NOTATION

PE Primary energy:

PE	Primary Energy Commodities
PE_{Nuc}	Nuclear Primary Energy Commodities
PE_{Fossil}	Fossil Primary Energy Commodities
PE_{Renew}	Renewable Primary Energy Commodities

CE Conversion energy:

CE	Conversion Energy Technologies
CE_{Pri}	Primary Conversion Energy Technologies (with PE input)
CE_{Sec}	Secondary Conversion Energy Technologies (with TE input)
CE_{Sto}	Storage Energy Technologies
CE_{Nuc}	Nuclear Energy Technologies
CE_{Coal}	Coal Energy Technologies
CE_{Hydro}	Hydro Energy technologies

TE Transformed Energy:

TE	Transformed/Final Energy Commodities

RM Raw Materials:

RM	Raw Materials commodities

ST Supply Technologies:

ST	Supply Technologies
ST_{Tra}	Supply Technologies. Transportation
ST_{Oth}	Supply Technologies. Others
ST_{Ind}	Supply Technologies. Industry
ST_{Cap}	Supply Technologies. Capacity
ST_{Uni}	Supply Technologies. Number of units

ES Energy Service Commodities:

ES	Energy Services Commodities
ES_{Tra}	Energy Services Commodities. Transportation
	Energy Services Commodities. Others
$ES_{Oth_{WAMAC}}$	Energy Services Commodities. Others. Washing Machine. Cold cycles
$ES_{Oth_{WAMAH}}$	Energy Services Commodities. Others. Washing Machine. Hot cycles
$ES_{Oth_{DIWAC}}$	Energy Services Commodities. Others. Dish Washer. Cold cycles
$ES_{Oth_{DIWAH}}$	Energy Services Commodities. Others. Dish Washer. Hot cycles
ES_{Ind}	Energy Services Commodities. Industry

SD Service demand Commodities:

SD	Service Demand

SD_{Tra}	Service Demand. Transportation
SD_{Oth}	Service Demand. Others
$SD_{Oth_{HE}}$	Service Demand. Others. High Efficiency Dwellings or commercial surface
$SD_{Oth_{LE}}$	Service Demand. Others. Low Efficiency Dwellings or commercial surface
SD_{Ind}	Service Demand. Industry

MD Macro Data:

MD	Macro Data
MD_{Tra}	Macro Data. Transportation
MD_{Oth}	Macro Data. Others
MD_{Ind}	Macro Data. Industry

BM Behavioural Measures:

BM	Behavioural Measures
BM_{Tra}	Behavioural Measures in Transportation
BM_{Oth}	Behavioural Measures in Others

DM Demand shift Measures:

DM	Demand shift Measures
DM_{Tra}	Demand shift Measures in Transportation
DM_{Oth}	Demand shift Measures in Others

Relational Sets:

$sQCEPriIN$	Input PE to Primary CE
$sQCESecIN$	Input TE to Secondary CE
$sQCEStoIN$	Input TE to Storage CE
$sQCEPriOUT$	Primary CE to Output TE
$sQCESecOUT$	Secondary CE to Output TE
$sQCEStoOUT$	Storage CE to Output TE
$sQSTInTE$	Input TE to ST
$sQSTInRM$	Input RM to ST
$sQSTInRM_{Cir}$	Input RM to ST. Circularity processes
$sQSTOUT$	ST to Output ES
$sQSTOUT_{Tra}$	ST to Output ES. Transportation
$sQSTOUT_{Oth}$	ST to Output ES. Others
$sQSTOUT_{Ind}$	ST to Output ES. Industry
$sQTESTES$	TE to ST to ES
$sQTESTES_{Ele}$	Electricity(TE) to ST to ES
$sQTESTES_{Ind}$	TE to Industry(ST) to ES
$sQESSD$	ES to Output SD
$sQSTESSD$	ST to ES to SD
$sQSTESSD_{Tra}$	ST to ES to SD. Transportation
$sQESSDMD_{Oth}$	ES to SD to MD. Others
$sQSDMD$	SD to Output MD
$sQSDMD_{Res}$	SD to Output MD. Residential
$sQSDMD_{Oth}$	SD to Output MD. Others
$sQSDMD_{Tra}$	SD to Output MD. Transportation

Variables:

$vSysCost$	Total System cost [G€]
$vTotalCost$	Annual Total cost [G€]
$vBMCost$	Annual Behavioural Measures cost [G€]
$vDMCost$	Annual Demand shift Measures cost [G€]

vPenalCost	Annual Penalization cost [G€]
vInvCostCE	Annual Total CE investment cost [G€]
vInvCostST	Annual Total ST investment cost [G€]
vOpCost	Annual Total operation cost [M€]
vOpVarom	Annual Total Varom cost [k€]
vQPEDom	PE domestic consumption [GWh]
vQPEImp	PE imports [GWh]
vQCEPriIN	PE consumed by CE techs [GWh]
vQCEPriOUT	TE produced in CE techs from PE energy [GWh]
vQCESecIN	TE consumed by CE techs [GWh]
vQCESecOUT	TE produced in CE techs from TE energy [GWh]
vQCEStoIN	TE stored by Storage techs [GWh]
vQCEStoOUT	TE released in Storage techs from TE energy [GWh]
vCEStoLevel	Accumulated energy stored in Storage processes [GWh]
vQTELoss	TE losses in transportation processes [GWh]
vQSTInTE	TE consumed by ST [GWh]
vQSTInRM	RM consumed by ST (industrial) [Tons]
vQSTOut	ES produced by ST [ES units]
vQESNS	ES not supplied (slack variable) [ES units]
vQES	Energy Services [ES units]
vBMTra	Behavioural Measures. Transportation [ES units]
vBMOth	Behavioural Measures. Others [ES units]
vBMOthWAMAC	Behavioural Measures. Others. Cold cycle Washing Machine [ES units]
vBMOthDIWAC	Behavioural Measures. Others. Cold cycle Dish Washer [ES units]
vBMOthTW	Behavioural Measures. Others. Telework [ES units]
vQSDTra	Transportation SD [SD units]
vQSDOth	Others SD [SD units]
vQSDInd	Industry SD [SD units]
vDMTra	Demand shift Measures. Transportation [SD units]
vDMOthHE	Demand shift Measures. Others. High Efficiency [SD units]
vDMOthLE	Demand shift Measures. Others. Low Efficiency [SD units]
vCENewCap	CE new installed capacity [GW]
vCETotCap	CE accumulated installed capacity [GW]
vCEDecCap	CE decommissioned capacity [GW]
vCEActCap	Active CE capacity [GW]
vCEHibCap	CE capacity in hibernation [GW]
vCEDeltaActCap	Reactivation of CE inactive capacity [GW]
vCEEleReserv	CE electricity reserves [GW]
vEleMaxDem	Yearly maximum electricity demand in a time slice [GW]
vSTNewCap	ST new installed capacity [GW]
vSTDecCap	ST decommissioned capacity [GW]
vSTTotCap	ST accumulated installed capacity [GW]
vEmiCO2CE	CO2 emissions produced in CE processes [ktCO2]
vEmiCO2CEPri	CO2 emissions produced in Primary CE processes [ktCO2]
vEmiCO2CESec	CO2 emissions produced in Secondary CE processes [ktCO2]
vEmiCO2CESto	CO2 emissions produced in Storage CE processes [ktCO2]
vEmiCO2TE	CO2 emissions produced in the transportation of TE [ktCO2]
vEmiCO2STTE	CO2 emissions produced in ST due to TE consumption [ktCO2]
vEmiCO2STPro	CO2 emissions produced in ST due to activity processes [ktCO2]
vEmiCO2ST	CO2 emissions produced in ST [ktCO2]
vEmiCO2ESNS	CO2 emissions related to ESNS [ktCO2]
vEmiCO2Tot	Annual Total CO2 emissions [MtCO2]

vEmiCO2CapExc	Excess of CO2 emissions regarding Annual Carbon Caps (slack variable) [MtCO2]
vEmiCO2BudgetExc	Excess of CO2 emissions regarding Carbon Budget (slack variable) [MtCO2]
vEmiNOxCE	NOx emissions produced in CE processes [ktNOx]
vEmiNOxCEPri	NOx emissions produced in Primary CE processes [tNOx]
vEmiNOxCESec	NOx emissions produced in Secondary CE processes [tNOx]
vEmiNOxCESto	NOx emissions produced in Storage CE processes [tNOx]
vEmiNOxSTTE	NOx emissions produced in ST due to TE consumption [tNOx]
vEmiNOxSTPro	NOx emissions produced in ST due to activity processes [tNOx]
vEmiNOxST	NOx emissions produced in ST [ktNOx]
vEmiNOxESNS	NOx emissions related to ESNS [ktNOx]
vEmiNOxTot	Total NOx emissions produced yearly [MtNOx]
vEmiNOxCapExc	Excess of NOx emissions regarding annual caps (slack variable) [MtNOx]
vEmiSOxCE	SOx emissions produced in CE processes [ktSOx]
vEmiSOxCEPri	SOx emissions produced in Primary CE processes [tSOx]
vEmiSOxCESec	SOx emissions produced in Secondary CE processes [tSOx]
vEmiSOxCESto	SOx emissions produced in Storage CE processes [tSOx]
vEmiSOxSTTE	SOx emissions produced in ST due to TE consumption [tSOx]
vEmiSOxSTPro	SOx emissions produced in ST due to activity processes [tSOx]
vEmiSOxST	SOx emissions produced in ST [ktSOx]
vEmiSOxESNS	SOx emissions related to ESNS [ktSOx]
vEmiSOxTot	Total SOx emissions produced yearly [MtSOx]
vEmiSOxCapExc	Excess of SOx emissions regarding annual caps (slack variable) [MtSOx]
vEmiPM25CE	PM25 emissions produced in CE processes [ktPM25]
vEmiPM25CEPri	PM25 emissions produced in Primary CE processes [tPM25]
vEmiPM25CESec	PM25 emissions produced in Secondary CE processes [tPM25]
vEmiPM25CESto	PM25 emissions produced in Storage CE processes [tPM25]
vEmiPM25STTE	PM25 emissions produced in ST due to TE consumption [tPM25]
vEmiPM25STPro	PM25 emissions produced in ST due to activity processes [tPM25]
vEmiPM25ST	PM25 emissions produced in ST [ktPM25]
vEmiPM25ESNS	PM25 emissions related to ESNS [ktPM25]
vEmiPM25CapExc	Excess of PM25 emissions regarding annual caps (slack variable) [MtPM25]
vEmiPM25Tot	Total PM25 emissions produced yearly [MtPM25]
vEmiCO2CapTraExc	Excess of CO2 emissions regarding Carbon Cap in Transport sector (slack variable) [MtCO2]
vEmiCO2CapEleExc	Excess of CO2 emissions regarding Carbon Cap in Electricity generation (slack variable)
vEmiCO2CapIndTEExc	Excess of CO2 emissions regarding Carbon Cap in Industrial sector (energy) (slack variable) [MtCO2]
vEmiCO2CapIndProExc	Excess of CO2 emissions regarding Carbon Cap in Industrial sector (process) (slack variable) [MtCO2]
vEmiCO2CapOthExc	Excess of CO2 emissions regarding Carbon Cap in ResidentialService sector (slack variable) [MtCO2]
vEmiCO2CapRefExc	Excess of CO2 emissions regarding Carbon Cap in Refinery sector (slack variable) [MtCO2]

PARAMETERS

pYr	Year numbers [years]
pYrGap	Year gap [years]
pTimeSlice	Time slice load factor [%]
pNumHours	Number of hours in the time period [hours]
pDisRate	Discount Rate [%]
pGreenfield	GreenField=1 — BrownField=0
pESNSCost	Energy service non supplied cost [M€ per ES units]
pEmiCO2Cap	DEACTIVATED CO2 emission cost [€ per tCO2]
pEmiCO2CapSectRestr	Emission Sectorial Cap=1 — Emission Global Cap=0
pEmiCO2BudgetRestr	CO2 emission budget =1 — CO2 emission cap=0
pCEResMar	Required reserve margin over peak demand, for adequacy restriction [%]
pCEDemErr	Average prediction error in demand, for reserves restriction [%]
pCEAFErr	Average prediction error in CE modelled with availability factors. Applied over mean yearly production [%]
pCEFailProb	Larger CE failure probability to be considered for reserves restriction [%]
pCEFailCap	Larger CE capacity to be considered for reserves restriction: the size of the larger plant that can fail [GW]
pEmiCO2Budget	CO2 emission budget [MtCO2]
pEmiCO2Cap	CO2 emission cap per year [MtCO2 per year]
pEmiNOxCap	NOx emission cap per year [MtNOx per year]
pEmiSOxCap	SOx emission cap per year [MtSOx per year]
pEmiPM25Cap	PM25 emission cap per year [MtPM25 per year]
pEmiCO2CapTra	Transport sector emission cap per year [MtCO2 per year]
pEmiCO2CapEle	Electricity generation emission cap per year [MtCO2 per year]
pEmiCO2CapIndTE	Industry (energy) sector emission cap per year [MtCO2 per year]
pEmiCO2CapIndPro	Industry (process) sector emission cap per year [MtCO2 per year]
pEmiCO2CapOth	Residential & Commercial sector emission cap per year [MtCO2 per year]
pEmiCO2CapRef	Refinery sector emission cap per year [MtCO2 per year]
pEmiCO2CEPri	Primary CE CO2 emission factor [tCO2 per MWh]
pEmiCO2CESec	Secondary CE CO2 emission factor [tCO2 per MWh]
pEmiCO2CESto	Storage CE CO2 emission factor [tCO2 per MWh]
pEmiCO2STTE	ST CO2 Energy emission factor [tCO2 per MWh]
pEmiCO2STPro	ST CO2 Process emission factor [tCO2 per MWh]
pEmiCO2TE	TE Transportation CO2 emission factor [tCO2 per MWh]
pEmiCO2ESNS	ESNS CO2 emission factor [tCO2 per MWh]
pEmiNOxCEPri	Primary CE NOx emission factor [kNOx per MWh]
pEmiNOxCESec	Secondary CE NOx emission factor [kNOx per MWh]
pEmiNOxCESto	Storage CE NOx emission factor [kNOx per MWh]
pEmiNOxSTTE	ST NOx Energy emission factor [kNOx per MWh]
pEmiNOxSTPro	ST NOx Process emission factor [kNOx per MWh]
pEmiNOxESNS	ESNS NOx emission factor [kNOx per MWh]
pEmiSOxCEPri	Primary CE SOx emission factor [kSOx per MWh]
pEmiSOxCESec	Secondary CE SOx emission factor [kSOx per MWh]
pEmiSOxCESto	Storage CE SOx emission factor [kSOx per MWh]
pEmiSOxSTTE	ST SOx Energy emission factor [kSOx per MWh]
pEmiSOxSTPro	ST SOx Process emission factor [kSOx per MWh]
pEmiSOxESNS	ESNS SOx emission factor [kSOx per MWh]
pEmiPM25CEPri	Primary CE PM25 emission factor [tPM25 per MWh]
pEmiPM25CESec	Secondary CE PM25 emission factor [tPM25 per MWh]
pEmiPM25CESto	Storage CE PM25 emission factor [tPM25 per MWh]
pEmiPM25STTE	ST PM25 Energy emission factor [tPM25 per MWh]
pEmiPM25STPro	ST PM25 Process emission factor [tPM25 per MWh]
pEmiCO2ESNS	ESNS CO2 emission factor [tPM25 per MWh]
pPECost	PE Cost [€ per MWh]

pPEDomCap	PE domestic consumption capacity [GW]
pPEImpCap	PE importation capacity [GW]
pCEOutShareMin	Minimum Output share [%]
pCEOutShareMax	Maximum Output share [%]
pCEPriEff	MWh of PE needed to generate 1 MWh of TE in a Primary CE tech [%]
pCESecEff	MWh of TE needed to generate 1 MWh of TE in a Secondary CE tech [%]
pCEStoEff	MWh of TE needed to generate 1 MWh of TE in a Storage CE tech [%]
pCELife	Life span of energy technologies [years]
pCEInsCap	Previous installed capacity of CE [GW]
pCEMaxCap	Maximum allowed capacity of CE [GW]
pCEStoCap	Storage capacity in terms of energy [MWh]
pCECapex	CAPEX of CE Conversion technologies [€ per kW]
pCEDecom	Decommission cost of CE [€ per kW]
pCEFixom	Fixed O&M costs of CE [€ per kW]
pCEVarom	Variable O&M costs of CE [€ per MWh]
pCEReact	Cost of Reactivation from hibernation of CE Conversion technologies [€ per kW]
pCEHiber	Cost of Hibernation of active CE Conversion technologies [€ per kW]
pCEAF	Availability factor [%]
pCEFlex	Electr. generation tech flexibility factor, i.e. a measure of how steep can be the slopes provided by CE [%]
pCEFirm	Electr. generation tech firmness factor, i.e. probability of producing in a critical moment for the system [%]
pTELoss	TE transportation losses [%]
pRMCost	RM Raw material cost [€ per ton]
pRMCost	RM Raw material. Circularity rate [%]
pSTOutShareMin	Minimum Output share [%]
pSTOutShareMax	Maximum Output share [%]
pSTTraMS	Modal Shares (calibration year) [%]
pMSMax	Maximum Modal Share between years [%]
pTCMax	Maximum Technological Choice between years [%]
pSTEffTE	TE final energy required to produce one unit of ES [MWh per ES unit]
pSTEffRM	RM raw materials required to produce one unit of ES [tons RM per ES unit]
pSTInsCap	Previous installed capacity of ST [ST units]
pSTMaxCap	Maximum allowed capacity of ST [ST units]
pSTMaxPro	Maximum annual production of ST [ES units per ST units]
pSTCapex	CAPEX of ST technologies [M€ per ST unit]
pSTDecom	Decommission cost of ST [M€ per ST unit]
pSTDecProb	Probability of decommission of ST technologies [%]
pSTFixom	Fixed O&M costs of ST [€ per ST unit]
pSTVarom	Variable O&M costs of ST [€ per ES unit]
pESLoad	Load profile of ES demand [%]
pAFTra	Occupancy rate [passengers per vehicles]
pAFOth	Representative energy service demands per dwelling [ES unit per Mdwelling or km2]
pAFInd	- [%]
pBMCost	Cost of Behavioural Measures [G€ per AF unit]
pDeltaAFTra	Maximum improvement allowed of occupancy rate per behavioural measure [passengers per vehicles]
pDeltaAFOth	Maximum improvement allowed of energy service demand per behavioural measure [ES unit per dwelling/km2]
pDC	Demand characterization [-]
pDMCost	Cost of Demand shift Measures [G€ per unit of DC]
pDeltaDC	Maximum improvement allowed of DC per Demand shift Measures [-]
pTW	Remote work: Trade-off between residential energy service and transportation demand [ES unit per Mpkm]
pMD	[Macro data units] Macro Data

EQUATIONS

Objective Function

$$\text{Total System Cost [G€]}: \quad vSysCost = \sum_{y} vTotalCost_{y} + \sum_{y} vPenalCost_{y} \quad + \sum_{BM,y} vBMCost_{BM,y} + \sum_{DM,y} vBMCost_{DM,y} + pEmiCO2BudgetRestr \cdot vEmiCO2BudgetExc \tag{1}$$

$$\text{Discount Factor (DF)}: \quad \frac{1}{(1+pDisRate)^{(pYrGap\cdot(y-1))}} \tag{2}$$

$$\begin{aligned}\text{Total Penalization Cost [G€]}: \quad & vPenalCost = DF \cdot pESNSCost \cdot (\\ & (1 - pEmiCO2CapSectRestr) \cdot (1 - pEmiCO2BudgetRestr) \cdot vEmiCO2CapExc_{y} \\ & + pEmiCO2CapSectRestr \cdot (1 - pEmiCO2BudgetRestr) \cdot (vEmiCO2CapTraExc_{y} \\ & + vEmiCO2CapEleExc_{y} + vEmiCO2CapIndTEExc_{y} + vEmiCO2CapIndProExc_{y} \\ & + vEmiCO2CapOthExc_{y} + vEmiCO2CapRefExc_{y}) \\ & + (vEmiNOxCapExc + vEmiSOxCapExc + vEmiPM25CapExc))\end{aligned} \tag{3}$$

$$\text{Annual Total Cost[G€]}: \quad vTotalCost_{sYear} = vOpCost_{sYear} + \sum_{CE} vInvCostCE_{CE,y} + \sum_{ST} vInvCostST_{ST,y} \tag{4}$$

$$\begin{aligned}\text{Annual Behavioural Measures Cost [G€]}: \quad & vBMCost_{sYear} = DF \cdot (\sum_{ST,ES,SD} pBMCost_{BM,y} \cdot vBMTra_{ST,ES,SD,BM,y} \\ & + \sum_{ES,SD,MD} pBMCost_{BM,y} \cdot vBMOth_{ES,SD,MD,BM,y})\end{aligned} \tag{5}$$

$$\begin{aligned}\text{Annual Demand shift Measures Cost [G€]}: \quad & vDMCost_{DM,y} = DF \cdot (\sum_{SD,MD} pDMCost_{DM,y} \cdot vDMTra_{SD,MD,DM,y} \\ & + \sum_{MD} pDMCost_{DM,y} \cdot (vDMOthHE_{MD,DM,y} - vDMOthHE_{MD,DM,y-1}))\end{aligned} \tag{6}$$

$$\begin{aligned}\text{Annual Total CE Investment Cost [G€]}: \quad & vInvCostCE_{CE,y} = DF \cdot (pCECapex_{CE,y} \cdot vCENewCap_{CE,y} \\ & + pCEDecom_{CE,y} \cdot vCEDecCap_{CE,y} + pCEReact_{CE,y} \cdot vCEDeltaActCap_{CE,y})\end{aligned} \tag{7}$$

$$\begin{aligned}\text{Annual Total Operation Cost [M€]}: \quad & vOpCost_{y} = pYrGap \cdot DF \\ & \cdot (\sum_{PE,s,d,h} pPECost_{PE,y} \cdot (vQPEImp_{PE,y,s,d,h} + vQPEDom_{PE,y,s,d,h}) \\ & + \sum_{CE} pCEFixom_{CE} \cdot vCEActCap_{CE,y} \\ & + \sum_{RM,ST,ES,Vin,s,d,h} pRMCost_{RM,y} \cdot vQSTInRM_{RM,ST,ES,Vin,y,s,d,h} \\ & + \sum_{ST,Vin} pSTFixom_{ST} \cdot vSTTotCap_{ST,Vin,y} \\ & + \sum_{ST,ES,Vin,s,d,h} pSTVarom_{ST,ES} \cdot vQSTOut_{ST,ES,Vin,y,s,d,h} \\ & + pESNSCost \cdot \sum_{ST,ES,s,d,h} vQESNS_{ST,ES,y,s,d,h} + vOpVarom_{y})\end{aligned} \tag{8}$$

$$\begin{aligned}\text{Annual Total Varom Cost [k€]}: \quad & vOpVarom_{sYear} = \sum_{CE,TE,s,d,h} pCEVarom_{CE,TE} \cdot vQCEPriOUT_{CE,TE,y,s,d,h} \\ & + \sum_{CE,TE,s,d,h} pCEVarom_{CE,TE} \cdot vQCESecOUT_{CE,TE,y,s,d,h} \\ & + \sum_{CE,TE,s,d,h} pCE\nabla arom_{CE,TE} \cdot vQCEStoOUT_{CE,TE,y,s,d,h}\end{aligned} \tag{9}$$

(10)

Constraints

Primary Energy PE

PE domestic production capacity [GWh] :
$$pPEDomCap_{PE} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \geq vQPEDom_{PE,y,s,d,h} \tag{11}$$

PE importation capacity [GWh] :
$$pPEImpCap_{PE} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \geq vQPEImp_{PE,y,s,d,h} \tag{12}$$

PE energy balance [GWh] :
$$vQPEDom_{PE,y,s,d,h} + vQPEImp_{PE,y,s,d,h} = \sum_{CE} vQCEPriIN_{PE,CE,y,s,d,h} \tag{13}$$

Primary Conversion Energy CEPri

Balance for Primary CE techs (using PE commodities) [GWh] :
$$\sum_{PE} pCEPriEff_{PE,CE_{Pri}} \cdot vQCEPriIN_{PE,CE_{Pri},y,s,d,h} = \sum_{TE} vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \tag{14}$$

Minimum CE output shares restriction [GWh] :
$$vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \geq pCEOutShareMin_{CE_{Pri},TE} \cdot \sum_{TE} vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \tag{15}$$

Maximum CE output shares restriction [GWh] :
$$pCEOutShareMax_{CE_{Pri},TE} \cdot \sum_{TE} vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \geq vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \tag{16}$$

Secondary Conversion Energy CEPri

Balance for CE techs using TE commodities [GWh] :
$$\sum_{TE} pCESecEff_{TE,CE_{Sec}} \cdot vQCESecIN_{TE,CE_{Sec},y,s,d,h} = \sum_{TE} vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \tag{17}$$

Minimum CE output shares restriction [GWh] :
$$vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \geq pCEOutShareMin_{CE_{Sec},TE} \cdot \sum_{TE} vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \tag{18}$$

Maximum CE output shares restriction [GWh] :
$$pCEOutShareMax_{CE_{Sec},TE} \cdot \sum_{TE} vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \geq vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \tag{19}$$

Storage Energy CESto

Seasonal balance for Storage CE techs [GWh] :

$$\sum_{TE,d,h} pCEStoEff_{TE,CE_{Sto}} \cdot vQCEStoIN_{TE,CE_{Sto},y,s,d,h} = \sum_{TE,d,h} vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \quad (20)$$

Storage level [GWh] :

$$CE_{Sto},y,s,d,h = CE_{Sto},y,s,d,h-1 + vQCEStoIN_{TE,CE_{Sto},y,s,d,h} - vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \quad (21)$$

Minimum CE output shares restriction [GWh] :

$$vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \geq pCEOutShareMin_{CE_{Sto},TE} \cdot \sum_{TE} vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \quad (22)$$

Maximum CE output shares restriction [GWh] :

$$pCEOutShareMax_{CE_{Sto},TE} \cdot \sum_{TE} vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \geq vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \quad (23)$$

Storage maximum level restriction [GWh] :

$$pCEStoCap CE_{Sto} \geq vCEStoLevel CE_{Sto}, y, s, d, h \quad (24)$$

Transported Energy TE

Balance for TE [GWh] :

$$\sum_{CE} vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} + \sum_{CE} vQCESecOUT_{CE_{Sec},TE,y,s,d,h} + \sum_{CE} vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} - \sum_{CE} vQCESecIN_{TE,CE_{Sec},y,s,d,h} - \sum_{CE} vQCEStoIN_{TE,CE_{Sto},y,s,d,h} - vQTELoss_{TE,y,s,d,h} = \sum_{ST,ES,Vin} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \quad (25)$$

TE losses for transportation processes [GWh] :

$$vQTELoss_{TE,y,s,d,h} = pTELoss_{TE} \cdot (\sum_{CE_{Pri}} vQCEPriOUT_{CE,TE,y,s,d,h} + \sum_{CE_{Sec}} vQCESecOUT_{CE,TE,y,s,d,h} + \sum_{CE_{Sto}} vQCEStoOUT_{CE,TE,y,s,d,h}) \quad (26)$$

Supply Technologies ST

$$\text{Balance for ST processes in Transportation [ES units]}: \quad \sum_{TE} vQSTInTE_{TE,ST_{Tra},ES_{Tra},Vin,y,s,d,h}/pSTEffTE_{ST_{Tra},ES_{Tra},TE,Vin} = vQSTOut_{ST_{Tra},ES_{Tra},Vin,y,s,d,h} \tag{27}$$

$$\text{Balance for ST processes in Others [ES units]}: \quad vQSTInTE_{TE,ST_{Oth},,Vin,y,s,d,h}/pSTEffTE_{ST_{Oth},,TE,Vin} = vQSTOut_{ST_{Oth},,Vin,y,s,d,h} \tag{28}$$

$$\text{Balance for ST processes in Industry [ES units]}: \quad vQSTInTE_{TE,ST_{Ind},ES_{Ind},Vin,y,s,d,h}/pSTEffTE_{ST_{Ind},ES_{Ind},TE,Vin} = vQSTOut_{ST_{Ind},ES_{Ind},Vin,y,s,d,h} \tag{29}$$

$$\text{Minimum ST output shares restriction [ES units]}: \quad vQSTOut_{ST,ES,Vin,y,s,d,h} \geq pSTOutShareMin_{ST,ES} \cdot \sum_{ES} vQSTOut_{ST,ES,Vin,y,s,d,h} \tag{30}$$

$$\text{Maximum ST output shares restriction [ES units]}: \quad pSTOutShareMax_{ST,ES} \cdot \sum_{ES} vQSTOut_{ST,ES,Vin,y,s,d,h} \geq vQSTOut_{ST,ES,Vin,y,s,d,h} \tag{31}$$

Transportation Modal Shares MS

$$\text{Minimum Modal Shares restrictions [ES units]}: \text{If} \quad y > 1: \quad \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y})} \geq \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y-1})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y-1})} - pMSMax \quad \forall (ST_{Tra}, ES_{Tra}) \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air) \tag{32}$$

$$\text{If} \quad y = 1: \quad \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y})} \geq pSTTraMS_{Modes,SD_{Tra}} \quad \forall (ST_{Tra}, ES_{Tra}) \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air) \tag{33}$$

$$\text{Maximum Modal Shares restrictions [ES units]}: \text{If} \quad y > 1: \quad \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y})} \leq \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y-1})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y-1})} + pMSMax \quad \forall (ST_{Tra}, ES_{Tra}) \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air) \tag{34}$$

$$\text{If} \quad y = 1: \quad \frac{\sum_{ES_{Tra},ST_{Tra}}(pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},Vin,y})}{\sum_{MD_{Tra}}(pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD,y})} \leq pSTTraMS_{Modes,SD_{Tra}} \quad \forall (ST_{Tra}, ES_{Tra}) \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air) \tag{35}$$

Technological Choice Shares TC

Technological Choice in Transportation [ST units] : If $y > 1$:

$$vSTNewCap_{ST_{Tra},y} \leq \sum_{Vin}(vSTTotCap_{ST_{Tra},Vin,y-1}) + pTCMax \cdot \sum_{ST_{Tra},Vin} vSTTotCap_{ST_{Tra},Vin,y-1}$$
$$\forall ST_{Tra} \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air)$$

If $y = 1$:

$$vSTNewCap_{ST_{Tra},y} \leq \sum_{Vin}(pSTInsCap_{ST_{Tra},Vin}) + pTCMax \cdot \sum_{ST_{Tra},Vin} pSTInsCap_{ST_{Tra},Vin}$$
$$\forall ST_{Tra} \in (Car, Bus, Moped, IntRail, UrbanRail, Sea, Air) \quad (36)$$

Technological Choice in Others [ST units] : If $y > 1$:

$$vSTNewCap_{ST_{Oth},y} \leq \sum_{Vin}(vSTTotCap_{ST_{Oth},Vin,y-1}) + pTCMax \cdot \sum_{ST_{Oth},Vin} vSTTotCap_{ST_{Oth},Vin,y-1}$$
$$\forall (ST_{Oth},)$$

If $y = 1$:

$$vSTNewCap_{ST_{Oth},y} \leq \sum_{Vin}(pSTInsCap_{ST_{Oth},Vin}) + pTCMax \cdot \sum_{ST_{Oth},Vin} pSTInsCap_{ST_{Oth},Vin}$$
$$\forall (ST_{Oth},) \quad (37)$$

Energy Services ES

ES energy balance [ES units] : $$\sum_{Vin} \cdot vQSTOut_{ST,ES,Vin,y,s,d,h} \geq vQES_{ST,ES,y} \cdot pESLoad_{ES,s,d,h} - vQESNS_{ST,ES,y,s,d,h} \quad (38)$$

Industrial demand

Balance for ST consumption of RM [RM units] : $$vQSTInRM_{RM,ST_{Ind},ES_{Ind},Vin,y,s,d,h} \geq vQSTOut_{ST_{Ind},ES_{Ind},Vin,y,s,d,h} \cdot pSTEffRM_{RM,ST_{Ind},ES_{Ind}} \quad (39)$$

Activity Factor Industry [SD units] : $$\sum_{ES_{Ind},ST_{Ind}} vQES_{ST_{Ind},ES_{Ind},y} \cdot pAFInd_{ES_{Ind},SD_{Ind}} \geq vQSDInd_{SD_{Ind},y} \quad (40)$$

Demand characterization Industry [MD units] : $$\sum_{SD_{Ind}} (vQSDInd_{SD_{Ind},y} \cdot pDC_{SD_{Ind},MD_{Ind}}) \geq pMD_{MD_{Ind},y} \quad (41)$$

Circularity constraints [RM units] : $$\sum_{ST_{Ind},Vin} vQSTOut_{ST_{Ind},ES,Vin,y,s,d,h} \geq \frac{vQSTInRM_{RM,ST_{Ind},ES,Vin,y,s,d,h}}{pRMCircular_{ES,RM}} \quad (42)$$

Transportation demand

$$\text{Activity Factor Transportation [SD units]}: \quad \sum_{ES_{Tra},ST_{Tra}} vQES_{ST_{Tra},ES_{Tra},y} \cdot pAFTra_{ST_{Tra},ES_{Tra},SD_{Tra}} + \sum_{ES_{Tra},ST_{Tra},BM_{Tra}} vBMTra_{ST_{Tra},ES_{Tra},SD_{Tra},BM_{Tra},y} \geq vQSDTra_{SD_{Tra},y} \tag{43}$$

$$\text{Behavioural Measures in Transportation [ES units]}: \quad vBMTra_{ST_{Tra},ES_{Tra},SD_{Tra},BM_{Tra},y} \leq pDeltaAFTra_{ST_{Tra},ES_{Tra},SD_{Tra},BM_{Tra}} \cdot vQES_{ST_{Tra},ES_{Tra},y} \tag{44}$$

$$\text{Demand characterization Transportation [SD units]}: \quad vQSDTra_{SD_{Tra},y} \geq \sum_{MD_{Tra}} (pDC_{SD_{Tra},MD_{Tra}} \cdot pMD_{MD_{Tra},y}) - \sum_{MD_{Tra},DM_{Tra}} vDMTra_{SD_{Tra},MD_{Tra},DM_{Tra},y} \tag{45}$$

$$\text{Demand shift Measures in Transportation [MD units]}: \quad vDMTra_{SD_{Tra},MD_{Tra},DM_{Tra},y} \leq pDeltaDC_{SD_{Tra},MD_{Tra},DM_{Tra}} \cdot pMD_{MD_{Tra},y} \tag{46}$$

Others demand

Activity Factor Others [ES units] :

$$\sum_{ST_{Oth}} vQES_{ST_{Oth},,y} \geq \sum_{SD_{Oth},MD_{Oth}} vQSDOth_{SD_{Oth},MD_{Oth},y} \cdot pAFOth_{,SD_{Oth},MD_{Oth}} - \sum_{SD_{Oth},MD_{Oth},BM_{Oth}} vBMOth_{,SD_{Oth},MD_{Oth},BM_{Oth},y} + \sum_{SD_{Oth},MD_{Oth},BM_{Oth}} vBMOthWAMAC_{SD_{Oth},MD_{Oth},BM_{Oth},y} \quad if \quad \in ES_{Oth_{WAMAC}}) + \sum_{SD_{Oth},MD_{Oth},BM_{Oth}} vBMOthDIWAC_{SD_{Oth},MD_{Oth},BM_{Oth},y} \quad if \quad \in ES_{Oth_{DIWAC}}) + \sum_{SD_{Oth},MD_{Oth}} vBMOthTW_{,SD_{Oth},MD_{Oth},y} \tag{47}$$

Behavioural Measures in Others [SD units] :

$$vBMOth_{,SD_{Oth},MD_{Oth},BM_{Oth},y} \leq pDeltaAFOth_{,SD_{Oth},MD_{Oth},BM_{Oth}} \cdot vQSDOth_{SD_{Oth},MD_{Oth},y} \tag{48}$$

Behavioural Measures. Washing Machine [SD units] :

$$vBMOth_{ES_{WAMAH},SD_{Oth},MD_{Oth},BM_{Oth},y} = -vBMOthWAMAC_{SD_{Oth},MD_{Oth},BM_{Oth},y} \tag{49}$$

Behavioural Measures. Dish Washer [SD units] :

$$vBMOth_{ES_{DIWAH},SD_{Oth},MD_{Oth},BM_{Oth},y} = \text{-}vBMOthDIWAC_{SD_{Oth},MD_{Oth},BM_{Oth},y} \tag{50}$$

Behavioural Measures. Remote work [SD units] :

$$vBMOthTW_{,SD_{Oth},MD_{Oth},y} = pTW_{,SD_{Oth},MD_{Oth}} \cdot \sum_{SD_{Tra},MD_{Tra}} vDMTra_{SD_{Tra},MD_{Tra},DM_{TW},y} \tag{51}$$

Demand characterization Others [SD units] :

$$vQSDOth_{SD_{Oth},MD_{Oth},y} \geq pDC_{SD_{Oth},MD_{Oth}} \cdot pMD_{MD_{Oth},y} + (\sum_{DM_{Oth}} vDMOthHE_{MD_{Oth},DM_{Oth},y} \quad if \quad SD_{Oth} \in SD_{Oth_{HE}}) - (\sum_{DM_{Oth}} vDMOthLE_{MD_{Oth},DM_{Oth},y} \quad if \quad SD_{Oth} \in SD_{Oth_{LE}}) \tag{52}$$

DM (thermal insulation) [MD units] :

$$vDMOthHE_{MD_{Oth},DM_{Oth},y} \leq \sum_{SD_{Oth_{HE}}} (pDeltaDC_{SD_{Oth},MD_{Oth},DM_{Oth}} \cdot pMD_{MD_{Oth},y}) \tag{53}$$

DM (shift from LE to HE) [MD units] :

$$vDMOthHE_{MD_{Oth},DM_{Oth},y} = vDMOthLE_{MD_{Oth},DM_{Oth},y} \tag{54}$$

DM (Insulation remains) [MD units] :

$$vDMOthHE_{MD_{Oth},DM_{Oth},y} \geq vDMOthHE_{MD_{Oth},DM_{Oth},y-1} \tag{55}$$

Conversion Energy Technology capacity constraints CE

Primary CE maximum production (CEPri) [GWh] :

$$vCEActCap_{CE_{Pri},y} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \cdot pCEAF_{CE_{Pri},s,d,h} \geq (vCEEleReserv_{CE_{Pri},y,s,d,h} \quad if \quad CE_{Pri} \in CE_{Ele}) + \sum_{sTE} vQCEPriOUT_{CE_{Pri},TE,y,s,d,h} \tag{56}$$

Secondary CE maximum production (CESec) [GWh] :

$$vCEActCap_{CE_{Sec},y} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \cdot pCEAF_{CE_{Sec},s,d,h} \geq (vCEEleReserv_{CE_{Sec},y,s,d,h} \quad if \quad CE_{Sec} \in CE_{Ele}) + \sum_{TE} vQCESecOUT_{CE_{Sec},TE,y,s,d,h} \tag{57}$$

Storage CE maximum production (CESto) [GWh] :

$$vCEActCap_{CE_{Sto},y} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \cdot pCEAF_{CE_{Sto},s,d,h} \geq (vCEEleReserv_{CE_{Sto},y,s,d,h} \quad if \quad CE_{Sto} \in CE_{Ele}) + \sum_{TE} vQCEStoOUT_{CE_{Sto},TE,y,s,d,h} \tag{58}$$

CE maximum allowed capacity [GW] :

$$pCEMaxCap_{CE,y} \geq vCETotCap_{CE,y} \tag{59}$$

CE installed capacity [GW] :

$$vCETotCap_{CE,y} = (vCETotCap_{CE,y-1} \quad if \quad y \neq 1 \quad else \quad (1 - pGreenfield) \cdot pCEInsCap_{CE}) + vCENewCap_{CE,y} - vCEDecCap_{CE,y} \tag{60}$$

CE decommissioned capacity [GW] :

$$vCEDecCap_{CE,y} = ((1 - pGreenfield) \cdot pYrGap \cdot \frac{pCEInsCap_{CE}}{pCELife_{CE}}) \quad if \quad y \leq \frac{pCELife_{CE}}{pYrGap} \quad else \quad 0 + vCENewCap_{CE,y-\frac{pCELife_{CE}}{pYrGap}} \quad if \quad y > \frac{pCELife_{CE}}{pYrGap} \quad else \quad 0 \tag{61}$$

CE active capacity [GW] :

$$vCEActCap_{CE,y} == vCETotCap_{CE,y} - vCEHibCap_{CE,y} \tag{62}$$

CE Reactivation of capacity [GW] :

$$vCEDeltaActCap_{CE,y} \geq -vCEHibCap_{CE,y} - vCEDecCap_{CE,y} + (vCEHibCap_{CE,y-1} \quad if \quad y \neq 1 \quad else \quad 0) \tag{63}$$

Electricity Energy Technology capacity constraints CE

$$\text{Reserves for electricity generation [GW]}: \quad \sum_{CE_{Ele}} (vCEEleReserv_{CE_{Ele},y,s,d,h} \cdot pCEFlex_{CE_{Ele}}) \geq (pCEFailCap + \sum_{TE,ST,ES,Vin} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \cdot pCEDemErr + \sum_{CE_{Var}} vCEActCap_{CE_{Var},y} \cdot pCEAF_{CE_{Var},s,d,h} \cdot pCEAFErr) \tag{64}$$

$$\text{Yearly maximum electricity power demand [GW]}: \quad vEleMaxDem_y \geq \sum_{TE,ST,ES,Vin} \frac{vQSTInTE_{TE,ST,ES,Vin,y,s,d,h}}{pNumHours \cdot pTimeSlice_{s,d,h}} \tag{65}$$

$$\text{Adequacy for electricity generation [GW]}: \quad \sum_{CE_{Ele}} vCEActCap_{CE_{Ele},y} \cdot pCEFirm_{CE_{Ele}} \geq (1 + pCEResMar) \cdot vEleMaxDem_y \tag{66}$$

$$\text{Nuclear dismantling restriction [GW]}: \quad (pCEInsCap_{CE_{Nuc}} \; if \quad y < y_{Nuc} \quad else \quad 0) \geq vCEActCap_{CE_{Nuc},y} \tag{67}$$

$$\text{Coal phase-out restriction [GW]}: \quad (pCEInsCap_{CE_{Coal}} \; if \quad y < y_{Coal} \quad else \quad 0) \geq vCEActCap_{CE_{Coal},y} \tag{68}$$

Supply Technology capacity constraints ST

$$\text{ST maximum production per capacity [ES units]}: \quad vSTTotCap_{ST_{Cap},Vin,y} \cdot pNumHours \cdot pTimeSlice_{s,d,h} \geq \sum_{ES} vQSTOut_{ST_{Cap},ES,Vin,y,s,d,h} \tag{69}$$

$$\text{ST maximum production per unit [ES units]}: \quad vSTTotCap_{ST_{Uni},Vin,y} \cdot pSTMaxPro_{ST_{Uni}} \geq \sum_{ES} vQSTOut_{ST_{Cap},ES,Vin,y,s,d,h} \tag{70}$$

$$\text{ST maximum capacity [ST units]}: \quad pSTMaxCap_{ST} \geq \sum_{Vin} vSTTotCap_{ST,Vin,y} \tag{71}$$

$$\begin{aligned}\text{ST installed capacity [ST units]}: \quad & vSTTotCap_{ST,Vin,y} = ((1 - pGreenfield) \cdot pSTInsCap_{ST,Vin} \quad if \quad y = 1 \quad else \quad 0) \\ & + (vSTTotCap_{ST,Vin,y-1} \quad if \quad y > 1 \; and \; pYr_y > pYr_{Vin} \quad else \quad 0) \\ & + (vSTNewCap_{ST,y} \quad if \quad pYr_y = pYr_{Vin} \quad else \quad 0) \\ & - (vSTDecCap_{ST,Vin,y} \quad if \quad pYr_y > pYr_{Vin} \quad else \quad 0)\end{aligned} \tag{72}$$

$$\begin{aligned}\text{ST decommissioned capacity [ST units]}: \quad & vSTDecCap_{ST,Vin,y} \\ & = (vSTTotCap_{ST,Vin,y-1} \quad if \quad y > 1 \quad else \quad (1 - pGreenfield) \cdot pSTInsCap_{ST,Vin}) \\ & \cdot \sum_{Vin} pSTDecProb_{ST,Age} \quad if \quad Age = pYr_y - pYr_{Vin}\end{aligned} \tag{73}$$

CO2 emissions

CO2 emissions produced in Primary CE Processes [ktCO2] :

$$vEmiCO2CEPri_{PE,CE_{Pri},y} = pEmiCO2CEPri_{PE,CE_{Pri}} \cdot \sum_{s,d,h} vQCEPriIN_{PE,CE_{Pri},y,s,d,h} \quad (74)$$

CO2 emissions produced in Secondary CE Processes [ktCO2] :

$$vEmiCO2CESec_{TE,CE_{Sec},y} = pEmiCO2CESec_{TE,CE_{Sec}} \cdot \sum_{s,d,h} vQCEPriIN_{TE,CE_{Sec},y,s,d,h} \quad (75)$$

CO2 emissions produced in Storage CE Processes [ktCO2] :

$$vEmiCO2CESto_{TE,CE_{Sto},y} = pEmiCO2CESto_{TE,CE_{Sto}} \cdot \sum_{s,d,h} vQCEStoIN_{TE,CE_{Sto},y,s,d,h} \quad (76)$$

CO2 emissions produced in Storage CE [ktCO2] :

$$vEmiCO2CE_{TE,CE_{Sto},y} = \sum_{PE} vEmiCO2CEPri_{PE,CE,y} + \sum_{TE} vEmiCO2CESec_{TE,CE,y} + \sum_{TE} vEmiCO2CESto_{TE,CE,y} \quad (77)$$

CO2 emissions produced in the transportation of TE [ktCO2] :

$$vEmiCO2TE_{TE,y} = pEmiCO2TE_{TE} \cdot \sum_{ST,ES,Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} + \sum_{s,d,h} vQTELoss_{TE,y,s,d,h} \quad (78)$$

CO2 emissions produced in ST due to TE consumption [ktCO2] :

$$vEmiCO2STTE_{TE,ST,ES,y} = pEmiCO2STTE_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \quad (79)$$

CO2 emissions produced in ST due to activity processes [ktCO2] :

$$vEmiCO2STPro_{ST,ES,y} = pEmiCO2STPro_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTOut_{ST,ES,Vin,y,s,d,h} \quad (80)$$

CO2 emissions produced in ST [ktCO2] :

$$vEmiCO2ST_{ST,ES,y} = \sum_{TE} vEmiCO2STTE_{TE,ST,ES,y} + vEmiCO2STPro_{ST,ES,y} \quad (81)$$

CO2 emissions related to ESNS [ktCO2] :

$$vEmiCO2ESNS_{y} = pEmiCO2ESNS_{ST,TE} \cdot \sum_{ST,ES,s,d,h} vQESNS_{ST,ES,y,s,d,h} \quad (82)$$

Annual Total CO2 Emissions [MtCO2] :

$$vEmiCO2Tot_{y} = \sum_{CE} vEmiCO2CE_{CE,y} + \sum_{TE} vEmiCO2TE_{TE,y} + \sum_{ST,ES} vEmiCO2ST_{ST,ES,y} \quad (83)$$

NOx emissions

NOx emissions produced in Primary CE Processes [ktNOx] :

$$vEmiNOxCEPri_{PE,CE_{Pri},y} = pEmiNOxCEPri_{PE,CE_{Pri}} \cdot \sum_{s,d,h} vQCEPriIN_{PE,CE_{Pri},y,s,d,h} \tag{84}$$

NOx emissions produced in Secondary CE Processes [ktNOx] :

$$vEmiNOxCESec_{TE,CE_{Sec},y} = pEmiNOxCESec_{TE,CE_{Sec}} \cdot \sum_{s,d,h} vQCEPriIN_{TE,CE_{Sec},y,s,d,h} \tag{85}$$

NOx emissions produced in Storage CE Processes [ktNOx] :

$$vEmiNOxCESto_{TE,CE_{Sto},y} = pEmiNOxCESto_{TE,CE_{Sto}} \cdot \sum_{s,d,h} vQCEStoIN_{TE,CE_{Sto},y,s,d,h} \tag{86}$$

NOx emissions produced in Storage CE [ktNOx] :

$$vEmiNOxCE_{TE,CE_{Sto},y} = \sum_{PE} vEmiNOxCEPri_{PE,CE,y} + \sum_{TE} vEmiNOxCESec_{TE,CE,y} + \sum_{TE} vEmiNOxCESto_{TE,CE,y} \tag{87}$$

NOx emissions produced in the transportation of TE [ktNOx] :

$$vEmiNOxTE_{TE,y} = pEmiNOxTE_{TE} \cdot \sum_{ST,ES,Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} + \sum_{s,d,h} vQTELoss_{TE,y,s,d,h} \tag{88}$$

NOx emissions produced in ST due to TE consumption [ktNOx] :

$$vEmiNOxSTTE_{TE,ST,ES,y} = pEmiNOxSTTE_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \tag{89}$$

NOx emissions produced in ST due to activity processes [ktNOx] :

$$vEmiNOxSTPro_{ST,ES,y} = pEmiNOxSTPro_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTOut_{ST,ES,Vin,y,s,d,h} \tag{90}$$

NOx emissions produced in ST [ktNOx] :

$$vEmiNOxST_{ST,ES,y} = \sum_{TE} vEmiNOxSTTE_{TE,ST,ES,y} + vEmiNOxSTPro_{ST,ES,y} \tag{91}$$

NOx emissions related to ESNS [ktNOx] :

$$vEmiNOxESNS_{y} = pEmiNOxESNS_{ST,TE} \cdot \sum_{ST,ES,s,d,h} vQESNS_{ST,ES,y,s,d,h} \tag{92}$$

Annual Total NOx Emissions [MtNOx] :

$$vEmiNOxTot_{y} = \sum_{CE} vEmiNOxCE_{CE,y} + \sum_{TE} vEmiNOxTE_{TE,y} + \sum_{ST,ES} vEmiNOxST_{ST,ES,y} \tag{93}$$

SOx emissions

SOx emissions produced in Primary CE Processes [ktSOx] :

$$vEmiSOxCEPri_{PE,CE_{Pri},y} = pEmiSOxCEPri_{PE,CE_{Pri}} \cdot \sum_{s,d,h} vQCEPriIN_{PE,CE_{Pri},y,s,d,h} \tag{94}$$

SOx emissions produced in Secondary CE Processes [ktSOx] :

$$vEmiSOxCESec_{TE,CE_{Sec},y} = pEmiSOxCESec_{TE,CE_{Sec}} \cdot \sum_{s,d,h} vQCEPriIN_{TE,CE_{Sec},y,s,d,h} \tag{95}$$

SOx emissions produced in Storage CE Processes [ktSOx] :

$$vEmiSOxCESto_{TE,CE_{Sto},y} = pEmiSOxCESto_{TE,CE_{Sto}} \cdot \sum_{s,d,h} vQCEStoIN_{TE,CE_{Sto},y,s,d,h} \tag{96}$$

SOx emissions produced in Storage CE [ktSOx] :

$$vEmiSOxCE_{TE,CE_{Sto},y} = \sum_{PE} vEmiSOxCEPri_{PE,CE,y} + \sum_{TE} vEmiSOxCESec_{TE,CE,y} + \sum_{TE} vEmiSOxCESto_{TE,CE,y} \tag{97}$$

SOx emissions produced in the transportation of TE [ktSOx] :

$$vEmiSOxTE_{TE,y} = pEmiSOxTE_{TE} \cdot \sum_{ST,ES,Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} + \sum_{s,d,h} vQTELoss_{TE,y,s,d,h} \tag{98}$$

SOx emissions produced in ST due to TE consumption [ktSOx] :

$$vEmiSOxSTTE_{TE,ST,ES,y} = pEmiSOxSTTE_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \tag{99}$$

SOx emissions produced in ST due to activity processes [ktSOx] :

$$vEmiSOxSTPro_{ST,ES,y} = pEmiSOxSTPro_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTOut_{ST,ES,Vin,y,s,d,h} \tag{100}$$

SOx emissions produced in ST [ktSOx] :

$$vEmiSOxST_{ST,ES,y} = \sum_{TE} vEmiSOxSTTE_{TE,ST,ES,y} + vEmiSOxSTPro_{ST,ES,y} \tag{101}$$

SOx emissions related to ESNS [ktSOx] :

$$vEmiSOxESNS_{y} = pEmiSOxESNS_{ST,TE} \cdot \sum_{ST,ES,s,d,h} vQESNS_{ST,ES,y,s,d,h} \tag{102}$$

Annual Total SOx Emissions [MtSOx] :

$$vEmiSOxTot_{y} = \sum_{CE} vEmiSOxCE_{CE,y} + \sum_{TE} vEmiSOxTE_{TE,y} + \sum_{ST,ES} vEmiSOxST_{ST,ES,y} \tag{103}$$

PM2.5 emissions

PM25 emissions produced in Primary CE Processes [ktPM25] :

$$vEmiPM25CEPri_{PE,CE_{Pri},y} = pEmiPM25CEPri_{PE,CE_{Pri}} \cdot \sum_{s,d,h} vQCEPriIN_{PE,CE_{Pri},y,s,d,h} \tag{104}$$

PM25 emissions produced in Secondary CE Processes [ktPM25] :

$$vEmiPM25CESec_{TE,CE_{Sec},y} = pEmiPM25CESec_{TE,CE_{Sec}} \cdot \sum_{s,d,h} vQCEPriIN_{TE,CE_{Sec},y,s,d,h} \tag{105}$$

PM25 emissions produced in Storage CE Processes [ktPM25] :

$$vEmiPM25CESto_{TE,CE_{Sto},y} = pEmiPM25CESto_{TE,CE_{Sto}} \cdot \sum_{s,d,h} vQCEStoIN_{TE,CE_{Sto},y,s,d,h} \tag{106}$$

PM25 emissions produced in Storage CE [ktPM25] :

$$vEmiPM25CE_{TE,CE_{Sto},y} = \sum_{PE} vEmiPM25CEPri_{PE,CE,y} + \sum_{TE} vEmiPM25CESec_{TE,CE,y} + \sum_{TE} vEmiPM25CESto_{TE,CE,y} \tag{107}$$

PM25 emissions produced in the transportation of TE [ktPM25] :

$$vEmiPM25TE_{TE,y} = pEmiPM25TE_{TE} \cdot \sum_{ST,ES,Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} + \sum_{s,d,h} vQTELoss_{TE,y,s,d,h} \tag{108}$$

PM25 emissions produced in ST due to TE consumption [ktPM25] :

$$vEmiPM25STTE_{TE,ST,ES,y} = pEmiPM25STTE_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTInTE_{TE,ST,ES,Vin,y,s,d,h} \tag{109}$$

PM25 emissions produced in ST due to activity processes [ktPM25] :

$$vEmiPM25STPro_{ST,ES,y} = pEmiPM25STPro_{ST,TE} \cdot \sum_{Vin,s,d,h} vQSTOut_{ST,ES,Vin,y,s,d,h} \tag{110}$$

PM25 emissions produced in ST [ktPM25] :

$$vEmiPM25ST_{ST,ES,y} = \sum_{TE} vEmiPM25STTE_{TE,ST,ES,y} + vEmiPM25STPro_{ST,ES,y} \tag{111}$$

PM25 emissions related to ESNS [ktPM25] :

$$vEmiPM25ESNS_{y} = pEmiPM25ESNS_{ST,TE} \cdot \sum_{ST,ES,s,d,h} vQESNS_{ST,ES,y,s,d,h} \tag{112}$$

Annual Total PM25 Emissions [MtPM25] :

$$vEmiPM25Tot_{y} = \sum_{CE} vEmiPM25CE_{CE,y} + \sum_{TE} vEmiPM25TE_{TE,y} + \sum_{ST,ES} vEmiPM25ST_{ST,ES,y} \tag{113}$$

Emissions limits

CO2 Emission cap restriction [MtCO2] : $$pEmiCO2Cap_y \geq vEmiCO2Tot_y - vEmiCO2CapExc_y \quad (114)$$

NOx Emission cap restriction [MtNOx] : $$pEmiNOxCap_y \geq vEmiNOxTot_y - vEmiNOxCapExc_y \quad (115)$$

SOx Emission cap restriction [MtSOx] : $$pEmiSOxCap_y \geq vEmiSOxTot_y - vEmiSOxCapExc_y \quad (116)$$

PM 2.5 Emission cap restriction [MtPM2.5] : $$pEmiPM25Cap_y \geq vEmiPM25Tot_y - vEmiPM25CapExc_y \quad (117)$$

CO2 Emission budget restriction [MtCO2] : $$pEmiCO2Budget_y \geq pYrGap \cdot \sum_y (vEmiCO2Tot_y) - vEmiCO2CapExc_y \quad (118)$$

CO2 sectorial emissions limits

Transport emission cap restriction [MtCO2] : $$pEmiCO2CapTra_y \geq \sum_{ST_{Tra}, ES_{Tra}} (vEmiCO2ST_{ST_{Tra}, ES_{Tra}, y}) - vEmiCO2CapTraExc_y \quad (119)$$

Electricity generation emission cap restriction [MtCO2] : $$pEmiCO2CapEle_y \geq \sum_{CE_{Ele}} (vEmiCO2CE_{CE_{Ele}, y}) - vEmiCO2CapEleExc_y \quad (120)$$

Energy-related industrial emission cap restriction [MtCO2] : $$pEmiCO2CapIndTE_y \geq \sum_{TE, ST_{Ind}, ES_{Ind}} (vEmiCO2STTE_{TE, ST_{Ind}, ES_{Ind}, y}) - vEmiCO2CapIndTEExc_y \quad (121)$$

Process-related industrial emission cap restriction [MtCO2] : $$pEmiCO2CapIndPro_y \geq \sum_{ST_{Ind}, ES_{Ind}} (vEmiCO2STPro_{ST_{Ind}, ES_{Ind}, y}) - vEmiCO2CapIndProExc_y \quad (122)$$

Residential & Commercial emission cap restriction [MtCO2] : $$pEmiCO2CapOth_y \geq \sum_{ST_{Oth},} (vEmiCO2ST_{ST_{Oth},,y}) - vEmiCO2CapOthExc_y \quad (123)$$

Refinery production emission cap restriction [MtCO2] : $$pEmiCO2CapRef_y \geq \sum (vEmiCO2CE_{,y}) - vEmiCO2CapRefExc_y \quad (124)$$