall\; p \in \mathcal{P} \tag{118}$$

5.97 Constraint 124

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

$$T^{CO_2} = \sum_{l \in \mathcal{L}} \sum_{p \in \mathcal{P}} T_{l,p}^{CO_2} \tag{119}$$

5.98 Constraint 125

Constraint setting an upper limit to the total carbon emissions of the system:
`Carbon_constraint_rule`

$$T^{CO_2} \leq \epsilon \tag{120}$$

5.99 Constraint 126

Constraint setting emissions to zero for the last year of the analysis:
`Net_zero_constraint_rule`

$$T_{max(y)}^{CO_2} = 0 \tag{121}$$

5.100 Constraint 127

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

$$POUT_{c,ec',l,y} = \begin{cases} \sum\limits_{\substack{w\in\mathcal{W} \\ y\geq y_w^{real} \\ y\leq y_w^{real}+cl_c-1}} \sum\limits_{d\in\mathcal{D}}\sum\limits_{t\in\mathcal{T}} POUT^{disp,tr}_{c,ec',l,w,y2p_y,d,t}\cdot nd_{y2p_y,d} & ,c\in\mathcal{C}_{d\_tr} \\ \sum\limits_{d\in\mathcal{D}}\sum\limits_{t\in\mathcal{T}} POUT^{disp,ntr}_{c,ec',l,y2p_y,d,t}\cdot nd_{y2p_y,d} & ,c\in\mathcal{C}_{d\_ntr} \\ \sum\limits_{\substack{w\in\mathcal{W} \\ y\geq y_w^{real} \\ y\leq y_w^{real}+cl_c-1}} \sum\limits_{d\in\mathcal{D}}\sum\limits_{t\in\mathcal{T}} POUT^{re,tr}_{c,ec',l,w,y2p_y,d,t}\cdot nd_{y2p_y,d} & ,c\in\mathcal{R}_{tr} \\ \sum\limits_{d\in\mathcal{D}}\sum\limits_{t\in\mathcal{T}} POUT^{re,ntr}_{c,ec',l,y2p_y,d,t}\cdot nd_{y2p_y,d} & ,c\in\mathcal{R}_{ntr} \end{cases} \tag{122}$$

$$\forall\ c\in\mathcal{C},\ ec'\in\mathcal{EC},\ l\in\mathcal{L},\ y\in\mathcal{Y}\ |\ cpl_{c,l}=1\wedge((c\in\mathcal{C}_d\wedge\exists\ ec\in\mathcal{EC}\ |\ ecc^{disp}_{c,ec,ec'}=1)\ \vee rcc_{c,ec'}=1)$$

5.101 Constraint 128

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

$$POUT_{c,ec',l,p} = \sum_{\substack{y\in\mathcal{Y} \\ y\geq(p-1)\cdot ny^p+1 \\ y\leq p\cdot ny^p}} POUT_{c,ec',l,y} \tag{123}$$

$$\forall\ c\in\mathcal{C},\ ec'\in\mathcal{EC},\ l\in\mathcal{L},\ p\in\mathcal{P}\ |\ cpl_{c,l}=1\wedge((c\in\mathcal{C}_d\wedge\exists\ ec\in\mathcal{EC}\ |\ ecc^{disp}_{c,ec,ec'}=1)\ \vee rcc_{c,ec'}=1)$$