SELARU modelling framework

Technical documentation

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1 Overview

SELARU (**S**patially-explicit **E**nergy and **LA**nd system Infrast**RU**cture) modelling framework is a high-resolution spatially explicit analytical tool for integrated assessments of energy and land systems using Mixed-Integer Linear Programming (MILP) optimization approach. The main feature of SELARU is its capability to address economies of scale that occur from geographical expansion of energy and land system infrastructures. This allows a more accurate system depiction to facilitate scientific investigations concerning long term infrastructure sitting/deployment in a highly complex and geographically diverse environment.

In this version, the application of SELARU is limited to Indonesia's electricity sector coupled with CCS infrastructures (**Figure 1**) to demonstrate the impact of myopic vis-à-vis perfect foresight decision-making in long-term energy system optimization. SELARU generates optimal configuration of technology application for power generation, transmission lines and substations that minimizes total system cost throughout the planning horizon. The optimization is achieved through minimizing total system costs while guaranteeing security of supply, ensuring technically feasible operation. SELARU endogenously determines the capacity expansion decisions in every 20-year timestep from 2020 to 2100.

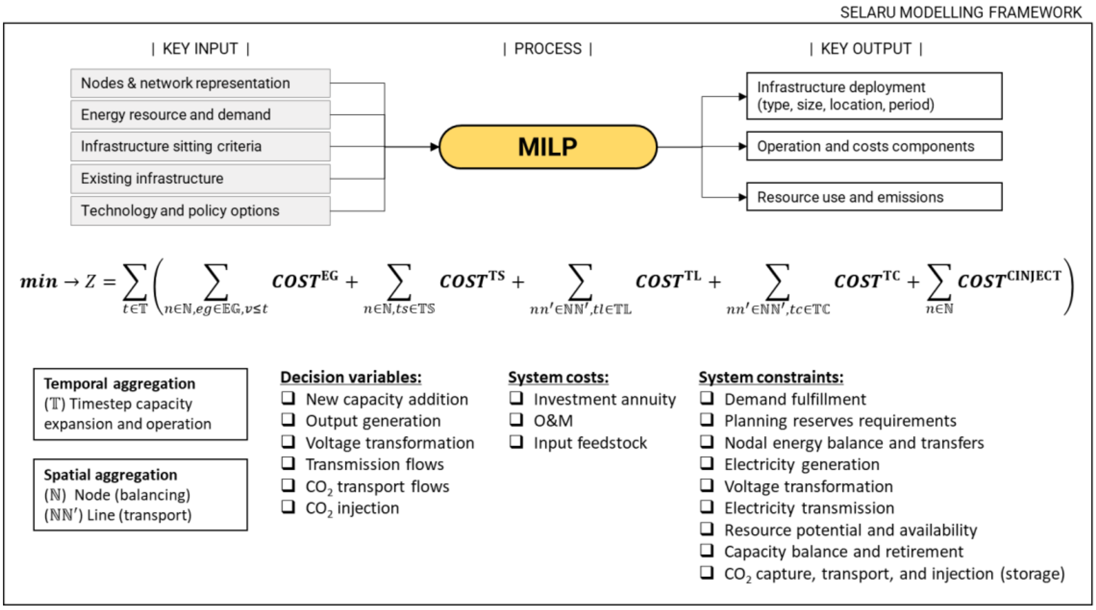

Figure 1 | Schematic overview of SELARU modelling framework for Indonesia power sector.

The modelled energy system is represented as a network of interconnecting nodes. A node in the network represents a region in which energy can be utilized, converted, stored, or send-in or -out. The lines connecting different nodes represent the connections or transmission corridors along which energy can be transported. Consequently, the basic framework of the energy system model is given by the energy balance and transfers at and from or to nodes in all times.

The required capacity deployment, generation, voltage-transformation, transmission flows, reserve capacity, and primary energy feedstock are endogenously determined by ensuring the nodal supply-demand balances are satisfied all the time. The modelled energy system is formulated using sets of equations defining the costs and technical constraints of capacity deployment and operation. The objective of optimization is to minimize the system's costs while guaranteeing security of supply, ensuring technically feasible operation, and considering region-specific resource availability and environmental restriction. Spatial-explicit information of resource, supply, and demand, as well as region-specific policy interventions are exogenously considered for each modelled timestep.

2 Spatial representation

SELARU uses nodes and lines to represent the spatial context of energy systems. The nodes represent geographic areas within which selection of technologies for power generation, storage, transmission lines and substations will be solved as decision variables. The nodes also contain information such as potential of renewables, energy demand, and area of exclusion zones originating from spatial aggregation within the regions that the nodes represent. The lines connecting different nodes represent eligible connections or transmission corridors along which electricity can be transported. The default mode of SELARU Indonesia application comprises 516 nodes and 1,624 lines that connect the nodes (**Figure 2**). The nodes are generated through clustering villages as the lowest administrative unit in Indonesia. This selection assumes that the village map is a suitable proximation for the geographic distribution of socio-economic activities. 83,458 villages are aggregated to 500 clusters using k-Clusters algorithm[1] performed in QGIS software. Under the algorithm, mean coordinates of villages that belong to a unique cluster—weighted using their population density and distances to neighbor villages—are used as the basis for Voronoi Tessellation[2] to generate polygons describing the clusters' bounding area. Clustered zones that include different islands or separated by water body are further divided, resulting in 516 nodes that represent areas ranging from 0.01-20,300 km^2, with an average of 217 km^2 which is comparable to 0.14° geographic grid resolution. International electricity trade with neighboring countries is not considered.

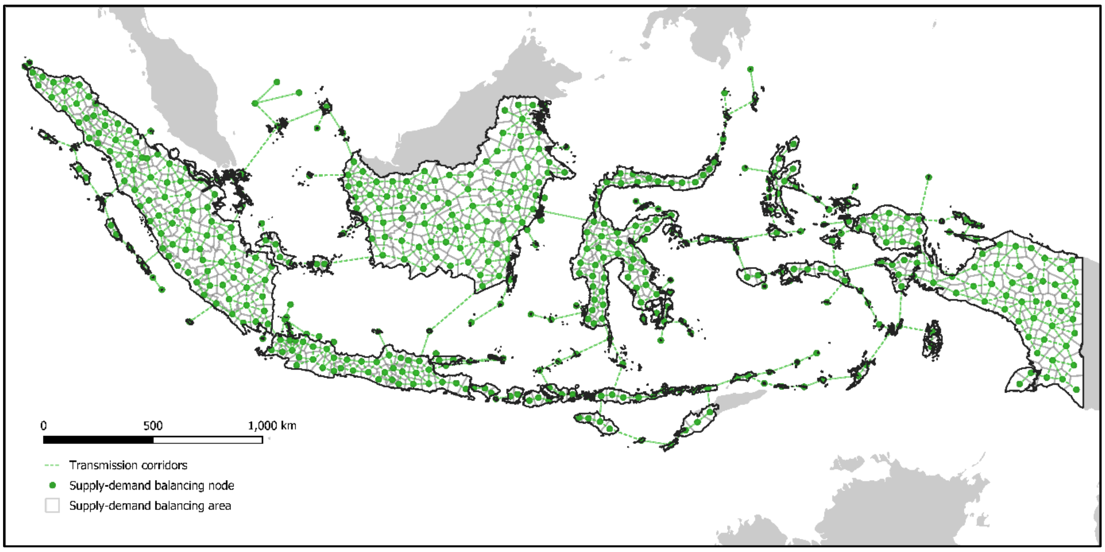

Figure 2 | Spatial representation for SELARU Indonesia application comprises 516 nodes of supply-demand balancing regions (green dots with associated bounding area outlined in black) and 1,624 possible inter-nodal connections (lines in green).

[1] Hartigan, J. A. & Wong, M. A. Algorithm AS 136: A K-Means Clustering Algorithm. *J. R. Stat. Soc. Ser. C Appl. Stat.* **28**, 100–108 (1979)
[2] Boots, B., Sugihara, K., Chiu, S. N. & Okabe, A. *Spatial Tessellations: Concepts and Applications of Voronoi Diagrams*. (John Wiley & Sons, 2009)

3 Input data

The input data that are used in this SELARU version were compiled from the following sources:

Geographical context

Includes administrative boundaries, land cover and topography:

https://data.humdata.org/dataset/cod-ab-idn
https://www.indonesia-geospasial.com/2020/09/download-shp-tutupan-lahan-tahun-2019.html
https://www.restoreplus.org/uploads/1/0/4/5/104525257/restore__technical_report_land_cover_mapping_july2022.pdf
https://www.earthenv.org/topography

Renewable energy resources

Geothermal, hydropower, solar, and wind resources:

https://geoportal.esdm.go.id/potensiebtke/
https://datacatalog.worldbank.org/search/dataset/0042082
https://globalsolaratlas.info/map

Fuel related parameters

Covers fossil fuel and biomass assumed to be abundantly available due to maturity of supply chain:

https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf
https://www2.deloitte.com/content/dam/Deloitte/ca/Documents/energy-resources/ca-en-energy-resources-industrials-o-g-price-forecast-report-Q4-aoda.pdf?icid=commentaryEN
https://www.eia.gov/outlooks/steo/report/prices.php
https://migas.esdm.go.id/uploads/harga-indek-pasar-/2020-hip/hip-solar-dalam-rangka-perhitungan-selisih-tahun-2020.pdf
https://www.minerba.esdm.go.id/harga_acuan
https://jdih.esdm.go.id/index.php/web/result/2355/detail
https://www.liputan6.com/bisnis/read/4401992/menengok-harga-keekonomian-biomassa-bahan-baku-cofiring-pltu
https://winrock.org/wp-content/uploads/2016/05/CIRCLE-Handbook-2nd-Edition-EN-25-Aug-2015-MASTER-rev02-final-new02-edited.pdf
https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/sustainable-supply-potential-and-costs
https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx#:~:text=Its%202020%20report%2C%20Capital%20Cost,%2FkWe%20(overnight%20cost).
https://www.eia.gov/opendata/v1/qb.php?category=40290&sdid=SEDS.NUETD.WI.A
https://www.eia.gov/uranium/marketing/#:~:text=During%202021%2C%2019%25%20of%20the,per%20pound%20(Table%207).
https://www.world-nuclear.org/uploadedfiles/org/info/pdf/economicsnp.pdf

Electricity generation parameters

Technoeconomic parameters related to plant-sitting investment decisions:

https://www.irena.org/publications/2021/Jun/Renewable-Power-Costs-in-2020
https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf

https://atb.nrel.gov/
https://atb.nrel.gov/electricity/2021/equations_&_variables#equations
https://www.nrel.gov/docs/fy19osti/74184.pdf
https://www.nrel.gov/docs/fy21osti/77324.pdf
https://www.nrel.gov/docs/fy13osti/56290.pdf
https://globalwindatlas.info/about/ReleaseNotes
https://www.nrel.gov/docs/fy21osti/78882.pdf
https://www.nrel.gov/analysis/tech-size.html
https://www.gem.wiki/Concentrating_solar_power_land_use
https://ourworldindata.org/land-use-per-energy-source
https://docs.wind-watch.org/US-footprints-Strata-2017.pdf
https://ens.dk/sites/ens.dk/files/Globalcooperation/technology_data_for_the_indonesian_power_sector_-_final.pdf

Grid related parameters

Substation, transmissions and basis for assumptions on planning reserve margin:

https://iea-etsap.org/E-TechDS/PDF/E12_el-t&d_KV_Apr2014_GSOK.pdf
https://www.adb.org/sites/default/files/linked-documents/47296-001-ea.pdf
https://www.wecc.org/Administrative/TEPPC_TransCapCostCalculator_E3_2019_Update.xlsx
https://web.pln.co.id/statics/uploads/2021/10/ruptl-2021-2030.pdf

CCS related parameters

CO_2 capture, transport, and storage assumptions:

https://iea-etsap.org/E-TechDS/PDF/E14_CCS_oct2010_GS_gc_AD_gs.pdf
https://ieaghg.org/docs/general_publications/cocapture.pdf
https://www.globalccsinstitute.com/archive/hub/publications/119811/costs-co2-transport-post-demonstration-ccs-eu.pdf
https://www.iea.org/data-and-statistics/charts/shipping-and-offshore-pipeline-transportation-costs-of-co2-by-distance

Socio-economic data for demand projection

Spatially explicit projections of electricity demand are exogenous input to the model. Demand information is obtained from national demand projection and its downscaling to take into account regional disparities in accordance with the spatial resolution of the analysis. Projection is based on linear regression throughout the modelling time horizon with dependent variables including historical data for electricity consumption[3], population[4], gross domestic product (GDP) at corresponding spatial resolutions (i.e. national, provincial and district levels)[5], and population projection from the Shared Socioeconomic Pathways "Middle of the road" scenario (SSP2)[6].

[3] PLN (2022), https://web.pln.co.id/statics/uploads/2022/08/Statistik-PLN-2021-29-7-22-Final.pdf
[4] BPS (2022), https://www.bps.go.id/pressrelease/2021/01/21/1854/hasil-sensus-penduduk-2020.html
[5] BPS (2019), https://www.bps.go.id/publication/2019/10/04/9812a1c4ea25298004839596/produk-domestik-regional-bruto-kabupaten-kota-di-indonesia-2014-2018.html
[6] Riahi, K. et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change 42, 153–168 (2017)

4 MILP formulation

Optimization in SELARU is formulated as an MILP model using the General Algebraic Modelling System (GAMS).

4.1 Nomenclature

Sets and indices

$y \in \mathbb{Y}$	year in parameterized time-step
$v \in \mathbb{Y}$	technology vintage year
$n\|n' \in \mathbb{N}$	nodes of energy supply and demand balancing
$nn' \in \mathbb{NN}$	lines of connection from node (n) to another node (n')
$i \in \mathbb{I}$	type of technology
$eg \in \mathbb{EG}$	type of electricity generation technology
$greg \in \mathbb{GREG}$	group of electricity generation technology
$ts \in \mathbb{TS}$	type of electricity transmission substation technology
$tl \in \mathbb{TL}$	type of electricity transmission line technology
$tc \in \mathbb{TC}$	type of CO_2 transport technology
$kv\|kv' \in \mathbb{KV}$	type of voltage
$f \in \mathbb{F}$	type of fuel

Parameters

yleng_y	(years) length of years of the modelled time-step (y)
$\mathrm{d}_{n,n2}$	(km) distance in km of corridor (n,n')
$\mathrm{D}_{n,y}^{\mathrm{ely}}$	(MWh) annual electricity demand at node (j) in year (y)
$\widehat{\mathrm{D}}_{n,y}^{\mathrm{ely}}$	(MW) peak electricity demand at node (j) in year (y)
typcap_i	(MW | $MtCO_2$ y^{-1}) typical capacity (size) of technology (i)
$\mathrm{life}_i^{\mathrm{tech}}$	(years) technical lifetime of technology (i)
$\mathrm{life}_i^{\mathrm{econ}}$	(years) economic lifetime of technology (i)
$\mathrm{CAPEX}_{n\|nn',i,y}$	(\$/MW) overnight capital costs per unit capacity of technology (i) at node (n) or corridor (nn') in year (y)
CRF_i	capital recovery factor of technology (i)
FOM_i	(\$/MW) fixed operating and maintenance costs per unit of capacity of technology (i)
VOM_i	(\$/MWh) variable operating and maintenance costs per unit of output of technology (i)
$\widehat{\mathrm{CF}}_i$	maximum capacity factor of technology (i)
$\widetilde{\mathrm{CF}}_i$	minimum capacity factor of technology (i)
η_i	rate of energy efficiency by technology (i)
η_i	rate of energy efficiency by technology (i)
$\mathrm{loss}_{nn',tl}$	(per 10 km) rate of energy losses of transmission line (tl) at corridor (n,n')
$\widehat{\mathrm{fmix}}_{eg,f}$	maximum share of fuel (f) in input aggregate for electricity generation (eg)
$\mathrm{landuse}_{eg}$	(km^2 MW^{-1}) area of land-use per unit of capacity of electricity generation (eg)
$\mathrm{P}_{n,f,y}$	(\$ GJ^{-1}) energy price of fuel (f) at node (n) in year (y)
$\mathrm{emsf}_f^{\mathrm{CO_2}}$	(tCO_2 GJ^{-1}) CO_2 emissions factor of fuel type (f)
$\mathrm{potential}_{n,greg}^{\mathrm{MW}}$	(MW) potential deployment capacity of electricity generation group (greg) at node (n)
GHI_n	(kWh m^{-2} y^{-1}) annual global horizontal irradiance at node (n)
DNI_n	(kWh m^{-2} y^{-1}) annual direct normal irradiance at node (n)
$\mathrm{CF}_{n,eg}^{\mathrm{WIND}}$	wind resource capacity factor at node (n) for electricity generation (eg)
$\mathrm{stock}_{n,eg,v,y}^{\mathbf{EG}}$	(MW) existing stock capacity of electricity generation (eg) at node (n) that was built in year (v)
$\mathrm{stock}_{n,ts,y}^{\mathbf{TS}}$	(MW) existing stock capacity of transmission substation (ts) at node (n) in year (y)
$\mathrm{stock}_{nn',tl,y}^{\mathbf{TL}}$	(MW) existing stock capacity of transmission line (tl) at corridor (n,n') in year (y)

$\mathrm{stock}^{\mathbf{TC}}_{nn',tc,y}$ (MtCO2 y-1) existing stock capacity of CO_2 transport infrastructure (tc) at corridor (n,n') in year (y)

$\mathrm{prescribed}^{\mathbf{EG}}_{n,eg,v,y}$ (MW) existing stock capacity of electricity generation (eg) at node (n) that was built in year (v)

$\mathrm{prescribed}^{\mathbf{TS}}_{n,ts,y}$ (MW) existing stock capacity of transmission substation (ts) at node (n) in year (y)

$\mathrm{prescribed}^{\mathbf{TL}}_{nn',tl,y}$ (MW) existing stock capacity of transmission line (tl) at corridor (n,n') in year (y)

$\mathrm{prescribed}^{\mathbf{TC}}_{nn',tc,y}$ (MtCO2 y-1) existing stock capacity of CO_2 transport infrastructure (tc) at corridor (nn') in year (y)

$\widehat{\mathrm{rate}}^{\mathbf{CINJECT}}_{n}$ (MtCO2 y-1) maximum rate of CO_2 injection at node (n)

$\widehat{\mathrm{strorage}}^{\mathbf{CO2}}_{n}$ ($MtCO_2$) maximum CO_2 storage capacity at node (n)

Variables

Z (\$) cumulative total system costs

TSC_y (\$ y^{-1}) annual cost of the total system in year (y)

$TSC^{\mathrm{EG}}_{n,eg,v,y}$ (\$ y^{-1}) annual costs of electricity generation (eg) vintage year (v) at node (n) in year (y)

$TSC^{\mathrm{TS}}_{n,ts,y}$ (\$ y^{-1}) annual costs of transmission substation (sub) at node (n) in year (y)

$TSC^{\mathrm{TL}}_{nn',tl,y}$ (\$ y^{-1}) annual costs of transmission line (tl) at corridor (nn') in year (y)

$TSC^{\mathrm{TC}}_{nn',tl,y}$ (\$ y^{-1}) annual costs of CO2 transport infrastructure (tc) at corridor (nn') in year (y)

Electricity generation

$CAP^{\mathbf{EG}}_{n,eg,v,y}$ (units) installed capacity of electricity generation (eg) vintage year (v) at node (n) in year (y)

$NEW^{\mathbf{EG}}_{n,eg,v,y}$ (MW) new capacity (summarized) addition of electricity generation (eg) vintage year (v) at node (n) in year (y)

$NEWi^{\mathbf{EG}}_{n,eg,v,y}$ (unitless) new unit (integer) addition of electricity generation (eg) vintage year (v) at node (n) in year (y)

$NEWc^{\mathbf{EG}}_{n,eg,v,y}$ (MW) new capacity (continuous) addition of electricity generation (eg) vintage year (v) at node (n) in year (y)

$RET^{\mathbf{EG}}_{n,eg,v,y}$ (units) retired units of electricity generation (eg) vintage year (v) at node (n) in year (y)

$INPUT_{n,eg,v,y}$ (GJ y^{-1}) primary energy input mixture of electricity generation (eg) vintage year (v) at node (n) in year (y)

$OUTPUT^{\mathbf{ely}}_{n,eg,v,y}$ (MWh y^{-1}) electricity output of electricity generation (eg) vintage year (v) at node (n) in year (y)

$FUEL_{n,eg,v,f,y}$ (GJ y^{-1}) input fuel (f) in electricity generation (eg) vintage year (v) at node (n) in year (y)

$Cems_{n,eg,v,y}$ (tCO_2 y^{-1}) CO_2 emissions from electricity generation (eg) vintage year (v) at node (n) in year (y)

$Cbio_{n,eg,v,y}$ (tCO_2 y^{-1}) CO_2 emissions from bioenergy of electricity generation (eg) vintage year (v) at node (n) in year (y)

Transmission substation

$CAP^{\mathbf{TS}}_{n,ts,y}$ (MW) installed capacity of transformer substation (ts) at node (n) in year (y)

$NEW^{\mathbf{TS}}_{n,ts,y}$ (MW) new capacity (summarized) addition of transformer substation (ts) at node (n) in year (y)

$NEWi^{\mathbf{TS}}_{n,ts,y}$ (unitless) new unit (integer) addition of transformer substation (ts) at node (n) in year (y)

$NEWc^{\mathbf{TS}}_{n,ts,y}$ (MW) new capacity (continuous) addition of transformer substation (ts) at node (n) in year (y)

$Vup^{\mathbf{ely}}_{n,kv',kv,y}$ (MWh y^{-1}) transformation of electricity from lower (kv') to higher (kv) voltage class at node (n) in year (y)

$Vdo^{\mathbf{ely}}_{n,kv',kv,y}$ (MWh y^{-1}) transformation of electricity from higher (kv') to lower (kv) voltage class at node (n) in year (y)

$Vup^{\mathbf{plrsv}}_{n,kv',kv,y}$ (MW) transformation of planning reserve capacity from lower (kv') to higher (kv) voltage class at node (n) in year (y)

$Vdo^{\mathbf{plrsv}}_{n,kv',kv,y}$ (MW) transformation of planning reserve capacity from higher (kv') to lower (kv) voltage class at node (n) in year (y)

Transmission line

$CAP^{\mathbf{TL}}_{nn',tl,y}$ (MW) installed capacity of transmission line (tl) at corridor (nn') in year (y)
$NEW^{\mathbf{TL}}_{nn',tl,y}$ (MW) new capacity (summarized) addition of transmission line (tl) at corridor (nn') in year (y)
$NEWi^{\mathbf{TL}}_{nn',tl,y}$ (integer) new unit (integer) addition of transmission line (tl) at corridor (nn') in year (y)
$NEWc^{\mathbf{TL}}_{nn',tl,y}$ (MW) new capacity (continuous) addition of transmission line (tl) at corridor (nn') in year (y)
$FLOW^{\mathbf{ely}}_{nn',tl,y}$ (MWh y^{-1}) flow of electricity in transmission line (tl) at corridor (nn') in year (y)
$FLOW^{\mathbf{plrsv}}_{nn',tl,y}$ (MW y^{-1}) flow of planning reserve capacity in transmission line (tl) at corridor (nn') in year (y)

CO_2 capture, transport and injection (storage)

$CCX_{n,eg,v,y}$ (tCO_2 y^{-1}) CO_2 captured from electricity generation (eg) vintage year (v) at node (n) in year (y)
$CAP^{\mathbf{TC}}_{nn',tc,y}$ (MW) installed capacity of CO_2 transport (tc) at corridor (nn') in year (y)
$NEW^{\mathbf{TC}}_{nn',tc,y}$ (MW) new capacity (summarized) addition of CO_2 transport (tc) at corridor (nn') in year (y)
$NEWi^{\mathbf{TC}}_{nn',tc,y}$ (MW) new unit (integer) addition of CO_2 transport (tc) at corridor (nn') in year (y)
$NEWc^{\mathbf{TC}}_{nn',tc,y}$ (MW) new capacity (continuous) addition of CO_2 transport (tc) at corridor (nn') in year (y)
$FLOW^{\mathbf{CO2}}_{nn',tc,y}$ (MWh y^{-1}) flow of CO_2 in CO_2 transport (tc) at corridor (nn') in year (y)
$CINJECT_{n,y}$ (tCO_2 y^{-1}) CO_2 injected at node (n) in year (y)

4.2 Objective function

The objective function of the optimization model is to minimize the cumulative total system costs (Z), which summarizes the total annual system costs ($TSC^{[\dots]}_{y}$) along the planning horizon ($\mathbb{Y}$) that consists of all deployed generation $\mathbb{EG}$, transmission substation $\mathbb{TS}$, transmissions $\mathbb{TL}$,. The Z is defined

$$Z = \sum_{y\in\mathbb{Y}} \left(\sum_{n\in\mathbb{N},eg\in\mathbb{EG},v} TSC^{\mathbf{EG}}_{n,eg,v,y} + \sum_{n\in\mathbb{N},ts\in\mathbb{TS}} TSC^{\mathbf{TS}}_{n,ts,y} + \sum_{nn'\in\mathbb{NN}',tl\in\mathbb{TL}} TSC^{\mathbf{TL}}_{nn',tl,y} + \sum_{nn'\in\mathbb{NN}',tc\in\mathbb{TC}} TSC^{\mathbf{TC}}_{nn',tc,y} + \sum_{n\in\mathbb{N}} TSC^{\mathbf{CINJECT}}_{n,y} \right)$$

The above formulation is set for perfect-foresight decision-making approach. However, the objective function needs to be adapted into a shorter time-horizon for myopic decision-making approach. The optimization problem of the fully investigated time horizon is divided into multiple shorter time horizons that are solved recursively from one timestep to the next. We use loop function in GAMS to solve multiple optimizations in sequence of timesteps from start to end of planning horizon. All variables solved in previous timestep are carried over to the next timestep to ensure the balance of stock capacities by considering previously deployed capacities.

4.3 Cost equations

The TSC for each technology class comprises of costs of capacity investment annuities, operation and maintenance, and when applicable costs of input feedstock and CO_2 emissions tax penalty, given for each node n or corridor nn' and planning period y, given by

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, y \in \mathbb{Y},$$
$$\begin{aligned} & TSC^{\mathbf{EG}}_{n,eg,y} \\ & = CAP_{n,eg,v,y} * \mathrm{CAPEX}_{n,eg,v} * \mathrm{CRF}_{eg} + CAP_{n,eg,v,y} * \mathrm{FOM}_{eg} + OUT^{\mathrm{ely}}_{n,eg,v,y} * \mathrm{VOM}_{eg} \\ & + \sum_{f} INPUT_{n,eg,v,f,y} * \mathrm{P}_{n,f,y} + \left(Cems_{n,eg,v,y} - Cbio_{n,eg,v,y}\right) * \mathrm{tax}^{\mathbf{Cems}}_{y} \end{aligned}$$

$$\forall n \in \mathbb{N}, ts \in \mathbb{TS}, y \in \mathbb{Y}, \qquad TSC^{\mathbf{TS}}_{n,ts,y} = CAP_{n,ts,y} * \mathrm{CAPEX}_{n,ts,y} * \mathrm{CRF}_{ts}$$

$$\forall nn' \in \mathbb{NN}', tl \in \mathbb{TL}, y \in \mathbb{Y}, \qquad TSC^{\mathbf{TL}}_{nn',tl,y} = CAP_{nn',tl,y} * \mathrm{d}_{nn'} * \mathrm{CAPEX}_{nn',tl,y} * \mathrm{CRF}_{tre}$$

$$\forall nn' \in \mathbb{NN}', tc \in \mathbb{TC}, y \in \mathbb{Y}, \qquad TSC^{\mathbf{TC}}_{nn',tc,y} = CAP_{nn',tc,y} * \mathrm{d}_{nn'} * \mathrm{CAPEX}_{nn',tl,y} * \mathrm{CRF}_{tre}$$

$$\forall n \in \mathbb{N}, y \in \mathbb{Y}, \qquad TSC^{\mathbf{CINJECT}}_{n,y} = CINJECT_{n,y} * (\mathrm{ucost}^{\mathbf{CINJECT}}_{n,y} - \mathrm{taxcred}^{\mathbf{CINJECT}}_{y})$$

The annuity of investment for each technology computed by the quantity of deployed capacities CAP, their overnight-capital costs per unit of capacity (CAPEX), their capital recovery factor (CRF), and their length (d) of connection of line nn' or from node n to node n'. Technology-specific interest rates and economical lifetime determines the CRF for each technology. The operation and maintenance (O&M) costs are determined by the unit fixed O&M costs multiplied by installed production capacity ($CAP_{\square}$) and by the level of production ($OUT^{\mathrm{ely}}_{\square}$) multiplied by the unit variable O&M costs ($\mathrm{VOM}_{\square}$). For fuel-firing power generation technologies, input feedstock costs are determined by the sum of all fuels f multiplied by the price of that fuel $\mathrm{P}_{n,f,y}$ at a given node n and in year y. CO_2 emissions tax-penalty are accounted for the net-amount of CO_2 emissions subtracted by CO_2 neutral from the use of sustainably sourced bioenergy, multiplied by the tax on CO_2 emissions $\mathrm{tax}^{\mathrm{Cems}}_{y}$ applicable at given year y. Furthermore, costs of CO_2 injection are determined by the unit cost of injection in specific node n ($\mathrm{ucost}^{\mathbf{CINJECT}}_{\square}$) minus the tax credits for CO_2 injection of a given year y ($\mathrm{taxcred}^{\mathbf{CINJECT}}_{\square}$)

4.4 Electricity supply-demand matching constraints

Electricity supply-demand matching, or energy balance constraints ensure the fulfilment of electricity demand at all nodes $\mathbb{N}$ for all voltage classes $\mathbb{kv}$ in all planning periods $\mathbb{Y}$, given by

$$\forall n \in \mathbb{N}, kv \in \mathbb{kv}, y \in \mathbb{Y}, \qquad \mathrm{D}_{n,kv,y}^{\mathbf{ely}} * \left(1 + \mathrm{loss}^{\mathbf{dsub}}\right) * \left(1 + \mathrm{loss}^{\mathbf{dline}}\right) \leq S_{n,kv,y}^{\mathbf{ely}}$$

$$\begin{aligned}
&\forall n \in \mathbb{N}, kv \in \mathbb{kv}, y \in \mathbb{Y}, \\
&S_{n,kv,y}^{\mathbf{ely}} \\
&= \sum_{eg \in (kv,eg), v \leq y} OUTPUT_{n,eg,v,y}^{\mathbf{ely}} + \sum_{n' \in n'n} FLOW_{n'n,kv,\, y}^{\mathbf{ely}} * \left(1 - loss_{tl \in (kv,tl)} \ * \mathrm{d}_{n'n}\right) \\
&- \sum_{n' \in nn'} FLOW_{nn',kv,\, y}^{\mathbf{ely}} + \sum_{kv' \leq kv} Vup_{n,kv',kv,y}^{\mathbf{ely}} \\
&+ \sum_{kv' \geq kv} Vdo_{n,kv',kv,y}^{\mathbf{ely}} * \left(1 - loss_{ts \in (kv,ts)}\right) - \sum_{kv' \geq kv} Vup_{n,kv,kv',y}^{\mathbf{ely}} \\
&- \sum_{kv' \leq kv} Vdo_{n,kv,kv',y}^{\mathbf{ely}} * \left(1 - loss_{ts \in (kv,ts)}\right)
\end{aligned}$$

Electricity demand at specific node n, voltage class kv, and planning period y ($\mathrm{D}_{\square}^{\mathbf{ely}}$) is supplied ($S_{\square}^{\mathbf{ely}}$) with the power generated $OUT_{eg \in (kv,eg)}^{\mathbf{ely}}$, plus all incoming transmission from all other nodes n', minus all outgoing transmission to all other nodes n' ($FLOW_{\square}^{\mathbf{ely}}$), and plus net-change of voltage classes step-up $Vup_{\square}^{\mathbf{ely}}$ and step-down $Vdo_{\square}^{\mathbf{ely}}$ to and from other voltage classes kv' with considering transformation and transmissions losses ($loss_{ts}, loss_{tl}$).

4.5 Planning reserve supply-demand matching constraints

Planning reserves is required for the system to have sufficient firm capacity to meet the forecasted demand peak load plus a reserve margin, given by

$$\begin{aligned}
&\forall n \in \mathbb{N}, kv \in \mathbb{kv}, y \in \mathbb{Y}, \\
&\widehat{\mathrm{D}}_{n,kv,y}^{\mathrm{ely}} * \left(1 + \mathrm{margin}_{n}^{\mathbf{plrsv}}\right) \\
&= \sum_{eg \in (kv,eg), v \leq y} CAP_{n,eg,v,y}^{\mathrm{plrsv}} + \sum_{n' \in n'n} FLOW_{n'n,tl,y}^{\mathbf{plrsv}} * \left(1 - loss_{tl \in (kv,tl)} * \mathrm{d}_{n'n}\right) \\
&- \sum_{n' \in nn'} FLOW_{nn',tl,y}^{\mathbf{plrsv}} + \sum_{kv' \leq kv} Vup_{n,kv',kv,y}^{\mathbf{plrsv}} \\
&+ \sum_{kv' \geq kv} Vdo_{n,kv',kv,y}^{\mathbf{plrsv}} * \left(1 - loss_{ts \in (kv,ts)}\right) - \sum_{kv' \geq kv \in (kv,ts)} Vup_{n,kv,kv',y}^{\mathbf{plrsv}} \\
&- \sum_{kv' \leq kv} Vdo_{n,kv,kv',y}^{\mathbf{plrsv}} * \left(1 - loss_{ts \in (kv,ts)}\right)
\end{aligned}$$

With $CAP_{e}^{\mathbf{plrsv}} \leq CAP_{n,eg,v,y} * \mathrm{capcredit}_{eg}^{\mathbf{plrsv}}$

The supplied reserve capacities must exceed the peak demand ($\widehat{\mathrm{D}}_{n,kv,y}^{\mathbf{ely}}$) plus a margin for planning reserve ($\mathrm{margin}_{\square}^{\mathbf{plrsv}}$) of respective supply-demand balancing region n. $\widehat{\mathrm{D}}_{n,kv,y}^{\mathbf{ely}}$ is approximated using load factor of annual demand. Reserve capacities ($CAP^{\mathbf{plrsv}}_{n,eg,v,y}$) are supplied by all generation capacity capped by technology specific capacity reserve credits ($\mathrm{capcredit}^{\mathbf{plrsv}}_{eg}$), plus net incoming-outgoing flows of planning reserve capacities ($FLOW^{\mathbf{plrsv}}_{\square}$), plus net-change of voltage class step-up and -down of reserve capacities ($Vup^{\mathbf{plrsv}}_{\square}, Vdo^{\mathbf{plrsv}}_{\square}$), with also taking into account the losses incurred at transmission substation and transmission line. Each technology is assigned with capacity credit. Reflecting on its expected availability when power is needed. For instance, conventional power generating technologies have their maximum availability committed for planning reserve capacity provision.

4.6 Electricity transmission and voltage transformation constraints

Transmissions of electricity ($FLOW^{\mathbf{ely}}_{\square}$) are capped by built transmission line capacities (CAP), or maximum transfer limit, given by

$\forall nn' \in \mathbb{NN}', tl \in \mathbb{TL}, kv(kv,tl), y \in \mathbb{Y},$

$$CAP^{\mathbf{TL}}_{nn',tl\in(kv,tl),y} * 8760 \geq FLOW^{\mathbf{ely}}_{nn',kv,\,y}$$

$$CAP^{\mathbf{TL}}_{nn',tl\in(kv,tl),y} \geq FLOW^{\mathbf{plrsv}}_{nn',kv,y}$$

Transformer substation maximum capacity limit determines the maximum voltage transformation and reserves for extra high voltage (EHV) and high voltage (HV) transmission. However, for medium voltage (MV), substation capacity must cover all incoming and outgoing transmission lines' capacity. This ensures a must built MV substation for each MV line-connected neighboring nodes. Detailed design and analysis of lower voltage (LV) transmissions or distribution network are out of the scope of study. The constraints governing how voltage transformation flows and capacities interacts are given by,

$\forall n \in \mathbb{N}, ts \in \mathbb{TS}, kv \in (kv,ts), y \in \mathbb{Y},$

$$CAP^{\mathbf{TS}}_{n,ts\in(kv,ts),y} * 8760 \geq \sum_{kv>kv'} Vup^{\mathbf{ely}}_{n,kv',kv,y}$$

$$CAP^{\mathbf{TS}}_{n,ts\in(kv,ts),y} * 8760 \geq \sum_{kv>kv'} Vdo^{\mathbf{ely}}_{n,kv,kv',y}$$

$$CAP^{\mathbf{TS}}_{n,ts\in(kv,ts),y} \geq \sum_{kv>kv'} Vup^{\mathbf{plrsv}}_{n,kv',kv,y}$$

$$CAP^{\mathbf{TS}}_{n,ts\in(kv,ts),y} \geq \sum_{kv>kv'} Vdo^{\mathbf{plrsv}}_{n,kv,kv',y}$$

$$\forall \ldots kv \in \{\mathrm{MV}\}, \qquad CAP^{\mathbf{TS}}_{n,ts\in(kv,ts),y} \geq \sum_{n'} CAP^{\mathbf{TL}}_{nn',tl\in(kv,tl),y} + \sum_{e'} CAP^{\mathbf{TL}}_{n'n,trl\in(kv,tl),y}$$

4.7 Electricity generation constraints

For all power generating technologies $\mathbb{EG}$ the input-output balance of energy conversion and maximum or minimum generation limits are given by,

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v, y \in \mathbb{Y},$

$$INPUT_{n,eg,v,y} * \eta_{eg} = OUTPUT^{\mathbf{ely}}_{n,eg,v,y}$$

$$CAP^{\mathbf{EG}}_{n,eg,v,y} * \widehat{\mathrm{CF}}_{eg} * 8760 \geq OUTPUT^{\mathbf{ely}}_{n,eg,v,y}$$

$$CAP^{\mathbf{EG}}_{n,eg,v,y} * \widetilde{\mathrm{CF}}_{eg} * 8760 \leq OUTPUT^{\mathbf{ely}}_{n,eg,v,y}$$

The output electricity generated ($OUTPUT^{ely}$) are influenced by the amount of energy input ($INPUT$) and the energy conversion efficiency (η) of specific electricity generation technology eg. Electricity generation is capped by $\widehat{\mathrm{CF}}$ as a factor of annual production of the installed generation capacity ($CAP^{\mathbf{EG}}$). For generation capacities that provide planning reserve capacities, $\widetilde{\mathrm{CF}}$ determines the minimum production threshold.

The input fuel feedstock constraints are given by,

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v, y \in \mathbb{Y},$

$$INPUT_{n,eg,v,y} = \sum_{f} FUEL_{n,eg,v,f,y}$$

$$INPUT_{n,eg,v,y} * \widehat{\mathrm{fmix}}_{eg,f} \geq FUEL_{n,eg,v,f,y}$$

The amount of energy input ($INPUT$) comprises of single or mixture of fuels f ($FUEL$) that are specific for each type of electricity generation technology (eg). $\widehat{\mathrm{fmix}}$ regulates the share of each fuel f in the mixture.

Plant CO_2 emissions are given by,

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v, y \in \mathbb{Y},$

$$Cems_{n,eg,v,\,y} = \sum_{f} INPUT_{n.eg,v,f,y} * \mathrm{emsf}_{f}^{\mathrm{CO_2}}$$

$$Cbio_{n,eg,v,\,y} = \sum_{f \in bioenergy} INPUT_{n.eg,v,f,y} * \mathrm{emsf}_{f}^{\mathrm{CO_2}} * \mathrm{neutral}_{f}^{\mathrm{CO_2}}$$

$$CCX_{n,eg,v,\,y} = Cems_{n,eg,v,\,y} * \mathrm{rateCCX}_{eg}$$

Plant annual CO_2 emissions ($Cems$) are accounted based on CO_2 emissions factor of fuels ($\mathrm{emsf}_{f}^{\boldsymbol{CO_2}}$) used and the respective consumption ($INPUT$). Note that biomass-based fuels are considered with a degree of emissions neutrality ($\mathrm{neutral}_{f}^{\mathrm{CO_2}}$). Furthermore, plant annual CO_2 capture is estimated by technology-specific CO_2 capture rate ($\mathrm{rateCCX}_{eg}$).

4.8 Resource constraints

Maximum potential-built capacity and availability of RES power generation $\mathbb{EG}^{\mathrm{RES}}$ at given location n is limited by the potential built capacity of RES group ($\mathrm{potential}_{\square}^{\mathrm{RES}}$), given by

$$\forall n \in \mathbb{N}, y \in \mathbb{Y}, \qquad \sum_{eg \in \mathrm{HYDRO|GEOT}, v \leq y} CAP_{n,eg,v,y}^{\mathbf{EG}} \leq \mathrm{potential}_{n}^{\mathrm{HYDRO|GEOT}}$$

$$\forall n \in \mathbb{N}, y \in \mathbb{Y}, \qquad \sum_{eg \in \mathrm{SOLAR|WIND}, v \leq y} CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{landuse}_{eg}^{\square} \leq \mathrm{landavail}_{n}^{\square}$$

The potential RES capacities in MW are estimated using a factor of capacity-land density for hydropower and geothermal power. Meanwhile for solar and wind power, potential deployable capacities are limited by land availability ($\mathrm{landavail}_{\square}^{\square}$) in each node n. The land availability excludes urban developed areas, water bodies, and protected areas.

Solar energy input is calculated based on by the size of irradiated-surface area multiplied by the average of annual Global Horizontal Irradiance (GHI) for PV $\mathbb{EG}^{\mathrm{PV}}$, or Direct Normal Irradiance (DNI) measured in kWh/m^2 for CSP $\mathbb{EG}^{\mathrm{CSP}}$.The availability of solar resource is given by,

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}^{\mathbf{UPV}}, v, y \in \mathbb{Y}, \qquad INPUT_{n,eg,v,y}^{\square} \leq CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{surface}_{eg}^{\mathrm{PV}} * \mathrm{GHI}_{n}^{\mathrm{UPV}} * 365.25$$

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}^{\mathbf{DPV}}, v, y \in \mathbb{Y}, \qquad INPUT_{n,eg,v,y}^{\square} \leq CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{surface}_{eg}^{\mathrm{PV}} * \mathrm{GHI}_{n}^{\mathrm{DPV}} * 365.25$$

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}^{\mathbf{CSP}}, v, y \in \mathbb{Y}, \qquad INPUT_{n,eg,v,y}^{\square} \leq CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{surface}_{eg}^{\mathrm{CSP}} * \mathrm{DNI}_{n} * 365.25$$

For wind power electricity generation $\mathbb{EG}^{\mathbf{WIND}}$, annual wind electricity generation are capped by the capacity factor of wind resource ($\mathrm{CF}_{n,eg}^{\mathbf{WIND}}$) that are geographically distributed and at different levels depending on the class of wind turbine technology suited for in situ wind speed and turbine heights. The classification of wind turbine technology refers to IEC 61400, the International Standard published by the International Electrotechnical Commission regarding wind turbines. The maximum production of wind electricity generation is given by,

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}^{\mathbf{WIND}}, v, y \in \mathbb{Y}, \qquad OUTPUT_{n,eg,v,y}^{\mathbf{ely}} \leq 8760 * CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{CF}_{n,eg}^{\mathbf{WIND}}$$

For hydropower, annual electricity generation are capped by maximum capacity factor that are site specific. The maximum production of hydropower electricity generation is given by,

$$\forall n \in \mathbb{N}, eg \in \mathbb{EG}^{\mathbf{HYDD\,|\,HYDR}}, v, y \in \mathbb{Y}, \qquad OUTPUT_{n,eg,v,y}^{\mathbf{ely}} \leq 8760 * CAP_{n,eg,v,y}^{\mathbf{EG}} * \mathrm{CF}_{n,eg}^{\mathbf{HYDD\,|\,HYDR}}$$

4.9 Capacity balance constraints

Capacity balance constraints ensure the planned capacity deployment with considering previously built, retired, and newly added capacities given by

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v, y \in \mathbb{Y}$,

$$CAP^{\mathrm{EG}}_{n,eg,v,y} = CAP^{\mathbf{EG}}_{n,eg,v,y-1} + NEW^{\mathbf{EG}}_{n,eg,v=y} - RET^{\mathbf{EG}}_{n,eg,v,y} + \mathrm{Stock}^{\mathbf{EG}}_{n,eg,v}[\mathrm{start}(y)], \forall n \in \mathbb{N}, eg \in \mathbb{EG}, v \leq y, y \in \mathbb{Y}$$

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v$,

$$NEW^{\mathbf{EG}}_{n,eg,v} = \left(NEWi^{\mathbf{EG}}_{n,eg,v} * \mathrm{typcap}^{\mathbf{EG}}_{eg}\right) + NEWc^{\mathbf{EG}}_{n,eg,v} + \mathrm{Prescribed}^{\mathbf{EG}}_{n,eg,y},$$

with $NEWi^{\mathbf{EG}}_{n,eg,v} \in \mathbb{Z} \geq 0$, and $NEWc^{\mathbf{EG}}_{n,eg,v} \in \mathbb{R} \geq 0$

$\forall n \in \mathbb{N}, eg \in \mathbb{EG}, v, y \in \mathbb{Y}$,

$$RET^{\mathbf{EG}}_{n,eg,v,y} = \sum\nolimits_{y-v \leq \mathrm{life}_{eg}} CAP^{\mathbf{EG}}_{n,eg,v,y-1}$$

In all locations $\mathbb{N}$, deployed generation capacity (CAP) of technology type eg in current period y includes the deployed capacities in previous period ($y-1$), minus capacities that exceed their economic lifetime ($y - v \leq \mathrm{life}_{eg}$), and plus new capacity additions (NEW). New capacity additions are defined in both integers ($NEWi \in \mathbb{Z}$) and real numbers ($NEWc \in \mathbb{R}$), respective to larger or smaller capacity numeration. Stock capacities (Stock) are taken into account in the initial period of the planning horizon. Moreover, prescribed capacities (Prescribed) are also considered in new capacity additions.

Electricity transmission substation (ts), transmission line (tl), and CO_2 transport (tc) capacities are assumed to have no retirement and the only way is to expand, given by

$\forall n \in \mathbb{N}, ts \in \mathbb{TS}, y \in \mathbb{Y}, \quad CAP^{\mathbf{TS}}_{n,ts,y} = CAP^{\mathbf{TS}}_{n,ts,y-1} + NEW^{\mathbf{TS}}_{n,ts,v=y} + \mathrm{Stock}^{\mathbf{TS}}_{n,ts,v=y}[\mathrm{start}(y)]$

$\forall n \in \mathbb{N}, tl \in \mathbb{TL}, y \in \mathbb{Y}, \quad CAP^{\mathbf{TL}}_{nn',tl,y} = CAP^{\mathbf{TL}}_{nn',tl,y-1} + NEW^{\mathbf{TL}}_{nn',tl,v=y} + \mathrm{Stock}^{\mathbf{TL}}_{nn',tl,v=y}[\mathrm{start}(y)]$

$\forall n \in \mathbb{N}, tc \in \mathbb{TC}, y \in \mathbb{Y}$,

$$CAP^{\mathbf{TC}}_{nn',tc,y} = CAP^{\mathbf{TC}}_{nn',tc,y-1} + NEW^{\mathbf{TC}}_{nn',tc,v=y} + \mathrm{Stock}^{\mathbf{TC}}_{nn',tc,v=y}[\mathrm{start}(y)]$$

4.10 CO_2 transport and storage constraints

CO_2 source-sink matching ensure that all captured CO_2 ($CCX_{\square}^{\square}$) are either injected in the same node n ($CINJECT_{\square}^{\square}$) or transported to and from another node n' ($FLOW_{\square}^{\mathbf{CO2}}$), given by

$$\forall n \in \mathbb{N}, y \in \mathbb{Y}, \qquad CINJECT_{n,y}^{\square} = \sum_{eg \in \mathrm{CCX}(eg), v \leq y} CCX_{n,eg,v,y}^{\square} + \sum_{n' \in n'n, tc \in \mathbb{TC}} FLOW_{n'n,tc,\,y}^{\mathbf{CO2}} - \sum_{n' \in nn', tc \in \mathbb{TC}} FLOW_{nn',tc,\,y}^{\mathbf{CO2}}$$

CO_2 transport flow ($FLOW_{\square}^{\mathbf{CO2}}$) is capped by built CO_2 transport capacity ($CAP^{\mathbf{TC}}$), or maximum transfer limit, given by

$$\forall n \in \mathbb{N}, tc \in \mathbb{TC}, y \in \mathbb{Y}, \; CAP_{nn',tc,y}^{\mathbf{TC}} \geq FLOW_{nn',tc,y}^{\mathbf{CO2}}$$

CO_2 injection and storage are capped by the annual maximum rate of CO2 injection ($\widehat{\mathrm{rate}}_{\square}^{\mathbf{CINJECT}}$) and the CO_2 storage availability ($\widehat{\mathrm{storage}}_{\square}^{\mathbf{CO2}}$), given by

$$\forall n \in \mathbb{N}, y \in \mathbb{Y}, \qquad CINJECT_{n,y}^{\square} \leq \widehat{\mathrm{rate}}_{n}^{\mathbf{CINJECT}}$$

$$\forall n \in \mathbb{N}, \qquad \sum_{y \in \mathbb{Y}} CINJECT_{n,y}^{\square} \leq \widehat{\mathrm{storage}}_{n}^{\mathbf{CO2}}$$

4.11 Climate policy constraints

Total system's long-term cumulative net CO_2 emissions cannot go over the long-term quota of CO_2 emissions ($LimitPF_{y}^{Cems}$). Scenarios that do not consider climate policy can put a very large number to virtually set without limits. Net CO_2 emissions is derived by subtracting CO_2 neutral ($Cbio$) and CO_2 captured (CCX) from gross CO_2 emissions ($Cems$).

$$LimitPF_{\square}^{Cems} \geq \sum_{n,eg,v,y} Cems_{n,eg,v,\,y} - \sum_{n,eg,v,y} Cbio_{n,eg,v,\,y} - \sum_{n,eg,v,y} CCX_{n,eg,v,\,y}$$

The above formulation is suited under perfect-foresight decision-making approach. However, in myopic approach, decisions do not consider long-term implications. Therefore, constraint on system's CO_2 emissions is set for each timestep. For myopic target setting, total system's annual net CO_2 emissions cannot go over the annual limit on CO_2 emissions ($LimitMF_{y}^{Cems}$).

$$LimitMF_{y}^{Cems} \geq \sum_{n,eg,v} Cems_{n,eg,v,\,y} - \sum_{n,eg,v} Cbio_{n,eg,v,\,y} - \sum_{n,eg,v,y} CCX_{n,eg,v,\,y}$$