Supplementary Material to "Spatio-temporal assessment on the impact of intensive palm oil-based bioenergy deployment on cross-sectoral energy decarbonization"

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S1. Description of the BeWhere Malaysia model

S1.1. Nomenclature

Sets	
Y	planning period
M	seasonal period
S	supply location
IP	pre-processing plant
P	conversion plant
D	demand location
H	harbor
G	spatial grid
E	energy sector
F	fossil fuel technology
C	commodity
$\mathrm{RM} \subset \mathrm{C}$	feedstock
$\mathrm{IBP} \subset \mathrm{C}$	intermediate product
$\mathrm{PD} \subset \mathrm{C}$	product
T	transport mode
TECH	technology group
MODE	technology mode
SIZE	technology size
$\mathrm{IPTECH} \subset \mathrm{TECH}$	pre-processing technology
$\mathrm{PTECH} \subset \mathrm{TECH}$	conversion technology
$\mathrm{IPMODE} \subset \mathrm{MODE}$	pre-processing technology mode
$\mathrm{PMODE} \subset \mathrm{MODE}$	conversion technology mode
$\mathrm{IPSIZE} \subset \mathrm{SIZE}$	pre-processing technology size
$\mathrm{PSIZE} \subset \mathrm{SIZE}$	conversion technology size
Indices	
$y \in \mathrm{Y}$	planning period (alternatively used to indicate retirement period)

$y' \in \mathrm{Y}$	planning period (alternatively used to indicate investment period)
$m \in \mathrm{M}$	seasonal period
$s \in \mathrm{S}$	supply location
$ip \in \mathrm{IP}$	pre-processing plant
$p \in \mathrm{P}$	conversion plant
$d \in \mathrm{D}$	demand location
$h \in \mathrm{H}$	harbor (alternatively used to indicate the origin harbor)
$h' \in \mathrm{H}$	harbor (alternatively used to indicate the destination harbor)
$g \in \mathrm{G}$	spatial grid (alternatively used to indicate the origin grid)
$g' \in \mathrm{G}$	spatial grid (alternatively used to indicate the destination grid)
$e \in \mathrm{E}$	energy sector
$f \in \mathrm{F}$	fossil fuel technology
$c \in \mathrm{C}$	commodity
$rm \in \mathrm{RM}$	feedstock
$ibp \in \mathrm{IBP}$	intermediate product
$pd \in \mathrm{PD}$	product
$t \in \mathrm{T}$	transport mode
$tech \in \mathrm{TECH}$	technology group
$mode \in \mathrm{MODE}$	technology mode
$size \in \mathrm{SIZE}$	technology size
$iptech \in \mathrm{IPTECH}$	pre-processing technology
$ptech \in \mathrm{PTECH}$	conversion technology
$ipmode \in \mathrm{IPMODE}$	pre-processing technology mode
$pmode \in \mathrm{PMODE}$	conversion technology mode
$ipsize \in \mathrm{IPSIZE}$	pre-processing technology size
$psize \in \mathrm{PSIZE}$	conversion technology size
Parameters	
$A_{y,g}^{avail}$	availability of land area of spatial grid g at year y (ha)
$A_{tech,mode}^{factor}$	area requirement for plant of technology mode $mode$ of technology group $tech$ (ha/TWh)
$BM_{y,s,rm}^{avail}$	availability of feedstock rm in supply location s at year y (TWh)
$Cap_{y,ip,iptech,ipmode,ipsize}^{ip}$	capacity level of pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at year y (TWh)
$Cap_{y,p,ptech,pmode,psize}^{p}$	capacity level of conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)
$Cap_{y,f,e,d}^{ref}$	capacity level of fossil fuel technology f associated with energy sector e in demand location d
$Cap_{y,s,rm}^{bm\_store}$	capacity level of storage facility for feedstock rm in supply location s at year y (TWh)

$Cap^{ip\_store}_{y,ip,iptech,ipmode,ipsize,ibp}$	capacity level of storage facility for intermediate product ibp in pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at year y (TWh)
$Cap^{p\_store}_{y,p,ptech,pmode,psize,pd}$	capacity level of storage facility for bioenergy product pd in conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)
$Cap^{ip\_retire}_{y,ip,iptech,ipmode,ipsize}$	known retired capacity of pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at year y (TWh)
$Cap^{p\_retire}_{y,p,ptech,pmode,psize}$	known retired capacity of conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)
$Dist^{sip}_{s,ip,t}$	transport distance from supply location s to pre-processing plant ip of transport mode t (km)
$Dist^{sp}_{s,p,t}$	transport distance from supply location s to conversion plant p of transport mode t (km)
$Dist^{ipp}_{ip,p,t}$	transport distance from pre-processing plant ip to conversion plant p of transport mode t (km)
$Dist^{iph}_{ip,h,t}$	transport distance from pre-processing plant ip to harbor h of transport mode t (km)
$Dist^{pd}_{p,d,t}$	transport distance from conversion plant p to demand location d of transport mode t (km)
$Dist^{hp}_{h,p,t}$	transport distance from harbor h to conversion plant p of transport mode t (km)
$Dist^{hh}_{h,h',t}$	transport distance from harbor h to harbor h' of transport mode t (km)
$DM^{bm}_{y,rm,p}$	demand of feedstock rm in the existing bioenergy plant p at year y (TWh)
$DM^{pr}_{y,e,d}$	demand of bioenergy product associated with energy sector e in demand location d at year y (TWh)
$emf^{ref}_{f,e}$	emission factor associated with reference energy sector e (tCO_2/MWh)
emf^{bm}_{rm}	emission factor associated with collection of feedstock rm (tCO_2/MWh)
emf^{avoid}_{rm}	emission avoidance factor associated with utilization of feedstock rm (tCO_2/MWh)
emf^{store}_{c}	emission factor associated with storage of commodity c (tCO_2/MWh)
$emf^{tload}_{c,t}$	emission factor associated with loading/unloading activity for transporting commodity c by using transport mode t (tCO_2/MWh)
$emf^{tVar}_{c,t}$	emission factor associated with transportation of commodity c by using transport mode t (tCO_2/MWh.km)

$emf_{c,t}^{shipload}$	emission factor associated with loading/unloading activity for shipping commodity c by using transport mode t (tCO_2/MWh)
$emf_{c,t}^{shipvar}$	emission factor associated with shipment of commodity c by using transport mode t (tCO_2/MWh.km)
$emf_{tech,mode}^{tech}$	emission factor associated with technology mode $mode$ of technology group $tech$ (tCO_2/MWh)
$grid_{y,c,g,g',t}^{initial}$	installed capacity of existing transmission/distribution line for commodity c that connects spatial grid g to spatial grid g' at the initial planning period ($y = 1$) (TWh)
$pf_{y,f,e}^{ref}$	price factor of fossil fuel technology f associated with reference energy sector e at year y (USD/MWh)
pf_{y}^{co2}	price factor of the CO_2 emission taxation at year y (USD/tCO_2)
$pf_{y,pd}^{subs}$	price factor associated with subsidy for product pd at year y (USD/MWh)
$pf_{y,c}^{c}$	price factor associated with collection of commodity c at year y (USD/MWh)
pf_{c}^{store}	price factor associated with storage of commodity c (USD/MWh)
$pf_{c,t}^{tload}$	price factor associated with loading/unloading activity for transporting commodity c by using transport mode t (USD/MWh)
$pf_{c,t}^{tvar}$	price factor associated with transportation of commodity c by using transport mode t (USD/MWh/km)
$pf_{y,c,t}^{tfuel}$	price factor associated with fuel consumption by transport mode t for transporting commodity c at year y (USD/MWh/km)
$pf_{c,t}^{shipload}$	price factor associated with loading/unloading activity for shipping commodity c by using transport mode t (USD/MWh)
$pf_{c,t}^{shipvar}$	price factor associated with shipment of commodity c by using transport mode t (USD/MWh/km)
$pf_{tech,mode,size}^{capex}$	price factor associated with investment of technology mode $mode$ of technology size $size$ of technology group $tech$ (USD/MWh)
$pf_{f,e}^{capexbal}$	price factor associated with the balance of investment of the substituted capacity of fossil fuel plant by co-firing/fuel switching technology (USD/MWh)
$pf_{tech,mode,size}^{opexfix}$	price factor associated with fix operation and maintenance (O&M) of technology mode $mode$ of technology size $size$ of technology group $tech$ (USD/MWh)
$pf_{tech,mode,size}^{opexvar}$	price factor associated with variable O&M of technology mode $mode$ of technology size $size$ of technology group $tech$ (USD/MWh)
$pf_{c,t}^{infrafix}$	price factor associated with investment of grid infrastructure connectivity in transporting commodity c by using transport mode t (USD/MWh)

$pf_{c,t}^{infravar}$	price factor associated with investment of grid infrastructure interconnection in transporting commodity c by using transport mode t (USD/MWh.km)
$Size_{y,ip,iptech,ipmode,ipsize}^{ip\_initial}$	installed capacity of existing pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at the initial planning period ($y = 1$) (TWh)
$Size_{y,p,ptech,pmode,psize}^{p\_initial}$	installed capacity of existing conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at the initial planning period ($y = 1$) (TWh)
$target_{y,e}^{bio}$	renewable energy target of energy sector e at year y (TWh)
$target_{y}^{em}$	emission target at year y ($MtCO_2$)
$XBm_{y,m,s,rm,iptech,ipmode,ipsize}^{sip\_storeinitial}$	initial storage of feedstock rm in supply location s at the initial season ($m = 1$) of year y, dedicated for use in pre-processing plant (TWh)
$XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_storeinitial}$	initial storage of feedstock rm in supply location s at the initial season ($m = 1$) of year y, dedicated for use in conversion plant (TWh)
$XBm_{y,m,s,rm}^{spc\_storeinitial}$	initial storage of feedstock rm in supply location s at the initial season ($m = 1$) of year y, dedicated for use in existing bioenergy plant (TWh)
$XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_storeinitial}$	initial storage of intermediate product ibp in pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at the initial season ($m = 1$) of year y (TWh)
$XPr_{y,m,p,ptech,pmode,psize,pd}^{p\_storeinitial}$	initial storage of product pd at conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at the initial season ($m = 1$) of year y (TWh)
$\beta_{y,y',ip,iptech,ipmode}^{ip\_retire}$	binary relationship between investment year y' and retirement year y of pre-processing plant ip of technology mode $ipmode$ of technology group $iptech$, 1 if true
$\beta_{y,y',p,ptech,pmode}^{p\_retire}$	binary relationship between investment year y' and retirement year y of conversion plant p of technology mode $pmode$ of technology group $ptech$, 1 if true
β_{c}^{ship}	binary value that indicates which commodity c can undergo shipping, 1 if true
β_{c}^{grid}	binary value that indicates which commodity c is associated with grid infrastructure installation, 1 if true
$\beta_{c,t}^{ct}$	binary relationship between commodity c and transport mode t, 1 if true
$\beta_{c,e}^{ce}$	binary relationship between commodity c and energy sector e, 1 if true
$\beta_{tech,e}^{teche}$	binary relationship between technology $tech$ and energy sector e, 1 if true

$\beta_{tech,f}^{techf}$	binary relationship between technology $tech$ and fossil fuel technology f, 1 if true
$\beta_{g,s}^{gs}$	binary relationship between spatial grid g and supply location s, 1 if true
$\beta_{g,ip}^{gip}$	binary relationship between spatial grid g and pre-processing plant ip, 1 if true
$\beta_{g,p}^{gp}$	binary relationship between spatial grid g and conversion plant p, 1 if true
$\beta_{g,d}^{gd}$	binary relationship between spatial grid g and demand d, 1 if true
$\beta_{g,h}^{gh}$	binary relationship between spatial grid g and harbor h, 1 if true
$\eta_{c,tech,mode,c}$	efficiency of technology mode $mode$ of technology group $tech$ for converting commodity c to commodity c (TWh_{out}/TWh_{in})
λ^{season}	number of seasons
$\lambda_{y,tech}^{limit}$	number of technology allowed to be built for each plant at year y
μ_{f}^{low}	lower boundary of capacity factor for fossil fuel technology f
μ_{f}^{up}	upper boundary of capacity factor for fossil fuel technology f
$\mu_{tech,mode}^{low}$	lower boundary of capacity factor for technology mode $mode$ of technology group $tech$
$\mu_{tech,mode}^{up}$	upper boundary of capacity factor for technology mode $mode$ of technology group $tech$
$\omega_{y,c}^{BM}$	fraction of commodity c availability in year y
ω_{c}^{DML}	fraction of dry matter loss of commodity c storage
$\omega_{y,m,c}^{season}$	fraction of season m in year y associated with commodity c
$\omega_{y,m,e}^{season}$	fraction of season m in year y associated with energy sector e
Free variables	
$TOTCOST_{y}$	total cost of energy supply chain at year y (MUSD)
$TOTEMISSION_{y}$	total emission of energy supply chain at year y ($MtCO_2$)
TSC	objective function (MUSD)
Positive variables	
$BM_{y,s,rm,iptech,ipmode,ipsize}^{sip\_avail}$	availability of feedstock rm in supply location s at year y, dedicated for the supply to pre-processing plant of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ (TWh)
$BM_{y,s,rm,ptech,pmode,psize}^{sp\_avail}$	availability of feedstock rm in supply location s at year y, dedicated for the supply to conversion plant of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ (TWh)
$BM_{y,s,rm}^{spc\_avail}$	availability of feedstock rm in supply location s at year y, dedicated for the supply to existing bioenergy plant (TWh)
$Cost_{y,e}^{bm}$	collection/purchase cost of feedstock associated with energy sector e at year y (MUSD)

$Cost_{y}^{bm\_pc}$	collection/purchase cost of feedstock associated with existing bioenergy plant at year y (MUSD)
$Cost_{y,e}^{bm\_t}$	transport cost of feedstock associated with energy sector e at year y (MUSD)
$Cost_{y}^{bm\_t\_pc}$	transport cost of feedstock associated with existing bioenergy plant at year y (MUSD)
$Cost_{y,e}^{ib\_t}$	transport cost of intermediate product associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{pr\_t}$	transport cost of product associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{bm\_ship}$	shipping cost of feedstock associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{ib\_ship}$	shipping cost of intermediate product associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{ip\_capex}$	investment cost of pre-processing plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{ip\_opex}$	O&M cost of pre-processing plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{p\_capex}$	investment cost of conversion plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{p\_opex}$	O&M cost of conversion plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{ip\_infra}$	infrastructure cost of pre-processing plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{p\_infra}$	infrastructure cost of conversion plant associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{bm\_store}$	storage cost of feedstock associated with energy sector e at year y (MUSD)
$Cost_{y}^{bm\_store\_pc}$	storage cost of feedstock associated with existing bioenergy plant at year y (MUSD)
$Cost_{y,e}^{ip\_store}$	storage cost of intermediate product associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{p\_store}$	storage cost of product associated with energy sector e at year y (MUSD)
$Cost_{y,e}^{ref}$	reference cost of energy sector e at year y (MUSD)
$Em_{y,e}^{avoid}$	avoided emission associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{bm}$	emission from feedstock collection associated with energy sector e at year y ($MtCO_2$)
$Em_{y}^{bm\_pc}$	emission from feedstock collection associated with existing bioenergy plant at year y ($MtCO_2$)
$Em_{y,e}^{bm\_t}$	emission from feedstock transport associated with energy sector e at year y ($MtCO_2$)

$Em_{y}^{bm\_t\_pc}$	emission from feedstock transport associated with existing bioenergy plant at year y ($MtCO_2$)
$Em_{y,e}^{ib\_t}$	emission from intermediate product transport associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{pr\_t}$	emission from product transport associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{bm\_ship}$	emission from feedstock shipping associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{ib\_ship}$	emission from intermediate product shipping associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{ip}$	emission from pre-processing activity associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{p}$	emission from conversion activity associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{bm\_store}$	emission from feedstock storage associated with energy sector e at year y ($MtCO_2$)
$Em_{y}^{bm\_store\_pc}$	Emission from feedstock storage associated with existing bioenergy plant at year y ($MtCO_2$)
$Em_{y,e}^{ip\_store}$	emission from intermediate product storage associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{p\_store}$	emission from product storage associated with energy sector e at year y ($MtCO_2$)
$Em_{y,e}^{ref}$	Reference emission of energy sector e at year y ($MtCO_2$)
$grid_{y,c,g,g\prime,t}$	installed capacity of transmission/distribution line for commodity c that connects spatial grid g to spatial grid g' at year y (TWh)
$grid_{y,c,g,g\prime,t}^{invest}$	installed capacity of new transmission/distribution line for commodity c that connects spatial grid g to spatial grid g' at year y (TWh)
$Size_{y,ip,iptech,ipmode,ipsize}^{ip}$	installed capacity of pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at year y (TWh)
$Size_{y,ip,iptech,ipmode,ipsize}^{ip\_invest}$	installed capacity of new pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at year y (TWh)
$Size_{y,ip,iptech,ipmode,ipsize}^{ip\_retire}$	retired capacity of pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of itechnology group $iptech$ at year y (TWh)
$Size_{y,p,ptech,pmode,psize}^{p}$	retired capacity of conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)
$Size_{y,p,ptech,pmode,psize}^{p\_invest}$	installed capacity of new conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)

$Size^{p\_retire}_{y,p,ptech,pmode,psize}$	retired capacity of conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at year y (TWh)
$SUBSIDY_y$	price subsidy of bioenergy product at year y (MUSD)
$XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}$	flow of feedstock rm of transport mode t from supply location s to pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at season m of year y (TWh)
$XBm^{sp}_{y,m,s,rm,p,ptech,pmode,psize,t}$	flow of feedstock rm of transport mode t from supply location s to conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at season m of year y (TWh)
$XBm^{spc}_{y,m,s,rm,p,t}$	flow of feedstock rm of transport mode t from supply location s to existing bioenergy plant p at season m of year y (TWh)
$XBm^{sip\_store}_{y,m,s,rm,iptech,ipmode,ipsize}$	storage of feedstock rm in supply location s at season m of year y, dedicated for the supply to pre-processing plant of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ (TWh)
$XBm^{sp\_store}_{y,m,s,rm,ptech,pmode,psize}$	storage of feedstock rm in supply location s at season m of year y, dedicated for the supply to conversion plant of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ (TWh)
$XBm^{spc\_store}_{y,m,s,rm}$	storage of feedstock rm in supply location s at season m of year y, dedicated for the supply to existing bioenergy plant (TWh)
$XBm^{sh}_{y,m,s,rm,h,ptech,pmode,psize,t}$	flow of feedstock rm of transport mode t from supply location s to harbor h at season m of year y, dedicated for the supply to conversion plant of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ (TWh)
$XBm^{hh}_{y,m,rm,h,h',ptech,pmode,psize,t}$	flow of feedstock rm of transport mode t from harbor h to harbor h' at season m of year y, dedicated for the supply to conversion plant of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ (TWh)
$XBm^{hp}_{y,m,rm,h',p,ptech,pmode,psize,t}$	flow of feedstock rm of transport mode t from harbor h' to conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at season m of year y (TWh)
$XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}$	flow of intermediate product ibp of transport mode t from pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ to conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at season m of year y (TWh)
$XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}$	flow of intermediate product ibp of transport mode t from pre-processing plant ip of technology mode $ipmode$ of technology

	size $ipsize$ of technology group $iptech$ to harbor h at season m of year y (TWh)
$XIb^{hh}_{y,m,ibp,h,h',ptech,pmode,psize,t}$	flow of intermediate product ibp of transport mode t from harbor h to harbor h' at season m of year y, dedicated for the supply to conversion plant of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ (TWh)
$XIb^{hp}_{y,m,ibp,h',p,ptech,pmode,psize,t}$	flow of intermediate product ibp of transport mode t from harbor h' to conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at season m of year y (TWh)
$XIb^{ip\_store}_{y,m,ip,iptech,ipmode,ipsize,ibp}$	storage of intermediate product ibp in pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ at season m of year y, dedicated for the supply to conversion plant (TWh)
$XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$	flow of product pd of transport mode t from conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ to demand location d at season m of year y (TWh)
$XPr^{p\_store}_{y,m,p,ptech,pmode,psize,pd}$	storage of product pd in conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ at season m of year y (TWh)
$XPr^{ref}_{y,m,f,e,d}$	reference energy production by fossil fuel technology f of energy sector e in demand location d at season m of year y (TWh)
Integer variables	
$UIP_{y,ip,iptech,ipmode,ipsize}$	number of pre-processing plant ip of technology mode $ipmode$ of technology size $ipsize$ of technology group $iptech$ built at year y
$UP_{y,p,ptech,pmode,psize}$	number of conversion plant p of technology mode $pmode$ of technology size $psize$ of technology group $ptech$ built at year y

S1.2. Mathematical formulation

Description of the mathematical formulation is presented here. The formulation comprises a series of interrelated equations on resource balances and conversions, resource demands, technology capacities, storage capacities, grid infrastructure capacities, policy-related targets, costs and emissions. It must be mentioned that the generations of the model outputs are not only limited by the variables declared in the equations. Depending on the outputs and visualizations needed for the scenario analysis, in-house programming algorithm was developed and applied for the specific customizations of the results.

S1.2.1. Resource balance and conversion

Eq. (1) defines the feedstock availability balance throughout the planning periods, consisted of the feedstock availability which maximally governs the portions of feedstock that can be allocated for consumption in pre-processing plant ($BM^{sip\_avail}_{y,s,rm,iptech,ipmode,ipsize}$), conversion plant ($BM^{sp\_avail}_{y,s,rm,ptech,pmode,psize}$) and existing bioenergy plant ($BM^{spc\_avail}_{y,s,rm}$). Availability fraction $\left(\omega^{BM}_{y,c}\right)$ is used as a factor that limits the amount of feedstock that can be allocated as supplies. For instance, as demand of crude palm oil (CPO) is mainly dedicated for food application, the portion of CPO that can be allowed for biodiesel production should be limited to avoid overconsumption, and this can be achieved by imposing the availability fraction on the feedstock availability parameter.

$$\sum_{iptech,ipmode,ipsize} BM^{sip\_avail}_{y,s,rm,iptech,ipmode,ipsize} + \sum_{ptech,pmode,psize} BM^{sp\_avail}_{y,s,rm,ptech,pmode,psize} + BM^{spc\_avail}_{y,s,rm} \leq BM^{avail}_{y,s,rm}\omega^{BM}_{y,rm}$$
$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{s} \in \mathrm{S}, \mathrm{rm} \in \mathrm{RM} \qquad (1)$$

The feedstock allocated for consumption is assigned to three separated inventory balances. First, $BM^{sip\_avail}_{y,s,rm,iptech,ipmode,ipsize}$ is assigned to the inventory balance of the pre-processing plant as shown in Eq. (2). In this equation, the feedstock allocated for the pre-processing plant ($BM^{sip\_avail}_{y,s,rm,iptech,ipmode,ipsize}$) is multiplied with the seasonality fraction ($\omega^{season}_{y,m,rm}$) to establish the seasonal feedstock flow. This flow is then directed to the flows of feedstock to intermediate plant ($XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}$) and storage facility ($XBm^{sip\_store}_{y,m,s,rm,iptech,ipmode,ipsize}$). For each season, the feedstock may be stored and then be brought up to the next season for consumption or storage. Dry matter loss (DML) (ω^{DML}_{rm}) is exerted to the associated feedstock stored to account for the efficiency of storage.

$$\sum_{ip,t|\beta^{ct}_{rm,t}} XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t} + XBm^{sip\_store}_{y,m,s,rm,iptech,ipmode,ipsize}$$
$$= BM^{sip\_avail}_{y,s,rm,iptech,ipmode,ipsize}\omega^{season}_{y,m,rm} + XBm^{sip\_storeinitial}_{y,m,s,rm,iptech,ipmode,ipsize}\big|_{(y=1)\wedge(m=1)}$$
$$+ (1-\omega^{DML}_{rm})XBm^{sip\_store}_{y,m-1,s,rm,iptech,ipmode,ipsize}\big|_{(m>1)}$$
$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{m} \in \mathrm{M}, \mathrm{s} \in \mathrm{S}, \mathrm{rm} \in \mathrm{RM}, \mathrm{iptech} \in \mathrm{IPTECH}, \mathrm{ipmode} \in \mathrm{IPMODE}, \mathrm{ipsize} \in \mathrm{IPSIZE} \qquad (2)$$

Second, the inventory balance of feedstock in the conversion plant is shown in Eq. (3). The structure of the equation is similar to Eq. (2), with different symbols used to indicate different feedstock allocations.

$$\sum_{p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp} + XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_store}$$
$$= BM_{y,s,rm,ptech,pmode,psize}^{sp\_avail} \omega_{y,m,rm}^{season} + XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_storeinitial}|_{(y=1)\wedge(m=1)}$$
$$+ (1 - \omega_{rm}^{DML}) XBm_{y,m-1,s,rm,ptech,pmode,psize}^{sp\_store}|_{(m>1)}$$
$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{m} \in \mathrm{M}, \mathrm{s} \in \mathrm{S}, \mathrm{rm} \in \mathrm{RM}, \mathrm{ptech} \in \mathrm{PTECH}, \mathrm{pmode} \in \mathrm{PMODE}, \mathrm{psize} \in \mathrm{PSIZE} \quad (3)$$

Third, the inventory balance of feedstock in the existing bioenergy plant/mill is shown in Eq. (4). The structure of the equation is similar to Eqs. (2) and (3), with different symbols used to indicate different feedstock allocations.

$$\sum_{p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,t}^{spc} + XBm_{y,m,s,rm}^{spc\_store}$$
$$= BM_{y,s,rm}^{spc\_avail} \omega_{y,m,rm}^{season} + XBm_{y,m,s,rm}^{spc\_storeinitial}|_{(y=1)\wedge(m=1)}$$
$$+ (1 - \omega_{rm}^{DML}) XBm_{y,m-1,s,rm}^{spc\_store}|_{(m>1)}$$
$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{m} \in \mathrm{M}, \mathrm{s} \in \mathrm{S}, \mathrm{rm} \in \mathrm{RM} \quad (4)$$

The conversion of feedstock to intermediate product is shown in Eq. (5). The flow of feedstock to pre-processing plant ($XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip}$) is multiplied with the respective technology efficiency ($\eta_{rm,iptech,ipmode,ibp}$) for the conversion into the intermediate product which are then allocated to three different flow variables. The first variable is the flow of intermediate product to conversion plant ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp}$), the second variable is the flow of intermediate product to harbor for shipping ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph}$) and the third variable is the flow of intermediate product to storage facility ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store}$). For each season, the intermediate product may be stored and then be brought up to the next season for consumption or storage. DML (ω_{ibp}^{DML}) is exerted to the associated intermediate product stored to account for the efficiency of storage. If an intermediate product is not associated with the loss due to storage, DML value is 0.

$$\sum_{s,rm,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip}\eta_{rm,iptech,ipmode,ibp} + XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_storeinitial}|_{(y=1)\wedge(m=1)} + (1-\omega_{ibp}^{DML})XIb_{y,m-1,ip,iptech,ipmode,ipsize,ibp}^{ip\_store}|_{(m>1)} = \sum_{t|_{\beta_{ibp,t}^{ct}}}\left(\sum_{p,ptech,pmode,psize} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp} + \sum_{h|\beta_{ibp}^{ship}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph}\right) + XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store}$$

$$\forall y \in Y, m \in M, ip \in IP, iptech \in IPTECH, ipmode \in IPMODE, ipsize \in IPSIZE, ibp \in IBP \quad (5)$$

Eq. (6) presents the formulation of the energy demand, based on the simultaneous conversions of feedstock and intermediate product to bioenergy product. For the conversion of feedstock to bioenergy product, the flows of feedstock from the supply ($XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp}$) and harbor ($XBm_{y,m,rm,h',p,ptech,pmode,psize,t}^{hp}$) points to conversion plant are multiplied with the respective efficiency ($\eta_{rm,ptech,pmode,pd}$) to obtain the associated bioenergy product ($XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd}$). For the conversion of intermediate product to bioenergy product, the flows of intermediate product from the supply ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp}$) and harbor ($XIb_{y,m,ibp,h',p,ptech,pmode,psize,t}^{hp}$) points are multiplied with the respective efficiency ($\eta_{ibp,ptech,pmode,pd}$) to obtain the associated bioenergy product ($XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd}$). For each season, the bioenergy product may be stored and then be brought up to the next season for consumption or storage. DML (ω_{pd}^{DML}) is exerted to the associated bioenergy product stored to account for the efficiency of storage. If a bioenergy product is not associated with the loss due to storage, DML value is 0.

$$\sum_{ibp,t|_{\beta^{ct}_{ibp,t}}} \left(\sum_{ip,iptech,ipmode,ipsize} XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t} + \sum_{h'|\beta^{ship}_{ibp}} XIb^{hp}_{y,m,ibp,h',p,ptech,pmode,psize,t} \right) \eta_{ibp,ptech,pmode,pd}$$
$$+ \sum_{rm,t|_{\beta^{ct}_{rm,t}}} \left(\sum_{s} XBm^{sp}_{y,m,s,rm,p,ptech,pmode,psize,t} + \sum_{h'|\beta^{ship}_{rm}} XBm^{hp}_{y,m,rm,h',p,ptech,pmode,psize,t} \right) \eta_{rm,ptech,pmode,pd}$$
$$+ XPr^{p\_storeinitial}_{y,m,p,ptech,pmode,psize,pd}|_{(y=1)\wedge(m=1)}$$
$$+ \left(1-\omega^{DML}_{pd}\right) XPr^{p\_store}_{y,m-1,p,ptech,pmode,psize,pd}|_{(m>1)}$$
$$= \sum_{d,t|\beta^{ct}_{pd,t}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} + XPr^{p\_store}_{y,m,p,ptech,pmode,psize,pd}$$
$$\forall y \in Y, m \in M, p \in P, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE, pd \in PD \quad (6)$$

Balances of the commodities at the shipping points are defined in Eqs. (7)-(10). It is noted that only feedstock and intermediate product are considered for shipping in the model, meaning that the bioenergy product will only satisfy the energy demand within the region domestically. The balances associated with the incoming flows of feedstock and intermediate product from the supply point and pre-processing plant to the harbors are respectively defined in Eqs. (7) and (8). The balances associated with the outgoing flows of feedstock and intermediate product from the harbors to the conversion plant are respectively defined in Eqs. (9) and (10).

$$\left(\sum_{s,t} XBm^{sh}_{y,m,s,rm,h,ptech,pmode,psize,t} = \sum_{h',t} XBm^{hh}_{y,m,rm,h,h',ptech,pmode,psize,t} \right)|_{\beta^{ct}_{rm,t} \wedge \beta^{ship}_{rm}}$$
$$\forall y \in Y, m \in M, rm \in RM, h \in H, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE \quad (7)$$

$$\left(\sum_{ip,iptech,ipmode,ipsize,t} XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t} = \sum_{h',ptech,pmode,psize,t} XIb^{hh}_{y,m,ibp,h,h',ptech,pmode,psize,t} \right)|_{\beta^{ct}_{ibp,t} \wedge \beta^{ship}_{ibp}}$$
$$\forall y \in Y, m \in M, ibp \in IBP, h \in H \quad (8)$$

$$\left(\sum_{h,t} XBm^{hh}_{y,m,rm,h,h',ptech,pmode,psize,t} = \sum_{p,t} XBm^{hp}_{y,m,rm,h',p,ptech,pmode,psize,t} \right)|_{\beta^{ct}_{rm,t} \wedge \beta^{ship}_{rm}}$$
$$\forall y \in Y, m \in M, rm \in RM, h' \in H, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE \quad (9)$$

$$\left(\sum_{h,t} XIb^{hh}_{y,m,ibp,h,h',ptech,pmode,psize,t} = \sum_{p,t} XIb^{hp}_{y,m,ibp,h',p,ptech,pmode,psize,t}\right)|_{\beta^{ct}_{ibp,t} \wedge \beta^{ship}_{ibp}}$$

$$\forall y \in Y, m \in M, ibp \in IBP, h' \in H, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE \qquad (10)$$

S1.2.2. Resource demand

Demand of feedstock in the existing bioenergy plant/mill is outlined in Eq. (11). Seasonality fraction of feedstock ($\omega^{season}_{y,m,rm}$) is multiplied with the demand parameter ($DM^{bm}_{y,rm,p}$) to establish the seasonal demand flow.

$$\sum_{s,t|\beta^{ct}_{rm,t}} XBm^{spc}_{y,m,s,rm,p,t} = DM^{bm}_{y,rm,p}\omega^{season}_{y,m,rm}$$

$$\forall y \in Y, m \in M, rm \in RM, p \in P \qquad (11)$$

Demand of bioenergy product is based on the competition of bioenergy ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$) and fossil fuel-based energy ($XPr^{ref}_{y,m,f,e,d}$) in fulfilling the required energy generation in different energy sectors as shown in Eq. (12). Bioenergy product ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$) is assigned to fulfil the energy demand of the respective energy sector by incorporating the product to energy sector relationship parameter ($\beta^{ce}_{pd,e}$). Seasonality fraction of the energy sector ($\omega^{season}_{y,m,e}$) is multiplied with the demand parameter ($DM^{pr}_{y,e,d}$) to establish the seasonal demand flow.

$$\sum_{p,ptech,pmode,psize,pd,t|\beta^{ct}_{pd,t} \wedge \beta^{ce}_{pd,e}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} + \sum_{f} XPr^{ref}_{y,m,f,e,d} = DM^{pr}_{y,e,d}\omega^{season}_{y,m,e}$$

$$\forall y \in Y, m \in M, e \in E, d \in D \qquad (12)$$

Fossil fuel-based energy generation is restricted by the planned capacity of fossil fuel technology as defined in Eq. (13). The upper boundary of the equation sets the planned capacity of the fossil fuel technology in contributing to the energy generation of the respective energy sector while the lower boundary sets the restriction on how much portion of fossil fuel technology that can be replaced by bioenergy.

$$Cap^{ref}_{y,f,e,d}\mu^{low}_{f}/\lambda^{season} \leq XPr^{ref}_{y,m,f,e,d} \leq Cap^{ref}_{y,f,e,d}\mu^{up}_{f}/\lambda^{season}$$

$$\forall y \in Y, m \in M, f \in F, e \in E, d \in D \qquad (13)$$

S1.2.3. Technology capacity constraint

Eq. (14) represents the technology size constraint for the pre-processing plant which is associated with the flows of intermediate product to conversion plant ($XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}$) and harbor ($XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}$). The flows are restricted by the seasonal capacity level of a technology which is set based on the division of the annual capacity ($Size^{ip}_{y,ip,iptech,ipmode,ipsize}$) with the number of seasons (λ^{season}).

$$\sum_{ibp,t|\beta^{ct}_{ibp,t}} \left(\sum_{p,ptech,pmode,psize} XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t} + \sum_{h|\beta^{ship}_{ibp}} XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t} \right) \leq Size^{ip}_{y,ip,iptech,ipmode,ipsize} / \lambda^{season}$$

$$\forall y \in Y, m \in M, ip \in IP, iptech \in IPTECH, ipmode \in IPMODE, ipsize \in IPSIZE \quad (14)$$

Eq. (15) represents the technology size constraint for the conversion plant which is associated with the flow of bioenergy product to demand point ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$). The flow is restricted by the seasonal capacity level of a technology which is set based on the division of the annual capacity ($Size^{p}_{y,p,ptech,pmode,psize}$) with the number of seasons (λ^{season}).

$$\sum_{pd,d,t|\beta^{ct}_{pd,t}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} \leq Size^{p}_{y,p,ptech,pmode,psize} / \lambda^{season}$$

$$\forall y \in Y, m \in M, p \in P, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE \quad (15)$$

To account for lifetime of technology in the annual capacity balance of a technology, variables that represent the current status of capacities as presented by $Size^{ip}_{y,ip,iptech,ipmode,ipsize}$ and $Size^{p}_{y,p,ptech,pmode,psize}$, the existing/planned capacities as presented by $Size^{ip\_initial}_{y,ip,iptech,ipmode,ipsize}$ and $Size^{p\_initial}_{y,p,ptech,pmode,psize}$, the new investment of capacities as presented by $Size^{ip\_invest}_{y,ip,iptech,ipmode,ipsize}$ and $Size^{p\_invest}_{y,p,ptech,pmode,psize}$, and the retirement of capacities as presented by $Size^{ip\_retire}_{y,ip,iptech,ipmode,ipsize}$ and $Size^{p\_retire}_{y,p,ptech,pmode,psize}$ are accounted as shown in Eqs. (16) and (17) for the balances in the pre-processing and conversion plant, respectively.

$$Size^{ip}_{y,ip,iptech,ipmode,ipsize} = Size^{ip}_{y-1,ip,iptech,ipmode,ipsize}|_{(y>1)} + Size^{ip\_initial}_{y,ip,iptech,ipmode,ipsize}|_{(y=1)} + Size^{ip\_invest}_{y,ip,iptech,ipmode,ipsize} - Size^{ip\_retire}_{y,ip,iptech,ipmode,ipsize}$$

$\forall y \in Y, ip \in IP, iptech \in IPTECH, ipmode \in IPMODE, ipsize \in IPSIZE$ (16)

$$Size^{p}_{y,p,ptech,pmode,psize} = Size^{p}_{y-1,p,ptech,pmode,psize}|_{(y>1)} + Size^{p\_initial}_{y,p,ptech,pmode,psize}|_{(y=1)} + Size^{p\_invest}_{y,p,ptech,pmode,psize} - Size^{p\_retire}_{y,p,ptech,pmode,psize}$$

$\forall y \in Y, p \in P, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE$ (17)

In defining the retired capacity of a technology for pre-processing plant ($Size^{ip\_retire}_{y,ip,iptech,ipmode,ipsize}$) and conversion plant ($Size^{p\_retire}_{y,p,ptech,pmode,psize}$), binary parameters, $\beta^{ip\_retire}_{y,y',ip,iptech,ipmode}$ and $\beta^{p\_retire}_{y,y',p,ptech,pmode}$, that point when should a technology retire its capacity after an investment has been made are incorporated in the capacity retirement balances as presented in Eqs. (18) and (19). These binary parameter relationships are adapted from the equations used in the previous modeling work.[1] For the binary parameters to work, two indices are needed for introducing the relationship between the retirement period y and the investment period y' of a technology. For example, if a technology with a 20-year lifetime is deployed in 2020, y' is subjected to 2020 while y is subjected to 2040, and the binary parameter is only subjected to the value of 1 when these two periods align. The parameters are multiplied with the associated invested capacities ($Size^{ip\_invest}_{y',ip,iptech,ipmode,ipsize}$ and $Size^{p\_invest}_{y',p,ptech,pmode,psize}$) and then added up with the known capacities of the retired facilities ($Cap^{ip\_retire}_{y,ip,iptech,ipmode,ipsize}$ and $Cap^{p\_retire}_{y,p,ptech,pmode,psize}$) to establish the annual retired capacities.

$$Size^{ip\_retire}_{y,ip,iptech,ipmode,ipsize} = Cap^{ip\_retire}_{y,ip,iptech,ipmode,ipsize} + \sum_{y'} Size^{ip\_invest}_{y',ip,iptech,ipmode,ipsize} \beta^{ip\_retire}_{y,y',ip,iptech,ipmode}$$

$\forall y \in Y, ip \in IP, iptech \in IPTECH, ipmode \in IPMODE, ipsize \in IPSIZE$ (18)

$$Size^{p\_retire}_{y,p,ptech,pmode,psize} = Cap^{p\_retire}_{y,p,ptech,pmode,psize} + \sum_{y'} Size^{p\_invest}_{y',p,ptech,pmode,psize} \beta^{p\_retire}_{y,y',p,ptech,pmode}$$

$\forall y \in Y, p \in P, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE$ (19)

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[1]Samsatli S., Samsatli N.J., Shah N., 2015, BVCM: A comprehensive and flexible toolkit for whole system biomass value chain analysis and optimisation – Mathematical formulation, Applied Energy, 147, 131-160.

Binary variables, $UIP_{y,ip,iptech,ipmode,ipsize}$ and $UP_{y,p,ptech,pmode,psize}$, are used to constrained the upper and lower boundary capacities of the new invested capacities of pre-processing technology ($Size^{ip\_invest}_{y,ip,iptech,ipmode,ipsize}$) as shown in Eq. (20) and conversion technology ($Size^{p\_invest}_{y,p,ptech,pmode,psize}$) as shown in Eq. (21).

$$UIP_{y,ip,iptech,ipmode,ipsize} Cap^{ip}_{y,ip,iptech,ipmode,ipsize} \mu^{low}_{iptech,ipmode} \leq Size^{ip\_invest}_{y,ip,iptech,ipmode,ipsize} \leq UIP_{y,ip,iptech,ipmode,ipsize} Cap^{ip}_{y,ip,iptech,ipmode,ipsize} \mu^{up}_{iptech,ipmode}$$

$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{ip} \in \mathrm{IP}, \mathrm{iptech} \in \mathrm{IPTECH}, \mathrm{ipmode} \in \mathrm{IPMODE}, \mathrm{ipsize} \in \mathrm{IPSIZE} \quad (20)$$

$$UP_{y,p,ptech,pmode,psize} Cap^{p}_{y,p,ptech,pmode,psize} \mu^{low}_{ptech,pmode} \leq Size^{p\_invest}_{y,p,ptech,pmode,psize} \leq UP_{y,p,ptech,pmode,psize} Cap^{p}_{y,p,ptech,pmode,psize} \mu^{up}_{ptech,pmode}$$

$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{p} \in \mathrm{P}, \mathrm{ptech} \in \mathrm{PTECH}, \mathrm{pmode} \in \mathrm{PMODE}, \mathrm{psize} \in \mathrm{PSIZE} \quad (21)$$

These binary variables are then constrained to limit the number of technologies that can be built for each pre-processing plant as shown in Eq. (22) and conversion plant as shown in Eq. (23).

$$\sum_{ipmode,ipsize} UIP_{y,ip,iptech,ipmode,ipsize} \leq \lambda^{limit}_{y,iptech}$$

$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{ip} \in \mathrm{IP}, \mathrm{iptech} \in \mathrm{IPTECH} \quad (22)$$

$$\sum_{pmode,psize} UP_{y,p,ptech,pmode,psize} \leq \lambda^{limit}_{y,ptech}$$

$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{p} \in \mathrm{P}, \mathrm{ptech} \in \mathrm{PTECH} \quad (23)$$

Land availability constraint is accounted to limit the capacity of technologies that can be deployed in a spatial grid as shown in Eq. (24). Parameters $A^{factor}_{iptech,ipmode}$ and $A^{factor}_{ptech,pmode}$ are adopted for calculating the area associated with the capacity deployments of pre-processing and conversion facilities. The capacities of the bioenergy technologies that can be deployed are restricted by the availability of land in a spatial grid ($A^{avail}_{y,g}$).

$$\sum_{ip,iptech,ipmode,ipsize|\beta^{gip}_{g,ip}} Size^{ip}_{y,ip,iptech,ipmode,ipsize} A^{factor}_{iptech,ipmode} + \sum_{p,ptech,pmode,psize|\beta^{gp}_{g,p}} Size^{p}_{y,p,ptech,pmode,psize} A^{factor}_{ptech,pmode} \leq A^{avail}_{y,g}$$

$$\forall \mathrm{y} \in \mathrm{Y}, \mathrm{g} \in \mathrm{G} \quad (24)$$

S1.2.4. Storage capacity constraint

Storages of feedstock ($XBm^{sip\_store}_{y,m,s,rm,iptech,ipmode,ipsize}$ and $XBm^{sp\_store}_{y,m,s,rm,ptech,pmode,psize}$ and $XBm^{spc\_store}_{y,m,s,rm}$), intermediate product ($XIb^{ip\_store}_{y,m,ip,iptech,ipmode,ipsize,ibp}$) and bioenergy product ($XPr^{p\_store}_{y,m,p,ptech,pmode,psize,pd}$) are defined to cater the seasonality effects of storing commodities in the model. The upper boundaries of the storage capacities for feedstock, intermediate product and product are defined in Eqs. (25)-(29), respectively. The seasonal capacity level of a storage facility is set based on the division of the annual capacity ($Cap^{bm\_store}_{y,s,rm}$ and $Cap^{ip\_store}_{y,ip,iptech,ipmode,ipsize,ibp}$ and $Cap^{p\_store}_{y,p,ptech,pmode,psize,pd}$) with the number of seasons (λ^{season}).

$$\sum_{iptech,ipmode,ipsize} XBm^{sip\_store}_{y,m,s,rm,iptech,ipmode,ipsize} \leq Cap^{bm\_store}_{y,s,rm}/\lambda^{season}$$
$$\forall y \in Y, m \in M, s \in S, rm \in RM \qquad (25)$$

$$\sum_{ptech,pmode,psize} XBm^{sp\_store}_{y,m,s,rm,ptech,pmode,psize} \leq Cap^{bm\_store}_{y,s,rm}/\lambda^{season}$$
$$\forall y \in Y, m \in M, s \in S, rm \in RM \qquad (26)$$

$$XBm^{spc\_store}_{y,m,s,rm} \leq Cap^{bm\_store}_{y,s,rm}/\lambda^{season}$$
$$\forall y \in Y, m \in M, s \in S, rm \in RM \qquad (27)$$

$$XIb^{ip\_store}_{y,m,ip,iptech,ipmode,ipsize,ibp} \leq Cap^{ip\_store}_{y,ip,iptech,ipmode,ipsize,ibp}/\lambda^{season}$$
$$\forall y \in Y, m \in M, ip \in IP, iptech \in IPTECH, ipmode \in IPMODE, ipsize \in IPSIZE, ibp \in IBP \qquad (28)$$

$$XPr^{p\_store}_{y,m,p,ptech,pmode,psize,pd} \leq Cap^{p\_store}_{y,p,ptech,pmode,psize,pd}/\lambda^{season}$$
$$\forall y \in Y, m \in M, p \in P, ptech \in PTECH, pmode \in PMODE, psize \in PSIZE, pd \in PD \qquad (29)$$

S1.2.5. Grid infrastructure capacity constraint

The annual capacity level of a grid infrastructure ($grid_{y,c,g,g',t}$) is established by accounting the existing capacity in operation ($grid^{initial}_{y,c,g,g',t}$) and the new capacity invested ($grid^{invest}_{y,c,g,g',t}$). Investment cost for the grid infrastructure will only be accounted if a new capacity is invested, meaning that for the existing capacity, the transport of a commodity is only associated with the operational cost. The grid infrastructure capacity constraint is defined in Eq. (30).

$$\left[grid_{y,c,g,g',t} = grid_{y-1,c,g,g',t|(y>1)} + grid^{initial}_{y,c,g,g',t|(y=1)} + grid^{invest}_{y,c,g,g',t}\right]|_{\beta^{grid}_{c} \wedge \beta^{ct}_{c,t}}$$
$$\forall y \in Y, c \in C, g \in G, g' \in G, t \in T \quad (30)$$

The capacity constraint formulated in Eq. (30) restricts the amount of commodities that can be transported using the infrastructures. These are shown in Eqs. (31) and (32) for the transport of intermediate product ($XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}$) and bioenergy product ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$), respectively.

$$\left(\sum_{m,ip,iptech,ipmode,ipsize,p,ptech,pmode,psize|\beta^{gip}_{g,ip} \wedge \beta^{gp}_{g',p}} XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t} \leq grid_{y,ibp,g,g',t}\right)|_{\beta^{grid}_{ibp} \wedge \beta^{ct}_{ibp,t}}$$
$$\forall y \in Y, ibp \in IBP, g \in G, g' \in G, t \in T \quad (31)$$

$$\left(\sum_{m,p,ptech,pmode,psize,d|\beta^{gp}_{g,p} \wedge \beta^{gd}_{g',d}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} \leq grid_{y,pd,g,g',t}\right)|_{\beta^{grid}_{pd} \wedge \beta^{ct}_{pd,t}}$$
$$\forall y \in Y, pd \in PD, g \in G, g' \in G, t \in T \quad (32)$$

S1.2.6. Renewable energy/emission target

Policy target is one of the mechanisms used to drive bioenergy in meeting the portion of energy demand. This is illustrated in Eq. (33), where renewable energy target is used to drive the future bioenergy capacity, and Eq. (34), where CO_2 emission target is used to drive the future production required to deliver emission reduction. It is noted that conditions $\left(target^{bio}_{y,e} > 0\right)$ and $\left(target^{em}_{y} > 0\right)$ are exerted to the respective equations in order to prevent the system from specifying null value as a target in a particular year, and also, to deactivate these two equations if policy instruments are being used as tools to drive the future renewable energy production and emission reduction.

$$\left(\sum_{m,p,ptech,pmode,psize,pd,d,t|\beta^{ce}_{pd,e} \wedge \beta^{ct}_{pd,t}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} \geq target^{bio}_{y,e}\right)|_{(target^{bio}_{y,e} > 0)}$$
$$\forall y \in Y, e \in E \quad (33)$$

$$\left[\sum_{f,e,d} DM^{pr}_{y,e,d} emf^{ref}_{f,e} - \left(TOTEMISSION_y + Em^{bm\_pc}_y + Em^{bm\_t\_pc}_y + Em^{bm\_store\_pc}_y\right) \geq target^{em}_y\right]\Big|_{(target^{em}_y > 0)}$$

$\forall y \in Y$ (34)

S1.2.7. Cost of energy supply chain

Total cost of the energy supply chain can be broken down into the collection/purchase costs of feedstock as defined in Eqs. (35) and (36), the storage costs of feedstock as defined in Eqs. (37) and (38), the storage costs of intermediate product and bioenergy product as defined in Eqs. (39) and (40), the transport costs of feedstock as defined in Eqs. (41) and (42), the transport costs of intermediate product and bioenergy product as defined in Eqs. (43) and (44), the shipping costs of feedstock and intermediate product as defined in Eqs. (45) and (46), the infrastructure costs associated with pre-processing and conversion plants as defined in Eqs. (47) and (48), the investment costs of pre-processing and conversion plants as defined in Eqs. (49) and Equation (50), the operating costs of pre-processing and conversion plants as defined in Eqs. (51) and (52), and the reference cost of the energy sectors as defined in Eq. (53).

Eq. (35) defines the collection/purchase cost of feedstock, consisted of the multiplications of the quantities of feedstock collected/purchased for supplies to the pre-processing plant ($XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}$), conversion plant ($XBm^{sp}_{y,m,s,rm,p,ptech,pmode,psize,t}$) and harbor ($XBm^{sh}_{y,m,s,rm,h,ptech,pmode,psize,t}$) with the unit price of feedstock ($pf^{c}_{y,rm}$).

$$Cost^{bm}_{y,e} = \sum_{m,s,rm,t|_{\beta^{ct}_{rm,t}}} \left[\sum_{ip,iptech,ipmode,ipsize|\beta^{teche}_{iptech,e}} XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t} + \sum_{ptech,pmode,psize} \left(\sum_{p} XBm^{sp}_{y,m,s,rm,p,ptech,pmode,psize,t} + \sum_{h|\beta^{ship}_{rm}} XBm^{sh}_{y,m,s,rm,h,ptech,pmode,psize,t}\right)\Big|_{\beta^{teche}_{ptech,e}}\right] pf^{c}_{y,rm}$$

$\forall y \in Y, e \in E$ (35)

Eq. (36) defines the collection/purchase cost of feedstock associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock collected/purchased for supply to the existing bioenergy plant/mill ($XBm^{spc}_{y,m,s,rm,p,t}$) with the unit price of feedstock ($pf^{c}_{y,rm}$).

$$Cost_y^{bm\_pc} = \sum_{m,s,rm,p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,t}^{spc} pf_{y,rm}^{c}$$

$\forall y \in Y$ (36)

Eq. (37) defines the storage cost of feedstock, consisted of the multiplication of the quantities of feedstock stored for supplies to pre-processing plant ($XBm_{y,m,s,rm,iptech,ipmode,ipsize}^{sip_{store}}$) and conversion plant ($XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_store}$) with the unit cost of storage (pf_{rm}^{store}).

$$Cost_{y,e}^{bm\_store} = \sum_{m,s,rm} \left(\sum_{iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,iptech,ipmode,ipsize}^{sip\_store} + \sum_{ptech,pmode,psize|\beta_{ptech,e}^{teche}} XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_store} \right) pf_{rm}^{store}$$

$\forall y \in Y, e \in E$ (37)

Eq. (38) defines the storage cost of feedstock associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock stored for supply to the existing bioenergy plant/mill ($XBm_{y,m,s,rm}^{spc\_store}$) with the unit cost of storage (pf_{rm}^{store}).

$$Cost_y^{bm\_store\_pc} = \sum_{m,s,rm} XBm_{y,m,s,rm}^{spc\_store} pf_{rm}^{store}$$

$\forall y \in Y$ (38)

Eq. (39) defines the storage cost of intermediate product, consisted of the multiplication of the quantity of intermediate product stored in the pre-processing plant ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store}$) with the unit cost of storage (pf_{ibp}^{store}).

$$Cost_{y,e}^{ip\_store} = \sum_{m,ip,iptech,ipmode,ipsize,ibp|\beta_{iptech,e}^{teche}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store} pf_{ibp}^{store}$$

$\forall y \in Y, e \in E$ (39)

Eq. (40) defines the storage cost of bioenergy product, consisted of the multiplication of the quantity of product stored in the conversion plant ($XPr_{y,m,p,ptech,pmode,psize,pd}^{p\_store}$) with the unit cost of storage (pf_{pd}^{store}).

$$Cost_{y,e}^{p\_store} = \sum_{m,p,ptech,pmode,psize,pd|\beta_{pd,e}^{ce}} XPr_{y,m,p,ptech,pmode,psize,pd}^{p\_store} pf_{pd}^{store}$$

$\forall y \in Y, e \in E$ (40)

Eq. (41) defines the transport cost of feedstock, consisted of the multiplication of the quantities of feedstock transported from the supply point to pre-processing plant ($XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip}$), conversion plant ($XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp}$) and harbor ($XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh}$), and from harbor to conversion plant ($XBm_{y,m,rm,h',p,ptech,pmode,psize,t}^{hp}$), with the respective cost parameters: 1) unit loading/unloading cost ($pf_{rm,t}^{tload}$); 2) unit transport cost ($pf_{rm,t}^{tvar}$) multiplied with distance; and 3) unit fuel transport cost ($pf_{y,rm,t}^{tfuel}$) multiplied with distance.

$$\begin{aligned} Cost_{y,e}^{bm\_t} &= \sum_{m,rm,t|_{\beta_{rm,t}^{ct}}} \left\{ \sum_{s,ip,iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip} \left[pf_{rm,t}^{tload} + Dist_{s,ip,t}^{sip}\left(pf_{rm,t}^{tvar} + pf_{y,rm,t}^{tfuel}\right)\right] \right. \\ &+ \sum_{s,p,ptech,pmode,psize|\beta_{ptech,e}^{teche}} XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp} \left[pf_{rm,t}^{tload} + Dist_{s,p,t}^{sp}\left(pf_{rm,t}^{tvar} + pf_{y,rm,t}^{tfuel}\right)\right] \\ &+ \sum_{s,h,ptech,pmode,psize|\beta_{ptech,e}^{teche} \wedge \beta_{rm}^{ship}} XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh} \left[pf_{rm,t}^{tload} + Dist_{s,h,t}^{sh}\left(pf_{rm,t}^{tvar} + pf_{y,rm,t}^{tfuel}\right)\right] \\ &\left. + \sum_{h',p,ptech,pmode,psize|\beta_{ptech,e}^{teche} \wedge \beta_{rm}^{ship}} XBm_{y,m,rm,h',p,ptech,pmode,psize,t}^{hp} \left[pf_{rm,t}^{tload} + Dist_{h',p,t}^{hp}\left(pf_{rm,t}^{tvar} + pf_{y,rm,t}^{tfuel}\right)\right] \right\} \end{aligned}$$

$\forall y \in Y, e \in E$ (41)

Eq. (42) defines the transport cost of feedstock associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock transported from the supply point to existing bioenergy plant/mill ($XBm_{y,m,s,rm,p,t}^{spc}$) with the respective cost parameters: 1) unit loading/unloading cost ($pf_{rm,t}^{tload}$); 2) unit transport cost ($pf_{rm,t}^{tvar}$) multiplied with distance; and 3) unit fuel transport cost ($pf_{y,rm,t}^{tfuel}$) multiplied with distance.

$$Cost_{y}^{bm\_t\_pc} = \sum_{m,s,rm,p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,t}^{spc} \left[pf_{rm,t}^{tload} + Dist_{s,p,t}^{sp}\left(pf_{rm,t}^{tvar} + pf_{y,rm,t}^{tfuel}\right)\right]$$

$\forall y \in Y$ (42)

Eq. (43) defines the transport cost of intermediate product, consisted of the multiplication of the quantity of intermediate product transported from the pre-processing plant to conversion plant ($XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}$) and harbor ($XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}$), and from harbor to conversion plant ($XIb^{hp}_{y,m,ibp,h',p,ptech,pmode,psize,t}$), with the respective cost parameters: 1) unit loading/unloading cost ($pf^{tload}_{ibp,t}$); 2) unit transport cost ($pf^{tvar}_{ibp,t}$) multiplied with distance; and 3) unit fuel transport cost ($pf^{tfuel}_{y,ibp,t}$) multiplied with distance.

$$Cost^{ib\_t}_{y,e} = \sum_{m,ibp,t|\beta^{ct}_{ibp,t}} \left\{ \sum_{ip,iptech,ipmode,ipsize,p,ptech,pmode,psize|\beta^{teche}_{iptech,e}} XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t} \begin{bmatrix} pf^{tload}_{ibp,t} + \\ Dist^{ipp}_{ip,p,t} \begin{pmatrix} pf^{tvar}_{ibp,t} + \\ pf^{tfuel}_{y,ibp,t} \end{pmatrix} \end{bmatrix} \right.$$
$$+ \sum_{ip,iptech,ipmode,ipsize,ibp,h|\beta^{teche}_{iptech,e} \wedge \beta^{ship}_{ibp}} XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t} \left[pf^{tload}_{ibp,t} + Dist^{iph}_{ip,h,t} \left(pf^{tvar}_{ibp,t} + pf^{tfuel}_{y,ibp,t} \right) \right]$$
$$\left. + \sum_{h',p,ptech,pmode,psize|\beta^{teche}_{ptech,e} \wedge \beta^{ship}_{ibp}} XIb^{hp}_{y,m,ibp,h',p,ptech,pmode,psize,t} \left[pf^{tload}_{ibp,t} + Dist^{hp}_{h',p,t} \left(pf^{tvar}_{ibp,t} + pf^{tfuel}_{y,ibp,t} \right) \right] \right\}$$
$$\forall y \in Y, e \in E \quad (43)$$

Eq. (44) defines the transport cost of bioenergy product, consisted of the multiplication of the quantity of product transported from the conversion plant to demand point ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$) with the respective cost parameters: 1) unit loading/unloading cost ($pf^{tload}_{pd,t}$); 2) unit transport cost ($pf^{tvar}_{pd,t}$) multiplied with distance; and 3) unit fuel transport cost ($pf^{tfuel}_{y,pd,t}$) multiplied with distance.

$$Cost^{pr\_t}_{y,e} = \sum_{m,p,ptech,pmode,psize,pd,d,t|\beta^{ce}_{pd,e} \wedge \beta^{ct}_{pd,t}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} \left[pf^{tload}_{pd,t} + Dist^{pd}_{p,d,t} \left(pf^{tvar}_{pd,t} + pf^{tfuel}_{y,pd,t} \right) \right]$$
$$\forall y \in Y, e \in E \quad (44)$$

Eq. (45) defines the shipping cost of feedstock, consisted of the multiplication of the quantity of feedstock shipped from harbor to harbor ($XBm^{hh}_{y,m,rm,h,h',ptech,pmode,psize,t}$) with the respective cost parameters: 1) unit loading/unloading cost ($pf^{shipload}_{rm,t}$); and 2) unit shipping cost ($pf^{shipvar}_{rm,t}$) multiplied with distance.

$$Cost^{bm\_ship}_{y,e} = \sum_{m,rm,h,h',ptech,pmode,psize,t|\beta^{teche}_{ptech,e} \wedge \beta^{ship}_{rm} \wedge \beta^{ct}_{rm,t}} XBm^{hh}_{y,m,rm,h,h',ptech,pmode,psize,t} \left(pf^{shipload}_{rm,t} + Dist^{hh}_{h,h',t} pf^{shipvar}_{rm,t} \right)$$

$\forall y \in Y, e \in E$ (45)

Eq. (46) defines the shipping cost of intermediate product, consisted of the multiplication of the quantity of intermediate product shipped from harbor to harbor ($XIb^{hh}_{y,m,ibp,h,h',ptech,pmode,psize,t}$) with the respective cost parameters: 1) unit loading/unloading cost ($pf^{shipload}_{ibp,t}$); and 2) unit shipping cost ($pf^{shipvar}_{ibp,t}$) multiplied with distance.

$$Cost^{ib\_ship}_{y,e} = \sum_{m,ibp,h,h',ptech,pmode,psize,t|\beta^{teche}_{ptech,e}\wedge\beta^{ship}_{ibp}\wedge\beta^{ct}_{ibp,t}} XIb^{hh}_{y,m,ibp,h,h',ptech,pmode,psize,t}\left(pf^{shipload}_{ibp,t} + Dist^{hh}_{h,h',t}pf^{shipvar}_{ibp,t}\right)$$

$\forall y \in Y, e \in E$ (46)

Eq. (47) defines the infrastructure cost of the pre-processing plant, consisted of the multiplication of the invested grid infrastructure capacity ($grid^{invest}_{y,ibp,g,g',t}$) with the respective cost parameters: 1) unit investment cost of grid connectivity ($pf^{infrafix}_{ibp,t}$); and 2) unit investment cost of grid interconnection ($pf^{infravar}_{ibp,t}$) multiplied with distance.

$$Cost^{ip\_infra}_{y,e} = \sum_{ibp,g,g',t|\beta^{ce}_{ibp,e}\wedge\beta^{grid}_{ibp}\wedge\beta^{ct}_{ibp,t}} grid^{invest}_{y,ibp,g,g',t}\left(pf^{infrafix}_{ibp,t} + \sum_{ip,p\left|\beta^{gip}_{g,ip}\wedge\beta^{gp}_{g',p}\right.} Dist^{ipp}_{ip,p,t}pf^{infravar}_{ibp,t}\right)$$

$\forall y \in Y, e \in E$ (47)

Eq. (48) defines the infrastructure cost of the conversion plant, consisted of the multiplication of the invested grid infrastructure capacity ($grid^{invest}_{y,pd,g,g',t}$) with the respective unit cost parameters: 1) unit investment cost of grid connectivity ($pf^{infrafix}_{pd,t}$); and 2) unit investment cost of grid interconnection ($pf^{infravar}_{pd,t}$) multiplied with distance.

$$Cost^{p\_infra}_{y,e} = \sum_{pd,g,g',t|\beta^{ce}_{pd,e}\wedge\beta^{grid}_{pd}\wedge\beta^{ct}_{pd,t}} grid^{invest}_{y,pd,g,g',t}\left[pf^{infrafix}_{pd,t} + \sum_{p,d\left|\beta^{gp}_{g,p}\wedge\beta^{gd}_{g',d}\right.} Dist^{pd}_{p,d,t}pf^{infravar}_{pd,t}\right]$$

$\forall y \in Y, e \in E$ (48)

Eq. (49) defines the investment cost of the pre-processing plant, consisted of the multiplication of pre-processing plant capacity ($Size^{ip}_{y,ip,iptech,ipmode,ipsize}$) with the unit investment cost ($pf^{capex}_{iptech,ipmode,ipsize}$).

$$Cost^{ip\_capex}_{y,e} = \sum_{ip,iptech,ipmode,ipsize|\beta^{teche}_{iptech,e}} Size^{ip}_{y,ip,iptech,ipmode,ipsize} pf^{capex}_{iptech,ipmode,ipsize}$$

$$\forall y \in Y, e \in E \quad (49)$$

Eq. (50) defines the investment cost of the conversion plant, consisted of the multiplication of conversion plant capacity ($Size^{p}_{y,p,ptech,pmode,psize}$) with the unit investment cost ($pf^{capex}_{ptech,pmode,psize}$).

$$Cost^{p\_capex}_{y,e} = \sum_{p,ptech,pmode,psize|\beta^{teche}_{ptech,e}} Size^{p}_{y,p,ptech,pmode,psize} pf^{capex}_{ptech,pmode,psize}$$

$$\forall y \in Y, e \in E \quad (50)$$

Eq. (51) defines the O&M cost of the pre-processing plant, involving the summations of the following multiplications: 1) multiplication of the pre-processing plant capacity ($Size^{ip}_{y,ip,iptech,ipmode,ipsize}$) with the unit fix O&M cost ($pf^{opexfix}_{iptech,ipmode,ipsize}$); and 2) multiplication of the production quantities of intermediate product ($XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}$ and $XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}$) with the unit variable O&M cost ($pf^{opexvar}_{iptech,ipmode,ipsize}$).

$$\begin{aligned} Cost^{ip\_opex}_{y,e} = & \sum_{ip,iptech,ipmode,ipsize|_{\beta^{teche}_{iptech,e}}} \Bigg[Size^{ip}_{y,ip,iptech,ipmode,ipsize} pf^{opexfix}_{iptech,ipmode,ipsize} \\ & + \sum_{m,ibp,t|_{\beta^{ct}_{ibp,t}}} \Bigg(\sum_{p,ptech,pmode,psize} XIb^{ipp}_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t} \\ & + \sum_{h|\beta^{ship}_{ibp}} XIb^{iph}_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t} \Bigg) pf^{opexvar}_{iptech,ipmode,ipsize} \Bigg] \end{aligned}$$

$$\forall y \in Y, e \in E \quad (51)$$

Eq. (52) defines the O&M cost of the conversion plant, involving the summations of the following multiplications: 1) multiplication of conversion plant capacity ($Size^{p}_{y,p,ptech,pmode,psize}$) with the unit fix O&M cost ($pf^{opexfix}_{ptech,pmode,psize}$); and 2) multiplication of the production quantity of bioenergy product ($XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t}$) with the unit variable O&M cost ($pf^{opexvar}_{ptech,pmode,psize}$).

$$Cost^{p\_opex}_{y,e} = \sum_{p,ptech,pmode,psize|\beta^{teche}_{ptech,e}} \left(Size^{p}_{y,p,ptech,pmode,psize} pf^{opexfix}_{ptech,pmode,psize} + \sum_{m,pd,d,t|\beta^{ct}_{pd,t}} XPr^{pd}_{y,m,p,ptech,pmode,psize,pd,d,t} pf^{opexvar}_{ptech,pmode,psize} \right)$$

$\forall y \in Y, e \in E$ (52)

Eq. (53) defines the reference cost associated with the energy sectors. The reference fossil fuel-based energy production ($XPr^{ref}_{y,m,f,e,d}$) is multiplied with the associated fossil fuel technology cost ($pf^{ref}_{y,f,e}$) in quantifying the reference energy cost. It is noted that the base investment cost of fossil fuel technology ($pf^{capexbal}_{f,e}$) is also included to account the cost associated with the substituted capacity of fossil fuels by renewable energy (i.e., co-firing).

$$Cost^{ref}_{y,e} = \sum_{m,f,e,d} XPr^{ref}_{y,m,f,e,d} pf^{ref}_{y,f,e} + \sum_{p,ptech,pmode,psize,f|\beta^{teche}_{ptech,e} \wedge \beta^{techf}_{ptech,f}} Size^{p}_{y,p,ptech,pmode,psize} pf^{capexbal}_{f,e}$$

$\forall y \in Y, e \in E$ (53)

S1.2.8. Emission of energy supply chain

Total emission of the energy supply chain can be broken down into the emissions from feedstock collection as defined in Eqs. (54) and (55), the emissions from feedstock storage as defined in Eqs. (56) and (57), the emissions from intermediate product and bioenergy product storages as defined in Eqs. (58) and (59), the emissions from feedstock transport as defined in Eqs. (60) and (61), the emissions from intermediate product and bioenergy product storages as defined in Eqs. (62) and (63), the emissions from feedstock and intermediate product shipping as defined in Eqs. (64) and (65), the emissions from pre-processing and conversion activities as defined in Eqs. (66) and (67), the avoided emission associated with the utilization of feedstock as defined in Eq. (68) and the total emission of the reference energy sectors as defined in Eq. (69).

Eq. (54) defines the emission from feedstock collection, consisted of the multiplications of the quantities of feedstock collected for supplies to the pre-processing plant ($XBm^{sip}_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}$), conversion plant ($XBm^{sp}_{y,m,s,rm,p,ptech,pmode,psize,t}$) and harbor ($XBm^{sh}_{y,m,s,rm,h,ptech,pmode,psize,t}$) with the emission factor of feedstock collection (emf^{bm}_{rm}).

$$Em_{y,e}^{bm} = \sum_{m,s,rm,t|\beta_{rm,t}^{ct}} \left[\sum_{ip,iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip} + \sum_{ptech,pmode,psize} \left(\sum_{p} XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp} + \sum_{h|\beta_{rm}^{ship}} XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh} \right) |_{\beta_{ptech,e}^{teche}} \right] emf_{rm}^{bm}$$

$\forall y \in Y, e \in E$ (54)

Eq. (55) defines the emission from feedstock collection associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock collected for supply to the existing bioenergy plant/mill ($XBm_{y,m,s,rm,p,t}^{spc}$) with the emission factor of feedstock collection (emf_{rm}^{bm}).

$$Em_{y}^{bm\_pc} = \sum_{m,s,rm,p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,t}^{spc} emf_{rm}^{bm}$$

$\forall y \in Y$ (55)

Eq. (56) defines the emission from feedstock storage, consisted of the multiplication of the quantities of feedstock stored for supplies to pre-processing plant ($XBm_{y,m,s,rm,iptech,ipmode,ipsize}^{sip_{store}}$) and conversion plant ($XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_store}$) with the emission factor of feedstock storage (emf_{rm}^{store}).

$$Em_{y,e}^{bm\_store} = \sum_{m,s,rm} \left(\sum_{iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,iptech,ipmode,ipsize}^{sip\_store} + \sum_{ptech,pmode,psize|\beta_{ptech,e}^{teche}} XBm_{y,m,s,rm,ptech,pmode,psize}^{sp\_store} \right) emf_{rm}^{store}$$

$\forall y \in Y, e \in E$ (56)

Eq. (57) defines the emission from feedstock storage associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock stored for supply to the existing bioenergy plant/mill ($XBm_{y,m,s,rm}^{spc\_store}$) with the emission factor of feedstock storage (emf_{rm}^{store}).

$$Em_{y}^{bm\_store\_pc} = \sum_{m,s,rm} XBm_{y,m,s,rm}^{spc\_store}\ emf_{rm}^{store}$$

$$\forall y \in Y \qquad (57)$$

Eq. (58) defines the emission from intermediate product storage, consisted of the multiplication of the quantity of intermediate product stored in the pre-processing plant ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store}$) with the emission factor of intermediate product storage (emf_{ibp}^{store}).

$$Em_{y,e}^{ip\_store} = \sum_{m,ip,iptech,ipmode,ipsize,ibp|\beta_{iptech,e}^{teche}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp}^{ip\_store} emf_{ibp}^{store}$$

$$\forall y \in Y, e \in E \qquad (58)$$

Eq. (59) defines the emission from bioenergy product storage, consisted of the multiplication of the quantity of product stored in the conversion plant ($XPr_{y,m,p,ptech,pmode,psize,pd}^{p\_store}$) with the emission factor of product storage (emf_{pd}^{store}).

$$Em_{y,e}^{p\_store} = \sum_{m,p,ptech,pmode,psize,pd|\beta_{pd,e}^{ce}} XPr_{y,m,p,ptech,pmode,psize,pd}^{p\_store} emf_{pd}^{store}$$

$$\forall y \in Y, e \in E \qquad (59)$$

Eq. (60) defines the emission from feedstock transport, consisted of the multiplications of the quantities of feedstock transported from the supply point to pre-processing plant ($XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip}$), conversion plant ($XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp}$) and harbor ($XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh}$), and from harbor to conversion plant ($XBm_{y,m,rm,h',p,ptech,pmode,psize,t}^{hp}$), with the respective emission factors: 1) emission factor associated with loading and unloading of feedstock ($emf_{rm,t}^{tload}$); and 2) emission factor associated with feedstock transport ($emf_{rm,t}^{tvar}$) multiplied with distance.

$$Em_{y,e}^{bm\_t} = \sum_{m,rm,t|_{\beta_{rm,t}^{ct}}} \left[\sum_{s,ip,iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip} \left(emf_{rm,t}^{tload} + Dist_{s,ip,t}^{sip} emf_{rm,t}^{tvar} \right) + \sum_{s,p,ptech,pmode,psize|\beta_{ptech,e}^{teche}} XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp} \left(emf_{rm,t}^{tload} + Dist_{s,p,t}^{sp} emf_{rm,t}^{tvar} \right) + \sum_{s,h,ptech,pmode,psize|\beta_{ptech,e}^{teche} \wedge \beta_{rm}^{ship}} XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh} \left(emf_{rm,t}^{tload} + Dist_{s,h,t}^{sh} emf_{rm,t}^{tvar} \right) + \sum_{h',p,ptech,pmode,psize|\beta_{ptech,e}^{teche} \wedge \beta_{rm}^{ship}} XBm_{y,m,rm,h',p,ptech,pmode,psize,t}^{hp} \left(emf_{rm,t}^{tload} + Dist_{h',p,t}^{hp} emf_{rm,t}^{tvar} \right) \right]$$

$\forall y \in Y, e \in E$ (60)

Eq. (61) defines the emission from feedstock transport associated with the existing bioenergy plant/mill. It consisted of the multiplication of the quantity of feedstock transported from the supply point to the existing bioenergy plant/mill ($XBm_{y,m,s,rm,p,t}^{spc}$) with the respective emission parameters: 1) emission factor associated with loading and unloading of feedstock ($emf_{rm,t}^{tload}$); and 2) emission factor associated with feedstock transport ($emf_{rm,t}^{tvar}$) multiplied with distance.

$$Em_{y}^{bm\_t\_pc} = \sum_{m,s,rm,p,t|\beta_{rm,t}^{ct}} XBm_{y,m,s,rm,p,t}^{spc} \left(emf_{rm,t}^{tload} + Dist_{s,p,t}^{sp} emf_{rm,t}^{tvar} \right)$$

$\forall y \in Y$ (61)

Eq. (62) defines the emission from intermediate product transport, consisted of the multiplications of the quantities of intermediate product transported from the pre-processing plant to conversion plant ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp}$) and harbor ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph}$), and from harbor to conversion plant ($XIb_{y,m,ibp,h',p,ptech,pmode,psize,t}^{hp}$), with the respective emission factors: 1)emission factor associated with loading and unloading of intermediate product ($emf_{ibp,t}^{tload}$); and 2) emission factor associated with intermediate product transport ($emf_{ibp,t}^{tvar}$) multiplied with distance.

$$Em_{y,e}^{ib\_t} = \sum_{m,ibp,t|\beta_{ibp,t}^{ct}} \left[\sum_{ip,iptech,ipmode,ipsize,p,ptech,pmode,psize|\beta_{iptech,e}^{teche}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp} \begin{pmatrix} emf_{ibp,t}^{tload} \\ +Dist_{ip,p,t}^{ipp} emf_{ibp,t}^{tvar} \end{pmatrix} \right.$$
$$+ \sum_{ip,iptech,ipmode,ipsize,ibp,h|\beta_{iptech,e}^{teche} \wedge \beta_{ibp}^{ship}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph} \left(emf_{ibp,t}^{tload} + Dist_{ip,h,t}^{iph} emf_{ibp,t}^{tvar} \right)$$
$$\left. + \sum_{h',p,ptech,pmode,psize|\beta_{ptech,e}^{teche} \wedge \beta_{ibp}^{ship}} XIb_{y,m,ibp,h',p,ptech,pmode,psize,t}^{hp} \left(emf_{ibp,t}^{tload} + Dist_{h',p,t}^{hp} emf_{ibp,t}^{tvar} \right) \right]$$
$\forall y \in Y, e \in E$ (62)

Eq. (63) defines the emission from bioenergy product transport, consisted of the multiplication of the quantity of product transported from the conversion plant to the demand point ($XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd}$) with the respective emission factors: 1) emission factor associated with loading and unloading of bioenergy product ($emf_{pd,t}^{tload}$); and 2) emission factor associated with bioenergy product transport ($emf_{pd,t}^{tvar}$) multiplied with distance.

$$Em_{y,e}^{pr\_t} = \sum_{m,p,ptech,pmode,psize,pd,d,t|\beta_{pd,e}^{ce} \wedge \beta_{pd,t}^{ct}} XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd} \left(emf_{pd,t}^{tload} + Dist_{p,d,t}^{pd} emf_{pd,t}^{tvar} \right)$$
$\forall y \in Y, e \in E$ (63)

Eq. (64) defines the emission from feedstock shipping, consisted of the multiplication of the quantity of feedstock shipped from harbor to harbor ($XBm_{y,m,rm,h,h',ptech,pmode,psize,t}^{hh}$) with the respective emission factors: 1) emission factor associated with loading and unloading of feedstock ($emf_{rm,t}^{shipload}$); and 2) emission factor associated with feedstock shipping ($emf_{rm,t}^{shipvar}$) multiplied with distance.

$$Em_{y,e}^{bm\_ship} = \sum_{m,rm,h,h',ptech,pmode,psize,t|\beta_{ptech,e}^{teche} \wedge \beta_{rm}^{ship} \wedge \beta_{rm,t}^{ct}} XBm_{y,m,rm,h,h',ptech,pmode,psize,t}^{hh} \left(emf_{rm,t}^{shipload} + Dist_{h,h',t}^{hh} emf_{rm,t}^{shipvar} \right)$$
$\forall y \in Y, e \in E$ (64)

Eq. (65) defines the emission from intermediate product shipping, consisted of the multiplication of the quantity of intermediate product shipped from harbor to harbor ($XIb_{y,m,ibp,h,h',ptech,pmode,psize,t}^{hh}$) with the respective emission factors: 1) emission factor associated with loading and unloading of intermediate product ($emf_{ibp,t}^{shipload}$); and 2) emission factors associated with intermediate product shipping ($emf_{ibp,t}^{shipvar}$) multiplied with distance.

$$Em_{y,e}^{ib\_ship} = \sum_{m,ibp,h,h',ptech,pmode,psize,t|\beta_{ptech,e}^{teche} \wedge \beta_{ibp}^{ship} \wedge \beta_{ibp,t}^{ct}} XIb_{y,m,ibp,h,h',ptech,pmode,psize,t}^{hh} \left(emf_{ibp,t}^{shipload} + Dist_{h,h',t}^{hh} emf_{ibp,t}^{shipvar} \right)$$

$\forall y \in Y, e \in E$ (65)

Eq. (66) defines the emission from pre-processing activity, consisted of the multiplication of the production quantities of intermediate product ($XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp}$ and $XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph}$) with the emission factor of pre-processing technology ($emf_{iptech,ipmode}^{tech}$).

$$Em_{y,e}^{ip} = \sum_{m,ip,iptech,ipmode,ipsize,ibp,t|\beta_{iptech,e}^{teche} \wedge \beta_{ibp,t}^{ct}} \left(\sum_{p,ptech,pmode,psize} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,p,ptech,pmode,psize,t}^{ipp} + \sum_{h|\beta_{ibp}^{ship}} XIb_{y,m,ip,iptech,ipmode,ipsize,ibp,h,t}^{iph} \right) emf_{iptech,ipmode}^{tech}$$

$\forall y \in Y, e \in E$ (66)

Eq. (67) defines the emission from conversion activity, consisted of the multiplication of the production quantity of bioenergy product ($XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd}$) with the emission factor of conversion technology ($emf_{ptech,pmode}^{tech}$).

$$Em_{y,e}^{p} = \sum_{m,p,ptech,pmode,psize,pd,d,t|\beta_{ptech,e}^{teche} \wedge \beta_{pd,t}^{ct}} XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd} emf_{ptech,pmode}^{tech}$$

$\forall y \in Y, e \in E$ (67)

Eq. (68) defines the avoided emission associated with the utilization of feedstock, consisted of the multiplications of the quantities of feedstock supplied to the pre-processing plant ($XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip}$), conversion plant ($XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp}$) and harbor ($XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh}$) with the emission avoidance factor associated with the utilization of feedstock (emf_{rm}^{avoid}).

$$Em_{y,e}^{avoid} = \sum_{m,s,rm,t|_{\beta_{rm,t}^{ct}}} \left[\sum_{ip,iptech,ipmode,ipsize|\beta_{iptech,e}^{teche}} XBm_{y,m,s,rm,ip,iptech,ipmode,ipsize,t}^{sip} + \sum_{ptech,pmode,psize} \left(\sum_{p} XBm_{y,m,s,rm,p,ptech,pmode,psize,t}^{sp} + \sum_{h|\beta_{rm}^{ship}} XBm_{y,m,s,rm,h,ptech,pmode,psize,t}^{sh} \right) |_{\beta_{ptech,e}^{teche}} \right] emf_{rm}^{avoid}$$

$\forall y \in Y, e \in E$ (68)

Eq. (69) defines the emission of the reference energy production. The reference fossil fuel-based energy production ($XPr_{y,m,f,e,d}^{ref}$) is multiplied with the emission factor of fossil fuel technology ($emf_{f,e}^{ref}$) in quantifying the emission of the reference energy production.

$$Em_{y,e}^{ref} = \sum_{m,f,e,d} XPr_{y,m,f,e,d}^{ref} emf_{f,e}^{ref}$$

$\forall y \in Y, e \in E$ (69)

S1.2.9. Objective function

The objective function of the model is to minimize the total cost of energy system (Eq. (70)), which is equivalent to the summation of the total cost of energy supply chain (Eq. (71)) and the product of the total emission of energy supply chain (Eq. (72)) and carbon price (pf_y^{co2}), subtracted with the total price subsidy of bioenergy product (Eq. (73)).

$$min\ TSC = \sum_{y} \left(TOTCOST_y + TOTEMISSION_y pf_y^{co2} - SUBSIDY_y \right) \quad (70)$$

$$TOTCOST_y = \sum_{e} \left(Cost_{y,e}^{bm} + Cost_{y,e}^{bm\_t} + Cost_{y,e}^{bm\_ship} + Cost_{y,e}^{bm\_store} + Cost_{y,e,}^{ip\_capex} + Cost_{y,e}^{ip\_opex} + Cost_{y,e}^{ip\_store} + Cost_{y,e,}^{ib\_t} + Cost_{y,e}^{ib\_ship} + Cost_{y,e}^{ip\_infra} + Cost_{y,e}^{p\_capex} + Cost_{y,e}^{p\_opex} + Cost_{y,e}^{p\_store} + Cost_{y,e}^{pr\_t} + Cost_{y,e}^{p\_infra} + Cost_{y,e}^{ref} \right) + Cost_{y}^{bm\_pc} + Cost_{y}^{bm\_t\_pc} + Cost_{y}^{bm\_store\_pc}$$

$\forall y \in Y$ (71)

$$TOTEMISSION_y = \sum_e \left(Em_{y,e}^{bm} + Em_{y,e}^{bm\_t} + Em_{y,e}^{bm\_ship} + Em_{y,e}^{bm\_store} + Em_{y,e}^{ip} + Em_{y,e}^{ip\_store} + Em_{y,e}^{ib\_t} + Em_{y,e}^{ib\_ship} + Em_{y,e}^{p} + Em_{y,e}^{p\_store} + Em_{y,e}^{pr\_t} + Em_{y,e}^{ref}\right) + Em_y^{bm\_pc} + Em_y^{bm\_t\_pc} + Em_y^{bm\_store\_pc}$$

$\forall y \in Y$ (72)

$$SUBSIDY_y = \sum_{m,p,ptech,pmode,psize,pd,d,t|\beta_{pd,t}^{ct}} XPr_{y,m,p,ptech,pmode,psize,pd,d,t}^{pd} pf_{y,pd}^{subs}$$

$\forall y \in Y$ (73)