energyRt model framework

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Sets

Name	Alias	Description
comm	c, cp, ce, cn	commodity
region	r, rp, re, rn	region
year	y, yp, ye, yn	year
slice	l, lp, le, ln	time slices
sup	u, up, ue, un	supply
dem	d, dp, de, dn	demand
tech	h, hp, he, hn	technology
stg	s, sp, se, sn	storage
trade	d, dp, de, dn	trade between regions
expp	x, xp, xe, xn	export to the rest of the world (ROW)
imp	m, mp, me, mn	import from the ROW
group	g, gp, ge, gn	group of input or output commodities in technology
weather	w, wp, we, wn	weather

Parameters

Name	Alias	Description
pTechOlife(tech, region)	$pTechOlife_{h,r}$	Operational life of technologies
pTechCinp2ginp(tech, comm, region, year, slice)	$pTechCinp2ginp_{h,c,r,y,l}$	Commodity input to group input
pTechGinp2use(tech, group, region, year, slice)	$pTechGinp2use_{h,g,r,y,l}$	Group input into use

pTechCinp2use(tech, comm, region, year, slice)	$pTechCinp2use_{h,c,r,y,l}$	Commodity input to use
pTechUse2cact(tech, comm, region, year, slice)	$pTechUse2cact_{h,c,r,y,l}$	Use to commodity activity
pTechCact2cout(tech, comm, region, year, slice)	$pTechCact2cout_{h,c,r,y,l}$	Commodity activity to commodity output
pTechEmisComm(tech, comm)	$pTechEmisComm_{h,c}$	Combustion factor for input commodity (from 0 to 1)
pTechAct2AInp(tech, comm, region, year, slice)	$pTechAct2AInp_{h,c,r,y,l}$	Activity to aux-commodity input
pTechCap2AInp(tech, comm, region, year, slice)	$pTechCap2AInp_{h,c,r,y,l}$	Capacity to aux-commodity input
pTechNCap2AInp(tech, comm, region, year, slice)	$pTechNCap2AInp_{h,c,r,y,l}$	New capacity to aux-commodity input
pTechCinp2AInp(tech, comm, comm, region, year, slice)	$pTechCinp2AInp_{h,c,c,r,y,l}$	Commodity input to aux-commodity input
pTechCout2AInp(tech, comm, comm, region, year, slice)	$pTechCout2AInp_{h,c,c,r,y,l}$	Commodity output to aux-commodity input
pTechAct2AOut(tech, comm, region, year, slice)	$pTechAct2AOut_{h,c,r,y,l}$	Activity to aux-commodity output
pTechCap2AOut(tech, comm, region, year, slice)	$pTechCap2AOut_{h,c,r,y,l}$	Capacity to aux-commodity output
pTechNCap2AOut(tech, comm, region, year, slice)	$pTechNCap2AOut_{h,c,r,y,l}$	New capacity to aux-commodity output
pTechCinp2AOut(tech, comm, comm, region, year, slice)	$pTechCinp2AOut_{h,c,c,r,y,l}$	Commodity to aux-commodity output
pTechCout2AOut(tech, comm, comm, region, year, slice)	$pTechCout2AOut_{h,c,c,r,y,l}$	Commodity-output to aux-commodity input
pTechFixom(tech, region, year)	$pTechFixom_{h,r,y}$	Fixed Operating and maintenance (O&M) costs (per unit of capacity)
pTechVarom(tech, region, year, slice)	$pTechVarom_{h,r,y,l}$	Variable O&M costs (per unit of acticity)
pTechInvcost(tech, region, year)	$pTechInvcost_{h,r,y}$	Investment costs (per unit of capacity)
pTechEac(tech, region, year)	$pTechEac_{h,r,y}$	Equivalent annual (investment) cost
pTechShareLo(tech, comm, region, year, slice)	$pTechShareLo_{h,c,r,y,l}$	Lower bound of the share of the commodity in total group input or output
pTechShareUp(tech, comm, region, year, slice)	$pTechShareUp_{h,c,r,y,l}$	Upper bound of the share of the commodity in total group input or output
pTechAfLo(tech, region, year, slice)	$pTechAfLo_{h,r,y,l}$	Lower bound on availability factor by slices
pTechAfUp(tech, region, year, slice)	$pTechAfUp_{h,r,y,l}$	Upper bound on availability factor by slices
pTechRampUp(tech, region, year, slice)	$pTechRampUp_{h,r,y,l}$	Ramp Up on availability factor
pTechRampDown(tech, region, year, slice)	$pTechRampDown_{h,r,y,l}$	Ramp Down on availability
pTechAfsLo(tech, region, year, slice)	$pTechAfsLo_{h,r,y,l}$	Lower bound on availability factor by groups of slices
pTechAfsUp(tech, region, year, slice)	$pTechAfsUp_{h,r,y,l}$	Upper bound on availability factor by groups of slices
pTechAfcLo(tech, comm, region, year, slice)	$pTechAfcLo_{h,c,r,y,l}$	Lower bound for commodity output
pTechAfcUp(tech, comm, region, year, slice)	$pTechAfcUp_{h,c,r,y,l}$	Upper bound for commodity output
pTechStock(tech, region, year)	$pTechStock_{h,r,y}$	Technology capacity stock
pTechCap2act(tech)	$pTechCap2act_h$	Technology capacity units to activity units conversion factor

pTechCvarom(tech, comm, region, year, slice)	$pTechCvarom_{h,c,r,y,l}$	Commodity-specific variable costs (per unit of commodity input or output)
pTechAvarom(tech, comm, region, year, slice)	$pTechAvarom_{h,c,r,y,l}$	Auxilary Commodity-specific variable costs (per unit of commodity input or output)
pDiscount(region, year)	$pDiscount_{r,y}$	Discount rate (can be region and year specific)
pDiscountFactor(region, year)	$pDiscountFactor_{r,y}$	Discount factor (cumulative)
pDiscountFactorMileStone(region, year)	$pDiscountFactorMileStone_{r,y}$	Discount factor (cumulative) sum for MileStone
pSupCost(sup, comm, region, year, slice)	$pSupCost_{u,c,r,y,l}$	Costs of supply (price per unit)
pSupAvaUp(sup, comm, region, year, slice)	$pSupAvaUp_{u,c,r,y,l}$	Upper bound for supply
pSupAvaLo(sup, comm, region, year, slice)	$pSupAvaLo_{u,c,r,y,l}$	Lower bound for supply
pSupReserveUp(sup, comm, region)	$pSupReserveUp_{u,c,r}$	Total supply reserve by region Up
pSupReserveLo(sup, comm, region)	$pSupReserveLo_{u,c,r}$	Total supply reserve by region Lo
pDemand(dem, comm, region, year, slice)	$pDemand_{d,c,r,y,l}$	Exogenous demand
pEmissionFactor(comm, comm)	$pEmissionFactor_{c,c}$	Emission factor
pDummyImportCost(comm, region, year, slice)	$pDummyImportCost_{c,r,y,l}$	Dummy costs parameters (for debugging)
pDummyExportCost(comm, region, year, slice)	$pDummyExportCost_{c,r,y,l}$	Dummy costs parameters (for debugging)
pTaxCostInp(comm, region, year, slice)	$pTaxCostInp_{c,r,y,l}$	Commodity taxes for input
pTaxCostOut(comm, region, year, slice)	$pTaxCostOut_{c,r,y,l}$	Commodity taxes for output
pTaxCostBal(comm, region, year, slice)	$pTaxCostBal_{c,r,y,l}$	Commodity taxes for balance
pSubCostInp(comm, region, year, slice)	$pSubCostInp_{c,r,y,l}$	Commodity subsidies for input
pSubCostOut(comm, region, year, slice)	$pSubCostOut_{c,r,y,l}$	Commodity subsidies for output
pSubCostBal(comm, region, year, slice)	$pSubCostBal_{c,r,y,l}$	Commodity subsidies for balance
pAggregateFactor(comm, comm)	$pAggregateFactor_{c,c}$	Aggregation factor of commodities
pPeriodLen(year)	$pPeriodLen_y$	Length of milestone-year-period
pSliceShare(slice)	$pSliceShare_l$	Share of slice
ordYear(year)	$ordYear_y$	ord year (used in GLPK-MathProg)
cardYear(year)	$cardYear_y$	card year (used in GLPK-MathProg)
pStorageInpEff(stg, comm, region, year, slice)	$pStorageInpEff_{s,c,r,y,l}$	Storage input efficiency
pStorageOutEff(stg, comm, region, year, slice)	$pStorageOutEff_{s,c,r,y,l}$	Storage output efficiency
pStorageStgEff(stg, comm, region, year, slice)	$pStorageStgEff_{s,c,r,y,l}$	Storage time-efficiency (annual)
pStorageStock(stg, region, year)	$pStorageStock_{s,r,y}$	Storage capacity stock
pStorageOlife(stg, region)	$pStorageOlife_{s,r}$	Storage operational life
pStorageCostStore(stg, region, year, slice)	$pStorageCostStore_{s,r,y,l}$	Storing costs per stored amount (annual)
pStorageCostInp(stg, region, year, slice)	$pStorageCostInp_{s,r,y,l}$	Storage input costs
pStorageCostOut(stg, region, year, slice)	$pStorageCostOut_{s,r,y,l}$	Storage output costs

pStorageFixom(stg, region, year)	$pStorageFixom_{s,r,y}$	Storage fixed O&M costs
pStorageInvcost(stg, region, year)	$pStorageInvcost_{s,r,y}$	Storage investment costs
pStorageEac(stg, region, year)	$pStorageEac_{s,r,y}$	Storage equivalent annual costs
pStorageCap2stg(stg)	$pStorageCap2stg_{s}$	Storage capacity units to activity units conversion factor
pStorageAfLo(stg, region, year, slice)	$pStorageAfLo_{s,r,y,l}$	Storage availability factor lower bound (minimum charge level)
pStorageAfUp(stg, region, year, slice)	$pStorageAfUp_{s,r,y,l}$	Storage availability factor upper bound (maximum charge level)
pStorageCinpUp(stg, comm, region, year, slice)	$pStorageCinpUp_{s,c,r,y,l}$	Storage input upper bound
pStorageCinpLo(stg, comm, region, year, slice)	$pStorageCinpLo_{s,c,r,y,l}$	Storage input lower bound
pStorageCoutUp(stg, comm, region, year, slice)	$pStorageCoutUp_{s,c,r,y,l}$	Storage output upper bound
pStorageCoutLo(stg, comm, region, year, slice)	$pStorageCoutLo_{s,c,r,y,l}$	Storage output lower bound
pStorageNCap2Stg(stg, comm, region, year, slice)	$pStorageNCap2Stg_{s,c,r,y,l}$	Initial storage charge level for new investment
pStorageCharge(stg, comm, region, year, slice)	$pStorageCharge_{s,c,r,y,l}$	Initial storage charge level for stock
pStorageStg2AInp(stg, comm, region, year, slice)	$pStorageStg2AInp_{s,c,r,y,l}$	Storage accumulated volume to auxilary input
pStorageStg2AOut(stg, comm, region, year, slice)	$pStorageStg2AOut_{s,c,r,y,l}$	Storage accumulated volume output
pStorageCinp2AInp(stg, comm, region, year, slice)	$pStorageCinp2AInp_{s,c,r,y,l}$	Storage input to auxilary input
pStorageCinp2AOut(stg, comm, region, year, slice)	$pStorageCinp2AOut_{s,c,r,y,l}$	Storage input to auxilary output
pStorageCout2AInp(stg, comm, region, year, slice)	$pStorageCout2AInp_{s,c,r,y,l}$	Storage output to auxilary input
pStorageCout2AOut(stg, comm, region, year, slice)	$pStorageCout2AOut_{s,c,r,y,l}$	Storage output to auxilary output
pStorageCap2AInp(stg, comm, region, year, slice)	$pStorageCap2AInp_{s,c,r,y,l}$	Storage capacity to auxilary input
pStorageCap2AOut(stg, comm, region, year, slice)	$pStorageCap2AOut_{s,c,r,y,l}$	Storage capacity to auxilary output
pStorageNCap2AInp(stg, comm, region, year, slice)	$pStorageNCap2AInp_{s,c,r,y,l}$	Storage new capacity to auxilary input
pStorageNCap2AOut(stg, comm, region, year, slice)	$pStorageNCap2AOut_{s,c,r,y,l}$	Storage new capacity to auxilary output
pTradeIrEff(trade, region, region, year, slice)	$pTradeIrEff_{d,r,r,y,l}$	Inter-regional trade efficiency
pTradeIrUp(trade, region, region, year, slice)	$pTradeIrUp_{d,r,r,y,l}$	Upper bound on trade flow
pTradeIrLo(trade, region, region, year, slice)	$pTradeIrLo_{d,r,r,y,l}$	Lower bound on trade flow
pTradeIrCost(trade, region, region, year, slice)	$pTradeIrCost_{d,r,r,y,l}$	Costs of trade flow
pTradeIrMarkup(trade, region, region, year, slice)	$pTradeIrMarkup_{d,r,r,y,l}$	Markup of trade flow
pTradeIrCsrc2Ainp(trade, comm, region, region, year, slice)	$pTradeIrCsrc2Ainp_{d,c,r,r,y,l}$	Auxiliary input commodity in source region
pTradeIrCsrc2Aout(trade, comm, region, region, year, slice)	$pTradeIrCsrc2Aout_{d,c,r,r,y,l}$	Auxiliary output commodity in source region
pTradeIrCdst2Ainp(trade, comm, region, region, year, slice)	$pTradeIrCdst2Ainp_{d,c,r,r,y,l}$	Auxiliary input commodity in destination region
pTradeIrCdst2Aout(trade, comm, region, region, year, slice)	$pTradeIrCdst2Aout_{d,c,r,r,y,l}$	Auxiliary output commodity in destination region
pExportRowRes(expp)	$pExportRowRes_{x}$	Upper bound on accumulated export to ROW
pExportRowUp(expp, region, year, slice)	$pExportRowUp_{x,r,y,l}$	Upper bound on export to ROW

pExportRowLo(expp, region, year, slice)	$pExportRowLo_{x,r,y,l}$	Lower bound on export to ROW
pExportRowPrice(expp, region, year, slice)	$pExportRowPrice_{x,r,y,l}$	Export prices to ROW
pImportRowRes(imp)	$pImportRowRes_m$	Upper bound on accumulated import to ROW
pImportRowUp(imp, region, year, slice)	$pImportRowUp_{m,r,y,l}$	Upper bount on import from ROW
pImportRowLo(imp, region, year, slice)	$pImportRowLo_{m,r,y,l}$	Lower bound on import from ROW
pImportRowPrice(imp, region, year, slice)	$pImportRowPrice_{m,r,y,l}$	Import prices from ROW
pTradeStock(trade, year)	$pTradeStock_{d,y}$	Existing capacity
pTradeOlife(trade)	$pTradeOlife_d$	Operational life
pTradeInvcost(trade, region, year)	$pTradeInvcost_{d,r,y}$	Overnight investment costs
pTradeEac(trade, region, year)	$pTradeEac_{d,r,y}$	Equivalent annual costs
pTradeCap2Act(trade)	$pTradeCap2Act_d$	Capacity to activity factor
pWeather(weather, region, year, slice)	$pWeather_{w,r,y,l}$	weather factors
pSupWeatherUp(weather, sup)	$pSupWeatherUp_{w,u}$	weather factor for supply upper value (ava.up)
pSupWeatherLo(weather, sup)	$pSupWeatherLo_{w,u}$	weather factor for supply lower value (ava.lo)
pTechWeatherAfLo(weather, tech)	$pTechWeatherAfLo_{w,h}$	weather factor for technology availability lower value (af.lo)
pTechWeatherAfUp(weather, tech)	$pTechWeatherAfUp_{w,h}$	weather factor for technology availability upper value (af.up)
pTechWeatherAfsLo(weather, tech)	$pTechWeatherAfsLo_{w,h}$	weather factor for technology availability lower value (af.lo)
pTechWeatherAfsUp(weather, tech)	$pTechWeatherAfsUp_{w,h}$	weather factor for technology availability upper value (afs.lo)
pTechWeatherAfcLo(weather, tech, comm)	$pTechWeatherAfcLo_{w,h,c}$	weather factor for technology availability lower value (afs.lo)
pTechWeatherAfcUp(weather, tech, comm)	$pTechWeatherAfcUp_{w,h,c}$	weather factor for commodity availability upper value (afc.lo)
pStorageWeatherAfLo(weather, stg)	$pStorageWeatherAfLo_{w,s}$	weather factor for storage availability lower value (af.lo)
pStorageWeatherAfUp(weather, stg)	$pStorageWeatherAfUp_{w,s}$	weather factor for storage availability upper value (af.up)
pStorageWeatherCinpUp(weather, stg)	$pStorageWeatherCinpUp_{w,s}$	weather factor for storage commodity input upper value (cinp.up)
pStorageWeatherCinpLo(weather, stg)	$pStorageWeatherCinpLo_{w,s}$	weather factor for storage commodity input lower value (cinp.lo)
pStorageWeatherCoutUp(weather, stg)	$pStorageWeatherCoutUp_{w,s}$	weather factor for storage commodity output upper value (cout.up)
pStorageWeatherCoutLo(weather, stg)	$pStorageWeatherCoutLo_{w,s}$	weather factor for storage commodity output lower value (cout.lo)
pLECLoACT(region)	$pLECLoACT_r$	levelized costs interim parameter

Variables

Name	Alias	Description
vTechInv(tech, region, year)	$\mathbf{vTechInv}_{h,r,y}$	Overnight investment costs
vTechEac(tech, region, year)	$\mathbf{vTechEac}_{h,r,y}$	Annualized investment costs
vTechOMCost(tech, region, year)	$\mathbf{vTechOMCost}_{h,r,y}$	Sum of all operational costs is equal vTechFixom + vTech-Varom (AVarom + CVarom + ActVarom)
vSupCost(sup, region, year)	$\mathbf{vSupCost}_{u,r,y}$	Supply costs
vEmsFuelTot(comm, region, year, slice)	$\mathbf{vEmsFuelTot}_{c,r,y,l}$	Total emissions from fuels combustion
vBalance(comm, region, year, slice)	$\mathbf{vBalance}_{c,r,y,l}$	Net commodity balance
vTotalCost(region, year)	$\mathbf{vTotalCost}_{r,y}$	Regional annual total costs
vObjective	$\mathbf{vObjective}$	Objective costs
vTaxCost(comm, region, year)	$\mathbf{vTaxCost}_{c,r,y}$	Total tax levies (tax costs)
vSubsCost(comm, region, year)	$\mathbf{vSubsCost}_{c,r,y}$	Total subsidies (for substraction from costs)
vAggOut(comm, region, year, slice)	$\mathbf{vAggOut}_{c,r,y,l}$	Aggregated commodity output
vStorageOMCost(stg, region, year)	$\mathbf{vStorageOMCost}_{s,r,y}$	Storage O&M costs
vTradeCost(region, year)	$\mathbf{vTradeCost}_{r,y}$	Total trade costs
vTradeRowCost(region, year)	$\mathbf{vTradeRowCost}_{r,y}$	Trade with ROW costs
vTradeIrCost(region, year)	$\mathbf{vTradeIrCost}_{r,y}$	Interregional trade costs

Positive Variables

Name	Alias	Description
vTechNewCap(tech, region, year)	$\mathbf{vTechNewCap}_{h,r,y}$	New capacity
vTechRetiredStock(tech, region, year)	$\mathbf{vTechRetiredStock}_{h,r,y}$	Early retired stock
vTechRetiredNewCap(tech, region, year, year)	$\mathbf{vTechRetiredNewCap}_{h,r,y,y}$	Early retired new capacity
vTechCap(tech, region, year)	$\mathbf{vTechCap}_{h,r,y}$	Total capacity of the technology
vTechAct(tech, region, year, slice)	$\mathbf{vTechAct}_{h,r,y,l}$	Activity level of technology
vTechInp(tech, comm, region, year, slice)	$\mathbf{vTechInp}_{h,c,r,y,l}$	Input level
vTechOut(tech, comm, region, year, slice)	$\mathbf{vTechOut}_{h,c,r,y,l}$	Output level
vTechAInp(tech, comm, region, year, slice)	$\mathbf{vTechAInp}_{h,c,r,y,l}$	Auxiliary commodity input
vTechAOut(tech, comm, region, year, slice)	$\mathbf{vTechAOut}_{h,c,r,y,l}$	Auxiliary commodity output
vSupOut(sup, comm, region, year, slice)	$\mathbf{vSupOut}_{u,c,r,y,l}$	Output of supply
vSupReserve(sup, comm, region)	$\mathbf{vSupReserve}_{u,c,r}$	Total supply reserve

vDemInp(comm, region, year, slice)	$\mathbf{vDemInp}_{c,r,y,l}$	Input to demand
vOutTot(comm, region, year, slice)	$\mathbf{vOutTot}_{c,r,y,l}$	Total commodity output (consumption is not substracted)
vInpTot(comm, region, year, slice)	$\mathbf{vInpTot}_{c,r,y,l}$	Total commodity input
vInp2Lo(comm, region, year, slice, slice)	$\mathbf{vInp2Lo}_{c,r,y,l,l}$	Desagregation of slices for input parent to (grand)child
vOut2Lo(comm, region, year, slice, slice)	$\mathbf{vOut2Lo}_{c,r,y,l,l}$	Desagregation of slices for output parent to (grand)child
vSupOutTot(comm, region, year, slice)	$\mathbf{vSupOutTot}_{c,r,y,l}$	Total commodity supply
vTechInpTot(comm, region, year, slice)	$\mathbf{vTechInpTot}_{c,r,y,l}$	Total commodity input to technologies
vTechOutTot(comm, region, year, slice)	$\mathbf{vTechOutTot}_{c,r,y,l}$	Total commodity output from technologies
vStorageInpTot(comm, region, year, slice)	$\mathbf{vStorageInpTot}_{c,r,y,l}$	Total commodity input to storage
vStorageOutTot(comm, region, year, slice)	$\mathbf{vStorageOutTot}_{c,r,y,l}$	Total commodity output from storage
vStorageAInp(stg, comm, region, year, slice)	$\mathbf{vStorageAInp}_{s,c,r,y,l}$	Aux-commodity input to storage
vStorageAOut(stg, comm, region, year, slice)	$\mathbf{vStorageAOut}_{s,c,r,y,l}$	Aux-commodity input from storage
vDummyImport(comm, region, year, slice)	$\mathbf{vDummyImport}_{c,r,y,l}$	Dummy import (for debugging)
vDummyExport(comm, region, year, slice)	$\mathbf{vDummyExport}_{c,r,y,l}$	Dummy export (for debugging)
vStorageInp(stg, comm, region, year, slice)	$\mathbf{vStorageInp}_{s,c,r,y,l}$	Storage input
vStorageOut(stg, comm, region, year, slice)	$\mathbf{vStorageOut}_{s,c,r,y,l}$	Storage output
vStorageStore(stg, comm, region, year, slice)	$\mathbf{vStorageStore}_{s,c,r,y,l}$	Storage level
vStorageInv(stg, region, year)	$\mathbf{vStorageInv}_{s,r,y}$	Storage investments
vStorageEac(stg, region, year)	$\mathbf{vStorageEac}_{s,r,y}$	Storage EAC investments
vStorageCap(stg, region, year)	$\mathbf{vStorageCap}_{s,r,y}$	Storage capacity
vStorageNewCap(stg, region, year)	$\mathbf{vStorageNewCap}_{s,r,y}$	Storage new capacity
vImport(comm, region, year, slice)	$\mathbf{vImport}_{c,r,y,l}$	Total regional import (Ir + ROW)
vExport(comm, region, year, slice)	$\mathbf{vExport}_{c,r,y,l}$	Total regional export (Ir + ROW)
vTradeIr(trade, comm, region, region, year, slice)	$\mathbf{vTradeIr}_{d,c,r,r,y,l}$	Total physical trade flows between regions
vTradeIrAInp(trade, comm, region, year, slice)	$\mathbf{vTradeIrAInp}_{d,c,r,y,l}$	Trade auxilari input
vTradeIrAInpTot(comm, region, year, slice)	$\mathbf{vTradeIrAInpTot}_{c,r,y,l}$	Trade total auxilari input
vTradeIrAOut(trade, comm, region, year, slice)	$\mathbf{vTradeIrAOut}_{d,c,r,y,l}$	Trade auxilari output
vTradeIrAOutTot(comm, region, year, slice)	$\mathbf{vTradeIrAOutTot}_{c,r,y,l}$	Trade auxilari output total
vExportRowAccumulated(expp, comm)	$\mathbf{vExportRowAccumulated}_{x,c}$	Accumulated export to ROW
vExportRow(expp, comm, region, year, slice)	$\mathbf{vExportRow}_{x,c,r,y,l}$	Export to ROW
vImportRowAccumulated(imp, comm)	$\mathbf{vImportRowAccumulated}_{m,c}$	Accumulated import from ROW
vImportRow(imp, comm, region, year, slice)	$\mathbf{vImportRow}_{m,c,r,y,l}$	Import from ROW
vTradeCap(trade, year)	$\mathbf{vTradeCap}_{d,y}$	Trade capacity
vTradeInv(trade, region, year)	$\mathbf{vTradeInv}_{d,r,y}$	Investment in trade capacity (overnight)
vTradeEac(trade, region, year)	$\mathbf{vTradeEac}_{d,r,y}$	Investment in trade capacity (EAC)

vTradeNewCap(trade, year)	$\mathbf{vTradeNewCap}_{d,y}$	New trade capacity
vTotalUserCosts(region, year)	$\mathbf{vTotalUserCosts}_{r,y}$	Total additional costs (set by user)

Equations

Technology

Activity Input & Output

Technology input to output
$\quad eqTechSng2Sng_{h,r,c,cp,y,l}$

$$\mathbf{vTechInp}_{h,c,r,y,l} * pTechCinp2use_{h,c,r,y,l} = \frac{\mathbf{vTechOut}_{h,cp,r,y,l}}{pTechUse2cact_{h,cp,r,y,l} * pTechCact2cout_{h,cp,r,y,l}} \tag{1}$$

Technology group input to output
$\quad eqTechGrp2Sng_{h,r,g,cp,y,l}$

$$pTechGinp2use_{h,g,r,y,l} * \sum_c \left(\mathbf{vTechInp}_{h,c,r,y,l} * pTechCinp2ginp_{h,c,r,y,l} \right) = \frac{\mathbf{vTechOut}_{h,cp,r,y,l}}{pTechUse2cact_{h,cp,r,y,l} * pTechCact2cout_{h,cp,r,y,l}} \tag{2}$$

Technology input to group output
$\quad eqTechSng2Grp_{h,r,c,gp,y,l}$

$$\mathbf{vTechInp}_{h,c,r,y,l} * pTechCinp2use_{h,c,r,y,l} = \sum_{cp} \left(\frac{\mathbf{vTechOut}_{h,cp,r,y,l}}{pTechUse2cact_{h,cp,r,y,l} * pTechCact2cout_{h,cp,r,y,l}} \right) \tag{3}$$

Technology group input to group output
$\quad eqTechGrp2Grp_{h,r,g,gp,y,l}$

$$pTechGinp2use_{h,g,r,y,l} * \sum_c \left(\mathbf{vTechInp}_{h,c,r,y,l} * pTechCinp2ginp_{h,c,r,y,l} \right) = \sum_{cp} \left(\frac{\mathbf{vTechOut}_{h,cp,r,y,l}}{pTechUse2cact_{h,cp,r,y,l} * pTechCact2cout_{h,cp,r,y,l}} \right) \tag{4}$$

Shares for grouped commodities

Technology lower bound on input share
$\quad eqTechShareInpLo_{h,r,g,c,y,l}$

$$\mathbf{vTechInp}_{h,c,r,y,l} \geq pTechShareLo_{h,c,r,y,l} * \sum_{cp} \left(\mathbf{vTechInp}_{h,cp,r,y,l} \right) \tag{5}$$

Technology upper bound on input share
$eqTechShareInpUp_{h,r,g,c,y,l}$

$$\mathbf{vTechInp}_{h,c,r,y,l} \leq pTechShareUp_{h,c,r,y,l} * \sum_{cp} \left(\mathbf{vTechInp}_{h,cp,r,y,l} \right) \tag{6}$$

Technology lower bound on output share
$eqTechShareOutLo_{h,r,g,c,y,l}$

$$\mathbf{vTechOut}_{h,c,r,y,l} \geq pTechShareLo_{h,c,r,y,l} * \sum_{cp} \left(\mathbf{vTechOut}_{h,cp,r,y,l} \right) \tag{7}$$

Technology upper bound on output share
$eqTechShareOutUp_{h,r,g,c,y,l}$

$$\mathbf{vTechOut}_{h,c,r,y,l} \leq pTechShareUp_{h,c,r,y,l} * \sum_{cp} \left(\mathbf{vTechOut}_{h,cp,r,y,l} \right) \tag{8}$$

Auxiliary input & output

Technology auxiliary commodity input
$eqTechAInp_{h,c,r,y,l}$

$$
\begin{aligned}
\mathbf{vTechAInp}_{h,c,r,y,l} \\
= (\mathbf{vTechAct}_{h,r,y,l} * pTechAct2AInp_{h,c,r,y,l}) \\
+ (\mathbf{vTechCap}_{h,r,y} * pTechCap2AInp_{h,c,r,y,l}) \\
+ (\mathbf{vTechNewCap}_{h,r,y} * pTechNCap2AInp_{h,c,r,y,l}) + \sum_{cp} \left(pTechCinp2AInp_{h,c,cp,r,y,l} * \mathbf{vTechInp}_{h,cp,r,y,l} \right) \\
+ \sum_{cp} \left(pTechCout2AInp_{h,c,cp,r,y,l} * \mathbf{vTechOut}_{h,cp,r,y,l} \right)
\end{aligned}
\tag{9}
$$

Technology auxiliary commodity output
$eqTechAOut_{h,c,r,y,l}$

$$\textbf{vTechAOut}_{h,c,r,y,l}$$

$$= (\textbf{vTechAct}_{h,r,y,l} * pTechAct2AOut_{h,c,r,y,l})$$
$$+ \big(\textbf{vTechCap}_{h,r,y} * pTechCap2AOut_{h,c,r,y,l}\big)$$
$$+ \big(\textbf{vTechNewCap}_{h,r,y} * pTechNCap2AOut_{h,c,r,y,l}\big) + \sum_{cp} \big(pTechCinp2AOut_{h,c,cp,r,y,l} * \textbf{vTechInp}_{h,cp,r,y,l}\big)$$
$$+ \sum_{cp} (pTechCout2AOut_{h,c,cp,r,y,l} * \textbf{vTechOut}_{h,cp,r,y,l}) \tag{10}$$

Availability

Technology availability factor lower bound
$eqTechAfLo_{h,r,y,l}$

$$pTechAfLo_{h,r,y,l} * pTechCap2act_h * \textbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfLo_{w,h} * pWeather_{w,r,y,l}) \leq \textbf{vTechAct}_{h,r,y,l} \tag{11}$$

Technology availability factor upper bound
$eqTechAfUp_{h,r,y,l}$

$$\textbf{vTechAct}_{h,r,y,l} \leq pTechAfUp_{h,r,y,l} * pTechCap2act_h * \textbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfUp_{w,h} * pWeather_{w,r,y,l}) \tag{12}$$

Technology availability factor for sum of slices lower bound
$eqTechAfsLo_{h,r,y,l}$

$$pTechAfsLo_{h,r,y,l} * pTechCap2act_h * \textbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfsLo_{w,h} * pWeather_{w,r,y,l}) \leq \sum_{lp} (\textbf{vTechAct}_{h,r,y,lp}) \tag{13}$$

Technology availability factor for sum of slices upper bound
$eqTechAfsUp_{h,r,y,l}$

$$\sum_{lp} (\textbf{vTechAct}_{h,r,y,lp}) \leq pTechAfsUp_{h,r,y,l} * pTechCap2act_h * \textbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfsUp_{w,h} * pWeather_{w,r,y,l}) \tag{14}$$

Technology ramp up
$eqTechRampUp_{h,r,y,l}$

$$\frac{\textbf{vTechAct}_{h,r,y,l}}{pSliceShare_l} - \sum_{lp} \left(\frac{\textbf{vTechAct}_{h,r,y,lp}}{pSliceShare_{lp}} \right) \leq \frac{pSliceShare_l * 365 * 24 * pTechCap2act_h * \textbf{vTechCap}_{h,r,y}}{pTechRampUp_{h,r,y,l}} \tag{15}$$

Technology ramp down
$eqTechRampDown_{h,r,y,l}$

$$\sum_{lp} \left(\frac{\mathbf{vTechAct}_{h,r,y,lp}}{pSliceShare_{lp}} \right) - \frac{\mathbf{vTechAct}_{h,r,y,l}}{pSliceShare_l} \leq \frac{pSliceShare_l * 365 * 24 * pTechCap2act_h * \mathbf{vTechCap}_{h,r,y}}{pTechRampDown_{h,r,y,l}} \tag{16}$$

Connect activity with output

Technology activity to commodity output
$eqTechActSng_{h,c,r,y,l}$

$$\mathbf{vTechAct}_{h,r,y,l} = \frac{\mathbf{vTechOut}_{h,c,r,y,l}}{pTechCact2cout_{h,c,r,y,l}} \tag{17}$$

Technology activity to group output
$eqTechActGrp_{h,g,r,y,l}$

$$\mathbf{vTechAct}_{h,r,y,l} = \sum_c \left(\frac{\mathbf{vTechOut}_{h,c,r,y,l}}{pTechCact2cout_{h,c,r,y,l}} \right) \tag{18}$$

Availability commodity factor

Technology commodity availability factor lower bound
$eqTechAfcOutLo_{h,r,c,y,l}$

$$pTechCact2cout_{h,c,r,y,l} * pTechAfcLo_{h,c,r,y,l} * pTechCap2act_h * \mathbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfcLo_{w,h,c} * pWeather_{w,r,y,l})$$
$$\leq \mathbf{vTechOut}_{h,c,r,y,l} \tag{19}$$

Technology commodity availability factor upper bound
$eqTechAfcOutUp_{h,r,c,y,l}$

$$\mathbf{vTechOut}_{h,c,r,y,l} \leq pTechCact2cout_{h,c,r,y,l} * pTechAfcUp_{h,c,r,y,l} * pTechCap2act_h * \mathbf{vTechCap}_{h,r,y} * \prod_w (pTechWeatherAfcUp_{w,h,c} * pWeather_{w,r,y,l}) \tag{20}$$

Technology commodity availability factor lower bound
$eqTechAfcInpLo_{h,r,c,y,l}$

$$pTechAfcLo_{h,c,r,y,l} * pTechCap2act_h * \mathbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfcLo_{w,h,c} * pWeather_{w,r,y,l}) \leq \mathbf{vTechInp}_{h,c,r,y,l} \tag{21}$$

11

Technology commodity availability factor upper bound
$eqTechAfcInpUp_{h,r,c,y,l}$

$$\mathbf{vTechInp}_{h,c,r,y,l} \leq pTechAfcUp_{h,c,r,y,l} * pTechCap2act_h * \mathbf{vTechCap}_{h,r,y} * pSliceShare_l * \prod_w (pTechWeatherAfcUp_{w,h,c} * pWeather_{w,r,y,l}) \quad (22)$$

Capacity and costs equations

Technology capacity
$eqTechCap_{h,r,y}$

$$\mathbf{vTechCap}_{h,r,y} = pTechStock_{h,r,y} - \mathbf{vTechRetiredStock}_{h,r,y} + \sum_{yp} \left(pPeriodLen_{yp} * \left(\mathbf{vTechNewCap}_{h,r,yp} - \sum_{ye} \left(\mathbf{vTechRetiredNewCap}_{h,r,yp,ye} \right) \right) \right)$$

$$(23)$$

Retirement of new capacity
$eqTechRetiredNewCap_{h,r,y}$

$$\sum_{yp} \left(\mathbf{vTechRetiredNewCap}_{h,r,y,yp} \right) \leq \mathbf{vTechNewCap}_{h,r,y} \quad (24)$$

Retirement of stock
$eqTechRetiredStock_{h,r,y}$

$$\mathbf{vTechRetiredStock}_{h,r,y} \leq pTechStock_{h,r,y} \quad (25)$$

Technology Equivalent Annual Cost (EAC)
$eqTechEac_{h,r,y}$

$$\mathbf{vTechEac}_{h,r,y} = \sum_{yp} \left(pTechEac_{h,r,yp} * pPeriodLen_{yp} * \left(\mathbf{vTechNewCap}_{h,r,yp} - \sum_{ye} \left(\mathbf{vTechRetiredNewCap}_{h,r,yp,ye} \right) \right) \right) \quad (26)$$

Technology overnight investment costs
$eqTechInv_{h,r,y}$

$$\mathbf{vTechInv}_{h,r,y} = pTechInvcost_{h,r,y} * \mathbf{vTechNewCap}_{h,r,y} \quad (27)$$

Technology O&M costs
$eqTechOMCost_{h,r,y}$

$$\mathbf{vTechOMCost}_{h,r,y} = pTechFixom_{h,r,y} * \mathbf{vTechCap}_{h,r,y} + \sum_{l} \left(pTechVarom_{h,r,y,l} * \mathbf{vTechAct}_{h,r,y,l} \right)$$

$$+ \sum_{l} \left(\sum_{c} \left(pTechCvarom_{h,c,r,y,l} * \mathbf{vTechInp}_{h,c,r,y,l} \right) \right) + \sum_{l} \left(\sum_{c} \left(pTechCvarom_{h,c,r,y,l} * \mathbf{vTechOut}_{h,c,r,y,l} \right) \right) \quad (28)$$

$$+ \sum_{l} \left(\sum_{c} \left(pTechAvarom_{h,c,r,y,l} * \mathbf{vTechAOut}_{h,c,r,y,l} \right) \right) + \sum_{l} \left(\sum_{c} \left(pTechAvarom_{h,c,r,y,l} * \mathbf{vTechAInp}_{h,c,r,y,l} \right) \right)$$

Supply

Supply availability upper bound
    $eqSupAvaUp_{u,c,r,y,l}$

$$\mathbf{vSupOut}_{u,c,r,y,l} \leq pSupAvaUp_{u,c,r,y,l} * \prod_{w} \left(pSupWeatherUp_{w,u} * pWeather_{w,r,y,l} \right) \quad (29)$$

Supply availability lower bound
    $eqSupAvaLo_{u,c,r,y,l}$

$$\mathbf{vSupOut}_{u,c,r,y,l} \geq pSupAvaLo_{u,c,r,y,l} * \prod_{w} \left(pSupWeatherLo_{w,u} * pWeather_{w,r,y,l} \right) \quad (30)$$

Total supply of each commodity
    $eqSupTotal_{u,c,r}$

$$\mathbf{vSupReserve}_{u,c,r} = \sum_{y,l} \left(pPeriodLen_{y} * \mathbf{vSupOut}_{u,c,r,y,l} \right) \quad (31)$$

Total reserve upper value
    $eqSupReserveUp_{u,c,r}$

$$pSupReserveUp_{u,c,r} \geq \mathbf{vSupReserve}_{u,c,r} \quad (32)$$

Total reserve lower value
    $eqSupReserveLo_{u,c,r}$

$$\mathbf{vSupReserve}_{u,c,r} \geq pSupReserveLo_{u,c,r} \quad (33)$$

Total supply costs
    $eqSupCost_{u,r,y}$

$$\mathbf{vSupCost}_{u,r,y} = \sum_{c,l} \left(pSupCost_{u,c,r,y,l} * \mathbf{vSupOut}_{u,c,r,y,l} \right) \quad (34)$$

Demand

Demand equation
$eqDemInp_{c,r,y,l}$

$$\textbf{vDemInp}_{c,r,y,l} = \sum_{d} (pDemand_{d,c,r,y,l}) \tag{35}$$

Emission & Aggregating commodity equation

Aggregating commodity output
$eqAggOut_{c,r,y,l}$

$$\textbf{vAggOut}_{c,r,y,l} = \sum_{cp} \left(pAggregateFactor_{c,cp} * \sum_{lp} (\textbf{vOutTot}_{cp,r,y,lp}) \right) \tag{36}$$

Emissions from commodity consumption (i.e. fuels combustion)
$eqEmsFuelTot_{c,r,y,l}$

$$\textbf{vEmsFuelTot}_{c,r,y,l} = \sum_{cp} \left(pEmissionFactor_{c,cp} * \sum_{h} \left(pTechEmisComm_{h,cp} * \sum_{lp} \left(\textbf{vTechInp}_{h,cp,r,y,lp} \right) \right) \right) \tag{37}$$

Storage

Input & Output

Storage level
$eqStorageAInp_{s,c,r,y,l}$

$$\textbf{vStorageAInp}_{s,c,r,y,l} = \sum_{cp} \left(pStorageStg2AInp_{s,c,r,y,l} * \textbf{vStorageStore}_{s,cp,r,y,l} \right) + \sum_{cp} \left(pStorageCinp2AInp_{s,c,r,y,l} * \textbf{vStorageInp}_{s,cp,r,y,l} \right)$$
$$+ \sum_{cp} \left(pStorageCout2AInp_{s,c,r,y,l} * \textbf{vStorageOut}_{s,cp,r,y,l} \right) + \sum_{cp} \left(pStorageCap2AInp_{s,c,r,y,l} * \textbf{vStorageCap}_{s,r,y} \right) \tag{38}$$
$$+ \sum_{cp} \left(pStorageNCap2AInp_{s,c,r,y,l} * \textbf{vStorageNewCap}_{s,r,y} \right)$$

Storage availability factor lower
$eqStorageAOut_{s,c,r,y,l}$

$$\mathbf{vStorageAOut}_{s,c,r,y,l} = \sum_{cp} \left(pStorageStg2AOut_{s,c,r,y,l} * \mathbf{vStorageStore}_{s,cp,r,y,l} \right) + \sum_{cp} \left(pStorageCinp2AOut_{s,c,r,y,l} * \mathbf{vStorageInp}_{s,cp,r,y,l} \right)$$
$$+ \sum_{cp} \left(pStorageCout2AOut_{s,c,r,y,l} * \mathbf{vStorageOut}_{s,cp,r,y,l} \right) + \sum_{cp} \left(pStorageCap2AOut_{s,c,r,y,l} * \mathbf{vStorageCap}_{s,r,y} \right) \qquad (39)$$
$$+ \sum_{cp} \left(pStorageNCap2AOut_{s,c,r,y,l} * \mathbf{vStorageNewCap}_{s,r,y} \right)$$

Storage availability factor upper
$eqStorageStore_{s,c,r,y,l}$

$\mathbf{vStorageStore}_{s,c,r,y,l}$
$$= pStorageCharge_{s,c,r,y,l} + \left(pStorageNCap2Stg_{s,c,r,y,l} * \mathbf{vStorageNewCap}_{s,r,y} \right) + \sum_{lp} \left(pStorageInpEff_{s,c,r,y,lp} * \mathbf{vStorageInp}_{s,c,r,y,lp} \right)$$
$$+ \sum_{lp} \left(\left(pStorageStgEff_{s,c,r,y,l}{}^{pSliceShare_l} \right) * \mathbf{vStorageStore}_{s,c,r,y,lp} \right) - \sum_{lp} \left(\frac{\mathbf{vStorageOut}_{s,c,r,y,lp}}{pStorageOutEff_{s,c,r,y,lp}} \right)$$
$$(40)$$

Storage output vs level
$eqStorageAfLo_{s,c,r,y,l}$

$$\mathbf{vStorageStore}_{s,c,r,y,l} \geq pStorageAfLo_{s,r,y,l} * pStorageCap2stg_s * \mathbf{vStorageCap}_{s,r,y} * \prod_{w} \left(pStorageWeatherAfLo_{w,s} * pWeather_{w,r,y,l} \right) \qquad (41)$$

Storage aux-commodity input
$eqStorageAfUp_{s,c,r,y,l}$

$$\mathbf{vStorageStore}_{s,c,r,y,l} \leq pStorageAfUp_{s,r,y,l} * pStorageCap2stg_s * \mathbf{vStorageCap}_{s,r,y} * \prod_{w} \left(pStorageWeatherAfUp_{w,s} * pWeather_{w,r,y,l} \right) \qquad (42)$$

Storage aux-commodity output
$eqStorageClean_{s,c,r,y,l}$

$$\frac{\mathbf{vStorageOut}_{s,c,r,y,l}}{pStorageOutEff_{s,c,r,y,l}} \leq \mathbf{vStorageStore}_{s,c,r,y,l} \qquad (43)$$

Storage input upper constraint
$eqStorageInpUp_{s,c,r,y,l}$

$$\textbf{vStorageInp}_{s,c,r,y,l} \leq pStorageCap2stg_s * \textbf{vStorageCap}_{s,r,y} * pStorageCinpUp_{s,c,r,y,l} * pSliceShare_l * \prod_w \left(pStorageWeatherCinpUp_{w,s} * pWeather_{w,r,y,l} \right)$$

(44)

Storage input lower constraint
$\quad eqStorageInpLo_{s,c,r,y,l}$

$$\textbf{vStorageInp}_{s,c,r,y,l} \geq pStorageCap2stg_s * \textbf{vStorageCap}_{s,r,y} * pStorageCinpLo_{s,c,r,y,l} * pSliceShare_l * \prod_w \left(pStorageWeatherCinpLo_{w,s} * pWeather_{w,r,y,l} \right)$$

(45)

Storage output upper constraint
$\quad eqStorageOutUp_{s,c,r,y,l}$

$$\textbf{vStorageOut}_{s,c,r,y,l} \leq pStorageCap2stg_s * \textbf{vStorageCap}_{s,r,y} * pStorageCoutUp_{s,c,r,y,l} * pSliceShare_l * \prod_w \left(pStorageWeatherCoutUp_{w,s} * pWeather_{w,r,y,l} \right)$$

(46)

Storage output lower constraint
$\quad eqStorageOutLo_{s,c,r,y,l}$

$$\textbf{vStorageOut}_{s,c,r,y,l} \geq pStorageCap2stg_s * \textbf{vStorageCap}_{s,r,y} * pStorageCoutLo_{s,c,r,y,l} * pSliceShare_l * \prod_w \left(pStorageWeatherCoutLo_{w,s} * pWeather_{w,r,y,l} \right)$$

(47)

Capacity and costs for storage

Storage capacity
$\quad eqStorageCap_{s,r,y}$

$$\textbf{vStorageCap}_{s,r,y} = pStorageStock_{s,r,y} + \sum_{yp} \left(pPeriodLen_{yp} * \textbf{vStorageNewCap}_{s,r,yp} \right)$$

(48)

Storage overnight investment costs
$\quad eqStorageInv_{s,r,y}$

$$\textbf{vStorageInv}_{s,r,y} = pStorageInvcost_{s,r,y} * \textbf{vStorageNewCap}_{s,r,y}$$

(49)

Storage equivalent annual cost
$\quad eqStorageEac_{s,r,y}$

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$$\mathbf{vStorageEac}_{s,r,y} = \sum_{yp} \left(pStorageEac_{s,r,yp} * pPeriodLen_{yp} * \mathbf{vStorageNewCap}_{s,r,yp} \right) \tag{50}$$

Storage total costs
$eqStorageCost_{s,r,y}$

$$\mathbf{vStorageOMCost}_{s,r,y} = pStorageFixom_{s,r,y} * \mathbf{vStorageCap}_{s,r,y} \tag{51}$$

$$+ \sum_{c} \left(\sum_{l} \left(pStorageCostInp_{s,r,y,l} * \mathbf{vStorageInp}_{s,c,r,y,l} \right) \right) + \sum_{l} \left(pStorageCostOut_{s,r,y,l} * \mathbf{vStorageOut}_{s,c,r,y,l} \right) + \sum_{l} \left(pStorageCostStore_{s,r,y,l} * \mathbf{vStorageStore}_{s,c,r,y,l} \right)$$

Interregional and ROW Trade equations

Flow

Import equation
$eqImport_{c,dst,y,l}$

$$\mathbf{vImport}_{c,dst,y,l} = \sum_{lp} \left(\sum_{d} \left(\sum_{src} \left(pTradeIrEff_{d,src,dst,y,lp} * \mathbf{vTradeIr}_{d,c,src,dst,y,lp} \right) \right) \right) + \sum_{lp} \left(\sum_{m} \left(\mathbf{vImportRow}_{m,c,dst,y,lp} \right) \right) \tag{52}$$

Export equation
$eqExport_{c,src,y,l}$

$$\mathbf{vExport}_{c,src,y,l} = \sum_{lp} \left(\sum_{d} \left(\sum_{dst} \left(\mathbf{vTradeIr}_{d,c,src,dst,y,lp} \right) \right) \right) + \sum_{lp} \left(\sum_{x} \left(\mathbf{vExportRow}_{x,c,src,y,lp} \right) \right) \tag{53}$$

Trade upper bound
$eqTradeFlowUp_{d,c,src,dst,y,l}$

$$\mathbf{vTradeIr}_{d,c,src,dst,y,l} \leq pTradeIrUp_{d,src,dst,y,l} \tag{54}$$

Trade lower bound
$eqTradeFlowLo_{d,c,src,dst,y,l}$

$$\mathbf{vTradeIr}_{d,c,src,dst,y,l} \geq pTradeIrLo_{d,src,dst,y,l} \tag{55}$$

Total trade costs
$eqCostTrade_{r,y}$

$$\mathbf{vTradeCost}_{r,y} = \mathbf{vTradeRowCost}_{r,y} + \mathbf{vTradeIrCost}_{r,y} \tag{56}$$

Costs of trade with the Rest of the World (ROW)
$eqCostRowTrade_{r,y}$

$$\mathbf{vTradeRowCost}_{r,y} = \sum_{m,c,l} \left(pImportRowPrice_{m,r,y,l} * \mathbf{vImportRow}_{m,c,r,y,l} \right) - \sum_{x,c,l} \left(pExportRowPrice_{x,r,y,l} * \mathbf{vExportRow}_{x,c,r,y,l} \right) \tag{57}$$

Costs of import
$eqCostIrTrade_{r,y}$

$$\mathbf{vTradeIrCost}_{r,y} = \sum_{d} \left(\mathbf{vTradeEac}_{d,r,y} \right) + \sum_{d,src} \left(\sum_{c} \left(\sum_{l} \left(\left(\left(pTradeIrCost_{d,src,r,y,l} + pTradeIrMarkup_{d,src,r,y,l} \right) * \mathbf{vTradeIr}_{d,c,src,r,y,l} \right) \right) \right) \right)$$
$$- \sum_{d,dst} \left(\sum_{c} \left(\sum_{l} \left(\left(pTradeIrMarkup_{d,r,dst,y,l} * \mathbf{vTradeIr}_{d,c,r,dst,y,l} \right) \right) \right) \right) \tag{58}$$

Export to ROW upper constraint
$eqExportRowUp_{x,c,r,y,l}$

$$\mathbf{vExportRow}_{x,c,r,y,l} \leq pExportRowUp_{x,r,y,l} \tag{59}$$

Export to ROW lower constraint
$eqExportRowLo_{x,c,r,y,l}$

$$\mathbf{vExportRow}_{x,c,r,y,l} \geq pExportRowLo_{x,r,y,l} \tag{60}$$

Cumulative export to ROW
$eqExportRowCumulative_{x,c}$

$$\mathbf{vExportRowAccumulated}_{x,c} = \sum_{r,y,l} \left(pPeriodLen_y * \mathbf{vExportRow}_{x,c,r,y,l} \right) \tag{61}$$

Cumulative export to ROW upper constraint
$eqExportRowResUp_{x,c}$

$$\mathbf{vExportRowAccumulated}_{x,c} \leq pExportRowRes_x \tag{62}$$

Import from ROW upper constraint
$eqImportRowUp_{m,c,r,y,l}$

$$\mathbf{vImportRow}_{m,c,r,y,l} \leq pImportRowUp_{m,r,y,l} \tag{63}$$

Import of ROW lower constraint
$eqImportRowLo_{m,c,r,y,l}$

$$\mathbf{vImportRow}_{m,c,r,y,l} \geq pImportRowLo_{m,r,y,l} \tag{64}$$

Cumulative import from ROW
$eqImportRowAccumulated_{m,c}$

$$\mathbf{vImportRowAccumulated}_{m,c} = \sum_{r,y,l} \left(pPeriodLen_y * \mathbf{vImportRow}_{m,c,r,y,l} \right) \tag{65}$$

Cumulative import from ROW upper constraint
$eqImportRowResUp_{m,c}$

$$\mathbf{vImportRowAccumulated}_{m,c} \leq pImportRowRes_m \tag{66}$$

Trade capacity
$eqTradeCapFlow_{d,c,y,l}$

$$pSliceShare_l * pTradeCap2Act_d * \mathbf{vTradeCap}_{d,y} \geq \sum_{src,dst} \left(\mathbf{vTradeIr}_{d,c,src,dst,y,l} \right) \tag{67}$$

Trade overnight investment costs
$eqTradeCap_{d,y}$

$$\mathbf{vTradeCap}_{d,y} = pTradeStock_{d,y} + \sum_{yp} \left(pPeriodLen_{yp} * \mathbf{vTradeNewCap}_{d,yp} \right) \tag{68}$$

Trade equivalent annual costs
$eqTradeInv_{d,r,y}$

$$\mathbf{vTradeInv}_{d,r,y} = pTradeInvcost_{d,r,y} * \mathbf{vTradeNewCap}_{d,y} \tag{69}$$

Trade capacity to activity
$eqTradeEac_{d,r,y}$

$$\mathbf{vTradeEac}_{d,r,y} = \sum_{yp} \left(pTradeEac_{d,r,yp} * pPeriodLen_{yp} * \mathbf{vTradeNewCap}_{d,yp} \right) \tag{70}$$

Trade IR capacity equations

Auxiliary input & output equations

Trade auxiliary commodity input
$eqTradeIrAInp_{d,c,r,y,l}$

$$\mathbf{vTradeIrAInp}_{d,c,r,y,l} = \sum_{dst}\left(pTradeIrCsrc2Ainp_{d,c,r,dst,y,l} * \sum_{cp}\left(\mathbf{vTradeIr}_{d,cp,r,dst,y,l}\right)\right) + \sum_{src}\left(pTradeIrCdst2Ainp_{d,c,src,r,y,l} * \sum_{cp}\left(\mathbf{vTradeIr}_{d,cp,src,r,y,l}\right)\right)$$
(71)

Trade auxiliary commodity output
$eqTradeIrAOut_{d,c,r,y,l}$

$$\mathbf{vTradeIrAOut}_{d,c,r,y,l} = \sum_{dst}\left(pTradeIrCsrc2Aout_{d,c,r,dst,y,l} * \sum_{cp}\left(\mathbf{vTradeIr}_{d,cp,r,dst,y,l}\right)\right) + \sum_{src}\left(pTradeIrCdst2Aout_{d,c,src,r,y,l} * \sum_{cp}\left(\mathbf{vTradeIr}_{d,cp,src,r,y,l}\right)\right)$$
(72)

Trade auxiliary commodity input
$eqTradeIrAInpTot_{c,r,y,l}$

$$\mathbf{vTradeIrAInpTot}_{c,r,y,l} = \sum_{d,lp}\left(\mathbf{vTradeIrAInp}_{d,c,r,y,lp}\right)$$
(73)

Trade auxiliary commodity output
$eqTradeIrAOutTot_{c,r,y,l}$

$$\mathbf{vTradeIrAOutTot}_{c,r,y,l} = \sum_{d,lp}\left(\mathbf{vTradeIrAOut}_{d,c,r,y,lp}\right)$$
(74)

Balance equations & dummy import & export

PRODUCTION ¡= CONSUMPTION commodity balance
$eqBalLo_{c,r,y,l}$

$$\mathbf{vBalance}_{c,r,y,l} \geq 0$$
(75)

PRODUCTION ¿= CONSUMPTION commodity balance
$eqBalUp_{c,r,y,l}$

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$$\mathbf{vBalance}_{c,r,y,l} \leq 0 \tag{76}$$

PRODUCTION == CONSUMPTION commodity balance
$\quad eqBalFx_{c,r,y,l}$

$$\mathbf{vBalance}_{c,r,y,l} = 0 \tag{77}$$

Commodity balance
$\quad eqBal_{c,r,y,l}$

$$\mathbf{vBalance}_{c,r,y,l} = \mathbf{vOutTot}_{c,r,y,l} - \mathbf{vInpTot}_{c,r,y,l} \tag{78}$$

Total commodity output
$\quad eqOutTot_{c,r,y,l}$

$$\begin{aligned} \mathbf{vOutTot}_{c,r,y,l} = {} & \mathbf{vDummyImport}_{c,r,y,l} + \mathbf{vSupOutTot}_{c,r,y,l} + \mathbf{vEmsFuelTot}_{c,r,y,l} + \mathbf{vAggOut}_{c,r,y,l} + \mathbf{vTechOutTot}_{c,r,y,l} \\ & + \mathbf{vStorageOutTot}_{c,r,y,l} + \mathbf{vImport}_{c,r,y,l} + \mathbf{vTradeIrAOutTot}_{c,r,y,l} + \sum_{lp} \left(\mathbf{vOut2Lo}_{c,r,y,lp,l} \right) \end{aligned} \tag{79}$$

Total commodity input
$\quad eqOut2Lo_{c,r,y,l}$

$$\begin{aligned} \sum_{lp} \left(\mathbf{vOut2Lo}_{c,r,y,l,lp} \right) = {} & \mathbf{vSupOutTot}_{c,r,y,l} + \mathbf{vEmsFuelTot}_{c,r,y,l} + \mathbf{vAggOut}_{c,r,y,l} + \mathbf{vTechOutTot}_{c,r,y,l} \\ & + \mathbf{vStorageOutTot}_{c,r,y,l} + \mathbf{vImport}_{c,r,y,l} + \mathbf{vTradeIrAOutTot}_{c,r,y,l} \end{aligned} \tag{80}$$

From commodity slice to lo level
$\quad eqInpTot_{c,r,y,l}$

$$\begin{aligned} \mathbf{vInpTot}_{c,r,y,l} = {} & \mathbf{vDemInp}_{c,r,y,l} + \mathbf{vDummyExport}_{c,r,y,l} + \mathbf{vTechInpTot}_{c,r,y,l} + \mathbf{vStorageInpTot}_{c,r,y,l} \\ & + \mathbf{vExport}_{c,r,y,l} + \mathbf{vTradeIrAInpTot}_{c,r,y,l} + \sum_{lp} \left(\mathbf{vInp2Lo}_{c,r,y,lp,l} \right) \end{aligned} \tag{81}$$

From commodity slice to lo level
$\quad eqInp2Lo_{c,r,y,l}$

$$\sum_{lp} \left(\mathbf{vInp2Lo}_{c,r,y,l,lp} \right) = \mathbf{vTechInpTot}_{c,r,y,l} + \mathbf{vStorageInpTot}_{c,r,y,l} + \mathbf{vExport}_{c,r,y,l} + \mathbf{vTradeIrAInpTot}_{c,r,y,l} \tag{82}$$

Supply total output

$eqSupOutTot_{c,r,y,l}$

$$\mathbf{vSupOutTot}_{c,r,y,l} = \sum_{u} \left(\sum_{lp} \left(\mathbf{vSupOut}_{u,c,r,y,lp} \right) \right) \tag{83}$$

Technology total input
$eqTechInpTot_{c,r,y,l}$

$$\mathbf{vTechInpTot}_{c,r,y,l} = \sum_{h} \left(\sum_{lp} \left(\mathbf{vTechInp}_{h,c,r,y,lp} \right) \right) + \sum_{h} \left(\sum_{lp} \left(\mathbf{vTechAInp}_{h,c,r,y,lp} \right) \right) \tag{84}$$

Technology total output
$eqTechOutTot_{c,r,y,l}$

$$\mathbf{vTechOutTot}_{c,r,y,l} = \sum_{h} \left(\sum_{lp} \left(\mathbf{vTechOut}_{h,c,r,y,lp} \right) \right) + \sum_{h} \left(\sum_{lp} \left(\mathbf{vTechAOut}_{h,c,r,y,lp} \right) \right) \tag{85}$$

Storage total input
$eqStorageInpTot_{c,r,y,l}$

$$\mathbf{vStorageInpTot}_{c,r,y,l} = \sum_{s} \left(\mathbf{vStorageInp}_{s,c,r,y,l} \right) + \sum_{s} \left(\mathbf{vStorageAInp}_{s,c,r,y,l} \right) \tag{86}$$

Storage total output
$eqStorageOutTot_{c,r,y,l}$

$$\mathbf{vStorageOutTot}_{c,r,y,l} = \sum_{s} \left(\mathbf{vStorageOut}_{s,c,r,y,l} \right) + \sum_{s} \left(\mathbf{vStorageAOut}_{s,c,r,y,l} \right) \tag{87}$$

Objective and aggregated costs equations

Total costs
$eqCost_{r,y}$

$$
\begin{aligned}
\mathbf{vTotalCost}_{r,y} = &\sum_{h} \left(\mathbf{vTechEac}_{h,r,y} \right) + \sum_{h} \left(\mathbf{vTechOMCost}_{h,r,y} \right) + \sum_{u} \left(\mathbf{vSupCost}_{u,r,y} \right) + \sum_{c,l} \left(pDummyImportCost_{c,r,y,l} * \mathbf{vDummyImport}_{c,r,y,l} \right) \\
&+ \sum_{c,l} \left(pDummyExportCost_{c,r,y,l} * \mathbf{vDummyExport}_{c,r,y,l} \right) + \sum_{c} \left(\mathbf{vTaxCost}_{c,r,y} \right) - \sum_{c} \left(\mathbf{vSubsCost}_{c,r,y} \right) \\
&+ \sum_{s} \left(\mathbf{vStorageOMCost}_{s,r,y} \right) + \sum_{s} \left(\mathbf{vStorageEac}_{s,r,y} \right) + \mathbf{vTradeCost}_{r,y} + \mathbf{vTotalUserCosts}_{r,y}
\end{aligned}
\tag{88}
$$

Commodity taxes
$eqTaxCost_{c,r,y}$

$$\mathbf{vTaxCost}_{c,r,y} = \sum_l \left(pTaxCostOut_{c,r,y,l} * \mathbf{vOutTot}_{c,r,y,l}\right) + \sum_l \left(pTaxCostInp_{c,r,y,l} * \mathbf{vInpTot}_{c,r,y,l}\right) + \sum_l \left(pTaxCostBal_{c,r,y,l} * \mathbf{vBalance}_{c,r,y,l}\right) \quad (89)$$

Commodity subsidy
$eqSubsCost_{c,r,y}$

$$\mathbf{vSubsCost}_{c,r,y} = \sum_l \left(pSubCostOut_{c,r,y,l} * \mathbf{vOutTot}_{c,r,y,l}\right) + \sum_l \left(pSubCostInp_{c,r,y,l} * \mathbf{vInpTot}_{c,r,y,l}\right) + \sum_l \left(pSubCostBal_{c,r,y,l} * \mathbf{vBalance}_{c,r,y,l}\right) \quad (90)$$

Objective equation
$eqObjective$

$$\mathbf{vObjective} = \sum_{r,y} \left(\mathbf{vTotalCost}_{r,y} * pDiscountFactorMileStone_{r,y}\right) \quad (91)$$

LEC equation

levelized costs (auxiliary equation)
$eqLECActivity_{h,r,y}$

$$\sum_l \left(\mathbf{vTechAct}_{h,r,y,l}\right) \geq pLECLoACT_r \quad (92)$$