EN-ROADS SIMULATOR REFERENCE GUIDE

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1. Background

1.1 Purpose and intended use

The En-ROADS simulator is a simple energy system model intended for interactive scenario exploration. It helps users to think about:

- Dynamics of capital stock turnover
- Growth, energy intensity and carbon intensity (elements of the Kaya identity) as drivers of emissions
- Implications of technological lock-in to particular technologies
- Effective combinations of supply-side vs. demand-side, or technology-driven vs. incentive-driven policies
- The scale of economic and emissions changes required to meet climate goals

In the interest of simplicity, the model includes only simple structures for economic feedbacks, primarily the effect of climate on GDP.

2. Model structure overview

2.1 Simulation method

En-ROADS simulations run from the year 1990 through the year 2100. Model values are updated every 0.125 years (Δt) and reported every 0.25 years. The very short Δt is necessary to avoid model error resulting from the stiffness in the system, i.e., both short and long term dynamics.

The model is an ordinary differential equation system, solved by Euler integration. No intertemporal or short-term equilibrium is assumed. Decisions about energy sources and intensities in the model are represented by simple heuristics with myopic expectations.

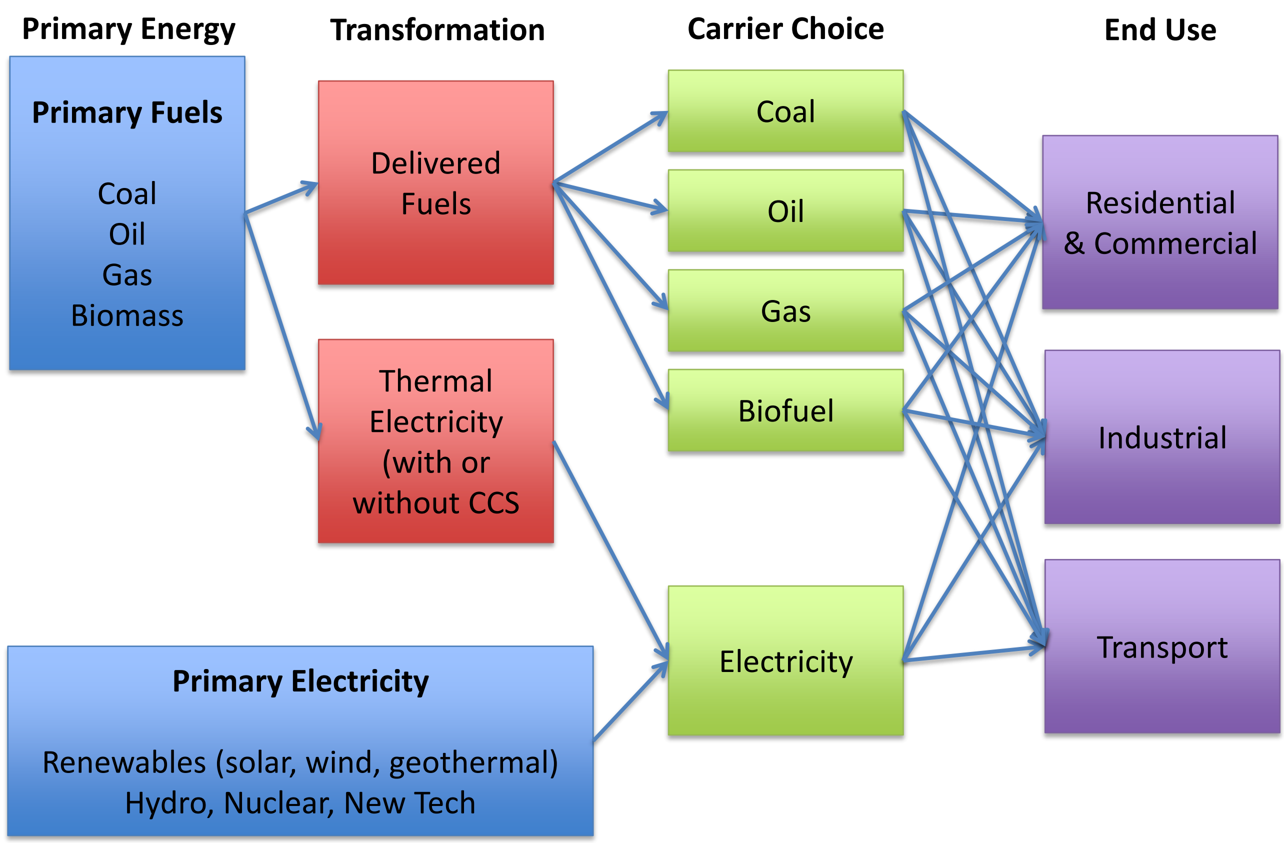
2.2 Scope & detail

The model represents key processes in the energy system for a single, global region. Distinctions among regions are obviously important in the real world, but would considerably complicate the simple accounting framework of the model, particularly by introducing trade issues, rendering it less useful for rapid scenario experimentation. Figure 2-1 summarizes the energy flows through the system.

Table 2-1. Scope

Endogenous		Excluded
Energy source choice	Nonrenewable resource depletion	Inventories
Energy carrier choice	Renewable resource saturation	Labor
Energy intensity	Energy Storage	
Energy variable and capital costs	CCS	
Price, capacity, and utilization of extracted fuels	GHG & climate dynamics	
Price, capacity, and utilization of delivered fuels	Population	
Price of electricity and capacity and utilization of each source	GDP	
Energy technology (learning by doing)		
Energy R&D		

Figure 2-1 Energy Flows



2.3 Organization

The En-ROADS simulator is a synthesis of several sub-models.

- Demand
- Choice between electric and four nonelectric energy carriers
- Supply of electricity sources
- Supply of delivered fuels
- Supply of extracted fuels
- Dispatch
- Supply marginal and embodied capital costs
- Supply marginal variable costs
- Supply and costs of storage for renewable energy
- Pricing and utilization
- Resources
- Emissions of CO_2 from energy
- Emissions of CO_2 from land use
- Emissions of other greenhouse gases (CH_4, N_2O, PFCs, SF_6, and HFCs);
- C-ROADS climate modules
  - Carbon cycle
  - Cycles of other GHGs;
  - Global Average Surface Temperature;
  - Sea level rise
  - Ocean pH

3. Formulation of Demand[1]

3.1 Population, GDP, and Capital

The **demand sector** defines the global energy demand for transport (transportation), residential and commercial, and industry end uses, all of which may be met by electric and non-electric carriers. The model determines the energy demand according to the stock of energy-consuming capital and its associated energy requirements.

Capital grows according to GDP as calculated by specified population scenarios and GDP per capita rates. The capital-output ratio is assumed to be fixed such that capital and GDP rates are equivalent. However, this assumption is no longer valid if the sensitivity parameters of feedback to capital-output ratio are changed from the default of 0. Damage functions relating to GDP impacts from

[1] In this section **sub-models** are written in bold, and model *variables* are written in italic.

temperature change are described in detail in Section 9.5. However, the structure and equations are also included in this section in Figure 3-4 and Table 3-1 and Table 3-2. Energy requirements are embodied in the capital stock at the time of investment, which introduces a lag between the energy intensity of new capital and the average energy intensity of the capital stock.

The energy intensity of new capital is governed by a response to the average market price of energy carriers and an exogenous user-specified technology trend.

The demand sector includes energy intensity of new and average energy consuming capital, which is disaggregated into three vintages, with energy requirements of each vintage, accounting for aging, early discarding and retiring, and retrofitting. The model structure is shown in Figure 3-12 through Figure 3-8. Capital and energy requirements of that capital are disaggregated by end use (residential & commercial, industry, and transport), as well as by carrier (four nonelectric and 1 electric). The nonelectric carriers are coal, oil, gas, and biomass. The model carefully tracks final and primary energy demand, where the former is the energy consumed by the end use capital, and the latter is the energy needed to be generated to meet that demand accounting for thermal efficiency that is less than 100% and other losses.

Figure 3-1 Structure of Population

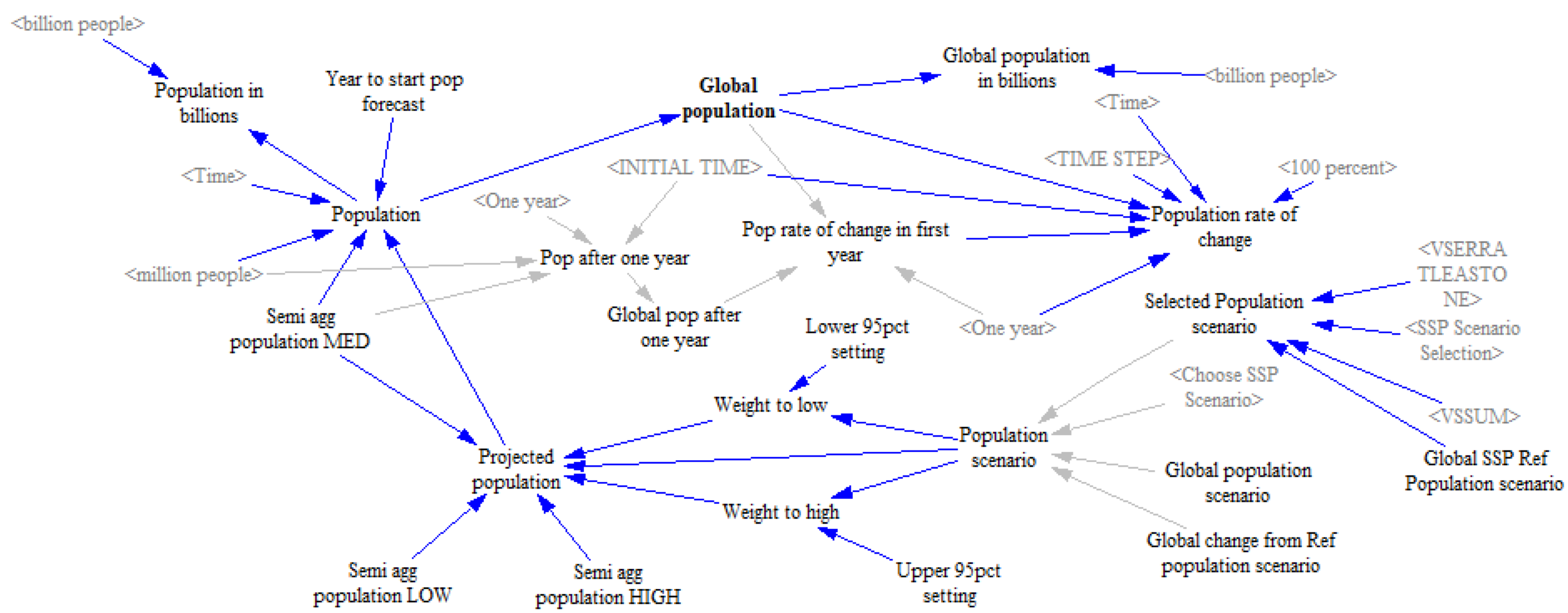


Figure 3-2 Structure of GDP per Capita and GDP

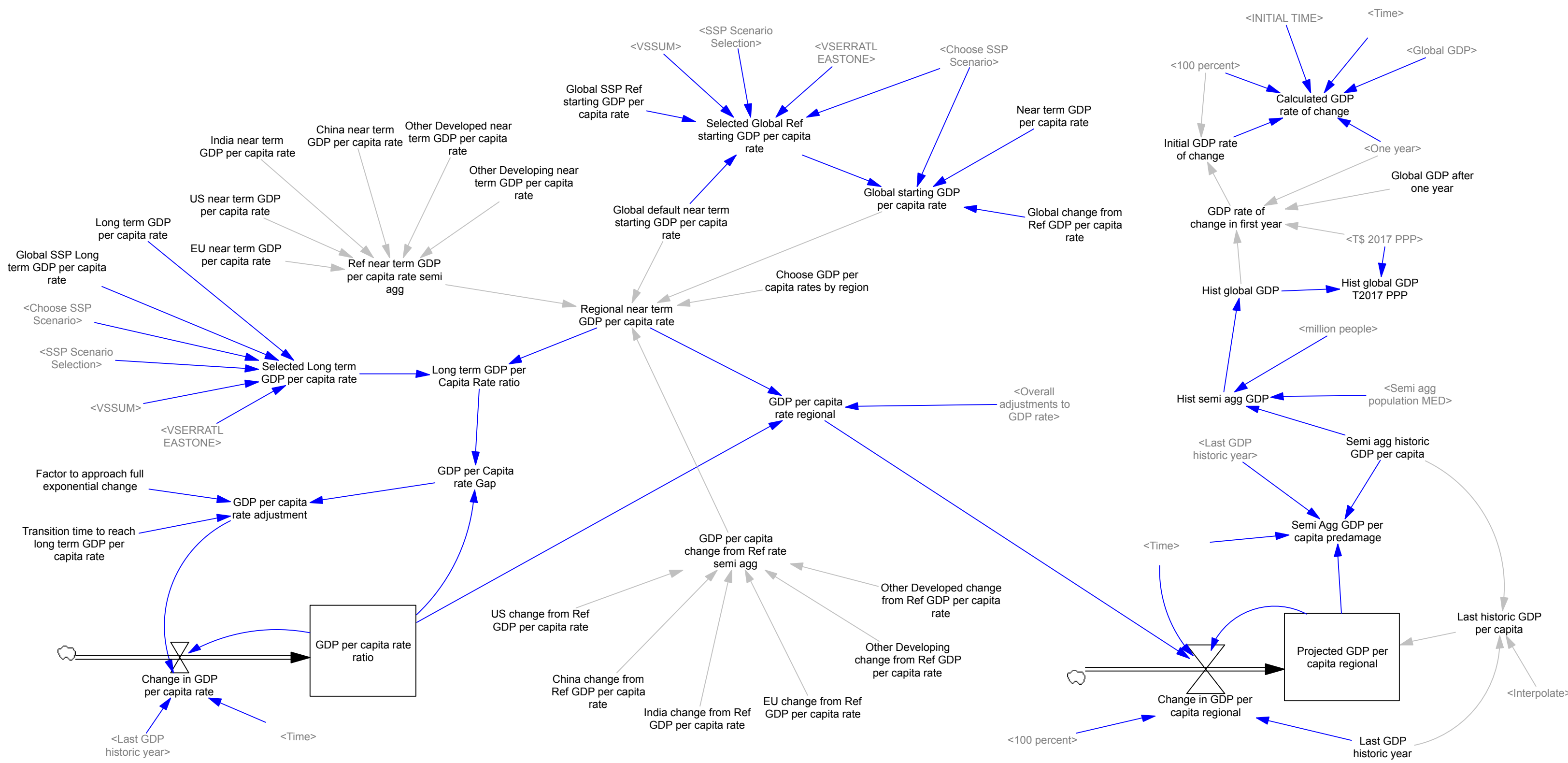


Figure 3-3 Structure of GDP per Capita Measures

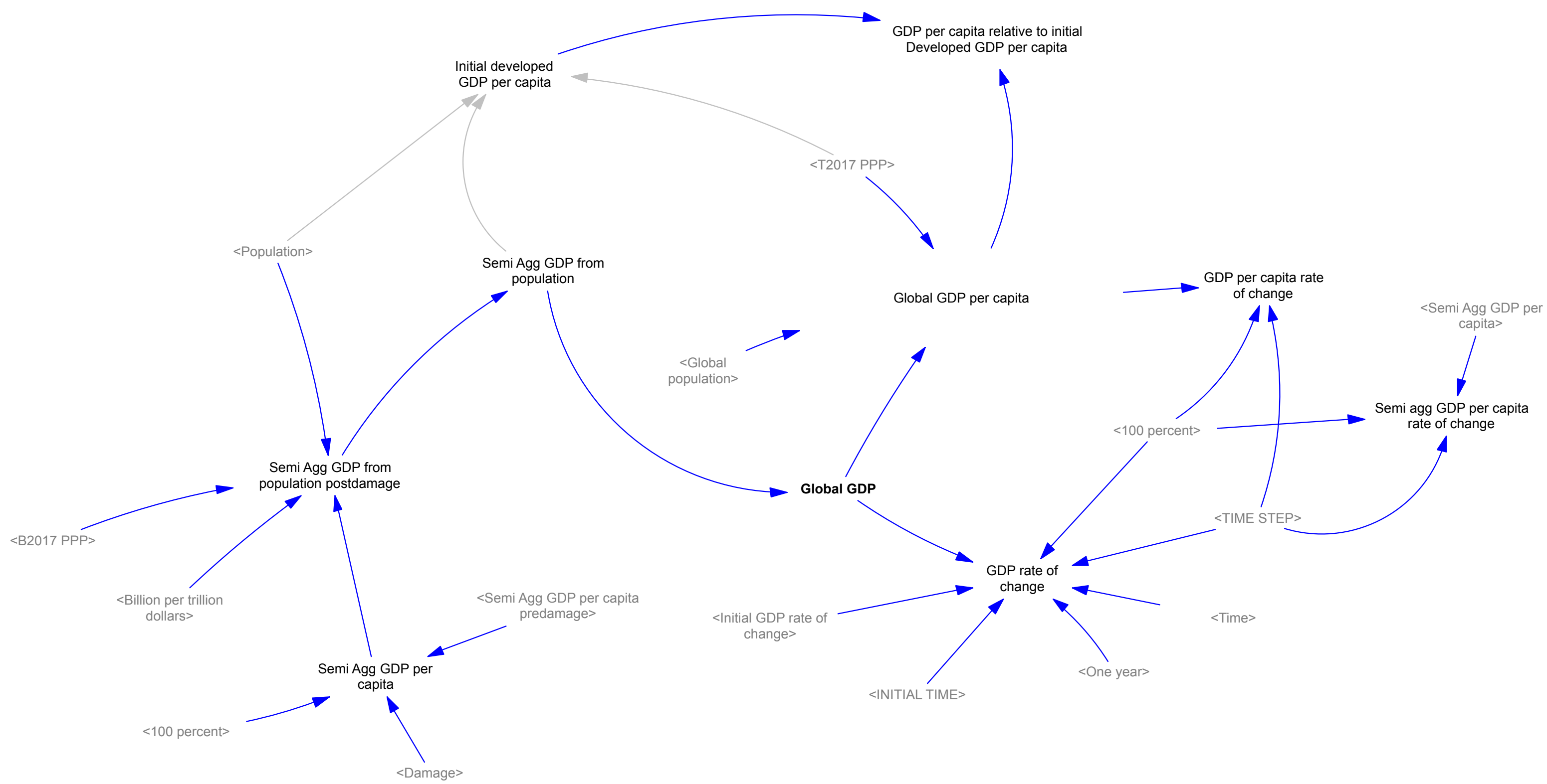


Figure 3-4 Structure of Damage Function

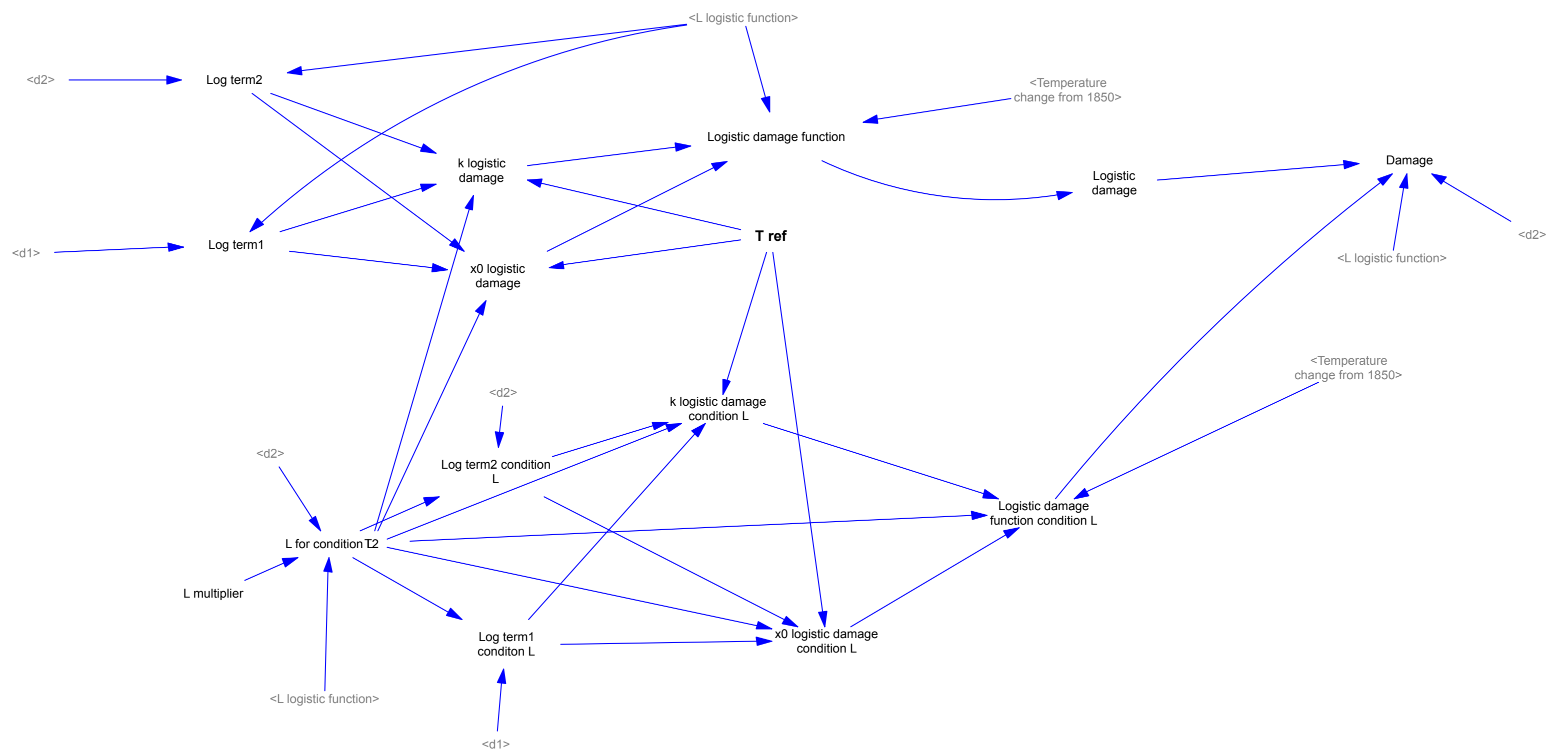


Figure 3-5 Structure of Energy Consuming Capital

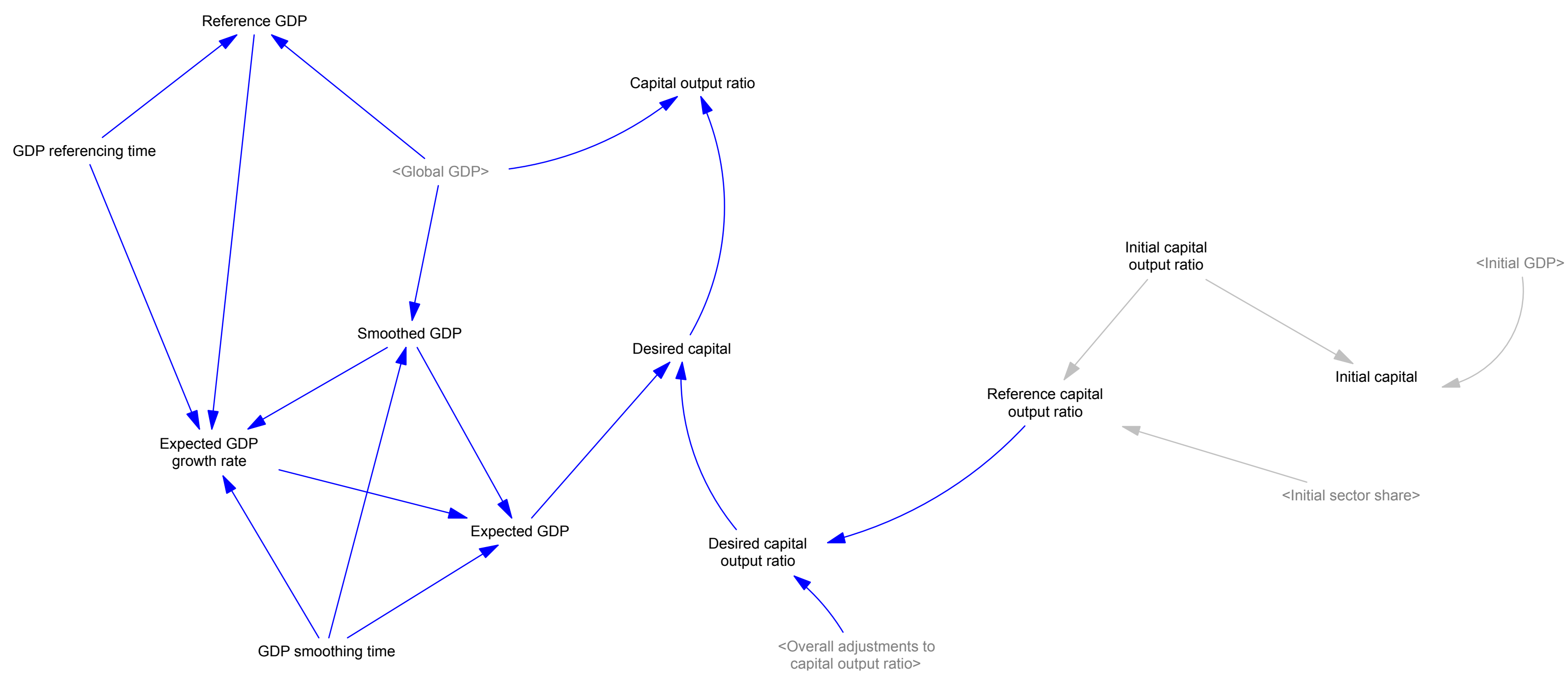


Table 3-1 Population and GDP Inputs

Parameter	Definition	Range	Default Values	Units
Year to start pop forecast	Year to start the population forecast rather than use history		2020	Year
Global population scenario	Determines future of global population based on UN projections, using UN projection (2019): -2=low UN scenario; 0=medium UN scenario; 2=high UN scenario. Bounds of -1 to +1 reflect approximate 95% probability.	-2-2	0	Dmnl
Choose GDP per capita rates by region	Select 1 to set GDP/capita rates by country/region.	0-1	0	Dmnl
Last GDP historic year	Last year of historical GDP data		2019	Year
Global default near term starting GDP per capita rate	GDP per capita rate from the year historical data is no longer available (2019).		2.5	Percent/year
Time to change GDP per capita rate	Year that the specified GDP per capita rate starts		2019	Year
Near term GDP per capita rate global	Starting in the year that the specified GDP per capita rate starts, the annual percent growth rate of GDP/capita if the rates are chosen globally. Consistent with recent trends from World Development Indicators (2020) and with SSP 2 and the EMF27 suite's median global GDP/capita rates.	1.7-3.7	2.5	Percent/year
Long term GDP per capita rate	Long term growth rate of GDP/capita if the rates are chosen globally. Consistent with the SSP 2 and EMF27 suite's median global GDP/capita rates.	0.5-2.5	1.5	Percent/year
Ref near term GDP per capita rate semi agg [Semi Agg]	GDP per capita rate for each region to be consistent with recent trends from World Development Indicators (2019)	0-10		Percent/year

Table 3-1 Population and GDP Inputs

Parameter	**Definition**	**Range**	**Default Values**	**Units**
US			1.4	
EU			1.7	
China			7	
India			6	
Other Developed			2.2	
Other Developing			1.9	
Transition time to reach long term GDP per capita rate	The time period over which the gap in GDP/Capita rate converges from the near term to long term values.	10-150	75	Year
Reduction in GDP at 2 C	d2	0-99	0	Percent
Maximum reduction in GDP due to temperature rise	L logistic function	0-100	0	Percent
Damage at Tref	d1. The damage at the current warming state, e.g. 1.1 degrees C		0.5	Percent
T ref	Temperature change from preindustrial times in 2020		1.1	DegreesC
L multiplier			1.1	Dmnl

Table 3-2. Population and GDP Calculated Parameters

Parameter	**Definition**	**Units**
Population scenario	Determines the selected UN population scenario. IF THEN ELSE (Choose SSP Scenario > 0, Selected Population scenario + Global change from Ref population scenario , Global population scenario + Global change from Ref population scenario)	Dmnl
Projected population[Semi Agg]	Projection population for each region according to United Nations (2019). Historic population data are from the same source. IF THEN ELSE (Population scenario < 0, Weight to low * Semi agg population LOW[Semi Agg] + (1- Weight to low) * Semi agg population MED[Semi Agg] , Weight to high * Semi agg population HIGH[Semi Agg] + (1 - Weight to high) * Semi agg population MED[Semi Agg])	Million people
Population[Semi Agg]	Bridges historical and projected population of each region. IF THEN ELSE (Time <= Year to start pop forecast , Semi agg population MED[Semi Agg] , Projected population[Semi Agg]) * million people	People
Global population	SUM(Population[Semi Agg!])	People
Pop after one year[Semi Agg]	INITIAL(GET DATA BETWEEN TIMES (Semi agg UN Population[Semi Agg], INITIAL TIME + One year, 1))	People
Global pop after one year	SUM(Pop after one year[Semi Agg!])	People
Population rate of change	IF THEN ELSE(Time<=INITIAL TIME+One year, Pop rate of change initial to first GDP projection year, LN(Global population/SMOOTH(Global population,one year))/one year)*"100 percent"	Percent/year
Pop rate of change initial to first GDP projection year	INITIAL(LN(Global pop after one year/Global population)/One year)	1/Year

Table 3-2. Population and GDP Calculated Parameters

Parameter	Definition	Units
Damage	Damage, i.e., reduction in GDP per capita rates, is a function of the chosen logistic function. IF THEN ELSE (d2 = 0 :OR: L logistic function = 0, 0, IF THEN ELSE (d2 < L logistic function , Logistic damage , MIN (Logistic damage function condition L , L logistic function)))	Percent
Logistic damage	MAX (0, Logistic damage function)	Percent
L logistic function	Maximum reduction in GDP due to temperature rise	Percent
Logistic damage function condition L	L for condition L / (1+ EXP (- k logistic damage condition L * (Temperature change from 1850 - x0 logistic damage condition L)))	Percent
Log term1	XIDZ (L logistic function - d1, d1, 1)	dmnl
Log term2	XIDZ (L logistic function - d2, d2 , 1)	Dmnl
k logistic damage	IF THEN ELSE (Log term2 = Log term1 :OR: Log term2 <= 0 :OR: Log term1 <= 0, 0, (LN (Log term1) - LN (Log term2)) / (T2 - T ref))	1/DegreesC
x0 logistic damage	IF THEN ELSE (Log term2 = Log term1 :OR: Log term2 <= 0 :OR: Log term1 <= 0, 0, T ref * ((T2 / T ref) * LN (Log term1) - LN (Log term2)) / (LN (Log term1) - LN (Log term2)))	DegreesC
Logistic damage function	L logistic function / (1 + EXP (- k logistic damage * (Temperature change from 1850 - x0 logistic damage)))	Percent
L for condition L	MAX (L multiplier * d2 , L logistic function)	Percent
Log term1 conditon L	XIDZ (L for condition L - d1 , d1 , 1)	Dmnl
Log term2 condition L	XIDZ (L for condition L - d2 , d2 , 1)	Dmnl

Table 3-2. Population and GDP Calculated Parameters

Parameter	Definition	Units
k logistic damage condition L	IF THEN ELSE (Log term2 condition L = Log term1 conditon L :OR: Log term2 condition L <= 0 :OR: Log term1 conditon L <= 0, 0, (LN (Log term1 conditon L) - LN (Log term2 condition L)) / (T2 - T ref))	1/DegreesC
x0 logistic damage condition L	IF THEN ELSE (Log term2 condition L = Log term1 conditon L :OR: Log term1 conditon L <= 0 :OR: Log term2 condition L <= 0, 0, T ref * ((T2 / T ref) * LN (Log term1 conditon L) - LN (Log term2 condition L)) / (LN (Log term1 conditon L) - LN (Log term2 condition L)))	DegreesC
Logistic damage function condition L	L for condition L / (1+ EXP (- k logistic damage condition L * (Temperature change from 1850 - x0 logistic damage condition L)))	percent
Global GDP	Accounts for loss in GDP as determined by Damage function. SUM (Semi Agg GDP from population[Semi Agg!])	T$ 2017 PPP/Year
Regional near term GDP per capita rate Semi Agg]	I IF THEN ELSE (Choose GDP per capita rates by region , Ref near term GDP per capita rate semi agg[Semi Agg] + GDP per capita change from Ref rate semi agg[Semi Agg] , Ref near term GDP per capita rate semi agg[Semi Agg] * ZIDZ (Global starting GDP per capita rate , Global default near term starting GDP per capita rate))	percent/Year
Long term GDP per Capita Rate ratio	Long term GDP per capita rate/Initial regional GDP per capita rate[Semi Agg]	Dmnl
GDP per Capita rate gap[Semi Agg]	The gap between the GDP/capita rate target and actual for each region, as a fraction of the actual. ZIDZ(Long term GDP per Capita Rate ratio[Semi Agg]-GDP per capita rate ratio[Semi Agg],GDP per capita rate ratio[Semi Agg])	Dmnl

Table 3-2. Population and GDP Calculated Parameters

Parameter	Definition	Units
GDP per capita rate adjustment[Semi Agg]	The fractional rate needed to close the gap between actual and target GDP/capita rate. The "Factor to approach full exponential change" equals 3. GDP per Capita rate Gap[Semi Agg]/(Time to reach long term GDP per capita rate[Semi Agg]/ Factor to approach full exponential change)	1/year
GDP per capita rate regional[Semi Agg]	Either the unconstrained or constrained rate, adjusted by feedbacks. Initial regional GDP per capita rate[Semi Agg]*GDP per capita rate ratio[Semi Agg]*Overall adjustments to GDP rate	Percent/year
Projected GDP per capita regional[Semi Agg]	INTEG(Change in GDP per capita [Semi Agg], First projected GDP per capita[Semi Agg])	$ 2017 PPP/Year/person
First projected GDP per capita[Semi Agg]	INITIAL(GET DATA BETWEEN TIMES(Semi agg hist and proj GDP per capita[Semi Agg], Last GDP historic year,Interpolate)*M2017 PPP)	$ 2017 PPP/Year/person
Change in GDP per capita[Semi Agg]	Changes at the projected annual rate starting at the first year of projections. IF THEN ELSE(Time<Last GDP historic year,0,GDP per capita rate regional[Semi Agg]/"100 percent"*Projected GDP per capita regional[Semi Agg])	$ 2017 PPP/Year/person/year
Semi Agg GDP per capita predamage[Semi Agg]	Bridges historical data with projections. IF THEN ELSE (Time <= Last GDP historic year, Semi agg historic GDP per capita[Semi Agg] , Projected GDP per capita regional[Semi Agg])	$ 2017 PPP/Year/person
Semi Agg GDP per capita [Semi Agg]	Semi Agg GDP per capita predamage[Semi Agg] * (1 - Damage / "100 percent")	T$ 2017 PPP /Year

Table 3-2. Population and GDP Calculated Parameters

Parameter	Definition	Units
Semi Agg GDP from population postdamage [Semi Agg]	Accounts for loss in GDP as determined by Damage function. Population[Semi Agg] * Semi Agg GDP per capita[Semi Agg] / B2017 PPP / Billion per trillion dollars	T$ 2017 PPP /Year
S Semi Agg GDP from population[Semi Agg]	Semi Agg GDP from population postdamage [Semi Agg]	T$ 2017 PPP /Year
Global GDP	Accounts for loss in GDP as determined by Damage function. SUM(Semi Agg GDP from population[Semi Agg!])	T$ 2017 PPP /Year
GDP rate of change in first year	INITIAL(LN(Global GDP after one year/(Hist global GDP/M2017 PPP))/One year)	1/year
Initial GDP rate of change	INITIAL(GDP rate of change in first year*"100 percent")	percent/Year
Calculated GDP rate of change	IF THEN ELSE(Time<=Last GDP historic year, Historical GDP rate of change, LN(Global GDP calculated/SMOOTH(Global GDP calculated, one year))/one year)*"100 percent"	percent/year
Global GDP per capita	Global GDP/Global population*T2017 PPP	$ 2017 PPP/Year/person
GDP per capita rate of change	The annual rate of change of GDP per capita. LN (Global GDP per capita / SMOOTH (Global GDP per capita , TIME STEP)) / TIME STEP * "100 percent"	Percent/year
GDP rate of change	The annual rate of change of GDP. IF THEN ELSE(Time<=INITIAL TIME + One year, Initial GDP rate of change, LN(Global GDP/SMOOTH(Global GDP, time step))/time step*"100 percent")	Percent/year
Global GDP per capita	Global GDP/Global population*T2017 PPP	$ 2017 PPP/Year/person
Initial developed GDP per capita	Aggregates the GDP per capita for the Developed countries. SUM(Semi Agg GDP from population[Developed semi agg!])/SUM(Population[Developed semi agg!])*T2017 PPP	$ 2017 PPP/Year/person

Table 3-2. Population and GDP Calculated Parameters

Parameter	Definition	Units
GDP per capita relative to initial Developed GDP per capita [EndUseSector]	The global GDP per capita relative to the initial GDP per capita of Developed countries. Global GDP per capita / Initial developed GDP per capita	Dmnl
Desired capital output ratio[EndUseSector]	Adjusts the desired capital output ratio by the overall effects of feedbacks from GDP per capita, energy cost, energy improvement, and temperature change. Reference capital output ratio[EndUseSector] * Overall adjustments to capital output ratio[EndUseSector]	$/($/Year)
Desired capital[EndUseSector]	Adjusts the desired capital by the overall effects of feedbacks from GDP per capita, energy cost, energy improvement, and temperature change. Expected GDP * Desired capital output ratio[EndUseSector]	T$ 2017 PPP
Expected GDP	Smoothed GDP * (1 + Expected GDP growth rate * GDP smoothing time)	T$ 2017 PPP/Year
Expected GDP growth rate	(Smoothed GDP - Reference GDP) / (Reference GDP * (GDP referencing time - GDP smoothing time))	1/year
Smoothed GDP	SMOOTH (Global GDP , GDP smoothing time)	T$ 2017 PPP/Year

3.2 Fuel and Carrier Choice

Energy is delivered to end use capital via five potential carriers; there are four nonelectric carriers and one electric carrier. Each of the nonelectric carriers matches 1:1 with each of the fuels, i.e., coal, oil, gas, and bio. The choice between each carrier is made in the **Carrier choice sector,** shown in Figure 3-6 and Figure 3-7

Shares of each carrier are allocated on the basis of the relative attractiveness of options according to a logit-type choice function, e.g.,

Share[Carrier] = Attractiveness[Carrier]/ΣAttractiveness[Carriers]

Attractiveness is an exponential function of cost, complementary assets (for transport only), and other factors including phase-out policies, technical feasibility, and other effects. Cost attractiveness is determined according to the total cost of ownership (TCO) in terms of dollars per energy service required ($/GJserv), i.e., the sum of levelized market price of energy services (market price of energy adjusted for end-use efficiency) and the capital and operating and maintenance cost of the capital. Costs associated with the market price of energy are driven by the energy dynamics (e.g., extracted fuel commodity cycle, market clearing algorithms). Costs associated with the end use capital may be reduced by learning from end use experience.

Complementary assets reflect the availability of infrastructure to support the carrier; the effect applies only to transport end uses, reflecting fueling points/charging stations for vehicles. Other non-cost policies, including electrification or fuel phase-out mandate, also affect attractiveness, as described in Section 4.4.2.

Figure 3-6 Structure of Carrier Choice

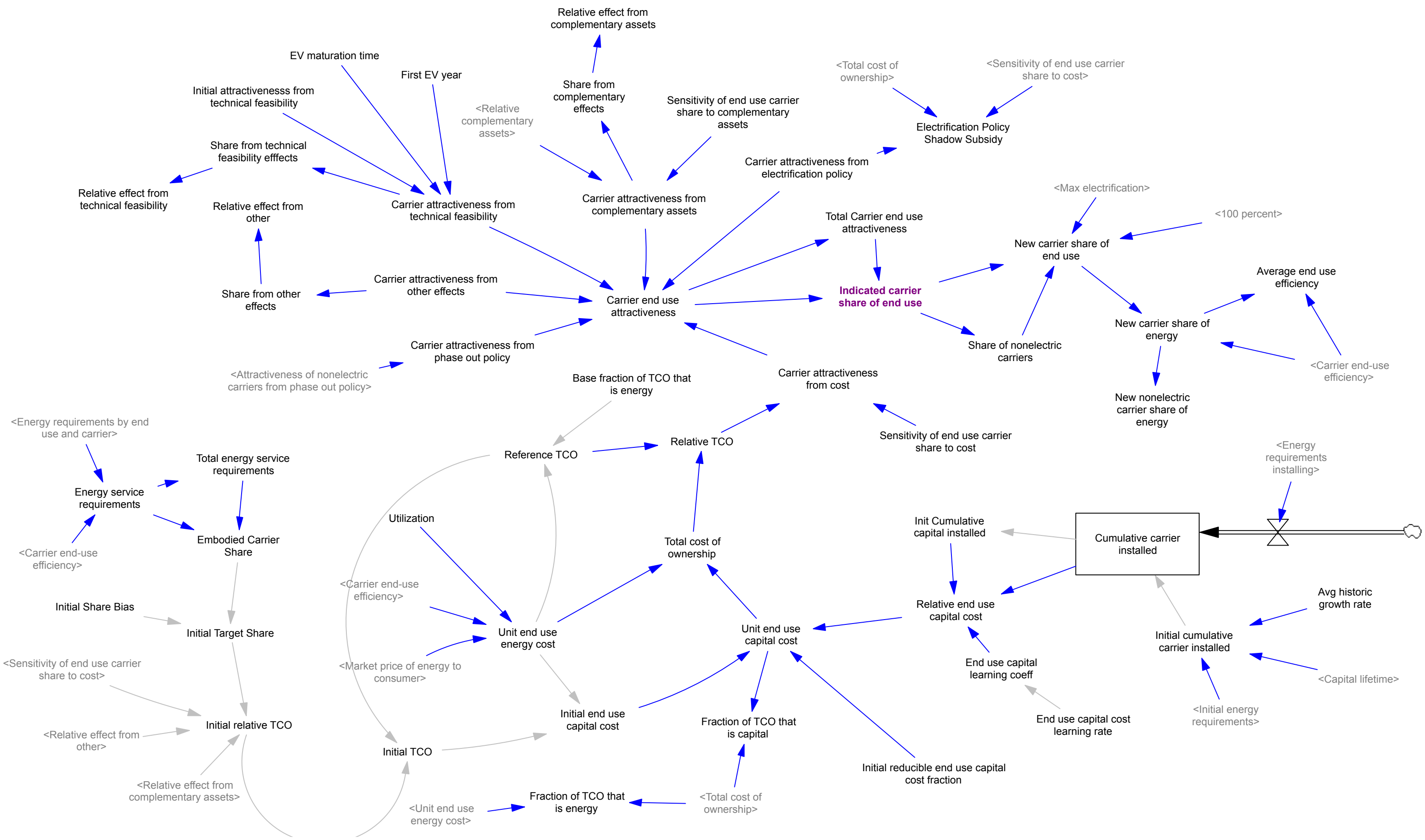


Figure 3-7 Structure of Complementary Assets and Mandated Electrification

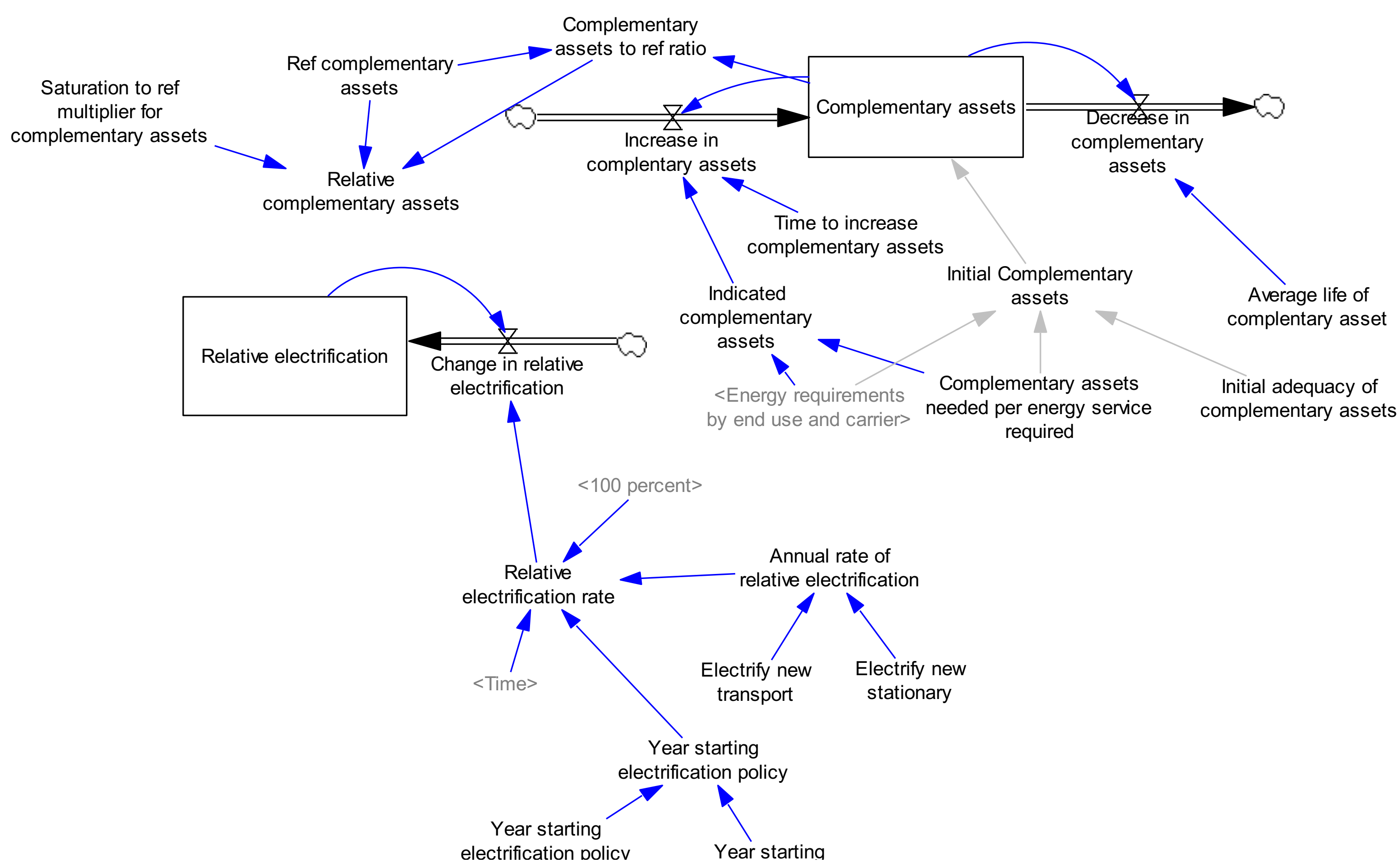


Table 3-3 Carrier Choice Sector Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Base fraction of TCO that is energy[EndUseSector]	The fraction of the reference TCO that is the energy cost. .			Dmnl
Residential & Commercial			0.8	
Industry			0.5	
Transport			0.2	
Utilization	Assumes same utilization of each carrier, e.g., electric cars driven as much as ICE cars.		1	GJ/Year/$
Initial Share Bias [EndUseSector,Carrier]	Ratio of initial share of new carrier capital to existing embodied share.	0-5	1	Dmnl
"Carrier end-use efficiency"[EndUseSector,Carrier]	Ratio of energy delivered to energy produced for each end use and carrier.	0-1		Dmnl
Efficiency of Elec Residential and Commercial			0.9	
Efficiency of Coal Carrier Residential and Commercial			0.6	
Efficiency of Oil Carrier Residential and Commercial			0.7	
Efficiency of Gas Carrier Residential and Commercial			0.9	
Efficiency of Bio Carrier Residential and Commercial			0.7	
Efficiency of Elec Industry			0.9	
Efficiency of Coal Carrier Industry			0.6	
Efficiency of Oil Carrier Industry			0.7	
Efficiency of Gas Carrier Industry			0.9	
Efficiency of Bio Carrier Industry			0.7	
Efficiency of Elec Transport			0.8	
Efficiency of Coal Carrier Transport			0.3	

Table 3-3 Carrier Choice Sector Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Efficiency of Oil Carrier Transport			0.4	
Efficiency of Gas Carrier Transport			0.4	
Efficiency of Bio Carrier Transport			0.4	
Sensitivity of end use carrier share to cost	The strength of the cost effect for preferring a given carrier based on total cost of ownership for each end use.	1-3	2	Dmnl
Sensitivity of end use carrier share to complementary assets	The strength of the network effect for preferring a given carrier as more capacity is provided by that carrier.	0.1-2	0.5	Dmnl
Initial attractivenesss from technical feasibility	Initial attractiveness of EVs such that the share from this effect approximates the initial embodied share.	0.1-1	0.1	Dmnl
First EV year	First year that electric vehicles entered the market	1990-2000	1998	Year
EV maturation time	Duration over which EVs reached the market share indicated by the embodied share.	1-20	10	Years
Electrify new stationary	Non cost policy forcing new energy to be electric for stationary end uses.	-5-5	0	Percent/year
Electrify new transport	Non cost policy forcing new energy to be electric for transport end uses.	-5-5	0	Percent/year
Year starting electrification policy stationary[EndUseSector]	Year starting electrification of new stationary demand capital by end use.	2021-2100	2021	Year

Table 3-3 Carrier Choice Sector Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Year starting electrification policy transport[EndUseSector]	Year starting electrification of new transport demand capital by end use.	2021-2100	2021	Years
Max electrification[EndUseSector]	Limits the extent to which electrification of the transport sector is possible.	0.8-1		Dmnl
Max electrification stationary			1	
Max electrification transport			0.8	
End use capital cost learning rate[Carrier]	Relative cost after a doubling in experience of electric end use demand	0-1		Dmnl
Electric carrier			0.8	
Nonelec carriers			0.9	
Initial reducible end use capital cost fraction[Endusesector, Carrier]	Fraction of the initial capital that is subject to reduction in cost due to the learning curve.		0.1	Dmnl
:EXCEPT: [Endusesector, Electric]			0.2	

Table 3-4. Carrier Choice Calculated Parameters

Parameter	Definition	Units
Indicated carrier share of capital [EndUseSector,Carrier]	The fraction of capital by each carrier for each end use. ZIDZ(Carrier end use attractiveness[EndUseSector,Carrier] Total Carrier end use attractiveness[EndUseSector])	Dmnl
New carrier share of end use [EndUseSector,Carrier]	The fraction of capital by each carrier for each end use, accounting for electrification policies.	Dmnl
[EndUseSector,Electric Carrier]	MIN(Indicated carrier share of end use[EndUseSector,Electric Carrier], Max electrification[EndUseSector]/"100 percent")	Dmnl
[EndUseSector,NonElec]	ZIDZ((1-New carrier share of end use[EndUseSector,Electric Carrier])*Share of nonelectric carriers[EndUseSector, NonElec Carriers], SUM(Share of nonelectric carriers [EndUseSector,NonElec Carriers!]))	Dmnl
Share of nonelectric carriers[EndUseSector,NonElec Carriers]	ZIDZ(Indicated carrier share of end use[EndUseSector,NonElec Carriers], SUM(Indicated carrier share of end use [EndUseSector, NonElec Carriers!]))	Dmnl
New carrier share of energy[EndUseSector,Carrier]	ZIDZ(New carrier share of end use[EndUseSector,Carrier]/ "Carrier end-use efficiency"[EndUseSector,Carrier], SUM(New carrier share of end use[EndUseSector,Carrier!]/ "Carrier end-use efficiency"[EndUseSector,Carrier!]))	Dmnl
Total Carrier end use attractiveness [EndUseSector]	For each end use, the sum of the attractiveness of all carriers. SUM(Carrier end use attractiveness[EndUseSector,Carrier!])	Dmnl

Table 3-4. Carrier Choice Calculated Parameters

Parameter	Definition	Units
Carrier end use attractiveness[EndUseSector,Carrier]	A measure of how preferable one carrier is over another for each end use, as a product of the attractiveness components. Carrier attractiveness from cost[EndUseSector,Carrier]*Carrier attractiveness from complementary assets[EndUseSector, Carrier]*Carrier attractiveness from phase out policy[Carrier]* Carrier attractiveness from electrification policy [EndUseSector, Carrier]*Carrier attractiveness from other effects[EndUseSector, Carrier]*Carrier attractiveness from technical feasibility [EndUseSector, Carrier]	Dmnl
Cost Attractiveness		
Energy service requirements[EndUseSector,Carrier]	Energy services provided by energy requirements for each end use by each carrier. Energy requirements by end use and carrier[EndUseSector,Carrier]*"Carrier end-use efficiency"[EndUseSector,Carrier]	EJ/Year
Total energy service requirements[EndUseSector]	Energy services provided by energy requirements for each end use by both carriers together. SUM(Energy service requirements[EndUseSector,Carrier!])	EJ/Year
Embodied Carrier Share [EndUseSector,Carrier]	For each end use, the fraction of existing end use energy service requirements allocated to each carrier. ZIDZ(Energy service requirements[EndUseSector,Carrier],Total energy service requirements[EndUseSector])	Dmnl

Table 3-4. Carrier Choice Calculated Parameters

Parameter	Definition	Units
Initial Target Share[EndUseSector,Carrier]	For each end use, the fraction of new end use energy service requirements initially allocated to each carrier, based on the embodied share from data and the initial share bias to capture initial growth or decline in shares. Embodied Carrier Share[EndUseSector,Carrier]*Initial Share Bias[EndUseSector,Carrier]/SUM(Embodied Carrier Share[EndUseSector,Carrier!]*Initial Share Bias [EndUseSector,Carrier!])	Dmnl
Unit end use energy cost [EndUseSector,Carrier]	The effective market price to consumers of each carrier considering the price and the end use efficiency for each carrier by end use. Market price of energy to consumer[Carrier] / "Carrier end-use efficiency"[EndUseSector,Carrier] * Utilization	$/Year/$
Carrier attractiveness from cost[EndUseSector,Carrier]	EXP(-Sensitivity of end use carrier share to cost*Relative TCO[EndUseSector, Carrier])	Dmnl
Relative TCO[EndUseSector,Carrier]	Total cost of ownership relative to the end use reference total cost of ownership. Total cost of ownership[EndUseSector,Carrier]/Reference TCO[EndUseSector]	Dmnl
Initial relative TCO[EndUseSector,Carrier]	The initial relative TCO based on the initial target share and the sensitivity of end use carrier share to cost, accounting for the relative effects of complementary assets and other effects. LN((Initial Target Share[EndUseSector,Carrier]/ 1/ELMCOUNT(Carrier))*Relative effect from complementary assets[EndUseSector,Carrier]*Relative effect from other[EndUseSector,Carrier])/(-Sensitivity of end use carrier share to cost)	Dmnl

Table 3-4. Carrier Choice Calculated Parameters

Parameter	Definition	Units
Initial TCO[EndUseSector,Carrier]	The initial total cost of ownership per energy service required as a function of the calculated initial relative TCO for each end use of each carrier and the reference TCO for each end use. Initial relative TCO[EndUseSector,Carrier]*Reference TCO[EndUseSector]	$/Year/$
Reference TCO[EndUseSector]	The reference total cost of ownership as determined by the initial unit end use cost of energy for the oil carrier and the fraction of its TCO that is the energy cost. Unit end use energy cost[EndUseSector,Oil Carrier] / Base fraction of TCO that is energy[EndUseSector]	$/Year/$
Initial end use capital cost[EndUseSector,Carrier]	The initial cost of end use capital per unit of energy service required as the difference of the initial TCO and the initial unit end use energy cost. Initial TCO[EndUseSector,Carrier] - Unit end use energy cost[EndUseSector,Carrier]	$/Year/$
End use capital cost[EndUseSector,Carrier]	The cost of end use capital based on its initial cost and the reduction of cost with learning on the fraction of the initial cost that is subject to learning. Initial end use capital cost[EndUseSector,Carrier]*(1-Initial reducible end use capital cost fraction[EndUseSector,Carrier]) +Initial end use capital cost[EndUseSector,Carrier]*Initial reducible end use capital cost fraction[EndUseSector,Carrier]* Relative end use capital cost[EndUseSector, Carrier]	$/Year/$

Table 3-4. Carrier Choice Calculated Parameters

Parameter	Definition	Units
Relative end use capital cost[EndUseSector, Carrier]	The reduction in cost of capital with the cumulative installations of that carrier for each end use. INITIAL ACTIVE ((Cumulative carrier installed[EndUseSector,Carrier]/Init Cumulative capital installed[EndUseSector, Carrier])^End use capital learning coeff[Carrier], 1)	dmnl
Cumulative carrier installed[EndUseSector, Carrier]	INTEG(Energy requirements installing[EndUseSector,Carrier], Initial cumulative carrier installed[EndUseSector,Carrier])	EJ/year
Initial cumulative carrier installed[EndUseSector,Carrier]	XIDZ(Initial energy requirements[EndUseSector,Carrier] *(1/Capital lifetime[EndUseSector]+Avg historic growth rate[EndUseSector,Carrier]),Avg historic growth rate[EndUseSector,Carrier], 1)	EJ/year
End use capital learning coeff[Carrier[	Learning coefficient of each carrier. LN(End use capital cost learning rate[Carrier])/LN(2)	Dmnl
Total cost of ownership[EndUseSector,Carrier]	Unit end use energy cost[EndUseSector,Carrier] + Unit end use capital cost[EndUseSector,Carrier]	$/Year/$
Complementarty Assets Attractiveness		
Carrier attractiveness from complementary assets[EndUseSector,Carrier]	For each end use, the preference of each carrier as more capacity is provided by that carrier. Only applies to transport.	Dmnl
[Stationary, Carrier]	1	
[Transport, Carrier]	EXP(Sensitivity of end use carrier share to complementary assets*Relative complementary assets[Carrier])-1	
Relative complementary assets[Carrier]	Saturation to ref multiplier for complementary assets*Ref complementary assets*Complementary assets to ref ratio[Carrier]/(Ref complementary assets*(Complementary assets to ref ratio[Carrier]+1))	Dmnl
Complementary assets to ref ratio[Carrier]	Complementary assets[Carrier]/Ref complementary assets	Dml

Table 3-4. Carrier Choice Calculated Parameters

Parameter	**Definition**	**Units**
Complementary assets[Carrier]	INTEG(Increase in complentary assets[Carrier]-Decrease in complementary assets[Carrier], Initial Complementary assets[Carrier])	$
Increase in complentary assets[Carrier]	(Indicated complementary assets[Carrier]-Complementary assets[Carrier])/Time to increase complementary assets	$/Year
Decrease in complementary assets[Carrier]	Complementary assets[Carrier]/Average life of complentary asset	
Initial Complementary assets[Carrier]	Energy requirements by end use and carrier[Transport, Carrier]*Complementary assets needed per energy service required*Initial adequacy of complementary assets	$
Indicated complementary assets[Carrier]	Energy requirements by end use and carrier[Transport,Carrier]* Complementary assets needed per energy service required	$
Technical Feasibility Attractiveness		
Carrier attractiveness from technical feasibility[EndUseSector, Carrier]	Captures the fact that electric vehicles did not enter the market until 1998. Only applies to the electric carrier for transport; equals 1 for all other end uses and carriers.	dmnl
[Transport, Electric Carrier]	Initial attractivenesss from technical feasibility + ramp((1-Initial attractivenesss from technical feasibility)/EV maturation time, First EV year, First EV year + EV maturation time)	
Phase Out Mandates Attractiveness		
Carrier attractiveness from phase out policy[Carrier]	Captures a phase out mandate of a fuel. Only applies to nonelectric carriers; equals 1 for the electric carrier.	Dmnl
[Nonelec Carriers]	Attractiveness of nonelectric carriers from phase out policy[Primary Fuels]	
Electrification Mandates Attractiveness		
Relative electrication rate[EndUseSector]	IF THEN ELSE(Time<Year starting electrification policy[EndUseSector], 0, Annual rate of relative electrification [EndUseSector])/"100 percent"	1/year
Change in relative electrification	Relative electrification[EndUseSector]*Relative electrication rate[EndUseSector]	1/year

Figure 3-8 Structure of Vintage Initialization

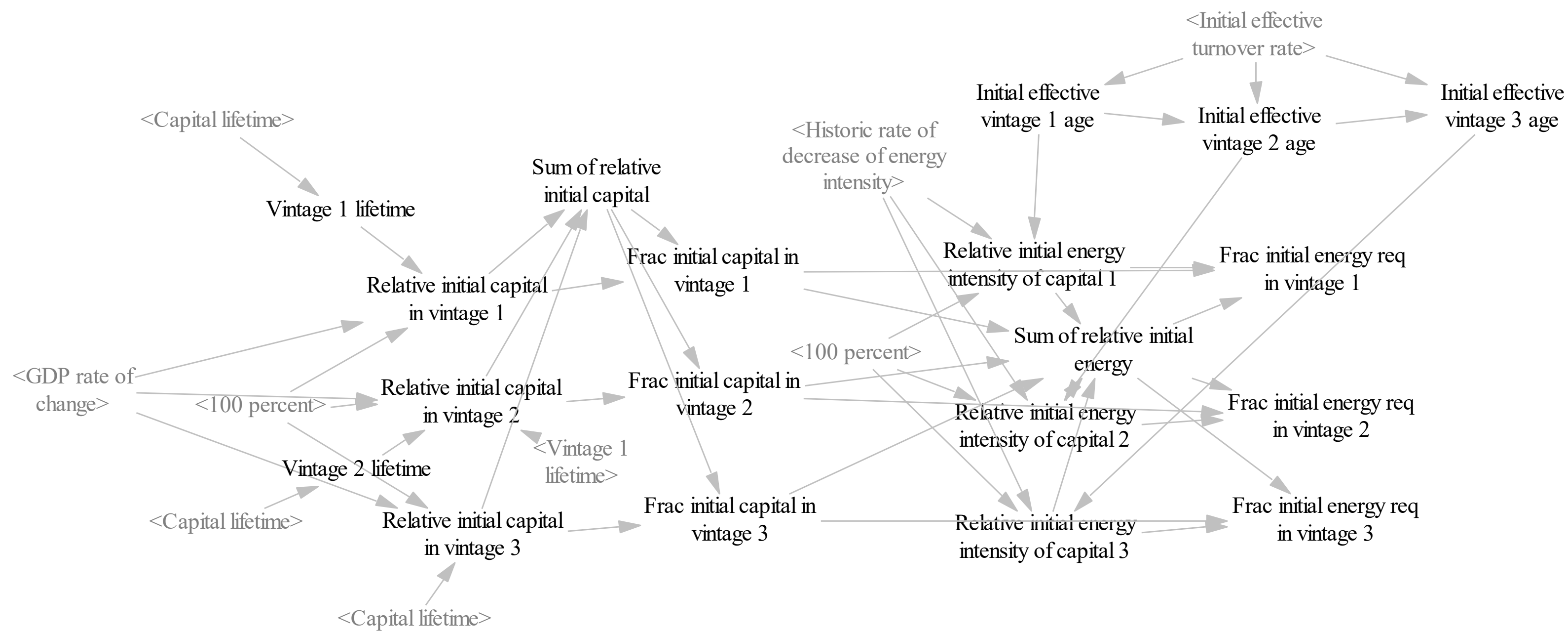


Figure 3-9 Structure of Electric Energy Consuming Capital

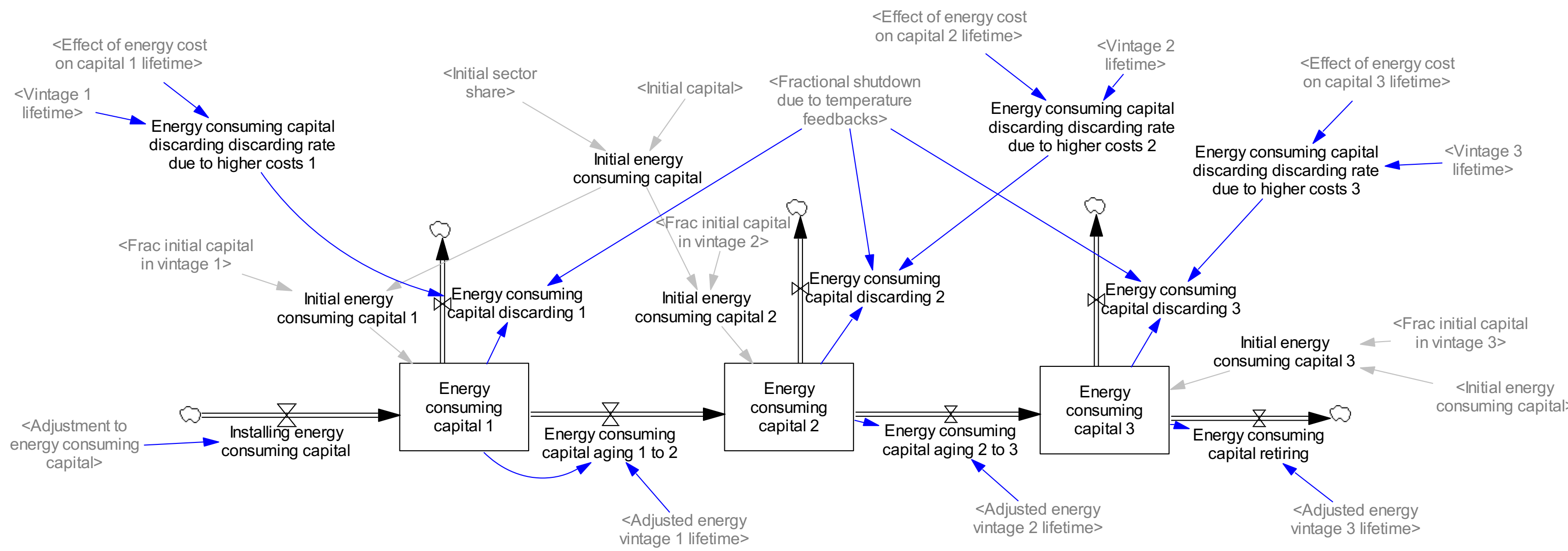


Table 3-5. Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Installing energy consuming capital [EndUseSector]	Capital for each end use that is added each year, accounting for desired capital, the existing capital, and the replacement of discarded and retired capital. MAX(0, Adjustment to energy consuming capital [EndUseSector])	T$ 2017 PPP/Year
Energy consuming capital 1 [EndUseSector]	The energy consuming capital in vintage 1 for each end use. INTEG(Installing energy consuming capital[EndUseSector]-Energy consuming capital aging 1 to 2[EndUseSector]-Energy consuming capital discarding 1[EndUseSector], Initial energy consuming capital 1[EndUseSector])	T$ 2017 PPP
Energy consuming capital 2 [EndUseSector]	The energy consuming capital in vintage 2 for each end use. INTEG(Energy consuming capital aging 1 to 2[EndUseSector]-Energy consuming capital aging 2 to 3[EndUseSector]-Energy consuming capital discarding 2[EndUseSector] Initial energy consuming capital 2[EndUseSector])	T$ 2017 PPP
Energy consuming capital 3 [EndUseSector]	The energy consuming capital in vintage 3 for each end use. INTEG(Energy consuming capital aging 2 to 3[EndUseSector]-Energy consuming capital discarding 3[EndUseSector]-Energy consuming capital retiring[EndUseSector], Initial energy consuming capital 3[EndUseSector])	T$ 2017 PPP
Initial energy consuming capital 1 [EndUseSector]	INITIAL(Initial energy consuming capital[EndUseSector]*Frac initial capital in vintage 1[EndUseSector])	T$ 2017 PPP
Initial energy consuming capital 2 [EndUseSector]	INITIAL(Initial energy consuming capital[EndUseSector]*Frac initial capital in vintage 2[EndUseSector])	T$ 2017 PPP
Initial energy consuming capital 3 [EndUseSector]	INITIAL(Initial energy consuming capital[EndUseSector]*Frac initial capital in vintage 3[EndUseSector])	T$ 2017 PPP

Table 3-5. Energy Consuming Capital Calculated Parameters

Parameter	**Definition**	**Units**
Initial energy consuming capital [EndUseSector]	INITIAL(Initial capital*Initial sector share[EndUseSector])	T$ 2017 PPP
Initial sector share[EndUseSector]	Initial share of capital for each end use, calculated from WEO 2020 data for 1990 and estimated *Carrier end-use efficiency* values. 0.520779, 0.318416, 0.160806	Dmnl
Energy consuming capital aging 1 to 2 [EndUseSector]	Energy consuming capital moving from vintage 1 into vintage 2. Energy consuming capital 1[EndUseSector]/ Adjusted energy vintage 1 lifetime[EndUseSector]	T$ 2017 PPP/Year
Elec aging 2 to 3[EndUseSector]	Energy consuming capital moving from vintage 2 into vintage 3. Energy consuming capital 2[EndUseSector]/ Adjusted energy vintage 2 lifetime[EndUseSector]	T$ 2017 PPP/Year
Energy consuming capital retiring [EndUseSector]	Energy consuming capital moving from vintage 3 to no longer being used. Energy consuming capital 3[EndUseSector]/Adjusted energy vintage 3 lifetime[EndUseSector]	T$ 2017 PPP/Year
Energy consuming capital discarding 1 [EndUseSector]	The amount of ecapital in vintage 1 lost due to factors other than aging. Energy consuming capital 1[EndUseSector]*(Energy consuming capital discarding discarding rate due to higher costs 1[EndUseSector]+Fractional shutdown due to temperature feedbacks[EndUseSector])	T$ 2017 PPP/Year

Table 3-5. Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Energy consuming capital discarding 2 [EndUseSector]	The amount of ecapital in vintage 2 lost due to factors other than aging. Energy consuming capital 2[EndUseSector]*(Energy consuming capital discarding discarding rate due to higher costs 2[EndUseSector]+Fractional shutdown due to temperature feedbacks[EndUseSector])	T$ 2017 PPP/Year
Energy consuming capital discarding 3 [EndUseSector]	The amount of ecapital in vintage 3 lost due to factors other than aging. Energy consuming capital 3[EndUseSector]*(Energy consuming capital discarding discarding rate due to higher costs 3[EndUseSector]+Fractional shutdown due to temperature feedbacks[EndUseSector])	T$ 2017 PPP/Year
Energy consuming capital discarding discarding rate due to higher costs 1 [EndUseSector]	MIN(1, MAX(0, 1/Vintage 1 lifetime[EndUseSector]*(1-Effect of energy cost on capital 1 lifetime[EndUseSector])))	1/year
Energy consuming capital discarding discarding rate due to higher costs 2[EndUseSector]	MIN(1, MAX(0, 1/Vintage 2 lifetime[EndUseSector]*(1-Effect of energy cost on capital 2 lifetime[EndUseSector])))	1/year
Energy consuming capital discarding discarding rate due to higher costs 3 [EndUseSector]	MIN(1, MAX(0, 1/Vintage 3 lifetime[EndUseSector]*(1-Effect of energy cost on capital 3 lifetime[EndUseSector])))	1/year
Total energy consuming capital for each end use [EndUseSector]	The sum of energy consuming capital of each vintage by end use. Energy consuming capital 1[EndUseSector]+Energy consuming capital 2[EndUseSector]+Energy consuming capital 3[EndUseSector]	T$ 2017 PPP

Table 3-5. Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Total energy consuming capital	The sum of electric energy consuming capital for all end uses. SUM(Total energy consuming capital for each end use[EndUseSector!])	T$ 2017 PPP

3.3 Feedbacks to Capital and GDP

Several feedbacks to the demand sector exist, and are reflected in the model structure according to user-specified sensitivities to these feedbacks. Specifically, the three factors affecting capital that we considered to be most relevant include the rate of improvement of energy intensity of new capital, energy costs, and temperature change. These three factors affect capital through three primary feedbacks, i.e., to the rate of change of GDP per capita, the capital output ratio, and the fractional shutdown of existing capital. The GDP per capita rate affects the GDP, which in turn affects the desired amount of capital. GDP per capita growth could be hindered by required improvements in energy intensity of new capital at a rate greater than the default BAU, by energy costs greater than initial costs, and/or by temperature change. The capital output ratio could increase as the global GDP per capita approaches that of the Developed countries. It is also vulnerable to these three factors, as each could cause less of the GDP to come from capital-intensive sectors. Existing capital may also be discarded early according to the sensitivity of temperature change. Accordingly, there would be eight sensitivities of interest, all of which are controlled by the user.

1. GDP per capita
a) Sensitivity of GDP per capita to annual energy improvement rate;
b) Sensitivity of GDP per capita to energy cost;
c) Sensitivity of GDP per capita to temperature change

2. Capital output ratio
a) Sensitivity of capital output ratio to GDP per capita;
b) Sensitivity of capital output ratio to annual energy improvement rate;
c) Sensitivity of capital output ratio to energy cost; and
d) Sensitivity of capital output ratio to temperature change.

3. Early discarding of existing capital
a) Sensitivity of capital discard rate to temperature change; and
b) Effect of energy cost on capital discard of each vintage.

The demand-side feedbacks affect new and existing capital, but the degree and direction of the feedback is not necessarily intuitive.

Figure 3-10 Structure of Feedbacks to GDP, Capital Growth and Capital Output Ratio

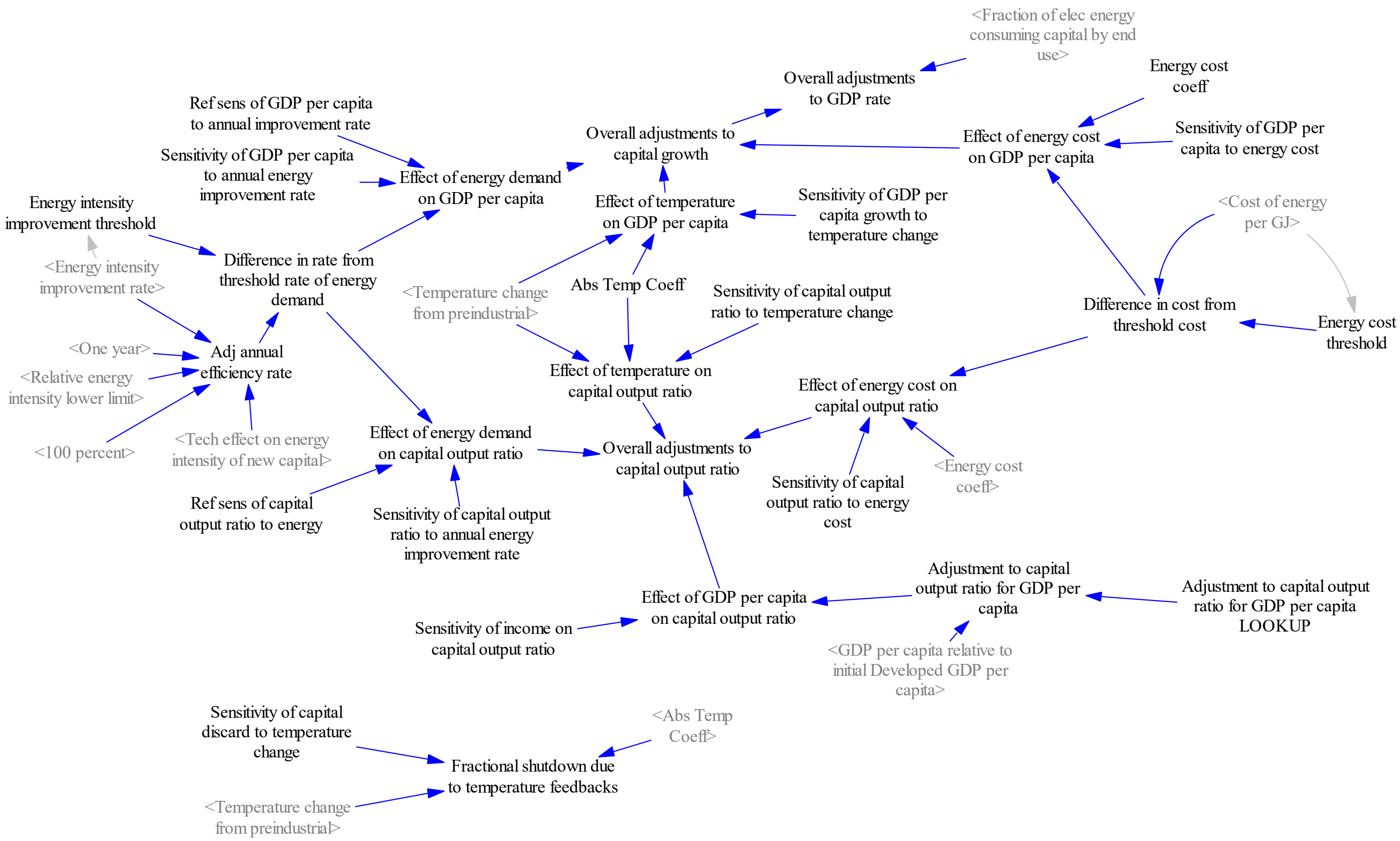


Figure 3-11 Structure of Feedback of Energy Cost on Early Discarding of Energy Consuming Capital

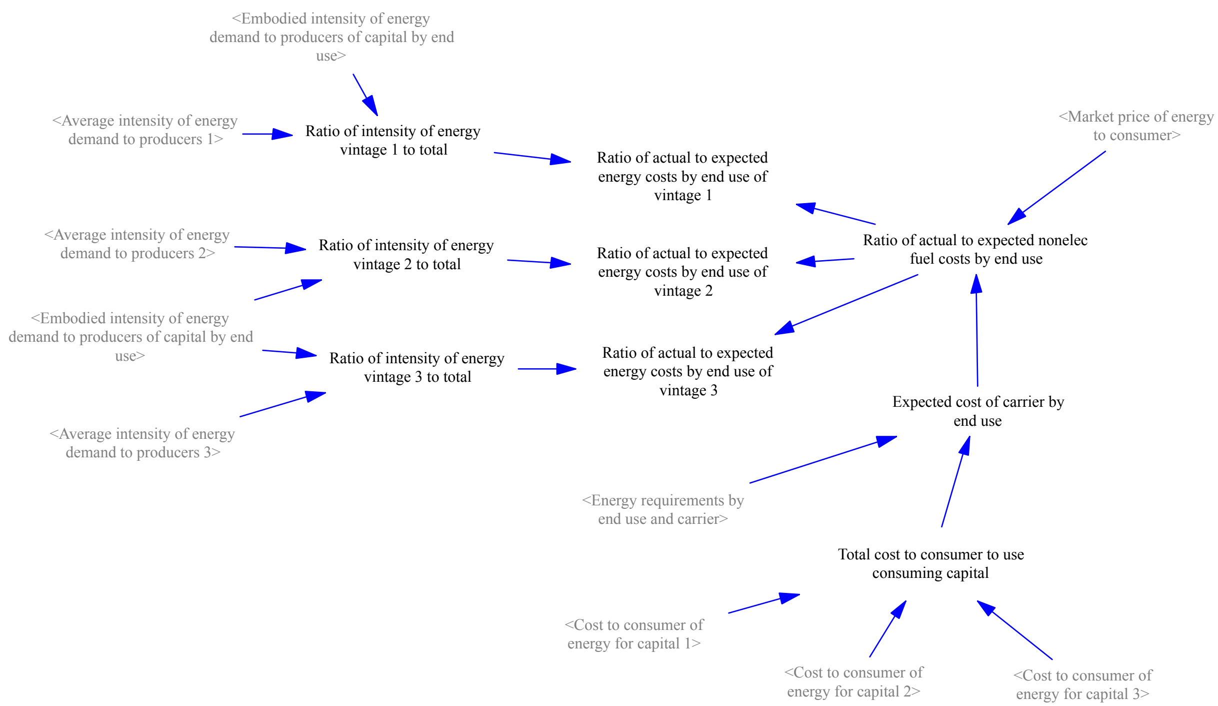


Table 3-6 Energy-Consuming Capital Feedback Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Sensitivity of GDP per capita to annual energy improvement rate	Sensitivity of GDP per capita h rate to the annual improvement rate of energy intensity of new capital above a threshold.	0-2.5	0	Dmnl
Ref sens of capital output ratio to annual energy improvement rate		0-10	0.1	T$ 2017 PPP/Year
Sensitivity of GDP per capita to energy cost	Sensitivity of GDP per capita rate to the total energy cost above a threshold.	0-2.5	0	T$ 2017 PPP
Abs Temp Coeff			0.1	1/DegreesC
Energy cost coeff			0.1	GJ/$
Sensitivity of capital output ratio to GDP per capita[EndUseSector]	Sensitivity of capital output rati o to GDP per capita for each end use.	0-2.5	0	Dmnl
Sensitivity of capital output ratio to annual energy improvement rate		0-2.5	0	T$ 2017 PPP
Sensitivity of capital output ratio to energy cost		0-2.5	0	T$ 2017 PPP
Sensitivity of capital output ratio to temperature change		0-2.5	0	T$ 2017 PPP
Sensitivity of capital discard to temperature change	Sensitivity of early discarding of capital per year to temperature change	0-2.5	0	1/year
Demand early retirement sensitivity	Adjusts the sensitivity of the demand chain to retire exisiting energy consuming capital early as the market price to use the energy required for it increases above the expected price as determined at the time of installation.	0-2	0.5	Dmnl

Table 3-7. Energy-Consuming Capital Feedback Calculated Parameters

Parameter	Definition	Units
Energy intensity improvement threshold[EndUseSector]	Threshold annual improvement rate of energy intensity of new capital above which capital growth is hindered and capital output ratio increases. INITIAL(Energy intensity improvement rate[EndUseSector])	1/year
Difference in rate from threshold rate of energy demand[EndUseSector]	Adj annual efficiency rate[EndUseSector]-Energy intensity improvement threshold[EndUseSector]	1/year
Adj annual efficiency rate[EndUseSector]	MIN(Energy intensity improvement rate[EndUseSector], MAX(0, Tech effect on energy intensity of new capital[EndUseSector]-Relative energy intensity lower limit/"100 percent")/One year)	1/year
Effect of energy demand on capital growth[EndUseSector]	1-MAX(0, Sensitivity of GDP per capita to annual energy improvement rate/Ref sens of capital to annual improvement rate*Difference in rate from threshold rate of energy demand[EndUseSector])	Dmnl
Effect of energy cost on capital growth	1-Difference in cost from threshold cost*Energy cost coeff*Sensitivity of capital growth to energy cost	Dmnl
Adjustment to capital output ratio for GDP per capita	Increases capital output ratio as the global GDP per capita approaches the initial GDP per capita of Developed countries. Adjustment to capital output ratio for GDP per capita LOOKUP(GDP per capita relative to initial Developed GDP per capita)	Dmnl
Adjustment to capital output ratio for GDP per capita LOOKUP	[(0,0)-(1,2)],(0,1),(0.2,1),(0.4,1.05),(0.5,1.1),(0.6,1.1),(0.7,1),(1,1)	Dmnl

Table 3-7. Energy-Consuming Capital Feedback Calculated Parameters

Parameter	Definition	Units
Effect of GDP per capita on capital output ratio[EndUseSector]	Applies the adjustment to capital output ratio according to the end use specific sensitivity to GDP per capita relative to the initial GDP per capita of Developed countries. Sensitivity of capital output ratio to GDP per capita[EndUseSector]*Adjustment to capital output ratio for GDP per capita[EndUseSector]+(1-Sensitivity of capital output ratio to GDP per capita[EndUseSector])	Dmnl
Effect of energy demand on capital output ratio[EndUseSector]	1+MAX(0, Sensitivity of capital output ratio to annual energy improvement rate/Ref sens of capital output ratio to energy*Difference in rate from threshold rate of energy demand[EndUseSector])	Dmnl
Effect of energy cost on capital output ratio	1+MAX(0,Difference in cost from threshold cost *Energy cost coeff *Sensitivity of capital output ratio to energy cost)	Dmnl
Effect of temperature on capital output ratio	1+Abs Temp Coeff*Temp change from preindust*Sensitivity of capital output ratio to temperature change	Dmnl
Overall adjustments to capital growth[EndUseSector]	Effect of energy demand on capital growth[EndUseSector]*Effect of energy cost on capital growth	Dmnl
Overall adjustments to capital output ratio[EndUseSector]	Overall effect on capital output ratio from GDP per capita, energy cost, energy improvement, and temperature change. Effect of energy demand on capital output ratio[EndUseSector]*Effect of temperature on capital output ratio*Effect of energy cost on capital output ratio*Effect of GDP per capita on capital output ratio[EndUseSector]	Dmnl
Fractional shutdown due to temperature feedbacks	Forces early shutdownof energy consuming capita due to feedbacks of temperature change. MAX(0, Abs Temp Coeff*(Temp change from preindust- INIT(Temp change from preindust))*Sensitivity of capital discard to temperature change)	1/year

3.4 Energy Intensity of New Capital

In the D**emand sector**, energy requirements are embodied separately for each fuel and for electricity. Energy intensity of each new unit of capital drives the embodied requirements. Technological improvements and price of energy affect the energy intensity of new capital. The technological effect defaults to the historically observed improvements, assuming those persist into the future. However, the user may change those rates of improvement. Price effects are determined according to the long-term demand elasticity and the relative costs to the reference levels. The indicated price effects are delayed over time.

Figure 3-12 Structure of Energy Demand

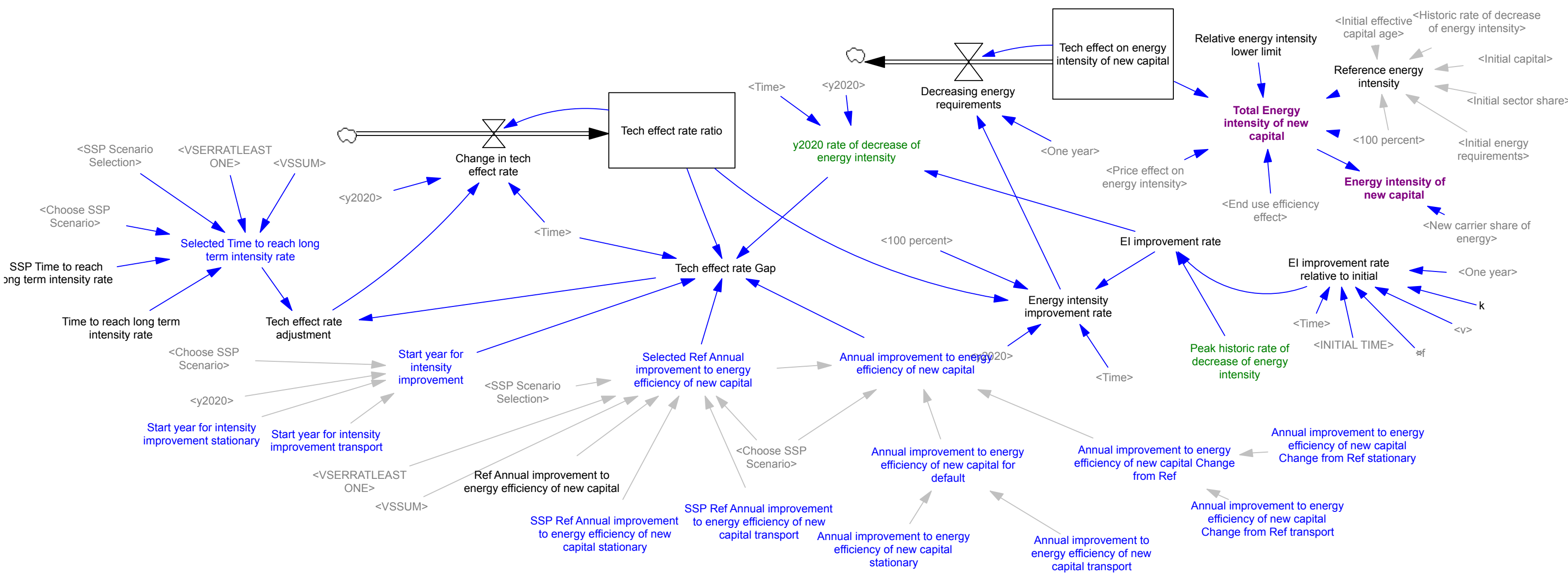


Figure 3-13 Structure of Price Effects on Energy Intensity

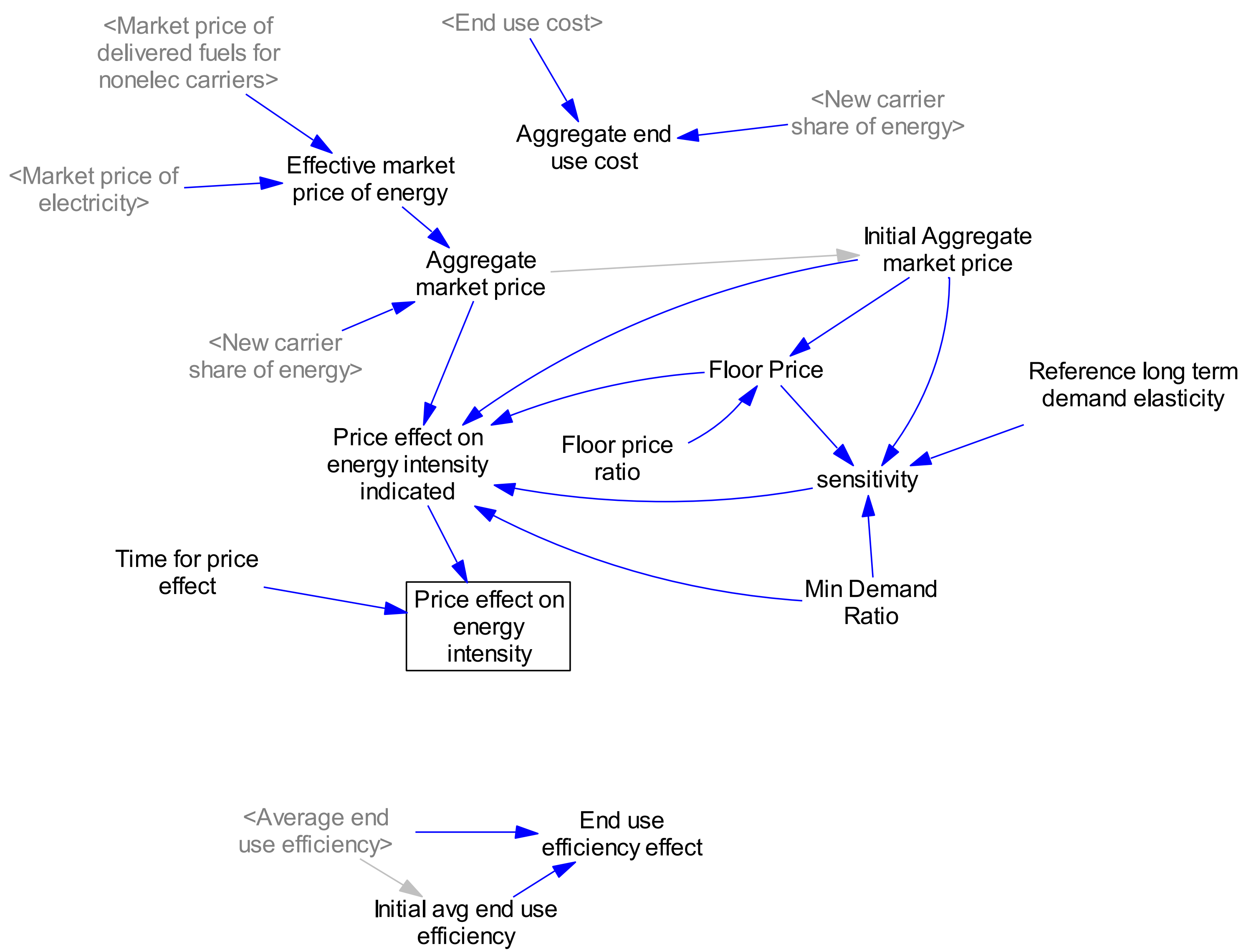


Table 3-8 Energy Intensity of Capital Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Annual improvement to energy efficiency of new capital [EndUseSector]	The projected decrease in energy intensity of new energy-demanding capital by end use, occurring from technological change and sectoral shifts. Increasing this value increases global energy efficiency. A 7% per year drop of new capital gives approximately 3% per year drop to average energy intensity from 2010-2050.	-1-7		Percent/year
[Stationary]	Applies to residential and commercial and to industry end uses.		1.2	
[Transport]			0.5	
Ref rate of decrease of energy intensity [EndUseSector]	The projected baseline decrease in energy intensity of new energy-demanding capital by end use, occurring from technological change and sectoral shifts. Increasing this value increases global energy efficiency. A 7% per year drop of new capital gives approximately 3% per year drop to average energy intensity from 2010-2050.			Percent/year
[Stationary]	Applies to residential and commercial and to industry end uses.		1.2	
[Transport]			0.5	
Historic rate of decrease of energy intensity [EndUseSector]	The historic decrease in energy intensity of new energy-demanding capital by end use over the period leading up to the initial simulation time, used to determine the reference energy intensity of new capital.		0.5, 1, -0.5	Percent/year
Peak historic rate of decrease of energy intensity [EndUseSector]	The peak historic decrease in energy intensity of new energy-demanding capital by end use over the period of 1990-2020.		3.2, 2.5, 2.4	Percent/year
Time to reach long term intensity rate	The time period over which the gap in tech effect should be closed.	5-100	10	Years

Table 3-8 Energy Intensity of Capital Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Relative energy intensity lower limit	Sets the floor for how low the intensity can fall as a fraction of the original intensity.	0-100	10	Percent
Start year for intensity improvement [EndUseSector]	Year to start improving the energy intensity of new capital by end use.	2021-2040	2021	Year
Reference long term demand elasticity	The sensitivity of long-term demand to changes in cost of the cost of electricity. Set to be absolute value so that greater values increase demand more with decreasing energy costs.	0.5-2	0.7	Dmnl
Floor price ratio			0.5	Dmnl
Min Demand Ratio			0	dmnl
Time for price effect		1-10	5	Year

Table 3-9. Energy Intensity of Capital Calculated Parameters

Parameter	Definition	Units
Tech effect on energy intensity of new capital[EndUseSector]	The multiplying factor to reduce energy intensity from its reference value as technology improves by end use. INTEG(-Decreasing energy requirements[EndUseSector], 1)	Dmnl
Energy intensity improvement rate [EndUseSector]	Rate of change in energy intensity of new capital by end use, accounting for historical and projected rates. EI improvement rate[EndUseSector] * IF THEN ELSE (Time < y2020, 1, Tech effect rate ratio[EndUseSector]) / "100 percent"	1/year
EI improvement rate relative to initial	Defines smooth curve from initial improvement rates to rate in 2020 1/ (1+ k * EXP (- f * (Time - INITIAL TIME) / One year) ^ (1/ v))	Dmnl
y2020 rate of decrease of energy intensity[EndUseSector]	SAMPLE IF TRUE(Time = y2020 , EI improvement rate[EndUseSector] , EI improvement rate[EndUseSector])	percent/Year
Tech effect rate ratio[EndUseSector]	Relative tech effect from Post 2010 Historic rate of decrease of energy intensity to long term projected rate. INTEG(Change in tech effect rate[EndUseSector], 1)	Dmnl
Tech effect rate Gap[EndUseSector]	ZIDZ(IF THEN ELSE(Time<Start year for intensity improvement[EndUseSector], BAU rate of decrease of energy intensity[EndUseSector], Annual improvement to energy efficiency of new capital[EndUseSector])/Post 2010 Historic rate of decrease of energy intensity[EndUseSector]-Tech effect rate ratio[EndUseSector],Tech effect rate ratio[EndUseSector])	dmnl
Change in tech effect rate[EndUseSector]	IF THEN ELSE(Time<=y2020, 0, Tech effect rate adjustment[EndUseSector]*Tech effect rate ratio[EndUseSector])	1/year

Table 3-9. Energy Intensity of Capital Calculated Parameters

Parameter	Definition	Units
Decreasing energy requirements[EndUseSector]	Change with time of the multiplying factor to reduce energy intensity from its reference value by end use. MIN(Tech effect on energy intensity of new capital[EndUseSector] *Energy intensity improvement rate[EndUseSector], MAX(0, (Tech effect on energy intensity of new capital[EndUseSector])/One year))	1/year
Total Energy intensity of new capital [EndUseSector]	The energy intensity, i.e., energy per unit of capital, by end use sector of new energy consuming capital as a function of the its reference intensity and the multiplying factors of the tech effect and the price effect. Reference energy intensity[EndUseSector] * End use efficiency effect[EndUseSector] * (Relative energy intensity lower limit/"100 percent"(1- Relative energy intensity lower limit / "100 percent") * Tech effect on energy intensity of new capital[EndUseSector]*Price effect on energy intensity[EndUseSector])	(EJ/Year)/T$ 2017 PPP
Energy intensity of new capital [EndUseSector,Carrier]	The energy intensity, i.e., energy per unit of capital, by end use sector and by carrier of new energy consuming capital. Total Energy intensity of new capital[EndUseSector]*New carrier share of energy[EndUseSector,Carrier]	(EJ/Year)/T$ 2017 PPP
Reference energy intensity[EndUseSector]	The initial electric energy intensity by end use. INITIAL(SUM(Initial energy requirements[EndUseSector,Carrier!]) /(Initial capital*Initial sector share[EndUseSector])*EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"* Initial effective capital age[EndUseSector]))	(EJ/Year)/T$ 2017 PPP

3.5 Long Term Energy Requirements

The long term energy requirements are a function of the energy intensity of new energy, capital growth rates, and discarding as determined in the previous sections. Retrofitting for each end use also occurs, with the retrofits at the capital share and intensity of new energy.

Figure 3-14 Structure of Long Term Energy Requirements of Capital - Original

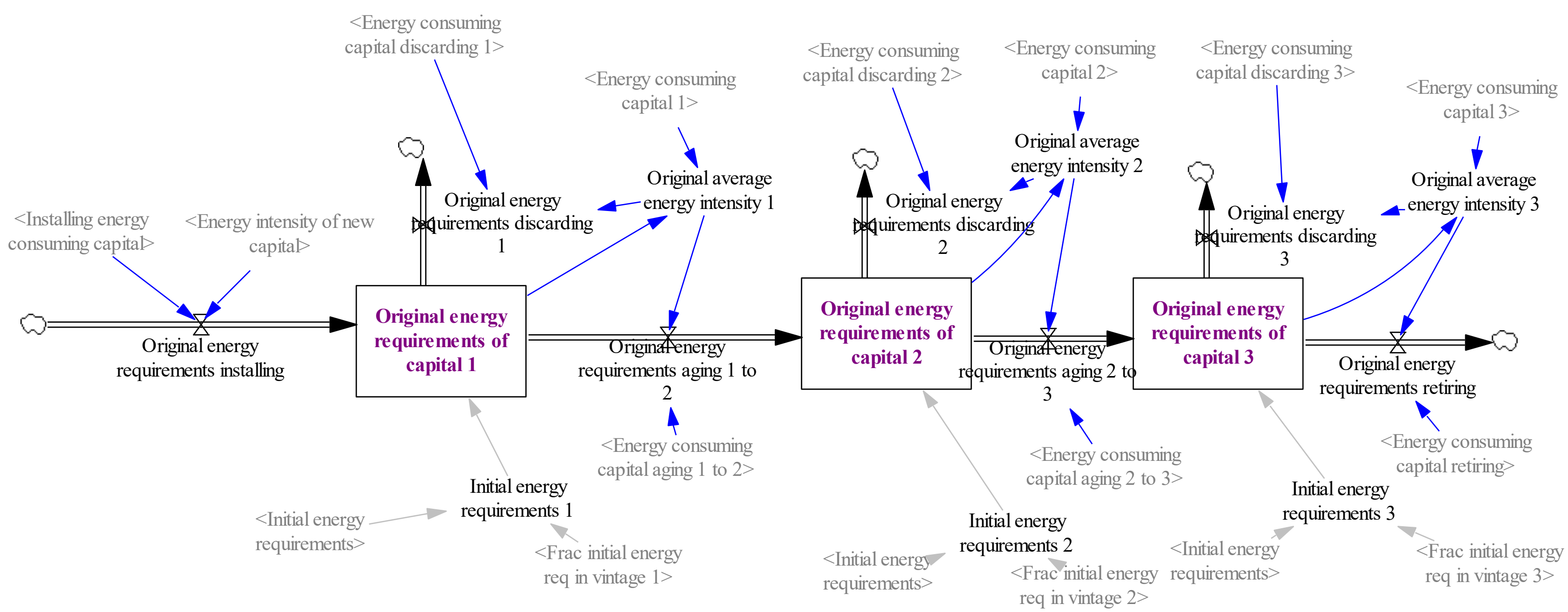


Figure 3-15 Structure of Long Term Energy Requirements of Capital (with Retrofit Potential)

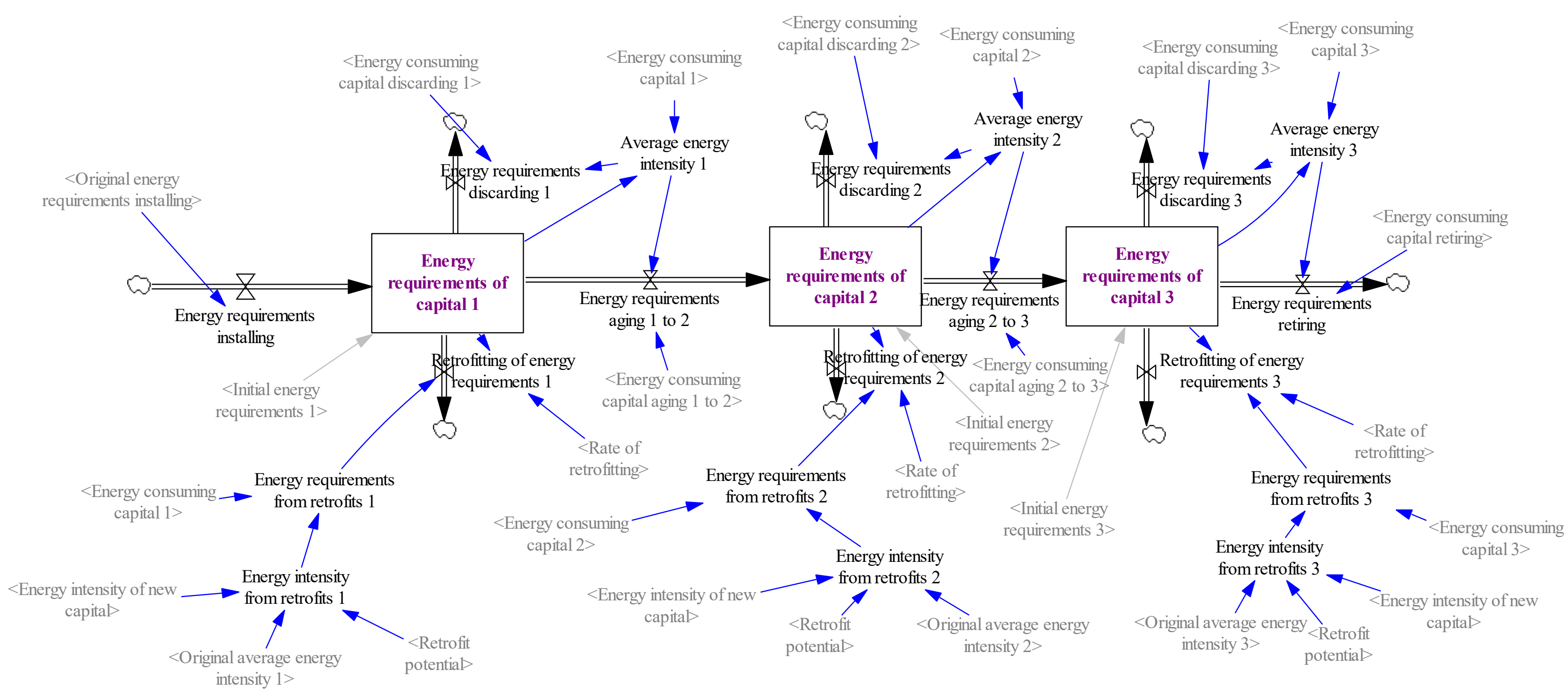


Figure 3-16 Structure of Retrofit Potential and Rate

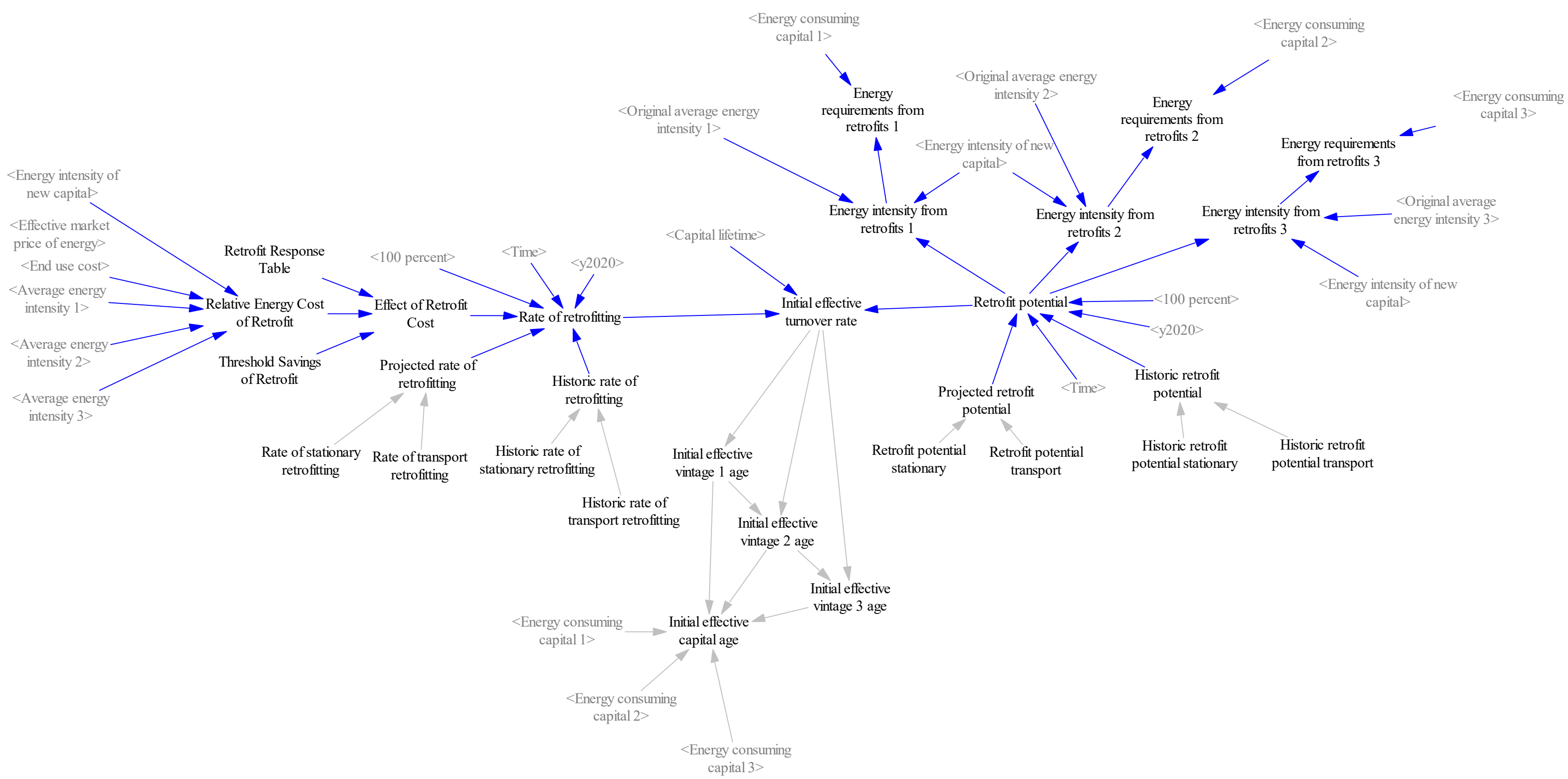


Figure 3-17 Measures of Long Term Energy Requirements of Capital

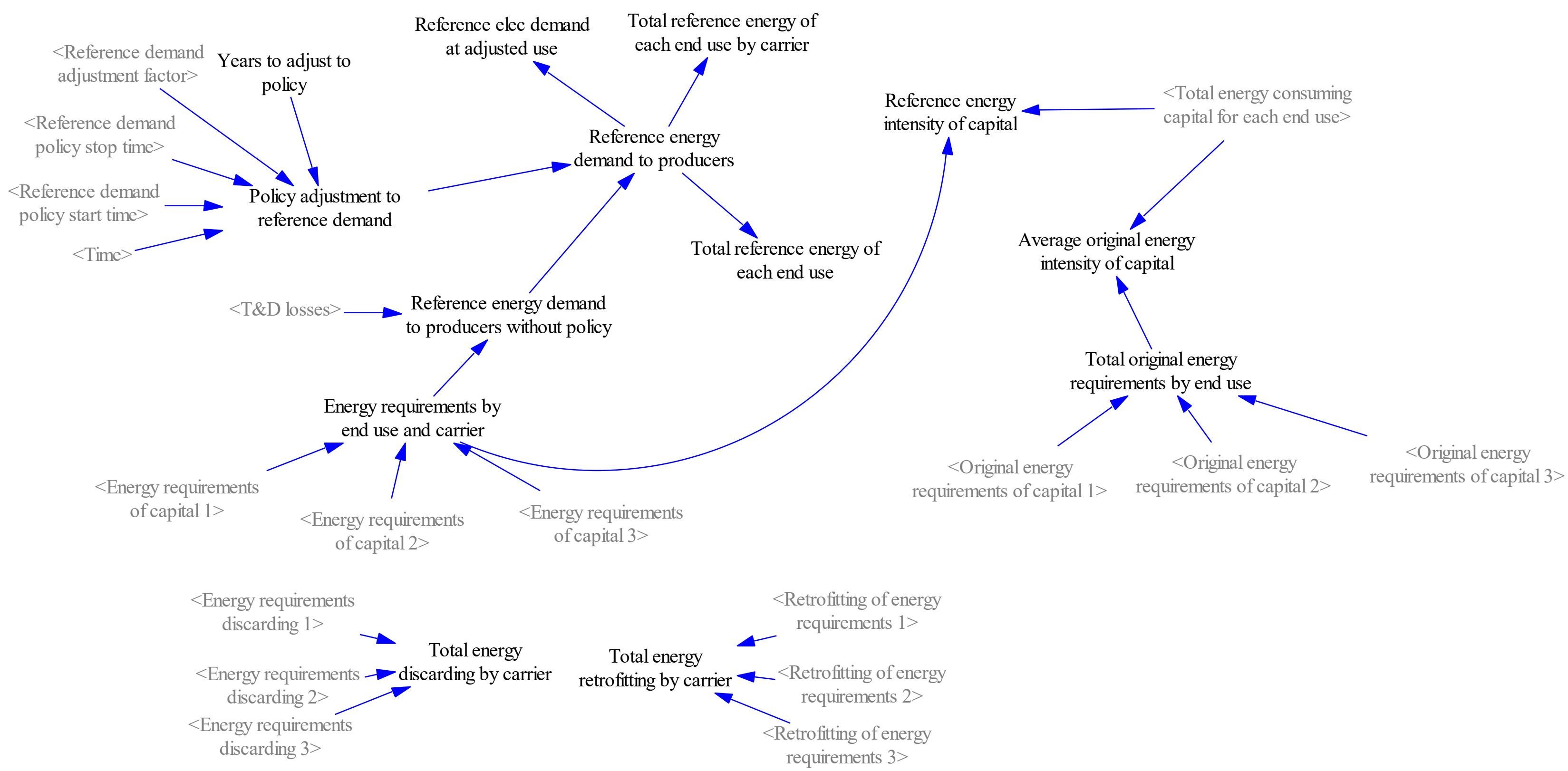


Figure 3-18 Measures of Long Term Energy Requirements and Intensity of Capital

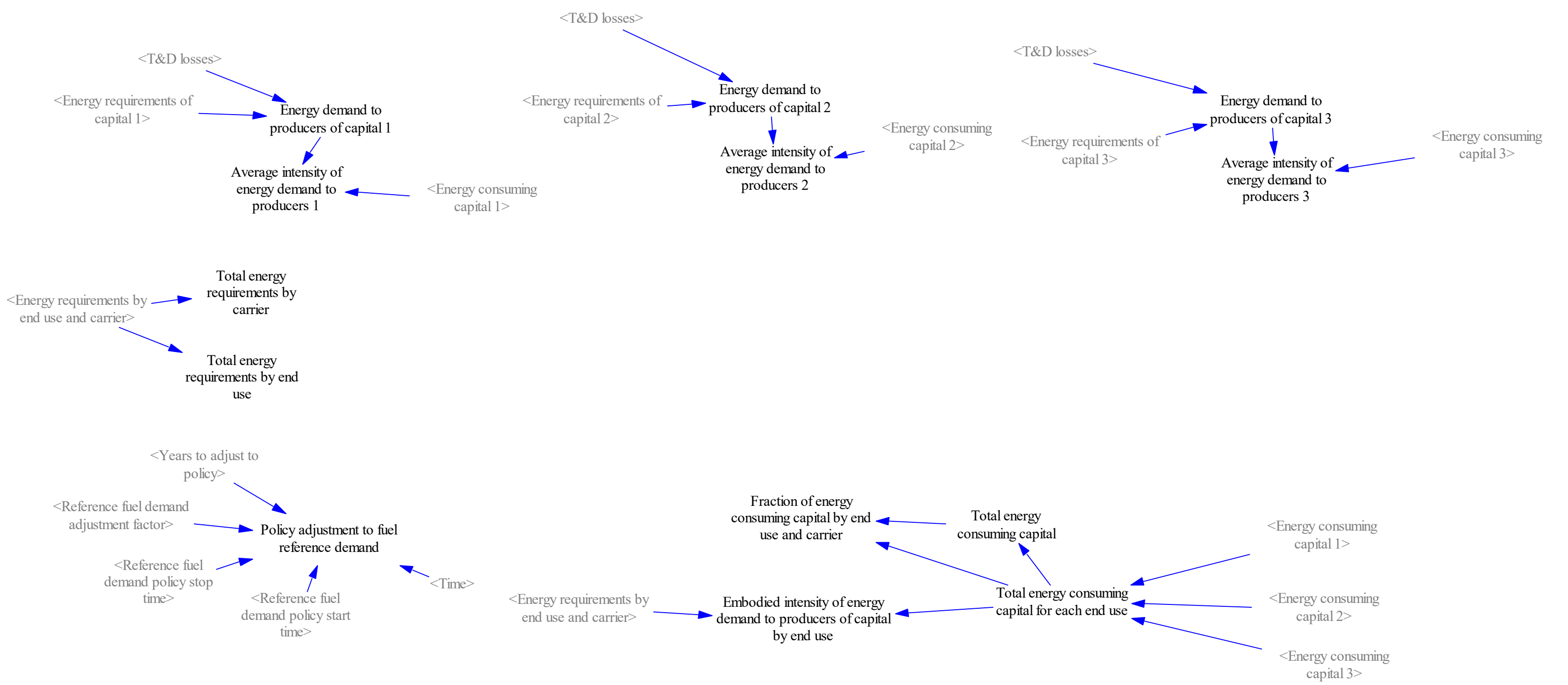


Table 3-10. Electric Long Term Energy Requirements (Original) Calculated Parameters

Parameter	Definition	Units
Energy requirements of capital original 1[EndUseSector,Carrier]	For each end use and by carrier, the energy required of capital in vintage 1 as originally installed (prior to retrofits, if any). INTEG(Original energy requirements installing [EndUseSector,Carrier]-Original energy requirements discarding 1[EndUseSector,Carrier]-Original energy requirements aging 1 to 2[EndUseSector,Carrier], Initial energy requirements 1[EndUseSector, Carrier])	EJ/Year
Energy requirements of capital original 2[EndUseSector,Carrier]	For each end use and by carrier, the energy required of capital in vintage 2 as originally installed (prior to retrofits, if any). INTEG(Original energy requirements aging 1 to 2[EndUseSector, Carrier]-Original energy requirements aging 2 to 3[EndUseSector, Carrier]-Original energy requirements discarding 2[EndUseSector, Carrier], Initial energy requirements 2[EndUseSector, Carrier])	EJ/Year
Energy requirements of capital original 3[EndUseSector,Carrier]	For each end use and by carrier, the energy required of capital in vintage 3 as originally installed (prior to retrofits, if any). INTEG(Original energy requirements aging 2 to 3[EndUseSector, Carrier]-Original energy requirements discarding 3[EndUseSector, Carrier]-Original energy requirements retiring[EndUseSector, Carrier], Initial energy requirements 3[EndUseSector, Carrier])	EJ/Year
Initial energy requirements 1[EndUseSector,Carrier]	Initial energy requirements[EndUseSector,Carrier]*Frac initial energy req in vintage 1[EndUseSector]	EJ/Year
Initial energy requirements 2[EndUseSector,Carrier]	Initial energy requirements[EndUseSector,Elec]*Frac initial energy req in vintage 2[EndUseSector]	EJ/Year
Initial energy requirements 3[EndUseSector,Carrier]	Initial energy requirements[EndUseSector,Elec]*Frac initial energy req in vintage 3[EndUseSector]	EJ/Year

Table 3-10. Electric Long Term Energy Requirements (Original) Calculated Parameters

Parameter	Definition	Units
Original energy requirements installing [EndUseSector,Carrier]	Energy requirements of capital that is installed for each end use by each carrier. Energy intensity of new capital[EndUseSector,Carrier]*Installing energy consuming capital[EndUseSector]	(EJ/Year)/Year
Original energy aging 1 to 2 [EndUseSector,Carrier]	Energy requirements of capital by each carrier as originally installed moving from vintage 1 into vintage 2. Original average energy intensity 1[EndUseSector,Carrier]*Energy consuming capital aging 1 to 2[EndUseSector]	(EJ/Year)/Year
Original energy aging 2 to 3 [EndUseSector,Carrier]	Energy requirements of capital by each carrier as originally installed moving from vintage 2 into vintage 3. Original average energy intensity 2[EndUseSector,Carrier]*Energy consuming capital aging 2 to 3[EndUseSector]	(EJ/Year)/Year
Original energy retiring[EndUseSector,Carrier]	Energy requirements of capital by each carrier as originally installed moving from vintage 3 to no longer being used. Original average energy intensity 3[EndUseSector,Carrier]*Energy consuming capital retiring[EndUseSector]	(EJ/Year)/Year
Original energy discarding 1[EndUseSector,Carrier]	The decrease in energy requirements by each carrier for vintage 1 due to the amount of capital as originally installed in this vintage lost due to early retirement. Average original energy intensity 1[EndUseSector]*Early discarding 1[EndUseSector]	(EJ/Year)/Year

Table 3-10. Electric Long Term Energy Requirements (Original) Calculated Parameters

Parameter	Definition	Units
Original energy discarding 2[EndUseSector,Carrier]	The decrease in energy requirements by each carrier for vintage 2 due to the amount of capital as originally installed in this vintage lost due to early retirement. Average original energy intensity 2[EndUseSector]*Early discarding 2[EndUseSector]	(EJ/Year)/Year
Original energy discarding 3[EndUseSector,Carrier]	The decrease in energy requirements by each carrier for vintage 3 due to the amount of capital as originally installed in this vintage lost due to early retirement. Average original energy intensity 3[EndUseSector]*Early discarding 3[EndUseSector]	(EJ/Year)/Year
Original average energy intensity 1 [EndUseSector,Carrier]	Average of annual energy by each carrier required per dollar of vintage 1 capital as originally installed (prior to retrofits, if any). ZIDZ(Original energy requirements of capital 1[EndUseSector, Carrier],Energy consuming capital 1[EndUseSector])	(EJ/Year)/T$ 2017 PPP
Original average energy intensity 2 [EndUseSector,Carrier]	Average of annual energy by each carrier required per dollar of vintage 2 capital as originally installed (prior to retrofits, if any). ZIDZ(Original energy requirements of capital 2[EndUseSector, Carrier],Energy consuming capital 2[EndUseSector])	(EJ/Year)/T$ 2017 PPP
Original average energy intensity 3 [EndUseSector,Carrier]	Average of annual energy by each carrier required per dollar of vintage 3 capital as originally installed (prior to retrofits, if any). ZIDZ(Original energy requirements of capital 3[EndUseSector, Carrier],Energy consuming capital 3[EndUseSector])	(EJ/Year)/T$ 2017 PPP

Table 3-10. Electric Long Term Energy Requirements (Original) Calculated Parameters

Parameter	Definition	Units
Total original energy requirements by end use [EndUseSector,Carrier]	Sum of electric energy requirements of capital in each vintage as originally installed. Original energy requirements of capital 1[EndUseSector,Carrier] +Original energy requirements of capital 2 [EndUseSector, Carrier]+Original energy requirements of capital 3 [EndUseSector,Carrier]	EJ/Year
Average original energy intensity of capital[EndUseSector,Carrier]	Average annual energy by carrier required per dollar of total capital as originally installed. ZIDZ(Total original energy requirements by end use[EndUseSector,Carrier],Total energy consuming capital for each end use[EndUseSector])	(EJ/Year)/T$ 2017 PPP

Table 3-11 . Retrofits and Noncost Policy Adjustment Inputs for Long Term Energy Requirements

Parameter	Definition	Range	Default Values	Units
Retrofit potential[EndUseSector]	Fraction of capital that can be retrofitted with new energy intensity			Dmnl
Retrofit potential stationary		0-1	0.7	
Retrofit potential transport		0-1	0.05	
Historic retrofit potential [EndUseSector]	Historic fraction (until *Year to change retrofitting*) of capital that can be retrofitted with new energy intensity			1/year
Historic retrofit potential stationary		0-1	0.7	
Historic retrofit potential transport		0-1	0.05	
Rate of retrofitting[EndUseSector]	Rate it takes to retrofit capital to make it more energy efficient in each sector.			1/year
Rate of Stationary Retrofitting		0-1	0.05	
Rate of Transport Retrofitting		0-1	0.05	
Historic rate of retrofitting[EndUseSector]	Historic rate (until *Year to change retrofitting*) it takes to retrofit capital to make it more energy efficient in each sector.			1/year
Historic rate of stationary retrofitting		0-1	0.05	
Historic rate of transport retrofitting		0-1	0.05	
Year to change retrofitting			2021	Year
Reference demand adjustment factor[Carrier, EndUseSector]	Reflects noncost policy to reduce normal demand by multiplicative fraction.	0-1	0	Dmnl
Reference demand policy start time[Carrier, EndUseSector]	Year to start the noncost policy to adjust the reference demand.	2021-2100	2021	Year

Table 3-11 . Retrofits and Noncost Policy Adjustment Inputs for Long Term Energy Requirements

Parameter	Definition	Range	Default Values	Units
Reference demand policy stop time[Carrier, EndUseSector]	Year to stop the noncost policy to adjust the reference demand.	2021-2100	2050	Year
Years to adjust to policy	Time to ramp up to full noncost adjustment.	1-20	10	Years
Threshold Savings of Retrofit			0.2	Dmnl
Retrofit Response Table	Lookup table of response of costs of retrofitting	(-1,0), (0,0), (0.314985,0.149123), (1,1), (1.46177,1.64912), (1.67584,1.88596), (2,2), (4,2)		Dmnl

Table 3-12. Retrofitting and Noncost Policy Adjustments Calculated Parameters

Parameter	**Definition**	**Units**
Rate of retrofitting[EndUseSector]	The rate of retrofitting depends on the specified rate adjusted by effects of cost of retrofitting. IF THEN ELSE(Time< Year to change retrofitting, Historic rate of retrofitting[EndUseSector], Projected rate of retrofitting[EndUseSector]*Effect of Retrofit Cost[EndUseSector,Vintage])/"100 percent"	1/year
Retrofit potential[EndUseSector]	IF THEN ELSE(Time<Year to change retrofitting, Historic retrofit potential [EndUseSector], Projected retrofit potential[EndUseSector])	Dmnl
Effect of Retrofit Cost[EndUseSector,Vintage]	ACTIVE INITIAL(Retrofit Response Table((1-Relative Energy Cost of Retrofit[EndUseSector,Vintage])/Threshold Savings of Retrofit), 1)	Dmnl
Relative Energy Cost of Retrofit[EndUseSector,Vintage]		Dmnl
[EndUseSector,v1]	SUM(Energy intensity of new capital[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])/SUM(Average energy intensity 1[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])	
[EndUseSector,v2]	SUM(Energy intensity of new capital[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])/SUM(Average energy intensity 2[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])	
[EndUseSector,v3]	SUM(Energy intensity of new capital[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])SUM(Average energy intensity 3[EndUseSector,Carrier!]*End use cost[EndUseSector,Carrier!])	

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Energy requirements of capital 1 [EndUseSector, Carrier]	For each end use and by carrier, the energy required of capital in vintage 1 as originally installed including any retrofits. INTEG(Energy requirements installing[EndUseSector, Carrier]- Energy requirements aging 1 to 2[EndUseSector, Carrier]- Energy requirements discarding 1[EndUseSector, Carrier]- Retrofitting of energy requirements 1[EndUseSector, Carrier], Initial energy requirements 1[EndUseSector, Carrier])	EJ/Year
Energy requirements of capital 2 [EndUseSector, Carrier]	For each end use and by carrier, the energy required of capital in vintage 2 as originally installed including any retrofits. INTEG(Energy requirements aging 1 to 2[EndUseSector, Carrier]- Energy requirements aging 2 to 3[EndUseSector, Carrier]- Energy requirements discarding 2[EndUseSector, Carrier]- Retrofitting of energy requirements 2[EndUseSector, Carrier], Initial energy requirements 2[EndUseSector, Carrier])	EJ/Year
Energy requirements of capital 3 [EndUseSector, Carrier]	For each end use and by carrier, the energy required of capital in vintage 3 as originally installed including any retrofits. INTEG(Energy requirements aging 2 to 3[EndUseSector, Carrier]- Energy requirements discarding 3[EndUseSector, Carrier]- Energy requirements retiring[EndUseSector, Carrier]- Retrofitting of energy requirements 3[EndUseSector, Carrier], Initial energy requirements 3[EndUseSector, Carrier])	EJ/Year

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	**Definition**	**Units**
Energy requirements installing [EndUseSector, Carrier]	Energy requirements of capital that is installed for each end use and delivered by each carrier, same as for original energy requirements without retrofits by carrier because both are based on energy intensity of new capital. Original energy requirements installing[EndUseSector, Carrier]	(EJ/Year)/Year
Energy requirements aging 1 to 2 [EndUseSector, Carrier]	Energy requirements by carrier of capital as originally installed moving from vintage 1 into vintage 2. Average energy intensity 1[EndUseSector,Carrier]*Energy consuming capital aging 1 to 2[EndUseSector]	(EJ/Year)/Year
Energy requirements aging 2 to 3 [EndUseSector, Carrier]	Energy requirements of capital as originally installed moving from vintage 2 into vintage 3. Average energy intensity 2[EndUseSector,Carrier]*Energy consuming capital aging 2 to 3[EndUseSector]	(EJ/Year)/Year
Energy requirements retiring [EndUseSector, Carrier]	Energy requirements by fuel of capital as originally installed moving from vintage 3 to no longer being used. Average energy intensity 3[EndUseSector,Carrier]*Energy consuming capital retiring[EndUseSector]	(EJ/Year)/Year
Energy requirements discarding 1 [EndUseSector, Carrier]	The decrease in energy requirements by fuel for vintage 1 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average energy intensity 1[EndUseSector, Carrier]*Energy consuming capital discarding 1[EndUseSector]	(EJ/Year)/Year

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Energy requirements discarding 2 [EndUseSector, Carrier]	The decrease in energy requirements by fuel for vintage 2 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average energy intensity 2[EndUseSector, Carrier]*Energy consuming capital discarding 2[EndUseSector]	(EJ/Year)/Year
Energy requirements discarding 3 [EndUseSector, Carrier]	The decrease in energy requirements by fuel for vintage 3 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average energy intensity 3[EndUseSector, Carrier]*Energy consuming capital discarding 3[EndUseSector]	(EJ/Year)/Year
Average energy intensity 1 [EndUseSector, Carrier]	Average of annual energy by fuel required per dollar of vintage 1 capital, including any retrofits. ZIDZ(Energy requirements of capital 1[EndUseSector, Carrier], Energy consuming capital 1[EndUseSector])	(EJ/Year)/T$ 2017 PPP
Average energy intensity 2 [EndUseSector, Carrier]	Average of annual energy by fuel required per dollar of vintage 2 capital, including any retrofits. ZIDZ(Energy requirements of capital 2[EndUseSector, Carrier],Energy consuming capital 2[EndUseSector])	(EJ/Year)/T$ 2017 PPP
Average energy intensity 3 [EndUseSector, Carrier]	Average of annual energy by fuel required per dollar of vintage 3 capital, including any retrofits. ZIDZ(Energy requirements of capital 3[EndUseSector, Carrier],Energy consuming capital 3[EndUseSector])	(EJ/Year)/T$ 2017 PPP

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Energy intensity from retrofits 1 [EndUseSector,Carrier]	Annual energy by fuel requirements of retrofitted capital in vintage 1. Retrofit potential [EndUseSector]*Energy intensity of new capital [EndUseSector,Carrier]+ (1-Retrofit potential [EndUseSector]) *Original average energy intensity 1[EndUseSector,Carrier]	EJ/Year
Energy intensity from retrofits 2 [EndUseSector,Carrier]	Annual nonelectric energy by fuel requirements of retrofitted capital in vintage 2. Retrofit potential [EndUseSector]*Energy intensity of new capital [EndUseSector, Carrier] + (1-Retrofit potential [EndUseSector]) *Original average energy intensity 2[EndUseSector, Carrier]	EJ/Year
Energy intensity from retrofits 3 [EndUseSector,Carrier]	Annual nonelectric energy by fuel requirements of retrofitted capital in vintage 3. Retrofit potential [EndUseSector]*Energy intensity of new capital [EndUseSector,Carrier] + (1-Retrofit potential [EndUseSector]) *Original average energy intensity 3[EndUseSector,Carrier]	EJ/Year
Energy requirements from retrofits 1 [EndUseSector,Carrier]	Annual energy by carrier requirements of retrofitted capital in vintage 1. Energy consuming capital 1[EndUseSector]*Energy intensity from retrofits 1[EndUseSector, Carrier]	(EJ/Year)/T$ 2017 PPP
Energy requirements from retrofits 2 [EndUseSector,Carrier]	Annual energy by carrier requirements of retrofitted capital in vintage 2. Energy consuming capital 2[EndUseSector]*Energy intensity from retrofits 2[EndUseSector, Carrier]	(EJ/Year)/T$ 2017 PPP

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Energy requirements from retrofits 3 [EndUseSector,Carrier]	Annual energy by carrier requirements of retrofitted capital in vintage 3. Energy consuming capital 3[EndUseSector]*Energy intensity from retrofits 3[EndUseSector, Carrier]	(EJ/Year)/T$ 2017 PPP
Retrofitting of energy requirements 1 [EndUseSector,Carrier]	The decrease in energy requirements by carrier of vintage 1 from the originally installed capital due to retrofitting. MAX(0, (Energy requirements of capital 1[EndUseSector, Carrier]-Energy requirements from retrofits 1[EndUseSector,Carrier]) *Rate of retrofitting [EndUseSector])	(EJ/Year)/Year
Retrofitting of energy requirements 2 [EndUseSector,Carrier]	The decrease in energy requirements by carrier of vintage 2 from the originally installed capital due to retrofitting. MAX(0,(Energy requirements of capital 2[EndUseSector, Carrier]-Energy requirements from retrofits 2[EndUseSector, Carrier]) *Rate of retrofitting[EndUseSector])	(EJ/Year)/Year
Retrofitting of energy requirements 3 [EndUseSector,Carrier]	The decrease in energy requirements by carrier of vintage 3 from the originally installed capital due to retrofitting. MAX(0, (Energy requirements of capital 3[EndUseSector, Carrier]-Energy requirements from retrofits 3[EndUseSector, Carrier]) *Rate of retrofitting[EndUseSector])	(EJ/Year)/Year
Total energy retrofitting by carrier [EndUseSector,Carrier]	Sum of energy retrofitting of each vintage by carrier. Retrofitting of energy requirements 1[EndUseSector,Carrier] +Retrofitting of energy requirements 2[EndUseSector,Carrier] +Retrofitting of energy requirements 3[EndUseSector,Carrier]	(EJ/Year)/Year

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Total energy discarding by carrier [EndUseSector, Carrier]	Sum of energy discarding of each vintage by carrier. Energy requirements discarding 1[EndUseSector, Carrier]+Energy requirements discarding 2[EndUseSector, Carrier]+Energy requirements discarding 3[EndUseSector,Carrier]	(EJ/Year)/Year
Energy requirements by end use and carrier [EndUseSector,Carrier]	Energy requirements by carrier of capital by end use, calculated as the sum of those requirements in each vintage of capital. This is the energy demanded when price equals the price basis. Energy requirements of capital 1[EndUseSector,Carrier]+Energy requirements of capital 2[EndUseSector,Carrier]+Energy requirements of capital 3[EndUseSector,Carrier]	EJ/Year
Policy adjustment to normal demand[EndUseSector]	Policy adjustment to reference demand. IF THEN ELSE(Time>Reference demand policy stop time[Carrier,EndUseSector], 1, 1-ramp((1-Reference demand adjustment factor[Carrier,EndUseSector])/Years to adjust to policy, Reference demand policy start time[Carrier,EndUseSector], Reference demand policy start time[Carrier,EndUseSector]+Years to adjust to policy))	Dmnl
Energy demand at normal utilization without policy	The long term energy requirements of each carrier before noncost policy adjustments. T&D losses for nonelec carriers is zero.	EJ/Year
EndUseSector,NonElec Carriers	Energy requirements by end use and carrier[EndUseSector,NonElec Carriers]/(1-"T&D losses"[NonElec Carriers])	
EndUseSector,Electric Carrier	Energy requirements by end use and carrier[EndUseSector,Electric Carrier]/(1-"T&D losses"[Electric Carrier])	

Table 3-13. Long Term Energy Requirements by Fuel with Retrofits Calculated Parameters

Parameter	Definition	Units
Energy demand at normal utilization [EndUseSector,Carrier]	The long term energy requirements of each carrier adjusted by any noncost policy. Energy demand at normal utilization without policy[EndUseSector, Carrier]*Policy adjustment to normal demand[EndUseSector,Carrier]	EJ/year
Electricity demand at normal utilization	Energy demand at normal utilization[EndUseSector, Electric Carrier]	EJ/year
Total energy demand at normal utilization of each carrier [Carrier]	The long term energy requirements of each carrier. SUM(Energy demand at normal utilization[EndUseSector!, Carrier])	EJ/year
End use share of each carrier [EndUseSector, Carrier]	For each carrier, the fraction of adjusted energy for each end use. Energy demand at normal utilization[EndUseSector,Carrier] /SUM(Energy demand at normal utilization[EndUseSector!,Carrier])	Dmnl
Total energy demand at normal utilization of each end use [EndUseSector]	The long term energy requirements of each end use. SUM(Energy demand at normal utilization[EndUseSector, Carrier!])	EJ/year

Table 3-14. Energy Requirements and Intensity Measures Calculated Parameters

Parameter	Definition	Units
Reference energy intensity of capital [EndUseSector,Carrier]	For each end use and by each carrier, the long term energy intensity of capital ZIDZ(Energy requirements by end use and carrier[EndUseSector,Carrier],Total energy consuming capital for each end use[EndUseSector])	EJ/Year

Table 3-15. Initial Capital and Energy Requirements in Each Vintage

Parameter	Definition	Units
Initial effective turnover rate[EndUseSector,Vintage]	Effective rate of retirement of capital for each end use accounting for retrofit potential and the rate of retrofitting. Retrofit potential[EndUseSector]*(3/Capital lifetime[EndUseSector]+Rate of retrofitting[EndUseSector, Vintage]) +(1-Retrofit potential[EndUseSector])*(3/Capital lifetime[EndUseSector])	1/year
Initial effective vintage 1 age[EndUseSector]	The effective time that the capital remains in the first vintage. 1/Initial effective turnover rate[EndUseSector,v1]	Year
Initial effective vintage 2 age[EndUseSector]	The effective time that the capital remains in the second vintage. Initial effective vintage 1 age[EndUseSector]+(1/Initial effective turnover rate[EndUseSector,v2])	Year
Initial effective vintage 3 age[EndUseSector]	The effective time that the capital remains in the third vintage. Initial effective vintage 2 age[EndUseSector]+1/Initial effective turnover rate[EndUseSector,v3]	Year
Relative Initial Capital in Vintage 1 [EndUseSector]	Relative initial capital in vintage 1, assuming steady-state growth equilibrium at the historic growth rate over the time in vintage 1. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 1 age[EndUseSector]))	Dmnl

Table 3-15. Initial Capital and Energy Requirements in Each Vintage

Parameter	Definition	Units
Relative Initial Capital in Vintage 2 [EndUseSector]	Relative initial capital in vintage 2, assuming steady-state growth equilibrium at the historic growth rate over the time in vintages 1 and 2. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 2 age[EndUseSector]))	Dmnl
Relative Initial Capital in Vintage 3 [EndUseSector]	Relative initial capital in vintage 3, assuming steady-state growth equilibrium at the historic growth rate over the time in all three vintages, i.e., the capital lifetime. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 3 age[EndUseSector]))	Dmnl
Sum of Relative Initial Capital [EndUseSector]	Initial relative capital as the weighted average of the initial relative capital of each vintage. INITIAL(Relative Initial Capital in Vintage 1[EndUseSector]+Relative Initial Capital in Vintage 2[EndUseSector]+Relative Initial Capital in Vintage 3[EndUseSector])	Dmnl
Frac Initial Capital in Vintage 1 [EndUseSector]	Initial share of capital in vintage 1, assuming steady-state growth equilibrium at the historic growth rate. INITIAL(Frac initial capital in vintage 1[EndUseSector]*Relative initial energy intensity of capital 1[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl

Table 3-15. Initial Capital and Energy Requirements in Each Vintage

Parameter	Definition	Units
Frac Initial Capital in Vintage 2 [EndUseSector]	Initial share of capital in vintage 2, assuming steady-state growth equilibrium at the historic growth rate. INITIAL(Frac initial capital in vintage 2[EndUseSector]*Relative initial energy intensity of capital 2[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl
Frac Initial Capital in Vintage 3 [EndUseSector]	Initial share of capital in vintage 3, assuming steady-state growth equilibrium at the historic growth rate. INITIAL(Frac initial capital in vintage 3[EndUseSector]*Relative initial energy intensity of capital 3[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl
Relative Initial Energy Intensity of Capital 1 [EndUseSector]	Initial energy intensity of capital stock in vintage 1, assuming steady state equilibrium at the historic energy intensity trend rate, in which case intensity of the stock lags intensity of new capital by the by the effective time in vintage 1. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 1 age[EndUseSector]))	Dmnl
Relative Initial Energy Intensity of Capital 2 [EndUseSector]	Relative initial energy intensity of capital stock in vintage 2, assuming steady state equilibrium at the historic energy intensity trend rate, in which case intensity of the stock lags intensity of new capital by the effective time in vintages 1 and 2. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 2 age[EndUseSector]))	Dmnl

Table 3-15. Initial Capital and Energy Requirements in Each Vintage

Parameter	Definition	Units
Relative Initial Energy Intensity of Capital 3 [EndUseSector]	Relative initial energy intensity of capital stock in vintage 3, assuming steady state equilibrium at the historic energy intensity trend rate, in which case intensity of the stock lags intensity of new capital by the effective time in all three vintages, i.e., the effective capital lifetime. INITIAL(EXP(-Historic rate of decrease of energy intensity[EndUseSector]/"100 percent"*Initial effective vintage 3 age[EndUseSector]))	Dmnl
Sum of relative initial energy [EndUseSector]	Initial relative energy intensity of capital as the weighted average of the initial relative intensity of each vintage. INITIAL(Frac initial capital in vintage 1[EndUseSector]*Relative initial energy intensity of capital 1[EndUseSector]+Frac initial capital in vintage 2[EndUseSector]*Relative initial energy intensity of capital 2[EndUseSector]+Frac initial capital in vintage 3[EndUseSector]*Relative initial energy intensity of capital 3[EndUseSector])	Dmnl
Frac Initial Energy Req in Vintage 1 [EndUseSector]	Fraction of initial energy requirements in vintage 1, assuming steady-state growth and energy intensity trend. INITIAL(Frac Initial Capital in Vintage 1[EndUseSector]*Relative Initial Energy Intensity of Capital 1[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl
Frac Initial Energy Req in Vintage 2 [EndUseSector]	Fraction of initial energy requirements in vintage 2, assuming steady-state growth and energy intensity trend. INITIAL(Frac Initial Capital in Vintage 2[EndUseSector]*Relative Initial Energy Intensity of Capital 2[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl

Table 3-15. Initial Capital and Energy Requirements in Each Vintage

Parameter	Definition	Units
Frac Initial Energy Req in Vintage 3 [EndUseSector]	Fraction of initial energy requirements in vintage 3, assuming steady-state growth and energy intensity trend. INITIAL(Frac Initial Capital in Vintage 3[EndUseSector]*Relative Initial Energy Intensity of Capital 3[EndUseSector]/Sum of relative initial energy[EndUseSector])	Dmnl

4. Formulation of Supply

4.1 Supply of Extracted Fuels, Delivered Fuels, and Electricity Generation

There are three main supply chains to capture the stock and flow of supply capacity of extracted fuel (coal, oil, gas, and biofuel), delivered fuel (coal, oil, gas, and biofuel), and electricity production from each of the electric paths (coal, oil, gas, biofuel, nuclear, hydro, wind, solar, geothermal, other renewables , and new, plus CCS paths of each coal, oil, gas, and biofuel). The model assumes that each extracted fuel is available only for its respective delivered fuel type. Each delivered fuel is available for nonelectric and electric use. Table 4-1 through Table 4-2 define these sources and groupings of sources.

The capacity and utilization and cost of extracted fuels affect the market price of extracted fuels, which feeds into the variable cost of delivered fuels. As such, the market price of extracted fuels affects the capacity, utilization, and market price of delivered fuels, which in turn feeds into the variable cost of electric producers using those fuels. Accordingly, the costs of delivered fuels affect the capacity and utilization of those electricity sources. Section 5 details the market clearing and utilization of delivered fuels and electricity sources.

Figure 4-1, Figure 4-2, and Figure 4-3 show the structure of the sectors for extraction, delivered fuel, and electric generation capacity, respectively. For each of these phases, the capacity represents the installed base of usable capital. It depreciates via a constant fractional rate, without age vintaging of the stock. The profitability, however, affects the rate of depreciation. For delivered fuels and electric supply, capacity must go through the development phase and then constructed before it can be used, introducing a delay between initiating and completing the acquisition of new capacity. The amount of capacity that is planned for construction accounts for the total capacity needed to meet the energy demand, including transmission and delivery losses, plus a reserve margin and expected growth of energy requirements.

For capacities of extracted fuels and of delivered fuels for nonelectric consumption, the desired capacity of each depends in part on the centralized effect of expected growth and normal utilization, as well as on the the profitability and current capacity of each fuel. Any non-cost policies banning new capacity adjust the resulting desired capacity. For electric generation, the desired capacity of each source depends on the demand of electricity and the *Fraction invested in elec energy source*, as well as the profitability and current capacity of each source. Desired capacities are adjusted by dividing by the capacity factor of each resource, requiring more of each energy path to be constructed to get the actual desired supply. The constructed supply is then multiplied by the capacity factor to yield the actual capacity. While the *Actual Supply Capacity* represents the amount of energy from each path that can be dispatched, the *Energy Supply Capacity* is the amount of energy that is constructed.

The rate of capacity completion is constrained by *Development industry capacity*. This structure captures supply chain constraints, for example the fact that if wind turbine orders double overnight, completion of new turbines cannot also double immediately. It takes time to acquire labor and machinery and build up other aspects of the necessary supply chain. This has two consequences: with increasing pressure to construct capacity, the effective lead time increases, and the cost of new capacity rises.

Table 4-1 Carriers

Carriers	**Sources Used**
	Primary Fuels
Coal Carrier	PCoal
Oil Carrier	POil
Gas Carrier	PGas
Bio Carrier	PBio
Electric Carrier	**Elec Paths**
	ECoal, ECoal CCS
	EOil, EOil CCS
	EGas, EGas CCS
	EBio, EBio CCS
	Nuclear
	Hydro
	Renewable Type (Wind, Solar, Geothermal, Other Renewables)
	New

Table 4-2 Energy Sources

Primary Energy Sources	**Primary Fuels**	**Elec Paths**
Primary Coal	PCoal	ECoal, ECoal CCS
Primary Oil	POil	EOil, EOil CCS
Primary Gas	PGas	EGas, EGas CCS
Primary Bio	PBio	EBio, EBio CCS
Primary Nuclear		Nuclear
Primary Hydro		Hydro
Primary Renewables		Renewable Types (Wind, Solar, Geothermal, Other Renewables)
Primary New		New

Table 4-3 Subscript Aggregates

Range	Paths Included
Fossil Fuels	Coal: Primary Coal, PCoal, ECoal, ECoal CCS
	Oil: Primary Oil, POil, EOil, EOil CCS
	Gas: Primary Gas, PGas, EGas, EGas CCS
Elec thermal	ECoal,EOil,EGas,EBio
CCS Paths	ECoal CCS,EOil CCS,EGas CCS,EBio CCS
Elec thermal plus CCS	Elec thermal, CCS Paths
Elec Exists	Elec thermal, Nuclear, Hydro, Wind, Solar, Geothermal, Other Renewables

Figure 4-1 Structure of Extracted Fuel Supply Capacity

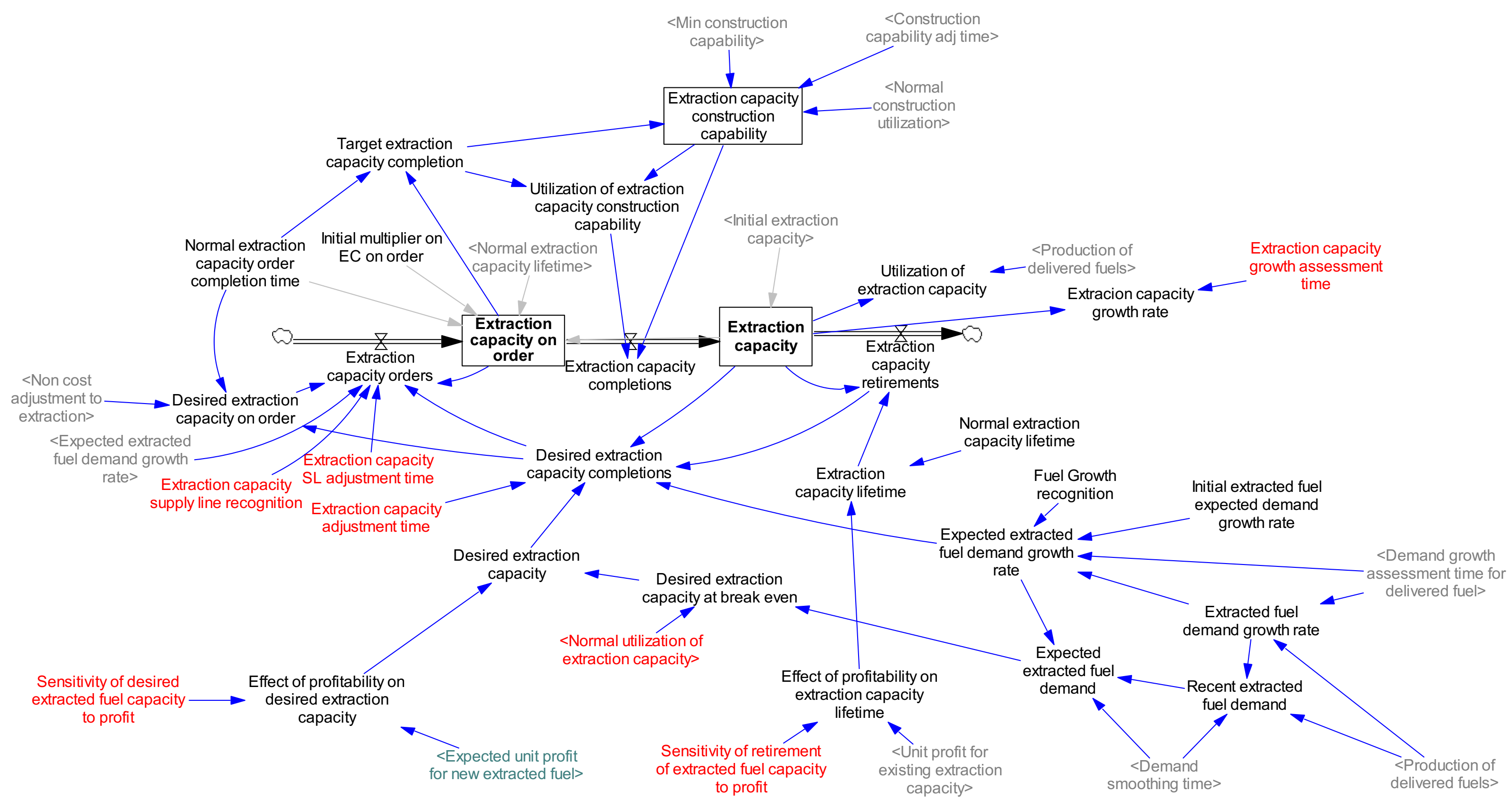


Figure 4-2 Structure of Delivered Fuel Supply Capacity

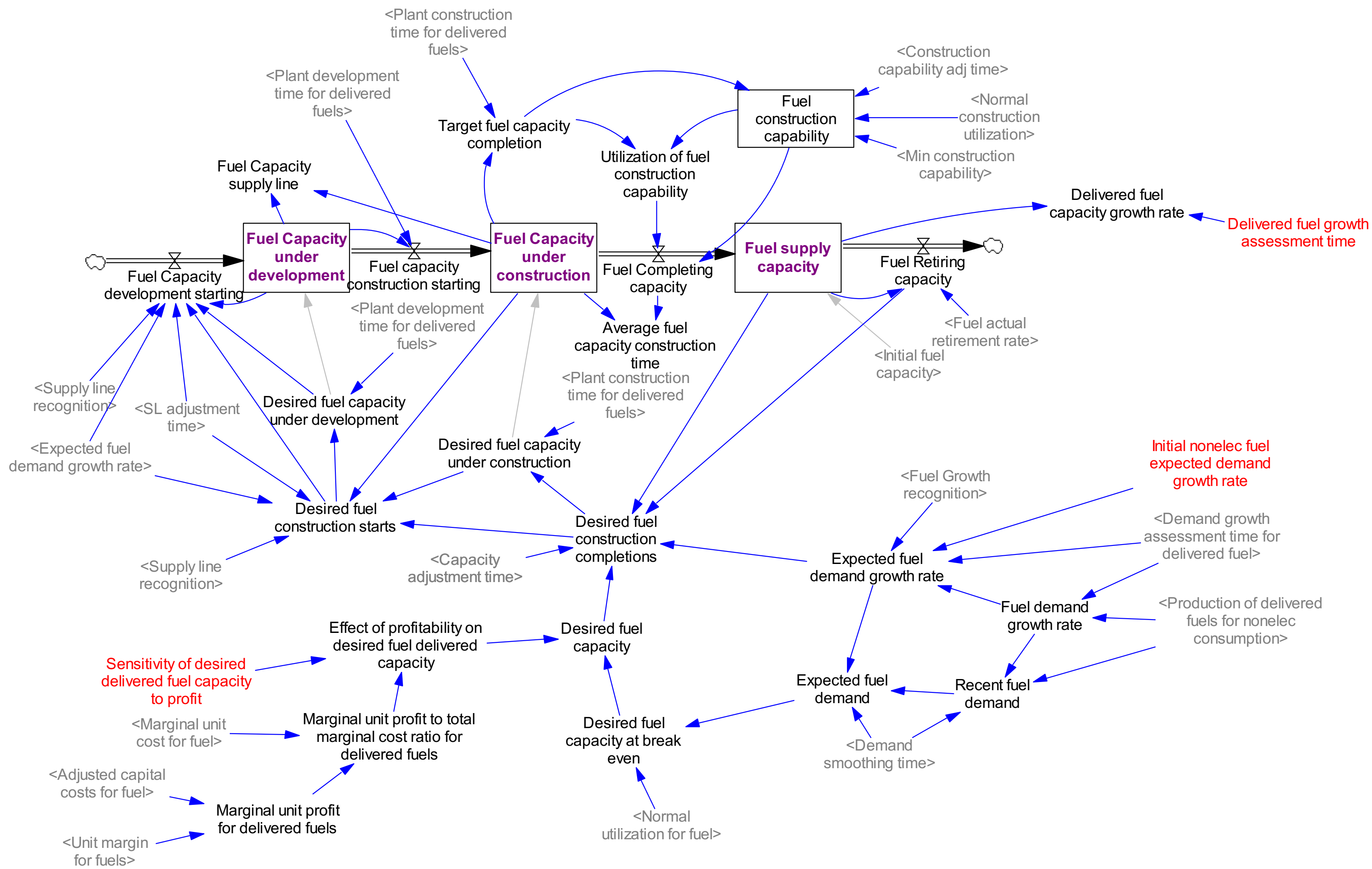


Figure 4-3 Structure of Electric Supply Capacity

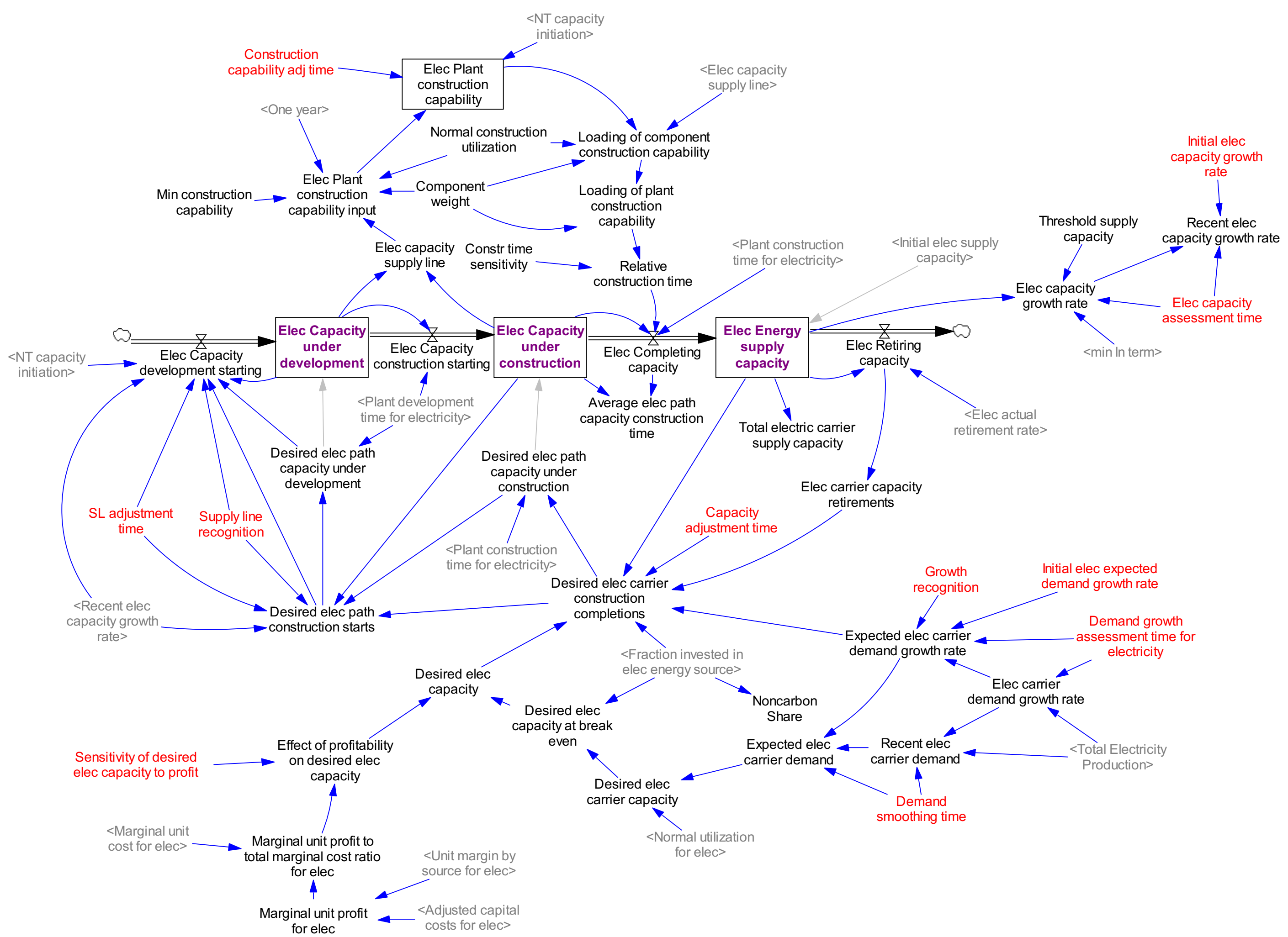


Figure 4-4 Retirement Rates of Delivered Fuel and Electric Supply Capacity

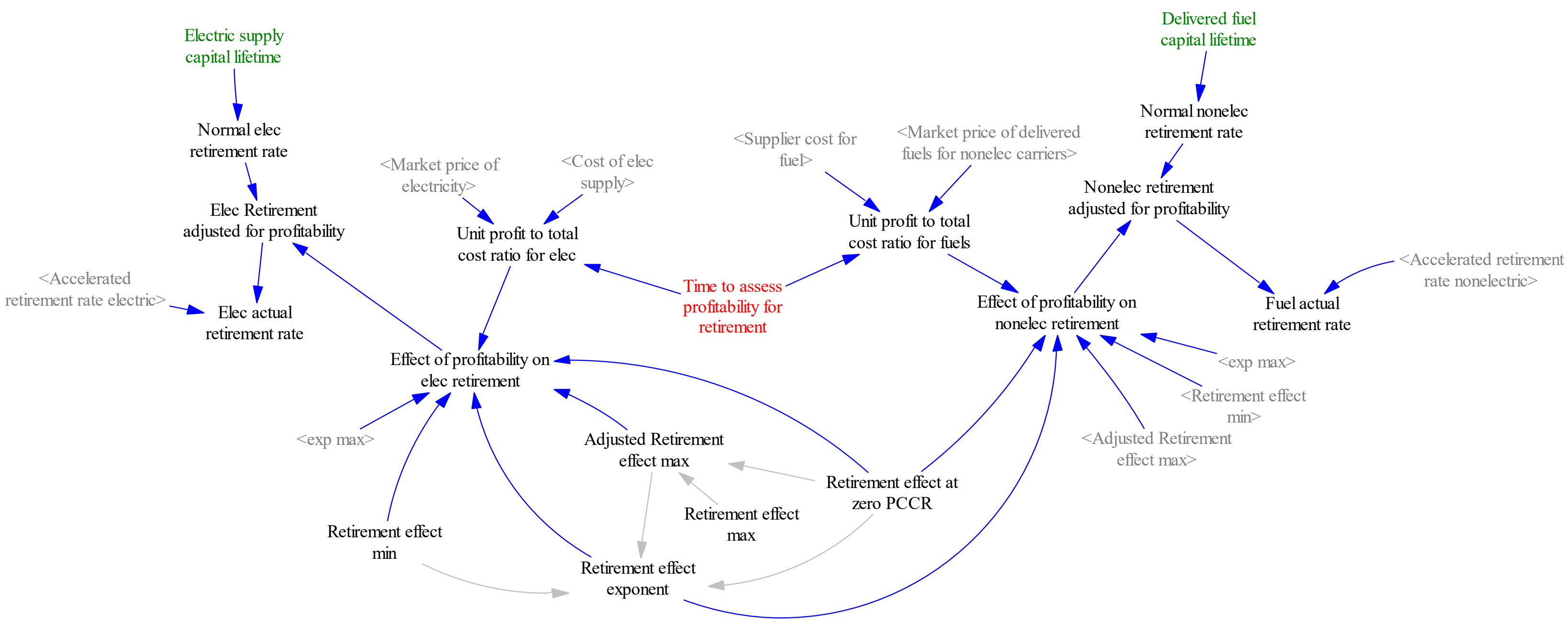


Table 4-4 Extracted Fuel Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Extraction capacity supply line recognition	Multiplier to recognize fraction of difference between desired capacity on order and actual capacity on order to what is added to the capacity added to the order.	0-1	0.5	Dmnl
Sensitivity of desired extracted fuel capacity to profit	The sensitivity parameter driving the expansion or contraction per year as a fraction of existing production capacity.	0-1	0.5	Dmnl
Maximum profitability effect	Ceiling of profitability effect as multiple of desired capacity relative to that at breakeven point.	1-2	1.5	Dmnl
Normal utilization of extraction capacity		0-1	0.8	Dmnl
Initial multiplier on EC on order[Primary Fuels]		1-5	1	Dmnl
Normal extraction capacity order completion time [Primary Fuels]		1-10	4	Years
Extraction capacity SL adjustment time	Time to adjust stock of supply line extracted capacity to desired level.	1-10	2	Years
Extraction capacity adjustment time	Time to adjust stock of extracted capacity on order to desired level.	1-10	8	Years
Initial profit margin for extracted fuel [Primary Fuels]			0	Dmnl
Initial utilization of extraction capacity [Primary Fuels]			0.8	Dmnl

Table 4-4 Extracted Fuel Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Normal extraction capacity lifetime	Coal: Coal Demand, Market Forces, and US Coal Mine Closures. The model fits the data reasonable well across the most frequently observed mine ages (5-35 years). However, the model under-predicts closure early in a mine's life, and over-predicts closure for the few mines between 35-40 years old (albeit with large measured error). https://media.rff.org/documents/RFF20WP2018-13.pdf. Oil and gas fields generally have a lifespan ranging from 15 to 30 years, from first oil to abandonment. Production can last 50 years or more for the largest deposits. Deepwater fields, however, are operated just five to ten years due the very high extraction costs. https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields.		30	Years
Sensitivity of retirement of extracted fuel capacity to profit	The sensitivity parameter driving the retirement per year as a fraction of existing production capacity.	0-0.5	0.5	Dmnl
Initial extracted fuel expected demand growth rate[Primary Fuels]	Based loosely on WEO (2020) primary growth 1990-2000			1/year
Coal			0.005	
Oil			0.01	
Gas			0.03	
Bio			0.01	

Table 4-5 Delivered Fuel Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Stock adjustment time	Time to adjust stock of capacity under construction to desired level.	1-10	8	Years
SL adjustment time	Time to adjust stock of capacity under development to desired level.	1-10	2	Years
Supply line recognition	Multiplier to recognize fraction of difference between desired capacity under development and under construction and actual capacity under development and under construction to what is added to the capacity added to the order.	0-1	0.5	Dmnl
Sensitivity of desired delivered fuel capacity to profit	The sensitivity parameter driving the expansion or contraction per year as a fraction of existing production capacity.	0-1	0.5	Dmnl
Initial nonelec fuel expected demand growth rate[Primary Fuels]	Based loosely on WEO (2020) primary growth 1990-2000			1/year
Coal			0.005	
Oil			0.01	
Gas			0.03	
Bio			0.01	
Demand growth assessment time for delivered fuel		1-20	4	Years
Plant construction capability adjustment time	Adjusts the time to complete construction to reflect capacitated delays due to the limits of construction materials/resources.	1-40	5	Years
Normal construction utilization			0.7	Dmnl

Table 4-5 Delivered Fuel Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Plant development time for delivered fuels[Primary Fuels]	The number of years between ordering a unit of this type of source until the time that construction begins. The time it takes to get government approval for siting, safety, air quality, waste disposal, and other needs, including public comment and review, planning, and securing financing. As studied by Jacobsen, 2009 and others.			Years
Coal			2	
Oil			2	
Gas			2	
Bio			1	
Plant construction time for delivered fuels[Primary Fuels]	The number of years between starting to construct the new resource unit until the time that construction is completed; assumes permitting, planning and financing precede construction.			Years
Coal			4	
Oil			4	
Gas			2	
Bio			4	

Table 4-6 Electric Energy Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Initial elec expected demand growth rate			0.03	1/year
Demand growth assessment time for electricity		1-20	8	Years
Plant construction capability adjustment time	Adjusts the time to complete construction to reflect capacitated delays due to the limits of construction materials/resources.	1-40	5	Years
Sensitivity of desired elec capacity to profit	The sensitivity parameter driving the expansion or contraction per year as a fraction of existing production capacity.	0-1	0.5	Dmnl
Plant development time for electricity[Elec Paths]	The number of years between ordering a unit of this type of source until the time that construction begins. The time it takes to get government approval for siting, safety, air quality, waste disposal, and other needs, including public comment and review, planning, and securing financing. As studied by Jacobsen, 2009 and others.	1-10		Years
Coal			2	
Coal CCS			2	
Oil			2	
Oil CCS			2	
Gas			2	
Gas CCS			2	
Bio			1	
Bio CCS			1	
Nuclear			6	
Hydro			1	
Renewable Types			1	

Table 4-6 Electric Energy Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
New Tech			5	
Plant construction time for electricity [Elec Paths]	The number of years between starting to construct the new resource unit until the time that construction is completed; assumes permitting, planning and financing precede construction.	1-10		Years
Coal			6	
Coal CCS			6	
Oil			4	
Oil CCS			4	
Gas			2	
Gas CCS			2	
Bio			4	
Bio CCS			4	
Nuclear			6	
Hydro			4	
Renewable Types			2	
New Tech			5	
Min construction capability			0.01	(EJ/Year)/ Year
Construction capability adj time	This value adjusts the time to complete construction to reflect capacitated delays due to the limits of construction materials/resources.	1-40	5	years

Table 4-6 Electric Energy Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Component weight[Elec Paths,Component]	Applies the construction of each path to the aggregated construction type.	1, 1, 0, 0, 0, 0, 0, 0, 0, 0; 1, 1, 1, 0, 0, 0, 0, 0, 0, 0; 1, 1, 0, 0, 0, 0, 0, 0, 0, 0; 1, 1, 1, 0, 0, 0, 0, 0, 0, 0; 1, 1, 0, 0, 0, 0, 0, 0, 0, 0; 1, 1, 1, 0, 0, 0, 0, 0, 0, 0; 1, 1, 0, 0, 0, 0, 0, 0, 0, 0; 1, 1, 1, 0, 0, 0, 0, 0, 0, 0; 0, 1, 0, 1, 0, 0, 0, 0, 0, 0; 0, 1, 0, 0, 1, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 1, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0, 1, 0, 0, 0; 0, 0, 0, 0, 0, 0, 0, 1, 0, 0; 0, 0, 0, 0, 0, 0, 0, 0, 1, 0; 0, 0, 0, 0, 0, 0, 0, 0, 0, 1;		Dmnl
Constr time sensitivity	Sensitivity of how much longer construction takes as afunction of loading, where a value of 1 indicates a linear relationship.		1	dmnl

Table 4-7 Retirement Rates of Delivered Fuel and Electric Supply Capacity Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Delivered fuel capital lifetime[Primary Fuels]	Time that the delivered fuel capital is active before being retired for each energy resource.	1-50		Years
Coal, Oil , Gas			30	
Bio			40	
Electric supply capital lifetime[Elec Paths]	Time that the electric supply capital is active before being retired for each energy resource.	1-50		Years
Bio, Bio CCS			40	
Renewables			25	
All others			30	
Retirement effect max	Defines the function for profitability effects of supply on retirement rates		8	Dmnl
Retirement effect at zero margin to total cost ratio by carrier			1.1	Dmnl
Retirement effect min by source			0.8	Dmnl
Retirement effect exponent			2	Dmnl
Time to assess profitability for retirement		1-30	5	Years
Target accelerated retirement rate delivered fuels[Primary Fuels]	The forced increase in retirement rate starting in the specified year for each delivered fuel.	0-0.1	0	1/year
Target accelerated retirement rate electric[Elec Paths]	The forced increase in retirement rate starting in the specified year for each electric path.	0-0.1	0	1/year

Table 4-8. Extracted Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Extraction capacity[Primary Fuels]	The available extraction capacity for each fuel. INTEG(Extraction capacity completions[Primary Fuels]-Extraction capacity retirements[Primary Fuels], Initial extraction capacity[Primary Fuels])	
Extraction capacity on order[Primary Fuels]	The extraction capacity for each extracted fuel on order. INTEG(Extraction capacity orders[Primary Fuels]-Extraction capacity completions[Primary Fuels], (Extraction capacity[Primary Fuels]/Normal extraction capacity lifetime[Primary Fuels])*Normal extraction capacity order completion time[Primary Fuels]* Initial multiplier on EC on order[Primary Fuels])	EJ/Year
Initial extraction capacity[Primary Fuels]	Demand of delivered fuels[Primary Fuels]/Initial utilization of extraction capacity[Primary Fuels]	EJ/year
Utilization of extraction capacity[Primary Fuels]	The fraction of capacity that is used, assuming all extracted is delivered. ZIDZ(Demand of delivered fuels[Primary Fuels],Extraction capacity[Primary Fuels])	Dmnl
Extraction capacity orders[Primary Fuels]	The amount of extraction capacity being ordered each year. MAX(0, Desired extraction capacity completions[Primary Fuels] + Desired extraction capacity on order[Primary Fuels]*Expected fuel demand growth rate[Primary Fuels] + Extraction capacity supply line recognition * (Desired extraction capacity on order[Primary Fuels] - Extraction capacity on order[Primary Fuels])/Extraction capacity adjustment time)	EJ/year/ year
Extraction capacity retirements[Primary Fuels]	The amount of extraction capacity being retired each year. Extraction capacity[Primary Fuels] / Extraction capacity lifetime[Primary Fuels]	EJ/year/ year

Table 4-8. Extracted Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Extraction capacity completions[Primary Fuels]	The amount of extraction capacity of each fuel that completes the construction process each year. Extraction capacity construction capability[Primary Fuels] * Utilization of extraction capacity construction capability[Primary Fuels]	EJ/year/ year
Desired extraction capacity on order[Primary Fuels]	Desired extraction capacity adjusted for non cost policies. Desired extraction capacity completions[Primary Fuels] * Normal extraction capacity order completion time*Non cost adjustment to extraction[Primary Fuels]	EJ/year
Desired extraction capacity completions[Primary Fuels]	MAX(0, Extraction capacity retirements[Primary Fuels] + Desired extraction capacity[Primary Fuels]*Expected extracted fuel demand growth rate[Primary Fuels]+ (Desired extraction capacity[Primary Fuels]-Extraction capacity[Primary Fuels])/Extraction capacity adjustment time)	EJ/year/ year
Target extraction capacity completion[Primary Fuels]	Extraction capacity on order[Primary Fuels] / Normal extraction capacity order completion time	EJ/year/ year
Utilization of extraction capacity construction capability [Primary Fuels]	MIN(1, Target extraction capacity completion[Primary Fuels] / Extraction capacity construction capability[Primary Fuels])	Dmnl
Extraction capacity construction capability[Primary Fuels]	The industry capacity is a function of what the current target is, delayed by the time it takes to adjust the plant's capability. SMOOTH(MAX(Min construction capability, Target extraction capacity completion[Primary Fuels]/Normal construction utilization) , Construction capability adj time)	EJ/year/ year
Desired extraction capacity at break even [Primary Fuels]	Expected extracted fuel demand[Primary Fuels]/Normal utilization of extraction capacity	EJ/Year

Table 4-8. Extracted Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Effect of profitability on desired extraction capacity [Primary Fuels]	Development increases when expected profits are high and contracts when expected profits are low. The sensitivity parameter is the fractional rate of expansion or contraction per year as a fraction of existing production capacity. Smoothly approaches the floor of 0 and ceiling of *Maximum profitibaility effect*, defaulted to 1.5. Maximum profitability effect / (1 + Sensitivity of desired extracted fuel capacity to profit * EXP (MIN (Max exp term , - Profitability exponent * Expected unit profit for new extracted fuel[Primary Fuels])))	Dmnl
Desired extraction capacity	Desired capacity accounting for growth and profitability. Desired extraction capacity at break even[Primary Fuels]*Effect of profitability on desired extraction capacity[Primary Fuels]	EJ/year
Effect of profitability on extraction capacity lifetime [Primary Fuels]	Increases or decreases the retirement rate of the extraction capacity depending on its profitability. MAX(0, 1 + Sensitivity of retirement of extracted fuel capacity to profit*Unit profit for existing extraction capacity[Primary Fuels])	Dmnl
Extraction capacity lifetime [Primary Fuels]	Normal extraction capacity lifetime [Primary Fuels] * Effect of profitability on extraction capacity lifetime[Primary Fuels]	Years
Extraction capacity growth rate	LN(Extraction capacity[Primary Fuels]/SMOOTH(Extraction capacity[Primary Fuels], Extraction capacity growth assessment time))/Extraction capacity growth assessment time	1/year
Recent extraction capacity growth rate[Primary Fuels]	SMOOTHi(Extracion capacity growth rate[Primary Fuels], Extraction capacity growth assessment time,Initial extraction capacity growth rate[Primary Fuels])	1/year
Extracted fuel demand growth rate[Primary Fuels]	LN(Production of delivered fuels [Primary Fuels]/SMOOTH(Production of delivered fuels[Primary Fuels], Demand growth assessment time for delivered fuel))/Demand growth assessment time for delivered fuel	1/year

Table 4-8. Extracted Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Recent extracted fuel demand[Primary Fuels]	SMOOTHi(Production of delivered fuels [Primary Fuels], Demand smoothing time, Production of delivered fuels [Primary Fuels]*EXP(-Extracted fuel demand growth rate[Primary Fuels]*Demand smoothing time))	EJ/year
Expected extracted fuel demand[Primary Fuels]	MAX(0, Recent extracted fuel demand[Primary Fuels]* (1 + Expected extracted fuel demand growth rate[Primary Fuels]*Demand smoothing time))	EJ/year
Expected extracted fuel demand growth rate[Primary Fuels]	Fuel Growth recognition[Primary Fuels] * SMOOTHi(Extracted fuel demand growth rate[Primary Fuels], Demand growth assessment time for delivered fuel,Initial extracted fuel expected demand growth rate[Primary Fuels])	1/year

Table 4-9. Delivered Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Fuel supply capacity[Primary Fuels]	The available capacity of each delivered fuel. INTEG(Fuel Completing capacity[Primary Fuels]-Fuel Retiring capacity[Primary Fuels], Initial fuel capacity[Primary Fuels])	
Fuel Capacity under construction [Primary Fuels]	The capacity under construction of each delivered fuel. INTEG(Fuel capacity construction starting[Primary Fuels]-Fuel Completing capacity[Primary Fuels], Desired fuel capacity under construction[Primary Fuels])	EJ/Year
Fuel Capacity under development[Primary Fuels]	The capacity under development of each delivered fuel. INTEG(Fuel Capacity development starting[Primary Fuels]-Fuel capacity construction starting[Primary Fuels], Desired fuel capacity under development[Primary Fuels])	EJ/year
Initial fuel capacity [Primary Fuels]	WEO primary energy EJ[Primary Fuels]/Initial utilization from initial margin to total cost ratio[Primary Fuels]	EJ/year
Fuel Retiring capacity[Primary Fuels]	The amount of delivered fuel capacity being retired each year. Fuel supply capacity[Primary Fuels]*Actual retirement rate [Primary Fuels]	EJ/year/year
Fuel Completing capacity[Primary Fuels]	The amount of capacity of each delivered fuel that completes the construction process each year. Fuel Plant construction capability[Primary Fuels]*Utilization of fuel plant construction capability[Primary Fuels]	EJ/year/year
Fuel capacity construction starting[Primary Fuels]	The amount of capacity of each delivered fuel that begins the construction process each year, following development. Fuel Capacity under development[Primary Fuels]/Plant development time for delivered fuels[Primary Fuels]	EJ/year/year

Table 4-9. Delivered Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Fuel Capacity development starting[Primary Fuels]	The amount of capacity of each delivered fuel that begins the development process each year. MAX(0, Desired fuel construction starts[Primary Fuels] + Desired fuel capacity under development[Primary Fuels]*Expected fuel demand growth rate [Primary Fuels] + Supply line recognition *(Desired fuel capacity under development[Primary Fuels]-Fuel Capacity under development[Primary Fuels])/Stock adjustment time)	EJ/year/year
Desired fuel capacity under development[Primary Fuels]	The amount of delivered fuel capacity being ordered each year. Desired fuel construction starts[Primary Fuels] * Plant development time for delivered fuels[Primary Fuels]	EJ/year
Desired fuel construction starts[Primary Fuels]	MAX(0, Desired fuel construction completions[Primary Fuels] + Desired fuel capacity under construction[Primary Fuels]*Expected fuel demand growth rate[Primary Fuels] + Supply line recognition* (Desired fuel capacity under construction[Primary Fuels]-Fuel Capacity under construction[Primary Fuels])/Stock adjustment time)	EJ/year/year
Desired fuel capacity under construction[Primary Fuels]	Desired fuel construction completions[Primary Fuels]* Plant construction time for delivered fuels[Primary Fuels]	EJ/year
Desired fuel capacity at break even [Primary Fuels]	Expected fuel demand[Primary Fuels] / Normal utilization for fuel[Primary Fuels]	EJ/Year

Table 4-9. Delivered Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Effect of profitability on desired delivered fuel capacity[Primary Fuels]	Development increases when expected profits are high and contracts when expected profits are low. The sensitivity parameter is the fractional rate of expansion or contraction per year as a fraction of existing production capacity. Smoothly approaches the floor of 0 and ceiling of *Maximum profitibaility effect*, defaulted to 1.5. Maximum profitability effect / (1+ Sensitivity of desired delivered fuel capacity to profit * EXP (MIN (Max exp term , -Profitability exponent * Marginal unit profit to total marginal cost ratio for delivered fuels[Primary Fuels])))	Dmnl
Marginal unit profit to total marginal cost ratio for delivered fuels[Primary Fuels]	ZIDZ(Marginal unit profit for delivered fuels[Primary Fuels], Marginal unit cost for fuel[Primary Fuels])	Dmnl
Marginal unit profit for delivered fuels[Primary Fuels]	Unit margin for fuels[Primary Fuels]-Adjusted capital costs for fuel[Primary Fuels]	$/GJ
Desired fuel capacity[Primary Fuels]	Desired capacity accounting for growth and profitability. Desired fuel capacity at break even[Primary Fuels]*Effect of profitability on desired fuel delivered capacity[Primary Fuels]	EJ/year
Expected fuel demand growth rate[Primary Fuels]	Fuel Growth recognition[Primary Fuels] * SMOOTHi(Fuel demand growth rate[Primary Fuels], Demand growth assessment time for delivered fuel, Initial nonelec fuel expected demand growth rate[Primary Fuels])	1/year
Fuel demand growth rate[Primary Fuels]	LN(Production of delivered fuels for nonelec consumption[Primary Fuels]/SMOOTH(Production of delivered fuels for nonelec consumption[Primary Fuels], Demand growth assessment time for delivered fuel))/Demand growth assessment time for delivered fuel	1/year

Table 4-9. Delivered Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Recent fuel demand[Primary Fuels]	SMOOTHi(Production of delivered fuels for nonelec consumption[Primary Fuels], Demand smoothing time, Production of delivered fuels for nonelec consumption[Primary Fuels]*EXP(-Fuel demand growth rate[Primary Fuels]*Demand smoothing time))	EJ/year
Expected fuel demand[Primary Fuels]	MAX(0, Recent fuel demand[Primary Fuels]* (1 + Expected fuel demand growth rate[Primary Fuels]*Demand smoothing time))	EJ/year
Target fuel capacity completion[Primary Fuels]	Fuel Capacity under construction[Primary Fuels]/Plant construction time for delivered fuels[Primary Fuels]	EJ/year/year
Utilization of fuel construction capability[Primary Fuels]	MIN(1,Target fuel capacity completion[Primary Fuels]/Fuel construction capability[Primary Fuels])	Dmnl
Fuel Plant construction capability[Primary Fuels]	The industry capacity is a function of what the current target is, delayed by the time it takes to adjust the plant's capability. SMOOTH(MAX(Min construction capability,Target fuel capacity completion[Primary Fuels]/Normal construction utilization),Construction capability adj time)	EJ/year/year
Average fuel capacity construction time	ZIDZ(Fuel Capacity under construction[Primary Fuels],Fuel Completing capacity[Primary Fuels])	Years
Normal fuel capacity supply line time[Primary Fuels]	The total delay from construction and development without capacitated delays. Plant construction time for delivered fuels[Primary Fuels]+Plant development time for delivered fuels[Primary Fuels]	Years
Fuel Development fraction[Primary Fuels]	Plant development time for delivered fuels[Primary Fuels]/Normal fuel capacity supply line time[Primary Fuels]	Dmnl
Fuel Capacity supply line[Primary Fuels]	Fuel Capacity under development[Primary Fuels]+Fuel Capacity under construction[Primary Fuels]	EJ/year

Table 4-9. Delivered Fuel Supply Capacity Calculated Parameters

Parameter	Definition	Units
Delivered fuel capacity growth rate[Primary Fuels]	LN(Fuel supply capacity[Primary Fuels]/SMOOTH(Fuel supply capacity[Primary Fuels], Delivered fuel growth assessment time))/Delivered fuel growth assessment time	1/year

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Elec Energy supply capacity[Elec Paths	The available capacity of each electric path. INTEG(Elec Completing capacity[Elec Paths]-Elec Retiring capacity[Elec Paths], Initial supply capacity[Elec Paths])	EJ/year
Elec Capacity under construction[Elec Paths]	The electric energy capacity of each source under construction. INTEG(Elec Capacity construction starting[Elec Paths]-Elec Completing capacity[Elec Paths], Desired elec path capacity under construction[Elec Paths])	EJ/Year
Elec Capacity under development[Elec Paths]	The electric energy capacity of each source path under development. INTEG(Elec Capacity development starting[Elec Paths]-Elec Capacity construction starting[Elec Paths], Desired elec path capacity under development[Elec Paths])	EJ/year
Initial supply capacity[Elec Paths]	Initialized to 1990 WEO (2020) power generation and initial electric utilization consistent with calculated indicated utilization as per market clearing and utilization, discussed in Section 5. ZIDZ(Initial generation[Elec Paths],Initial elec utilization[Elec Paths])	EJ/year
Elec Retiring capacity[Elec Paths]	The amount of electric energy capacity of each source is retired each year. Elec Energy supply capacity[Elec Paths]*Actual retirement rate[Elec Paths]	EJ/year/year

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Elec Completing capacity[Elec Paths]	The amount of electric energy capacity of each source that completes the construction process each year. Elec Capacity under construction[Elec Paths]/(Relative construction time[Elec Paths]*Plant construction time for electricity[Elec Paths])	EJ/year/year
Average elec path capacity construction time[Elec Paths]	ZIDZ(Elec Capacity under construction[Elec Paths],Elec Completing capacity[Elec Paths])	years
Elec Capacity construction starting[Elec Paths]	The amount of electric energy capacity of each source that begins the construction process each year, following development. Elec Capacity under development[Elec Paths]/Plant development time for electricity[Elec Paths]	EJ/year/year
Elec Capacity development starting[Elec Paths]	The amount of electric energy capacity of each source that begins the development process each year.	EJ/year/year
[All elec but new]	MAX(0, Desired elec path construction starts[All elec but new] + Desired elec path capacity under development[All elec but new]*Expected elec carrier demand growth rate+ Supply line recognition*(Desired elec path capacity under development[All elec but new] -Elec Capacity under development[All elec but new])/SL adjustment time)	
[New]	MAX(NT capacity initiation/SL adjustment time, MAX(0, Desired elec path construction starts[new] + Desired elec path capacity under development[new]*Expected elec carrier demand growth rate+ Supply line recognition*(Desired elec path capacity under development[new] -Elec Capacity under development[new])/SL adjustment time))	

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Desired elec path capacity under development[Elec Paths]	For each source, the desired amount of electric energy capacity under development to achieve the desired amount of electric capacity. Desired elec path construction starts[Elec Paths] * Plant development time for electricity[Elec Paths]	EJ/year
Desired elec path capacity under construction[Elec Paths]	For each source, the desired amount of electric energy capacity under construction to achieve the desired amount of electric capacity. Desired elec carrier construction completions[Elec Paths] * Plant construction time for electricity[Elec Paths]	EJ/year
NT capacity initiation	ramp(Commercialized NT capacity initiation rate /Breakthrough commercialization time for electricity[new], Breakthrough success year for elec[new], Year new tech enters market)	EJ/year
Year new tech enters market	Breakthrough success year for elec[new]+Breakthrough commercialization time for electricity[new]	Year
Desired elec path construction starts[Elec Paths]	For each source, the desired amount of electric energy capacity starting construction to achieve the desired amount of electric capacity. MAX(0, Desired elec carrier construction completions[Elec Paths] + Desired elec path capacity under construction[Elec Paths] *Expected elec carrier demand growth rate+ Supply line recognition*(Desired elec path capacity under construction[Elec Paths] -Elec Capacity under construction[Elec Paths])/SL adjustment time)	EJ/year/year

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Desired elec construction completions[Elec Paths]	The desired amount of electric energy capacity from each path to be completing construction, where the fraction of the total desired capacity is determined in the logit function, discussed in Section 6. MAX(0, Fraction invested in elec energy source[Elec Paths]*Elec carrier capacity retirements + Desired elec capacity[Elec Paths]*Expected elec carrier demand growth rate +(Desired elec capacity[Elec Paths]-Elec Energy supply capacity[Elec Paths])/Capacity adjustment time)	EJ/year
Desired elec carrier capacity	The desired amount of total electric capacity. Assumes 100% centralized. Expected elec carrier demand/ Normal utilization for elec	EJ/year
Desired elec capacity at break even[Elec Paths]	Desired elec carrier capacity*Fraction invested in elec energy source[Elec Paths]	EJ/year
Desired elec capacity[Elec Paths]	Desired capacity accounting for growth and profitability. Effect of profitability on desired elec capacity[Elec Paths]*Desired elec capacity at break even[Elec Paths]	EJ/year

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Effect of profitability on desired elec capacity[Elec Paths]	Development increases when expected profits are high and contracts when expected profits are low. The sensitivity parameter is the fractional rate of expansion or contraction per year as a fraction of existing production capacity. Smoothly approaches the floor of 0 and ceiling of *Maximum profitibaility effect*, defaulted to 1.5. Maximum profitability effect / (1+ Sensitivity of desired elec capacity to profit * EXP (MIN (Max exp term , - Profitability exponent * Marginal unit profit to total marginal cost ratio for elec[Elec Paths])))	Dmnl
Marginal unit profit to total marginal cost ratio for elec[Elec Paths]	ZIDZ(Marginal unit profit for elec[Elec Paths], Marginal unit cost for elec[Elec Paths])	Dmnl
Expected elec carrier demand	Net unit profit divided by the embodied annualized capital cost. Recent elec carrier demand* (1 + Expected elec carrier demand growth rate*Demand smoothing time)	EJ/year
Recent elec carrier demand	SMOOTHi(Aggregate elec demand to producers, Demand smoothing time, Aggregate elec demand to producers*EXP(-Elec carrier demand growth rate*Demand smoothing time))	EJ/year
Elec carrier demand growth rate	LN(Aggregate elec demand to producers/SMOOTH(Aggregate elec demand to producers, Demand growth assessment time for electricity))/Demand growth assessment time for electricity	1/year
Expected elec carrier demand growth rate	Growth recognition * SMOOTHi(Elec carrier demand growth rate, Demand growth assessment time for electricity, Initial elec expected demand growth rate)	1/year
Elec carrier energy supply capacity	Total electric energy capacity. SUM(Elec Energy supply capacity[Elec Paths!])	EJ/year

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Elec carrier capacity retirements	Total electric energy retiring. SUM(Elec Retiring capacity[Elec Paths!])	EJ/year/year
Elec capacity supply line[Elec Paths]	Elec Capacity under development[Elec Paths]+Elec Capacity under construction[Elec Paths]	EJ/year
Elec Plant construction capability input[Component]	MAX (Min construction capability , SUM (Elec Capacity under construction[Elec Paths!] / Plant construction time for electricity[Elec Paths!] * Component weight[Elec Paths!,Component]))	EJ/year
Elec Plant construction capability	The industry capacity is a of what the current target is, delayed by the time it takes to adjust the plant's capability.	EJ/year
[All components but new]	SMOOTH (Elec Plant construction capability input[All components but new] / Normal construction utilization , Construction capability adj time)	
[Cnew]	NT capacity initiation / One year + SMOOTH (Elec Plant construction capability input[Cnew] / Normal construction utilization , Construction capability adj time)	
Utilization of elec plant construction capability[Elec Paths]	MIN(1,Ratio of target elec capacity completion to current capability[Elec Paths])	Dmnl
Loading of component construction capability[Component]	ZIDZ (Elec Plant construction capability input[Component] , Elec Plant construction capability[Component])	Dmnl
Loading of plant construction capability[Elec Paths]	SUM (Component weight[Elec Paths,Component!] * Loading of component construction capability[Component!]) / SUM (Component weight[Elec Paths,Component!])	Dmnl
Relative construction time[Elec Paths]	MAX(1,Loading of plant construction capability[Elec Paths])^Constr time sensitivity	dmnl

Table 4-10. Electric Energy Supply Capacity Calculated Parameters

Parameter	Definition	Units
Normal elec capacity supply line time[Elec Paths]	The total delay from construction and development without capacitated delays. Plant construction time for electricity[Elec Paths]+Plant development time for electricity[Elec Paths]	Years
Elec Development fraction[Elec Paths]	Plant development time for electricity[Elec Paths]/Normal elec capacity supply line time[Elec Paths]	Dmnl
Elec capacity supply line[Elec Paths]	Elec Capacity under development[Elec Paths]+Elec Capacity under construction[Elec Paths]	EJ/year
Elec capacity growth rate		1/year
ElecExist	LN(Elec Energy supply capacity[Elec exists]/SMOOTH(Elec Energy supply capacity[Elec exists], Elec capacity assessment time))/Elec capacity assessment time	
CCS and New	LN(MAX(min ln term, Elec Energy supply capacity[CCS and New]/SMOOTH(MAX(Threshold supply capacity,Elec Energy supply capacity[CCS and New]), Elec capacity assessment time)))/Elec capacity assessment time	

Table 4-11. Retirement Rates of Delivered Fuel and Electric Supply Capacity Calculated Parameters

Parameter	Definition	Units
Normal elec retirement rate [Elec Paths	1/Electric supply capital lifetime[Elec Paths]	1/year
Elec Retirement adjusted for profitability [Elec Paths]	Normal elec retirement rate[Elec Paths] *Effect of profitability on elec retirement[Elec Paths]	1/year
Actual elec retirement rate[Elec Paths]	Accelerated retirement rate electric[Elec Paths]+Elec Retirement adjusted for profitability[Elec Paths]	1/year
Unit profit to total cost ratio for elec [Elec Paths]	SMOOTHi(ZIDZ(Market price of electricity - Cost of elec supply[Elec Paths],Cost of elec supply[Elec Paths]), Time to assess profitability for retirement, 1)	Dmnl
Normal nonelec retirement rate[Primary Fuels]	1/Delivered fuel capital lifetime[Primary Fuels]	1/year
Nonelec retirement adjusted for profitability[Primary Fuels]	Normal nonelec retirement rate[Primary Fuels] *Effect of profitability on nonelec retirement[Primary Fuels]	1/year
Fuel actual retirement rate[Primary Fuels]	Accelerated retirement rate nonelectric[Primary Fuels]+Nonelec retirement adjusted for profitability[Primary Fuels]	1/year
Unit profit to total cost ratio for fuels [Primary Fuels]	SMOOTHi(ZIDZ(Market price of delivered fuels for nonelec carriers[Primary Fuels]-Supplier cost for fuel[Primary Fuels],Supplier cost for fuel[Primary Fuels]), Time to assess profitability for retirement, 1)	dmnl

Table 4-11. Retirement Rates of Delivered Fuel and Electric Supply Capacity Calculated Parameters

Parameter	Definition	Units
Effect of profitability on retirement by path[Elec Paths]	Affects the lifetime of supply capital depending on profitability over the time to assess it according to an S-shape curve defined by the min, max, and zero effect parameters. 1/ (((1/Adjusted Retirement effect max) + ((1/Retirement effect at zero margin to total cost ratio)-(1/Adjusted Retirement effect max))*EXP(MIN(exp max,Retirement effect exponent*Unit profit to total cost ratio for elec[Elec Paths]))) / (1 + ((1/Retirement effect at zero margin to total cost ratio)-(1/Adjusted Retirement effect max)) / (1/Retirement effect min) *(EXP(MIN(exp max,Retirement effect exponent*Unit profit to total cost ratio for elec[Elec Paths]))-1)))	Dmnl
Effect of profitability on nonelec retirement[Primary Fuels]	Affects the lifetime of supply capital depending on profitability over the time to assess it according to an S-shape curve defined by the min, max, and zero effect parameters. 1/ (((1/Adjusted Retirement effect max) + ((1/Retirement effect at zero margin to total cost ratio)-(1/Adjusted Retirement effect max))*EXP(MIN(exp max,Retirement effect exponent*Unit profit to total cost ratio for fuels[Primary Fuels]))) / (1 + ((1/Retirement effect at zero margin to total cost ratio)-(1/Adjusted Retirement effect max)) / (1/Retirement effect min) *(EXP(MIN(exp max,Retirement effect exponent*Unit profit to total cost ratio for fuels[Primary Fuels]))-1)))	dmnl

4.2 Drivers of Cost of Supply

Several factors affect the cost *of each supply source*, including,

- A baseline or *reference cost*
- a learning-by-doing effect from the accumulation of experience in capacity installation
- a reduction in cost due to the accumulation of R&D
- an exogenous user-specified cost reduction from technological breakthroughs
- cost of fuels as determined by the delivered fuel market price and efficiency of fuel use
- resource constraints
- source subsidies/taxes
- storage costs for renewables
- soft costs for renewables
- emissions cost from carbon pricing
- a "pipeline overheating" premium from supply chain constraints on capacity installation, Section 4.1

Figure 4-5 shows the model structure to determine the reference cost, while Figure 4-6 through Figure 4-16 show the structures to calculate the drivers of the marginal and average costs, i.e., tech effect, pipeline effect, and emissions cost.

Figure 4-5 Reference Cost

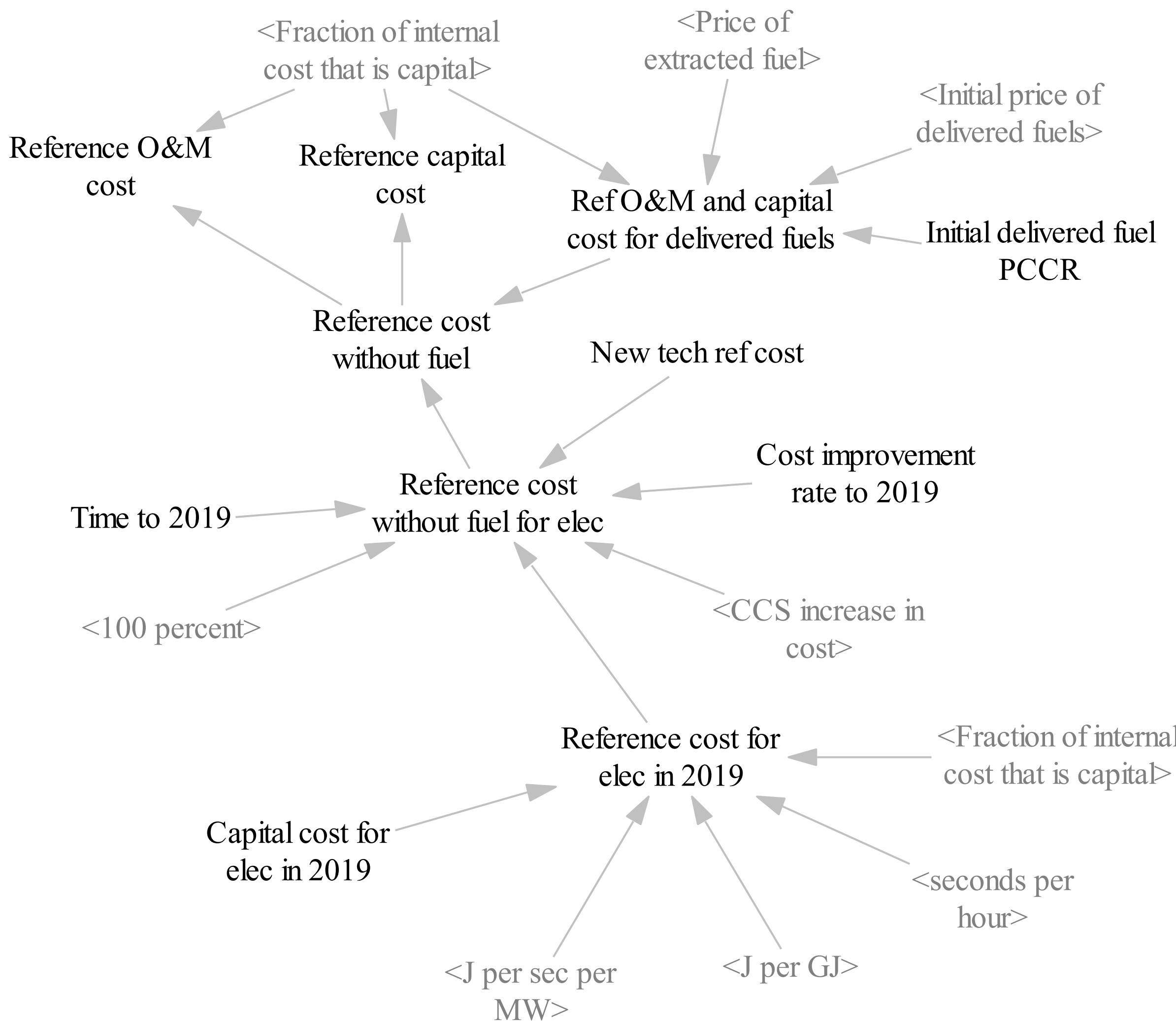


Table 4-12 Reference Cost Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Cost improvement rate to 2018[All but new sources]	Estimated rate of cost improvement of each path. Renewables set to approximate 1990 levels			1/year
Coal			0	
Oil			0	
Gas			0.014	
Bio			0.001	
Nuclear			0	
Hydro			0	
Wind			0.05	
Solar			0.125	
Geothermal			0	
Other renewables			0.05	
Time to 2018	Time from 1990 to 2018		28	Years
Capital cost for elec in 2018[ElecExist]	Total levelized cost of electricity (LCOE) without fuel in 2018. Lazard 2019. https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf IRENA 2018. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf IEA. 2019. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf			dollars/(MW*hour)
Coal			40	

Table 4-12 Reference Cost Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Oil			40	
Gas			25	
Bio			40	
Nuclear			90	
Hydro			85	
Wind			40	
Solar			40	
Geothermal			65	
Other renewables			100	
New tech ref cost	Sets the reference cost of new tech to be conceptually infinite, reflecting that the new tech does not yet exist.		2000	$/GJ
Fraction of delivered fuels internal cost that is capital [Primary Fuels]	Fraction of marginal internal cost of each path that represents the marginal annualized capital costs. The remainder is the marginal O&M cost. Assumes the fraction is the same for the electric thermal paths with and without CCS.	0-1		Dmnl
Coal			0.8	
Oil			0.8	
Gas			0.8	
Bio			0.8	
Fraction of elec internal cost that is capital [Elec Paths]				
Coal			0.95	
Oil			0.95	
Gas			0.7	
Bio			0.8	
Nuclear			0.8	
Hydro			0.8	

Table 4-12 Reference Cost Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Wind			0.8	
Solar			0.9	
Geothermal			0.7	
Other Renewables			0.8	
New			0.9	
CCS increase in cost[CCS Paths]	Set to 90% increase to so that with CCS learning since 1990, achieves current 66% increase, which is calculated for coal and gas from NREL (https://www.nrel.gov/docs/fy17osti/67645.pdf).		90	Percent

Table 4-13. Reference Cost Calculated Parameters

Parameter	Definition	Units
Reference cost for elec in 1990[Elec Paths]	Takes capital cost from 2018 and calculates the total cost, converting it to $/GJ. Capital cost for elec in 2018[ElecExist]*(J per GJ/J per sec per MW/seconds per hour)/Fraction of internal cost that is capital[ElecExist]	$/GJ
Reference cost without fuel for elec[Elec Paths]	The baseline cost of each electric energy path without fuel costs, calculated for the existing paths by taking the reported 2019 values and assumed cost improvement rates.	$/GJ
[Elec Paths] :EXCEPT: [CCS and New]	INITIAL(Reference cost for elec in 2018[ElecExist]*EXP(Time to 2018*Cost improvement rate to 2018[ElecExist]))	
[CCS Paths]	INITIAL(Reference cost without fuel for elec[Elec thermal] *(1+CCS increase in cost[CCS Paths]/"100 percent"))	
[New]	INITIAL(New tech ref cost)	
"Reference elec O&M cost"[Elec Paths]	INITIAL(Reference cost without fuel for elec[Elec Paths]*(1-Fraction of elec internal cost that is capital[Elec Paths])	$/GJ
Reference elec capital cost[Elec Paths]	INITIAL(Reference cost without fuel for elec[Elec Paths]*Fraction of elec internal cost that is capital[Elec Paths])	$/GJ
"Ref O&M and capital cost for delivered fuels"	INITIAL((Initial price of delivered fuels[Primary Fuels]-Price of extracted fuel[Primary Fuels])/(1+(Initial delivered fuel margin to total cost ratio-1)*Fraction of delivered fuels internal cost that is capital[Primary Fuels]))	$/GJ
Reference fuel capital cost[Primary Fuels]	INITIAL("Ref O&M and capital cost for delivered fuels"[Primary Fuels]*Fraction of delivered fuels internal cost that is capital[Primary Fuels])	$/GJ
"Reference fuel O&M cost"[Primary Fuels]	INITIAL("Ref O&M and capital cost for delivered fuels"[Primary Fuels]*(1-Fraction of delivered fuels internal cost that is capital[Primary Fuels]))	$/GJ

4.2.1 Experience and Tech Breakthrough Effects on Cost

Figure 4-6 Experience Effect on Cost

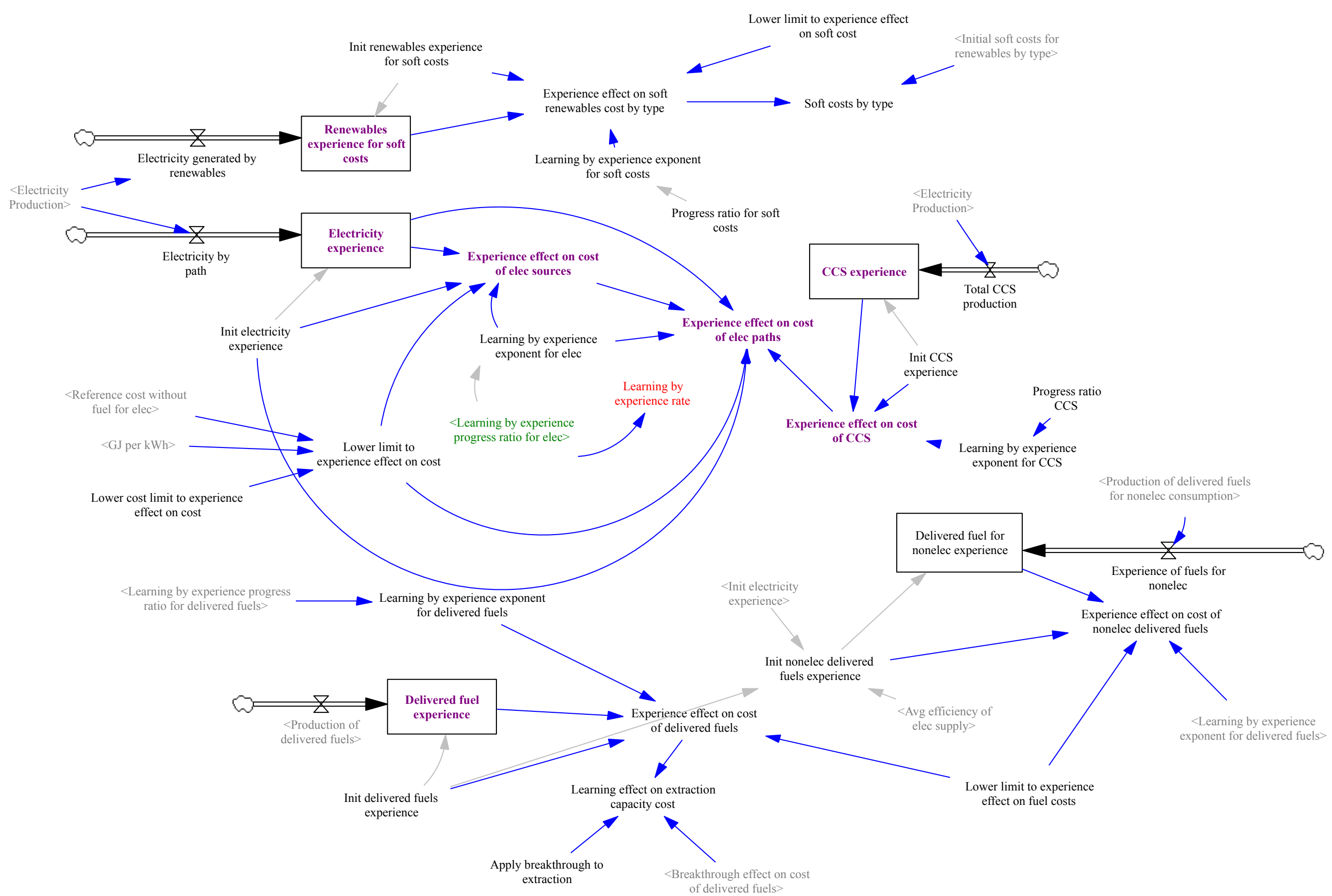


Figure 4-7 Breakthrough Effect on Cost for Electric Energy

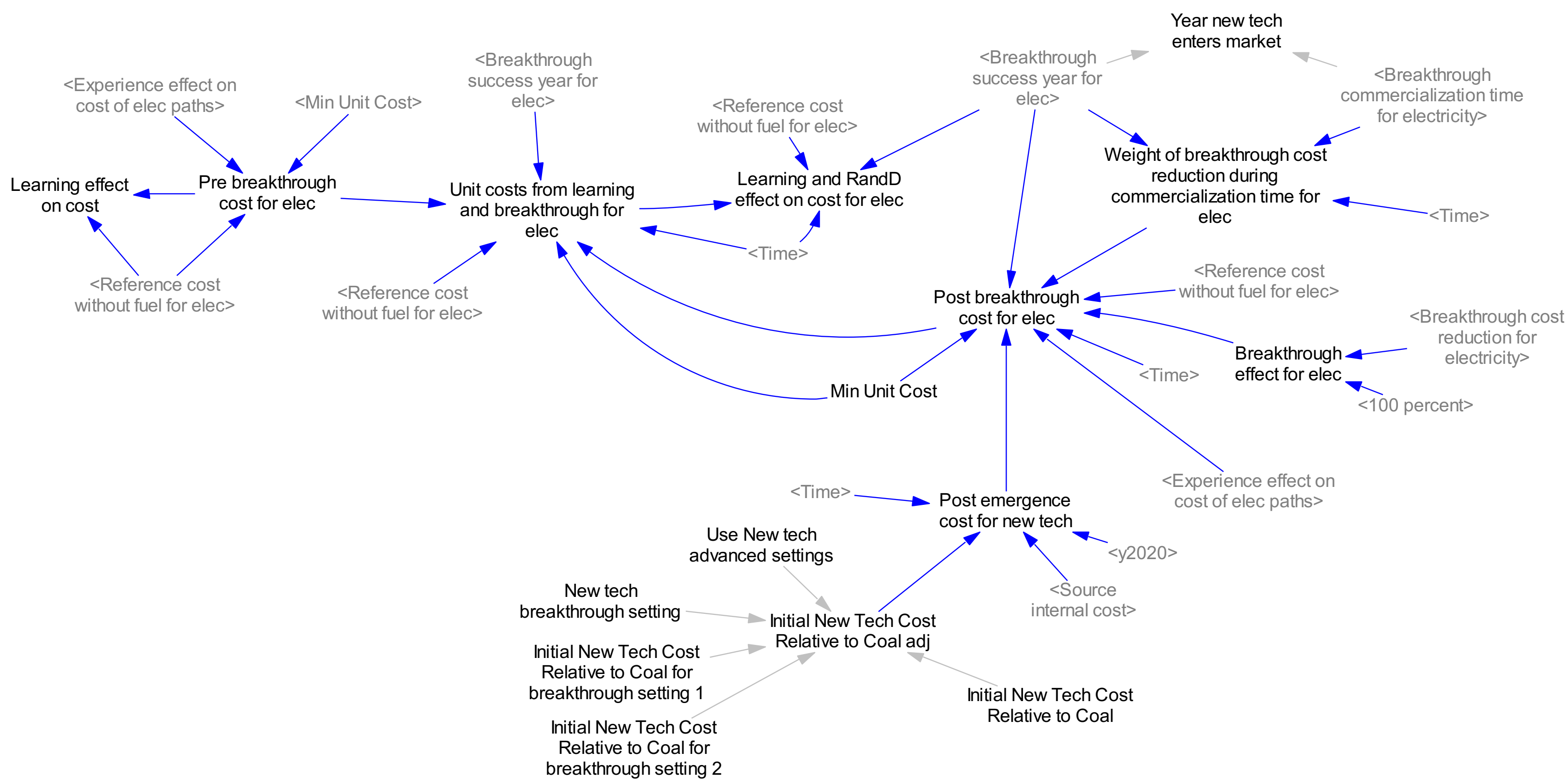


Figure 4-8 Breakthrough Effect on Cost for NonElectric Energy

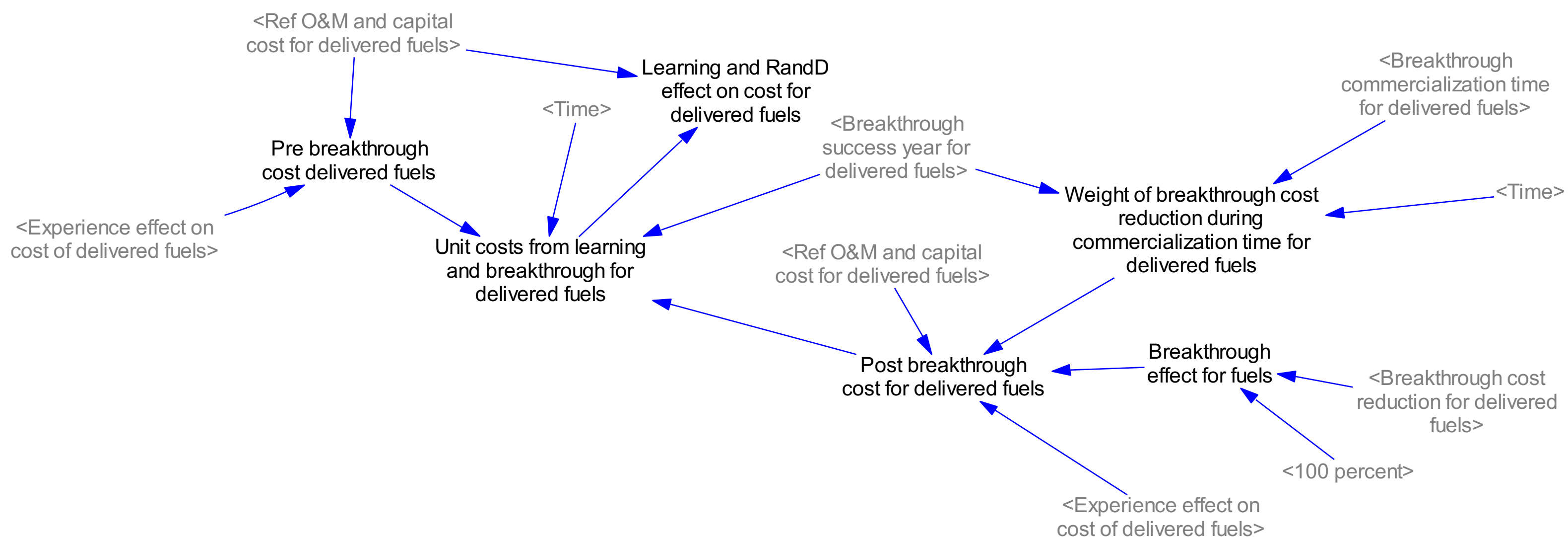


Table 4-14 Parametric Inputs to Drivers of Cost

Parameter	Definition	Range	Default Values	Units
Min Unit Cost	Lower limit of unit cost, excluding extracted fuel costs for delivered fuels and delivered fuel costs for electricity, that the learning and breakthrough effects can reduce costs to asymptotically approach.		1	$/GJ
Init CCS experience	Estimated initial energy source experience from CCS aggregate experience.		10	EJ/year
Learning by experience progress ratio for elec [Primary energy sources]	The unit cost of output from this source, after doubling the cumulative installed capacity, relative to the initial cost. This ratio is used to derive the learning curve, which measures the cost reduction as the market share of new technology increases. Think of manufacturing plants increasing their production efficiency, capitalizing on economies of scale, gaining experience in their staff, and figuring out ways to reduce unit costs. Based on estimate of progress ratio for renewables. McDonald *et al* (2001)			Dmnl
Progress ratio electric coal		0.75-1	0.98	
Progress ratio electric oil		0.75-1	0.98	
Progress ratio electric gas		0.6-1	0.9	
Progress ratio electric bio		0.6-1	0.85	
Progress ratio nuclear		0.6-1	0.98	
Progress ratio hydro		0.6-1	0.9	
Progress ratio renewables		0.6-1	0.8	
Progress ratio new tech		0.6-1	0.8	
Learning by experience progress ratio for delivered fuels[Primary Fuels]				Dmnl
Progress ratio delivered coal		0.75-1	0.98	

Table 4-14 Parametric Inputs to Drivers of Cost

Parameter	Definition	Range	Default Values	Units
Progress ratio delivered oil		0.75-1	0.98	
Progress ratio delivered gas		0.6-1	0.9	
Progress ratio delivered bio		0.6-1	0.98	
Progress ratio CCS		0.6-1	0.95	
Breakthrough for electricity success year		2021-2100		Year
[All elec but new]	The year when a breakthrough reduces the potential cost of the given source. Between the breakthrough year and commercialization time, the reduction in cost is linearly reached to have its full effect in the market.		2030	
[New]	The year when a breakthrough reduces the potential cost of the given source; the breakthrough must subsequently be commercialized to enter the market.		2100	
Breakthrough commercialization time for electricity[Elec Paths]	The number of years it takes for the breakthrough cost reduction to be commercialized, i.e. to go from laboratory to product catalog. The greater this number, the longer is takes to achieve the breakthrough cost reduction and therefore delays the source in gaining market share. Time spent understanding the market, creating business plans, building partnerships with suppliers, customers, and others, piloting, marketing, etc.	1-50	5	Year
Initial New Tech Cost Relative to Coal	At the time when new tech first comes onto the market (breakthrough year plus commercialization time), its cost before any learning is determined by this factor multiplied by the current source internal cost of electric coal.	0.5-10	2	Dmnl

Table 4-14 Parametric Inputs to Drivers of Cost

Parameter	Definition	Range	Default Values	Units
New tech breakthrough setting	0 = Status Quo, or specified by New Tech Breakthrough Year (default = 2100) and Initial Price Relative to Coal (default = 2). 1 = Breakthrough. New Tech Breakthrough Year = 2022. Initial Price Relative to Coal = 2 2 = Huge Breakthrough. New Tech Breakthrough Year = 2022. Initial Price Relative to Coal = 1.	0-2	0	Dmnl
Initial New Tech Cost Relative to Coal for breakthrough setting 1			2	Dmnl
Initial New Tech Cost Relative to Coal for breakthrough setting 2			1	Dmnl
Use New tech advanced settings	Switch to use advanced settings when set to 1 instead of prescribed new tech breakthrough settings	0-1	0	Dmnl
Breakthrough cost reduction for electricity [Elec Paths]	The percent to which the cost of a technology steps down from the cost as determined from the learning curves.	0-50	0	Percent
Breakthrough for delivered fuels success year[Primary Fuels]	The year when a breakthrough reduces the potential cost of the given source; the breakthrough must subsequently be commercialized to have an effect in the market. This is when the technology to reduce the cost of an energy source emerges from R&D and commercialization and comes on the market.	2021-2100	2030	Year

Table 4-14 Parametric Inputs to Drivers of Cost

Parameter	Definition	Range	Default Values	Units
Breakthrough commercialization time for delivered fuels [Primary Fuels]	The number of years it takes for the breakthrough cost reduction to be commercialized, i.e. to go from laboratory to product catalog. The greater this number, the longer is takes to achieve the breakthrough cost reduction and therefore delays the source in gaining market share. Time spent understanding the market, creating business plans, building partnerships with suppliers, customers, and others, piloting, marketing, etc.	1-50	5	Year
Breakthrough cost reduction for delivered fuels[Primary Fuels]	The percent to which the cost of a technology steps down from the cost as determined from the learning curve.	0-50	0	Percent
Apply breakthrough to extraction	Applies the same breakthrough as specified for delivered fuels of corresponding fuel.	0-1	1	Dmnl
Lower cost limit to experience effect on cost	Lower bound to cost as a function of technical improvement from learning	0-0.5	0.01	$/kWh
Init electricity experience[Elec Paths]	The cumulative production for each electric primary source at the start of the simulation. Estimated first by data from Our World in Data. https://ourworldindata.org/grapher/electricity-prod-source-stacked?tab=table&year=latest&time=earliest..latest. Renewables set through optimization.			EJ
Coal			220	
Oil			60	
Gas			80	
Bio			4	
Nuclear			65	
Hydro			140	

Table 4-14 Parametric Inputs to Drivers of Cost

Parameter	Definition	Range	Default Values	Units
Wind			0.17	
Solar			0.0008	
Geothermal			5	
Other renewables			0.004	
New			1	
Init delivered fuels experience[Primary Fuels]	The cumulative production for each primary fuel at the start of the simulation. Determined by data from Our World in Data. https://ourworldindata.org/grapher/global-primary-energy			EJ
Coal			4851	
Oil			3696	
Gas			1476	
Bio			4971	

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
Unit costs from learning and breakthrough for elec [Elec Paths]	The unit internal cost of each energy path due to experience along the learning curve and breakthroughs stepping down the curve.	$/GJ
[All elec but new]	MAX(Min Unit Cost, IF THEN ELSE(Time<=Breakthrough success year for elec[All elec but new],Pre breakthrough cost for elec[All elec but new], Post breakthrough cost for elec[All elec but new]))	
[New]	IF THEN ELSE(Time<=Breakthrough success year for elec[new], Reference cost without fuel for elec[new], Post breakthrough cost for elec[new])	
Pre breakthrough cost for elec	Cost accounting for learning, asymptotically approaching the minimum unit cost.	$/GJ
[All elec but new]	Min Unit Cost+(Reference cost without fuel for elec[All elec but new]-Min Unit Cost)*Experience effect on cost of elec paths[All elec but new]	
[New]	Reference cost without fuel for elec[new]	
Post breakthrough cost for elec	Cost accounting for learning and breakthroughs, asymptotically approaching the minimum unit cost.	$/GJ
[All elec but new]	Min Unit Cost+(Reference cost without fuel for elec[All elec but new]*(Breakthrough effect for elec[All elec but new]*(Weight of breakthrough cost reduction during commercialization time for elec[All elec but new])+(1-Weight of breakthrough cost reduction during commercialization time for elec[All elec but new]))-Min Unit Cost)*Experience effect on cost of elec paths[All elec but new]	

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
[New]	IF THEN ELSE(Time<=Breakthrough success year for elec[new], Reference cost without fuel for elec[new], Min Unit Cost+(Post emergence cost for new tech-Min Unit Cost)*Experience effect on cost of elec paths[new])	
Breakthrough cost reduction for electricity[Elec Paths]		percent
All but Bio CCS	Breakthrough cost reduction electric[All but EBio CCS]	
Bio CCS	If Bio CCS breakthrough settings = 0, then activated BECCS CDR settings greater than 0 proportionally affect the Bio CCS breakthrough. IF THEN ELSE(Breakthrough cost reduction electric bio CCS, Breakthrough cost reduction electric bio CCS, MIN (Max Breakthrough cost reduction electric bio CCS, IF THEN ELSE(BECCS Percent of max CDR achieved :AND: Choose CDR by type=2, BECCS Percent of max CDR achieved, IF THEN ELSE(Non afforestation Percent of max CDR achieved :AND: Choose CDR by type = 1, Non afforestation Percent of max CDR achieved, IF THEN ELSE(Choose CDR by type=0 :AND: Percent of total CDR achieved, Percent of total CDR achieved, 0)))))	
Initial New Tech Cost Relative to Coal adj	IF THEN ELSE(Use New tech advanced settings :OR: New tech breakthrough setting=0, Initial New Tech Cost Relative to Coal, IF THEN ELSE(New tech breakthrough setting=1, Initial New Tech Cost Relative to Coal for breakthrough setting 1, Initial New Tech Cost Relative to Coal for breakthrough setting 2))	$/GJ

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
Post emergence cost for new tech	The initial cost of new tech at the time when it first comes onto the market (breakthrough year plus commercialization time), before any learning further reduces its cost. Determined relative to the cost of electric coal. Time<y2020, Source internal cost [ECoal]* Initial New Tech Cost Relative to Coal adj,Source internal cost [ECoal]* Initial New Tech Cost Relative to Coal adj	$/GJ
Weight of breakthrough cost reduction during commercialization time	Ramps up breakthrough over commercialization time. For New tech, the commercialization time is instead applied to the *NT Capacity Initiation.*	dmnl
All but new	MIN(1,MAX(0,ZIDZ(Time-Breakthrough success year for elec[All elec but new],Breakthrough commercialization time for electricity[All elec but new])))	
New	0	
Lower limit to experience effect on cost[Elec Paths]	Lower cost limit to experience effect on cost / GJ per kWh / Reference cost without fuel for elec[Elec Paths]	dmnl
Experience effect on cost of elec paths [Elec Paths]	The change in internal cost of each energy path due to experience along the learning curve. Accounts for aggregate CCS learning for CCS paths.	Dmnl
[All elec but CCS paths]	Experience effect on cost of elec sources[Primary Energy Sources]	
[CCS Paths]	Lower limit to experience effect on cost+(1-Lower limit to experience effect on cost)*(Electricity experience[Primary energy fuel sources]/Init electricity experience[Primary energy fuel sources])^Learning by experience exponent for elec[Primary energy fuel sources]*Experience effect on cost of CCS	

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
Experience effect on cost of elec sources[All elec but CCS paths]	Lower limit to experience effect on cost[All elec but CCS paths] + (1 - Lower limit to experience effect on cost[All elec but CCS paths]) * (Electricity experience[All elec but CCS paths] / Init electricity experience[All elec but CCS paths]) ^ Learning by experience exponent for elec[Primary Energy Sources]	Dmnl
Experience effect on cost for CCS	(CCS experience/Init CCS experience)^Learning by experience exponent for CCS	Dmnl
Learning by experience rate[Primary Energy Sources]	1-Learning by experience progress ratio for elec[Primary Energy Sources]	Dmnl
Learning by experience exponent for elec[Primary energy sources]	Coefficient of learning curve. LN(Learning by experience progress ratio for elec[Primary Energy Sources])/LN(2)	Dmnl
Learning by experience exponent for CCS	LN(Progress ratio CCS)/LN(2)	Dmnl
Electricity experience[Elec Paths]	The total cumulative production for each electric primary source. INTEG(Electricity by path[All elec but CCS paths], Init electricity experience[All elec but CCS paths])	EJ
CCS experience	The total cumulative production for CCS in aggregate. INTEG(Total CCS production, Init CCS experience)	EJ
Learning effect on cost		Dmnl
[All elec but new]	Pre breakthrough cost for elec[All elec but new]/Reference cost without fuel for elec[All elec but new]	
[New]	1	
Learning and RandD effect on cost for elec		Dmnl
[All elec but new]	Unit costs from learning and breakthrough for elec[All elec but new]/Reference cost without fuel for elec[All elec but new]	

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
[New]	IF THEN ELSE(Time<=Breakthrough success year for elec[new], 1, Unit costs from learning and breakthrough for elec[new]/ Reference cost without fuel for elec[new])	
Unit costs for delivered fuels[Primary Fuels]	Min Unit Cost+(Ref unit cost for delivered fuels[Primary Fuels]-Min Unit Cost)*Breakthrough effect on cost of delivered fuels[Primary Fuels]*Experience effect on cost of nonelec delivered fuels[Primary Fuels]	$/GJ
Breakthrough effect on cost of delivered fuels[Primary Fuels]	Weight of breakthrough cost reduction during commercialization time for delivered fuels[Primary Fuels]*Breakthrough effect for fuels[Primary Fuels]+(1-Weight of breakthrough cost reduction during commercialization time for delivered fuels[Primary Fuels])	$/GJ
Breakthrough effect for fuels[Primary Fuels]	1-Breakthrough cost reduction for delivered fuels[Primary Fuels]/"100 percent"	Dmnl
Weight of breakthrough cost reduction during commercialization time for delivered fuels[Primary Fuels]	MIN(1,MAX(0,ZIDZ(Time-Breakthrough success year for delivered fuels[Primary Fuels],Breakthrough commercialization time for delivered fuels[Primary Fuels])))	Dmnl
Delivered fuel for nonelec experience[Primary Fuels]	INTEG(Experience of fuels for nonelec[Primary Fuels], Init nonelec delivered fuels experience[Primary Fuels])	EJ
Init nonelec delivered fuels experience[Primary Fuels]	The cumulative production for each primary fuel at the start of the simulation. Determined by the initial total fuel minus the initial fuel for electricity. Init delivered fuels experience[Primary Fuels] - Init electricity experience[Elec thermal] / Avg efficiency of elec supply[Elec thermal]	EJ

Table 4-15. Drivers of Cost Calculated Parameters

Parameter	Definition	Units
Experience effect on cost of nonelec delivered fuels[Primary Fuels]	Lower limit to experience effect on fuel costs + (1 - Lower limit to experience effect on fuel costs) * ZIDZ (Delivered fuel for nonelec experience[Primary Fuels] , Init nonelec delivered fuels experience[Primary Fuels]) ^ Learning by experience exponent for delivered fuels[Primary Fuels]	Dmnl
Delivered fuel experience[Primary Fuels]	INTEG(Production of delivered fuels[Primary Fuels], Init delivered fuels experience[Primary Fuels])	EJ
Experience effect on cost of delivered fuels[Primary Fuels	Lower limit to experience effect on fuel costs + (1 - Lower limit to experience effect on fuel costs) * ZIDZ (Delivered fuel experience[Primary Fuels] , Init delivered fuels experience[Primary Fuels]) ^ Learning by experience exponent for delivered fuels[Primary Fuels]	Dmnl
Learning effect on extraction capacity cost [Primary Fuels]	The change in extraction cost of each fuel path due to experience along the learning curve and, if applicable, to any breakthroughs. IF THEN ELSE(Apply breakthrough to extraction, Learning and RandD effect on cost for delivered fuels[Primary Fuels], Experience effect on cost of delivered fuels[Primary Fuels])	Dmnl

4.2.2 Resource Constraints

The **Resource Constraints** sector addresses the potential limits to available energy resources and the effects those limits may have on supply costs. The resource effect cost is a function of the *depletion effect on cost* and the *supply curve effect on cost*.

The depletion effect is dynamic, with cost increasing as cumulative production grows. This captures cost escalation with the depletion of fossil fuels. It is possible to discover unconventional resources, thereby reducing the depletion effect; however, it is assumed that the unconventional resources have a different carbon intensity, adjusted by the user. Biomass is not limited by depletion but rather by the supply constraint, which reflects the limit of production of energy from a source from the saturation of production opportunities. These resource constraints affect the extraction costs of fuels, resulting in a greater market price of extracted fuels. In turn, a greater market price of extracted fuels drives up the market price of delivered fuels for nonelectric use and increases the cost to produce electricity from the thermal paths with and without CCS.

The supply curve constraint can also affect the cost to produce the electric only paths, i.e., nuclear, hydro, renewable types, and new tech; of these sources, the model defaults to only affect hydro and renewables. Supply limitations for these paths affect the O&M and capital costs, capturing, for example, the escalation in cost of wind power that occurs as the cheapest sites are exploited first.

Parameters are based on IPCC 2007 and IEA 2012 estimates. Figure 4-9 illustrates the structure.

Figure 4-9 Structure of Resources Sector

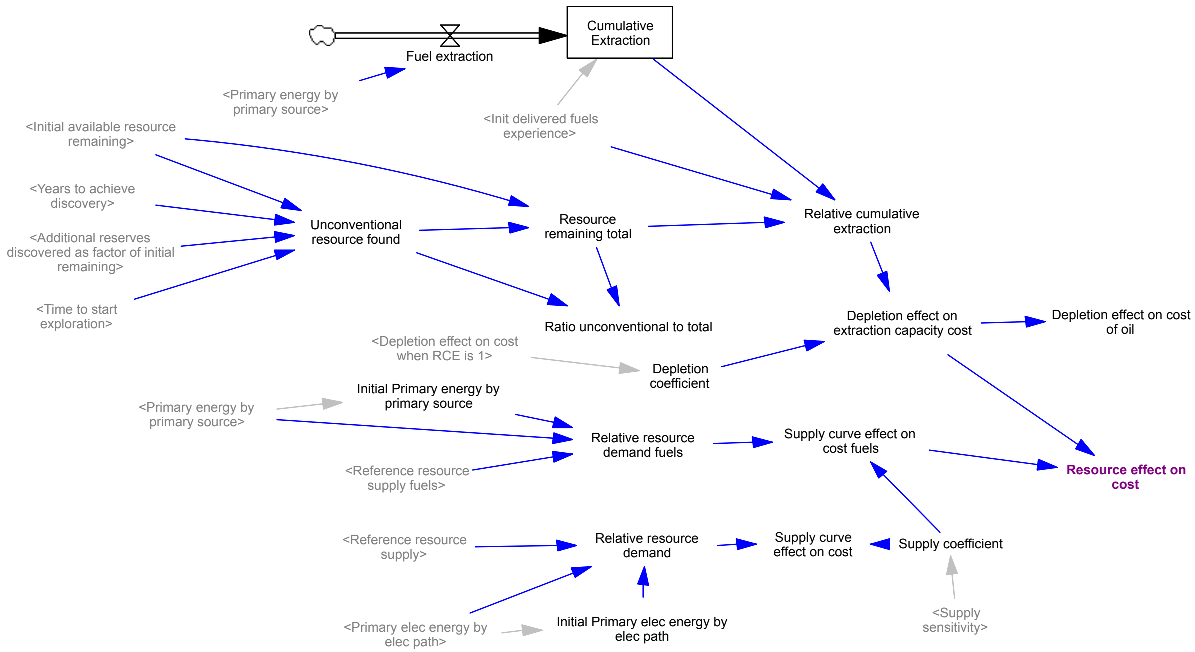


Table 4-16 Resource Constraints Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Depletion effect on cost when RCE is 1 [Primary Fuels]	Escalation of cost with increasing cumulative production; interpreted as cost relative to initial cum prod at reference point on depletion curve (1 = no effect; 2 = cost doubles; etc.)	1-10		Dmnl
Coal			2	
Oil			2	
Gas			2	
Bio			1	
Ultimate resource remaining[Primary Fuels]	How many EJ of energy from this source type remain unexploited at the beginning of the simulation.			EJ
Coal		25,000-132,000	100,000	
Oil		7000-45,000	15,000	
Gas		6500-31,500	15,000	
Bio		10-1,000,000	1,000,000	
Additional reserves discovered as factor of initial remaining[Primary Fuels]			0	EJ
Time to start exploration[Primary Fuels]		2021-2100	2021	Year
Years to achieve discovery[Primary Fuels]		1-50	20	Years
Reference resource supply[Elec Paths]	The energy flow (EJ/yr) at which costs for energy from this resource begin to rise based on approaching the limits of the feasible annual flow. .			EJ/year

Table 4-16 Resource Constraints Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Reference resource supply coal		1-20000	20000	
Reference resource supply oil		1-20000	20000	
Reference resource supply gas		1-20000	20000	
Reference resource supply bio		10-400	100	
Reference resource supply nuclear		1-20000	20000	
Reference resource supply hydro		10-60	40	
Reference resource supply wind		500-2000	1000	
Reference resource supply solar		500-2000	1000	
Reference resource supply geothermal		500-2000	1000	
Reference resource supply other renew		500-2000	1000	
Reference resource supply new tech		10-20000	1000	
Supply sensitivity[Primary energy sources]	Escalation of cost with increasing capacity; interpreted as cost relative to zero output at reference point on supply curve (1 = no effect; 2 = cost doubles; etc.)	1-10		Dmnl
:EXCEPT: bio, hydro, and renewables			1	
Primary Bio, Primary Hydro, Primary Renewables			2	

Table 4-17. Resource Constraints Calculated Parameters

Parameter	Definition	Units
Cumulative Extraction[Primary Fuels]	INTEG(Fuel extraction[Primary Fuels], Init Cum Extraction[Primary Fuels])	EJ
Fuel extraction[Primary Fuels]	Primary energy by primary source[Primary energy fuel sources]	EJ/year
Primary energy by primary source[Primary energy sources]	Primary energy demand of each source, combining primary energy of nonelec and elec for primary fuels.	EJ/year
[Primary energy fuel sources]	Primary nonelec energy by fuel[Primary Fuels]+Primary elec energy by primary source[Primary energy fuel sources]	
[Primary elec only sources]	Primary elec energy by primary source[Primary elec only sources]	
Init Cum Extraction[Primary Fuels]	Based on historical growth rates and level observed in 1990. INITIAL(Primary Energy Demand by aggregated resource[Primary Fuels]/Ref Hist growth rate[Primary Fuels])	EJ
Relative cumulative extraction[Primary Fuels]	Cumulative extraction relative to resources remaining. (Cumulative Extraction [Primary Fuels]-Init delivered fuels experience[Primary Fuels])/(Resource remaining total[Primary Fuels]-Init delivered fuels experience[Primary Fuels])	Dmnl
Resource remaining total[Primary Fuels]	Initial available resource remaining[Primary Fuels]+Unconventional resource found[Primary Fuels]	EJ
Unconventional resource found[Primary Fuels	ramp(Additional reserves discovered as factor of initial remaining[Primary Fuels]*Initial available resource remaining[Primary Fuels]/Years to achieve discovery[Primary Fuels] , Time to start exploration[Primary Fuels] , Time to start exploration[Primary Fuels]+Years to achieve discovery[Primary Fuels])	EJ
Ratio unconventional to total[Primary Fuels]	Unconventional resource found[Primary Fuels]/Resource remaining total[Primary Fuels]	

Table 4-17. Resource Constraints Calculated Parameters

Parameter	Definition	Units
Depletion coefficient[Primary Fuels]	Escalation of cost with increasing cumulative extraction; interpreted as cost relative to initial cum extraction at reference point on depletion curve (1 = no effect; 2 = cost doubles; etc.) INITIAL(LN(Depletion effect on cost when RCE is 1[Primary Fuels]))	Dmnl
Depletion effect on extraction capacity cost[Primary Fuels]	EXP(Relative cumulative extraction[Primary Fuels]*Depletion coefficient[Primary Fuels])	Dmnl
Relative resource demand fuels[Primary Fuels]	Resource flow for fuels feedstocks relative to reference supply. If the reference supply is less than or equal to the initial potential energy demand, the relative resource demand is the ratio of that demand to the reference supply. Otherwise, it increases as the potential demand approaches the reference supply. MAX (0, Primary energy by primary source[Primary energy fuel sources] - Initial Primary energy by primary source[Primary energy fuel sources])/ Reference resource supply fuels[Primary Fuels]	Dmnl
Supply curve effect on cost fuels[Primary Fuels]	Prevents the supply curve effect from being less than 1. MAX (1, EXP (Relative resource demand fuels[Primary Fuels]* Supply coefficient[Primary energy fuel sources]))	Dmnl
Resource effect on cost[Primary Fuels]	Depletion effect on extraction capacity cost[Primary Fuels] * Supply curve effect on cost fuels[Primary Fuels]	Dmnl
Relative resource demand[Elec Paths]	Resource flow for electric generation relative to reference supply. If the reference supply is less than or equal to the initial potential energy demand, the relative resource demand is the ratio of that demand to the reference supply. Otherwise, it increases as the potential demand approaches the reference supply. MAX (0, Primary elec energy by elec path[Elec Paths] - Initial Primary elec energy by elec path[Elec Paths])/ Reference resource supply[Elec Paths]	Dmnl

Table 4-17. Resource Constraints Calculated Parameters

Parameter	Definition	Units
Supply curve effect on cost[Elec Paths]	Prevents the supply curve effect from being less than 1. MAX (1, EXP (Relative resource demand[Elec Paths] * Supply coefficient[Primary Energy Sources]))	Dmnl
Supply coefficient[Primary Energy Sources]	INITIAL(LN(Supply sensitivity[Primary Energy Sources]))	Dmnl

4.2.3 Storage for Renewables

Storage capacity for renewable energy must meet its demand when the source is not available, Such storage could be in the form of batteries, e.g., with solar panels for nighttime, or charging stations for electric vehicles. However, load management can minimize storage needs; the fraction of which depends on learning and investments in smart technology. While the model assumes that storage requirements will not limit utilization, costs of renewables account for those for storage. Comparable to the experience and breakthrough effects for energy, storage costs also decrease with cumulative capacity installation and potential technological breakthroughs.

Figure 4-10 Structure of Storage Capacity Demand

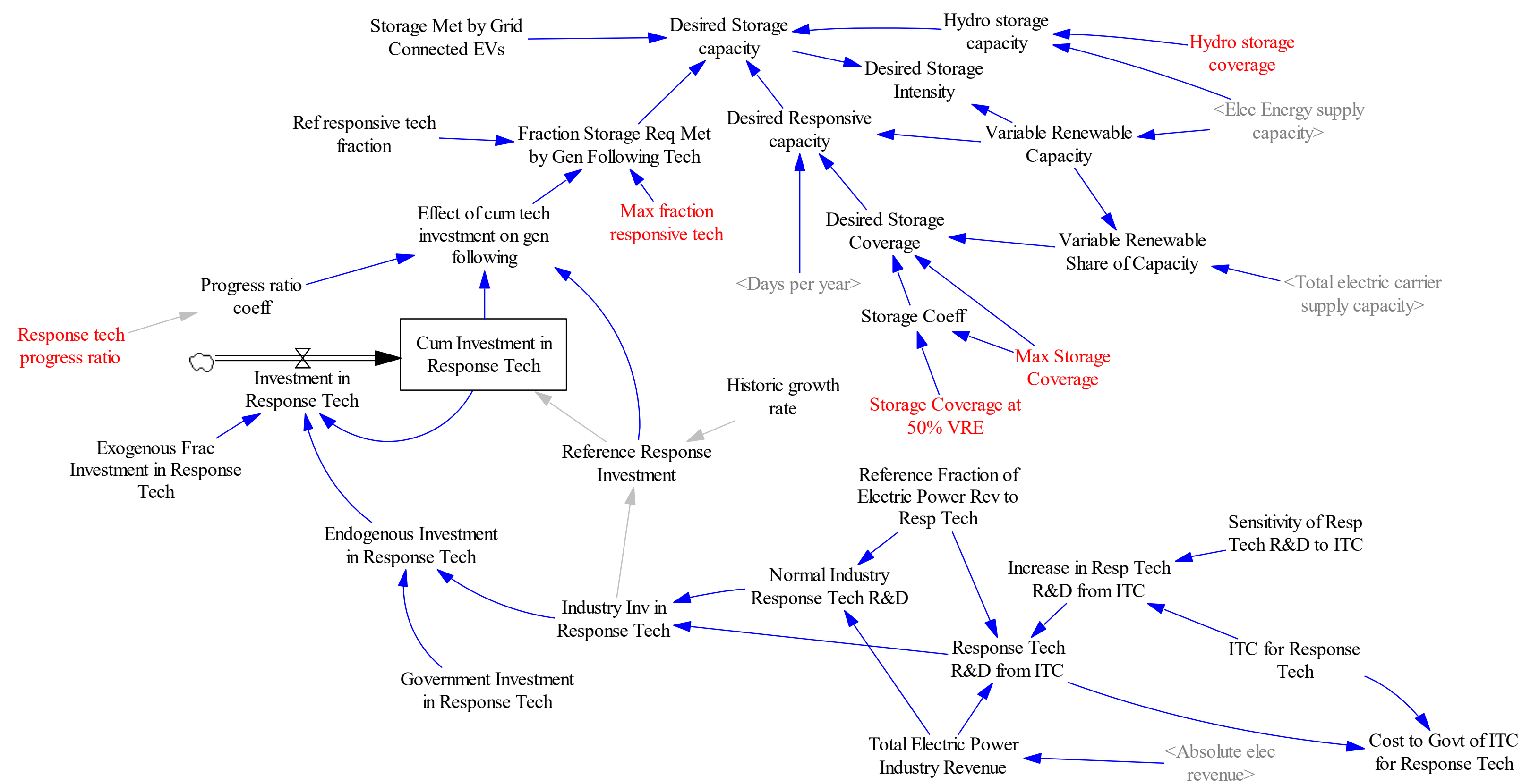


Figure 4-11 Structure of Storage Costs of Energy

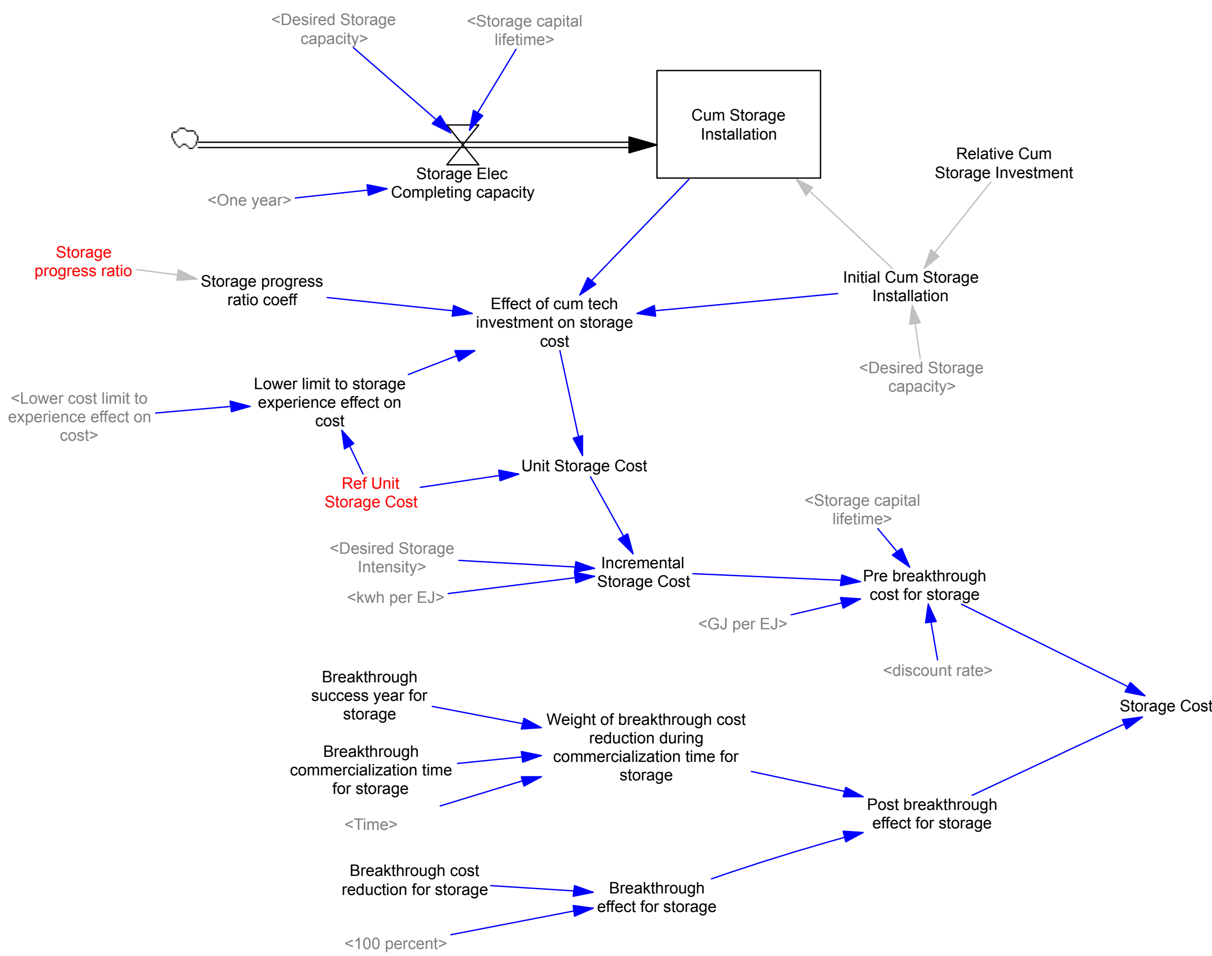


Table 4-18 Storage Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Government Investment in Response Tech		0-20	0	Trillion $/Year
Exogenous Frac Investment in Response Tech		0-0.1	0.01	1/year
Response tech progress ratio			0.8	Dmnl
Ref responsive tech percent		1-100	10	dmnl
Max percent responsive tech		10-100	50	dmnl
Storage Met by Grid Connected EVs		0-1	0	Dmnl
ITC for Response Tech				Dmnl
"Sensitivity of Resp Tech R&D to ITC"			0.1	Dmnl
Reference Fraction of Electric Power Rev to Resp Tech			0.01	Dmnl
"Storage Coverage at 50% VRE"	Highly uncertain. Based on: A.A. Solomon et al. 2017, How much energy storage is needed to incorporate very large intermittent renewables? Shaner et al. 2018, Geophysical constraints on the reliability of solar and wind power in the United States		1	Dmnl
Max Storage Coverage	Highly uncertain. Based on: A.A. Solomon et al. 2017, How much energy storage is needed to incorporate very large intermittent renewables? Shaner et al. 2018, Geophysical constraints on the reliability of solar and wind power in the United States		32	Days

Table 4-18 Storage Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Hydro storage coverage			0	EJ/(EJ/Year)
Historic growth rate			0.05	1/year
Storage progress ratio	The measure of how much costs fall as learning and development about storage technologies occurs.	0.6-1	0.8	Dmnl
Ref Unit Storage Cost			750	$/kWh
Relative Cum Storage Investment	Multiplier representing implicit R&D and other experience relevant to storage, relative to explicit investment in storage capacity.		4	Dmnl
Breakthrough cost reduction for storage	The percent that a research and development (R&D) breakthrough suddenly reduces the supply cost of energy storage. Values represent a decrease in cost from the point when the breakthrough occurs.	0-50	0	Percent
Breakthrough success year for storage	The year when the breakthrough occurs. The breakthrough must subsequently be commercialized to have an effect in the market.	2021-2100	2030	Year
Breakthrough commercialization time for storage	The number of years it takes for the storage technology breakthrough to be commercialized.	1-20	5	Years

Table 4-19. Storage Capacity Calculated Parameters

Parameter	Definition	Units
Desired Storage capacity	The desired amount of total storage capacity. Assumes 100% centralized. MAX(0,Desired Responsive capacity*(1-Percent Storage Req Met by Gen Following Tech/"100 percent")-Storage Met by Grid Connected EVs-Hydro storage capacity)	EJ
Desired Responsive capacity	Variable Renewable Capacity*Desired Storage Coverage/Days per year	
Desired Storage Intensity	Desired Storage capacity/Variable Renewable Capacity	EJ/(EJ/Year)
Variable Renewable Capacity	Elec Energy supply capacity[renewables]	EJ/year
Variable Renewable Share of Capacity	Variable Renewable Capacity/Total electric carrier supply capacity	Dmnl
Desired Storage Coverage	Max Storage Coverage*EXP(-Storage Coeff*(1-Variable Renewable Share of Capacity))	Days
Storage Coeff	-2*LN("Storage Coverage at 50% VRE"/Max Storage Coverage)	Dmnl
Hydro storage capacity	Elec Energy supply capacity[hydro]*Hydro storage coverage	EJ
Percent Storage Req Met by Gen Following Tech	Ref responsive tech percent + (Max percent responsive tech-Ref responsive tech percent)*(1-Effect of cum tech investment on gen following)	Percent
Effect of cum tech investment on gen following	ZIDZ(Cum Investment in Response Tech,Reference Response Investment)^Progress ratio coeff	Dmnl
Cum Investment in Response Tech	INTEG(Investment in Response Tech, Reference Response Investment)	Trillion $
Progress ratio coeff	LN(Response tech progress ratio)/LN(2)	Dmnl
Investment in Response Tech	Cum Investment in Response Tech*Exogenous Frac Investment in Response Tech + Endogenous Investment in Response Tech	Trillion $/Year
Reference Response Investment	Industry Inv in Response Tech/Historic growth rate	Trillion $
Endogenous Investment in Response Tech	Industry Inv in Response Tech + Government Investment in Response Tech	Trillion $/Year
Industry Inv in Response Tech	"Normal Industry Response Tech R&D" + "Response Tech R&D from ITC"	Trillion $/Year
"Normal Industry Response Tech R&D"	Reference Fraction of Electric Power Rev to Resp Tech*Total Electric Power Industry Revenue	Trillion $/Year
"Increase in Resp Tech R&D from ITC"	"Sensitivity of Resp Tech R&D to ITC"*ITC for Response Tech	dmnl

Table 4-20. Storage Costs Calculated Parameters

Parameter	Definition	Units
Storage Cost[Elec Paths]		$/GJ
Renewable types	Pre breakthrough cost for storage*(1-Post breakthrough effect for storage)	
All elec but renew	0	
Pre breakthrough cost for storage	Incremental Storage Cost*(discount rate+1/Storage capital lifetime)/GJ per EJ	$/GJ
Incremental Storage Cost	Desired Storage Intensity*Unit Storage Cost*kwh per EJ	$/(EJ/Year)
Unit Storage Cost	Ref Unit Storage Cost*Effect of cum tech investment on storage cost	$/kWh
Lower limit to storage experience effect on cost	Lower cost limit to experience effect on cost / Ref Unit Storage Cost	dmnl
Effect of cum tech investment on storage cost	Lower limit to storage experience effect on cost + (1 - Lower limit to storage experience effect on cost) * XIDZ (Cum Storage Installation, Initial Cum Storage Installation, 1) ^ Storage progress ratio coeff	Dmnl
Storage progress ratio coeff	LN(Storage progress ratio)/LN(2)	Dmnl
Initial Cum Storage Installation	Desired Storage capacity*Relative Cum Storage Investment	EJ
Cum Storage Installation	INTEG(Storage Elec Completing capacity, Initial Cum Storage Installation)	EJ
Storage Elec Completing capacity	MAX(0, (Desired Storage capacity-SMOOTH(Desired Storage capacity,One year))/One year + Desired Storage capacity/Storage capital lifetime)	EJ/year
Post breakthrough effect for storage	(1-Breakthrough effect for storage)* Weight of breakthrough cost reduction during commercialization time for storage	Dmnl
Breakthrough effect for storage	1-Breakthrough cost reduction for storage/"100 percent"	Dmnl
Weight of breakthrough cost reduction during commercialization time for storage	MIN(1,MAX(0,ZIDZ(Time-Breakthrough success year for storage, Breakthrough commercialization time for storage)))	dmnl

4.2.4 Soft Costs and Historic Subsidies for Renewables

The levelized cost of electricity (LCOE) of renewables, particularly wind and solar energy, have decreased dramatically since 1990, especially over the past decade. Two opposing forces have contributed to those declines with the energy generated by them. There have been historic subsidies jump-starting their growth. However, there have also been soft costs, i.e., indirect costs, that have made the investment in these sources less attractive than direct cost alone would suggest. En-ROADS captures the historic subsidies as a fraction of the direct cost through 2020, phasing out by 2030. It captures the soft costs as an initial level that declines with experience at a rate determined by a progress ratio. The values defining these subsidies and soft costs were estimated from literature and set through optimization to fit historic cost (IRENA, 2020; Lazard, 2020; IEA, 2020) and energy data (WEO, 2020; BP, 2020; IEA, 2020).

Sources of LCOE data for renewables are not consistently presented and only available for some years, therefore requiring conversions and bridging between datasets.

IRENA (https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019): All LCOE results are reported in $2019 USD. Reported values calculated excluding any financial support and using a fixed assumption of a real cost of capital of 7.5% in OECD countries and China, and 10% in the rest of the world, unless explicitly mentioned. All LCOE calculations exclude the impact of any financial support. Converted to $2017.

LAZARD 3.0- 13.0 (https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf): All LCOE results reported in nominal $. Each analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost; Unless otherwise indicated, the analysis herein does not reflect decommissioning costs, ongoing maintenance-related capital expenditures or the potential economic impacts of federal loan guarantees or other subsidies; Lazard's unsubsidized LCOE analysis indicates significant historical cost declines for utility-scale renewable energy generation technologies. Converted to $2017.

IEA (https://www.iea.org/data-and-statistics/charts/global-average-lcoes-and-auction-results-for-utility-scale-pv-by-commissioning-date): Global average LCOEs and auction results for utility-scale PV by commissioning date. Last updated 7 Jan 2020. Data shown = LCOE in $2017.

IEA: Evolution of solar PV module cost by data source, 1970-2020. Last updated 30 Jun 2020. https://www.iea.org/data-and-statistics/charts/evolution-of-solar-pv-module-cost-by-data-source-1970-2020.
While the LCOE data for solar PV is not readily available before 2009, IEA's cost per watt of solar PV from IEA 1970-2020 provides data to estimate the LCOE from 1990. Using the ratio of annual costs per watt to that in 2010 and applying that ratio to the IRENA solar PV LCOE in 2010 provides an estimate of LCOE from 1990-2019.

Berkeley (https://emp.lbl.gov/utility-scale-solar). Median 30-Year LCOE without the ITC reported in $2018. Converted to $2017.

There are also differences between utility scale and distributed solar PV.

Utility vs distributed solar PV:

IEA

According to IEA Historical capacity data for OECD countries based on IEA (2017), Renewables Information 2017, https://www.iea.org/data-and-statistics/charts/net-renewable-capacity-additions-main-and-accelerated-case-2006-2023, fraction of PV that is utility scale has grown from 29% to 63% of solar PV between 2006-2011 to 2012 -2017.

Lazard provides utility scale and distributed cost data; accordingly, comparisons are made to the weighted average of these. The weights assume assume the trend of increasing utility scale relative to distributed increases at a comparable rate to history

Likewise, there are differences between onshore and offshore wind.

Onshore vs offshore wind

IEA

IRENA presents onshore and offshore wind costs. Used the weighted average of onshore fraction of wind from IEA Wind TCP Task 26 Technical Report. April 2019. https://community.ieawind.org/task26/home) to get weighted average of wind LCOE. Estimated from regional graphs of onshore vs offshore wind to be 100% onshore until 2010 when offshore wind starts to present, decreasing down to 95% by 2019.

Figure 4-12 Historic Cost of Wind and Solar

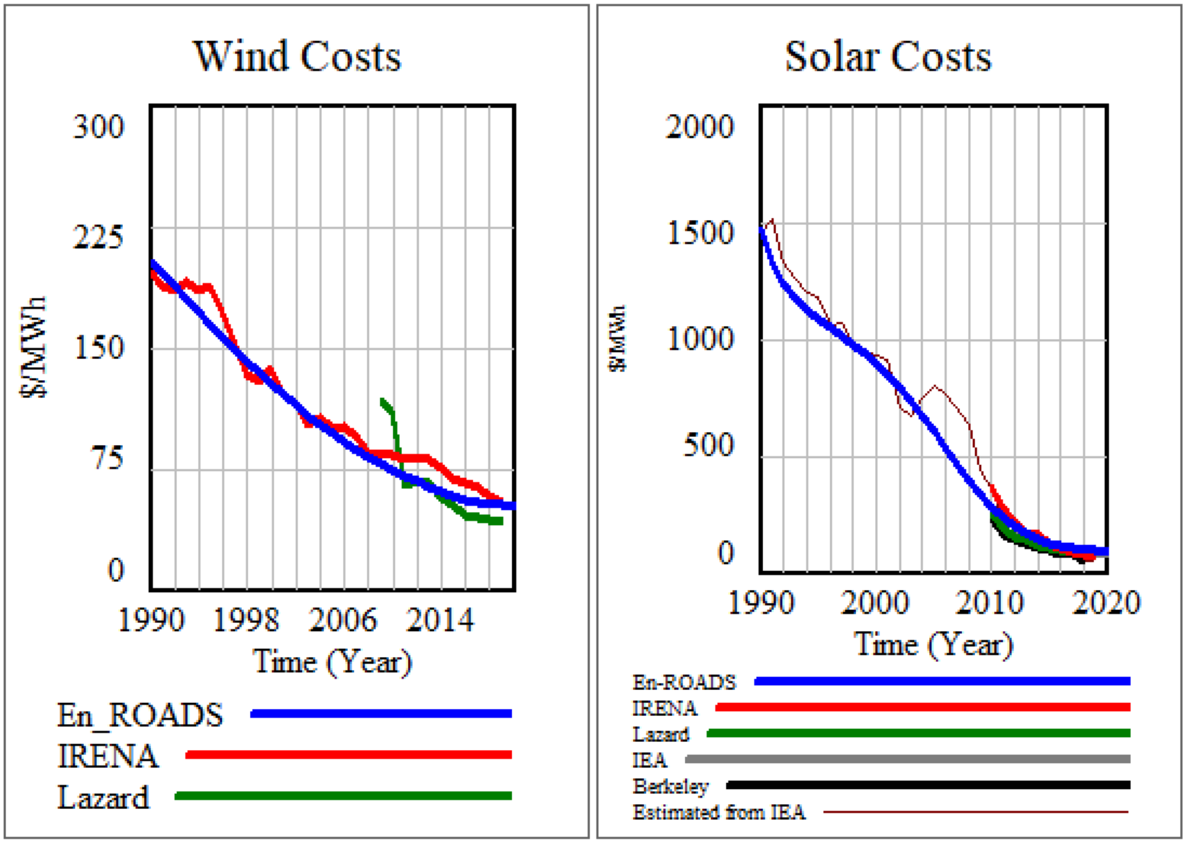


Table 4-21 Parameteric Inputs for Renewables Historic Subsidies and Soft Costs

Init renewables experience for soft costs[Renewable types]	Initial experience for learning curve of soft costs of renewables, capturing "hassle costs" associated with them.			EJ
Wind			6	
Solar			9	
Geothermal			70	
Other renewables			70	
Initial soft costs for renewables by type[Renewable types]	Initial soft costs for renewables.			$/GJ
Wind			41	
Solar			28.4	
Geothermal			65	
Other renewables			55	
Progress ratio for soft costs			0.8	Dmnl
Max Renewable subsidy	Limits the historic renewables subsidy.		0.7	$/kWh
Renewable historic subsidies fraction of marginal cost [Renewable types]	Historic subsidies as a fraction of marginal cost without storage			Dmnl
Wind			0.15	
Solar			0.6	
Geothermal			0.2	
Other renewables			0.04	
Status quo renewable subsidies start phase out year	Year when the max fraction of solar subsidies starts to phase out so as to not assume continued support.		2020	Year
Duration over which status quo renewable subsidies phase out	Time it takes for renewables subsidies to complete phase out period.		10	Year

Table 4-22 Calculated Parameters for Renewables Historic Subsidies and Soft Costs

Renewables experience for soft costs	INTEG(Electricity generated by renewables[Renewable types], Init renewables experience for soft costs[Renewable types])	EJ
Learning by soft exponent for soft costs	LN (Progress ratio for soft costs) / LN (2)	Dmnl
Experience effect on soft renewables cost by type[Renewable types]	Lower limit to experience effect on soft cost + (1 - Lower limit to experience effect on soft cost) * (Renewables experience for soft costs[Renewable types] / Init renewables experience for soft costs[Renewable types]) ^ Learning by experience exponent for soft costs	Dmnl
Renewable historic subsidies fraction over time[Renewable types]	Renewable historic subsidies fraction of marginal cost[Renewable types] - ramp (Renewable historic subsidies fraction of marginal cost[Renewable types] / Duration over which status quo renewable subsidies phase out , Status quo renewable subsidies start phase out year , Status quo renewable subsidies start phase out year + Duration over which status quo renewable subsidies phase out)	dmnl
Renewable subsidies over time KWh[Renewable types]	MIN (Max Renewable subsidy , Renewables adjusted source internal cost without storage MWh by type[Renewable types] / KWh per MWh * Renewable historic subsidies fraction of marginal cost over time[Renewable types])	$/kWh
Soft costs by type[Renewable types]	Initial soft costs for renewables by type[Renewable types] * Experience effect on soft renewables cost by type[Renewable types]	$/GJ
Net soft costs[Elec Paths]	Soft costs assumed to only apply to renewables.	$/GJ
Renewable types	Soft costs net of subsidies by type[Renewable types]	
Elec except renewables	0	
Soft costs by type KWh[Renewable types]	Soft costs by type[Renewable types] * GJ per kWh	$/kWh
Soft costs net of subsidies by type KWh	Soft costs by type KWh[Renewable types] - Renewable subsidies over time KWh[Renewable types]	$/kWh

4.3 Instant and Embodied Supply Costs and Efficiencies

The embodied costs of supply are modeled in the **Embodied Supply Costs** sector. These costs factor into the utilization of energy capacity in the **Market Clearing and Utilization** sector. Embodied costs represent the actual physically-imposed costs, which are locked in at the time of capacity investment, i.e., new capacity development. Variable costs include operation and maintenance (O&M) and fuel costs. The fuel costs for delivered fuels are the extracted fuel costs. The fuel cost for each electric source requiring fuel is the market price of extracted fuel, accounting for a markup, divided by the embodied thermal efficiency of the source; fuel prices for the primary electric paths are 0. Unit profit, which is the market price less the variable costs, may be adjusted by a tax/subsidy and/or carbon tax to the producers of delivered fuels. As in the **Supply** sector, the construction pipeline is explicit but without vintaging of capital as there is in the demand side; costs are assumed to be well-mixed. All inputs to this sub-model are determined in other sub-models except for the Overheating cost sensitivity, which is set at 0.5.

4.3.1 Instant Levelized Capital Costs and Variable Costs

The effects on costs described in Section 4.2 apply to the levelized capital costs as well as to O&M and fuel costs.

Figure 4-13 Structure of Variable Costs of Energy

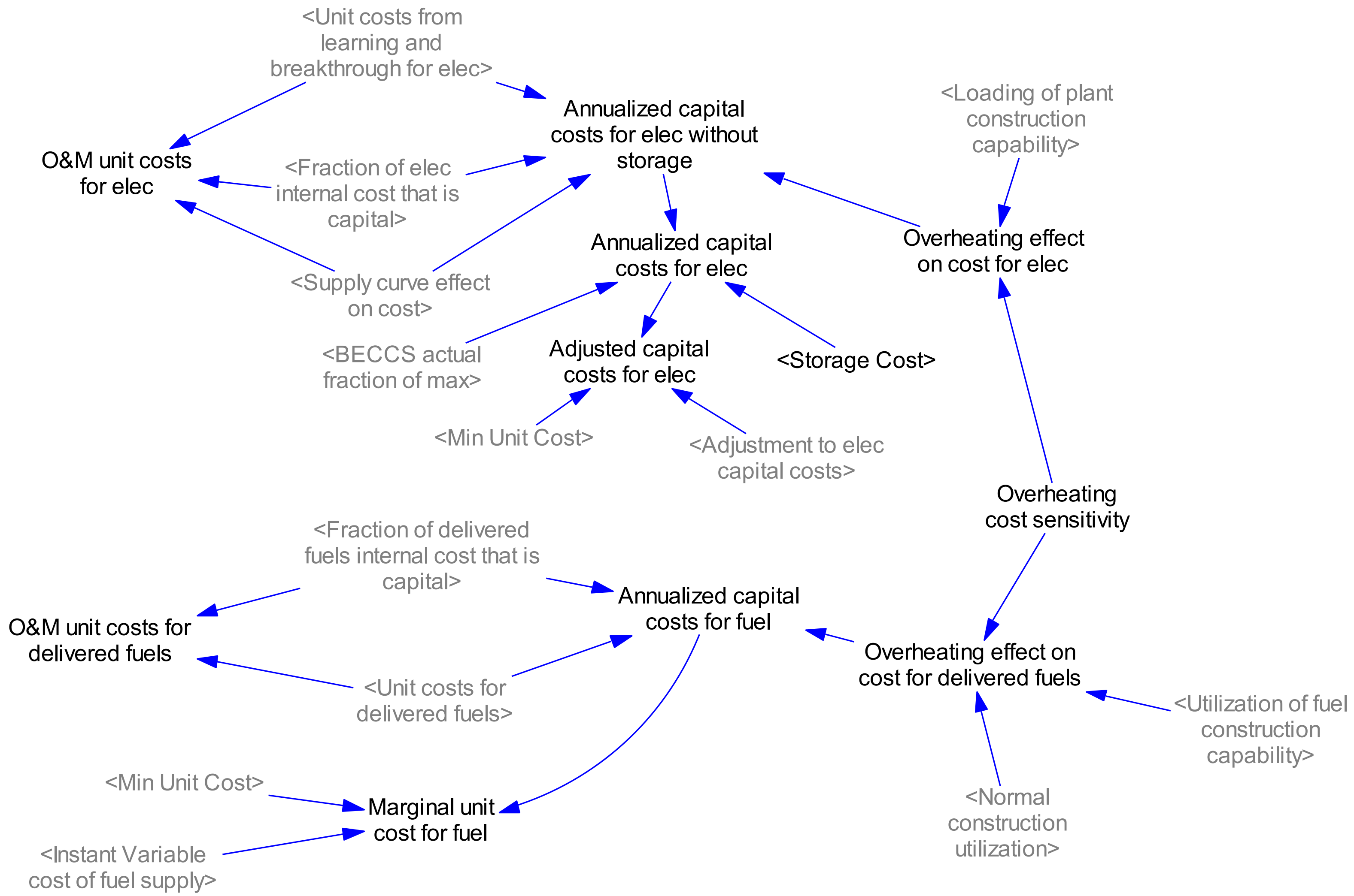


Figure 4-14 Structure of Variable Costs of Energy

Table 4-23. Instant Energy Cost Calculated Parameters

Parameter	Defiefnition	Units
Annualized capital costs of fuel [Primary Fuels]	The marginal unit capital costs of each delivered fuel for nonelectric carriers. Unit costs from learning and breakthrough for delivered fuels[Primary Fuels]*Fraction of delivered fuels internal cost that is capital[Primary Fuels]*Overheating effect on cost for delivered fuels[Primary Fuels]	$/GJ
O&M unit costs for delivered fuels [Primary Fuels]	The marginal unit O&M costs of each delivered fuel for nonelectric carriers. Unit costs from learning and breakthrough for delivered fuels[Primary Fuels]*(1-Fraction of delivered fuels internal cost that is capital[Primary Fuels])	$/GJ
Overheating effect on cost for delivered fuels[Primary Fuels]	ACTIVE INITIAL (((Utilization of fuel construction capability[Primary Fuels]/Normal construction utilization)^Overheating cost sensitivity, 1)	Dmnl
Annualized capital costs for elec without storage	The marginal unit capital costs of each elec path, excluding costs of storage for renewables.	$/GJ
[Elec but bio]	Unit costs from learning and breakthrough for elec[Elec but bio] *Fraction of elec internal cost that is capital[Elec but bio] *Overheating effect on cost for elec[Elec but bio] *Supply curve effect on cost[Elec but bio]	
[Elec bio]	Unit costs from learning and breakthrough for elec[Elec bio] *Fraction of elec internal cost that is capital[Elec bio] *Overheating effect on cost for elec[Elec bio]	
O&M unit costs for elec[Elec Path]		$/GJ
[Elec but bio]	Unit costs from learning and breakthrough for elec[Elec but bio] *(1-Fraction of elec internal cost that is capital[Elec but bio]) *Supply curve effect on cost[Elec but bio]	
[Elec bio]	Unit costs from learning and breakthrough for elec[Elec bio] *(1-Fraction of elec internal cost that is capital[Elec bio])	

Table 4-23. Instant Energy Cost Calculated Parameters

Parameter	Defiefnition	Units
Overheating effect on cost for elec[Elec Path]	ACTIVE INITIAL ((Loading of plant construction capability[Elec Paths] / Normal construction utilization) ^ Overheating cost sensitivity, 1)	Dmnl
Annualized capital costs for elec[Elec Path]	The marginal unit capital costs of each elec path. Annualized capital costs for elec without storage[Elec Paths] +Storage Cost[Elec Paths]	

Table 4-24.Variable Cots Calculated Parameters

Spot fuel costs[Primary Fuels]	Cost of extracted fuel to producers of delivered fuels smoothed over fuel contract time. SMOOTH(Price of extracted fuel[Primary Fuels], Years of fuel contract)	$/GJ
Instant Variable cost of fuel supply[Primary Fuels]	"O&M unit costs for delivered fuels"[Primary Fuels]+Spot fuel costs[Primary Fuels]/Avg efficiency of fuel capacity[Primary Fuels]	$/GJ
Market price of delivered fuels for elec[Primary Fuels]	Price of extracted fuel[Primary Fuels]*Ratio of fuel price for elec to extracted price[Primary Fuels]	$/GJ
Contracted fuel costs for elec[Primary Fuels]	Cost of delivered fuel for electric producers smoothed over fuel contract time. SMOOTH(Market price of delivered fuels for elec[Primary Fuels], Years of fuel contract)	$/GJ
Instant Variable cost of elec supply[Elec Paths]	Variable costs (O&M plus fuel), used to calculate the source profit margin.	$/GJ
[Elec thermal plus CCS]	"O&M unit costs for elec"[Elec thermal plus CCS]+Contracted fuel costs for elec[Primary Fuels]/Avg efficiency of elec supply[Elec thermal plus CCS]	
[Elec only paths]	"O&M unit costs for elec"[Elec only paths]	
Carbon tax per elec GJ[Elec Paths]	Carbon tax based on intensity of each path. Allows for biofuels to be included or not.	$/GJ
[Elec but bio]	Carbon tax per tonCO2*CO2 intensity of elec path [Elec but bio]/GJ per TJ	
[Elec bio]	Carbon tax per tonCO2*CO2 intensity of elec path [Elec bio]/GJ per TJ*Apply carbon tax to biofuels	
Adjustment to elec costs[Elec Paths]	Adjustment to elec capital costs[Elec Paths]+Adjustment to elec variable costs[Elec Paths]	$/GJ
Adjustment to elec variable costs Elec Paths]	Adjustment to elec costs that apply to variable costs	$/GJ

[Elec thermal plus CCS]	Carbon tax per elec GJ[Elec thermal plus CCS]-Source subsidy for fuels over time[Primary Fuels]/Avg efficiency of elec supply [Elec thermal plus CCS]-Source subsidy to electric consumers over time[Elec thermal plus CCS]*(1-Fraction of elec source adjustment for capital[Elec thermal plus CCS])	
[Elec only paths]	-Source subsidy to electric consumers over time[Elec only paths]*(1-Fraction of elec source adjustment for capital[Elec only paths])	
Adjustment to elec capital costs[Elec Paths]	Adjustment to elec costs that apply to capital costs -Source subsidy to electric consumers over time[Elec Paths]*Fraction of elec source adjustment for capital[Elec Paths]	$/GJ
Instant effective variable cost of elec supply[Elec Paths]	Instant Variable cost of elec supply[Elec Paths]+Adjustment to elec variable costs[Elec Paths]	$/GJ
Adjustment to delivered fuel costs for nonelec consumption[Primary Fuels]	(Carbon tax per GJ[Primary Fuels]-Source subsidy for fuels over time[Primary Fuels])/Avg efficiency of fuel capacity[Primary Fuels]	$/GJ
Instant effective variable cost of fuel supply[Primary Fuels]	Instant Variable cost of fuel supply[Primary Fuels]+Adjustment to delivered fuel variable costs for nonelec consumption[Primary Fuels]	$/GJ
Supplier cost for fuel[Primary Fuels]	MAX(Min Unit Cost, Instant effective variable cost of fuel supply[Primary Fuels]+Avg embodied fixed cost of fuel capacity[Primary Fuels])	$/GJ

4.3.2 Embodied Supply Costs and Efficiencies

The embodied costs and efficiencies of supply are locked in at the time new capacity development.

Figure 4-15 Structure of Electric Supply Embodied Fixed Costs

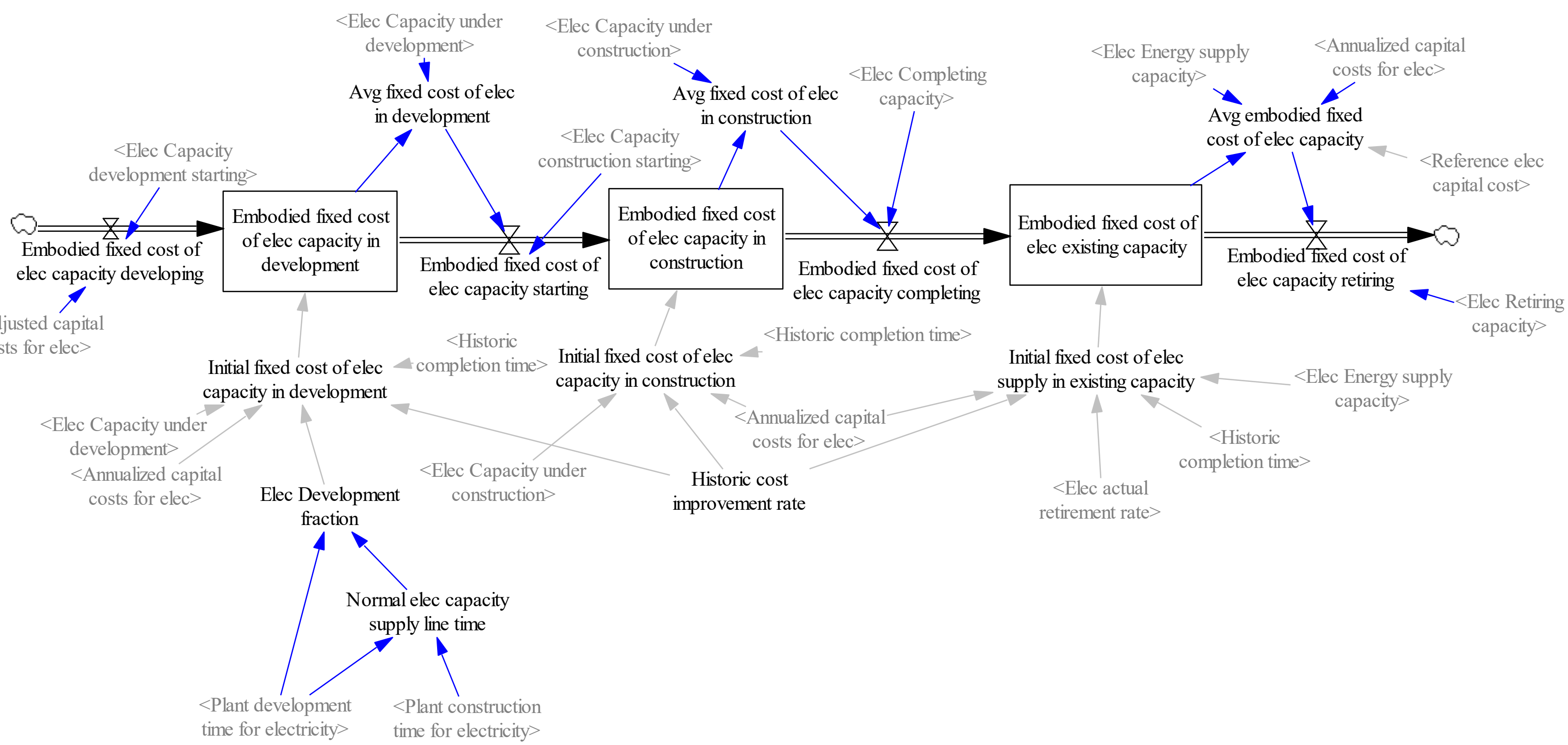


Figure 4-16 Structure of Delivered fuels Supply Embodied Fixed Costs

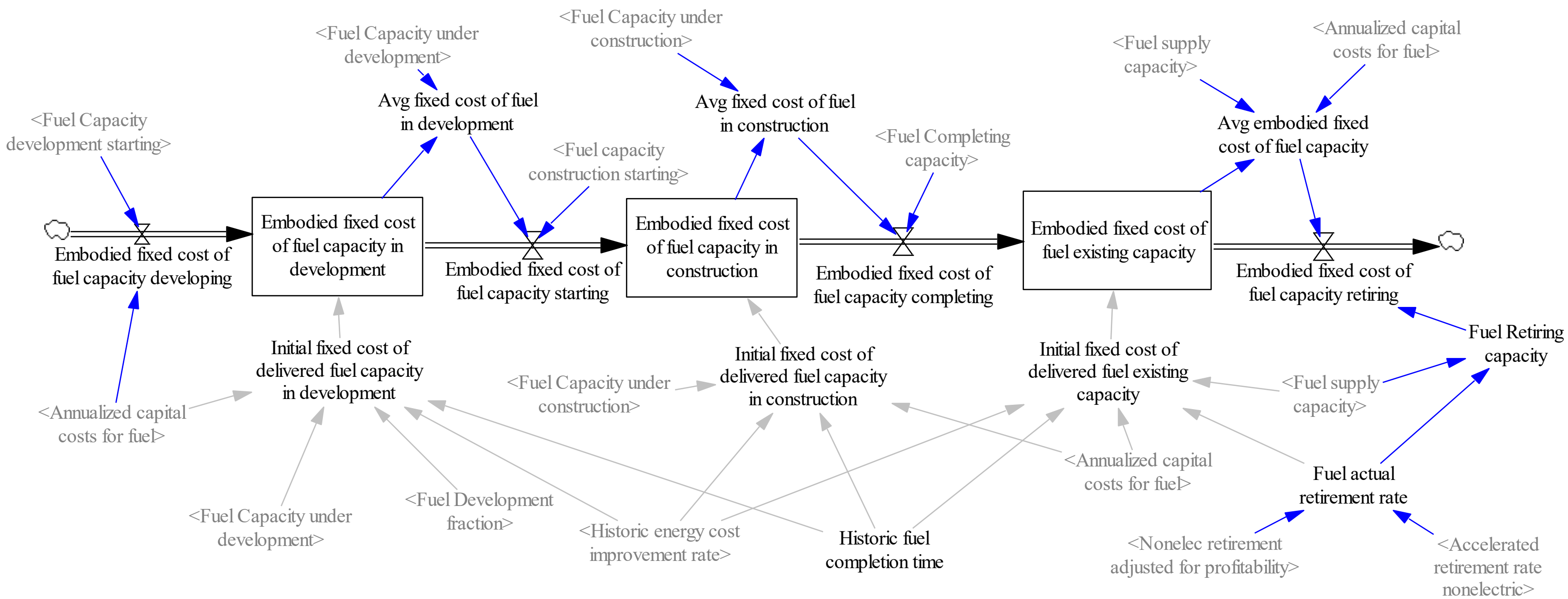


Table 4-25.Electricity Supply Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Embodied fixed cost of elec capacity in development [Elec Paths]	Embodied fixed costs, i.e., the actual physically-imposed costs, of capacity under development of each electric energy path. These are locked in at the time of development. INTEG(Embodied fixed cost of elec capacity developing[Elec Paths]-Embodied fixed cost of elec capacity starting[Elec Paths], Initial fixed cost of elec capacity in development[Elec Paths])	($/GJ)*(EJ/Year)
Embodied fixed cost of elec capacity in construction [Elec Paths]	Embodied fixed costs, i.e., the actual physically-imposed costs, of capacity under construction of each electric energy path. These are locked in at the time of development. INTEG(Embodied fixed cost of elec capacity starting[Elec Paths]-Embodied fixed cost of elec capacity completing[Elec Paths], Initial fixed cost of elec capacity in construction[Elec Paths])	($/GJ)*(EJ/Year)
Embodied fixed cost of elec existing capacity [Elec Paths]	Embodied fixed costs, i.e., the actual physically-imposed costs, of existing capacity of each electric energy path. These are locked in at the time of development. INTEG(Embodied fixed cost of elec capacity completing[Elec Paths]-Embodied fixed cost of elec capacity retiring[Elec Paths], Initial fixed cost of elec supply in existing capacity[Elec Paths])	($/GJ)*(EJ/Year)

Table 4-25.Electricity Supply Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Initial fixed cost of elec capacity in development [Elec Paths]	Initial fixed cost of electric energy supply in under development. INITIAL(Elec Capacity under development[Elec Paths]*Annualized capital costs[Elec Paths]*EXP(Historic cost improvement rate[Elec Paths]*Historic completion time[Elec Paths]*(1-Elec Development fraction[Elec Paths])))	($/GJ)*(EJ/Year)
Initial fixed cost of elec capacity in construction [Elec Paths]	Initial fixed cost of electric energy supply in under construction. INITIAL(Elec Capacity under construction[Elec Paths]*Annualized capital costs[Elec Paths]*EXP(Historic cost improvement rate[Elec Paths]*Historic completion time[Elec Paths]))	($/GJ)*(EJ/Year)
Initial fixed cost of elec supply in existing capacity [Elec Paths]	Initial fixed cost of existing electric energy supply capacity. INITIAL(Elec Energy supply capacity[Elec Paths]*Annualized capital costs[Elec Paths]*EXP(Historic cost improvement rate[Elec Paths]*(Historic completion time[Elec Paths]+1/Actual retirement rate[Elec Paths])))	($/GJ)*(EJ/Year)
Embodied fixed cost of elec capacity developing [Elec Paths]	Embodied fixed costs of capacity starting development each year of each electric energy path, locked in at that time. Adjusted capital costs for elec[Elec Paths]*Elec Capacity development starting[Elec Paths]	($/GJ)*(EJ/Year)/Year
Embodied fixed cost of elec capacity starting [Elec Paths]	Embodied fixed costs of capacity starting construction each year of each electric energy path, locked in at the time of development. Avg fixed cost of elec in development[Elec Paths]*Elec Capacity construction starting[Elec Paths]	($/GJ)*(EJ/Year)/Year

Table 4-25.Electricity Supply Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Embodied fixed cost of elec capacity completing [Elec Paths]	Embodied fixed costs of capacity completed each year of each electric energy path, locked in at the time of development. Avg fixed cost of elec in construction[Elec Paths]*Elec Completing capacity[Elec Paths]	($/GJ)*(EJ/Year)/Year
Embodied fixed cost of elec capacity retiring [Elec Paths]	Embodied fixed costs of capacity being retired each year of each electric energy path, locked in at the time of development. Avg embodied fixed cost of elec capacity[Elec Paths]*Elec Retiring capacity[Elec Paths]	($/GJ)*(EJ/Year)/Year
Avg fixed cost in development of elec[Elec Paths]	Embodied unit fixed costs of capacity of each electric path under developement, locked in at that time. ZIDZ(Embodied fixed cost of elec capacity in development[Elec Paths] ,Elec Capacity under development[Elec Paths])	$/GJ
Avg fixed cost of elec in construction [Elec Paths]	Embodied unit fixed costs of capacity of each electric path under construction, locked in at the time of devleopment. ZIDZ(Embodied fixed cost of elec capacity in construction[Elec Paths] ,Elec Capacity under construction[Elec Paths])	$/GJ
Avg embodied fixed cost of elec capacity [Elec Paths]	Embodied unit fixed costs of completed capacity of each electric energy path, locked in at the time of development. ACTIVE INITIAL(XIDZ(XIDZ(Embodied fixed cost of elec existing capacity[Elec Paths],Elec Energy supply capacity[Elec Paths],Annualized capital costs for elec[Elec Paths]), Reference capital cost[Elec Paths])	$/GJ

Table 4-26. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Embodied fixed cost of fuel capacity in development [Primary Fuels]	Embodied fixed costs, i.e., the actual physically-imposed costs, of capacity under development of each delivered fuel. These are locked in at the time of development. INTEG(Embodied fixed cost of fuel capacity developing[Primary Fuels]-Embodied fixed cost of fuel capacity starting[Primary Fuels], Initial fixed cost of delivered fuel capacity in development[Primary Fuels])	($/GJ)*(EJ/Year)
Embodied fixed cost of fuel capacity in construction [Primary Fuels]	Embodied fixed costs, i.e., the actual physically-imposed costs, of capacity under construction of each delivered fuel. These are locked in at the time of development. INTEG(Embodied fixed cost of fuel capacity starting[Primary Fuels]-Embodied fixed cost of fuel capacity completing[Primary Fuels], Initial fixed cost of delivered fuel capacity in construction[Primary Fuels])	($/GJ)*(EJ/Year)
Embodied fixed cost of fuel existing capacity [Primary Fuels]	Embodied fixed costs, i.e., the actual physically-imposed costs, of existing capacity of each delivered fuel. These are locked in at the time of development. INTEG(Embodied fixed cost of fuel capacity completing[Primary Fuels]-Embodied fixed cost of fuel capacity retiring[Primary Fuels], Initial fixed cost of delivered fuel existing capacity[Primary Fuels])	($/GJ)*(EJ/Year)

Table 4-26. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Initial fixed cost of delivered fuel capacity in development [Primary Fuels]	Initial fixed cost of delivered fuel supply in under development. INITIAL(Fuel Capacity under development [Primary Fuels]*Annualized capital costs of fuel[Primary Fuels]*EXP(Historic cost improvement rate[FuelPath]*Historic completion time[FuelPath]*(1-Fuel Development fraction [Primary Fuels])))	($/GJ)*(EJ/Year)
Initial fixed cost of delivered fuel capacity in construction [Primary Fuels]	Initial fixed cost of delivered fuel supply in under construction. INITIAL(Fuel Capacity under construction [Primary Fuels]*Annualized capital costs of fuel[Primary Fuels]*EXP(Historic cost improvement rate[FuelPath]*Historic completion time[FuelPath]))	($/GJ)*(EJ/Year)
Initial fixed cost of delivered fuel existing capacity [Primary Fuels]	Initial fixed cost of existing delivered fuel supply capacity. INITIAL(Fuel supply capacity [Primary Fuels]*Annualized capital costs of fuel[Primary Fuels] *EXP(Historic cost improvement rate[FuelPath]*(Historic completion time[FuelPath]+1/Actual retirement rate[FuelPath])))	($/GJ)*(EJ/Year)
Embodied fixed cost of fuel capacity developing [Primary Fuels]	Embodied fixed costs of capacity starting development each year of each delivered fuel, locked in at that time. Annualized capital costs for fuel[Primary Fuels]*Fuel Capacity development starting [Primary Fuels]	($/GJ)*(EJ/Year)/Year

Table 4-26. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Embodied fixed cost of fuel capacity starting [Primary Fuels]	Embodied fixed costs of capacity starting construction each year of each delivered fuel, locked in at the time of development. Avg fixed cost of fuel in development[Primary Fuels]*Fuel capacity construction starting [Primary Fuels]	($/GJ)*(EJ/Year)/Year
Embodied fixed cost of fuel capacity completing [Primary Fuels]	Embodied fixed costs of capacity completed each year of each delivered fuel, locked in at the time of development. Avg fixed cost of fuel in construction[Primary Fuels]*Fuel Completing capacity [Primary Fuels]	($/GJ)*(EJ/Year)/Year
Embodied fixed cost of fuel capacity retiring [Primary Fuels]	Embodied fixed costs of capacity being retired each year of each delivered fuel, locked in at the time of development. Avg embodied fixed cost of fuel capacity[Primary Fuels]*Fuel Retiring capacity [Primary Fuels]	($/GJ)*(EJ/Year)/Year
Avg fixed cost of fuel in development [Primary Fuels]	Embodied unit fixed costs of capacity of each delivered fuel under developement, locked in at that time. ZIDZ(Embodied fixed cost of fuel capacity in development[Primary Fuels], Fuel Capacity under development [Primary Fuels])	$/GJ
Avg fixed cost of fuel in construction [Primary Fuels]	Embodied unit fixed costs of capacity of each delivered fuel under construction, locked in at the time of development. ZIDZ(Embodied fixed cost of fuel capacity in construction[Primary Fuels], Fuel Capacity under construction [Primary Fuels])	$/GJ

Table 4-26. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Avg embodied fixed cost of fuel capacity [Primary Fuels]	Embodied unit fixed costs of completed capacity of each delivered fuel, locked in at the time of development. ACTIVE INITIAL(XIDZ(Embodied fixed cost of fuel existing capacity[Primary Fuels],Fuel supply capacity[Primary Fuels],Annualized capital costs for fuel[Primary Fuels]), Reference capital cost[FuelPath])	$/GJ

Figure 4-17 Structure of Efficiency

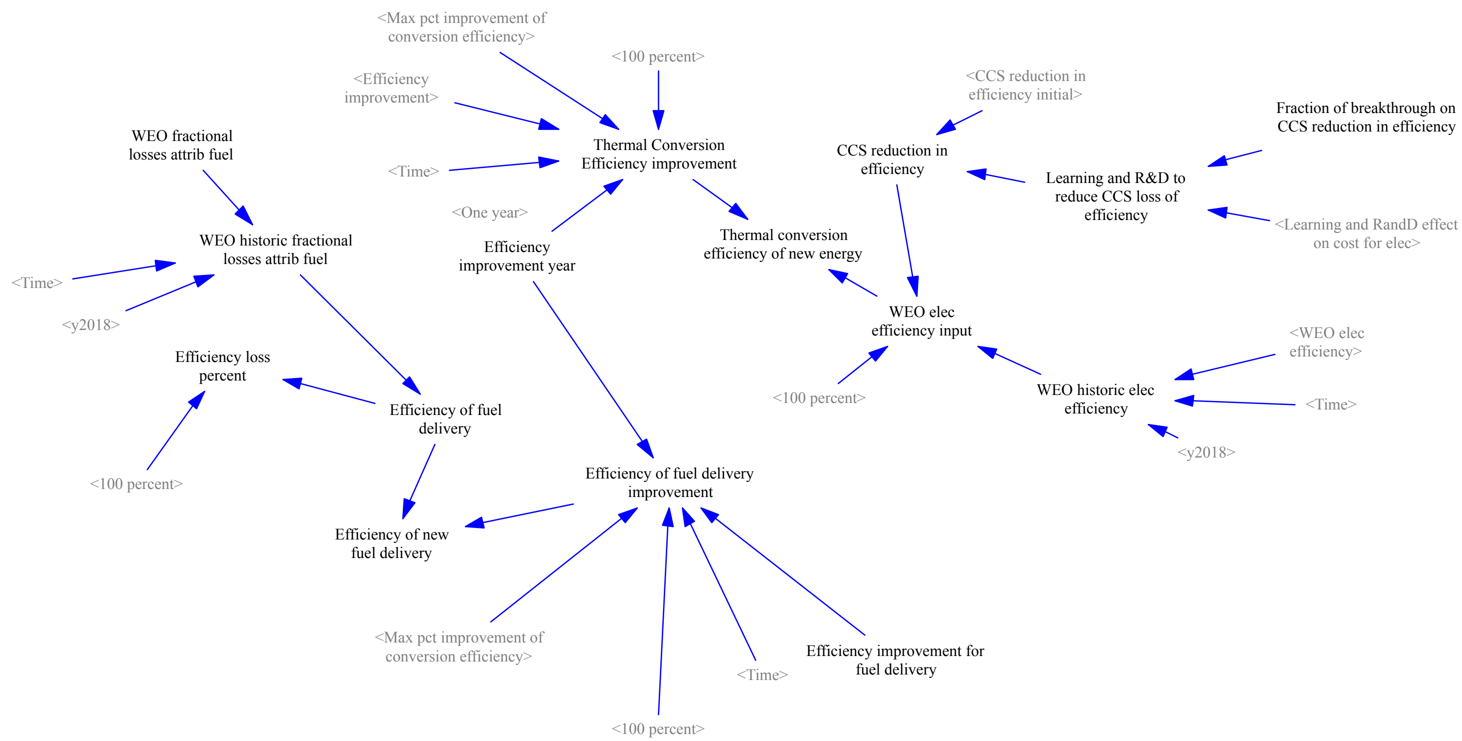


Figure 4-18 Structure of Electric Supply Embodied Efficiency

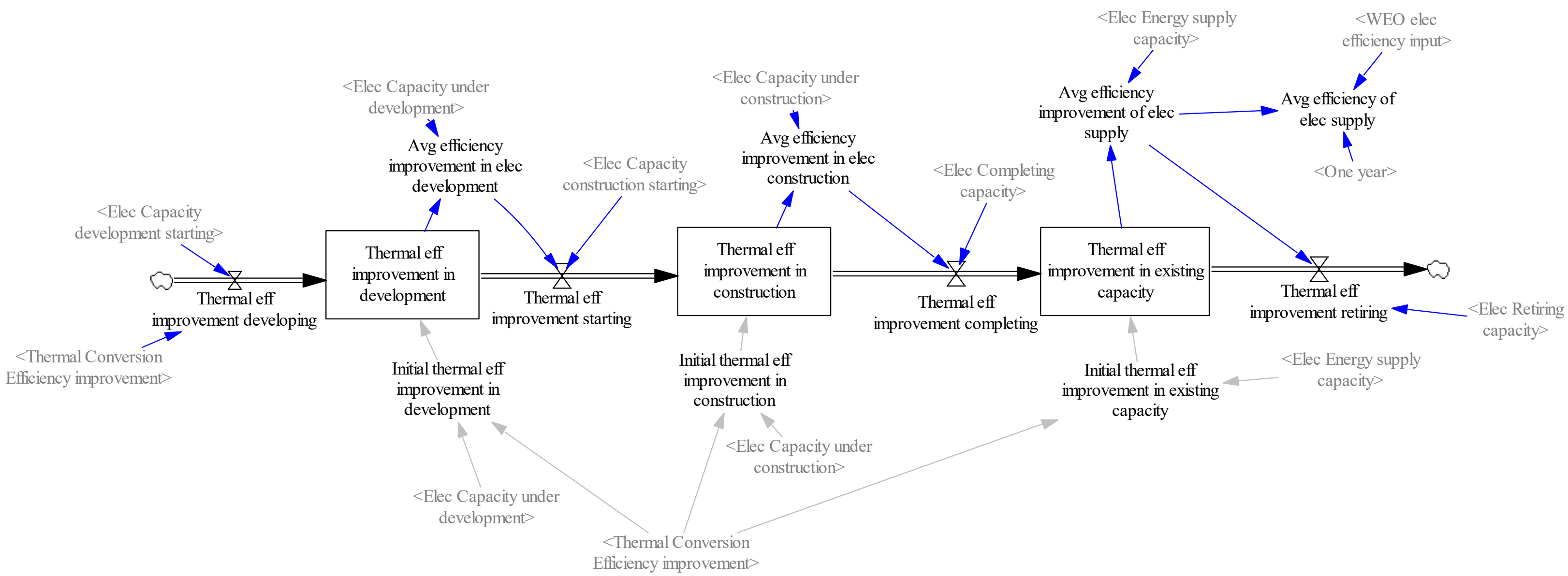


Figure 4-19 Structure of Delivered Fuel Supply Embodied Efficiency

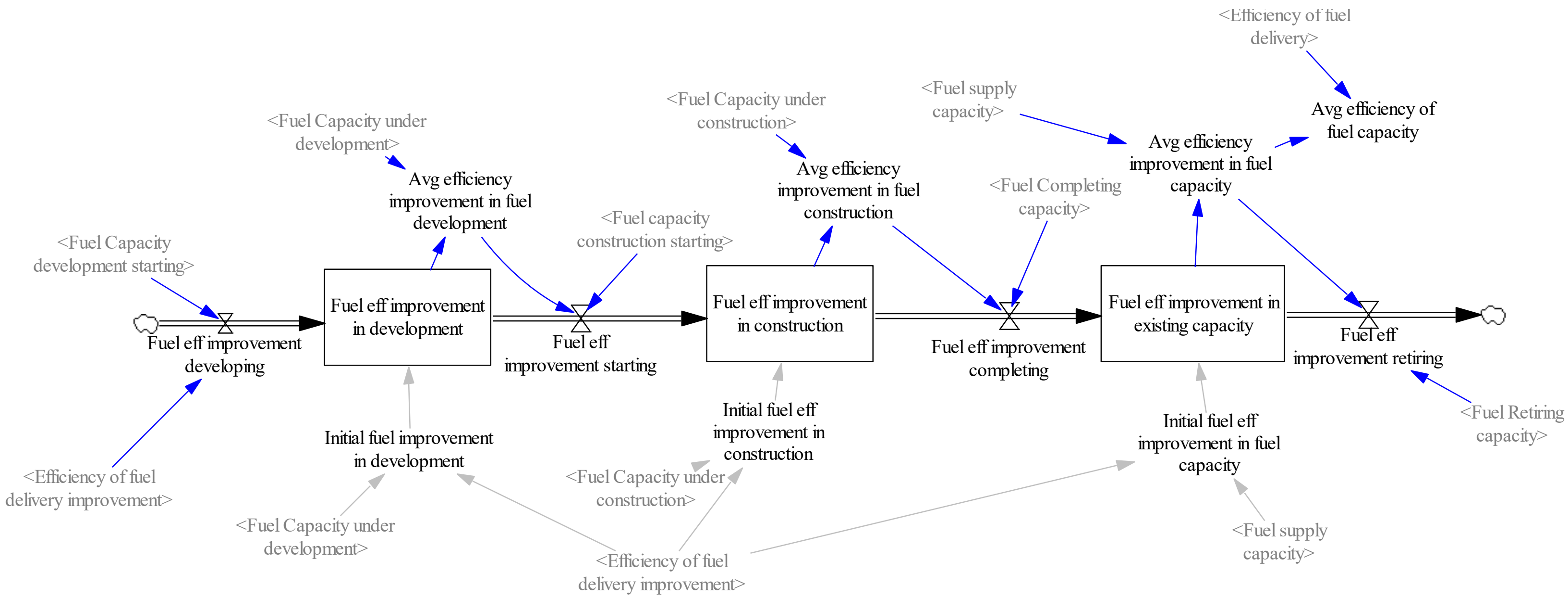


Table 4-27 Efficiency Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Efficiency improvement[Primary Fuels]	Estimated to be consistent with improvement of average efficiency of WEO (2020) data.		0.1	percent/Year
Max conversion efficiency[Primary Fuels]	Estimated to be consistent with improvement of average efficiency of WEO (2020) data.			percent
Coal			50	
Oil			50	
Gas			50	
Bio			50	
Carbon capture effectiveness[CCS Paths]	Reduction in carbon emissions factor from the nonCCS counterpart. Folger, Carbon Capture and Sequestration (CCS) in the United States. 2018. https://fas.org/sgp/crs/misc/R44902.pdf.			Percent
Coal, Oil, Gas			90	
Bio	Assumes approximately 50% of Bio emissions are due to upstream energy use and are therefore not subject to being captured.		50	
Fraction of breakthrough on CCS reduction in efficiency	Fraction of breakthrough effect that also applies to bring the efficiency of each CCS path closer to that of its nonCCS counterpart.	0-1	1	Dmnl
Fraction of breakthrough on CCS reduction in efficiency	Fraction of breakthrough effect that also applies to improve efficiency.	0-1	1	Dmnl
Efficiency improvement for fuel delivery [Primary Fuels]	Estimated to be consistent with improvement of average efficiency of WEO (2016 and 2018) data.		0	percent/Year

Table 4-27 Efficiency Parameter Inputs

Parameter	Definition	Range	Default Values	Units
WEO fractional losses attrib fuel	Inputted as Lookup as calculated from WEO (2016 and 2018) data through 2017. Averages of 0.25, 0.075, 0.15, and 0.1 for coal, oil, gas, and bio over that period.			Dmnl

Table 4-28. Efficiency Calculated Parameters

Parameter	Definition	Units
WEO elec efficiency input[Elec Paths]		Dmnl
[Elec thermal]	WEO historic elec efficiency[Primary energy fuel sources]	
[CCS Paths]	WEO elec efficiency input[Elec thermal]*(1-CCS reduction in efficiency[CCS Paths]/"100 percent")	
[Renewable types]	1, 1, 0.1, 1	
[Nuc Hydro New]	1	
Thermal conversion efficiency of new energy	WEO elec efficiency input[Elec Paths]*Thermal Conversion Efficiency improvement[Elec Paths]	Dmnl
Thermal Conversion Efficiency improvement [Elec Paths]	Thermal conversion of electricity. 1 by definition for all pathways except thermal generation of electricity. Calibrated to WEO2020.	Dmnl
[Elec thermal]	MIN(1+Max pct improvement of conversion efficiency[Primary Fuels]/"100 percent", EXP(MAX(0, (Time-Efficiency improvement year))*Efficiency improvement[Primary Fuels]/"100 percent"))	
[CCS Paths]	Thermal Conversion Efficiency improvement[Elec thermal]	
[Elec only paths]	1	
CCS reduction in efficiency[CCS Paths]	Loss in efficiency for a CCS path compared to its nonCCS counterpart. CCS reduction in efficiency initial*"Learning and R&D to reduce CCS loss of efficiency"[CCS Paths]	Dmnl
"Learning and R&D to reduce CCS loss of efficiency" [CCS **Paths]**	Learning and RandD effect on cost for elec[CCS Paths]*Fraction of breakthrough on CCS reduction in efficiency+1-Fraction of breakthrough on CCS reduction in efficiency	Dmnl

Table 4-28. Efficiency Calculated Parameters

Parameter	Definition	Units
Efficiency of new fuel delivery[Primary Fuels]	WEO fractional losses attrib fuel is calculated from WEO (2018) data. Efficiency of fuel delivery[Primary Fuels]*Efficiency of fuel delivery improvement[Primary Fuels]	Dmnl
Efficiency of fuel delivery improvement[Primary Fuels]	MIN(1+Max pct improvement of conversion efficiency[Primary Fuels]/"100 percent", EXP(MAX(0, (Time-Efficiency improvement year))*Efficiency improvement for fuel delivery[Primary Fuels]/"100 percent"))	Dmnl
Efficiency of fuel delivery[Primary Fuels]	1-WEO historic fractional losses attrib fuel[Primary Fuels]	Dmnl
Efficiency loss percent[Primary Fuels]	(1-Efficiency of fuel delivery[Primary Fuels])*"100 percent"	percent

Table 4-29.Electricity Capacity Embodied Efficiency Calculated Parameters

Parameter	Definition	Units
Thermal eff improvement in development [Elec Paths]	Thermal efficiency improvements in development, reduced from total according to efficiency in development, where the efficiencies are locked in at that time. INTEG(Thermal eff improvement developing[Elec Paths]-Thermal eff improvement starting[Elec Paths], Initial thermal eff improvement in development[Elec Paths])	EJ/year
Thermal eff improvement in construction [Elec Paths]	Thermal efficiency improvements in construction, where the efficiency improvements are locked in at the time of development. INTEG(Thermal eff improvement starting[Elec Paths]-Thermal eff improvement completing[Elec Paths], Initial thermal eff improvement in construction[Elec Paths])	EJ/year
Thermal eff improvement in existing capacity [Elec Paths]	Thermal efficiency improvements in existing capacity, where the efficiency improvements are locked in at the time of development. INTEG(Thermal eff improvement completing[Elec Paths]-Thermal eff improvement retiring[Elec Paths], Initial thermal eff improvement in existing capacity[Elec Paths])	EJ/year
Initial thermal eff improvement in development[Elec Paths]	Initial thermal efficiency improvements in development. INITIAL(Elec Capacity under development[Elec Paths]*Thermal Conversion Efficiency improvement[Elec Paths])	EJ/year
Initial thermal eff improvement in construction [Elec Paths]	Initial thermal efficiency improvements in construction. INITIAL(Elec Capacity under construction[Elec Paths]*Thermal Conversion Efficiency improvement[Elec Paths])	EJ/year

Table 4-29.Electricity Capacity Embodied Efficiency Calculated Parameters

Parameter	Definition	Units
Initial thermal eff improvement in existing capacity [Elec Paths]	Initial thermal efficiency improvements in existing capacity. INITIAL(Elec Energy supply capacity[Elec Paths]*Thermal Conversion Efficiency improvement[Elec Paths])	EJ/year
Thermal eff improvement developing [Elec Paths]	Thermal efficiency improvements starting development each year of each elec energy path, locked in at that time. Thermal Conversion Efficiency improvement[Elec Paths]*Elec Capacity development starting[Elec Paths]	(EJ/Year)/Year
Thermal eff improvement starting [Elec Paths]	Thermal efficiency improvements starting, locked in at the time of development. Avg efficiency improvement in elec development[Elec Paths]* Elec Capacity construction starting[Elec Paths]	(EJ/Year)/Year
Thermal eff improvement completing Elec Paths]	Thermal efficiency improvements completing, locked in at the time of development. Avg efficiency improvement in elec construction[Elec Paths]*Elec Completing capacity[Elec Paths]	(EJ/Year)/Year
Actual elec energy retiring [Elec Paths]	Thermal efficiency improvements retiring, locked in at the time of development. Avg efficiency improvement of elec supply[Elec Paths]* Elec Retiring capacity[Elec Paths]	(EJ/Year)/Year
Avg efficiency improvement in elec development [Elec Paths]	Embodied thermal efficiency improvements of capacity under development of each electric energy path, locked in at that time. XIDZ(Thermal eff improvement in development[Elec Paths] ,Elec Capacity under development[Elec Paths], 1)	Dmnl

Table 4-29.Electricity Capacity Embodied Efficiency Calculated Parameters

Parameter	Definition	Units
Avg efficiency improvement in elec construction [Elec Paths]	Embodied thermal efficiency improvements of capacity under construction of each electric energy path, locked in at the time of development. XIDZ(Thermal eff improvement in construction[Elec Paths] ,Elec Capacity under construction[Elec Paths], 1)	Dmnl
Avg efficiency improvement of elec supply [Elec Paths]	Embodied thermal efficiency improvements of existing capacity of each electric energy path, locked in at the time of development. XIDZ(Thermal eff improvement in existing capacity[Elec Paths],Elec Energy supply capacity[Elec Paths], 1)	Dmnl
Avg efficiency of elec supply[Elec Paths]	Embodied thermal efficiency of existing capacity of each electric energy path, locked in at the time of development SMOOTH(Avg efficiency improvement of elec supply[Elec Paths]*WEO elec efficiency input[Elec Paths], One year)	Dmnl

Table 4-30. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Fuel eff improvement in development [Primary Fuels]	Actual fuel capacity in development, reduced from total according to efficiency in development, where the efficiencies are locked in at that time. INTEG(Fuel eff improvement developing[Primary Fuels]-Fuel eff improvement starting[Primary Fuels], Initial fuel improvement in development[Primary Fuels])	EJ/year
Fuel eff improvement in construction [Primary Fuels]	Actual fuel capacity in construction, reduced from total according to efficiency in construction, where the efficiencies are locked in at the time of development. INTEG(Fuel eff improvement starting[Primary Fuels]-Fuel eff improvement completing[Primary Fuels], Initial fuel eff improvement in construction[Primary Fuels])	EJ/year
Fuel eff improvement in existing capacity [Primary Fuels]	Actual existing fuel capacity, reduced from total according to efficiency in existing capacity, where the efficiencies are locked in at the time of development. INTEG(Fuel eff improvement completing[Primary Fuels]-Fuel eff improvement retiring[Primary Fuels], Initial fuel eff improvement in fuel capacity[Primary Fuels])	EJ/year
Initial fuel improvement in development [Primary Fuels]	Initial fuel efficiency improvements in development. INITIAL(Fuel Capacity under development[Primary Fuels]*Efficiency of fuel delivery improvement[Primary Fuels])	EJ/year

Table 4-30. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Initial fuel eff improvement in construction [Primary Fuels]	Initial fuel efficiency in construction. INITIAL(Fuel Capacity under construction[Primary Fuels]*Efficiency of fuel delivery improvement[Primary Fuels])	EJ/year
Initial fuel eff improvement in fuel capacity [Primary Fuels]	Initial fuel efficiency existing capacity. INITIAL(Fuel supply capacity[Primary Fuels]*Efficiency of fuel delivery improvement[Primary Fuels])	EJ/year
Fuel eff improvement developing [Primary Fuels]	Fuel efficiency improvements starting development each year of each fuel path, locked in at that time. Efficiency of fuel delivery improvement[Primary Fuels]*Fuel Capacity development starting[Primary Fuels]	(EJ/Year)/Year
Fuel eff improvement starting [Primary Fuels]	Fuel efficiency improvements starting construction each year of each fuel path, locked in at the time of development. Avg efficiency improvement in fuel development[Primary Fuels]*Fuel capacity construction starting[Primary Fuels]	(EJ/Year)/Year
Fuel eff improvement completing [Primary Fuels]	Fuel efficiency improvements, completed each year of each fuel path, locked in at the time of development. Avg efficiency improvement in fuel construction[Primary Fuels]*Fuel Completing capacity[Primary Fuels]	(EJ/Year)/Year
Fuel eff improvement retiring [Primary Fuels]	Fuel efficiency improvements retiring each year of each fuel path, locked in at the time of development. Avg efficiency improvement in fuel capacity[Primary Fuels]* Fuel Retiring capacity[Primary Fuels]	(EJ/Year)/Year

Table 4-30. Delivered Fuel Capacity Embodied Fixed Costs Calculated Parameters

Parameter	Definition	Units
Avg efficiency improvement in fuel development [Primary Fuels]	Embodied fuel efficiency improvments of capacity under development of each fuel path, locked in at that time. XIDZ(Fuel eff improvement in development[Primary Fuels] ,Fuel Capacity under development[Primary Fuels], 1)	Dmnl
Avg efficiency improvement in fuel construction [Primary Fuels]	Embodied fuel efficiency improvments of capacity under construction of each fuel path, locked in at the time of development. XIDZ(Fuel eff improvement in construction[Primary Fuels] ,Fuel Capacity under construction[Primary Fuels], 1)	Dmnl
Avg efficiency improvement in fuel capacity [Primary Fuels]	Embodied fuel efficiency improvments of existing capacity of each fuel path, locked in at the time of development. XIDZ(Fuel eff improvement in existing capacity[Primary Fuels],Fuel supply capacity[Primary Fuels], 1)	Dmnl
Avg efficiency of fuel capacity	Embodied fuel efficiency of each fuel path, locked in at the time of development. Efficiency of fuel delivery[Primary Fuels]*Avg efficiency improvement in fuel capacity[Primary Fuels]	Dmnl

4.4 Electric Supply Choice

As in the **Carrier and Fuel Choice** sectors, the fraction of new investment allocated to each of the electric energy sources is a function of its attractiveness relative to that of the other sources. Attractiveness synthesizes cost effect and the effect of a performance standard, as shown in Figure 4-20.

4.4.1 Cost Effect Attractiveness

The cost, adjusted by any source subsidies/taxes drives the cost attractiveness of each electric path relative to the other electric paths. The cost attractiveness for each nonCCS/CCS couple is nested within the cost attractiveness of all the electric paths.

Figure 4-20 Electric Energy Source Attractiveness

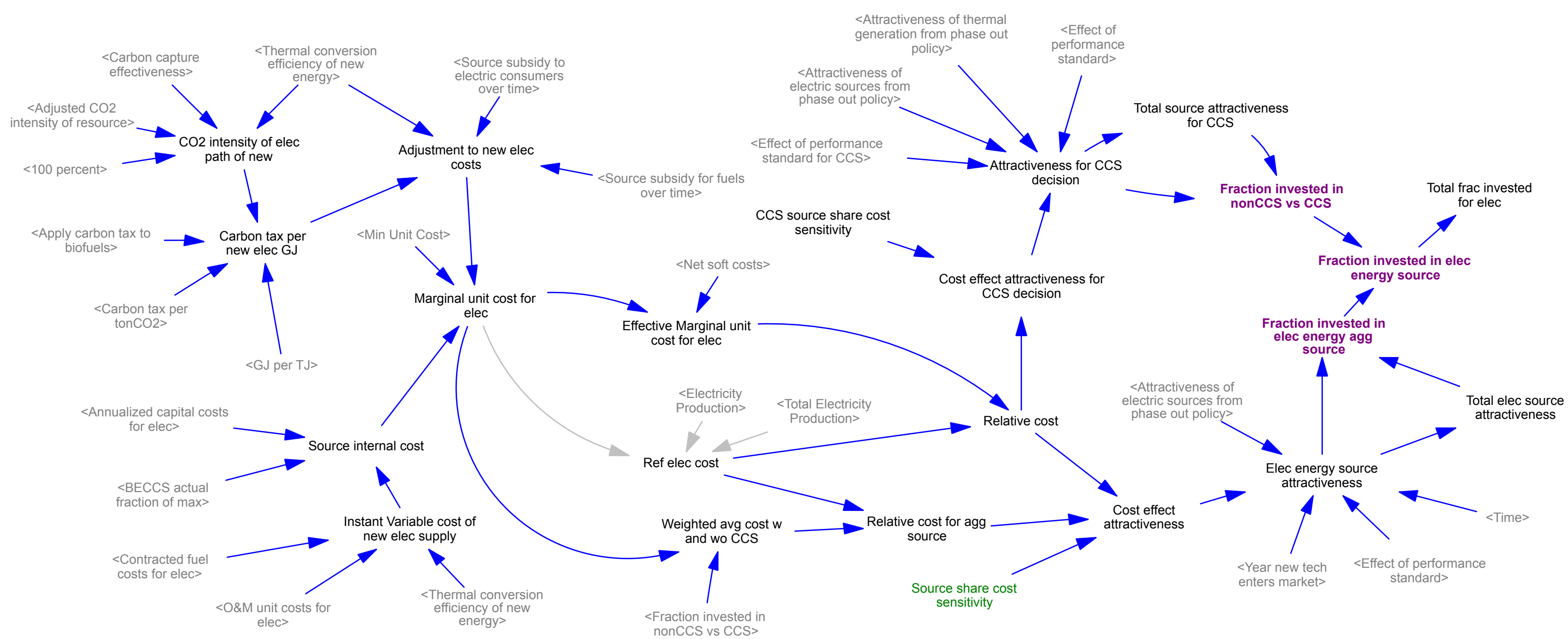


Table 4-31 Cost Effect Attractiveness Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Source share cost sensitivity	The sensitivity of technology choice to the profit margin of competing options. Set to be absolute value so that greater values lead the more costly technologies to make up a smaller share of new energy system capacity.	0.1-10	2	Dmnl
CCS source share cost sensitivity	The sensitivity of technology choice to the profit margin of competing options between CCS/nonCCS couples. Set to be absolute value so that greater values lead the more costly technologies to make up a smaller share of new energy system capacity.	0.1-10	8	Dmnl

Table 4-32 Attractiveness Calculated Parameter

Parameter	Definition	Units
Fraction invested in elec energy source[Elec Paths]	The fraction of all the new elec capacity that is to be provided by each energy path.	Dmnl
[Elec thermal]	Fraction invested in nonCCS vs CCS[Elec thermal] * Fraction invested in elec energy agg source[Elec thermal]	
[CCS Paths]	Fraction invested in nonCCS vs CCS[CCS Paths] * Fraction invested in elec energy agg source[Elec thermal]	
[Elec only paths]	Fraction invested in elec energy agg source[Elec only paths]	
Fraction invested in elec energy agg source[Elec Paths]	The fraction of all the new electric capacity that is to be provided by each energy source. ZIDZ (Elec energy source attractiveness[Elec Paths] , Total elec source attractiveness)	Dmnl
Elec energy source attractiveness[Elec Paths]	The preference of each energy path relative to the others, synthesizing cost, network, and performance standard.	Dmnl
[All elec but new]	Cost effect attractiveness[All elec but new] * Effect of performance standard[All but new sources] * Attractiveness of electric sources from phase out policy[All but new sources]	
[New]	IF THEN ELSE (Time < Year new tech enters market , 0, Cost effect attractiveness[new] * Effect of performance standard[Primary new] * Attractiveness of electric sources from phase out policy[Primary new])	
Total elec source attractiveness	The total attractiveness of all the electric energy sources. SUM (Elec energy source attractiveness[Elec Paths!])	Dmnl

Table 4-32 Attractiveness Calculated Parameter

Parameter	Definition	Units
Cost effect attractiveness	The preference of each energy path relative to the others based on more costly paths being less preferable. Measure of the market potential of each energy source as a function of the relative cost of each energy source. The attractiveness of elec thermal paths accounts for the weighted average of the fraction of the CCS/nonCCS couples, which are reincorporated in the fraction *Fraction invested in energy source*.	Dmnl
[Elec only paths]	EXP (- Source share cost sensitivity * Relative cost[Elec only paths])	
[Elec thermal]	EXP (- Source share cost sensitivity * Relative cost for agg source[Primary energy fuel sources])	
[CCS Paths]	0	

Table 4-33. Cost Effect Attractiveness Calculated Parameters

Parameter	Deifefnition	Units
Source internal cost[Elec Paths]	The internal cost of each energy path for electric capacity investment decisions. Includes storage for renewables. Instant Variable cost of new elec supply[Elec Paths]+Annualized capital costs for elec[Elec Paths]	$/GJ
Marginal unit cost for elec[Elec Paths]	Source internal cost adjusted for emissions costs and subsidies. MAX (Min Unit Cost , Source internal cost[Elec Paths] + Adjustment to new elec costs[Elec Paths])	$/GJ
Effective Marginal unit cost for elec Elec Paths]	Marginal cost adjusted to reflect soft costs and historic subsidies of renewables. Soft costs[Elec Paths] + Marginal unit cost for elec[Elec Paths]	$/GJ
Relative cost[Elec Paths]	Ratio of the adjusted costs to the reference average cost. Effective Marginal unit cost for elec[Elec Paths]/ Ref elec cost	dmnl
Cost effect attractiveness for CCS decision [Elec thermal plus CCS]	The preference of each energy path relative to the others based on more costly paths being less preferable. Measure of the market potential of each energy source as a function of the relative cost of each energy source. The attractiveness of elec thermal paths accounts for the weighted average of the fraction of the CCS/nonCCS couples, which are reincorporated in the fraction *Fraction invested in energy source*. EXP (- CCS source share cost sensitivity * Relative cost[Elec thermal plus CCS])	Dmnl

Table 4-33. Cost Effect Attractiveness Calculated Parameters

Parameter	Deflefnition	Units
Attractiveness for CCS decision [Elec thermal plus CCS]	The preference of each elec thermal path with and without CCS relative to the others based on more costly paths being less preferable.	Dmnl
[Elec thermal]	Cost effect attractiveness for CCS decision[Elec thermal]*Non cost adjustment to attractiveness[Primary energy fuel sources]*Effect of performance standard[Primary energy fuel sources]	
[CCS Paths]	Cost effect attractiveness for CCS decision[CCS Paths]*Non cost adjustment to attractiveness[Primary energy fuel sources]*Effect of performance standard for CCS[CCS Paths]	
Total source attractiveness for CCS[Elec thermal]	For each elec thermal path, the sum of the attractiveness of it and its CCS counterpart.	Dmnl
Coal	SUM(Cost effect attractiveness for CCS[Elec coal!])	
Oil	SUM(Cost effect attractiveness for CCS[Elec oil!])	
Gas	SUM(Cost effect attractiveness for CCS[Elec gas!])	
Bio	SUM(Cost effect attractiveness for CCS[Elec bio!])	
Weighted avg cost w and wo CCS [Primary fuels]	Makes adjusted cost of each elec thermal path to be the adjusted cost weighted average of it and its CCS counterpart.	$/GJ
Coal	SUM(Marginal unit cost[Elec coal!]*Actual Fraction invested in nonCCS vs CCS [Elec coal!])	
Oil	SUM(Marginal unit cost[Elec oil!]*Actual fraction invested in nonCCS vs CCS[Elec oil!])	
Gas	SUM(Marginal unit cost[Elec gas!]*Actual fraction invested in nonCCS vs CCS[Elec gas!])	
Bio	SUM(Marginal unit cost[Elec bio!]*Actual fraction invested in nonCCS vs CCS[Elec bio!])	

Table 4-33. Cost Effect Attractiveness Calculated Parameters

Parameter	Defiefnition	Units
Relative cost for agg source [Primary fuels]	For each elec thermal path, the ratio of the adjusted costs, weighted according to the fraction of CCS/nonCCS, to the reference average cost of each carrier. Weighted avg cost w and wo CCS[Primary fuels]/Ref elec cost	Dmnl
Fraction invested in nonCCS vs CCS[Elec thermal plus CCS]	The fraction of all the new capacity of each elec thermal path that is to be provided by CCS vs nonCCS paths.	Dmnl
[Elec thermal]	ZIDZ(Attractiveness for CCS decision[Elec thermal], Total source attractiveness for CCS[Elec thermal])	
[CCS Paths]	1-Fraction invested in nonCCS vs CCS[Elec thermal]	
Fraction invested in nonCCS vs CCS [Elec thermal plus CCS]	The fraction of all the new capacity of each elec thermal path that is to be provided by CCS vs nonCCS paths, accounting for the percentage of the world with the non cost policy of no new investment in a given source.	Dmnl
[Elec thermal]	ZIDZ (Attractiveness for CCS decision[Elec thermal], Total source attractiveness for CCS[Elec thermal])	
[CCS Paths]	1-Fraction invested in nonCCS vs CCS[Elec thermal]	

4.4.2 Performance Standard and Other Non-Cost Policies

The performance standard effect is a function of a specified carbon intensity threshold and the carbon intensity of each energy source resource, defined in Section 7. The performance standard creates a soft threshold, beyond which sources with high emissions intensity (e.g., coal) are greatly diminished in attractiveness and are effectively eliminated from the investment mix. The structures of these effects are shown in Figure 4-21. The effect of non-cost policies, Figure 4-22, aims to capture any legislation or rule demanding no new investment in a specified source for a percentage of the global energy needs.

Figure 4-21 Performance Standard and Network Effect Attractiveness

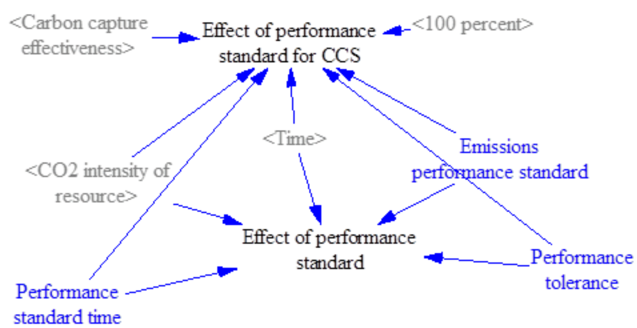


Figure 4-22 Effect of Phase-Out Policies

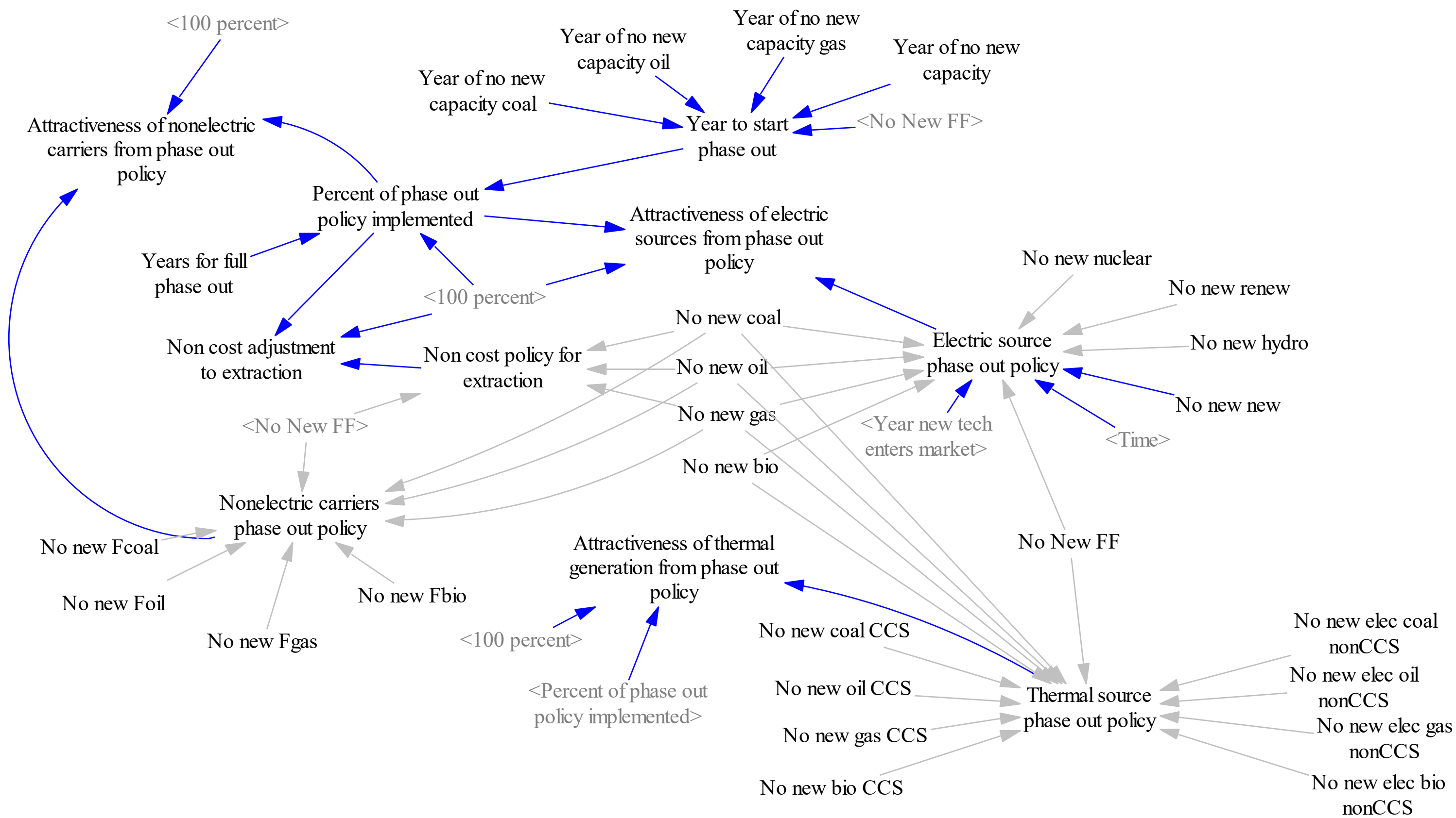


Table 4-34 Performance Standard, Network Effect, and Other Non-Cost Policy Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Emissions performance standard	A lower standard disincentives higher emitting sources. This has a default value of 100. Costs will show up at lower levels: Coal 91, Oil 71, Gas 50 TonCO2/TJ	10-100	100	TonCO2/TJ
Performance tolerance	Tolerance for marginally-performing sources	1-40	5	TonCO2/TJ
Performance standard time	Year when the performance standard is implemented.	2021-2100	2021	Year
No New FF	A non cost phase-out policy that specifies no new investments in coal, oil, or gas sources.	0-1	0	Dmnl
No new XX	A non cost phase-out policy that specifies no new investments in each of the primary energy sources	0-1	0	Dmnl
No new eXXX	A non cost phase-out policy that specifies no new investments determining the CCS/nonCCS fractions for each thermal path, defaults to 0 for no such constraint.	0-1	0	Dmnl
Years for full phase out	Time to reach the full percentage specified for the non cost phase-out policy.	1-20	10	Year

Table 4-35. Non-Cost Policy Calculated Parameters

Parameter	Definition	Units
Effect of performance standard[Primary Energy Sources]	Performance standard effect on attractiveness for investment - sets a soft limit (some tolerance for marginally-performing sources) IF THEN ELSE(Time>=Performance standard time,EXP(-MAX(0,CO2 intensity of resource[Primary Energy Sources]-Emissions performance standard) /Performance tolerance), 1)	dmnl
Effect of performance standard for CCS[Elec Paths]	Makes effect of performance standard of each elec thermal path to be the adjusted cost weighted average of it and its CCS counterpart. IF THEN ELSE(Time>=Performance standard time,EXP(-MAX(0,CO2 intensity of resource[Primary energy fuel sources]*(1-Carbon capture effectiveness[CCS Paths]/"100 percent")-Emissions performance standard) /Performance tolerance),1)	Dmnl
Year to start phase out[Primary Fuels]	Year that the non cost phase-out policy starts to takes effect.	Year
Primary Coal	IF THEN ELSE(No New FF, MIN(Year of no new capacity, Year of no new capacity coal), Year of no new capacity coal)	
Primary Oil	IF THEN ELSE(No New FF, MIN(Year of no new capacity, Year of no new capacity oil), Year of no new capacity oil)	
Primary Gas	IF THEN ELSE(No New FF, MIN(Year of no new capacity, Year of no new capacity gas), Year of no new capacity gas)	
Non FF resources	Year of no new capacity	
Percent of phase out policy implemented[Primary Energy Sources]	ramp("100 percent"/Years for full phase out ,Year to start phase out[Primary Energy Sources] , Year to start phase out[Primary Energy Sources]+Years for full phase out)	Percent
Thermal source phase out policy[Elec Thermal plus CCS]		Dmnl

Table 4-35. Non-Cost Policy Calculated Parameters

Parameter	Definition	Units
ECoal CCS	MAX(No New FF,MAX(No new coal, No new coal CCS))	
EOil CCS	MAX(No New FF,MAX (No new oil, No new oil CCS))	
EGas CCS	MAX(No New FF,MAX(No new gas, No new gas CCS))	
EBio CCS	MAX(No new bio, No new bio CCS)	
ECoal	MAX(No New FF,MAX(No new coal,No new elec coal nonCCS))	
EOil	MAX(No New FF,MAX (No new oil, No new elec oil nonCCS))	
EGas	MAX(No New FF,MAX(No new gas, No new elec gas nonCCS))	
EBio	MAX(No new bio, No new elec bio nonCCS)	
Attractiveness of thermal generation from phase out policy[Elec thermal plus CCS]	1-(Thermal source phase out policy[Elec thermal plus CCS])*Percent of phase out policy implemented[Primary energy fuel sources]/"100 percent"	Dmnl
Electric source phase out policy[Primary Energy Sources]		Dmnl
Primary Coal	1-MAX(No New FF,No new coal)	
Primary Oil	1-MAX(No New FF, No new oil)	
Primary Gas	1-MAX(No New FF,No new gas)	
Primary Bio	1-No new bio	
Primary Nuclear	1-No new nuclear	
Primary Hydro	1-No new hydro	
Primary Renewables	1-No new renew	
Primary New	IF THEN ELSE(Time<=Year new tech enters market, 0, 1-No new new)	
Attractiveness of electric sources from phase out policy[Primary Energy Sources]	1-(1-Electric source phase out policy[Primary Energy Sources])*Percent of phase out policy implemented[Primary Energy Sources]/"100 percent"	Dmnl
Nonelectric carriers phase out policy[Primary Fuels]		Dmnl

Table 4-35. Non-Cost Policy Calculated Parameters

Parameter	Definition	Units
PCoal	1-MAX(No New FF,MAX(No new coal, No new Fcoal))	
POil	1-MAX(No New FF, MAX(No new oil, No new Foil))	
PGas	1-MAX(No New FF,MAX(No new gas, No new Fgas))	
PBio	1-No new Fbio	
Attractiveness of nonelectric carriers from phase out policy[Primary Fuels]	1-(1-Nonelectric carriers phase out policy[Primary Fuels])*Percent of phase out policy implemented[Primary energy fuel sources]/"100 percent"	Dmnl

5. Market Clearing and Utilization Formulation

The **Market and Utilization** sector uses a market clearing theory to balance supply and demand given costs, prices, and assumed market attributes. In summary, the model includes the following:

1. Extraction capacity and price of extracted fuels.

2. Supply/demand/price of each fuel for nonelectric consumption. The variable costs include the extracted fuel price from 1 contracted over a period, adjusted by any taxes or subsidies.

3. Supply/demand/price of electricity, where the variable cost includes the market price of delivered fuels from 1 marked up by a ratio and contracted over a period, adjusted by any taxes or subsidies.

4. For each delivered fuel for nonelectric consumption, the recent market price of each fuel relative to the expected market price to each fuel adjusts the actual demand from that at normal utilization. For each fuel, the normal demand is the sum of the long term demand for nonelectric consumption accounting for noncost phase-out policies (Section 3.5).

5. For electricity, the recent market price relative to expected market price adjusts the actual demand from that at normal utilization.

5.1 Market Price of Extracted Fuel

The market price of extracted fuels depends on the utilization and price effects as well as the cost of extraction, which depends on technological cost improvements and overheating of capacity (Section 4.2.1), and resource constraints (Section 4.2.2). That capacity is defined in Section 4.1.

Figure 5-1 Structure of Market Price of Extracted Fuels

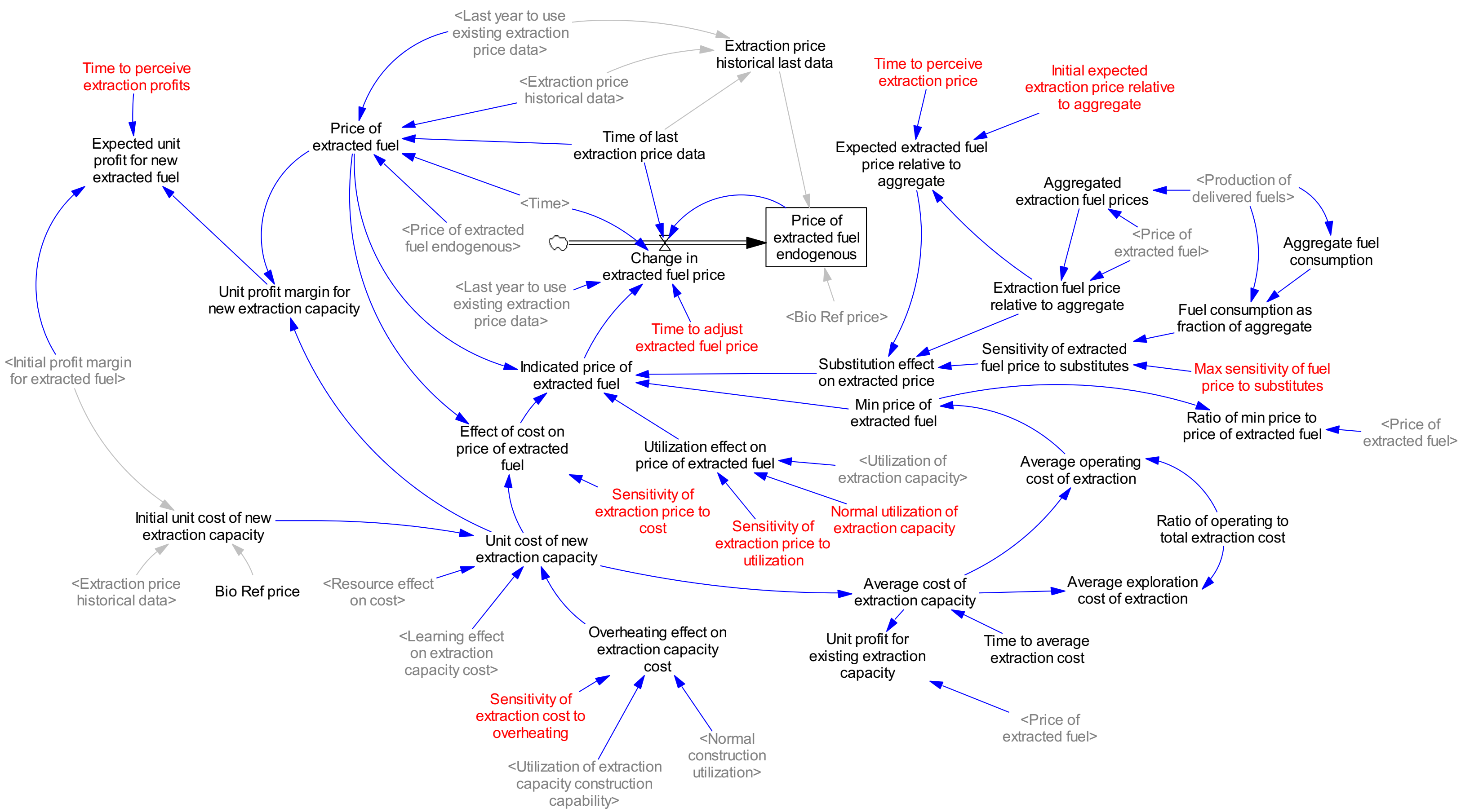


Table 5-1 Market Price of Extracted Fuels Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Ratio of operating to total extraction cost [Primary Fuels]	Ratio of O&M costs to total cost of extraction, where the remainder is exploration costs.	0-1	0.6, 0.4, 0.4, 0.4	Dmnl
Time to average extraction cost	Time over which new costs of extraction are averaged.	1-10	10	Year
Max sensitivity of fuel price to substitutes	Measure of the effect of the aggregate of the prices of other fuels has on the price of each fuel.	0-1	0.2	Dmnl
Initial expected fuel price relative to aggregate[Primary Fuels]				Dmnl
Coal			0.6	
Oil			1.5	
Gas			0.6	
Bio			1.5	
Sensitivity of extraction price to utilization	Measure of how much the price changes with utilization variance from normal. Utilization greater than normal increases the price; conversely, utilization below normal decreases the price. The increases and decreases are greater as the sensitivity value increases.	0-1	0.5	dmnl
Sensitivity of extraction price to cost	Measure of how much the cost increases with the marginal cost of new extraction capacity.	0-1	0.5	Dmnl
Sensitivity of extraction cost to overheating	Measure of how much the cost increases with the target extraction capacity completion relative to the current capability.	0-2	0.2	Dmnl

Table 5-1 Market Price of Extracted Fuels Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Bio Ref price	Large range. http://biofuel.org.uk/cost.html	0-10	7	$/GJ
Initial profit margin for extracted fuel[Primary Fuels]			0	Dmnl
Time to perceive extracted profits		2-10	4	Years
Time to perceive extracted price		2-10	4	Years
Time to adjust extracted fuel price		1-5	1	Year
Time of last extraction price data[Primary Fuels]	Last available historical data of extraction prices	1990-2100	1990	Year
Last year to use existing extraction price data	Year through which extraction price data is used if available.	1990-2017	1990	Year

Table 5-2. Market Price of Extracted Fuels Calculated Parameters

Parameter	Definition	Units
Price of extracted fuel endogenous[Primary Fuels]		$/GJ
[Primary FF]	INTEG(Change in extracted fuel price[Primary FF], Extraction price historical last data[Primary FF])	
[Rbio]	INTEG(Change in extracted fuel price[RBio], Bio Ref price)	
Extraction price historical last data [Primary Fuels]	GET DATA BETWEEN TIMES(Extraction price historical data[Primary Fuels], MIN(Last year to use existing extraction price data, Time of last extraction price data[Primary Fuels]), 1)	$/GJ
Change in extracted fuel price[Primary Fuels]		$/GJ
[Primary Fuels]	IF THEN ELSE(Time<=MIN(Last year to use existing extraction price data, Time of last extraction price data[Primary Fuels]), 0, (Indicated price of extracted fuel[Primary Fuels]-Price of extracted fuel endogenous[Primary Fuels])/Time to adjust extracted fuel price)	
Indicated price of extracted fuel [Primary Fuels]	MAX(Price of extracted fuel [Primary Fuels] * Utilization effect on extracted price[Primary Fuels]*Substitution effect on extracted price[Primary Fuels], Min price of extracted fuel[Primary Fuels])	$/GJ
Price of extracted fuel		$/GJ
[Primary FF]	IF THEN ELSE(Time<=MIN(Last year to use existing extraction price data, Time of last extraction price data[Primary FF]) , Extraction price historical data[Primary FF], Price of extracted fuel endogenous[Primary FF])	
[Rbio]	Price of extracted fuel endogenous[RBio]	
Average operating cost of extraction[Primary Fuels]	Average cost of extraction capacity[Primary Fuels]*"Ratio of operating to total extraction cost"[Primary Fuels]	$/GJ

Table 5-2. Market Price of Extracted Fuels Calculated Parameters

Parameter	Definition	Units
Average exploration cost of extraction[Primary Fuels]	Average cost of extraction capacity[Primary Fuels]*(1-"Ratio of operating to total extraction cost"[Primary Fuels])	$/GJ
Profit margin for existing extraction capacity[Primary Fuels]	(Price of extracted fuel [Primary Fuels] - Average cost of extraction capacity[Primary Fuels]+Source subsidy to extractors[Primary Fuels])/Average cost of extraction capacity[Primary Fuels]	$/GJ
Min price of extracted fuel[Primary Fuels]	The minimum price is assumed to be the average cost of operating the extraction as the exploration costs are already sunk. Average operating cost of extraction[Primary Fuels]	$/GJ
Utilization effect on price of extracted fuel [Primary Fuels]	(Utilization of extraction capacity[Primary Fuels]/Normal utilization of extraction capacity[Primary Fuels])^Sensitivity of extraction price to utilization	Dmnl
Effect of cost on price of extracted fuel[Primary Fuels]	(Unit cost of new extraction capacity[Primary Fuels]/Price of extracted fuel[Primary Fuels])^Sensitivity of extraction price to cost	Dmnl
Substitution effect on price[Primary Fuels]	(Expected fuel price relative to aggregate[Primary Fuels]/Fuel Price relative to aggregate[Primary Fuels])^Sensitivity of fuel price to substitutes[Primary Fuels]	Dmnl
Fuel consumption as fraction of aggregate[Primary Fuels	Production of delivered fuels[Primary Fuels] / Aggregate fuel consumption	Dmnl
Aggregate fuel consumption	Sum of all extracted energy. SUM(Production of delivered fuels[Primary Fuels!])	EJ/year
Aggregated primary fuel prices	Aggregate extracted price of fuels. SUM(Production of delivered fuels[Primary Fuels!]*Price of extracted fuel[Primary Fuels!])/SUM(Production of delivered fuels[Primary Fuels!])	$/GJ
Extraction fuel price relative to aggregate [Primary Fuels]	ZIDZ(Price of extracted fuel [Primary Fuels],Aggregated extraction fuel prices)	Dmnl

Table 5-2. Market Price of Extracted Fuels Calculated Parameters

Parameter	Definition	Units
Expected fuel price relative to aggregate[Primary Fuels]	DELAY1I(Extraction fuel price relative to aggregate[Primary Fuels], Time to perceive extraction price, Initial expected extraction price relative to aggregate[Primary Fuels])	Dmnl
Min price of extracted fuel[Primary Fuels]	Average operating cost of extraction[Primary Fuels]	$/GJ
Average operating cost of extraction[Primary Fuels]	Average cost of extraction capacity[Primary Fuels]*Ratio of operating to total extraction cost[Primary Fuels]	$/GJ
Ratio of min price to price of extracted fuel	Min price of extracted fuel[Primary Fuels]/Price of extracted fuel[Primary Fuels]	Dmnl
Unit cost of new extraction capacity[Primary Fuels]	Initial unit cost of new extraction capacity [Primary Fuels]*Resource effect on cost[Primary Fuels]*Learning effect on extraction capacity cost[Primary Fuels]*Overheating effect on extraction capacity cost[Primary Fuels]	$/GJ
Overheating effect on extraction capacity cost[Primary Fuels]	MAX(1,Utilization of extraction capacity construction capability[Primary Fuels]/Normal construction utilization)^Sensitivity of extraction cost to overheating	$/GJ
Initial unit cost of new extraction capacity [Primary Fuels]		$/GJ
[Primary FF]	Extraction price historical data[Primary FF]/ (1 + Initial profit margin for extracted fuel)	
[PBio]	Bio Ref pruce/(1 + Initial profit margin for extracted fuel)	
Unit profit margin for new extraction capacity[Primary Fuels]	(Price of extracted fuel [Primary Fuels] - Unit cost of new extraction capacity[Primary Fuels])/Unit cost of new extraction capacity[Primary Fuels]	$/GJ
Expected unit profit for new extracted fuel[Primary Fuels]	SMOOTHi(Profit margin for new extraction capacity[Primary Fuels], Time to perceive extraction profits, Initial profit margin for extracted fuel)	$/GJ

5.2 Electricity and Delivered Fuels for Nonelectric Consumption

5.2.1 Market Clearing and Utilization

The market price and utilization of electricity and delivered fuels for nonelectric consumption depends on the long term demand defined in Section 3.5, the supply capacity defined in 4.1, costs of supply defined in 4.2, and market price adjustments defined in 5.2.2. Utilization of each source is a function of profits and the short term supply curves, but may be reduced by noncost phase-out policies. Capacity of extracted fuels is utilized for electric generation and also processed for delivered fuels for nonelectric carriers.

Figure 5-2 Structure of Market Clearing and Utilization of Electric Energy

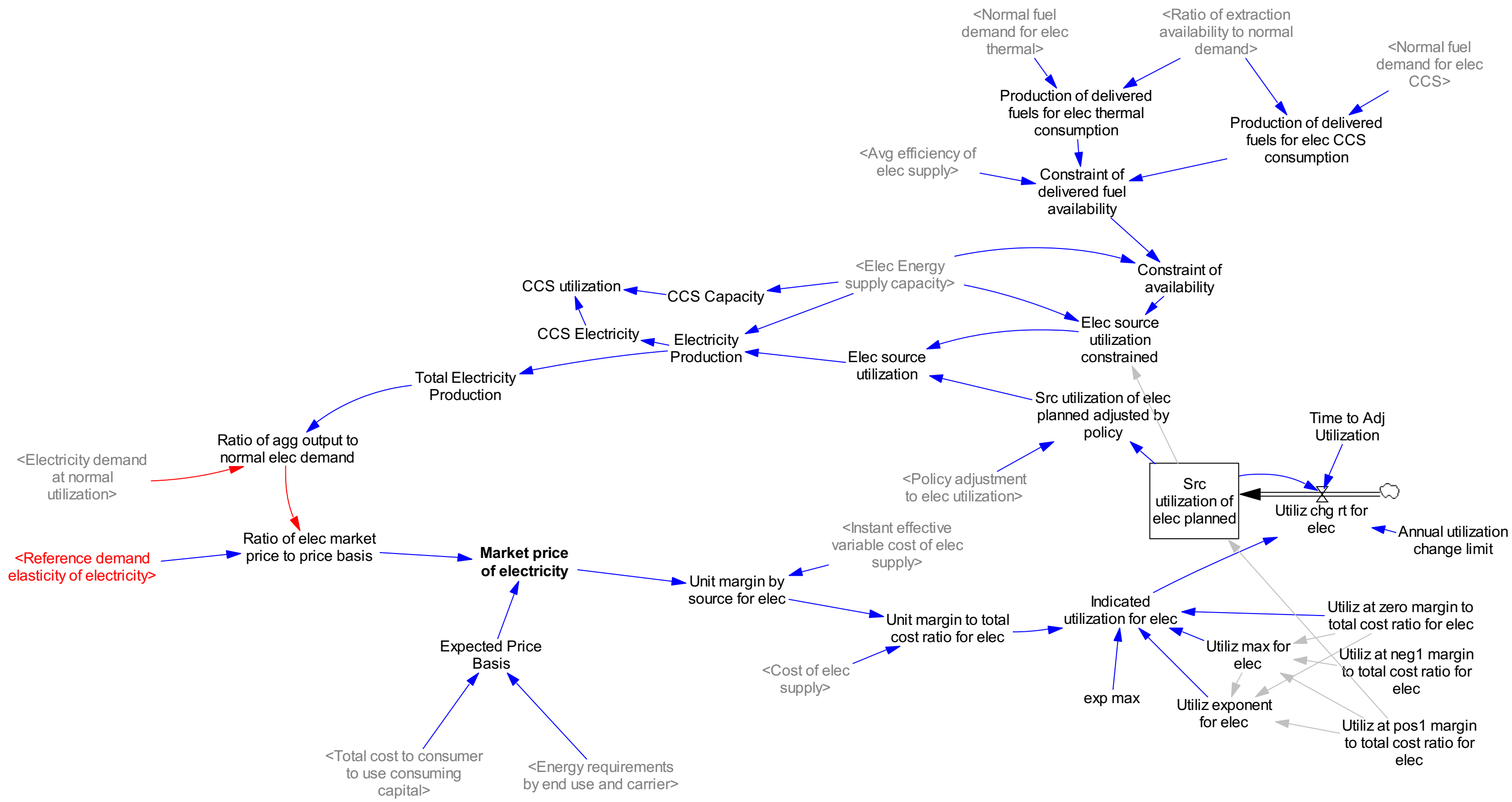


Figure 5-3 Structure of Market Clearing and Utilization of Delivered fuels for Nonelectric Carriers

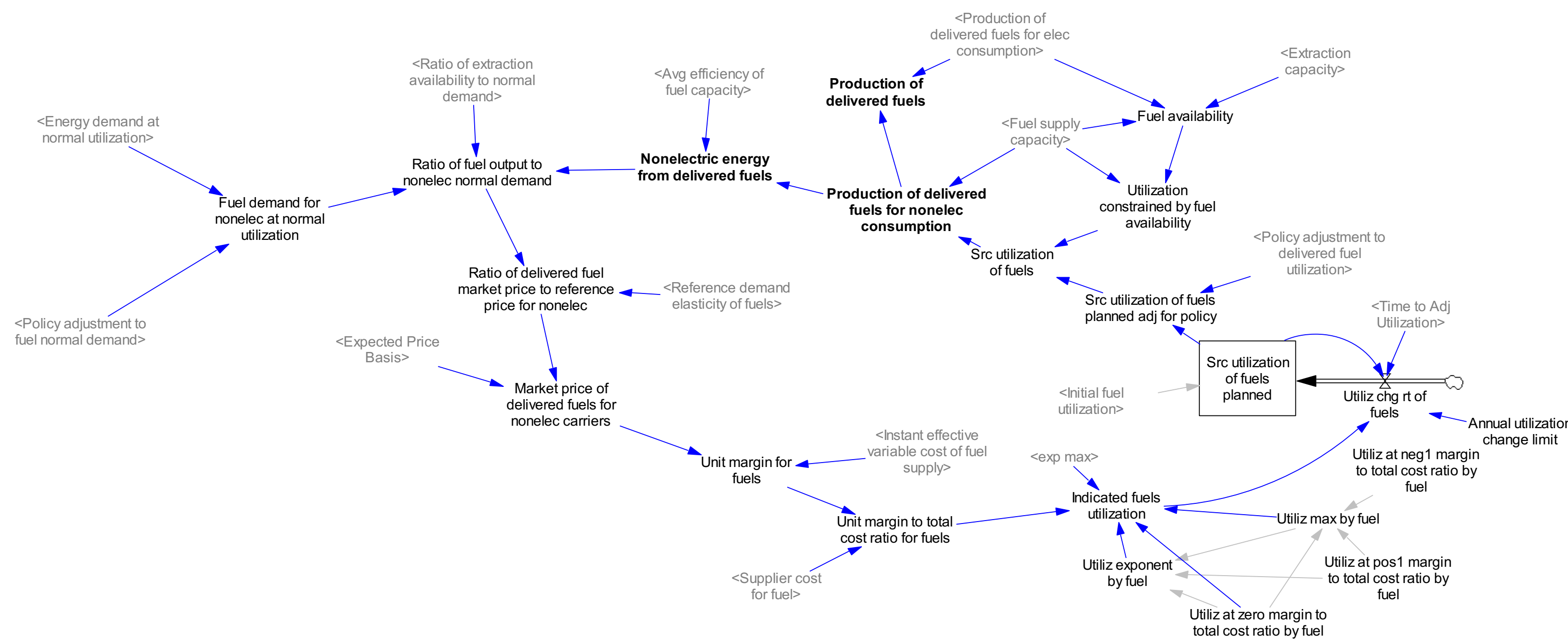


Figure 5-4 Structure of Utilization of Extracted Fuels for Electric and Nonelectric Carriers

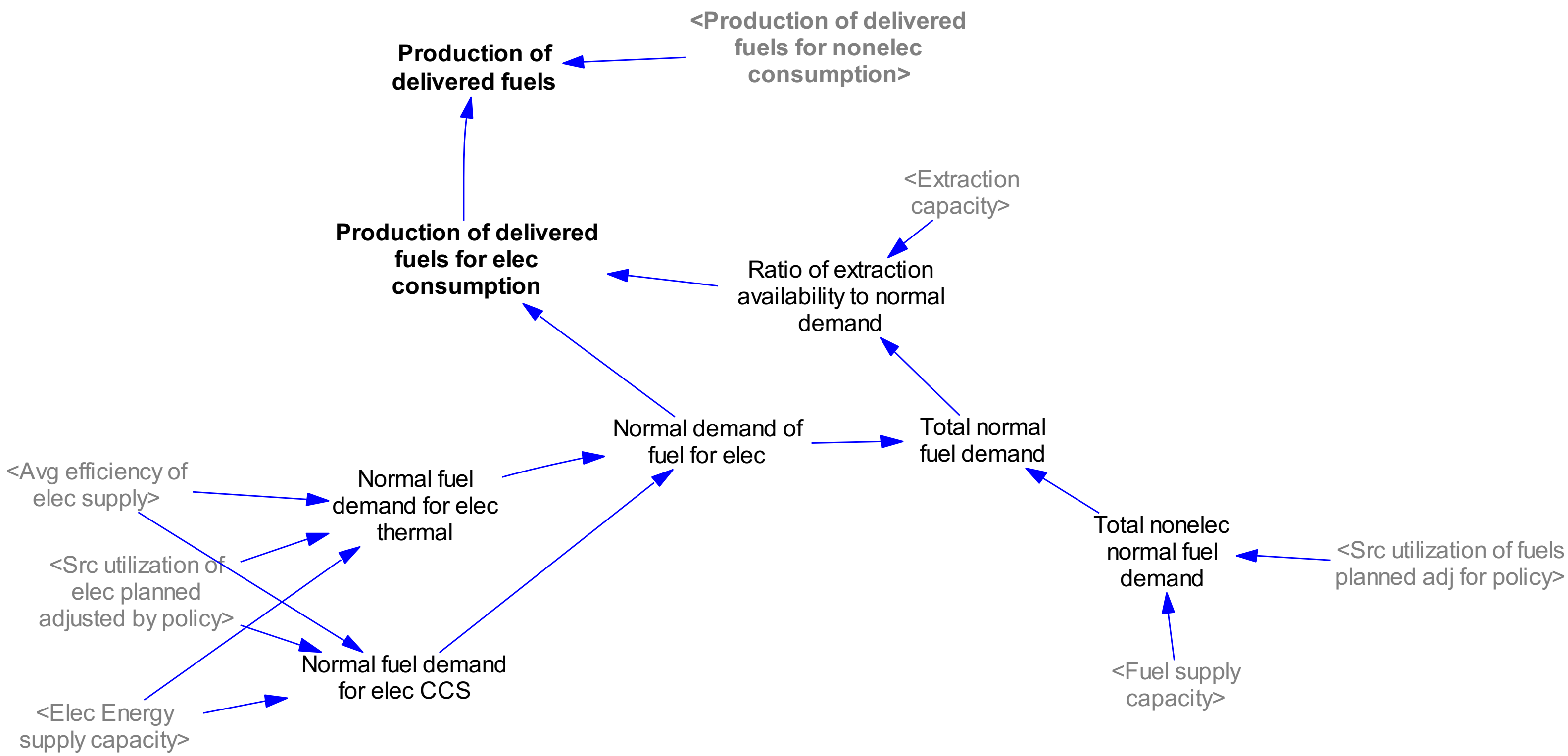


Figure 5-5 Structure of Market Clearing and Utilization of Initialization

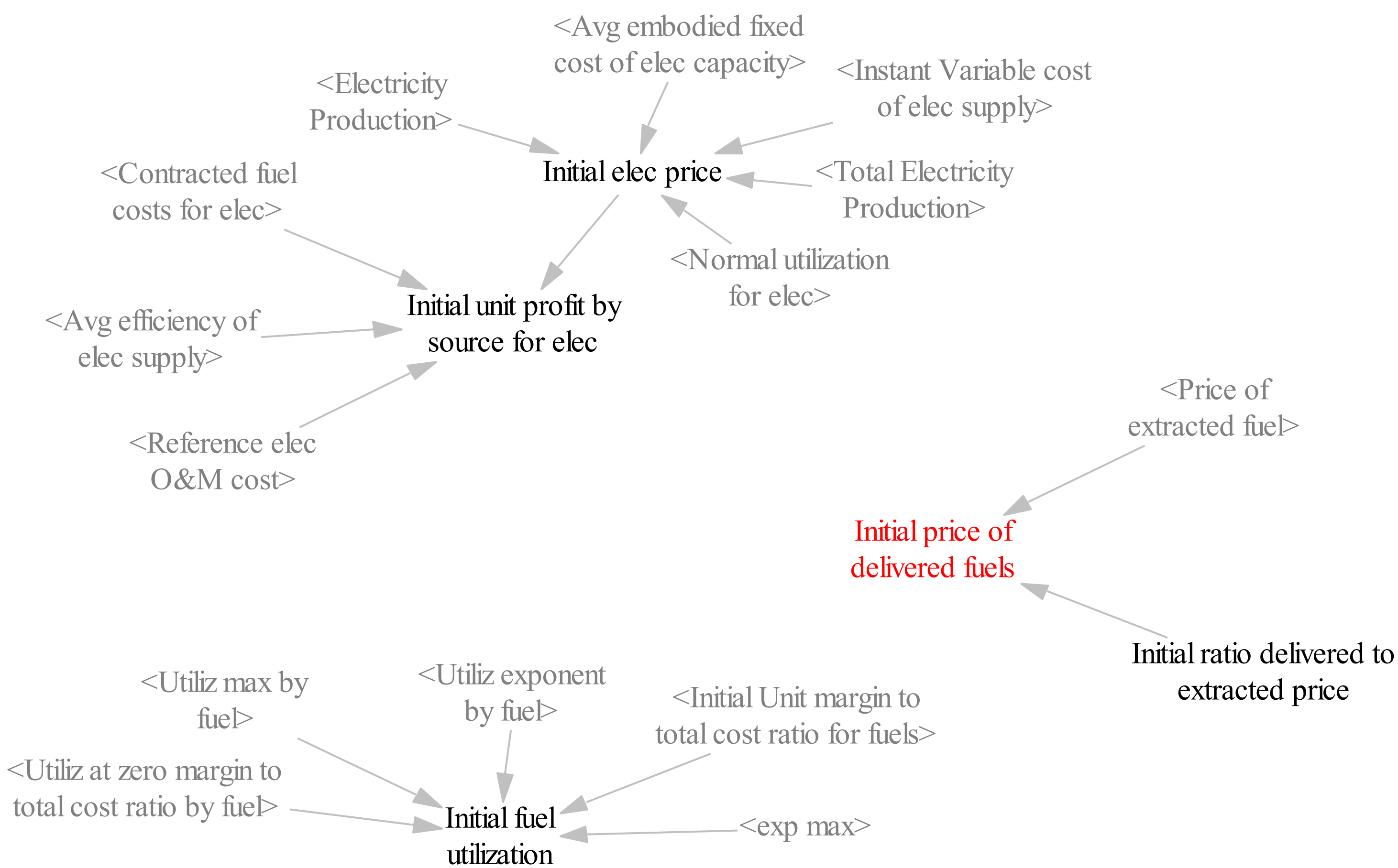


Figure 5-6 Structure of Energy Produced

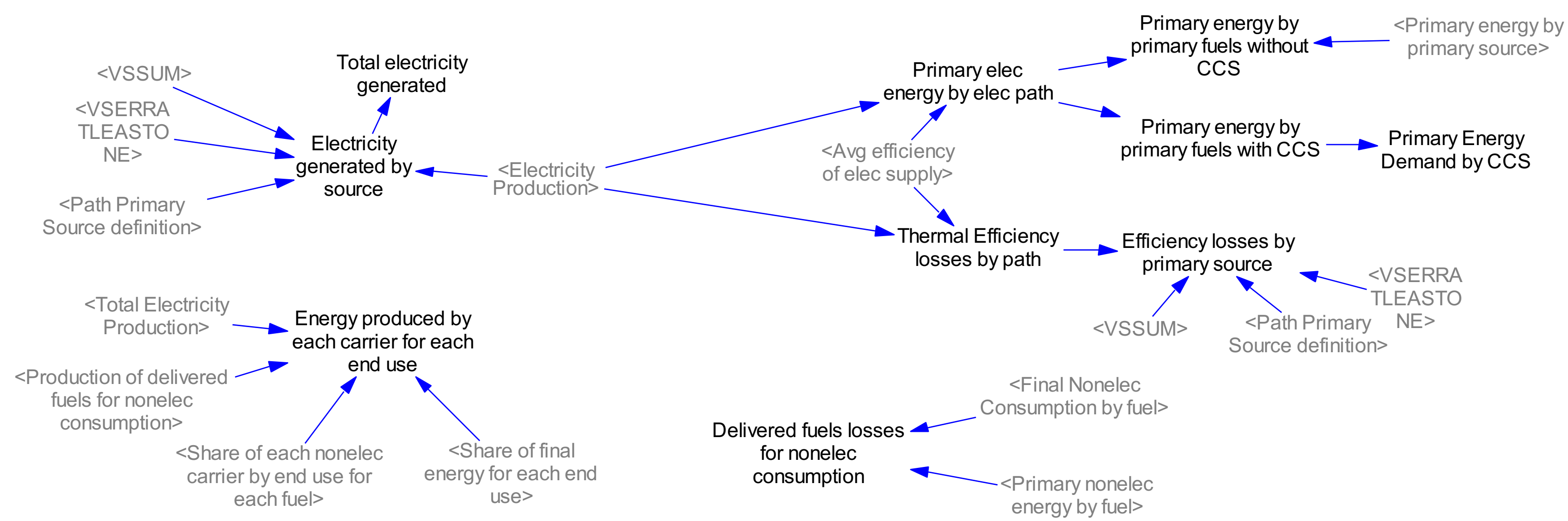


Figure 5-7 Structure of Final Energy Consumption by Carrier

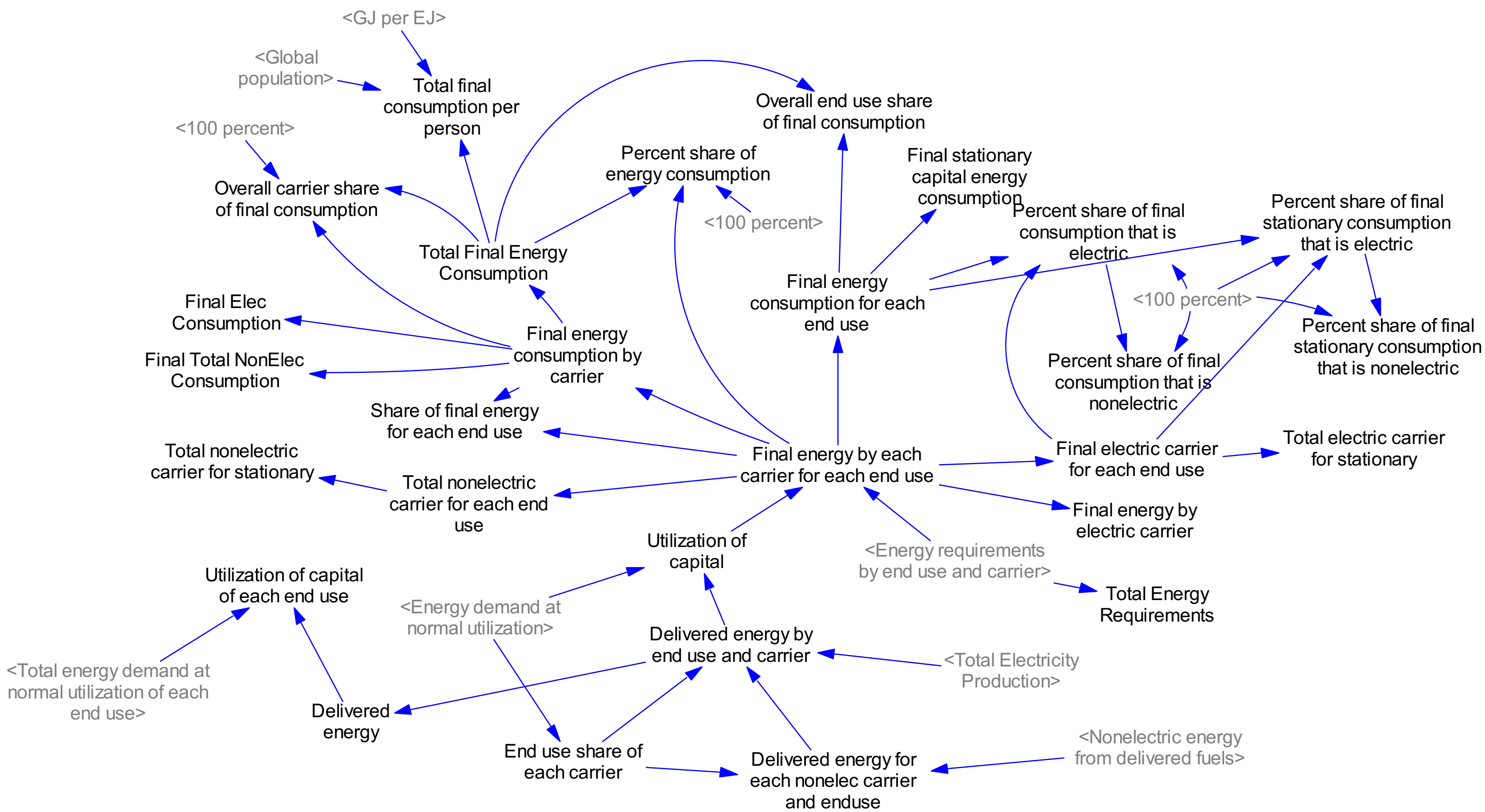


Figure 5-8 Structure of Final Energy Consumption by Source

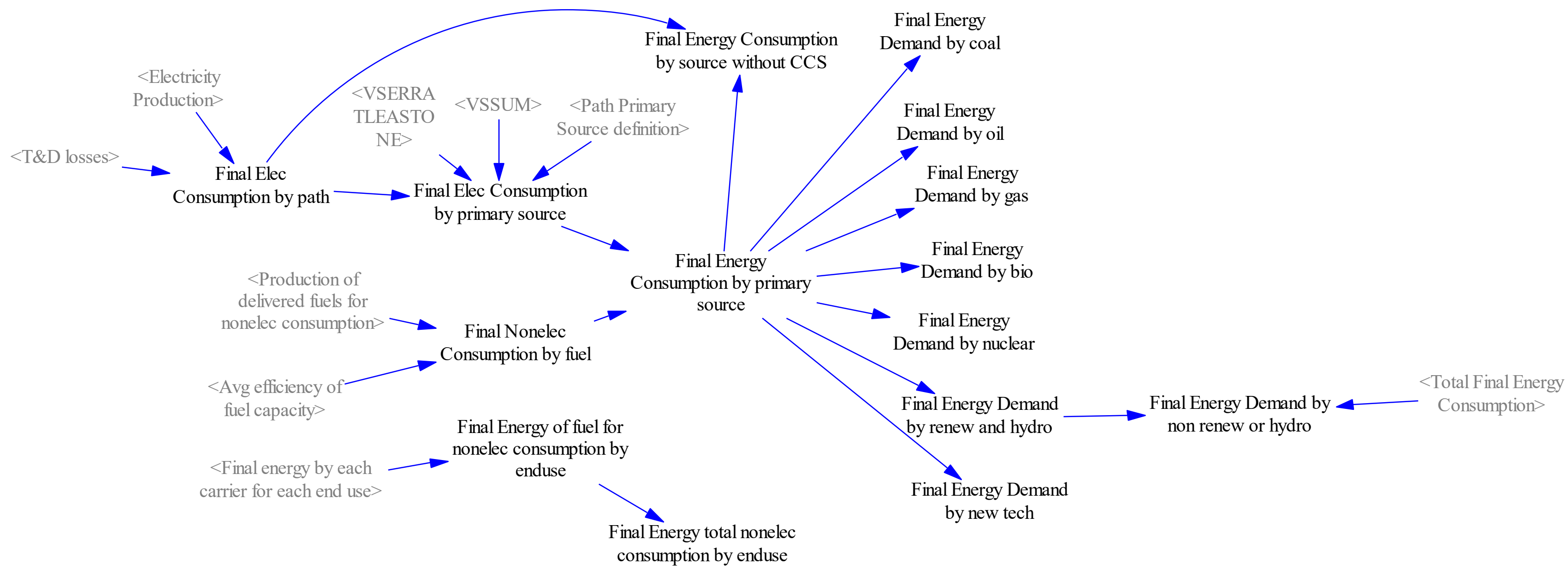


Figure 5-9 Structure of Primary Energy Demand by Source

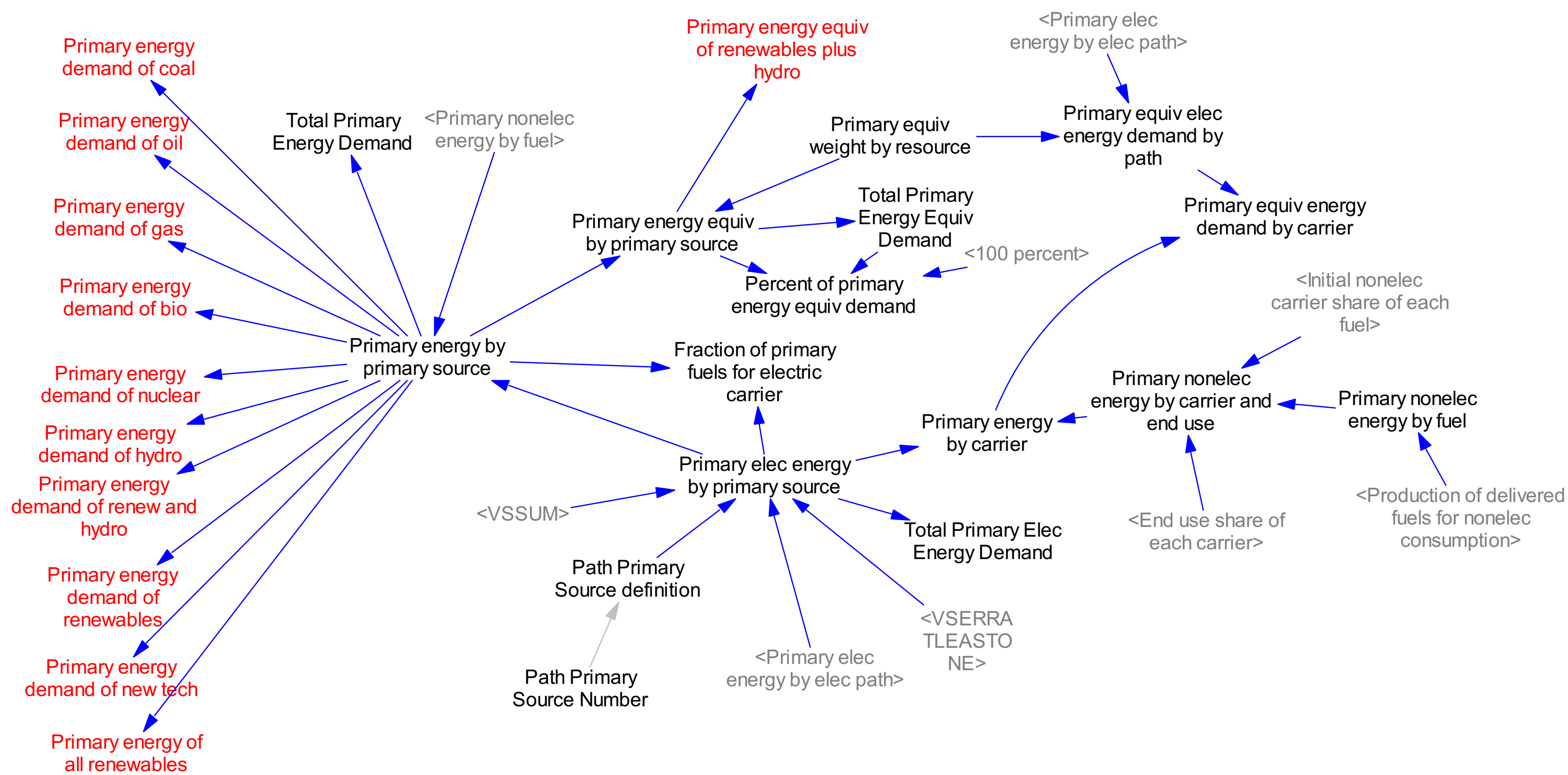


Table 5-3 Electricity and Delivered fuels Market and Utilization Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Reference demand elasticity of electricity	The elasticity of the short term demand, which is a measure of (dy/dx)/(y/x) = (dy/y)/(dx/x). Assumes a linear demand curve such that this elasticity is at the normal operating point.	0.1-.5	0.2	Dmnl
Reference demand elasticity of fuels[Primary Fuels]	For each fuel, the elasticity of the short term demand. Assumes a linear demand curve such that this elasticity is at the normal operating point.	0.1-.5	0.2	Dmnl
Time to Adj Utilization		1-2	1	Year
Utiliz at neg1 margin to total cost ratio for elec	Defines short term utilization curve for electricity.	0.1-0.4	0.3	Dmnl
Utiliz at zero margin to total cost ratio for elec	Defines short term utilization curve for electricity.	0.41-0.7	0.7	Dmnl
Utiliz at pos1 margin to total cost ratio for elec	Defines short term utilization curve for electricity.	0.7-1	0.91	Dmnl
Utiliz at neg1 margin to total cost ratio by fuel[Primary Fuels]	Defines short term utilization curve for each fuel..	0.1-0.4	0.3	Dmnl
Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]	Defines short term utilization curve for each fuel.	0.41-0.7	0.7	Dmnl
Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]	Defines short term utilization curve for each fuel.	0.7-1	0.91	Dmnl
exp max	Prevents term in the exponent of S-curve function from exceeding the limitations of the modeling software.		10	Dmnl
Min price	Prevents the price to the consumer from becoming free with subsidies.		1	$/GJ
Annual utilization change limit	Prevents integration error from occurring when extreme scenarios outside realistic ranges are tested.		0.1	1/year
Initial ratio delivered to extracted price [Primary Fuels]	Used to calculate the initial price of fuels for nonelectric carriers.			Dmnl

Table 5-3 Electricity and Delivered fuels Market and Utilization Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Coal			3.3	
Oil			3.0	
Gas			3.0	
Bio			2.5	
Utilization of elec adjustment factor[Primary Energy Sources]	Noncost policy to reduce electric source utilization. A value of 0 is for no change to planned utilization. A value of 70 forces the planned utilization of the source to be 30% of what it would be without the policy.	0-100	0	Percent
Utilization of elec policy start time[Primary Energy Sources]	Start year of noncost policy to reduce electric source utilization.	2021-2100	2021	Year
Utilization of elec policy stop time[Primary Energy Sources]	Stop year of noncost policy to reduce electric source utilization.	2021-2100	2021	Year
Utilization of delivered fuel adjustment factor [Primary Fuels]	Noncost policy to reduce fuel utilization for nonelectric and electric consumption. A value of 0 is for no change to planned utilization. A value of 70 forces the planned utilization of the source to be 30% of what it would be without the policy.	0-100	0	Percent
Utilization adjustment factor FF	Noncost policy to reduce all fossil fuel utilization for nonelectric and electric consumption.	0-100	0	Percent
Utilization of delivered fuel policy start time[Primary Fuels]	Start year of noncost policy to reduce fuel utilization.	2021-2100	2021	Year
Utilization of delivered fuel policy stop time[Primary Fuels]	Stop year of noncost policy to reduce fuel utilization.	2021-2100	2021	Year
Utilization policy start time FF	Start year of noncost policy to reduce all fossil fuel utilization.	2021-2100	2021	Year
Utilization policy stop time FF	Stop year of noncost policy to reduce all fossil fuel utilization.	2021-2100	2021	Year
Utilization adjustment ramp time	Time to achieve full specified reduction in utilization, reached linearly from the start time.	1-100	10	Year

Table 5-4. Electricity Market and Utilization Calculated Parameters

Parameter	Definition	Units
Market price of electricity	ACTIVE INITIAL(Expected Price Basis[Electric Carrier]*Ratio of elec market price to price basis , Initial elec price)	$/GJ
Initial elec price	SUM(Electricity Production[Elec Paths!]/Normal utilization for elec*(Avg embodied fixed cost of elec capacity[Elec Paths!] +Instant Variable cost of elec supply[Elec Paths!]))/Total Electricity Production	$/GJ
Initial unit profit by source for elec[Elec Paths]		$/GJ
[Elec thermal]	Initial elec price-"Reference elec O&M cost"[Elec thermal]-Contracted fuel costs for elec[Primary Fuels]/Avg efficiency of elec supply[Elec thermal]	
[Elec only paths]	Initial elec price-"Reference elec O&M cost"[Elec only paths]	
Ratio of agg output to normal elec demand	The ratio of the total of electricity production to the adjusted normal demand of electricity. ACTIVE INITIAL(ZIDZ(Total Electricity Production, SUM(Electricity demand at normal utilization[EndUseSector!])), 1)	Dmnl
Ratio of elec market price to price basis	This ratio yields the market clearing price according to the demand elasticity of electricity and the ratio of aggregate output to adjusted demand at normal utilization. For a given ratio of output to normal demand, a larger elasticity yields less of a response to price. MAX(0, 1 - (Ratio of agg output to normal elec demand-1)/ Reference demand elasticity of electricity)	Dmnl
Ratio of elec agg demand to ref demand	1-Demand elasticity of electricity*(Ratio of elec market price to price basis-1)	Dmnl

Table 5-4. Electricity Market and Utilization Calculated Parameters

Parameter	Definition	Units
Unit margin by source for elec [Elec Paths]	For each elec path, the net of market price and variable costs. Market price of electricity- Instant effective variable cost of elec supply[Elec Paths]	$/GJ
Unit margin to total cost ratio for elec [Elec Paths]	Net unit profit divided by the total cost. ZIDZ(Unit margin by source for elec[Elec Paths], Cost of elec supply[Elec Paths])	Dmnl
Indicated utilization for elec[Elec Paths]	The indicated utilization according to an increasing S-shaped function based on the PTCR. MAX(0, MIN(1,ZIDZ(Utiliz max for elec * Utiliz at zero margin to total cost ratio for elec*EXP(MIN(exp max, Utiliz exponent for elec*Unit margin to total cost ratio for elec [Elec Paths])) , (Utiliz max for elec + Utiliz at zero margin to total cost ratio for elec*(EXP(MIN(exp max,Utiliz exponent for elec*Unit margin to total cost ratio for elec [Elec Paths]))-1)))))	Dmnl
Utiliz exponent for elec	Defining the S-shaped curve. LN(MAX(1, ZIDZ(Utiliz at pos1 margin to total cost ratio for elec*(Utiliz max for elec-Utiliz at zero margin to total cost ratio for elec) , (Utiliz at zero margin to total cost ratio for elec * (Utiliz max for elec-Utiliz at pos1 margin to total cost ratio for elec)))))	Dmnl

Table 5-4. Electricity Market and Utilization Calculated Parameters

Parameter	Definition	Units
Utiliz max for elec	Defining the S-shaped curve. ZIDZ((2*Utiliz at zero margin to total cost ratio for elec*Utiliz at pos1 margin to total cost ratio for elec*Utiliz at neg1 margin to total cost ratio for elec - Utiliz at zero margin to total cost ratio for elec^2*(Utiliz at pos1 margin to total cost ratio for elec+Utiliz at neg1 margin to total cost ratio for elec)) , (Utiliz at pos1 margin to total cost ratio for elec*Utiliz at neg1 margin to total cost ratio for elec - Utiliz at zero margin to total cost ratio for elec^2))	Dmnl
Src utilization of elec planned[Elec Paths]	The planned utilization of each electric path. INTEG(Utiliz chg rt for elec[Elec Paths], Utiliz at pos1 margin to total cost ratio for elec)	Dmnl
Utiliz chg rt for elec[Elec Paths]	The change in utilization of each electric path based on the indicated utilization and the planned utilization and the time it takes to adjust from the former to the latter. The constraint of Annual utilization change limit prevents integration error from occurring when extreme scenarios outside realistic ranges are tested. MAX(-Annual utilization change limit, MIN(Annual utilization change limit,(Indicated utilization for elec[Elec Paths]-Src utilization of elec planned[Elec Paths])/Time to Adj Utilization))	1/year
Constraint of availability[Elec Paths]	For elec thermal and CCS paths, the minimum of the energy possible considering the delivered fuel constraints and the existing electric energy capacity. For the elec only paths, the existing electric energy capacity is the only constraint.	EJ/year

Table 5-4. Electricity Market and Utilization Calculated Parameters

Parameter	Definition	Units
[Elec Thermal plus CCS]	MIN(Constraint of delivered fuel availability[Elec thermal plus CCS], Elec Energy supply capacity[Elec thermal plus CCS])	
[Only elec paths]	Elec Energy supply capacity[Elec only paths]	
Elec source utilization constrained [Elec Paths]	For each electric source, the utilization is constrained by the electric energy that could be produced and the existing electric energy capacity to produce it. ACTIVE INITIAL(ZIDZ(Constraint of availability[Elec Paths], Elec Energy supply capacity[Elec Paths]), Src utilization of elec planned[Elec Paths])	Dmnl
Src utilization of elec planned adjusted by policy [Elec Paths]	Src utilization of elec planned[Elec Paths]*Policy adjustment to elec utilization[Primary Energy Sources]	Dmnl
Policy adjustment to elec utilization[Primary Energy Sources]	Adjusts the utilization of electric sources by noncost policies, starting and stopping in given years.	Dmnl
[Primary energy fuel sources]	MIN(MAX(Min utilization,IF THEN ELSE(Time>Utilization of elec policy stop time[Primary energy fuel sources] :OR: Time<Utilization of elec policy start time[Primary energy fuel sources], 1, 1-Utilization of elec adjustment factor[Primary energy fuel sources]/"100 percent"*Percent with elec utilization adjustment policy in time[Primary energy fuel sources]/"100 percent")),Policy adjustment to delivered fuel utilization[Primary Fuels])	

Table 5-4. Electricity Market and Utilization Calculated Parameters

Parameter	Definition	Units
[Primary elec only sources]	MAX(Min utilization,IF THEN ELSE(Time>Utilization of elec policy stop time[Primary elec only sources] :OR: Time<Utilization of elec policy start time[Primary elec only sources], 1, 1-Utilization of elec adjustment factor[Primary elec only sources]/"100 percent"*Percent with elec utilization adjustment policy in time[Primary elec only sources]/"100 percent"))	
Percent with elec utilization adjustment policy in time[Primary Energy Sources]	ramp("100 percent"/Utilization adjustment ramp time,Utilization of elec policy start time[Primary Energy Sources] , Utilization of elec policy start time[Primary Energy Sources]+Utilization adjustment ramp time)	Percent
Elec source utilization [Elec Paths]	The utilization of each electric source is that which is planned, constrained by availability, and adjusted for by noncost policies.	Dmnl
[Elec thermal plus CCS]	Elec source utilization constrained[Elec thermal plus CCS]	
[Elec only paths]	MIN(Elec source utilization constrained[Elec only paths], Src utilization of elec planned adjusted by policy[Elec only paths])	
Electricity Production[Elec Paths]	The electric energy produced by each resource. Elec Energy supply capacity[Elec Paths]*Elec source utilization[Elec Paths]	EJ/year
Total Electricity Production	The sum of electricity produced by all resources. SUM(Electricity Production[Elec Paths!])	EJ/year
CCS Electricity	SUM(Electricity Production[CCS Paths!])	EJ/year
CCS Capacity	SUM(Elec Energy supply capacity[CCS Paths!])	EJ/year
CCS utilization	ZIDZ(CCS Electricity, CCS Capacity)	dmnl

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Market price of delivered fuels[Primary Fuels]	Market price of each delivered fuel based on market clearing. Expected Price Basis[NonElec Carriers]*Ratio of delivered fuel market price to reference price for nonelec[Primary Fuels]	$/GJ
Initial price of delivered fuels[Primary Fuels]	Initial market price of each delivered fuel based on extracted fuel price and an initial markup ratio. Price of extracted fuel[Primary Fuels]*Initial ratio delivered to extracted price[Primary Fuels]	$/GJ
Initial fuel utilization [Primary Fuels]	Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]	Dmnl
Energy demand at normal utilization [EndUseSector,Carrier]	The long term energy requirements of each carrier. Energy demand at normal utilization without policy[EndUseSector, Carrier]*Policy adjustment to normal demand[EndUseSector,Carrier]	EJ/year
Fuel demand for nonelec at normal utilization [Primary Fuels]	The demand for each fuel as a function of the adjusted normal demand of nonelec consumption and the planned demand of elec consumption. Energy demand at normal utilization[EndUseSector,NonElec Carriers]*Policy adjustment to fuel normal demand[Primary Fuels]	EJ/year

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Ratio of fuel output to nonelec normal demand [Primary Fuels]	For each fuel, the ratio of fuel production to the adjusted normal demand. ACTIVE INITIAL(ZIDZ(Nonelectric energy from delivered fuels[Primary Fuels], SUM(Fuel demand for nonelec at normal utilization[EndUseSector!, Primary Fuels]))*Ratio of extraction availability to normal demand[Primary Fuels],1)	Dmnl
Ratio of delivered fuel market price to reference price for nonelec [Primary Fuels]	This ratio yields the market clearing price according to the demand elasticity of fuels and the ratio of output to adjusted normal demand. For a given ratio of output to normal demand, a larger elasticity yields less of a response to price. MAX(0, 1 - (Ratio of fuel output to nonelec normal demand [Primary Fuels]-1)/Reference demand elasticity of fuels[Primary Fuels])	Dmnl
Unit margin for fuels[Primary Fuels]	For each fuel, the net of market price and variable costs. Market price of delivered fuels for nonelec carriers[Primary Fuels]-Instant effective variable cost of fuel supply[Primary Fuels]	$/GJ
Unit margin to total cost ratio for fuels [Primary Fuels]	The net unit margin divided by the embodied annualized capital cost. ZIDZ(Unit margin for fuels[Primary Fuels],Supplier cost for fuel[Primary Fuels])	Dmnl

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Indicated fuels utilization[Primary Fuels]	The indicated utilization according to an increasing S-shaped function based on the Unit margin to total cost ratio for fuels. MAX(0, MIN(1,ZIDZ(Utiliz max by fuel[Primary Fuels] * Utiliz at zero margin to total cost ratio by fuel [Primary Fuels]*EXP(MIN(exp max,Utiliz exponent by fuel [Primary Fuels]*Unit margin to total cost ratio for fuels[Primary Fuels])) , (Utiliz max by fuel [Primary Fuels] + Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]*(EXP(MIN(exp max,Utiliz exponent by fuel [Primary Fuels]*Unit margin to total cost ratio for fuels[Primary Fuels]))-1)))))	Dmnl
Utiliz exponent by fuel[Primary Fuels]	Defining the S-shaped curve for each fuel. LN(MAX(1, ZIDZ(Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]*(Utiliz max by fuel[Primary Fuels]-Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]) , (Utiliz at zero margin to total cost ratio by fuel[Primary Fuels] * (Utiliz max by fuel[Primary Fuels]-Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels])))))	Dmnl

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Utiliz max by fuel[Primary Fuels]	Defining the S-shaped curve for each fuel. ZIDZ((2*Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]*Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]*Utiliz at neg1 margin to total cost ratio by fuel[Primary Fuels] - Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]^2*(Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]+Utiliz at neg1 margin to total cost ratio by fuel[Primary Fuels])) , (Utiliz at pos1 margin to total cost ratio by fuel[Primary Fuels]*Utiliz at neg1 margin to total cost ratio by fuel[Primary Fuels] - Utiliz at zero margin to total cost ratio by fuel[Primary Fuels]^2))	Dmnl
Src utilization of fuels planned[Primary Fuels]	The planned delivered fuel utilization of each fuel. INTEG(Utiliz chg rt of fuels[Primary Fuels], Initial fuel utilization from initial margin to total cost ratio[Primary Fuels])	Dmnl
Utiliz chg rt of fuels[Primary Fuels]	The change in utilization of each delivered fuel based on the indicated utilization and the planned utilization and the time it takes to adjust from the former to the latter. The constraint of Annual utilization change limit prevents integration error from occurring when extreme scenarios outside realistic ranges are tested. MAX(-Annual utilization change limit, MIN(Annual utilization change limit, (Indicated fuels utilization [Primary Fuels]-Src utilization of fuels planned[Primary Fuels])/Time to Adj Utilization))	1/year

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Src utilization of fuels[Primary Fuels]	The utilization of each delivered fuel is the greater of the minimum desired utilization and that which is planned and adjusted for by noncost policies, however constrained by fuel availability. MIN(MAX(0, Src utilization of fuels planned[Primary Fuels]*Policy adjustment to delivered fuel utilization[Primary Fuels]),Utilization constrained by fuel availability[Primary Fuels])	Dmnl
Src utilization of fuels planned adj for policy[Primary Fuels]	Src utilization of fuels planned[Primary Fuels] *Policy adjustment to delivered fuel utilization[Primary Fuels]	Dmnl
Fuel availability[Primary Fuels]	The extraction capacity accounting for fuel losses as well as the fuel supply capacity constrain the amount of fuel delivered fuel is possible for production. MIN((Extraction capacity[Primary Fuels]-Production of delivered fuels for elec consumption[Primary Fuels]), Fuel supply capacity[Primary Fuels])	EJ/year
Utilization constrained by fuel availability [Primary Fuels]	The available fuel divided by the capacity of fuel constrains fuel utilization. ZIDZ(Fuel availability[Primary Fuels], Fuel supply capacity[Primary Fuels])	EJ/year

Table 5-5. Delivered Fuel Market and Utilization Calculated Parameters

Parameter	Definition	Units
Policy adjustment to delivered fuel utilization[Primary Fuels]	Adjusts the utilization of delivered fuel by noncost policies, starting and stopping in given years. The min fuel utilization prevents the policy from forcing the demand for a fuel to be 0. MAX(Min utilization,IF THEN ELSE(Time>Utilization of delivered fuel policy stop time[Primary Fuels] :OR: Time<Utilization of delivered fuel policy start time[Primary Fuels], 1, 1-Utilization of delivered fuel adjustment factor[Primary Fuels]/"100 percent"*Percent with fuel utilization adjustment policy in time[Primary Fuels]/"100 percent"))	Dmnl
Percent with fuel utilization adjustment policy in time[Primary Fuels]	ramp("100 percent"/Utilization adjustment ramp time,Utilization of delivered fuel policy start time[Primary Fuels] , Utilization of delivered fuel policy start time[Primary Fuels]+Utilization adjustment ramp time)	Percent
Production of delivered fuels for nonelec consumption[Primary Fuels]	Fuel supply capacity[Primary Fuels]*Src utilization of fuels[Primary Fuels]	EJ/year
Production of fuels[Primary Fuels]	The sum of production of fuels for electric and nonelectric consumption. Production of delivered fuels for elec consumption[Primary Fuels]+Production of delivered fuels for nonelec consumption[Primary Fuels]	EJ/year

Table 5-6. Demand and Contraints of Fuel for Electricity and for Delivered Fuels for Nonelectric Carriers Calculated Parameters

Parameter	Definition	Units
Constraint of delivered fuel availability[Elec Paths]	The delivered fuel availability and the source efficiency constrains the amount of electric energy is possible for production.	EJ/year
[Elec Thermal]	Production of delivered fuels for elec thermal consumption[Primary Fuels]*Avg efficiency of elec supply [Elec thermal]	
[CCS Paths]	Production of delivered fuels for elec CCS consumption[Primary Fuels]*Avg efficiency of elec supply[CCS Paths]	
Production of delivered fuels for elec thermal consumption[Primary Fuels]	Normal fuel demand for elec thermal[Primary Fuels]*Ratio of extraction availability to normal demand[Primary Fuels]	EJ/Year
Production of delivered fuels for elec CCS consumption[Primary Fuels	Reference fuel demand for elec CCS [Primary Fuels]*Ratio of extraction availability to normal demand[Primary Fuels]	EJ/Year
Normal fuel demand for elec thermal[Primary Fuels]	The planned demand of electric thermal consumption accounting for losses of fuel and thermal conversions inefficiencies. Elec Energy supply capacity[Elec thermal]/Avg efficiency of elec supply[Elec thermal]*Src utilization of elec planned adjusted by policy[Elec thermal]	EJ/year
Normal fuel demand for elec CCS[Primary Fuels]	The planned demand of electric CCS consumption accounting for losses of fuel and thermal conversions inefficiencies. Elec Energy supply capacity[CCS Paths]/Avg efficiency of elec supply[CCS Paths]*Src utilization of elec planned adjusted by policy[CCS Paths]	EJ/year
Normal demand of fuel for elec[Primary Fuels]	Normal fuel demand for elec thermal[Primary Fuels]+Normal fuel demand for elec CCS[Primary Fuels]	EJ/year
Production of delivered fuels for elec consumption[Primary Fuels]	Ratio of extraction availability to normal demand[Primary Fuels]*Normal demand of fuel for elec[Primary Fuels]	EJ/year

Table 5-6. Demand and Contraints of Fuel for Electricity and for Delivered Fuels for Nonelectric Carriers Calculated Parameters

Parameter	Definition	Units
Ratio of extraction availability to normal demand[Primary Fuels]	If the capacity of extracted fuels is not enough to meet demand, then the constraint is applied equally to all carriers. MIN(1, ZIDZ(Extraction capacity[Primary Fuels],Total reference fuel demand[Primary Fuels]))	Dmnl
Total normal fuel demand[Primary Fuels]	The sum of normal demand of fuels for electric and nonelectric carriers. Normal demand of fuel for elec[Primary Fuels]+Total nonelec normal fuel demand[Primary Fuels]	EJ/year
Production of delivered fuels[Primary Fuels]	The sum of fuel production for electric and nonelectric carriers. Production of delivered fuels for elec consumption[Primary Fuels]+Production of delivered fuels for nonelec consumption[Primary Fuels]	EJ/year

Table 5-7 Energy Indicators - Calculated Parameters

Parameter	Definition	Units
Electricity generated by source[Primary Energy Sources]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],Electricity Production[Elec Paths!],0,VSSUM,VSERRATLEASTONE)	EJ/year
Energy produced by each carrier for each end use [EndUseSector, Carrier]		EJ/year
[EndUseSector,NonElec Carriers]	Nonelectric energy from delivered fuels[Primary Fuels]*End use share of each carrier[EndUseSector,NonElec Carriers]	
[EndUseSector, Electric Carrier]	Total Electricity Production*Share of final energy for each end use[EndUseSector,Electric Carrier]	
Final Elec Consumption by path[Elec Path]	Electricity Production[Elec Paths]*(1-"T&D losses"[Electric Carrier])	EJ/year
Final Elec Consumption by primary source[Primary Energy Sources]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],Final Elec Consumption by path[Elec Paths!],0,VSSUM,VSERRATLEASTONE)	EJ/year
Final Nonelec Consumption by fuel[Primary Fuels]	Production of delivered fuels for nonelec consumption[Primary Fuels]*Avg efficiency of fuel capacity[Primary Fuels]	
Final Energy Consumption by primary source [Primary Energy Sources]	The energy consumed from each primary source, with the fuel sources aggregating the nonelec and electric consumption.	EJ/year
[Primary energy fuel sources]	Final Nonelec Consumption by fuel[Primary Fuels]+ Final Elec Consumption by primary source[Primary energy fuel sources]	
[Primary elec only sources]	Final Elec Consumption by primary source[Primary elec only sources]	
Final Energy total nonelec consumption by enduse [EndUseSector]	SUM(Final Energy of fuel for nonelec consumption by enduse[EndUseSector, Primary Fuels!])	EJ/year
Utilization of capital [EndUseSector, Carriers]	ZIDZ(Delivered energy by end use and carrier[EndUseSector,Carrier],Energy demand at normal utilization[EndUseSector,Carrier])	Dmnl

Table 5-7 Energy Indicators - Calculated Parameters

Parameter	Definition	Units
Final energy by each carrier for each end use[EndUseSector, Carrier]		Dmnl
[EndUseSector,NonElec Carriers]	Utilization of capital[EndUseSector,NonElec Carriers]*Energy requirements by end use and carrier[EndUseSector,NonElec Carriers]	
[EndUseSector, Electric Carrier]	Utilization of capital[EndUseSector, Electric Carrier]*Energy requirements by end use and carrier[EndUseSector,Electric Carrier]	
Final electric carrier for each end use[EndUseSector]	Final energy by each carrier for each end use[EndUseSector,Electric Carrier]	EJ/year
Final energy by electric carrier	SUM(Final energy by each carrier for each end use[EndUseSector!,Electric Carrier])	EJ/year
Final energy consumption for each end use[EndUseSector]	SUM(Final energy by each carrier for each end use[EndUseSector,Carrier!])	EJ/year
Percent share of final consumption that is electric[EndUseSector]	ZIDZ(Final electric carrier for each end use[EndUseSector], Final energy consumption for each end use[EndUseSector])*"100 percent"	Percent
Percent share of final consumption that is nonelectric [EndUseSector]	"100 percent"-Percent share of final consumption that is electric[EndUseSector]	Percent
Percent share of final stationary consumption that is electric	ZIDZ(SUM(Final electric carrier for each end use[Stationary!]), SUM(Final energy consumption for each end use[Stationary!]))*"100 percent"	Percent
Percent share of final stationary consumption that is nonelectric	"100 percent"-Percent share of final stationary consumption that is electric	Percent
Total nonelectric carrier for each end use[EndUseSector]	SUM(Final energy by each carrier for each end use[EndUseSector, NonElec Carriers!])	EJ/year
Total nonelectric carrier for stationary	SUM(Total nonelectric carrier for each end use[Stationary!])	EJ/year
Share of final energy for each end use[EndUseSector, Carrier]	ZIDZ(Final energy by each carrier for each end use[EndUseSector,Carrier],Final energy consumption by carrier[Carrier])	Dmnl

Table 5-7 Energy Indicators - Calculated Parameters

Parameter	Definition	Units
Final energy consumption by carrier[Carrier]	SUM(Final energy by each carrier for each end use[EndUseSector!, Carrier])	EJ/year
Total Final Energy Consumption	SUM(Final energy consumption by carrier[Carrier!])	EJ/year
Total final consumption per person	Total Final Energy Consumption/Global population*GJ per EJ	GJ/Year/person
Overall carrier share of final consumption[Carrier]		Dmnl
[Electric Carrier]	Final energy consumption by carrier[Electric Carrier]/Total Final Energy Consumption*"100 percent"	
[NonElectric Carriers]	Final energy consumption by carrier[NonElec Carriers]/Total Final Energy Consumption*"100 percent"	
Percent share of energy consumption[EndUseSector, Carrier]	Final energy by each carrier for each end use[EndUseSector,Carrier]/Total Final Energy Consumption*"100 percent"	Percent
Overall end use share of final consumption[EndUseSector]	Final energy consumption for each end use[EndUseSector]/Total Final Energy Consumption	Dmnl
Final stationary capital energy consumption	SUM(Final energy consumption for each end use[Stationary!])	EJ/year
Final Energy Consumption by primary source[Primary energy sources]	Final energy demand of each source, combining primary energy of nonelec and elec for primary fuels.	EJ/Year
[Primary energy fuel sources]	Final Nonelec Consumption by fuel[Primary Fuels]+ Final Elec Consumption by primary source[Primary energy fuel sources]	
[Primary elec only sources]	Final Elec Consumption by primary source[Primary elec only sources]	

Table 5-8 Primary Energy Demand Calculated Parameters

Parameter	Definition	Units
Primary energy by primary source[Primary Energy Soures]	Primary energy demand, based on energy to meet demand and efficiency of each energy path, with the CCS Paths aggregated with their nonCCS counterpart.	EJ/Year
[Primary energy fuel sources]	Primary nonelec energy by fuel[Primary Fuels]+Primary elec energy by primary source[Primary energy fuel sources]	
[Primary elec only sources]	Primary elec energy by primary source[Primary elec only sources]	
Primary elec energy by elec path[Elec Paths]	Electricity Production[Elec Paths]/Avg efficiency of elec supply [Elec Paths]	EJ/Year
Primary elec energy by primary source[Primary Energy Sources]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],Primary elec energy by elec path[Elec Paths!],0,VSSUM,VSERRATLEASTONE)	EJ/Year
Total Primary Elec Energy Demand	SUM(Primary elec energy by primary source[Primary Energy Sources!])	EJ/Year
Primary nonelec energy by fuel[Primary Fuels]	Production of delivered fuels for nonelec consumption[Primary Fuels]	EJ/Year
Primary nonelec energy by carrier and end use[EndUseSector, NonElec Carriers]	SUM(Primary nonelec energy by fuel[Primary Fuels!]*Share of each nonelec carrier by end use for each fuel[EndUseSector,Primary Fuels!,NonElec Carriers])	EJ/Year
Primary energy by carrier[Carrier]		EJ/Year
[Electric Carrier]	SUM(Primary elec energy by primary source[Primary Energy Sources!])	
[NonElec Carriers]	SUM(Primary nonelec energy by carrier and end use[EndUseSector!, NonElec Carriers])	
Primary energy equiv by primary source[Primary Energy Sources]	Primary energy by primary source[Primary Energy Sources]*Primary equiv weight by resource[Primary Energy Sources]	EJ/Year
Primary equiv elec energy demand by path[Elec Paths]	Primary elec energy by elec path[Elec Paths]*Primary equiv weight by resource[Primary Energy Sources]	

Table 5-8 Primary Energy Demand Calculated Parameters

Parameter	Definition	Units
Primary equiv energy demand by carrier [Carrier]		EJ/Year
[Electric Carrier]	SUM(Primary equiv elec energy demand by path[Elec Paths!])	
[NonElec Carriers]	Primary energy by carrier[NonElec Carriers]	
Total Primary Energy Equiv Demand	SUM(Primary energy equiv by primary source[Primary Energy Sources!])	EJ/Year
Percent of primary energy equiv demand[Primary Energy Sources]	Primary energy equiv by primary source[Primary Energy Sources]/Total Primary Energy Equiv Demand*"100 percent"	Percent

5.2.2 Tax and Subsidy Adjustments to Costs

A carbon tax on fuels and source taxes reduce the margin and profit of that source; conversely, source subsidies increase the margin and profit of that source. Source taxes/subsidies can be applied either to capital costs or to variable costs, the fraction of which is determined by Fraction of fuel source adjustment for capital and Fraction of elec source adjustment for capital. For nonelectric consumption, the default is that all taxes/subsidies apply to the variable costs, whereas for electric consumption, the default is that they apply to capital costs. Carbon taxes, which depend on the carbon density of the fuel, increase the variable costs of that fuel. For fuel-generated electricity, the adjustment to the cost of fuel also depends on the thermal efficiency of that source.

Parameter values for source subsidy/tax inputs range from highly subsidized, defined to be 60% of the marginal cost in 2020, to very highly taxed, defined to be 200% of the marginal cost in 2020. For fuel-generated electricity, the percent thresholds apply to the marginal costs excluding those for fuel. Bounds are set to policy-relevant limits, which are source-dependent. Table 5-10, which presents the input bounds for each source, greys out the thresholds which are outside those limits.

Figure 5-10 Structure of Carbon Tax

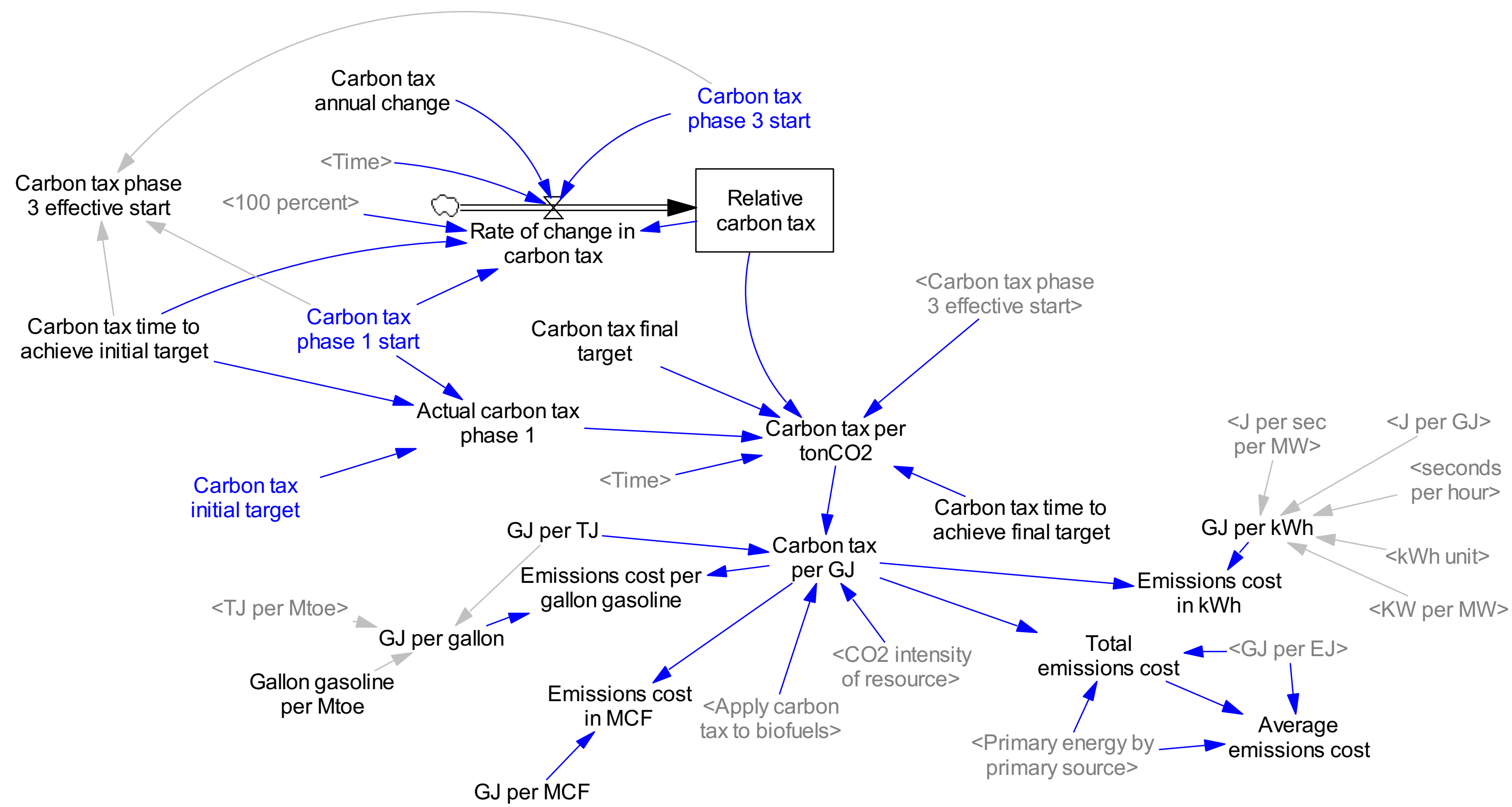


Table 5-9 Source Tax/Subsidy Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Source subsidy for delivered fuels[Primary Fuels]	An increase in net revenue for delivered fuels due to government subsidies (positive values) or decrease due to government burdens (negative values).	-10-10	0	$/GJ
Source subsidy for delivered fuels start time[Primary Fuels]	The year when a subsidy begins applying.	2021-2100	2021	Year
Source subsidy for delivered fuels stop time[Primary Fuels]	The year when a source subsidy stops applying. Source tax/subsidy on primary fuel. Applies to nonelectric and electric consumption.	2021-2100	2100	Year
Source subsidy to electric producers[Elec Paths]	An increase in net revenue for electric producers due to government subsidies (positive values) or decrease due to government burdens (negative values).	-10-10	0	$/GJ
Use Native Units	Switch to use native units for source subsidy/tax setting, for which positive values indicate tax and negative values indicate subsidy.	0-1	1	Dmnl
Source subsidy delivered coal tce	Source tax/subsidy on coal. Applies to raw fuel for nonelectric and electric consumption. See Table 5-10	-20-110	0	$/tce
Source subsidy delivered oil boe	Source tax/subsidy on coal. Applies to raw fuel for nonelectric and electric consumption. See Table 5-10	-15-100	0	$/boe
Source subsidy delivered gas MCF	Source tax/subsidy on coal. Applies to raw fuel for nonelectric and electric consumption. See Table 5-10	-1-5	0	$/MCF

Table 5-9 Source Tax/Subsidy Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Source subsidy delivered bio boe	Source tax/subsidy on coal. Applies to raw fuel for nonelectric and electric consumption. See Table 5-10	-30-90	0	$/boe
Source subsidy to electric consumers kWh[Elec Paths]	Source tax/subsidy on electricity generated by path. See Table 5-10		0	$/kWh
Source subsidy nuclear kWh		-0.07-0.07	0	
Source subsidy renewables kWh		-0.03-0.02	0	
Source subsidy to electric producers start time[Elec Path]	The year when a subsidy begins applying.	2021-2100	2021	Year
Source subsidy to electric producers stop time[Elec Path]	The year when a source subsidy stops applying.	2021-2100	2100	Year
Fraction of elec source adjustment for capital[Elec Paths]	The fraction of source subsidy/tax that is applied to the capital costs vs the variable costs. Defaults to all being applied to capital.	0-1	1	Dmnl
Fraction of fuel source adjustment for capital[Primary Fuels]	The fraction of source subsidy/tax that is applied to the capital costs vs the variable costs. Defaults to all being applied to variable.	0-1	0	Dmnl

Table 5-10 Source Tax/Subsidy Parameter Thresholds

Raw Fuels					
	% of 2020 marginal cost	**Coal ($/tce)**	**Oil ($/boe)**	**Gas ($/Mcf)**	**Bio ($/boe)**
Very Highly Taxed	+200%	110	100	5	90
Highly Taxed	+60%	60	50	3	50
Taxed	+30%	40	30	2	30
Slightly Taxed	+10%	6	5	0.3	5
Slightly Subidized	-10%	6	5	0.3	5
Subsidized	-30%	20	15	1	15
Highly Subsidized	-60%	40	30	2	30
Power Plant, Electric only					
		Nuclear ($/kWh)	**Renewables ($/kWh)**	**Hdyro ($/KWh)**	
Very Highly Taxed	+200%	0.24	0.23	0.23	
Highly Taxed	+60%	0.12	0.11	0.07	
Taxed	+30%	0.07	0.03	0.03	
Slightly Taxed	+10%	0.01	0.01	0.01	
Slightly Subidized	-10%	0.01	0.01	0.01	
Subsidized	-30%	0.03	0.02	0.03	
Highly Subsidized	-60%	0.07	0.03	0.07	

Table 5-11 Source Tax/Subsidy Calculated Parameters

Parameter	Definition	Units
Source subsidy for delivered fuels over time[Primary Fuels]	Source subsidy/tax over time. IF THEN ELSE(Time>Source subsidy for delivered fuels stop time[Primary Fuels], 0, ramp(IF THEN ELSE(Use native units,-Source subsidy for delivered fuels from native units[Primary Fuels],Source subsidy for delivered fuels[Primary Fuels])/Source subsidy ramp time, Source subsidy for delivered fuels start time[Primary Fuels], Source subsidy for delivered fuels start time[Primary Fuels]+Source subsidy ramp time))	$/GJ
Source subsidy to electric consumers over time[Elec Paths]	Applies the specified source subsidy after the start time until the stop time. IF THEN ELSE(Time>Source subsidy to electric consumers stop time[Elec Paths], 0, ramp(Effective Source subsidy to electric consumers[Elec Paths]/Source subsidy ramp time, Source subsidy to electric consumers start time[Elec Paths], Source subsidy to electric consumers start time[Elec Paths]+Source subsidy ramp time))	$/GJ
Source subsidy for delivered fuels from native units[Primary Fuels]	Converts native units to $/GJ	$/GJ
Coal	Source subsidy delivered coal tce/GJ per tce	
Oil	Source subsidy delivered oil boe/GJ per BOE	
Gas	Source subsidy delivered gas MCF/GJ per MCF	
Bio	Source subsidy delivered bio boe/GJ per BOE	
Source subsidy to electric consumers from kWh	Converts native units to $/GJ Source subsidy to electric consumers kWh[Elec Paths]/GJ per kWh	$/GJ
Effective Source subsidy to electric consumers	IF THEN ELSE(Use native units, -Source subsidy to electric consumers from kWh[Elec Paths],Source subsidy to electric consumers[Elec Paths])	

Table 5-12 Carbon Tax Parameter Inputs

Parameter	Definition	Range	Default Values	Units
Carbon tax initial target	The price per ton of CO_2 emitted. This could be implemented by a carbon tax to the consumer.	0-250	0	$/TonCO2
Carbon tax phase 1 start	Year to start on path to achieve initial carbon tax.	2021-2100	2021	Year
Carbon tax time to achieve initial target	Time to linearly achieve full initial carbon tax.	1-20	10	Years
Carbon tax annual change	Initial percent increase of carbon tax.	-5-5	0	Percent/year
Carbon tax final target	Final emissions target to be achieved linearly, starting from its level at the **Carbon tax phase 3 start,** in the time specified by the **Carbon tax time to achieve final target.**	0-850	0	$/TonCO2
Carbon tax time to achieve final target	Time to achieve the **Carbon tax final target** starting from the **Carbon tax phase 3 start.**	1-100	10	Year
Carbon tax phase 3 start	Year that the emissions start on the path to the final emissions target, to be achieved linearly in the years specified by the **Carbon tax time to achieve final target.**	2021-2100	2100	Year

Table 5-13 Carbon Tax and Electric Subsidy Calculated Parameters

Parameter	Definition	Units
Carbon tax per GJ [Primary Fuels]	Cost of emissions with an emission price on carbon, based on carbon density of source. The switch "Apply carbon tax to biofuels" allows the user to test the effect of not including bioenergy emissions, if set to 0, to be more consistent with how many other models treat bioenergy. En-ROADS, however, defaults this value to 1 to tax carbon emissions from bioenergy.	$/GJ
[Primary FF]	Carbon tax per tonCO2*CO2 intensity of resource [Primary FF Sources]/GJ per TJ	
[PBio]	Carbon tax per tonCO2*CO2 intensity of resource [Primary bio]/GJ per TJ*Apply carbon tax to biofuels	
Carbon tax per tonCO2	Carbon tax based on the three potential phases. *To test the SSP Scenarios, the selected SSP model carbon price projections overrides the specified carbon tax.* IF THEN ELSE (Choose SSP Scenario > 0 :AND: Time>First selected SSP year :AND: :NOT: "Selected SSP - Price|Carbon for input" = :NA: , "Selected SSP - Price|Carbon for input" , Actual carbon tax phase 1 * Relative carbon tax + IF THEN ELSE (Time < Carbon tax phase 3 effective start , 0, ramp ((Carbon tax final target - Actual carbon tax phase 1 * Relative carbon tax) / Carbon tax time to achieve final target , Carbon tax phase 3 effective start , Carbon tax phase 3 effective start + Carbon tax time to achieve final target)))	$/TonCO2
Carbon tax phase 3 effective start	MAX(Carbon tax phase 1 start+Carbon tax time to achieve initial target, Carbon tax phase 3 start)	Year

Table 5-13 Carbon Tax and Electric Subsidy Calculated Parameters

Parameter	Definition	Units
Actual carbon tax phase 1	Linear increase from 0 at Carbon tax phase 1 start and reaching the Carbon tax initial target in the time specified by Carbon tax time to achieve initial target. ramp(Carbon tax initial target/Carbon tax time to achieve initial target, Carbon tax phase 1 start,Carbon tax phase 1 start+Carbon tax time to achieve initial target)	$/TonCO2
Relative carbon tax	Carbon tax in time, starting with the Carbon tax initial target (excluding the ramp up to it) and leveling at the Carbon tax phase 3 start. INTEG(Rate of change in carbon tax, 1)	Dmnl
Rate of change in carbon tax	Change in relative carbon tax during Phase 2. IF THEN ELSE(Time<Carbon tax phase 1 start +Carbon tax time to achieve initial target ,0, Relative carbon tax*IF THEN ELSE(Time<Carbon tax phase 3 start , Carbon tax annual change /"100 percent", 0))	$/TonCO2/Year
Total emissions cost	SUM(Carbon tax for delivered fuels[Primary Fuels!]*Primary Energy Demand by aggregated resource[Primary Fuels!])*GJ per EJ	$/GJ
Emissions cost in kWh[Primary Fuels[	Carbon tax [Primary Fuels]*GJ per kWh	$/kWh
Emissions cost in MCF[Primary Fuels]	Carbon tax [Primary Fuels]*GJ per MCF	$/MCF
Emissions cost per gallon gasoline[Primary Fuels]	Carbon tax [Primary Fuels]*GJ per gallon	$/gallon gasoline

5.2.3 Ratio of Actual to Expected Energy Costs to Consumers

As defined in Section 3.3, the early discarding of energy consuming capital can be vintage-specific and depends on the ratio of intensity of each vintage to the total. The actual cost to consumers to use energy consuming capital is a function of the current market price to consumers of that energy and the embodied energy intensity of that capital. The expected energy cost to consumers is the embodied market price to consumers of that energy and the average embodied intensity.

Figure 5-11 Expected Cost of Energy to Consumer Initialization

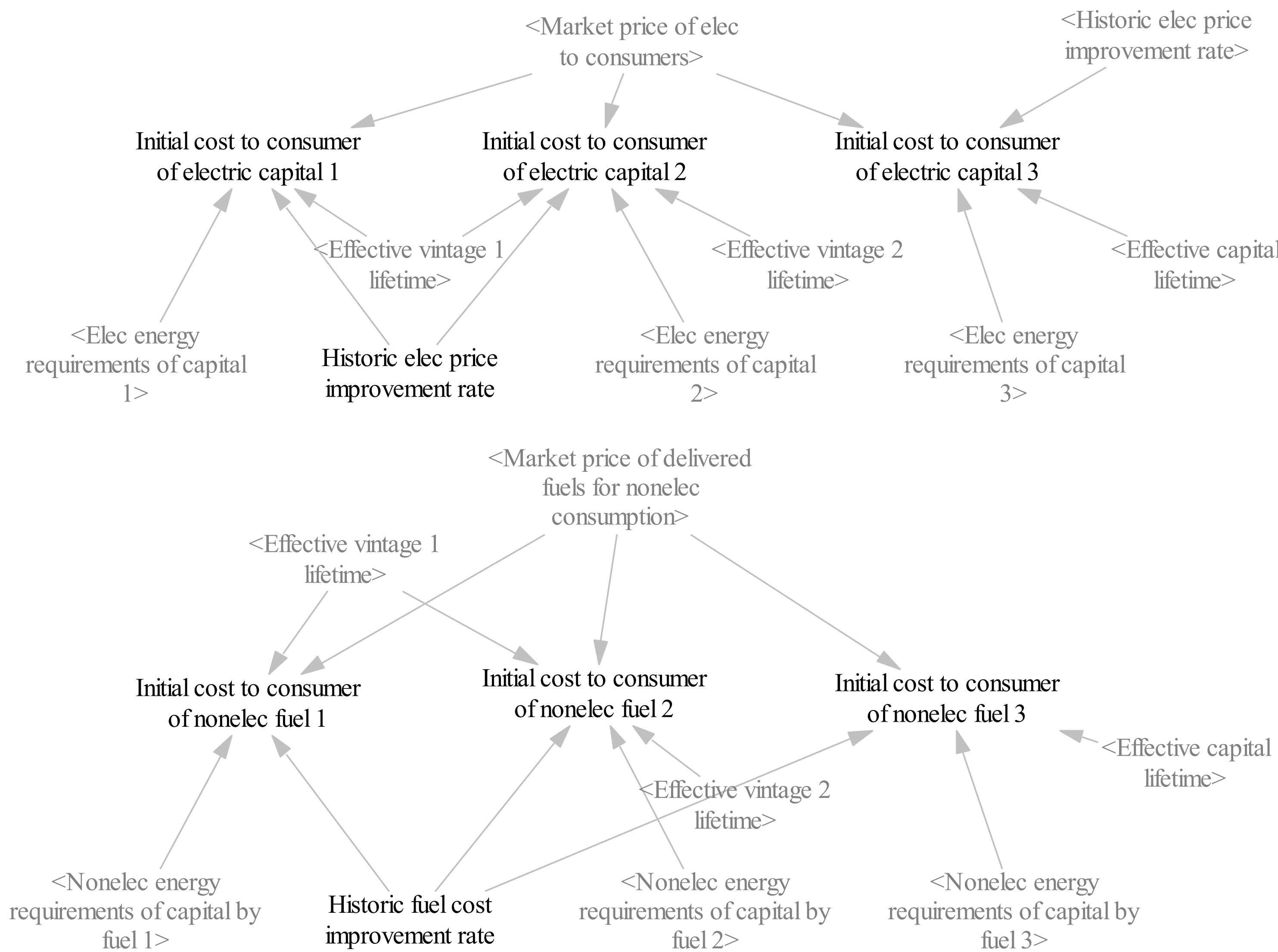


Figure 5-12 Structure of Expected Costs to Consumers of Electricity

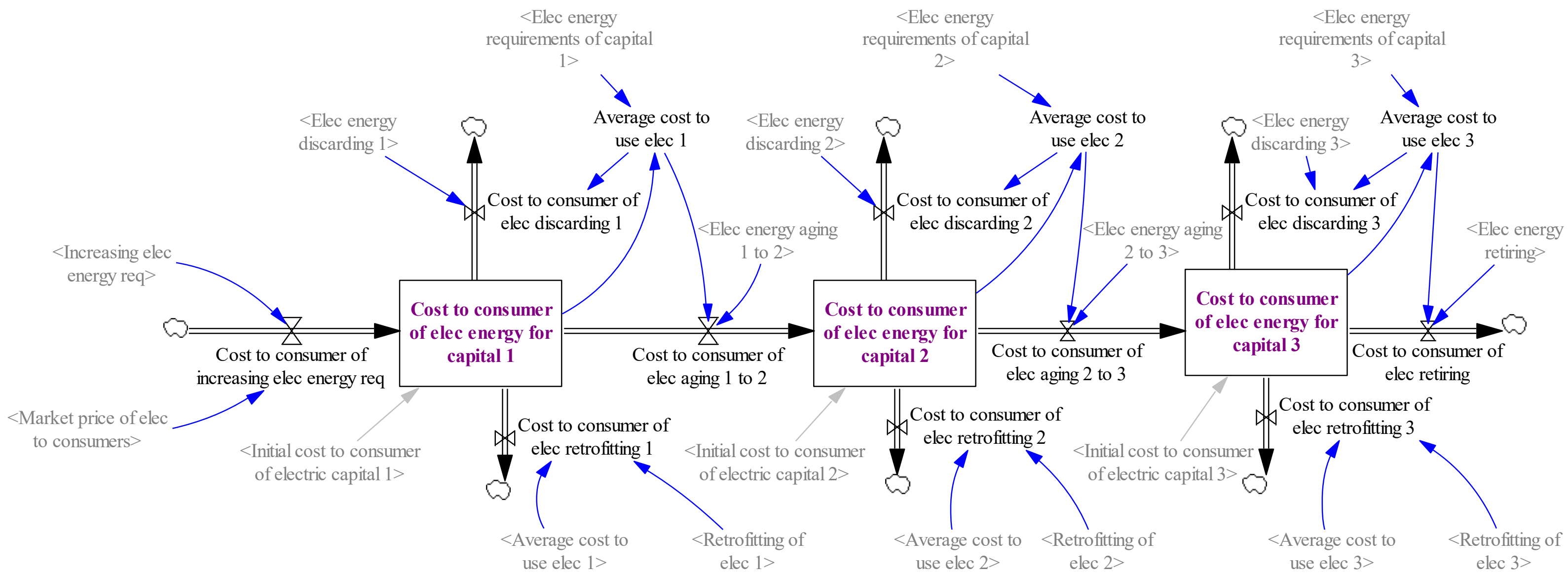


Figure 5-13 Structure of Expected Costs to Consumers of Fuel for Nonelectric Consumption

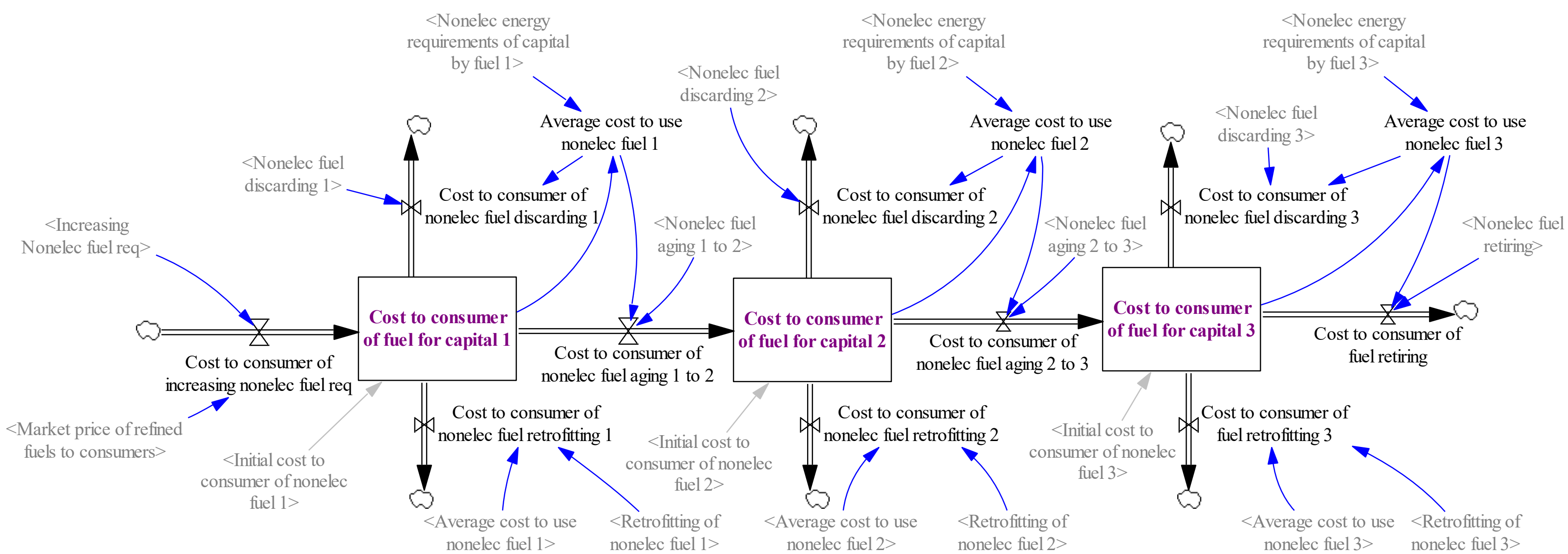


Figure 5-14 Structure of Actual versus Expected Costs to Use Energy

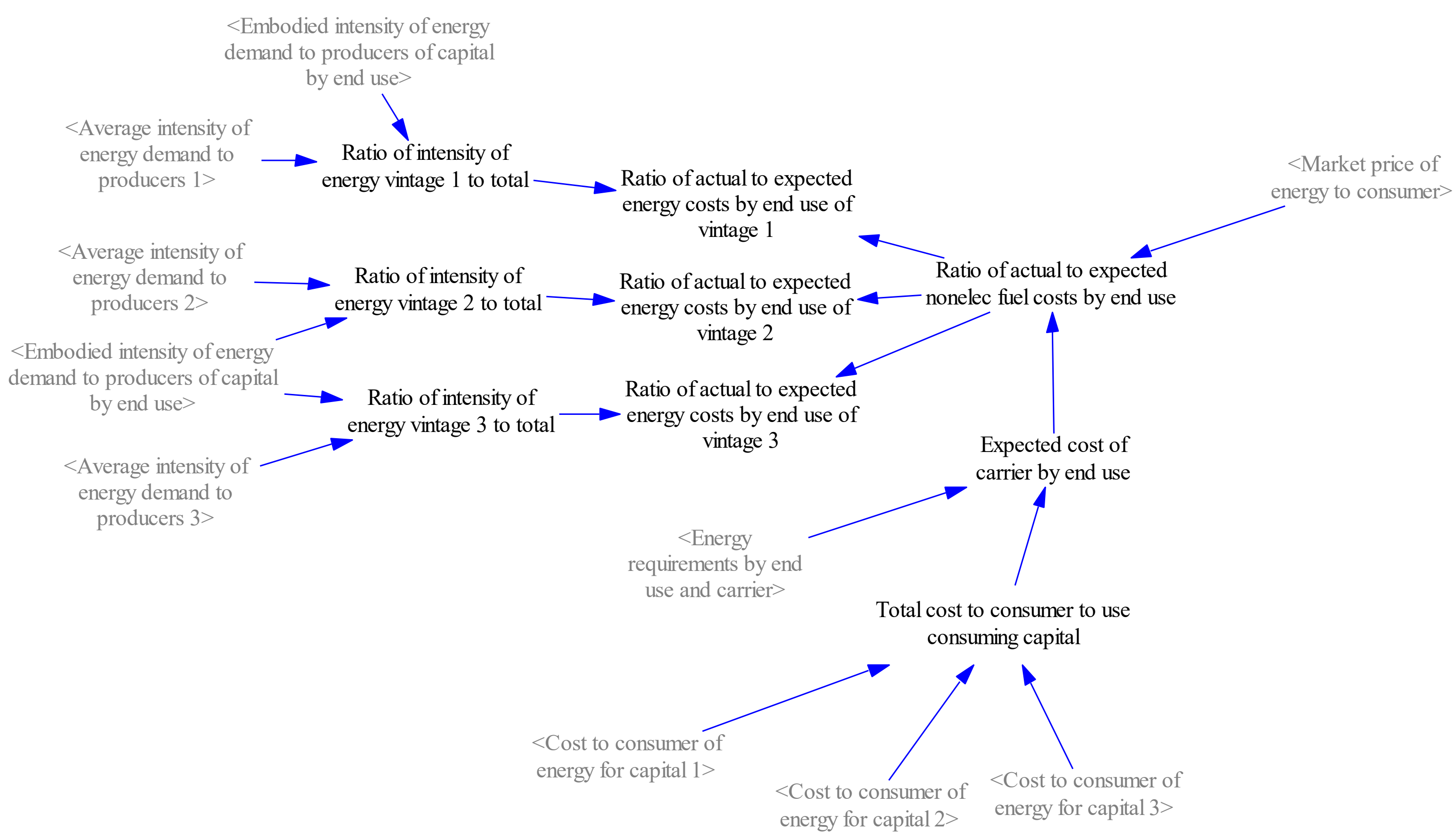


Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Expected cost of carrier by end use [EndUseSector,Carrier]	Expected cost to consumer of each carrier for consumption of each end use. ZIDZ(Total cost to consumer to use consuming capital[EndUseSector, Carrier], Energy requirements by end use and carrier [EndUseSector,Carrier])	$/GJ
Total cost to consumer to use consuming capital [EndUseSector, Carrier]	Cost to consumer of energy for capital 1[EndUseSector,Carrier]+Cost to consumer of energy for capital 2[EndUseSector,Carrier]+Cost to consumer of energy for capital 3[EndUseSector,Carrier]	($/GJ)*(EJ/Year)
Ratio of actual to expected costs by end use[EndUseSector, Carrier]	ZIDZ(Market price of energy to consumer[Carrier], Expected cost of carrier by end use[EndUseSector, Carrier])	Dmnl
Initial cost to consumer of energy 1 [EndUseSector, Carrier]	The initial expected annual cost of energy for vintage 1 capital assuming a Historic fuel price improvement rate of 0, i.e., costs relatively stable for the period from the time of installation to the initial time of 1990. INITIAL(Market price of energy to consumer[EndUseSector, Carrier]*Energy requirements of capital 1[EndUseSector,Carrier]*EXP(Historic energy cost improvement rate*Initial effective vintage 1 lifetime[EndUseSector]))	($/GJ)*(EJ/Year)

Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Initial cost to consumer of energy 2 [EndUseSector, Carrier]	The initial expected annual cost of energy for vintage 2 nonelectric capital assuming a Historic fuel price improvement rate of 0, i.e., costs relatively stable for the period from the time of installation to the initial time of 1990. INITIAL(Market price of energy to consumer[EndUseSector, Carrier]*Energy requirements of capital 2[EndUseSector,Carrier]*EXP(Historic energy cost improvement rate*(Initial effective vintage 1 lifetime[EndUseSector]+Initial effective vintage 2 lifetime[EndUseSector])))	($/GJ)*(EJ/Year)
Initial cost to consumer of energy 3 [EndUseSector, Carrier]	The initial expected annual cost of energy for vintage 3 nonelectric capital assuming a Historic fuel price improvement rate of 0, i.e., costs relatively stable for the period from the time of installation to the initial time of 1990. INITIAL(Market price of energy to consumer[EndUseSector, Carrier]*Energy requirements of capital 3[EndUseSector,Carrier]*EXP(Historic energy cost improvement rate*Initial effective capital lifetime[EndUseSector]))	($/GJ)*(EJ/Year)
Cost to consumer of energy for capital 1 [EndUseSector, Carrier]	For each end use, the expected cost of each carrier required of capital in vintage 1, including any retrofits. INTEG(Cost to consumer of increasing energy requirements[EndUseSector,Carrier]-Cost to consumer of consuming capital aging 1 to 2[EndUseSector, Carrier]-Cost to consumer of energy discarding 1[EndUseSector, Carrier]-Cost to consumer of energy retrofitting 1[EndUseSector, Carrier], Initial cost to consumer of energy 1[EndUseSector, Carrier])	($/GJ)*(EJ/Year)

Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Cost to consumer of energy for capital 2 [EndUseSector, Carrier]	For each end use, the expected cost of each carrier required of capital in vintage 2, including any retrofits. INTEG(Cost to consumer of consuming capital aging 1 to 2[EndUseSector, Carrier]-Cost to consumer of consuming capital aging 2 to 3[EndUseSector, Carrier]-Cost to consumer of energy discarding 2[EndUseSector, Carrier]-Cost to consumer of energy retrofitting 2[EndUseSector, Carrier], Initial cost to consumer of energy 2[EndUseSector, Carrier])	($/GJ)*(EJ/Year)
Cost to consumer of energy for capital 3 [EndUseSector, Carrier]	For each end use, the expected cost of each carrier required of capital in vintage 3, including any retrofits. INTEG(Cost to consumer of consuming capital aging 2 to 3[EndUseSector, Carrier]-Cost to consumer of energy discarding 3[EndUseSector, Carrier]-Cost to consumer of consuming capital retiring[EndUseSector, Carrier]-Cost to consumer of energy retrofitting 3[EndUseSector, Carrier],Initial cost to consumer of energy 3[EndUseSector, Carrier])	($/GJ)*(EJ/Year)
Cost to consumer of increasing energy requirements [EndUseSector, Carrier]	Cost to consumer of each carrier required of capital that is installed for each end use. Energy requirements installing[EndUseSector,Carrier]*Market price of energy to consumer[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of consuming capital aging 1 to 2 [EndUseSector, Carrier]	Expected cost to consumer of each carrier required of capital with any retrofits moving from vintage 1 into vintage 2. Average cost to use energy 1[EndUseSector,Carrier]*Energy requirements aging 1 to 2[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year

Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Cost to consumer of consuming capital aging 2 to 3 [EndUseSector, Carrier]	Expected cost to consumer of each carrier required of capital with any retrofits moving from vintage 2 into vintage 3. Average cost to use energy 2[EndUseSector,Carrier]*Energy requirements aging 2 to 3[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of consuming capital retiring [EndUseSector, Carrier]	Expected cost to consumer of each carrier required of capital with any retrofits moving from vintage 3 to no longer being used. Average cost to use energy 3[EndUseSector,Carrier]*Energy requirements retiring[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of energy retrofitting 1 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of capital in vintage 1 from the originally installed capital due to retrofitting. Average cost to use energy 1[EndUseSector,Carrier]*Retrofitting of energy requirements 1[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of energy retrofitting 2 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of capital in vintage 2 from the originally installed capital due to retrofitting. Average cost to use energy 2[EndUseSector,Carrier]*Retrofitting of energy requirements 2[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of energy retrofitting 3 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of capital in vintage 3 from the originally installed capital due to retrofitting. Average cost to use energy 3[EndUseSector,Carrier]*Retrofitting of energy requirements 3[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year

Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Cost to consumer of energy discarding 1 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of capital in vintage 1 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average cost to use energy 1[EndUseSector, Carrier]*Energy requirements discarding 1[EndUseSector, Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of energy discarding 2 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of carrier capital in vintage 2 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average cost to use energy 2[EndUseSector, Carrier]*Energy requirements discarding 2[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Cost to consumer of energy discarding 3 [EndUseSector, Carrier]	The decrease in expected cost of each carrier required of capital in vintage 3 due to the amount of capital with any retrofits in this vintage lost due to early retirement. Average cost to use energy 3[EndUseSector, Carrier]*Energy requirements discarding 3[EndUseSector,Carrier]	($/GJ)*(EJ/Year)/Year
Average cost to use energy 1 [EndUseSector, Carrier]	Average of expected cost of each carrier required per dollar of vintage 1 capital, including any retrofits. ZIDZ(Cost to consumer of energy for capital 1[EndUseSector, Carrier], Energy requirements of capital 1[EndUseSector, Carrier])	$/GJ
Average cost to use energy 2 [EndUseSector, Carrier]	Average of expected cost of each carrier required per dollar of vintage 2 capital, including any retrofits. ZIDZ(Cost to consumer of energy for capital 2[EndUseSector, Carrier], Energy requirements of capital 2[EndUseSector,Carrier])	$/GJ

Table 5-14. Expected Costs of Energy Consumption to Consumersby Carrier Calculated Parameters

Parameter	Definition	Units
Average cost to use energy 3 [EndUseSector, Carrier]	Average of expected cost of each carrier required per dollar of vintage 3 capital, including any retrofits. ZIDZ(Cost to consumer of energy for capital 3[EndUseSector, Carrier], Energy requirements of capital 3[EndUseSector,Carrier])	$/GJ

6. Investment Formulation

The **Investment** sector calculates annual revenue and variable costs based on the energy used and the annual fixed cost based on capacity. It also calculates the government costs of subsidies and revenue from taxes.

Figure 6-1 Structure of Absolute Revenue, Costs, and Profits

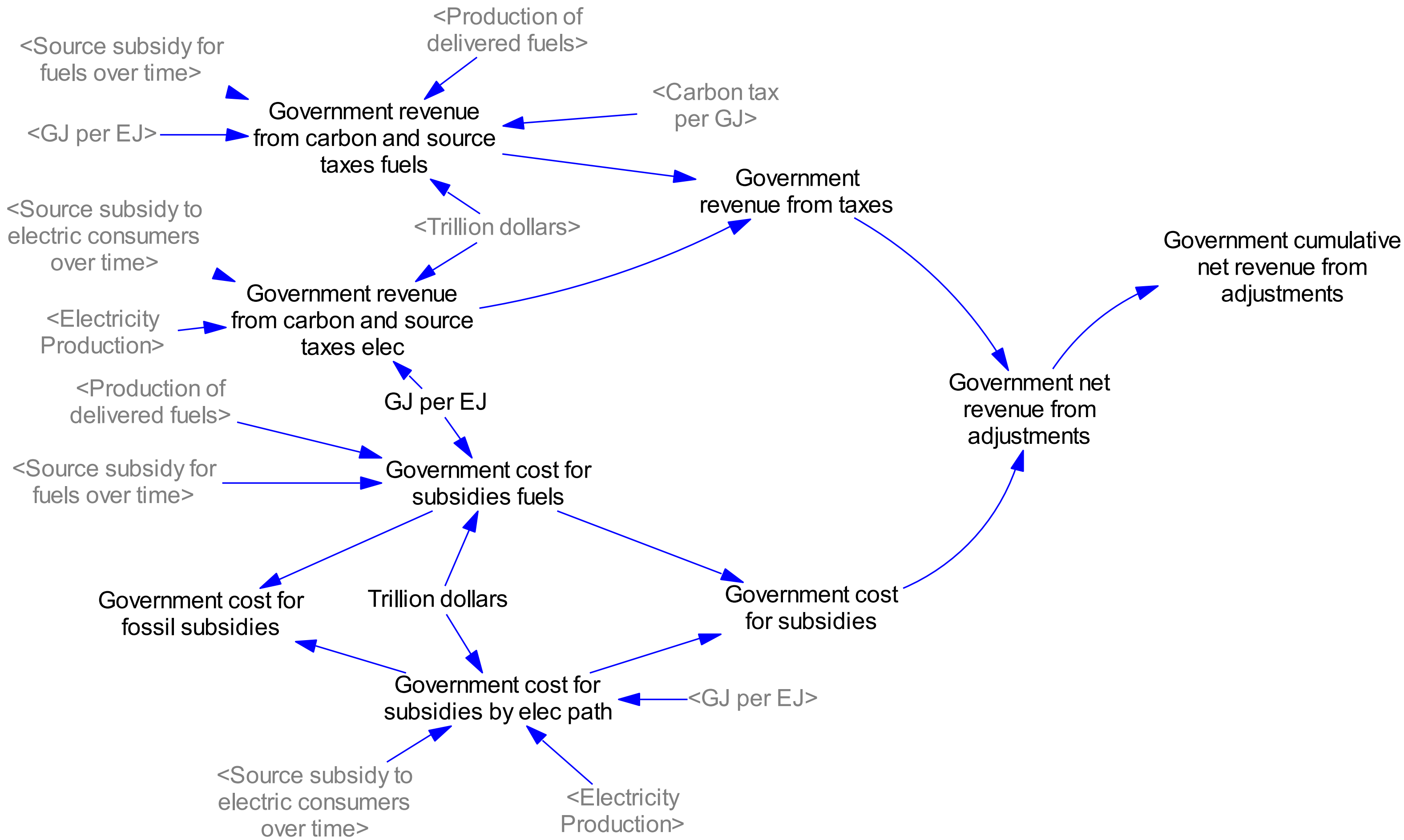


Figure 6-2 Structure of Absolute Revenue, Costs, and Profits

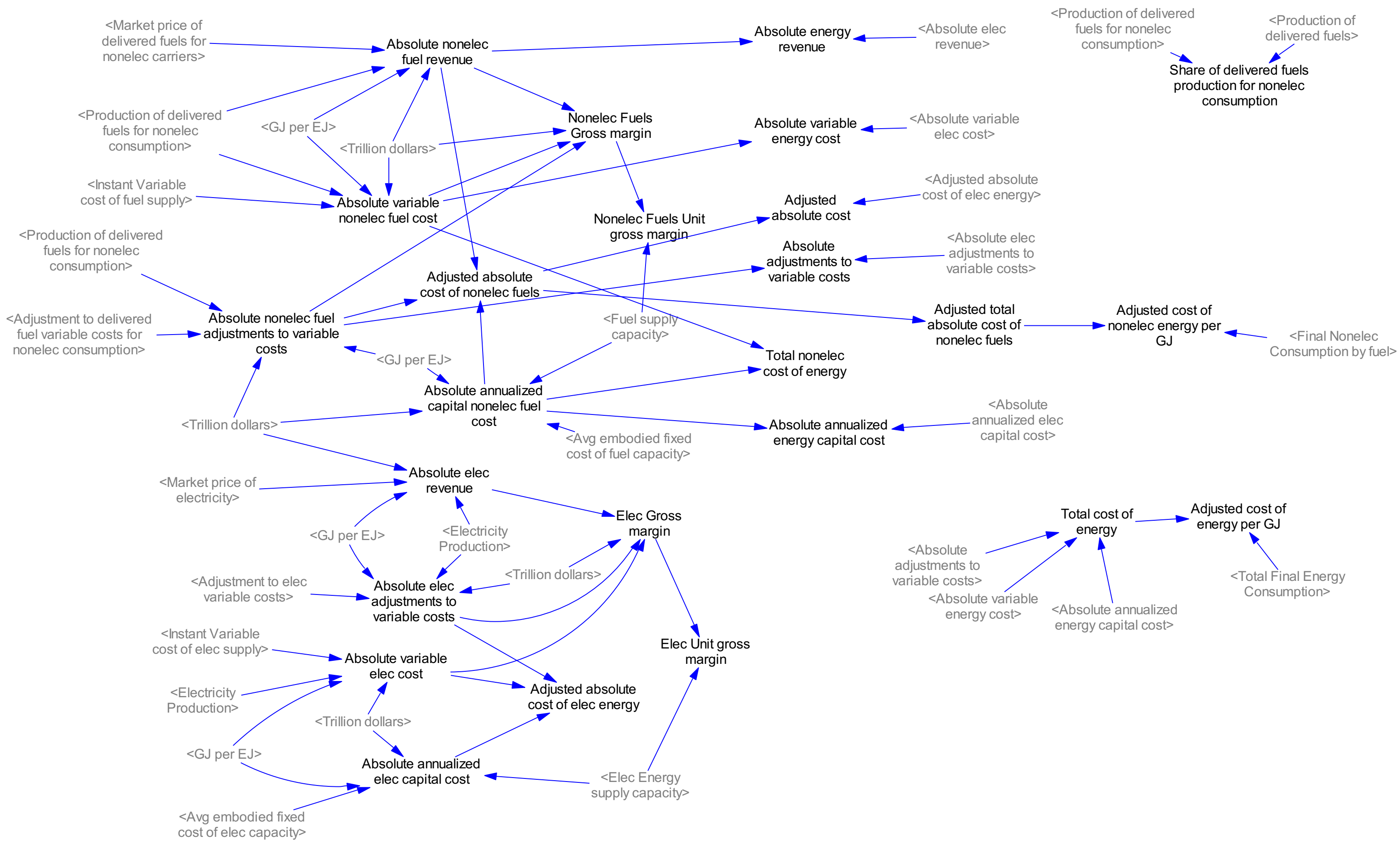


Table 6-1 Investment Sector Calculated Parameters

Parameter	Definition	Units
Absolute nonelec fuel revenue [Primary Fuels]	Production of delivered fuels for nonelec consumption[Primary Fuels]*Market price of delivered fuels for nonelec carriers[Primary Fuels]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute elec revenue[Elec Paths]	Electricity Production[Elec Paths]*Revenue from electricity[Elec Paths]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute variable nonelec fuel cost [Primary Fuels]	Production of delivered fuels for nonelec consumption[Primary Fuels]*Instant Variable cost of fuel supply[Primary Fuels]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute variable elec cost[Elec Paths]	Electricity Production[Elec Paths]*Instant Variable cost of elec supply[Elec Paths]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute nonelec fuel adjustments to costs[Primary Fuels]	Production of delivered fuels for nonelec consumption[Primary Fuels] *Adjustment to delivered fuel variable costs for nonelec consumption[Primary Fuels]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute elec adjustments to costs[Elec Paths]	Electricity Production[Elec Paths]*Adjustment to elec costs[Elec Paths]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute annualized capital fuel cost [Primary Fuels]	Absolute capital cost for energy capacity of a given source based on the unit average capital costs and the actual capacity. This differs from the absolute variable costs which are based on the energy utilized. Avg embodied fixed cost of fuel capacity[Primary Fuels]* Fuel supply capacity[Primary Fuels]*GJ per EJ/Trillion dollars	Trillion $/Year
Absolute annualized elec capital cost[Elec Paths]	Avg embodied fixed cost of elec capacity[Elec Paths]* Elec Energy supply capacity[Elec Paths]*GJ per EJ/Trillion dollars	Trillion $/Year

Table 6-1 Investment Sector Calculated Parameters

Parameter	Definition	Units
Adjusted absolute cost of nonelec fuels[Primary Fuels	Absolute cost of carbon and source taxes, less subsidies, to produce nonelec energy from a given source based on the unit costs and the energy utilized. Absolute nonelec fuel revenue[Primary Fuels]+Absolute annualized capital nonelec fuel cost[Primary Fuels]+Absolute nonelec fuel adjustments to variable costs[Primary Fuels]	Trillion $/Year
Adjusted absolute cost of elec energy[Elec Paths]	Absolute variable elec cost[Elec Paths]+Absolute annualized elec capital cost[Elec Paths]+Absolute elec adjustments to costs[Elec Paths]	Trillion $/Year
Nonelec Fuels Gross margin[Primary Fuels]	(Absolute fuel revenue[Primary Fuels]-Absolute variable fuel cost [Primary Fuels])*Trillion dollars	$/Year
Nonelec Fuels Unit gross margin[Primary Fuels]	ZIDZ(Fuels Gross margin[Primary Fuels], Fuel supply capacity[Primary Fuels])	$/EJ
Elec Gross margin[Elec Paths]	(Absolute elec revenue[Elec Paths]-Absolute variable elec cost [Elec Paths])*Trillion dollars	$/Year
Elec Unit gross margin[Elec Paths]	ZIDZ(Elec Gross margin[Elec Paths],Elec Energy supply capacity[Elec Paths])	$/EJ
Absolute variable nonelec fuel cost[Primary Fuels]	Share of delivered fuels production for nonelec consumption[Primary Fuels]*Absolute variable fuel cost[Primary Fuels]	Trillion $/Year
Absolute energy revenue	SUM(Absolute elec revenue[Elec Paths!])+SUM(Absolute nonelec fuel revenue[Primary Fuels!])	Trillion $/Year
Absolute variable energy cost	SUM(Absolute variable elec cost[Elec Paths!])+SUM(Absolute variable nonelec fuel cost[Primary Fuels!])	Trillion $/Year
Absolute energy adjustments to costs	SUM(Absolute elec adjustments to costs[Elec Paths!])+SUM(Absolute nonelec fuel adjustments to costs[Primary Fuels!])	Trillion $/Year
Absolute annualized energy capital cost	SUM(Absolute annualized elec capital cost[Elec Paths!])+SUM(Absolute annualized capital nonelec fuel cost[Primary Fuels!])	Trillion $/Year
Total cost of energy	Absolute variable energy cost+Absolute annualized energy capital cost+Absolute energy adjustments to costs	Trillion $/Year

Table 6-1 Investment Sector Calculated Parameters

Parameter	Definition	Units
Adjusted cost of energy per GJ	ZIDZ(Total cost of energy*trillion dollars,Total Final Energy Consumption*GJ per EJ)	$/GJ
Adjusted cost of nonelec energy per GJ	ZIDZ(Total cost of energy*trillion dollars,SUM(Final Nonelec Consumption by fuel[Primary Fuels!] *GJ per EJ))	$/GJ
Adjusted cost of elec energy per GJ	ZIDZ (SUM(Adjusted absolute cost of elec energy[Elec Paths!])*Trillion dollars , Final Elec Consumption *GJ per EJ)	$/GJ
Government revenue from carbon and source taxes fuels[Primary Fuels]	Absolute cost of government to pay for subsidies to use energy from a given source based on the unit costs and the energy utilized. Production of delivered fuels[Primary Fuels]*(Carbon tax per GJ[Primary Fuels]-MIN(0, Source subsidy for fuels over time[Primary Fuels]))*GJ per EJ/Trillion dollars	Trillion $/Year
Government revenue from carbon and source taxes elec	The total revenue to the government from emissions price and taxes to meet energy demand. Electricity Production[Elec Paths]*(MAX(0, -Source subsidy to electric consumers over time[Elec Paths]))*GJ per EJ/Trillion dollars	Trillion $/Year
Government revenue from taxes	The total costs of the government to pay for subsidies to use energy. SUM(Government revenue from carbon and source taxes elec[Elec Paths!])+SUM(Government revenue from carbon and source taxes fuels[Primary Fuels!])	Trillion $/Year
Government cost for subsidies fuels[Primary Fuels]	Production of delivered fuels [Primary Fuels]*MAX(0, Source subsidy for fuels over time[Primary Fuels])*GJ per EJ/Trillion dollars	Trillion $/Year
Government cost for subsidies by elec path[Elec Paths]	Electricity Production[Elec Paths]*(MAX(0, Source subsidy to electric consumers over time[Elec Paths]))*GJ per EJ/Trillion dollars	Trillion $/Year
Government cost for subsidies	SUM(Government cost for subsidies by elec path[Elec Paths!])+SUM(Government cost for subsidies fuels[Primary Fuels!])	Trillion $/Year
Government cost for fossil subsidies	SUM(Government cost for subsidies by elec path[Elec FF paths!])+SUM(Government cost for subsidies fuels[Primary FF!])	Trillion $/Year

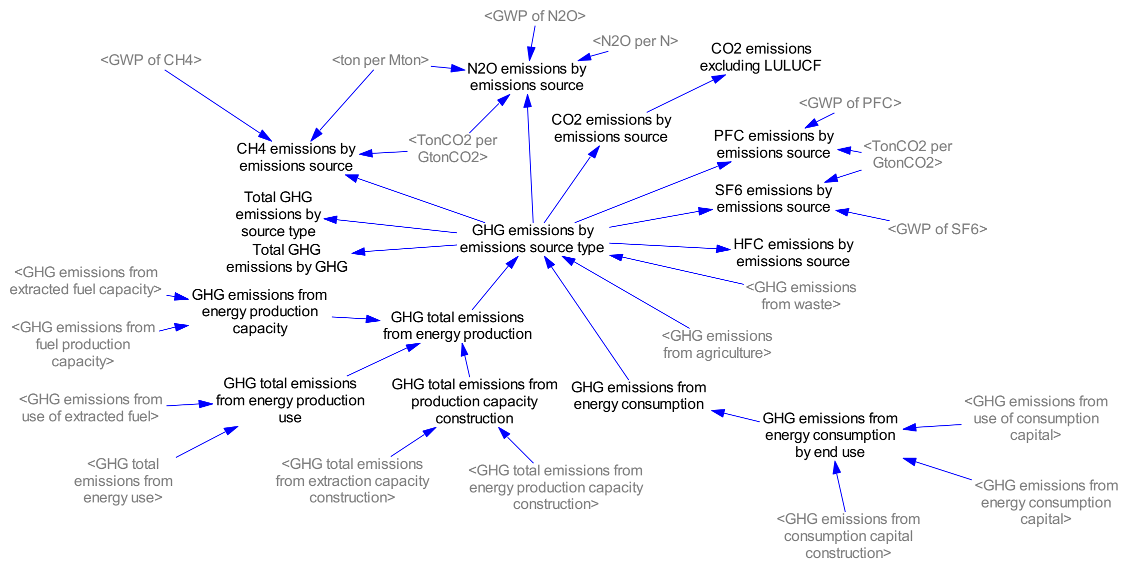
Table 6-1 Investment Sector Calculated Parameters

Parameter	Definition	Units
Government net revenue from adjustments	Government revenue from taxes-Government cost for subsidies	Trillion $/Year
Government cumulative net revenue from adjustments	INTEG(Government net revenue from adjustments, 0)	Trillion $

7. Emissions Formulation

Energy drives the primary source of greenhouse gases (GHGs), of which CO_2 is the largest fraction of total CO_2 equivalent annual emissions. However, En-ROADS models the emissions more generally of well-mixed GHGs, including CO_2, CH_4, N_2O, PFCs, SF_6, and HFCs, the source of each potentially from energy production, energy-consuming capital, agriculture, and waste. Initial emissions of each GHG that comes from each source are taken from 1990 data from PRIMAP 2019, assuming Agriculture includes PRIMAP MAG and LU categories, and Waste includes PRIMAP Waste and Other categories. The overview of this sector is shown in Figure 7-1. Section 7.1 through 7.3 provide information on each of the types of emissions. Land use CO2 emissions are currently handled separately, as discussed in Section 7.4.

Figure 7-1 Emissions Sector Overview



7.1 Emissions from Energy Production

Energy production emissions include those from production capacity, production capacity construction, and from production use. Each of these sources applies to extracted fuel, delivered fuel, and electricity generation from each power source. As shown in Figure 7-2, emissions from energy use depend on the energy intensity, the efficiency of, losses from, and energy produced by each source, i.e., primary energy. The emissions intensity is a measure of GHGs emitted per amount of energy produced. Energy production capacity emissions default to CH_4; energy production construction emissions default to CO_2; and energy production use emissions default to CO_2, CH_4, and N_2O. However, each phase of production is a potential source of each GHG, subject to the user's assumptions.

7.2 Emissions from Energy Consuming Capital

Emissions from energy consuming include those from the end use capital, the construction of that capital, and the use of that capital. Consumption capital capacity and use emissions default primarily to PFCs, SF_6, and HFCs. However, industry end use capital also emits CH_4 and N_2O. The construction of energy consuming capital defaults to CO_2 emissions only. However, each phase of end use capital is a potential source of each GHG, subject to the user's assumptions.

7.3 Emissions from Agriculture and Waste

Emissions from agriculture and waste depend on the production ratio, i.e., how much is produced, and the GHG intensity of that which is produced. While agriculture and waste sources default to emit only CH_4 and N_2O, they are also a potential source of each GHG, subject to the user's assumptions.

Figure 7-2 CO_2 Emissions from Delivered Fuel and Electricity Generation Use

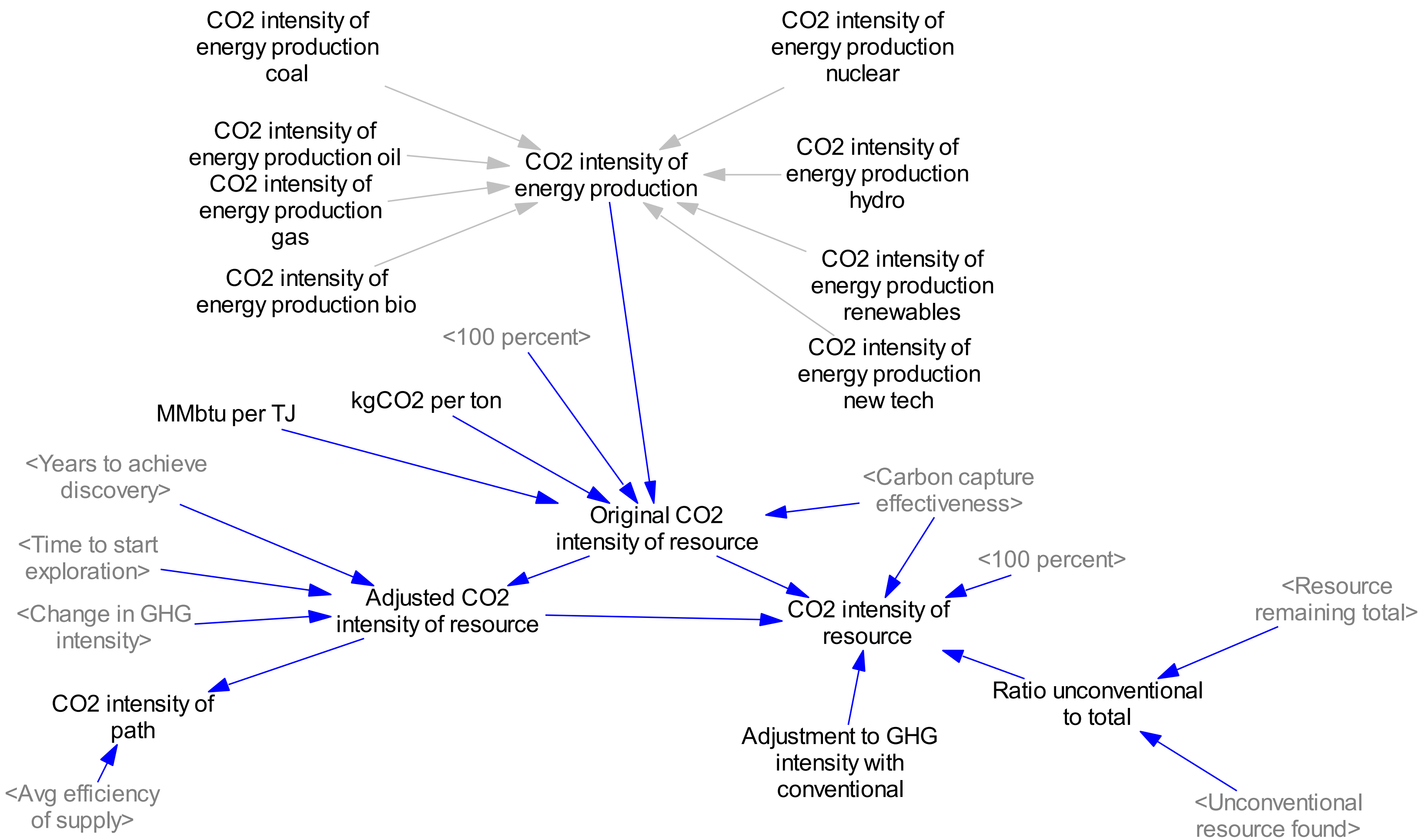


Figure 7-3 GHG Emissions from Delivered Fuel and Electricity Generation

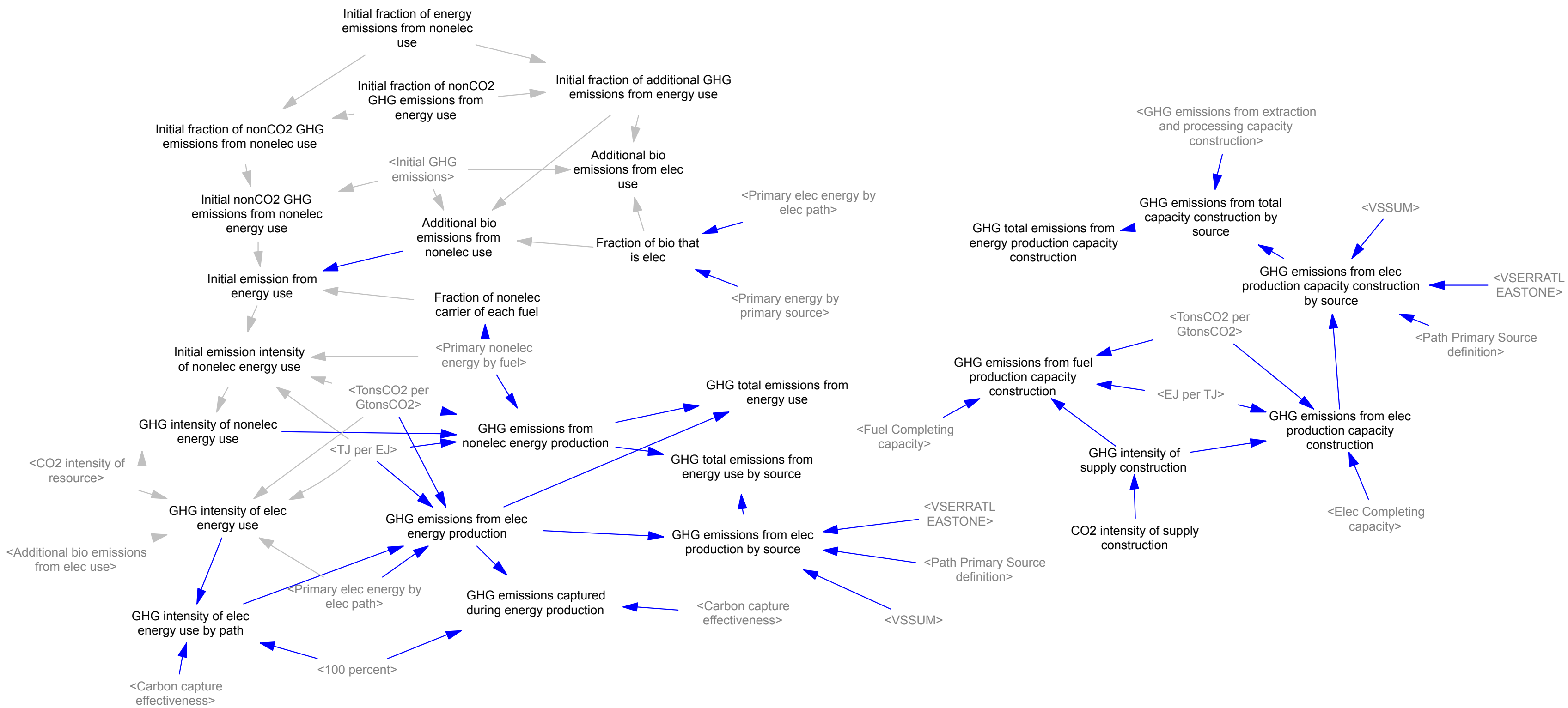


Figure 7-4 GHG Emissions from Extraction Phase

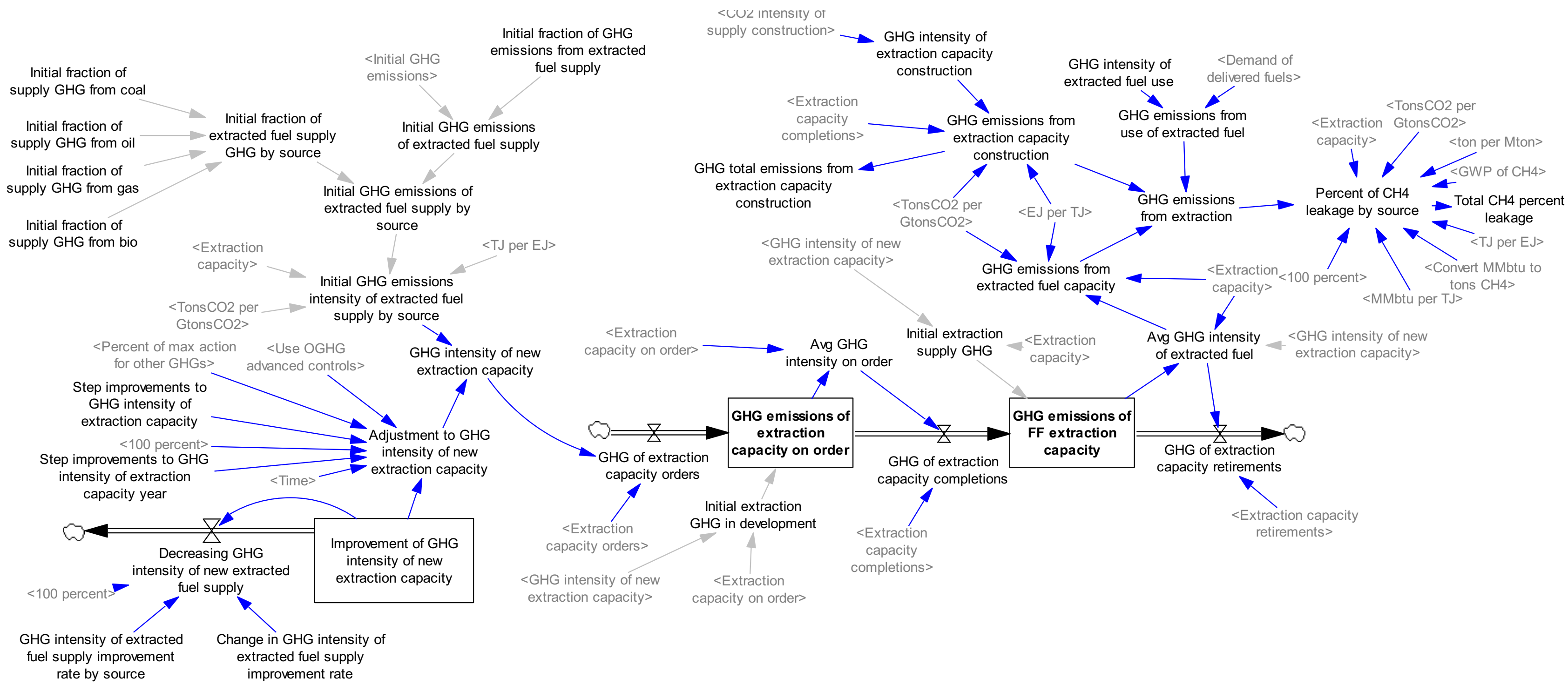


Figure 7-5 Aggregation of GHG Emissions from Energy Production

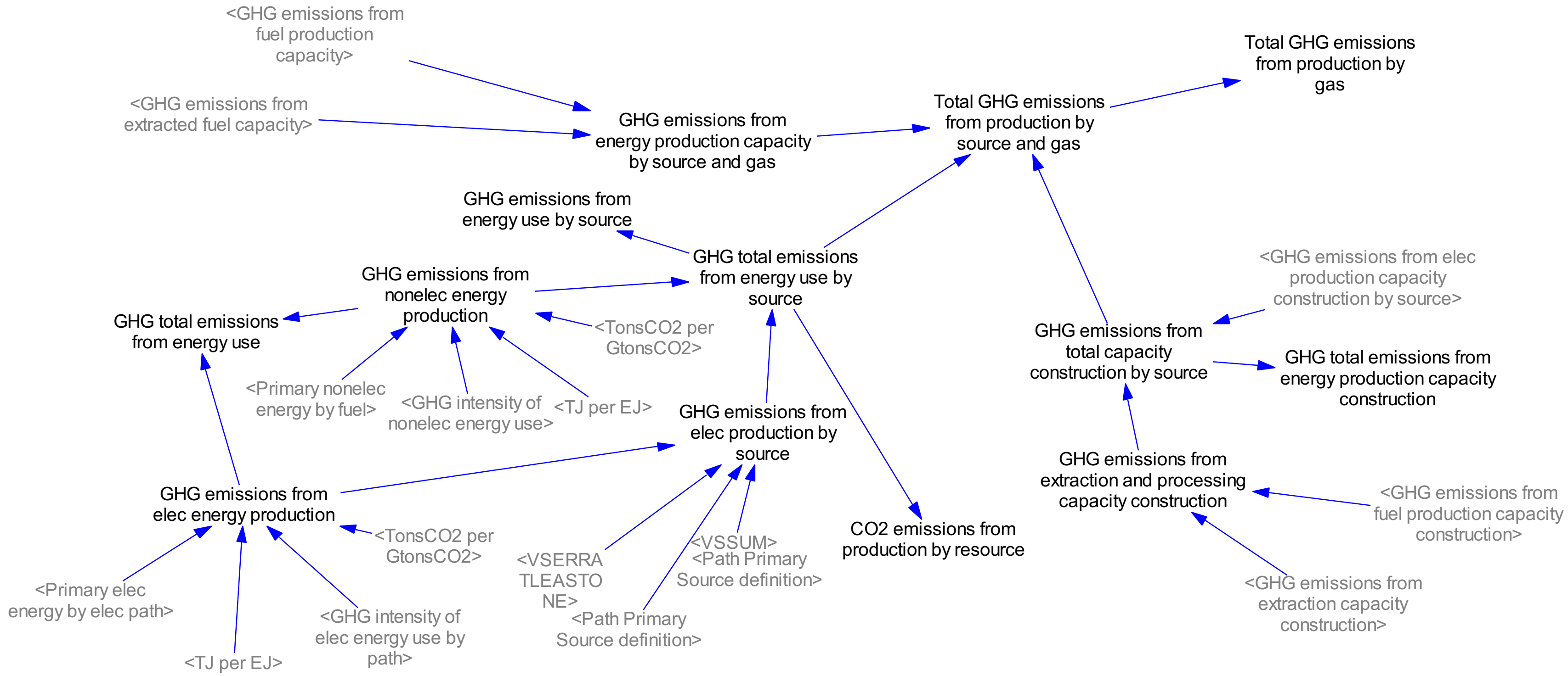


Table 7-1 Parametric Inputs to GHG Emissions from Delivered Fuel and Electricity Generation Use

Parameter	Definition	Range	Default Values	Units
CO2 intensity of energy production [Primary Energy Sources]	Mass of CO2 emitted for every MMBTU produced. Values for coal, oil, and gas are consistent with those from EIA's Carbon Dioxide Emissions Coefficients by Fuel. (2013). http://www.eia.gov/environment/emissions/co2_vol_mass.cfm			kgCO2/MMbtu
Coal		0-100	95	
Oil		0-100	70	
Gas		0-100	54	
Bio		0-100	60	
Nuclear		0-10	0	
Hydro		0-10	0	
Renewables		0-10	0	
New		0-10	0	
MMbtu per TJ	Conversion from millions BTU to terajoules. IEA http://www.iea.org/stats/unit.asp		947.8	MMbtu/TJ
kgCO2 per ton	Conversion of kilograms of CO_2 to tons of CO_2		1000	kgCO2/TonCO2
TonsCO2 per GtonsCO2	Conversion of tons CO_2 to gigatons CO_2.		1e+009	TonCO2/GtonCO2
EJ per TJ	Conversion of exajoules to terajoules.		1e-006	EJ/TJ
Adjustment to carbon intensity with conventional	Allows the user to change the emissions factor of conventional fuel at a specified year, e.g., different mix of various coal types.	0-1	0	Dmnl
Change in carbon intensity[Primary Fuels]		-1-2	0	Dmnl
Years to achieve discovery [Primary Fuels]		1-50	20	Years

Table 7-1 Parametric Inputs to GHG Emissions from Delivered Fuel and Electricity Generation Use

Parameter	Definition	Range	Default Values	Units
Time to start exploration [Primary Fuels [		2021-2100	2021	Year
Additional reserves discovered as factor of initial remaining [Primary Fuels]		0-5	0	Dmnl
Initial fraction of nonCO2 GHG emissions from energy use[Minor GHGs]	Initial fraction of the historical nonCO2 GHGs that come from combustion of fuel for energy. Assumes zero for F-gases.			
gCH_4			0.053,	
gN_2O			0.077	
F-Gases			0	
Initial fraction of energy emissions from nonelec use[Minor GHGs	Initial fraction of the the nonCO2 GHG emissions from energy use that comes from nonelectric consumption. Assumes 1 for F-gases.			
gCH_4			0.63	
gN_2O			0.75	
F-Gases			1	
CO2 intensity of supply construction	CO2 intensity of construction of supply capacity	0-50	10	TonCO2/TJ*Year
GHG intensity of delivered fuel supply capital[Primary Fuels]	GHG intensity of the capacity of delivered fuel. Defaults to zero to avoid double counting.		0	GtonsCO2/EJ

Table 7-1 Parametric Inputs to GHG Emissions from Delivered Fuel and Electricity Generation Use

Parameter	Definition	Range	Default Values	Units
GHG intensity of elec supply capital	GHG intensity of the capacity of electricity generation. Defaults to zero to avoid double counting.		0	GtonsCO2/EJ
Initial fraction of extracted fuel supply GHG by source[Primary Fuels, GHG type]	Fraction of GHG from extraction that comes from each fuel type. Defaults to only CH_4 being emitted from extraction. Calculated from 1990 data from PRIMAP 2019.			
Coal, gCH4			0.3	
Oil, gCH4			0.2	
Gas, gCH4			0.5	
All else			0	
Initial fraction of GHG emissions from extracted fuel supply[GHG type]	Initial fraction of the historical GHGs that come from the extraction of fuel. Defaults to zero for all GHGs except CH_4. Calculated from 1990 data from PRIMAP 2019.			Dmnl
gCH4			0.301	
All else			0	
GHG intensity of extracted fuel supply improvement rate by source[Primary Fuels]	Annual rate of extraction capacity GHG intensity improvement	-1-1	0	Percent/year
Change in GHG intensity of extracted fuel supply improvement rate	Change in the annual rate of GHG intensity improvement as additive of default.	-1-2	0	Dmnl

Table 7-1 Parametric Inputs to GHG Emissions from Delivered Fuel and Electricity Generation Use

Parameter	Definition	Range	Default Values	Units
Step improvements to GHG intensity of extraction capacity[Primary Fuels]	Adjusts the GHG intensity of extraction capacity	0-1	0	Dmnl
Step improvements to GHG intensity of extraction capacity year[Primary Fuels]	Year of step improvement to GHG intensity	2021-2100	2021	Year
GHG intensity of extracted fuel use[Primary Fuels, GHG type]	GHG intensity of use of extracted fuels. Defaults to 0 to avoid double counting.		0	GtonsCO2/EJ
Target change in other GHGs	Percent of maximum action of other GHGs (methane, N20, and the f-gases), where 0 reflects the baseline, i.e., no further action on non-CO_2 on drivers. Other GHG emissions from energy production may still be affected by the decisions driving energy paths.	-100-10	0	Percent
Target change in other GHGs for energy and industry	Percent of maximum action of other GHGs (methane, N20, and the f-gases) specific to energy and industry, where 0 reflects the baseline, i.e., no further action on non-CO_2 on drivers. Other GHG emissions from energy production may still be affected by the decisions driving energy paths.	-100-10	0	Percent

Table 7-1 Parametric Inputs to GHG Emissions from Delivered Fuel and Electricity Generation Use

Parameter	Definition	Range	Default Values	Units
"Use Ag/Waste and Energy/Industry OGHG controls"	When = 0, *Actual target change in other GHGs for energy and industry* and *Actual target change in other GHGs for Ag and Waste* are both set by *Target change in other GHGs*. Otherwise, *Actual target change in other GHGs for energy and industry* is set tby *Target change in other GHGs for energy and industry* and *Actual target change in other GHGs for Ag and Waste* is set by *Target change in other GHGs for ag and waste*	0-1	0	Dmnl

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
CO2 emissions from energy	The annual CO_2 emitted from production construction, capacity, and use from all the energy sources. SUM(CO2 emissions by source[Primary Energy Sources!])	GtonsCO2/Year
Original CO2 intensity of resource[Primary Energy Sources]	Carbon intensity of primary energy of each resource accounting for carbon capture effectiveness for the CCS paths. CO2 intensity of energy production[Primary Energy Sources]*MMbtu per TJ/kgCO2 per ton	TonCO2/TJ
Adjusted CO2 intensity of resource[Primary Energy Sources]	Adjusted carbon intensity of primary energy of each resource, accounting increases in intensity with unconventional fuel extraction.	TonCO2/TJ
[Primary energy fuel sources]	(1+ramp(Change in GHG intensity[Primary Fuels]/Years to achieve discovery[Primary Fuels],Time to start exploration[Primary Fuels], Time to start exploration[Primary Fuels]+Years to achieve discovery[Primary Fuels]))*Original CO2 intensity of resource[Primary energy fuel sources]	
[Primary elec only sources]	Original CO2 intensity of resource[Primary elec only sources]	
CO2 intensity of resource[Primary Energy Sources]	Adjusted CO2 intensity of resource[Primary Energy Sources]*Ratio unconventional to total[Primary Energy Sources]+IF THEN ELSE(Adjustment to GHG intensity with conventional , Adjusted CO2 intensity of resource[Primary Energy Sources], Original CO2 intensity of resource [Primary Energy Sources])*(1-Ratio unconventional to total[Primary Energy Sources])	
Ratio unconventional to total[Primary Energy Sources	Unconventional resource found[Primary Fuels]/Resource remaining total[Primary Fuels]	

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
[Primary energy fuel sources]	Unconventional resource found[Primary Fuels]/Resource remaining total[Primary Fuels]	
[Primary elec only sources]	1	
CO2 intensity of elec path[Elec Paths]	Carbon intensity of final energy in pathway, accounting for efficiency of each path and carbon capture effectiveness.	TonCO2/TJ
[All elec but CCS paths]	Adjusted CO2 intensity of resource[Primary Energy Sources]/Avg efficiency of elec supply [All elec but CCS paths]	
[CCS Paths]	Adjusted CO2 intensity of resource[Primary energy fuel sources]*(1-Carbon capture effectiveness[CCS Paths]/"100 percent")/Avg efficiency of elec supply [CCS Paths]	
CO2 intensity of resource[Primary Energy Sources]	Adjusted CO2 intensity of resource[Primary Energy Sources]*Ratio unconventional to total[Primary Energy Sources]+IF THEN ELSE(Adjustment to GHG intensity with conventional, Adjusted CO2 intensity of resource[Primary Energy Sources], Original CO2 intensity of resource[Primary Energy Sources])*(1-Ratio unconventional to total[Primary Energy Sources])	TonCO2/TJ
Initial fraction of nonCO2 GHG emissions from nonelec use[Minor GHGs]	Initial fraction of nonCO2 GHG emissions from energy use[Minor GHGs] * Initial fraction of energy emissions from nonelec use[Minor GHGs]	Dmnl
Initial fraction of additional GHG emissions from energy use [Minor GHGs]	Initial fraction of the historical nonCO2 GHGs that come from combustion of bioenergy use energy. Initial fraction of nonCO2 GHG emissions from energy use[Minor GHGs] * (1 - Initial fraction of energy emissions from nonelec use[Minor GHGs])	Dmnl
Initial nonCO2 GHG emissions from energy use[Minor GHGs]	Initial ratio of other GHG emissions (from PRIMAP, 2019) to initial other GHG emitting capital Initial fraction of nonCO2 GHG emissions from nonelec use[Minor GHGs]*Initial GHG emissions[Minor GHGs]	GtonsCO2eq/Year

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
Additional bio emissions from nonelec use[Minor GHGs]	Other GHG emissions from bio nonelec use. Initial GHG emissions[Minor GHGs]* Initial fraction of additional GHG emissions from energy use[Minor GHGs] * (1- Fraction of bio that is elec)	GtonsCO2/Year
Additional bio emissions from elec use[Minor GHGs]	Other GHG emissions from bio elec use. Initial GHG emissions[Minor GHGs] * Initial fraction of additional GHG emissions from energy use[Minor GHGs] * Fraction of bio that is elec	GtonsCO2/Year
Fraction of bio that is elec[Bio]	Fraction of bio that is for electric use. SUM(Primary elec energy by elec path[Elec bio!])/Primary energy by primary source[Primary bio]	Dmnl
Initial emission from energy use	Initial nonCO2 GHG emissions from nonelec energy use[Minor GHGs]*Fraction of nonelec carrier of each fuel[Primary FF]	
Initial nonCO2 GHG emissions from nonelec energy use[Primary Energy Sources,Minor GHGs]		GtonsCO2/Year
[Primary FF,Minor GHGs]	Initial fraction of nonCO2 GHG emissions from nonelec use[Minor GHGs]*Initial GHG emissions[Minor GHGs]	
[PBio,Minor GHGs]	Initial nonCO2 GHG emissions from nonelec energy use[Minor GHGs]*Fraction of nonelec carrier of each fuel[PBio]+Additional bio emissions from nonelec use[Minor GHGs]	
Fraction of nonelec carrier of each fuel[Primary Fuels]	Primary nonelec energy by fuel[Primary Fuels]/SUM(Primary nonelec energy by fuel[Primary Fuels!])	Dmnl
Initial emission intensity of nonelec energy use[Primary Fuels,Minor GHGs]	ZIDZ(Initial emission from energy use[Primary Fuels,Minor GHGs],Primary nonelec energy by fuel[Primary Fuels])*TonsCO2 per GtonsCO2/TJ per EJ	

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
GHG intensity of nonelec energy use[Primary Fuels, GHG type]	Brings CO2 intensity and minor GHG intensity of production use into one variable.	TonCO2/TJ
[Primary Fuels, gCO2]	CO2 intensity of resource[Primary energy fuel sources]	
[Primary Fuels, Minor GHGs]	Initial emission intensity of nonelec energy use[Primary Fuels,Minor GHGs]*Leakage effect[Primary Fuels,Minor GHGs]	
GHG intensity of elec energy use [Primary Energy Sources, GHG type]	Brings CO2 intensity and minor GHG intensity of production use into one variable.	TonCO2/TJ
[Primary Energy Source, gCO2]	CO2 intensity of resource[Primary Energy Sources]	
[Primary Energy Source, Minor GHGs]	Additional bio emissions from elec use[Minor GHGs]/SUM(Primary elec energy by elec path[Elec bio!])/TJ per EJ*TonsCO2 per GtonsCO2	
[Primary except bio,Minor GHGs]	0	
GHG emissions from elec energy production [Elec Paths, GHG type]	GHG emissions from each energy path as a product of intensity of primary energy and the primary energy of each path. Primary elec energy by elec path[Elec Paths]*GHG intensity of elec energy use by path[Elec Paths,GHG type]*TJ per EJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG emissions from nonelec energy production[Primary Fuels, GHG type]	Primary nonelec energy by fuel[Primary Fuels]*GHG intensity of nonelec energy use[Primary Fuels,GHG type]*TJ per EJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG total emissions from energy use[GHG type]	SUM(GHG emissions from elec energy production[Elec Paths!,GHG type])+SUM(GHG emissions from nonelec energy production[Primary Fuels!,GHG type])	GtonsCO2/Year
GHG total emissions from energy use by source[Primary Energy Sources		GtonsCO2/Year

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
[Primary energy fuel sources, GHG type]	GHG emissions from nonelec energy production[Primary Fuels,GHG type]+GHG emissions from elec production by source[Primary energy fuel sources,GHG type]	
[Primary elec only sources, GHG type]	GHG emissions from elec production by source[Primary elec only sources,GHG type]	
GHG emissions from elec production by source[Primary Energy Sources, GHG type]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],GHG emissions from elec energy production[Elec Paths!, GHG type],0,VSSUM,VSERRATLEASTONE)	GtonsCO2/Year
GHG emissions captured during energy production[CCS Paths, GHG type]	GHG emissions from elec energy production[CCS Paths,GHG type]/(1-Carbon capture effectiveness[CCS Paths]/"100 percent")	
CO2 captured by CCS	GHG emissions captured during energy production[CCS Paths,gCO2]	
[CCS Paths] :EXCEPT: [EBio CCS]	Net CDR by type[BECCS]	
GHG emissions from fuel production capacity[Primary Fuels, GHG type]	GHG intensity of delivered fuel supply capital[Primary Fuels]*Fuel supply capacity[Primary Fuels]*Leakage effect[Primary Fuels, GHG type]	GtonsCO2/Year
GHG emissions from elec production capacity construction by source[Primary Energy Sources, GHG type]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],GHG emissions from elec production capacity construction[Elec Paths!, GHG type], 0, VSSUM, VSERRATLEASTONE)	GtonsCO2/Year
GHG emissions from elec production capacity construction[Elec Paths, GHG type]	GHG intensity of supply construction [GHG type, Primary Energy Sources]*Elec Completing capacity[Elec Paths]/EJ per TJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG emissions from fuel production capacity construction[Primary Fuels, GHG type]	GHG intensity of supply construction [GHG type, Primary energy fuel sources]*Fuel Completing capacity[Primary Fuels]/EJ per TJ/TonsCO2 per GtonsCO2	GtonsCO2/Year

Table 7-2. GHG Emissions from Delivered Fuel and Electricity Generation Calculated Parameters

Parameter	Definition	Units
GHG total emissions from energy production capacity construction[GHG type]	SUM (GHG emissions from total capacity construction by source[Primary Energy Sources!,GHG type])	GtonsCO2/Year
Actual target change in other GHGs for energy and industry	IF THEN ELSE (Choose SSP Scenario > 0, - Selected SSP Target change in other GHGs , IF THEN ELSE ("Use Ag/Waste and Energy/Industry OGHG controls" , Target change in other GHGs for energy and industry , Target change in other GHGs))	Percent
Rate to achieve max action for other GHGs	LN (MAX (min ln term , 1+ Actual target change in other GHGs for energy and industry / "100 percent")) / MAX (One year , Time to achieve LULUCF and other GHG changes)	1/year

Table 7-3. GHG Emissions from Extraction Calculated Parameters

Parameter	Definition	Units
Initial GHG emissions of extracted fuel supply[GHG type]	Initial GHG emissions[GHG type]*Initial fraction of GHG emissions from extracted fuel supply[GHG type]	GtonsCO2eq/Year
Initial GHG emissions of extracted fuel supply by source[Primary Fuels, GHG type]	Initial fraction of extracted fuel supply GHG by source[Primary Fuels, GHG type]*Initial GHG emissions of extracted fuel supply[GHG type]	GtonsCO2eq/Year
Initial GHG emissions intensity of extracted fuel supply by source[Primary Fuels,GHG type]	Initial GHG emissions of extracted fuel supply by source[Primary Fuels, GHG type]/Extraction capacity[Primary Fuels]/TJ per EJ*TonsCO2 per GtonsCO2	TonCO2/TJ
GHG intensity of new extraction capacity[Primary Fuels,GHG type]	Initial GHG emissions intensity of extracted fuel supply by source[Primary Fuels,GHG type]*Adjustment to GHG intensity of new extraction capacity[Primary Fuels,GHG type]	TonCO2/TJ
Adjustment to GHG intensity of new extraction capacity[Primary Fuels,GHG type]	Adjusts GHG intensity. For Minor GHGs, affected by Percent of max action for other GHGs if Use OGHG advanced controls = 0, i.e., default.	Dmnl
Minor GHGs	Improvement of GHG intensity of new extraction capacity[Primary Fuels,Minor GHGs]*IF THEN ELSE(Use OGHG advanced controls=0 :AND:Time>Step improvements to GHG intensity of extraction capacity year[Primary Fuels], 1-Percent of max action for other GHGs/"100 percent",(1-STEP(Step improvements to GHG intensity of extraction capacity ,Step improvements to GHG intensity of extraction capacity year[Primary Fuels])))	

Table 7-3. GHG Emissions from Extraction Calculated Parameters

Parameter	Definition	Units
gCO2	Improvement of GHG intensity of new extraction capacity[Primary Fuels,gCO2]*(1-STEP(Step improvements to GHG intensity of extraction capacity ,Step improvements to GHG intensity of extraction capacity year[Primary Fuels]))	
Improvement of GHG intensity of new extraction capacity	INTEG(- Decreasing GHG intensity of new extracted fuel supply[Primary Fuels,GHG type], 1)	Dmnl
Decreasing GHG intensity of new extracted fuel supply[Primary Fuels,GHG type]	(IF THEN ELSE (Time < Other GHG emissions change start year , 0, - Rate to achieve max action for other GHGs) + (GHG intensity of extracted fuel supply improvement rate by source[Primary Fuels] + Change in GHG intensity of extracted fuel supply improvement rate)/ "100 percent") * Improvement of GHG intensity of new extraction capacity[Primary Fuels,GHG type]	1/year
GHG of extraction capacity orders[Primary Fuels,GHG type]	Extraction capacity orders[Primary Fuels]*GHG intensity of new extraction capacity[Primary Fuels,GHG type]	(TonCO2/TJ)*(EJ/Year)/Year
Initial extraction GHG in development[Primary Fuels,GHG type]	INITIAL(Extraction capacity on order[Primary Fuels]*GHG intensity of new extraction capacity[Primary Fuels,GHG type])	(TonCO2/TJ)*(EJ/Year)
Initial extraction supply GHG[Primary Fuels,GHG type]	INITIAL(Extraction capacity[Primary Fuels]*GHG intensity of new extraction capacity[Primary Fuels,GHG type])	(TonCO2/TJ)*(EJ/Year)
GHG emissions of extraction capacity on order [Primary Fuels,GHG type]	The extraction capacity for each extracted fuel on order. INTEG(GHG of extraction capacity orders[Primary Fuels,GHG type]-GHG of extraction capacity completions[Primary Fuels,GHG type], Initial extraction GHG in development[Primary Fuels,GHG type])	(TonCO2/TJ)*(EJ/Year)

Table 7-3. GHG Emissions from Extraction Calculated Parameters

Parameter	Definition	Units
GHG of extraction capacity completions[Primary Fuels,GHG type]	The amount of extraction capacity of each fuel that completes the construction process each year. Avg GHG intensity on order[Primary Fuels,GHG type]*Extraction capacity completions[Primary Fuels]	(TonCO2/TJ)*(EJ/Year)/Year
GHG emissions of FF extraction capacity[Primary Fuels, GHG type]	INTEG(GHG of extraction capacity completions[Primary Fuels,GHG type]-GHG of extraction capacity retirements[Primary Fuels,GHG type], Initial extraction supply GHG[Primary Fuels, GHG type])	(TonCO2/TJ)*(EJ/Year)
GHG of extraction capacity retirements[Primary Fuels,GHG type]	Avg GHG intensity of extracted fuel[Primary Fuels,GHG type]*Extraction capacity retirements[Primary Fuels]	(TonCO2/TJ)*(EJ/Year)/Year
Avg GHG intensity on order]Primary Fuels,GHG type]	Embodied GHG intensity of extraction capacity under development of each fuel path, locked in at that time. ZIDZ(GHG emissions of extraction capacity on order[Primary Fuels,GHG type], Extraction capacity on order[Primary Fuels])	TonCO2/TJ
Avg GHG intensity of extracted fuel	Embodied GHG intensity of extraction capacity of each fuel path, initialized to be the GHG intensity of new capacity. ACTIVE INITIAL(ZIDZ(GHG emissions of FF extraction capacity[Primary Fuels, GHG type],Extraction capacity[Primary Fuels]), GHG intensity of new extraction capacity[Primary Fuels,GHG type])	TonCO2/TJ
GHG emissions from extracted fuel capacity[Primary Fuels, GHG type]	Extraction capacity[Primary Fuels]*Avg GHG intensity of extracted fuel[Primary Fuels,GHG type]/EJ per TJ/TonsCO2 per GtonsCO2	GtonsCO2/Year

Table 7-3. GHG Emissions from Extraction Calculated Parameters

Parameter	Definition	Units
GHG emissions from extracted fuel capacity[Primary Fuels, GHG type]	Extraction capacity[Primary Fuels]*Avg GHG intensity of extracted fuel[Primary Fuels,GHG type]/EJ per TJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG intensity of extraction capacity construction		TonCO2/TJ*Year
gCO2	CO2 intensity of supply construction	
All else	0	
GHG emissions from extraction capacity construction[Primary Fuels, GHG type]	GHG intensity of extraction capacity construction [GHG type]*Extraction capacity completions[Primary Fuels]/EJ per TJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG total emissions from extraction capacity construction	SUM(GHG emissions from extraction capacity construction[Primary Fuels!,GHG type])	GtonsCO2/Year
GHG emissions from use of extracted fuel[Primary Fuels, GHG type]	GHG intensity of extracted fuel use[Primary Fuels,GHG type]*Demand of delivered fuels[Primary Fuels]	GtonsCO2/Year
GHG emissions from extraction[Primary Fuels, GHG type]	GHG emissions from use of extracted fuel[Primary Fuels, GHG type]+GHG emissions from extraction capacity construction[Primary Fuels,GHG type]+GHG emissions from extracted fuel capacity[Primary Fuels,GHG type]	GtonsCO2/Year

Table 7-3. GHG Emissions from Extraction Calculated Parameters

Parameter	Definition	Units
Percent of CH4 leakage by source	Natural gas that leaks into atmosphere, adding to global CH4 emissions. Assumes approximation of 100% natural gas = CH4. Includes leakage during mining, transportation, and distribution. GHG emissions from extraction[Primary Fuels, gCH4]/(Extraction capacity[Primary Fuels]*MMbtu per TJ*TJ per EJ/TonsCO2 per GtonsCO2*Convert MMbtu to tons CH4/ton per Mton)/(GWP of CH4 *ton per Mton)*"100 percent"	Percent
Total CH4 percent leakage	SUM (GHG emissions from extraction[Primary Fuels!,gCH4])/ (SUM (Extraction capacity[Primary Fuels!]) * MMbtu per TJ * TJ per EJ / TonsCO2 per GtonsCO2 * Convert MMbtu to tons CH4 / ton per Mton) / (GWP of CH4 * ton per Mton) * "100 percent"	Percent

Table 7-4. Aggregation of GHG Emissions from Energy Production

Parameter	Definition	Units
Total GHG emissions from production by gas	SUM(Total GHG emissions from production by source and gas[Primary Energy Sources!,GHG type])	GtonsCO2/Year
Total GHG emissions from production by source and gas[Primary Energy Sources,GHG type]	GHG emissions from energy production capacity by source and gas[Primary Energy Sources,GHG type]+GHG emissions from total capacity construction by source[Primary Energy Sources,GHG type]+GHG total emissions from energy use by source[Primary Energy Sources,GHG type]	GtonsCO2/Year
GHG emissions from energy production capacity by source and gas[Primary energy sources, GHG type]		GtonsCO2/Year
Primary energy fuel sources, GHG type	GHG emissions from fuel production capacity[Primary Fuels,GHG type]+GHG emissions from extracted fuel capacity [Primary Fuels, GHG type]	
Primary elec only sources, GHG type	0	
GHG total emissions from energy use by source [Primary energy sources, GHG type]		GtonsCO2/Year
Primary energy fuel sources, GHG type	GHG emissions from nonelec energy production[Primary Fuels,GHG type]+GHG emissions from elec production by source[Primary energy fuel sources,GHG type]	
Primary elec only sources, GHG type	GHG emissions from elec production by source[Primary elec only sources,GHG type]	
GHG emissions from total capacity construction by source[Primary energy sources, GHG type]		GtonsCO2/year

Table 7-4. Aggregation of GHG Emissions from Energy Production

Parameter	Definition	Units
Primary energy fuel sources, GHG type	GHG emissions from extraction and processing capacity construction[Primary Fuels,GHG type]+GHG emissions from elec production capacity construction by source[Primary energy fuel sources,GHG type]	
Primary elec only sources, GHG type	GHG emissions from elec production capacity construction by source[Primary elec only sources,GHG type]	
GHG emissions from extraction and processing capacity construction[Primary Fuels,GHG type]	GHG emissions from extraction capacity construction[Primary Fuels,GHG type]+GHG emissions from fuel production capacity construction[Primary Fuels,GHG type]	GtonsCO2/year
GHG total emissions from energy production capacity construction[GHG type]	SUM(GHG emissions from total capacity construction by source[Primary Energy Sources!,GHG type])	GtonsCO2/year
GHG emissions from elec production by source[Primary Energy Sources, GHG type]	VECTOR SELECT(Path Primary Source definition[Primary Energy Sources,Elec Paths!],GHG emissions from elec energy production[Elec Paths!, GHG type],0,VSSUM,VSERRATLEASTONE)	GtonsCO2/Year
GHG emissions from elec energy production[Elec Paths, GHG type]	Primary elec energy by elec path[Elec Paths]*GHG intensity of elec energy use by path[Elec Paths,GHG type]*TJ per EJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
GHG emissions from nonelec energy production[Primary Fuels, GHG type]	Primary nonelec energy by fuel[Primary Fuels]*GHG intensity of nonelec energy use[Primary Fuels,GHG type]*TJ per EJ/TonsCO2 per GtonsCO2	GtonsCO2/Year
CO2 emissions from production by resource [Primary Energy Sources]	GHG total emissions from energy use by source[Primary Energy Sources,gCO2]	GtonsCO2/Year

Figure 7-6 GHG Emissions from New End Use Capital

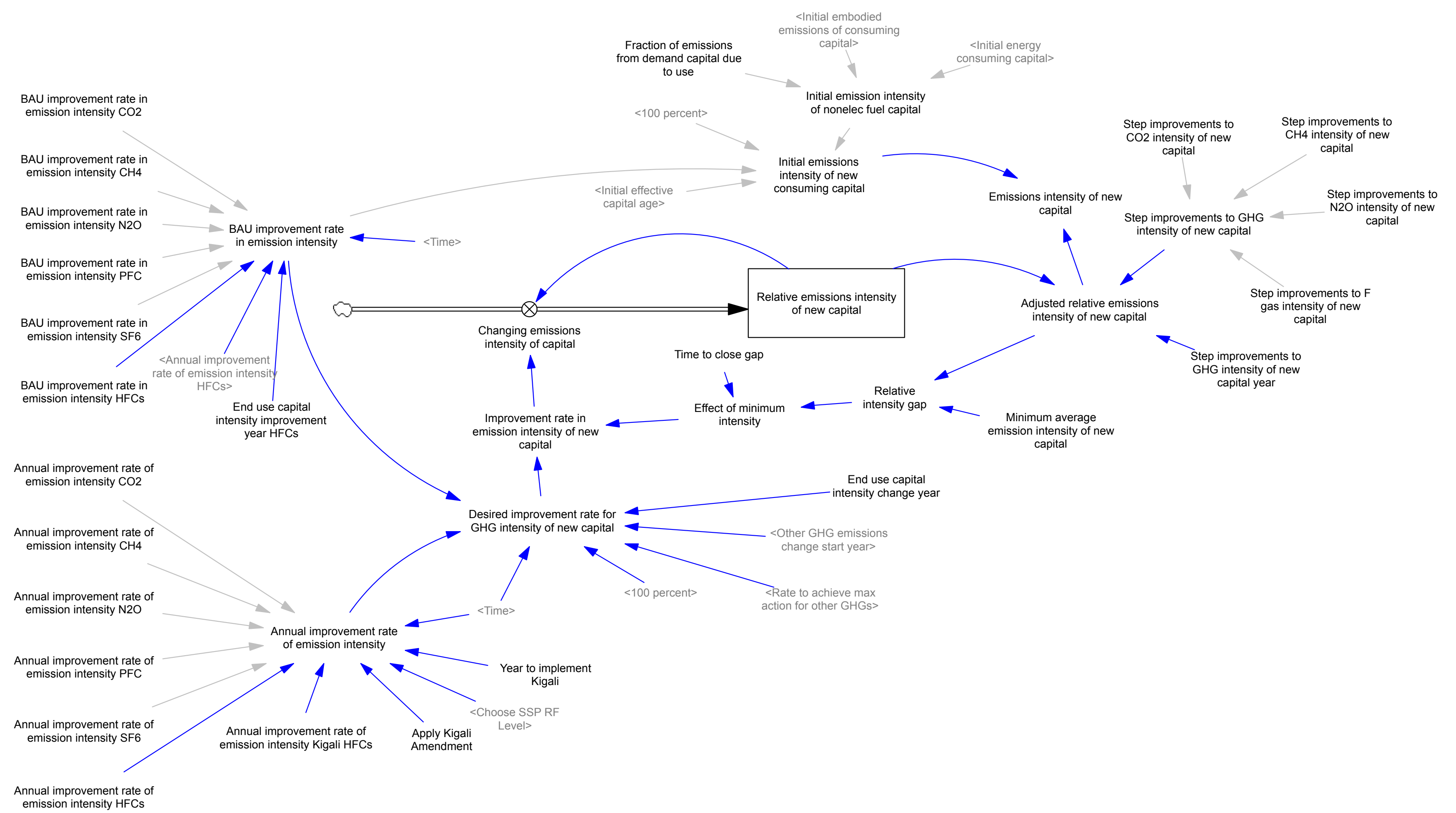


Figure 7-7 Embodied GHG Emissions from End Use Capital Before Retrofits

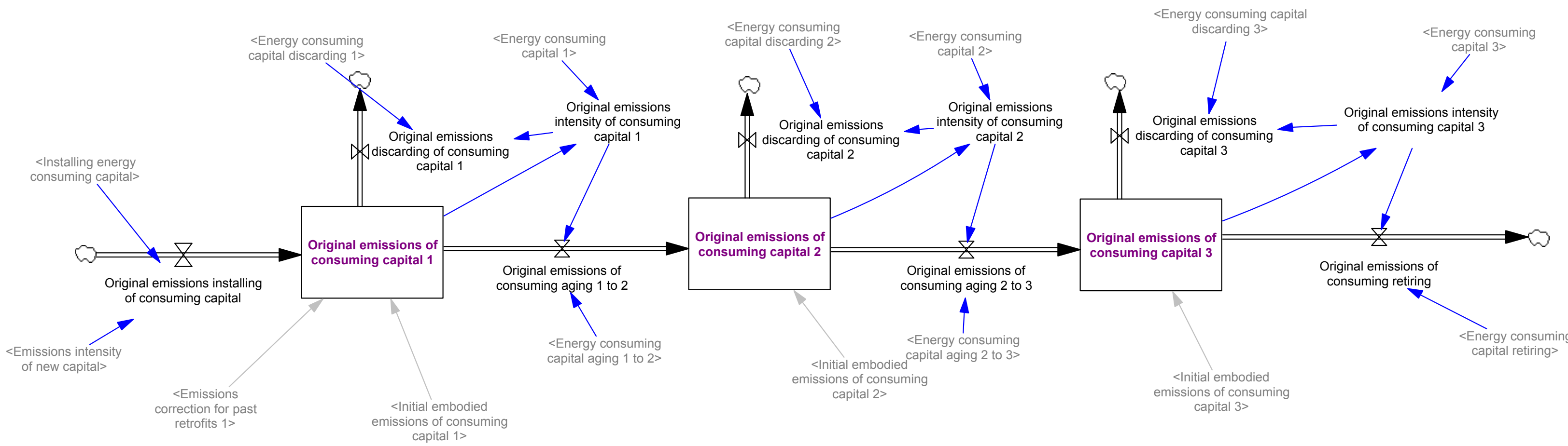


Figure 7-8 Embodied GHG Emissions from End Use Capital with Retrofits

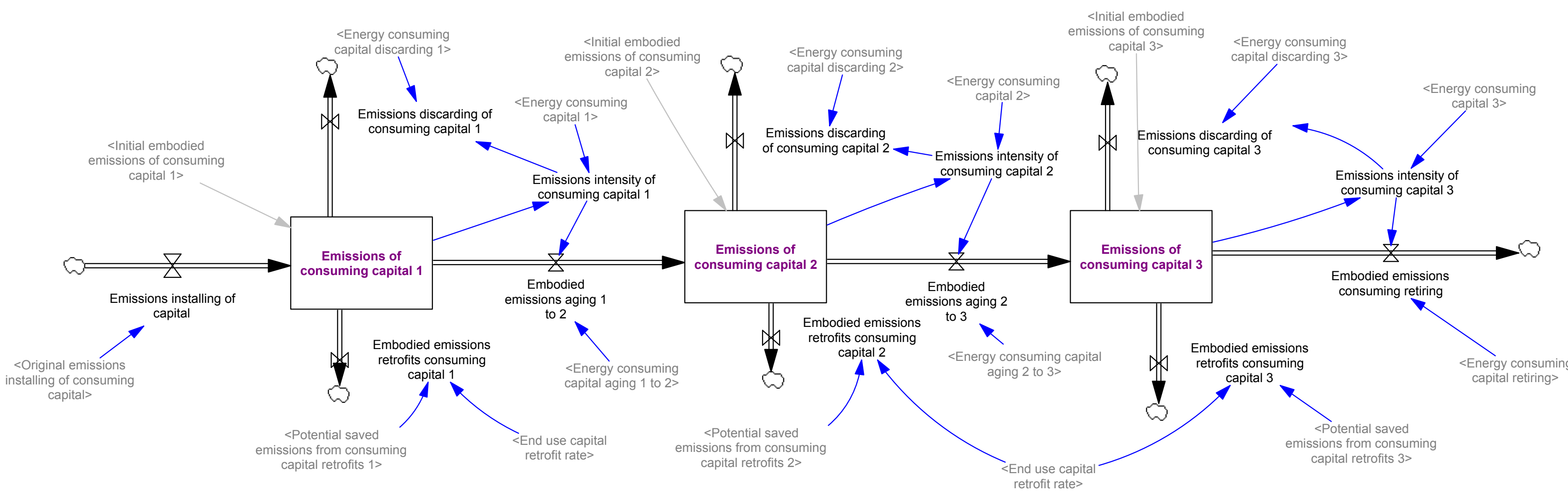


Figure 7-9 GHG Emissions from End Use Capital Construction, Capacity, and Use

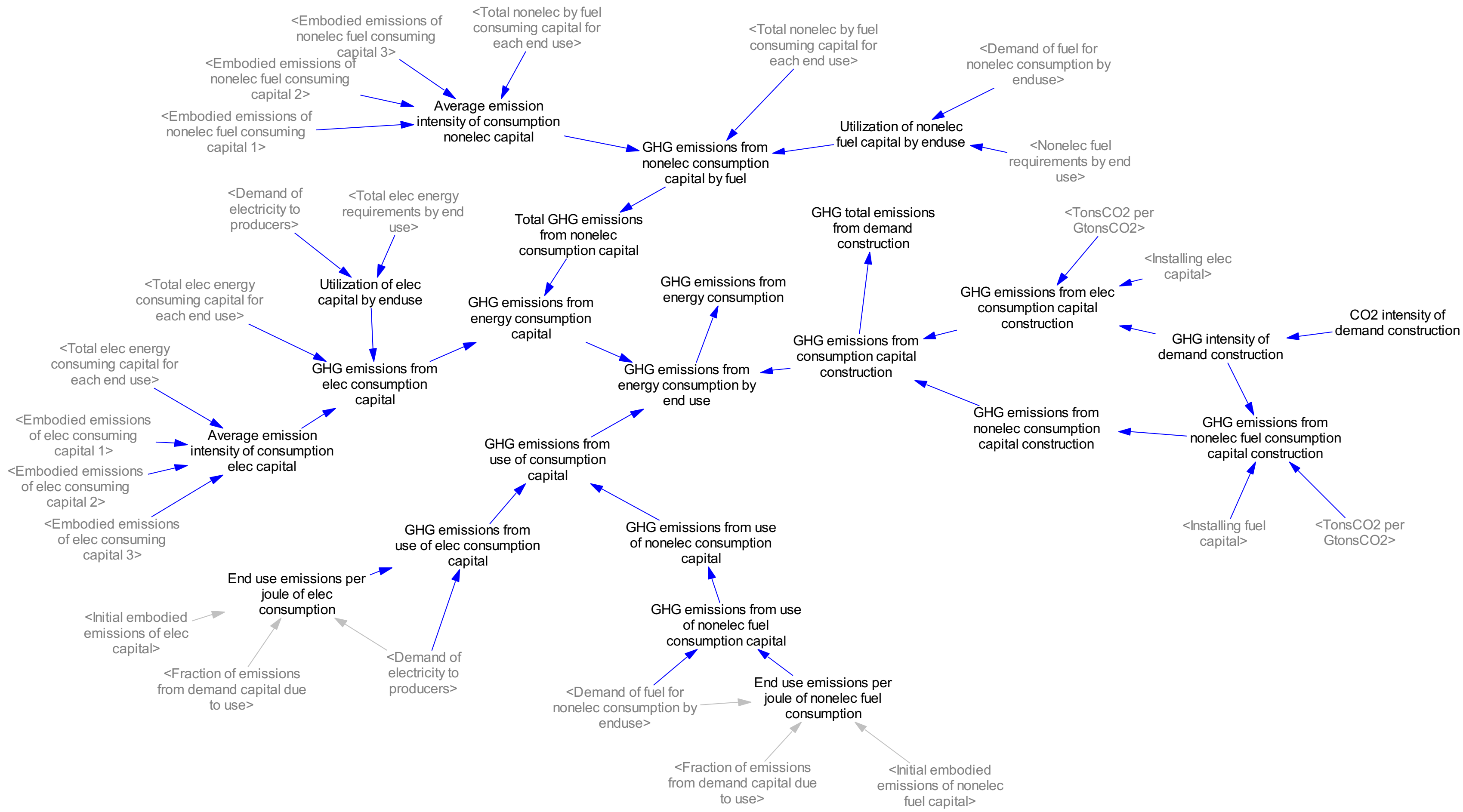


Figure 7-10 Parametric Inputs to GHG Emissions from New Energy-Consuming Capital

Parameter	Definition	Range	Default Values	Units
BAU improvement rate in emission intensity [GHG type]	Improvement rate in on emission intensity of new capital that emits GHG, without action	-1-5		percent/Year
gCO2			1	
gCH4			3	
gN2O			1	
gPFC			3	
gSF6			1	
gHFCs	IF THEN ELSE (Time < End use capital intensity improvement year HFCs , BAU improvement rate in emission intensity HFCs , Annual improvement rate of emission intensity HFCs)		-5	
End use capital intensity improvement year HFCs	Year when HFCs switch from growing to reducing at a Annual improvement rate of emission intensity HFCs		2010	year
Annual improvement rate of emission intensity[GHG type]	Improvement rate in emission intensity of new capital that emits GHG, after changing effort	-1-5		percent/Year
gCO2			1	
gCH4			2.5	
gN2O			1	
gPFC			0.5	
gSF6			0.5	
gHFCs			0.5	
Annual improvement rate of emission intensity Kigali HFCs	Improvement rate in HFC emissions intensity of new capital with Kigali Amendment enforced		10	percent/Year
Year to implement Kigali			2020	Year
Apply Kigali Amendment	Switch to turn on Kigali Amendment; defaults to not being enforced.	0-1	0	dmnl
Change in intensity of new capital for all nonCO2 GHGs			1	

Figure 7-10 Parametric Inputs to GHG Emissions from New Energy-Consuming Capital

Parameter	Definition	Range	Default Values	Units
End use capital intensity change year	Year to go from historic rates to annual projected rates, excluding changes from policies.		2020	Year
Time to close gap			10	Year
Minimum average emission intensity of new capital	The lowest emissions per unit of emitting capital achievable		0.05	Dmnl
Fraction of emissions from demand capital due to use			0.1	Dmnl
Step improvements to GHG intensity of new capital[GHG type]		0-1	0	Dmnl

Figure 7-11 GHG Emissions from New Energy-Consuming Capital Calculated Parameters

Parameter	Definition	Units
Effect of minimum intensity[EndUseSector,GHG type]	A soft minimum function to limit change in emission intensity as it nears it minimum Relative intensity gap[EndUseSector,GHG type]/Time to close gap	1/year
Relative intensity gap[EndUseSector,GHG type]	Adjusted relative emissions intensity of new capital[EndUseSector,GHG type]/Minimum average emission intensity of new capital-1	Dmnl
Improvement rate in emission intensity of new capital [EndUseSector,GHG type]	Progress (or degradation if negative) rate of emission intensity of new capital in other GHG MIN(Desired improvement rate for GHG intensity of new capital [GHG type], Effect of minimum intensity [EndUseSector,GHG type])	1/year
Desired improvement rate for GHG intensity of new capital[GHG type]		1/year
[CO2]	IF THEN ELSE (Time < End use capital intensity change year , BAU improvement rate in emission intensity[gCO2] , Annual improvement rate of emission intensity[gCO2]) / "100 percent"	
[All but CO2]	IF THEN ELSE (Time < End use capital intensity change year , BAU improvement rate in emission intensity[GHG type] / "100 percent" , Annual improvement rate of emission intensity[GHG type] / "100 percent" - IF THEN ELSE (Time < Other GHG emissions change start year , 0, Rate to achieve max action for other GHGs))	
Annual improvement rate of emission intensity[GHG type]		percent/Year
All GHGs but HFCs	Annual improvement rate of emission intensity XXX	

Figure 7-11 GHG Emissions from New Energy-Consuming Capital Calculated Parameters

Parameter	Definition	Units
[HFCs]	IF THEN ELSE(Apply Kigali Amendment :AND:Time>Year to implement Kigali, Annual improvement rate of emission intensity Kigali HFCs, Annual improvement rate of emission intensity HFCs)	
Changing emissions intensity of capital[EndUseSector,GHG type]	Relative emissions intensity of new capital[EndUseSector,GHG type]*-Improvement rate in emission intensity of new capital[EndUseSector,GHG type]	1/Year
Relative emissions intensity of new capital[EndUseSector,GHG type]	The emissions intensity, i.e., GHGs per unit of capital, by end use sector, of new capital as a function of changes to technolgy to reduce leaks and off-gassing INTEG(Changing emissions intensity of capital[EndUseSector,GHG type], 1)	Dmnl
Adjusted relative emissions intensity of new capital[EndUseSector,GHG type]	Relative emissions intensity of new capital[EndUseSector,GHG type]*(1-STEP(Step improvements to GHG intensity of new capital[GHG type], Step improvements to GHG intensity of new capital year))	Dmnl
Initial embodied emissions of consuming capital [EndUseSector, Carriers, GHG type]	Initial embodied emissions of consuming capital	GtonsCO2eq/Year
NonElec Carriers	Initial GHG emissions[GHG type] * Initial fraction of GHG emissions from demand capital[GHG type] * Fraction of capital emissions from each end use[EndUseSector,GHG type] * New carrier share of end use[EndUseSector,NonElec Carriers] * (1 - Fraction of emissions from demand capital due to use)	

Figure 7-11 GHG Emissions from New Energy-Consuming Capital Calculated Parameters

Parameter	Definition	Units
Electric Carrier	Initial GHG emissions[GHG type] * Initial fraction of GHG emissions from demand capital[GHG type] * Fraction of capital emissions from each end use[EndUseSector,GHG type] * New carrier share of end use[EndUseSector,Electric Carrier] * (1 - Fraction of emissions from demand capital due to use)	
Initial emission intensity of capital [EndUseSector, Carrier, GHG type]	Initial ratio of other GHG emissions expected per unit of other GHG emiting capital ZIDZ (Initial embodied emissions of consuming capital[EndUseSector,Carrier,GHG type] , Initial energy consuming capital[EndUseSector]* (1 - Fraction of emissions from demand capital due to use))	GtonsCO2eq/(Year*T$ 2017 PPP)
Initial emissions intensity of new consuming capital [EndUseSector, Carrier, GHG type]	Initial emission intensity of capital[EndUseSector,Carrier,GHG type] * EXP (- BAU improvement rate in emission intensity[GHG type] / "100 percent" * Initial effective capital age[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Emissions intensity of new capital [EndUseSector, Carrier, GHG type]	Adjusted relative emissions intensity of new capital [EndUseSector, GHG type] * Initial emissions intensity of new consuming capital[EndUseSector, Carrier, GHG type]	GtonsCO2eq/(Year*T$ 2017 PPP)

Figure 7-12 GHG Emissions from Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Initial embodied emissions of consuming capital 1[EndUseSector, Carrier, GHG type]	Initial embodied emissions of consuming capital[EndUseSector, Carrier, GHG type] * Fraction initial emissions in vintage 1[EndUseSector, GHG type]	GtonsCO2eq/Year
Initial embodied emissions of consuming capital 2[EndUseSector, Carrier, GHG type]	Initial embodied emissions of consuming capital[EndUseSector, Carrier, GHG type] * Fraction initial emissions in vintage 2[EndUseSector, GHG type]	GtonsCO2eq/Year
Initial embodied emissions of consuming capital 3[EndUseSector, Carrier, GHG type]	Initial embodied emissions of consuming capital[EndUseSector, Carrier, GHG type] * Fraction initial emissions in vintage 3[EndUseSector, GHG type]	GtonsCO2eq/Year
Original emissions installing of consuming capital [EndUseSector, Carrier, GHG type]	Emissions intensity of new capital[EndUseSector,Carrier,GHG type] * Installing energy consuming capital[EndUseSector]	GtonsCO2eq/(Year*Year)
Original emissions of consuming capital 1 [EndUseSector, Carrier, GHG type]	INTEG(Original emissions installing of consuming capital[EndUseSector, Carrier, GHG type] - Original emissions of consuming aging 1 to 2[EndUseSector, Carrier, GHG type] - Original emissions discarding of consuming capital 1[EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 1[EndUseSector, Carrier, GHG type] * Emissions correction for past retrofits 1[EndUseSector,GHG type])	GtonsCO2eq/Year
Original emissions intensity of consuming capital 1 [EndUseSector, Carrier, GHG type]	ZIDZ (Original emissions of consuming capital 1[EndUseSector, Carrier, GHG type] , Energy consuming capital 1[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)

Figure 7-12 GHG Emissions from Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Original emissions discarding of consuming capital 1 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 1[EndUseSector,Carrier,GHG type] * Energy consuming capital discarding 1[EndUseSector]	GtonsCO2eq/(Year*Year)
Original emissions of consuming aging 1 to 2 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 1[EndUseSector,Carrier,GHG type] * Energy consuming capital aging 1 to 2[EndUseSector]	GtonsCO2eq/(Year*Year)
Original emissions of consuming capital 2 [EndUseSector, Carrier, GHG type]	INTEG(Original emissions of consuming aging 1 to 2[EndUseSector, Carrier, GHG type] - Original emissions of consuming aging 2 to 3[EndUseSector, Carrier, GHG type] - Original emissions discarding of consuming capital 2 [EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 2 [EndUseSector, Carrier, GHG type])	GtonsCO2eq/Year
Original emissions intensity of consuming capital 2 [EndUseSector, Carrier, GHG type]	ZIDZ (Original emissions of consuming capital 2[EndUseSector,Carrier,GHG type] , Energy consuming capital 2[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Original emissions discarding of consuming capital 2 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 2[EndUseSector,Carrier,GHG type] * Energy consuming capital discarding 2[EndUseSector]	GtonsCO2eq/(Year*Year)
Original emissions of consuming aging 2 to 3 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 2[EndUseSector,Carrier,GHG type] * Energy consuming capital aging 2 to 3[EndUseSector]	GtonsCO2eq/(Year*Year)

Figure 7-12 GHG Emissions from Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Original emissions of consuming capital 3 [EndUseSector, Carrier, GHG type]	INTEG(Original emissions of consuming aging 2 to 3[EndUseSector, Carrier, GHG type] - Original emissions of consuming retiring[EndUseSector, Carrier, GHG type] - Original emissions discarding of consuming capital 3 [EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 3 [EndUseSector, Carrier, GHG type])	GtonsCO2eq/Year
Original emissions intensity of consuming capital 3 [EndUseSector, Carrier, GHG type]	ZIDZ (Original emissions of consuming capital 3[EndUseSector, Carrier ,GHG type] , Energy consuming capital 3[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Original emissions discarding of consuming capital 2 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 2[EndUseSector,Carrier,GHG type] * Energy consuming capital discarding 2[EndUseSector]	GtonsCO2eq/(Year*Year)
Original emissions of consuming aging 1 to 2 [EndUseSector, Carrier, GHG type]	Original emissions intensity of consuming capital 2[EndUseSector,Carrier,GHG type] * Energy consuming capital aging 2 to 3[EndUseSector]	GtonsCO2eq/(Year*Year)
Emissions installing of capital [EndUseSector, Carrier, GHG type]	Original emissions installing of consuming capital[EndUseSector,Carrier,GHG type]	GtonsCO2eq/(Year*Year)
Emissions of consuming capital 1[EndUseSector, Carrier, GHG type]	INTEG(Emissions installing of capital[EndUseSector, Carrier, GHG type] - Embodied emissions aging 1 to 2[EndUseSector, Carrier, GHG type] - Emissions discarding of consuming capital 1[EndUseSector, Carrier,GHG type] - Embodied emissions retrofits consuming capital 1[EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 1[EndUseSector, Carrier, GHG type])	GtonsCO2eq/Year

Figure 7-12 GHG Emissions from Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Emissions intensity of consuming capital 1[EndUseSector, Carrier, GHG type]	ZIDZ (Emissions of consuming capital 1[EndUseSector, Carrier, GHG type] , Energy consuming capital 1[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Emissions discarding of consuming capital 1[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 1[EndUseSector, Carrier, GHG type] * Energy consuming capital discarding 1[EndUseSector]	GtonsCO2eq/(Year*Year)
Embodied emissions aging 1 to 2[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 1[EndUseSector, Carrier, GHG type] * Energy consuming capital aging 1 to 2[EndUseSector]	GtonsCO2eq/(Year*Year)
Embodied emissions retrofits consuming capital 1[EndUseSector, Carrier, GHG type]	End use capital retrofit rate * Potential saved emissions from consuming capital retrofits 1[EndUseSector, Carrier, GHG type]	GtonsCO2eq/(Year*Year)
Emissions of consuming capital 2[EndUseSector, Carrier, GHG type]	INTEG(Embodied emissions aging 1 to 2[EndUseSector, Carrier, GHG type] - Embodied emissions aging 2 to 3[EndUseSector, Carrier, GHG type] - Emissions discarding of consuming capital 2[EndUseSector, Carrier,GHG type] - Embodied emissions retrofits consuming capital 2[EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 2[EndUseSector, Carrier, GHG type])	GtonsCO2eq/Year
Emissions intensity of consuming capital 2[EndUseSector, Carrier, GHG type]	ZIDZ (Emissions of consuming capital 2[EndUseSector, Carrier, GHG type] , Energy consuming capital 2[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Emissions discarding of consuming capital 2[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 2[EndUseSector, Carrier, GHG type] * Energy consuming capital discarding 2[EndUseSector]	GtonsCO2eq/(Year*Year)
Embodied emissions aging 2 to 3[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 2[EndUseSector, Carrier, GHG type] * Energy consuming capital aging 2 to 3[EndUseSector]	GtonsCO2eq/(Year*Year)

Figure 7-12 GHG Emissions from Energy Consuming Capital Calculated Parameters

Parameter	Definition	Units
Embodied emissions retrofits consuming capital 2[EndUseSector, Carrier, GHG type]	End use capital retrofit rate * Potential saved emissions from consuming capital retrofits 2[EndUseSector,Carrier,GHG type]	GtonsCO2eq/(Year*Year)
Emissions of consuming capital 2[EndUseSector, Carrier, GHG type]	INTEG(Embodied emissions aging 2 to 3[EndUseSector, Carrier, GHG type] - Embodied emissions consuming retiring [EndUseSector, Carrier, GHG type] - Emissions discarding of consuming capital 3[EndUseSector, Carrier,GHG type] - Embodied emissions retrofits consuming capital 3[EndUseSector, Carrier, GHG type], Initial embodied emissions of consuming capital 3[EndUseSector, Carrier, GHG type])	GtonsCO2eq/Year
Emissions intensity of consuming capital 3[EndUseSector, Carrier, GHG type]	ZIDZ (Emissions of consuming capital 3[EndUseSector, Carrier, GHG type] , Energy consuming capital 3[EndUseSector])	GtonsCO2eq/(Year*T$ 2017 PPP)
Emissions discarding of consuming capital 3[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 3[EndUseSector, Carrier, GHG type] * Energy consuming capital discarding 3[EndUseSector]	GtonsCO2eq/(Year*Year)
Embodied emissions consuming retiring[EndUseSector, Carrier, GHG type]	Emissions intensity of consuming capital 3[EndUseSector, Carrier, GHG type] * Energy consuming capital retiring[EndUseSector]	GtonsCO2eq/(Year*Year)
Embodied emissions retrofits consuming capital 3[EndUseSector, Carrier, GHG type]	End use capital retrofit rate * Potential saved emissions from consuming capital retrofits 3[EndUseSector,Carrier,GHG type]	GtonsCO2eq/(Year*Year)

Figure 7-13 GHG Emissions from Agriculture and Waste

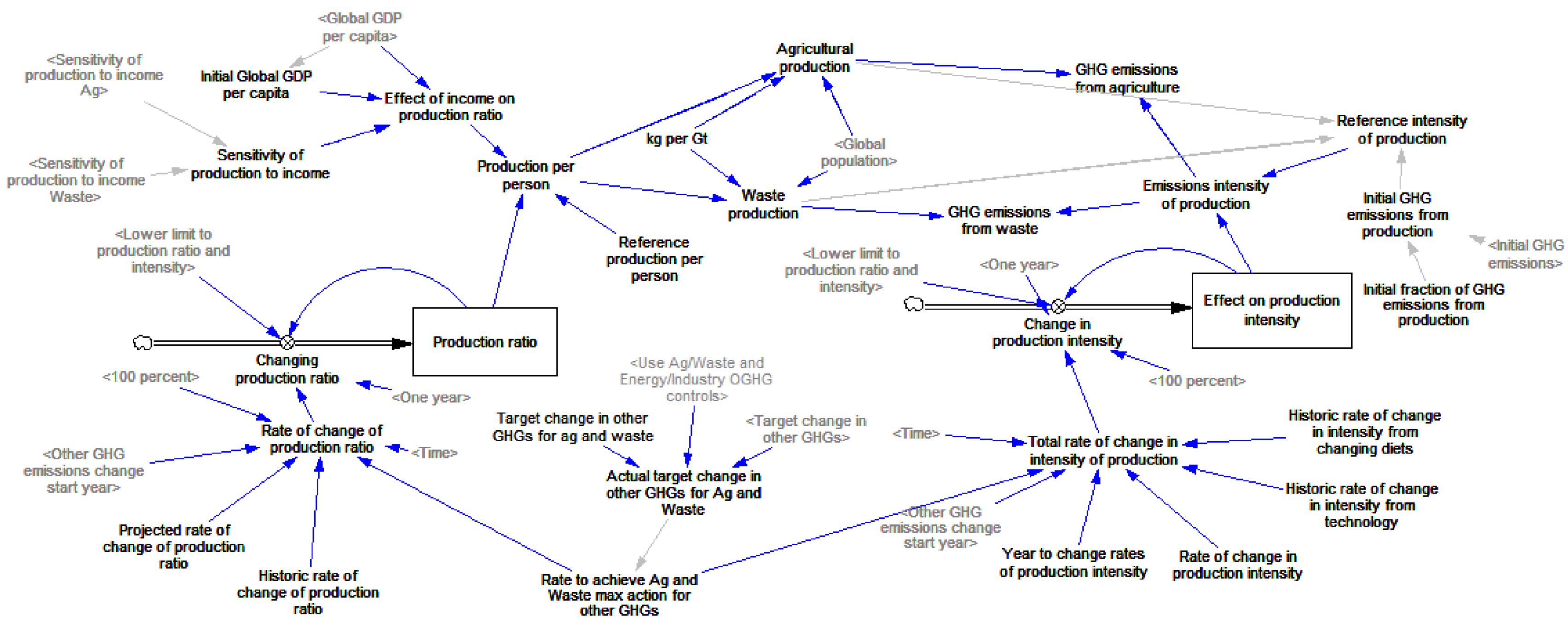


Figure 7-14 Parametric Inputs to GHG Emissions from Agriculture and Waste

Parameter	Definition	Range	Default Values	Units
Reference production per person[ProductionSector]	Food: 1.52kg/day (http://www.nationalgeographic.com/what-the-world-eats/ in 1990) * 365 = 555 Waste 1.2kg/day MSW (http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/Chap3.pdf) *365 = 438			
Agriculture			555	
Waste			438	
Year to change production ratio	Year to change the production ratio rates of change.	2021-2100	2021	Year
Historic rate of change of production ratio[ProductionSector]	Historic percent change in agriculture or waste per person per year from reducing losses, eg refrigerated storage, faster transit, etc	-100-0		Percent/year
Agriculture			-.05	
Waste			-0.1	
Projected rate of change of agriculture production ratio[ProductionSector]	Percent change in agriculture or waste per person per year from reducing losses, eg refrigerated storage, faster transit, etc	-100-0	-0.2	Percent/year
Year to change rates of production intensity	Year to change the production intensity rates of change.	2021-2100	2021	Year
Historic rate of change in intensity from changing diets [ProductionSector, GHG type]	Historic percent change per year in emissions per unit of agriculture or waste due to changing behavior and preferences, such as reducing meat, organic agriculture, reducing waste etc.		0	percent/Year

Figure 7-14 Parametric Inputs to GHG Emissions from Agriculture and Waste

Parameter	Definition	Range	Default Values	Units
Historic rate of change in intensity from technology [ProductionSector, GHG Type]	Historic percent change per year in emissions per unit of agriculture or waste due to changing availability or adoption of technological solutions, e.g. manure management, fertilizer efficiency, waste treatment, landfill gas capture	-100-0	0	Percent/year
Agriculture, CH4			-0.5	
Agriculture, N2O			-0.1	
All else			0	
Rate of change in agriculture production intensity[GHG Type]	Percent change per year in emissions per unit of agriculture production, starting in the year to change rates of production intensity.	-100-0		Percent/year
CH4			-0.1	
CO2, N2O, F-Gases			0	
Rate of change in waste production intensity[GHG Type]	Percent change per year in emissions per unit of waste production, starting in the year to change rates of production intensity.	-100-0	0	Percent/year
Initial fraction of GHG emissions from production [ProductionSector, GHG type]	Initial fraction of total emissions of each GHG that comes from each production sector. Calculated from 1990 data from PRIMAP 2019. Assumes Agriculture includes PRIMAP MAG and LU categories, and Waste includes PRIMAP Waste and Other categories.			Dmnl
Agriculture, gCH4			0.469	
Agriculture, gN2O			0.756	
Waste, gCH4			0.178	
Waste, gN2O			0.076	
All else			0	

Figure 7-14 Parametric Inputs to GHG Emissions from Agriculture and Waste

Parameter	Definition	Range	Default Values	Units
Sensitivity of production to income[ProductionSector]	Sensitivity of agriculture or waste production to changes in per capital GDP - if zero, production is purely proportional to population, if 1 production is proprtional to GDP	0-1	0	Dmnl
Other emissions start year	Year to start the change in rates of the other GHG reductions.	2021-2100	2021	year
Other emissions target year	Year to achieve the change in rates of the other GHG reductions.	2021-2100	2050	year
kg per Gt			1e12	kg/Gt

Figure 7-15 GHG Emissions from Agriculture and Waste Production Calculated Parameters

Parameter	Definition	Units
Effect of income on production ratio[ProductionSector]	Multiplier on per person production of waste or agriculture reflecting changes in per person GDP (Global GDP per capita /INIT(Global GDP per capita))^Sensitivity of production to income[ProductionSector]	Dmnl
Production per person[ProductionSector]	Production of agriculture or waste per person per year Reference production per person[ProductionSector]*Effect of income on production ratio[ProductionSector]*Production ratio[ProductionSector]	kg/(Year*person)
Agricultural production	Production of agriculture in tons for calculating agricultural emissions Global population *Production per person[Agriculture]/kg per Gt	Gt/Year
Waste production	Production of waste in aggregate mass per year for calculating emissions related to sewage, landfill, etc Global population *Production per person[Waste]/kg per Gt	Gt/Year
Production ratio[ProductionSector]	Multiplier on waste or agriculture produced per person reflecting changes to the mix of food systems, waste attitudes, storage and transit efficiency compared to initial conditions INTEG(Changing production ratio[ProductionSector], 1)	Dmnl
Changing production ratio[ProductionSector]	Change in production of agriculture and waste from factors other than income MAX (Rate of change of production ratio[ProductionSector] * Production ratio[ProductionSector] , MIN (0, (Lower limit to production ratio and intensity[ProductionSector] - Production ratio[ProductionSector]) / One year))	1/year

Figure 7-15 GHG Emissions from Agriculture and Waste Production Calculated Parameters

Parameter	Definition	Units
Rate of change of production ratio[ProductionSector]	IF THEN ELSE (Time <= Other GHG emissions change start year , Historic rate of change of production ratio[ProductionSector] , (Rate to achieve Ag and Waste max action for other GHGs[ProductionSector] + Projected rate of change of production ratio[ProductionSector])) / "100 percent"	percent/year
Rate of change in production intensity[ProductionSector, GHG type]		percent/year
[Agriculture, GHG type]	Rate of change in agriculture production intensity[GHG type]	
[Waste, GHG type]	Rate of change in waste production intensity[GHG type]	
Total rate of change in intensity of production[ProductionSector, GHG type]]	Total percent change per year in emissions intensity of agriculture and waste due to technology and behavior. If Use OGHG advanced controls=0 (default), this rate is the negative of the Percent of max action for other GHGs	percent/year
ProductionSector,Minor GHGs	IF THEN ELSE (Time < Other GHG emissions change start year , Historic rate of change in intensity from changing diets[ProductionSector,Minor GHGs] + Historic rate of change in intensity from technology[ProductionSector,Minor GHGs] , Rate to achieve Ag and Waste max action for other GHGs[ProductionSector] + Rate of change in production intensity[ProductionSector,Minor GHGs])	
ProductionSector,gCO2	IF THEN ELSE (Time < Year to change rates of production intensity , Historic rate of change in intensity from changing diets[ProductionSector,gCO2] + Historic rate of change in intensity from technology[ProductionSector,gCO2] , Rate of change in production intensity[ProductionSector,gCO2])	

Figure 7-15 GHG Emissions from Agriculture and Waste Production Calculated Parameters

Parameter	Definition	Units
Rate to achieve Ag and Waste max action for other GHGs	Rate per year to achieve the maximum action for other GHGs by the target year. LN (MAX (min ln term , MAX (1+ Actual target change in other GHGs for Ag and Waste / "100 percent" , Lower limit to production ratio and intensity[ProductionSector]))) / MAX (One year , Time to achieve LULUCF and other GHG changes) * "100 percent"	Percent/Year
Actual target change in other GHGs for Ag and Waste	IF THEN ELSE (Choose SSP RF Level > 0, - Selected SSP Target change in other GHGs , IF THEN ELSE ("Use Ag/Waste and Energy/Industry OGHG controls" , Target change in other GHGs for ag and waste , Target change in other GHGs))	
Effect on production intensity [ProductionSector,GHG type]	Multiplier to calculate emissions from agriculture and waste reflecting changes in practices, use or availablitiy of technology INTEG(Change in production intensity[ProductionSector,GHG type], 1)	Dmnl
Change in production intensity [ProductionSector,GHG type]	Annual change in emissions intensity of agriculture aand waste due to behavior and technology Total rate of change in intensity of production[ProductionSector,GHG type]/"100 percent"*Effect on production intensity[ProductionSector,GHG type]	1/year
Initial GHG emissions from production [ProductionSector,GHG type]		GtonsCO2eq/Year
Reference intensity of production [ProductionSector,GHG type]	Reference emissions per unit of production from agriculture and waste in terms of CO2eq. Defaults to 0 for all but CH4 and N2O.	GtonsCO2eq/Gt

Figure 7-15 GHG Emissions from Agriculture and Waste Production Calculated Parameters

Parameter	Definition	Units
Agriculture,GHG type	Initial GHG emissions from production[Agriculture,GHG type]/Agricultural production	
Waste, GHG type	Initial GHG emissions from production[Waste,GHG type]/Waste production	
Emissions intensity of production [ProductionSector,GHG type]	Emissions per unit of production from agriculture and waste in terms of CO2eq. Defaults to 0 for all but CH4 and N2O. Reference intensity of production[ProductionSector,GHG type]* Effect on production intensity[ProductionSector,GHG type]	GtonsCO2eq/Gt
GHG emissions from agriculture[GHG type]	Emissions of each GHG from agriculture. Defaults to 0 for all but CH4 and N2O. Agricultural production*Emissions intensity of production[Agriculture,GHG type]	GtonsCO2eq/Year
GHG emissions from waste[GHG type]	Production of GHG from waste (sewage, landfill, etc). Defaults to 0 for all but CH4 and N2O. Waste production*Emissions intensity of production[Waste,GHG type]	GtonsCO2eq/Year

7.4 Land Use CO_2 Emissions

As shown in Figure 7-16, emissions from land use and land use change and forestry (LULUCF) are defined by the bounds of the specified Business as Usual (BAU) trajectory and the least probable trajectory based on a maximum likely reduction rate. Reductions reflect global results curbing deforestation and growing more trees. The trajectory from BAU is defined by the *Annual rate of change in land use emissions.*

The BAU of LULUCF assumes the gross land use emissions and sinks will remain at current levels throughout the century, consistent with the default C-ROADS reference scenario. Specifically, the default BAU of LULUCF uses historic gross emissions and removals data from Houghton (2017) through 2015. Beyond 2015, the rate of change in *Annual rate of change in land use emissions* defaults to 0. This contrasts with assumptions from other modeling groups, including IPCCs SSP sceanrios, which assume a decrease in LULUCF emissions throughout the century. However, historic trends suggest otherwise; therefore, the model conservatively assumes no change. While the gross emissions and removals are both brought into the development version of the model as data variables, they are included as lookup tables in the model for general users.

Figure 7-16 CO_2 Emissions from Land Use

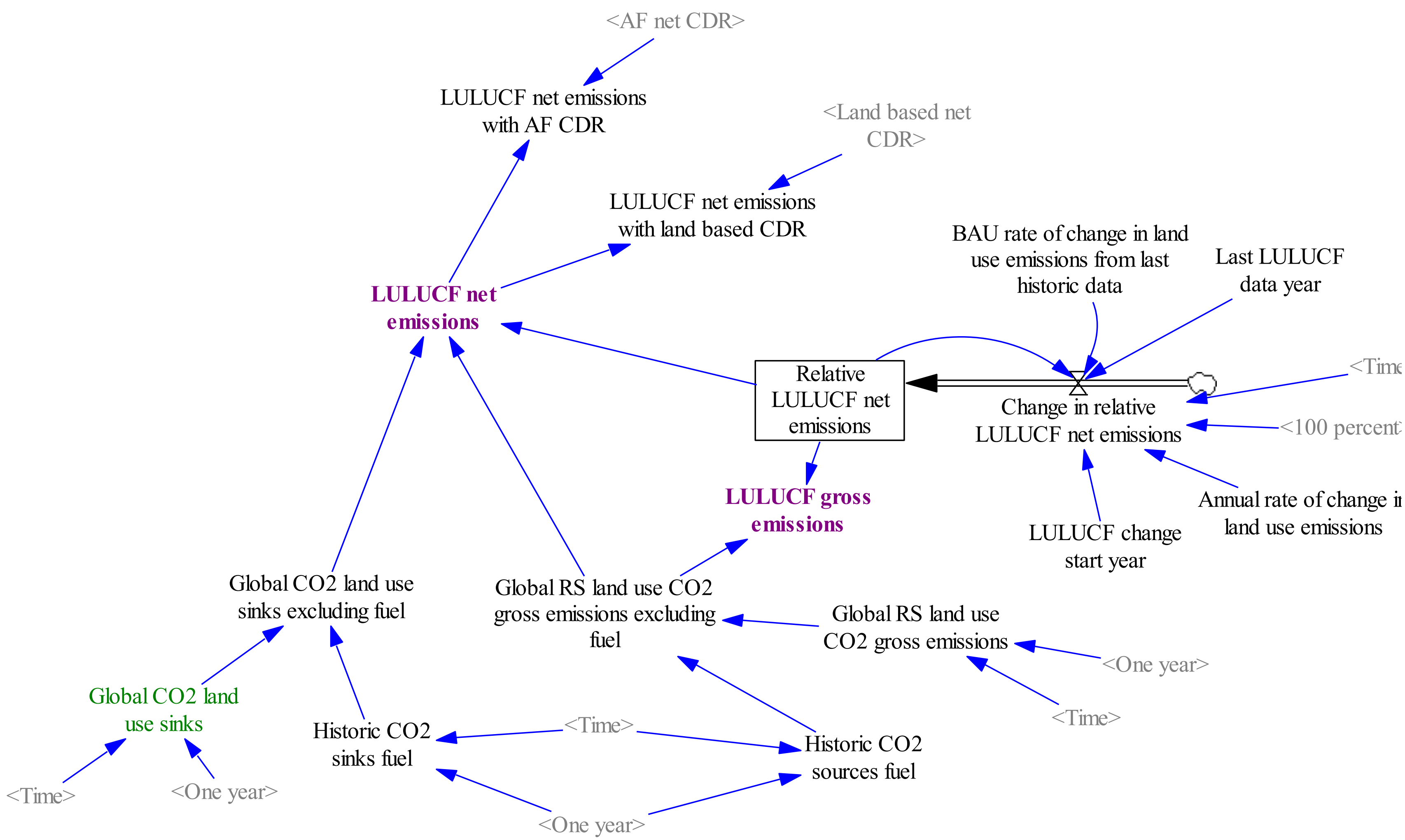


Table 7-5 Emissions from Land Use and Specified Emissions Parametric Inputs

Parameter	Definition	Range	Default Values	Units
Last LULUCF data year	Last year of available LULUCF data		2015	Year
BAU rate of change in land use emissions from last historic data	BAU annual percent change in LULUCF emissions starting in LULUCF start year.	-10-1	0	Percent/year
LULUCF change start year	Year to change LULUCF from BAU	2021-2100	2021	Year
Annual rate of change in land use emissions	Annual percent change in LULUCF emissions from BAU starting in LULUCF start year.	-10-1	0	Percent/year

Table 7-6. Emissions from Land Use and Specified Emissions Calculated Parameters

Parameter	Definition	Units
LULUCF net emissions	CO_2 net emissions from land use. (Global RS land use CO2 gross emissions excluding fuel-Global CO2 land use sinks excluding fuel)*Relative LULUCF net emissions	GtonsCO2/Year
LULUCF gross emissions	Global RS land use CO2 gross emissions excluding fuel*Relative LULUCF net emissions	GtonsCO2/Year
Change in relative LULUCF net emissions	IF THEN ELSE(Time<=Last LULUCF data year, 0, BAU rate of change in land use emissions from last historic data+IF THEN ELSE(Time<LULUCF change start year, 0, Annual rate of change in land use emissions))/"100 percent"*Relative LULUCF net emissions	1/Year
Relative LULUCF net emissions	INTEG(Change in relative LULUCF net emissions,1)	Dmnl
LULUCF net emissions	(Global RS land use CO2 gross emissions excluding fuel-Global CO2 land use sinks excluding fuel)*Relative LULUCF net emissions	GtonsCO2/Year
LULUCF net emissions with CDR	LULUCF net emissions-AF net CDR	GtonsCO2/Year
LULUCF net emissions with land based CDR	LULUCF net emissions-Land based net CDR	GtonsCO2/Year
Global RS land use CO2 gross emissions excluding fuel	Global RS land use CO2 gross emissions-Historic CO2 sources fuel	GtonsCO2/Year
Global CO2 land use sinks excluding fuel	Global CO2 land use sinks+Historic CO2 sinks fuel	GtonsCO2/Year
Total NonCO2 GHG emissions	Emissions of nonCO_2 GHGs in terms of CO2eq. SUM(NonCO2 GHG emissions[Minor GHGs!])	GtonsCO2eq/Year
"Land use & minor gas emissions"	LULUCF net emissions+Total NonCO2 GHG emissions	GtonsCO2eq/Year
CO2 Emissions	CO2 emissions excluding LULUCF+LULUCF net emissions	GtonsCO2/Year
CO2 Equivalent Emissions	CO2 Emissions+Other GHG emissions	GtonsCO2eq/Year

7.5 Carbon Dioxide Removal (CDR)

Besides sequestration accomplished through afforestation, there are other technologies that could remove CO_2 from the atmosphere. These other CDR technologies include soil carbon management, biochar, bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and enhanced weathering. A synthesis of literature (Table 7-7) provides maximum removal potential and the timing to achieve these, for each CDR type. While afforestation is specified as a percent of the maximum area available for planting, the other CDR types are specified as a percent of the maximum potential of each type.

A critical issue with CDR is energy and land demands for each type. Moreover, the potential reported in the literature for each CDR type does not consider the competing demands for energy and land. Moreover, there are storage losses over time, particularly for afforestation and soil carbon management, which decrease the continued removal of carbon.

Table 7-7 Literature Sources of CDR Potential

Caldecott, Ben, Lomax, Guy, & Workman, Max. (2015). *Stranded Carbon Assets and Negative Emission Technologies* (Working Paper). University of Oxford Stranded Assets Programme.

Gaunt, J. L., & Lehmann, J. (2008). Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production. *Environmental Science & Technology*, *42*(11), 4152–4158.

Humpenöder, F., Popp, A., Dietrich, J. P., Klein, D., Lotze-Campen, H., Markus Bonsch, Müller, C. (2014). Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environmental Research Letters*, *9*(6).

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 104). Geneva, Switzerland.

Koornneef, Joris, van Breevoort, Pieter, Hamelinck, Carlo, Hendriks, Chris, Hoogwijk, Monique, Koop, Klaas, & Koper, Michele. (2011). *Potential for Biomass and Carbon Dioxide Capture and Storage*. EcoFys for IEA GHG. Retrieved from https://www.eenews.net/assets/2011/08/04/document_cw_01.pdf

Kriegler, E., Edenhofer, O., Reuster, L., Luderer, G., & Klein, D. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change*, *118*(1), 45–57. https://doi.org/10.1007/s10584-012-0681-4

Lenton, T. M. (2010). The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management*, *1*(1), 145–160. https://doi.org/10.4155/cmt.10.12

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Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

van Vuuren, D. P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B. J., & Koelbl, B. (2013). The role of negative CO2 emissions for reaching 2 °C--insights from integrated assessment modelling. *Climatic Change; Dordrecht*, *118*(1), 15–27. https://doi.org/http://dx.doi.org.libproxy.tulane.edu:2048/10.1007/s10584-012-0680-5

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 1. https://doi.org/10.1038/ncomms1053

Figure 7-17 Net Carbon Removal

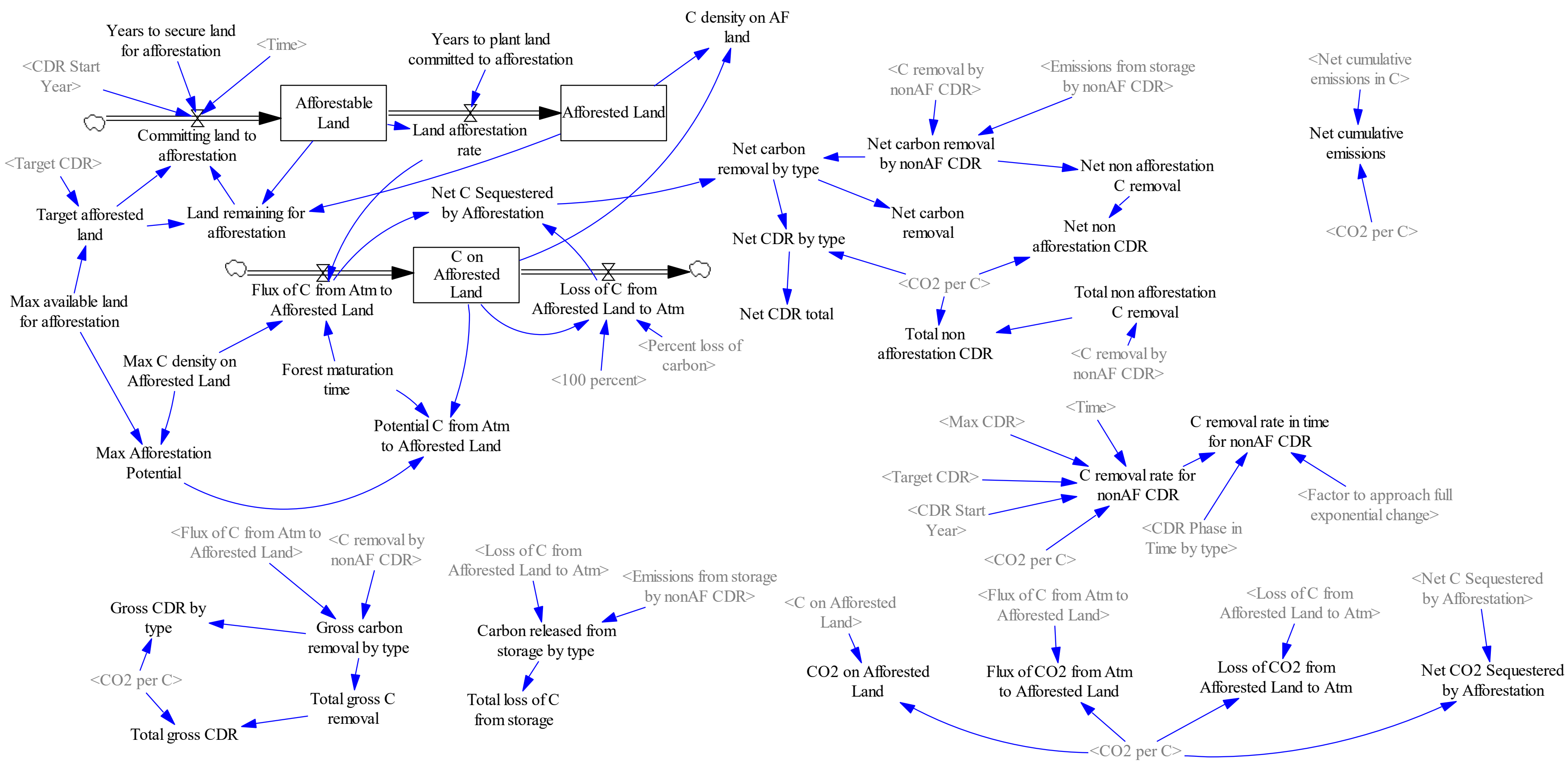


Figure 7-18 Net Carbon Removal

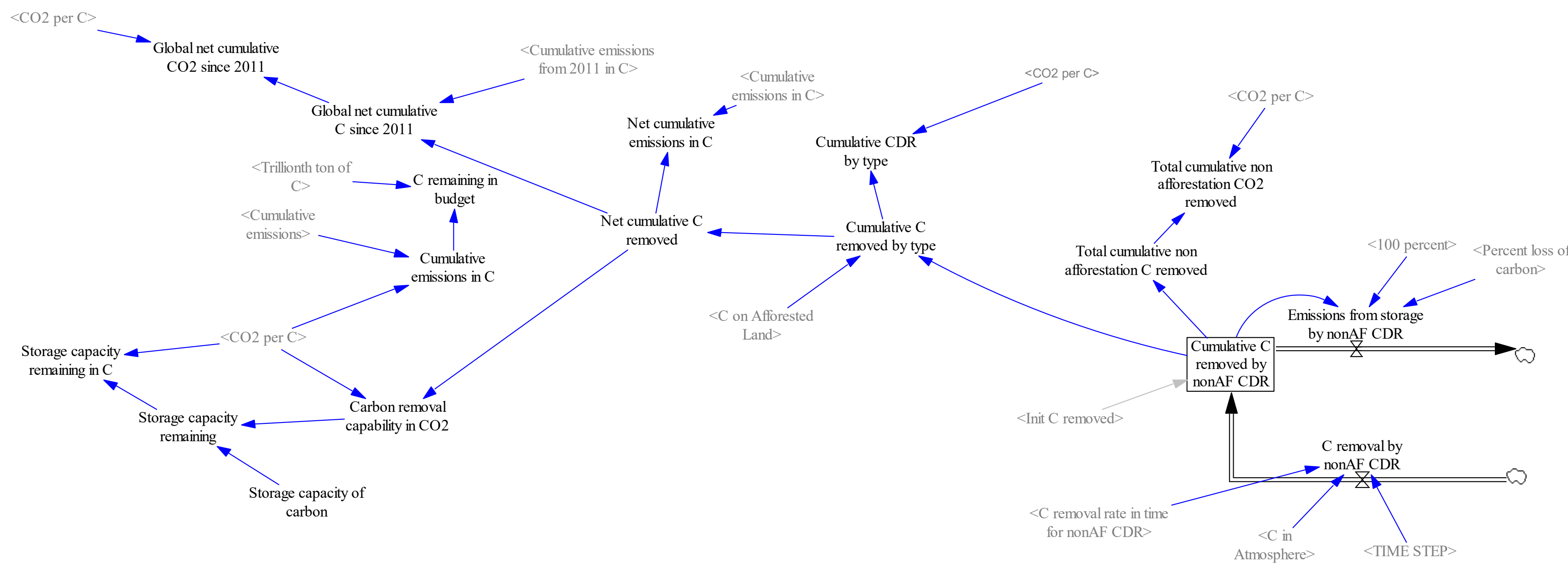


Table 7-8 CDR Input Parameters

Parameter	Definition	Range	Default Values	Units
Percent available land for afforestation	The percent of the **Max available land for afforestation** that is used for afforestation			
Afforestation CDR start year	Year to start afforestation efforts.			
Years to plant land committed to afforestation	Years it takes to plant the land that has been secured for afforestation	1-50	30	Years
Years to secure land for afforestation	Years it takes to plan and secure land for afforestation.	1-10	10	Years
Forest maturation time	Years for forests to reach maturity, approximately capturing net primary productivity growth curves..	10-100	80	Years
Max C density on Afforested Land	Bastin et al. (2019) calculates to 0.6 if 2%/year lost from storage.	0.2-1	0.6	GtonsC/Mha
Percent loss per year of afforestation	Percent loss per year of afforestation	0-2	2	Percent/year
Max available land for afforestation	With default growing time of 80 years and 2%/year loss, 700 Mha achieves an annual max removal consistent with the mid point of Royal Society estimates,which has a range of 3-20 in CO2 GtonsCO2/year, giving an average of 11.5 GtonsCO2/year (3.1 GtonsC/year). Bastin et al., Science 365, 76-79 (2019) 5 July 2019 indicates 900 MHa.	100-900	700	Mha
Max CDR[nonAF CDR]	The maximum potentially removed per year, taken as the average of the range from the Royal Society Report (2018).			GtonsCO2/year
Agricultural soil carbon		1-10	5.5	
Biochar		2-5	3.5	
BECCS		3-10	6	
Direct air capture		0.5-5	2.75	
Mineralization		0.5-4	2.25	

Table 7-8 CDR Input Parameters

Parameter	Definition	Range	Default Values	Units
Choose CDR	Switch to control aggregation of sequestration settings. 0 = Inputs for total CDRs apply 1 = Inputs for non afforestation CDR and afforestation CDR apply 2 = Inputs for each type of CDR apply	0-2	1	Dmnl
Target CDR by type [Sequestration type]	The percent of the maximum achieved for each CDR type	0-100	0	Percent
Percent of total CDR achieved	Sets the percent of the maximum achieved for all CDR types	0-100	0	Percent
CDR Start Year by type [Sequestration type]		2021-2100		Year
Direct air capture, Mineralization			2030	
All others			2021	
CDR time to reach max [nonAF CDR]				Years
Agricultural soil carbon			30	
Biochar			30	
BECCS			20	
Direct air capture			70	
Mineralization			70	
Percent loss of carbon by CDR type [Sequestration type]	Percent loss from sequestered carbon pool per year. Based on IPCC's WG1 AR5 Chapter 6. Table 6.15. 2013.	0-2		Percent/year
Afforestation	Also, based on typical biomass and soil release rates, through bacterial respiration (decay) and wildfire; determined through optimization of US forest data.		2	
Agricultural soil carbon	Also based on typical soil release rates determined through optimization of US forest data.		1	
Biochar	Also based on calculation from ~20% loss over long term (Caldecott et al, 2015)		0.2	

Table 7-8 CDR Input Parameters

Parameter	Definition	Range	Default Values	Units
BECCS	Based on IPCC assumption of permanence, storage loss is assumed to be zero		0	
Direct air capture	Based on IPCC assumption of permanence, storage loss is assumed to be zero		0	
Mineralization	Based on IPCC assumption of permanence, storage loss is assumed to be zero		0	

Table 7-9 CDR Calculated Parameters

Parameter	Definition	Units
Target afforested land	Max available land for afforestation*Target CDR[Afforestation]	Mha
Land remaining for afforestation	Target afforested land-(Afforestable Land+Afforested Land)	Mha
Committing land to afforestation	IF THEN ELSE(Time<CDR Start Year[Afforestation], 0, MIN(Target afforested land, Land remaining for afforestation)/Years to secure land for afforestation)	Mha/year
Land afforestation rate	Afforestable Land/Years to plant land committed to afforestation	Mha/year
Afforestable Land	INTEG(Committing land to afforestation-Land afforestation rate, 0)	Mha
Afforested Land	INTEG(Land afforestation rate, 0)	Mha
Flux of C from Atm to Afforested Land	Max C density on Afforested Land *DELAY3(Land afforestation rate, Forest maturation time)	GtonsC/Year
Loss of C from Afforested Land to Atm	C on Afforested Land*Percent loss of carbon[Afforestation]/"100 percent"	GtonsC/Year
Net C Sequestered by Afforestation	Flux of C from Atm to Afforested Land-Loss of C from Afforested Land to Atm	GtonsC/Year
C on Afforested Land	INTEG(Flux of C from Atm to Afforested Land-Loss of C from Afforested Land to Atm, 0)	GtonsC
Potential C from Atm to Afforested Land	(Max Afforestation Potential -C on Afforested Land)/Forest maturation time	GtonsC/Year
C density on AF land	ZIDZ(C on Afforested Land,Afforested Land)	GtonsC/Mha
Max Afforestation Potential	Max C density on Afforested Land*Max available land for afforestation	GtonsC/Mha
CO2 on Afforested Land	C on Afforested Land*CO2 per C	GtonsCO2
Flux of CO2 from Atm to Afforested Land	Flux of C from Atm to Afforested Land*CO2 per C	GtonsCO2/Year
Loss of CO2 from Afforested Land to Atm	Loss of C from Afforested Land to Atm*CO2 per C	GtonsCO2/Year
Net CO2 Sequestered by Afforestation	Net C Sequestered by Afforestation*CO2 per C	GtonsCO2/Year

Table 7-9 CDR Calculated Parameters

Parameter	Definition	Units
Target CDR[Sequestration type]	Fraction of max CDR or max available land for afforestation.	Dmnl
NonAF or BECCS CDR	IF THEN ELSE(Choose CDR by type=2, Target CDR by type[NonAF or BECCS CDR], IF THEN ELSE(Choose CDR by type=1, Non afforestation Percent of max CDR achieved, Percent of total CDR achieved))/"100 percent"	
Afforestation	IF THEN ELSE(Choose CDR by type>=1, Percent available land for afforestation, Percent of total CDR achieved)/"100 percent"	
BECCS	If active BECCS CDR settings = 0, then actions (breakthrough in Bio CCS) that increase Bio CCS primary demand also increase the Target CDR for BECCS. IF THEN ELSE(Choose CDR by type=2 :AND:Target CDR by type[BECCS], Target CDR by type[BECCS], IF THEN ELSE(Choose CDR by type=1 :AND:Non afforestation Percent of max CDR achieved, Non afforestation Percent of max CDR achieved, IF THEN ELSE(Choose CDR by type=0 :AND: Percent of total CDR achieved, Percent of total CDR achieved, Percent of PE Bio CCS over threshold)))/"100 percent"	
C removal rate effort nonAF CDR [nonAF CDR]	IF THEN ELSE(Time<CDR Start Year[NonAF CDR], 0, Max CDR[NonAF CDR]*Target CDR[NonAF CDR])/CO2 per C	GtonsC/year
C removal rate in time for nonAF CDR [nonAF CDR]	SMOOTH3(C removal rate for nonAF CDR[NonAF CDR] , CDR Phase in Time by type[NonAF CDR]/Factor to approach full exponential change)	GtonsC/year
C removal by nonAF CDR[nonAF CDR)	MIN(C removal rate in time for nonAF CDR[NonAF CDR], C in Atmosphere/ELMCOUNT(NonAF CDR)/TIME STEP)	GtonsC/year
Emissions from storage by nonAF CDR[nonAF CDR]	Loss of CO2 from storage back into atmosphere. Cumulative C removed by nonAF CDR[NonAF CDR]*Percent loss of carbon [NonAF CDR]/"100 percent"	GtonsC/year

Table 7-9 CDR Calculated Parameters

Parameter	Definition	Units
Net carbon removal by nonAF CDR[nonAF CDR]	C removal by nonAF CDR[NonAF CDR]-Emissions from storage by nonAF CDR[NonAF CDR]	GtonsC/year
Cumulative C removed by nonAF CDR	INTEG0C removal by nonAF CDR[NonAF CDR]-Emissions from storage by nonAF CDR[NonAF CDR], 0)	GtonsC
Cumulative C removed by type[Sequestration type]		GtonC
NonAF CDR	Cumulative C removed by nonAF CDR[NonAF CDR]	
Afforestation	C on Afforested Land	
Net carbon removal by type[Sequestration type]	Difference between carbon removed and carbon released from storage.	GtonsC/year
NonAF CDR	Net carbon removal by nonAF CDR[NonAF CDR]	
Afforestation	Net C Sequestered by Afforestation	
Net CDR by type[Sequestration type]	Net carbon removal by type[Sequestration type]*CO2 per C	GtonsCO2/year
Total non afforestation C removal	SUM(C removal by nonAF CDR[NonAF CDR!])	GtonsC/year
Total non afforestation CDR	Total non afforestation C removal*CO2 per C	GtonsCO2/year
Net carbon removal	SUM(C removal by type[Sequestration type!])	GtonsC/year
Net CDR total	SUM(Net CDR by type[Sequestration type!])	GtonsCO2/year
CDR by energy	CDR across all energy-based types, i.e., BECCS, DAC, and mineralization SUM(CDR by type[Energy based CDR!])	GtonsCO2/year
Net CDR by land	CDR across all land-based types, i.e., afforestation, agricultural soil carbon, and biochar SUM(Net CDR by type[Land based CDR!])	GtonsCO2/year
Net CDR by energy	SUM(Net CDR by type[Energy based CDR!])	GtonsCO2/year
Net CDR by land	SUM(Net CDR by type[Land based CDR!])	GtonsCO2/year

8. Carbon cycle

8.1.1 Introduction

The carbon cycle sub-model is adapted from the FREE model (Fiddaman, 1997). While the original FREE structure is based on primary sources that are now somewhat dated, we find that they hold up well against recent data. Calibration experiments against recent data and other models do not provide compelling reasons to adjust the model structure or parameters, though in the future we will likely do so.

Other models in current use include simple carbon cycle representations. Nordhaus' DICE models, for example, use simple first- and third-order linear models (Nordhaus, 1994, 2000). The first-order model is usefully simple, but does not capture nonlinearities (e.g., sink saturation) or explicitly conserve carbon. The third-order model conserves carbon but is still linear and thus not robust to high emissions scenarios. More importantly for education and decision support, neither model provides a recognizable carbon flow structure, particularly for biomass.

Socolow and Lam (2007) explore a set of simple linear carbon cycle models to characterize possible emissions trajectories, including the effect of procrastination. The spirit of their analysis is similar to ours, except that the models are linear (sensibly, for tractability) and the calibration approach differs. Socolow and Lam calibrate to Green's function (convolution integral) approximations of the 2x CO_2 response of larger models; this yields a calibration for lower-order variants that emphasizes long-term dynamics. Our calibration is weighted towards recent data, which is truncated, and thus likely emphasizes faster dynamics. Nonlinearities in the C-ROADS carbon uptake mechanisms mean that the 4x CO_2 response will not be strictly double the 2xCO2 response.

8.1.2 Structure

The adapted FREE carbon cycle (Figure 8-1) is an eddy diffusion model with stocks of carbon in the atmosphere, biosphere, mixed ocean layer, and three deep ocean layers. The model couples the atmosphere-mixed ocean layer interactions and net primary production of the Goudriaan and Kettner and IMAGE 1.0 models (Goudriaan and Ketner 1984; Rotmans 1990) with a 5-layer eddy diffusion ocean based on (Oeschger, Siegenthaler *et al.*, 1975) and a 2-box biosphere based on (Goudriaan and Ketner 1984).

In the FREE model, all emissions initially accumulate in the atmosphere. As the atmospheric concentration of C rises, the uptake of C by the ocean and biosphere increases, and carbon is gradually stored. The atmospheric flux to the biosphere consists of net primary production, which grows logarithmically as the atmospheric concentration of C increases (Wullschleger, Post *et al.*, 1995), according to:

Eq. 1

$$NPP = NPP_0 \left(1 + \beta_b \ln\left(\frac{C_a}{C_{a,0}} \right) \right)$$

NPP = net primary production
NPP_0 *= reference net primary production*
β_b *= biostimulation coefficient*
C_a *= C in atmosphere*
$C_{a,0}$ *= reference C in atmosphere*

Because the relationship is logarithmic, the uptake of C by the biosphere is less than proportional to the increase in atmospheric C concentration. This formulation, though commonly used, is not robust to large deviations in the atmospheric concentration of C. As the atmospheric concentration of C approaches zero, net primary production approaches minus infinity, which is not possible given the finite positive stock of biomass. As the concentration of C becomes very high, net primary production can grow arbitrarily large, which is also not possible in reality. Accordingly, we instead use a CES production function, which exhibits the following: 1) the slope around the preindustrial operating point is controlled by the biostimulation coefficient, which can be loosely interpreted as CO2's share of plant growth (at the margin), with the balance due to other factors like water and nutrients; 2) there is a finite slope at zero CO_2, such that there are no singularities; and 3) it controls saturation at high CO_2.

Eq. 2

$$NPP = NPP_0 \left(1 - \beta_b + \beta_b \frac{C_a}{C_{a,0}}^{CO_2\,sat} \right)^{\frac{1}{CO_2\,sat}}$$

CO_2 *sat = coefficient that determines the rate of* CO_2 *saturation*

Effects of the current biomass stock, and human disturbance are neglected. The flux of C from the atmosphere to biomass decreases with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100. The sensitivity parameter, set by the user, governs the strength of the effect. The default sensitivity of 1 yields the average value found in Friedlingstein et al., 2006.

The Goudriaan and Ketner and IMAGE models (Goudriaan and Ketner, 1984; Rotmans, 1990) have detailed biospheres, partitioned into leaves, branches, stems, roots, litter, humus, and charcoal. To simplify the model, these categories are aggregated into stocks of biomass (leaves, branches, stems, roots) and humus (litter, humus). Aggregate first-order time constants were calculated for each category on the basis of their equilibrium stock-flow relationships. Charcoal is neglected due to its long lifetime. The results are reasonably consistent with other partitionings of the biosphere and with the one-box biosphere of the Oeschger model (Oeschger, Siegenthaler *et al.*, 1975; Bolin, 1986).

Eq. 3

$$C_b(t) = \int \left(\mathrm{NPP}(t) - \frac{C_b(t)}{\tau_b} \right) dt$$

C_b = *carbon in biomass* τ_b = biomass residence time

Eq. 4

$$C_h(t) = \int \left(\frac{\phi C_b(t)}{\tau_b} - \frac{C_h(t)}{\tau_h} \right) dt$$

C_h = *carbon in biomass* τ_h = *humus residence time*

ϕ = *humidification fraction*

The interaction between the atmosphere and mixed ocean layer involves a shift in chemical equilibria (Goudriaan and Ketner, 1984). CO_2 in the ocean reacts to produce HCO_3^- and $CO_3^=$. In equilibrium,

Eq. 5

$$C_m = C_{m,0} \left(\frac{C_a}{C_{a,0}} \right)^{\left(\frac{1}{\zeta}\right)}$$

C_m = *C in mixed ocean layer* $C_{m,0}$ = *reference C in mixed ocean layer*

C_a = *C in atmosphere* $C_{a,0}$ = *reference C in atmosphere*

ζ = *buffer factor*

The atmosphere and mixed ocean adjust to this equilibrium with a time constant of 1 year. The buffer or Revelle factor, ζ, is typically about 10. As a result, the partial pressure of CO_2 in the ocean rises about 10 times faster than the total concentration of carbon (Fung, 1991). This means that the ocean, while it initially contains about 60 times as much carbon as the preindustrial atmosphere, behaves as if it were only 6 times as large.

The buffer factor itself rises with the atmospheric concentration of CO_2 (Goudriaan and Ketner, 1984; Rotmans, 1990) and temperature (Fung, 1991). This means that the ocean's capacity to absorb CO_2 diminishes as the atmospheric concentration rises. This temperature effect is another

of several possible feedback mechanisms between the climate and carbon cycle. The fractional reduction in the solubility of CO_2 in ocean falls with rising temperatures. Likewise for the temperature feedback on C flux to biomass, we assume a linear relationship, likely a good approximation over the typical range for warming by 2100. The sensitivity parameter that governs the strength of the effect on the flux to the biomass also governs the strength of the effect on the flux to the ocean. For both effects, the default sensitivity of 1 yields the average values found in Friedlingstein et al., 2006.

Eq. 6

$$\zeta = \zeta_0 + \delta_b \ln\left(\frac{C_a}{C_{a,0}}\right)$$

ζ = buffer factor
δ_b = buffer CO_2 coefficient
ζ_0 = reference buffer factor
C_a = CO_2 in atmosphere
$C_{a,0}$ = reference CO_2 in atmosphere

The deep ocean is represented by a simple eddy-diffusion structure similar to that in the Oeschger model, but with fewer layers (Oeschger, Siegenthaler *et al.*, 1975). Effects of ocean circulation and carbon precipitation, present in more complex models (Goudriaan and Ketner, 1984; Björkstrom, 1986; Rotmans, 1990; Keller and Goldstein, 1995), are neglected. Within the ocean, transport of carbon among ocean layers operates linearly. The flux of carbon between two layers of identical thickness is expressed by:

Eq. 6

$$F_{m,n} = \frac{\left(C_m - C_n\right)e}{d^2}$$

$F_{m,n}$ = carbon flux from layer m to layer n
C_k = carbon in layer k
e = eddy diffusion coefficient
d = depth of layers

The effective time constant for this interaction varies with d, the thickness of the ocean layers. To account for layer thicknesses that are not identical, the time constant uses the mean thickness of two adjacent layers. Table 8-1 summarizes time constants for the interaction between the layers used in C-ROADS, which employs a 100 meter mixed layer, and four deep ocean layers that are 300, 300, 1300, and 1800 meters, sequentially deeper. Simulation experiments show there is no material difference in the atmosphere-ocean flux between the five-layer ocean and more disaggregate structures, including an 11-layer ocean, at least through the model time horizon of 2100.

Table 8-1: Effective Time Constants for Ocean Carbon Transport

Layer Thickness	**Time Constant**
100 meters	1 year
300 meters	14 years
300 meters	20 years
1300 meters	236 years
1800 meters	634 years

Figure 8-1 Carbon Cycle

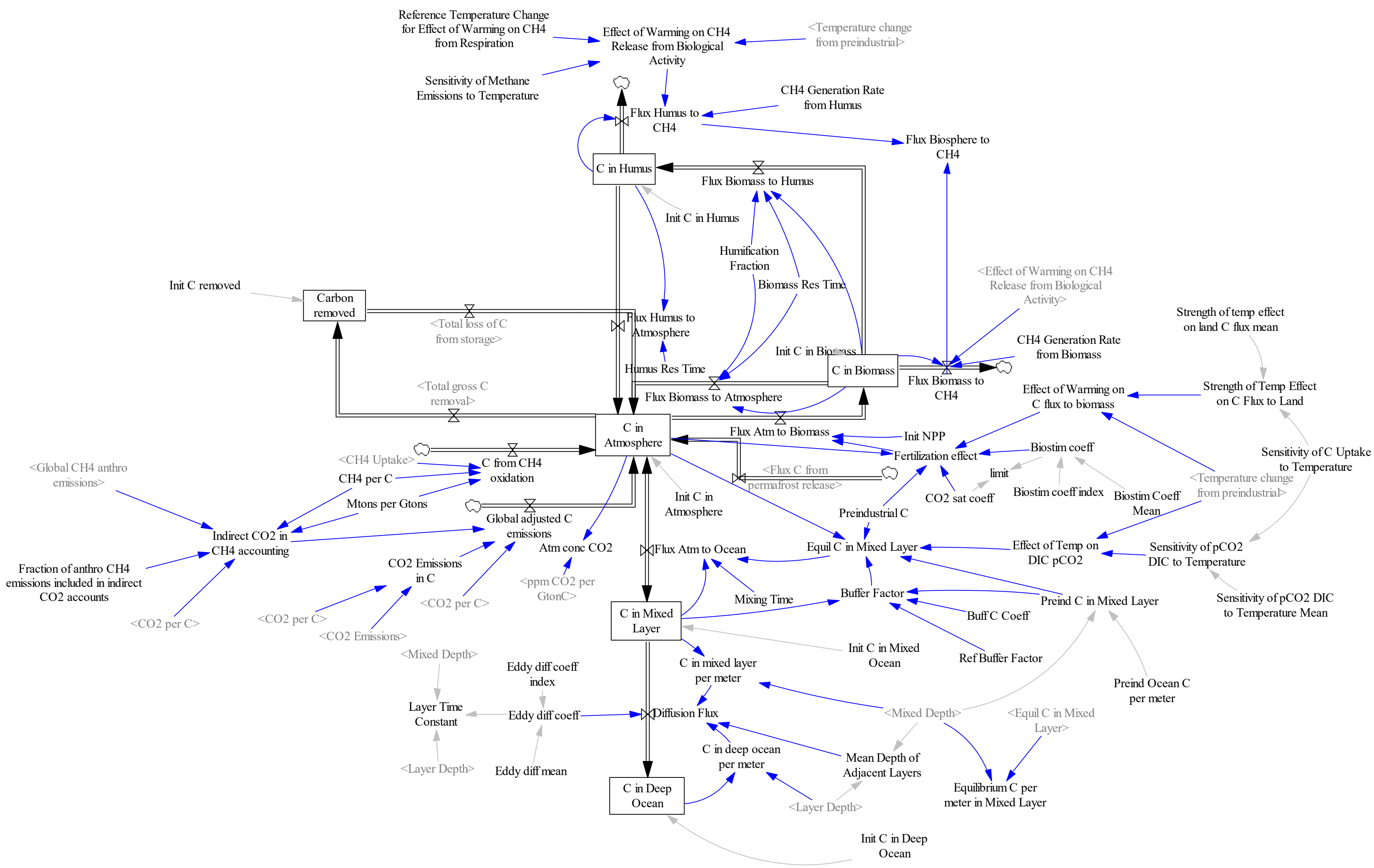


Table 8-2 Carbon Cycle Parameter Inputs

Parameter	**Definition**	**Default Values**	**Units**	**Source**
Preindustrial C	Preindustrial CO_2 content of atmosphere.	590	GtonsC	
Biomass residence time	Average residence time of carbon in biomass.	10.6	Year	Adapted from Goudriaan, 1984
Biostim coeff index	Index of coefficient for response of primary production to carbon concentration, as multiplying factor of the mean value.	1	Dmnl	
Biostim ceoeff mean	Mean coefficient for response of primary production to CO2 concentration. Consistent with AR5, at double the predindustrial CO2, the NPP increases by 20-25 of the initial level.	0.42	Dmnl	Goudriaan and Ketner, 1984; Rotmans, 1990, AR5, 2013
CO2 sat coeff	Rate of saturation of CO2 fertilization effect; a larger (more negative) value implies that saturation sets in more quickly. Controls the limit of NPP at high CO2.	-0.8	Dmnl	
Humification Fraction	Fraction of carbon outflow from biomass that enters humus stock.	0.428	Dmnl	Adapted from Goudriaan, 1984
Humus Res Time	Average carbon residence time in humus.	27.8	Year	Adapted from Goudriaan, 1984
Buff C coeff	Coefficient of C concentration influence on buffer factor.	3.92	Dmnl	Goudriaan and Ketner, 1984
Ref buffer factor.	Normal buffer factor.	9.7	Dmnl	Goudriaan and Ketner, 1984
Mixing Time	Atmosphere - mixed ocean layer mixing time.	1	Year	
Eddy diff coeff index	Index of coefficient for rate at which carbon is mixed in the ocean due to eddy motion, where 1 is equivalent to the expected value of 4400 meter/meter/year.	1	Dmnl	Expected eddy diff coeff from Oeschger, Siegenthaler et al., 1975
Mixed depth	Mixed ocean layer depth.	100	Meters	Oeschger, Siegenthaler et al., 1975

Table 8-2 Carbon Cycle Parameter Inputs

Parameter	**Definition**	**Default Values**	**Units**	**Source**
Preind Ocean C per meter	Corresponds with 767.8 GtC in a 75m layer.	10.2373	GtonsC/meter	
Layer Depth[layers]	Deep ocean layer thicknesses. 1 2 3 4	 300 300 1300 1800	 Meters Meters Meters Meters	
Init NPP	Initial net primary production	85.1771	GtonsC/year	Adapted from Goudriaan, 1984
Ppm CO_2 per TonsC	1 ppm by volume of atmosphere CO_2 = 2.13 Gt C	0.4695e	ppm/GtonsC	CDIAC (http://cdiac.ornl.gov/pns/convert.html)
Goal for CO_2 in the atmosphere	Assumed threshold of CO_2 in atmosphere above which irreversible climate changes may occur	450	Ppm	
Sensitivity of C Uptake to Temperature	Allows users to control the strength of the feedback effect of temperature on uptake of C by land and oceans. 0 means no temperature-carbon uptake feedback and default of 1 yields the average values found in Friedlingstein et al., 2006.	0-2.5 Default = 1	Dmnl	
Strength of temp effect on land C flux mean	Average effect of temperature on flux of carbon to land. Calibrated to be consistent with Friedlingstein et al., 2006. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested.	-0.01	1/DegreesC	Friedlingstein et al., 2006
Sensitivity of pCO2 DIC to Temperature Mean	Sensitivity of equilibrium concentration of dissolved inorganic carbon to temperature. Calibrated to be consistent with Friedlingstein et al., 2006. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested.	0.003	1/DegreesC	Friedlingstein et al., 2006

Table 8-2 Carbon Cycle Parameter Inputs

Parameter	Definition	Default Values	Units	Source
CH4 Generation Rate from Humus	The rate of the natural flux of methane from C in humus. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane.	1.5e-004	1/year	
CH4 Generation Rate from Biomass	The rate of the natural flux of methane from C in biomass. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane.	1.0e-005	1/year	
Fraction of anthro CH4 emissions included in indirect CO2 accounts	Accounts for CO_2 emissions that are already included in the CH4 emissions.	0.8	Dmnl	Estimated from EPA 2011 http://www.epa.gov/climatechange/economics/international.html
CH4 per C	Molar mass ratio of CH4 to C, 16/12	1.33	Mtons/Mtons C	
Mtons per Gtons	Converts MtonsC to GtonsC.	1000	MtonsC/GtonsC	
Sensitivity of Methane Emissions to Temperature	Allows users to control the strength of the feedback effect of temperature on release of C as CH4 from humus. Default of 0 means no temperature feedback and 1 is mean feedback.	0-2.5 Default = 0	Dmnl	
Reference Temperature Change for Effect of Warming on CH4 from Respiration	Temperature change at which the C as CH4 release from humus doubles for the Sensitivity of Methane Emissions to Temperature=1.	5	DegreesC	
Init C in Atmosphere	Initial carbon in atmosphere	353.98	Ppm	Mauna Loa, 2020
Init C in Humus	Initial carbon in humus. Data input from 1990 value in C-ROADS.		GtonsC	From 1990 C-ROADS data

Table 8-2 Carbon Cycle Parameter Inputs

Parameter	**Definition**	**Default Values**	**Units**	**Source**
Init C in Biomass	Initial carbon in biomass. Data input from 1990 value in C-ROADS.		GtonsC	From 1990 C-ROADS data
Init C in Mixed Ocean	Initial carbon in mixed ocean layer. Data input from 1990 value in C-ROADS.		GtonsC	From 1990 C-ROADS data
Init C in Deep Ocean[layers]	Initial carbon concentration in deep ocean layers. Data input from 1990 value in C-ROADS.		GtonsC	From 1990 C-ROADS data

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	Definition	Units
Atm conc CO2	Converts weight of CO_2 in atmosphere (GtonsC) to concentration (ppm CO_2). CO2 in Atmosphere*ppm CO2 per GtonC	Ppm
Flux Atm to Ocean	Carbon flux from atmosphere to mixed ocean layer, including feedback from temperature change (where default is set for no feedback). ((Equil C in Mixed Layer-C in Mixed Layer)/Mixing Time)	GtonsC/year
Flux Atm to Biomass	Carbon flux from atmosphere to biosphere (from primary production), including feedbacks from CO2 and temperature change. Init NPP*Fertilization effect	GtonsC/year
Biostim Coeff	Coefficient for response of primary production to carbon concentration, based on index and mean. INITIAL(Biostim coeff index*Biostim coeff mean)	Dmnl
Fertilization effect	Change in NPP due to feedbacks from CO2 and temperature change. The CO2 fertilization term is derived from the CES production function, for its desirable properties: - slope around the preindustrial operating point controlled by the CO2 share coefficient, which can be loosely interpreted as CO2's share of plant growth (at the margin), with the balance due to other factors like water and nutrients. - finite slope at zero CO2 (no singularities, unlike (C/C0)^b or (1+b*LN(C/C0)) - controllable saturation at high CO2 (1-Biostim coeff + Biostim coeff*(C in Atmosphere/Preindustrial C)^CO2 sat coeff)^(1/CO2 sat coeff)*Effect of Warming on C flux to biomass	Dmnl

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	**Definition**	**Units**
Effect of Warming on C flux to biomass	Feedback from temperature on carbon flux from atmosphere to the biomass. 1+Strength of Temp Effect on C Flux to Land*Temperature change from 1750	GtonsC
Temperature change from 1750	Change in temperature relative to preindustrial times. See Section 9.	DegreesC
Flux Biomass to Atmosphere	Carbon flux from biomass to atmosphere. CO2 in Biomass/Biomass Res Time*(1-Humification Fraction)	GtonsC/year
Flux Biomass to Humus	Carbon flux from biomass to humus. CO2 in Biomass/Biomass Res Time*Humification Fraction	GtonsC/year
Flux Humus to Atmosphere	Carbon flux from humus to atmosphere. CO2 in Humus/Humus Res Time	GtonsC/year
Global adjusted CO2 emissions	CO2 emissions from FF (includes cement) and forestry, net of indirect CO2 in CH4 accounts, which will be emitted later via CH4 oxidation. MAX(0, CO2 Emissions in C-Indirect CO2 in CH4 accounting/CO2 per C)	GtonsC/year
C in Atmosphere	Mass of carbon in the atmosphere. INTEG(C from CH4 oxidation+Emissions from storage+Flux Biomass to Atmosphere+Flux C from permafrost release+Flux Humus to Atmosphere+Global adjusted C emissions-Total C removal-Flux Atm to Biomass-Flux Atm to Ocean, Init C in Atmosphere/ ppm CO2 per GtonC)	GtonsC
C in Humus	Carbon in humus. INTEG(Flux Biomass to Humus-Flux Humus to Atmosphere-Flux Humus to CH4, Init C in Humus)	GtonsC

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	**Definition**	**Units**
C in Biomass	Carbon in the biomass. INTEG(Flux Atm to Biomass-Flux Biomass to Atmosphere-Flux Biomass to CH4-Flux Biomass to Humus, Init C in Biomass)	GtonsC
C in Mixed Layer	Carbon in the mixed layer. INTEG(Flux Atm to Ocean-Diffusion Flux [layer1], Init C in Mixed Ocean per meter*Mixed Depth)	GtonsC
C in Deep Ocean[layers]	Carbon in deep ocean.	GtonsC
C in Deep Ocean[upper]	INTEG(Diffusion Flux[upper]-Diffusion Flux[lower], Init C in Deep Ocean per meter[upper]*Layer Depth[upper])	
C in Deep Ocean[bottom]	INTEG(Diffusion Flux[bottom], Init C in Deep Ocean per meter[bottom]*Layer Depth[bottom])	
Equil C in Mixed Layer	Equilibrium carbon content of mixed layer. Determined by the Revelle buffering factor, and by temperature. For simplicity, we assume a linear impact of warming on the equilibrium solubility of CO2 in the ocean. The user controls the strength of that effect. Preind C in Mixed Layer*Effect of Temp on DIC pCO2*(C in Atmosphere/Preindustrial C)^(1/Buffer Factor)	GtonsC
Buffer Factor	Buffer factor for atmosphere/mixed ocean carbon equilibration. ACTIVE INITIAL(Ref Buffer Factor*(C in Mixed Layer/Preind C in Mixed Layer)^Buff C Coeff, Ref Buffer Factor)	Dmnl
Preind C in Mixed Layer	Initial carbon concentration of mixed ocean layer. INITIAL(Preind Ocean C per meter*Mixed Depth)	GtonsC
Mean Depth of Adjacent Layers[layers]	The mean depth of adjacent ocean layers.	Meters
Mean Depth of Adjacent Layers[layer1]	INITIAL((Mixed Depth+Layer Depth[layer1])/2)	

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	Definition	Units
Mean Depth of Adjacent Layers[lower]	INITIAL((Layer Depth[upper]+Layer Depth[lower])/2)	
Diffusion Flux[layers]	Diffusion flux between 5 ocean layers.	GtonsC/year
Diffusion Flux[layer1]	(C in mixed layer per meter-C in deep ocean per meter[layer1]) *Eddy diff coeff/Mean Depth of Adjacent Layers[layer1]	
Diffusion Flux[lower]	(C in deep ocean per meter[upper]-C in deep ocean per meter[lower]) *Eddy diff coeff/Mean Depth of Adjacent Layers[lower]	
Eddy Diff Coeff	Rate at which carbon is mixed in the ocean due to eddy motion, based on index and mean. INITIAL(Eddy diff coeff index*Eddy diff mean)	meter*meter/year
Layer Time Constant[layers]	Time constant of exchange between layers.	Year
Layer Time Constant[layer1]	INITIAL(Layer Depth[layer1]/(Eddy diff coeff/Mean Depth of Adjacent Layers[layer1]))	
Layer Time Constant[lower]	INITIAL(Layer Depth[lower]/(Eddy diff coeff/Mean Depth of Adjacent Layers[lower]))	
Effect of Temp on DIC pCO2	The fractional reduction in the solubility of CO2 in ocean falls with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100. 1-Sensitivity of pCO2 DIC to Temperature*Temperature change from 1750	Dmnl
Sensitivity of pCO2 DIC to Temperature	Sensitivity of pCO2 of dissolved inorganic carbon in ocean to temperature. INITIAL(Sensitivity of C Uptake to Temperature*Sensitivity of pCO2 DIC to Temperature Mean)	1/DegreesC
Strength of Temp Effect on C Flux to Land	Strength of temperature effect on C flux to the land. INITIAL(Sensitivity of C Uptake to Temperature*Strength of temp effect on land C flux mean)	1/DegreesC

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	**Definition**	**Units**
Effect of Warming on C flux to biomass	The fractional reduction in the flux of C from the atmosphere to biomass with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100. 1+Strength of Temp Effect on C Flux to Land*Temperature change from 1750	Dmnl
Flux Humus to CH4	The natural flux of methane from C in humus. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback. C in Humus*CH4 Generation Rate from Humus*Effect of Warming on CH4 Release from Biological Activity	GtonsC/year
Effect of Warming on CH4 Release from Biological Activity	The fractional increase in the flux of C as CH4 from humus with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100. 1+Sensitivity of Methane Emissions to Temperature*(Temperature change from 1750)/(Reference Temperature Change for Effect of Warming on CH4 from Respiration)	Dmnl
Flux Biomass to CH4	The natural flux of methane from C in biomass. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback. C in Biomass*CH4 Generation Rate from Biomass*Effect of Warming on CH4 Release from Biological Activity	GtonsC/year
Flux Biosphere to CH4	Carbon flux from biosphere as methane, in GtC/year, arising from anaerobic respiration. Flux Biomass to CH4+Flux Humus to CH4	GtonsC/year

Table 8-3 Carbon Cycle Calculated Parameters

Parameter	Definition	Units
C from CH4 oxidation	Flux of C into the atmosphere from the oxidation of CH4, the mode of removal of CH4 from atmosphere. CH4 Uptake/CH4 per C/Mtons per Gtons	GtonsC/year
Indirect CO2 in CH4 accounting	Indirect CO2 emissions included in accounting data that occurs due to oxidation of CH4; in this model the indirect emissions are explicit from the methane cycle, and therefore are deducted from the CO2 accounting to correct the data. Also includes emissions for which CH4 represents recently-extracted biomass (e.g. enteric fermentation). Total anthropogenic global CH4 emissions/CH4 per C/Mtons per Gtons*CO2 per C*Fraction of anthro CH4 emissions included in indirect CO2 accounts	GtonsCO2/year

8.2 Other greenhouse gases

8.2.1 Other GHGs included in CO2equivalent emissions

En-ROADS explicitly models other well–mixed greenhouses gases, including methane (CH_4), nitrous oxide (N_2O), and the fluorinated gases (PFCs, SF_6, and HFCs). PFCs are represented as CF_4-equivalents due to the comparably long lifetimes of the various PFC types. HFCs, on the other hand, are represented as an array of the nine primary HFC types, each with its own parameters. The structure of each GHG's cycle reflects first order dynamics, such that the gas is emitted at a given rate and is taken up from the atmosphere according to its concentrationnd its time constant. Initialization is based on 1990 levels of data from GISS for CH4 and N2O and according to C-ROADS 5.7.10 for F-gases. The remaining mass in the atmosphere is converted, according to its molecular weight, to the concentration of that gas. The multiplication of each gas concentration by the radiative coefficient of the gas yields its instantaneous radiative forcing (RF). This RF is included in the sum of all RFs to determine the total RF on the system.

For those explicitly modeled GHGs, the CO_2 equivalent emissions of each gas are calculated by multiplying its emissions by its 100-year Global Warming Potential. Time constants, radiative forcing coefficients, and the GWP are taken from the IPCCs Fifth Assessment Report (AR5) Working Group 1 Chapter 8. (Table 8.A.1. Lifetimes, Radiative Efficiencies and Metric Values GWPs relative to CO2).

In addition to the anthropogenic emissions considered as part of the CO_2 equivalent emissions, CH_4, N_2O, and PFCs also have a natural component. The global natural CH_4 and N_2O emissions are based on MAGICC output, using the remaining emissions in their "zero emissions" scenario. The global natural PFC emissions are calculated by dividing Preindustrial mass of CF_4 equivalents by the time constant for CF_4. Figure 8-2 illustrates the general GHG cycle.

Table 8-4 provides the general equations for the other GHGs, with each gas modeled as its own structure. The units of each gas are: MtonsCH$_4$, MtonsN$_2$O-N, tonsCF$_4$, tonsSF$_6$, and tonsHFC for each of the primary HFC types. To calculate the CO2 equivalent emissions of N_2O, the model first converts the emissions from MtonsN$_2$O-N/year to Mtons N_2O/year.

CH_4 is unique in that there are additional natural emissions from permafrost and clathrate. The sensitivity of this release defaults to 0 but may be increased by the user.

Figure 8-2 Other GHG cycle

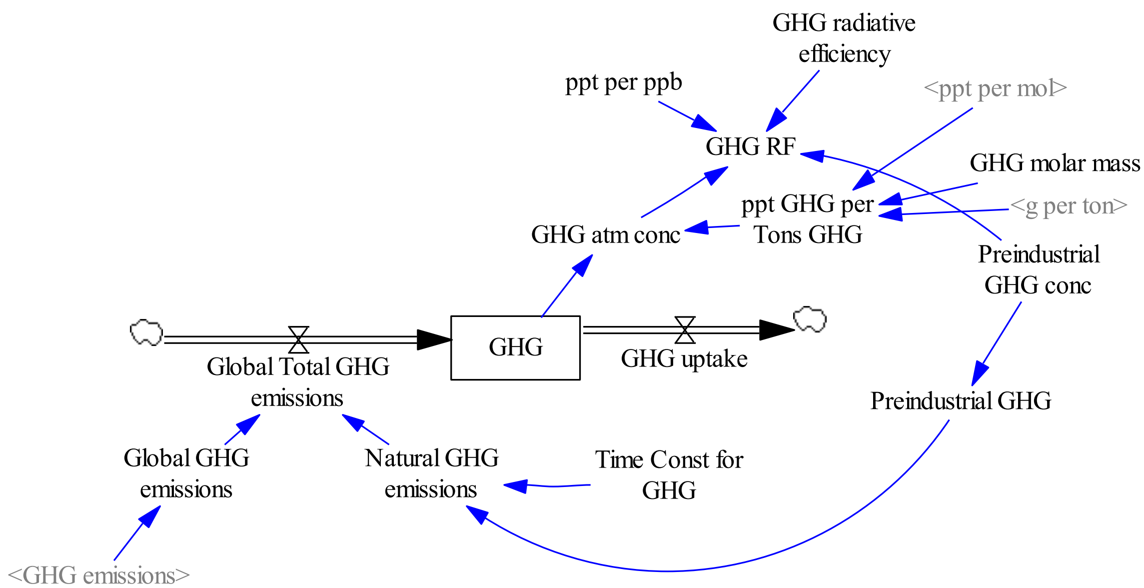


Figure 8-3 CH_4 cycle

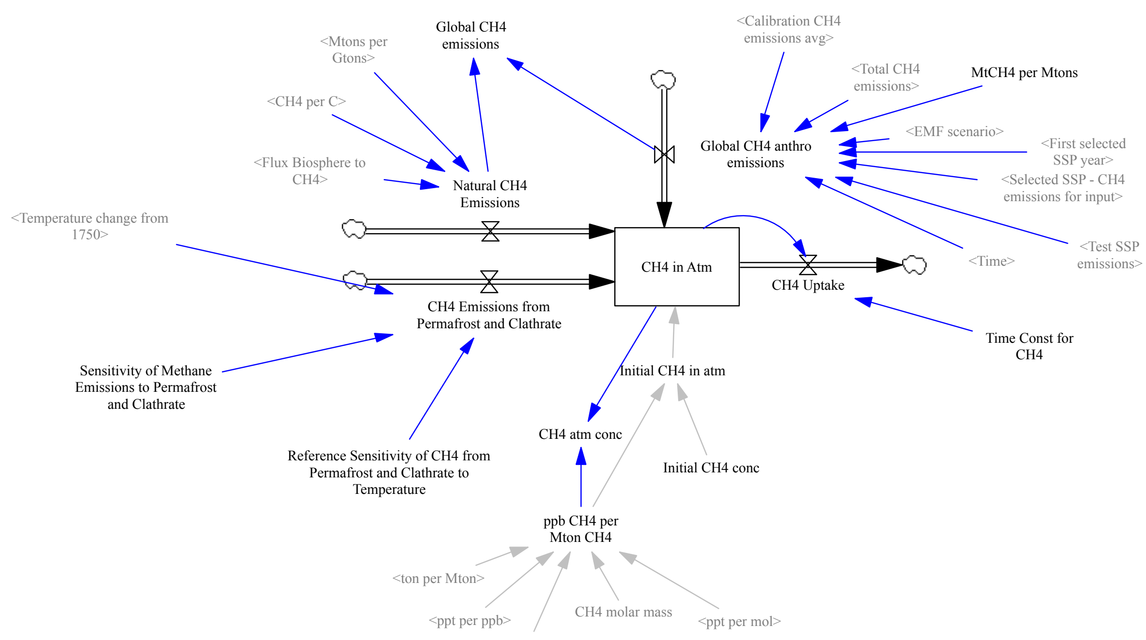


Table 8-4 Calculated Parameters of Other GHG Cycles

Parameter	**Definition**	**Units**
GHG Uptake	GHG/Time constant for GHG	CH4: MtonsCH4/year N2O: MtonsN2O-N/year PFCs: tonsCF4/year SF6: tonsSF6/year HFCs: tonsHFC/year
Mass of GHG	The mass of GHG in the atmosphere at each time: INTEG(Global GHG Emissions-GHG Uptake, Initial GHG mass)	CH4: MtonsCH4 N2O: MtonsN2O-N PFCs: tonsCF4 SF6: tonsSF6 HFCs: tonsHFC/year
Preindustrial GHG mass	The mass of GHG in the atmosphere at the start of the simulation (1850) based on the initial concentration and the conversion to concentration. Preindustrial GHG conc/conversion mass to concentrations	CH4: MtonsCH4 N2O: MtonsN2O-N PFCs: tonsCF4 SF6: tonsSF6 HFCs: tonsHFC/year
ppt per mol	5.68e-009	ppt/mole
ppt GHG per ton GHG	ppt per mol/molar mass GHG*g per ton	Ppt/ton
ppb GHG per Mton GHG (CH4 and N2O)	ppt per mol/GHG molar mass*g per ton*ton per Mton/ppt per ppb	Ppb/Mton
GHG atm conc	Mass of GHG*conversion mass to concentration	CH4 and N2O: ppb All other GHGs: ppt
GHG RF	(GHG atm conc-Preindustrial GHG conc)*GHG radiative efficiency/ppt per ppb	Watt/(meter*meter)

*HFCs are modeled with the HFC type subscript, such that each HFC type moves through its own cycle independent of the other HFC types. The HFC RF is the sum of RFs from each HFC type

.

Table 8-5 Time Constants, Radiative Forcing Coefficients, 100-year Global Warming Potential, and Molar Mass of other GHGs[2]

Gas	Preindustrial concentration	Natural Emissions	Time Constant (years)[3]	Radiative Forcing Efficiency (watts/ppb/meter^2)	100-year Global Warming Potential (tonsCO2/ton gas)	Molar Mass (g/mole)
CH4	722 ppb	Flux Biosphere to CH4*CH4 per C*Mtons per Gtons	9.3	0.036 watts/meter^2	28 (includes indirect effects from enhancements of ozone and stratospheric water vapour)	16
N2O	270 ppb	11.2 Mtons/year	117	0.12 watts/meter^2	265	28 (N2O-N)
Fluorinated Gases						
PFCs (assuming CF4 equivalents)	40 ppt	Preindustrial PFC/Time Const for PFC (tons/year)	50000	0.09	6630	88
SF6	0	0	3200	0.57	23500	146
HFCs						
HFC 134a	0	0	13.4	0.19	1300	102
HFC23	0	0	222	0.18	12,400	70
HFC32	0	0	5.2	0.11	677	52
HFC125	0	0	28.2	0.23	3170	120
HFC143a	0	0	47.1	0.16	4800	84
HFC152a	0	0	1.5	0.1	138	66
HFC227ea	0	0	38.9	0.26	3350	170
HFC245ca	0	0	6.5	0.24	716	134
HFC4310mee	0	0	16.1	0.42	1650	252

[2] NOAA AGGI (2020), AR5 WG1 Chapter 8. Table 8.A.1. Lifetimes, Radiative Efficiencies and Metric Values, AR5 WG1 Chapter 6 Table 6.9

[3] Value of CH4 and N2O time constants reported in AR5 WG1 Chapter 8 Table 8.A.1 noted to be for calculation of GWP, not for cycle. ("Perturbation lifetime is used in the calculation of metrics"). Values for their atmospheric time constants determined through optimization.

Figure 8-4 RF of CH_4 and N_2O

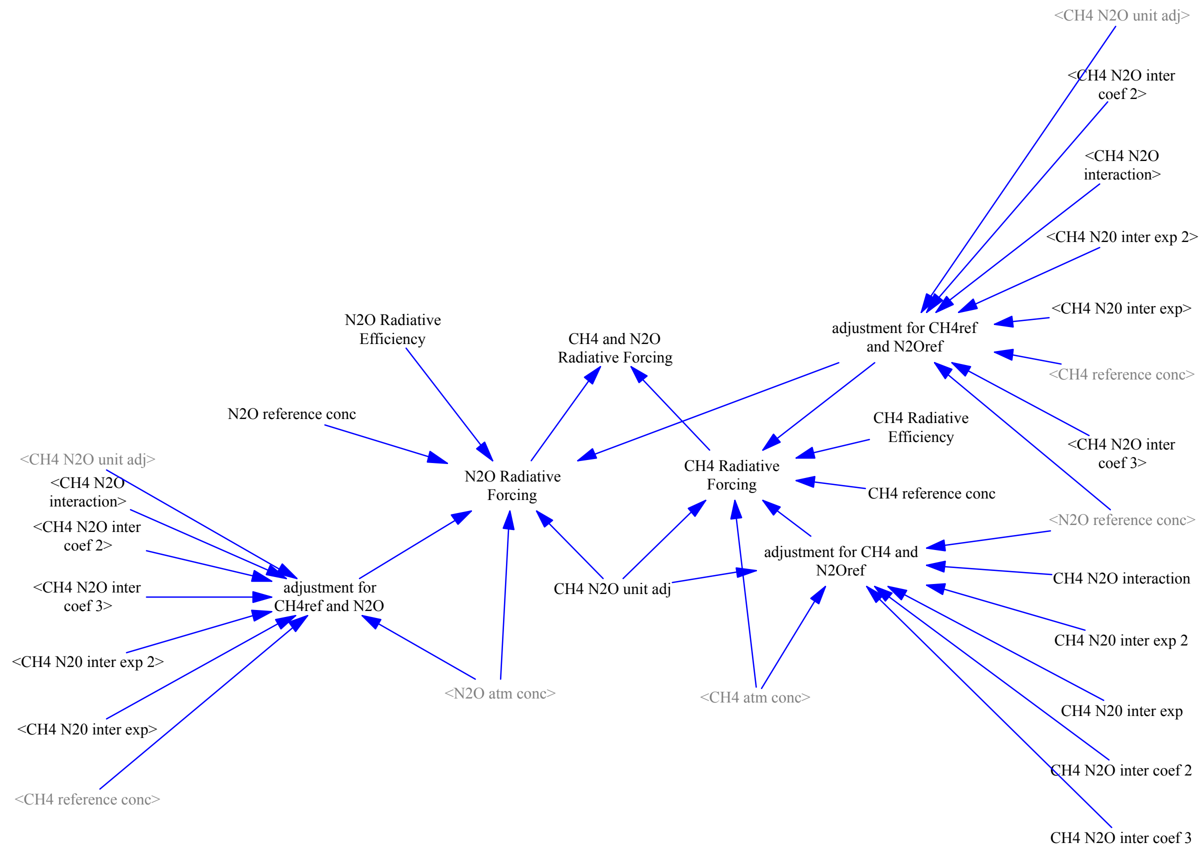


Table 8-6 CH_4 and N_2O RF Input and Calculated Parameters

Parameter	Definition	Value	Units	Source
N_2O concentration at reference year	Assumes reference year of 1750	270	Ppb	AR5, 2014; NOAA, 2020
CH_4 concentration at reference year	Assumes reference year of 1750	722	Ppb	
CH_4 and N_2O Radiative Forcing	The sum of the unit radiative forcing due to CH_4 and N_2O: CH4 Radiative Forcing + N2O Radiative Forcing		Watt/(meter^2)	
N2O Radiative Forcing	Adjusts total RF from CH_4 and N_2O to be less than the sum of RF from each individually to account for interactions between both gases. N2O Radiative Efficiency*(sqrt(N2O atm conc*CH4 N2O unit adj)-sqrt(N2O reference conc*CH4 N2O unit adj))-(adjustment for CH4ref and N2O-adjustment for CH4ref and N2Oref)		Watt/(meter^2)	
CH4 Radiative Forcing	Adjusts total RF from CH_4 and N_2O to be less than the sum of RF from each individually to account for interactions between both gases. CH4 Radiative Efficiency*(sqrt(CH4 atm conc*CH4 N2O unit adj)-sqrt(CH4 reference conc*CH4 N2O unit adj))-(adjustment for CH4 and N2Oref-adjustment for CH4ref and N2Oref)		Watt/(meter^2)	

Table 8-6 CH_4 and N_2O RF Input and Calculated Parameters

Parameter	Definition	Value	Units	Source
adjustment for CH4ref and N2O	CH4 N2O interaction * LN(1 +CH4 N2O inter coef 2 *(CH4 reference conc*N2O atm conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp +CH4 N2O inter coef 3 *CH4 reference conc*CH4 N2O unit adj *(CH4 reference conc*N2O atm conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp 2)		Watt/(meter^2)	
adjustment for CH4 and N2Oref	CH4 N2O interaction * LN(1 +CH4 N2O inter coef 2 *(CH4 atm conc*N2O reference conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp +CH4 N2O inter coef 3 *CH4 atm conc*CH4 N2O unit adj *(CH4 atm conc*N2O reference conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp 2)		Watt/(meter^2)	
adjustment for CH4ref and N2Oref	CH4 N2O interaction * LN(1 +CH4 N2O inter coef 2 *(CH4 reference conc*N2O reference conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp +CH4 N2O inter coef 3 *CH4 reference conc*CH4 N2O unit adj *(CH4 reference conc*N2O reference conc *CH4 N2O unit adj*CH4 N2O unit adj)^CH4 N20 inter exp 2)		watt/(meter^2)	

8.2.2 Montréal Protocol Gases

Rather than explicitly modeling the cycles of the Montreal Protocol (MP) gases, whose emissions are dictated by the MP, En-ROADS uses the calculated RF for historical and projected concentrations, inputted as a data variable.

8.3 Cumulative Emissions

En-ROADS calculates the cumulative CO_2 and CO_2eq with the initial value taken as the 1990 C-ROADS value starting in 1870. Cumulative emissions are determined through the simulation. The trillionth ton is a marker of cumulative emissions above which a two degree future is far less likely. Budgets are also presented from 2011 and from 2018, based on IPCC thresholds.

Figure 8-5 Cumulative Emissions

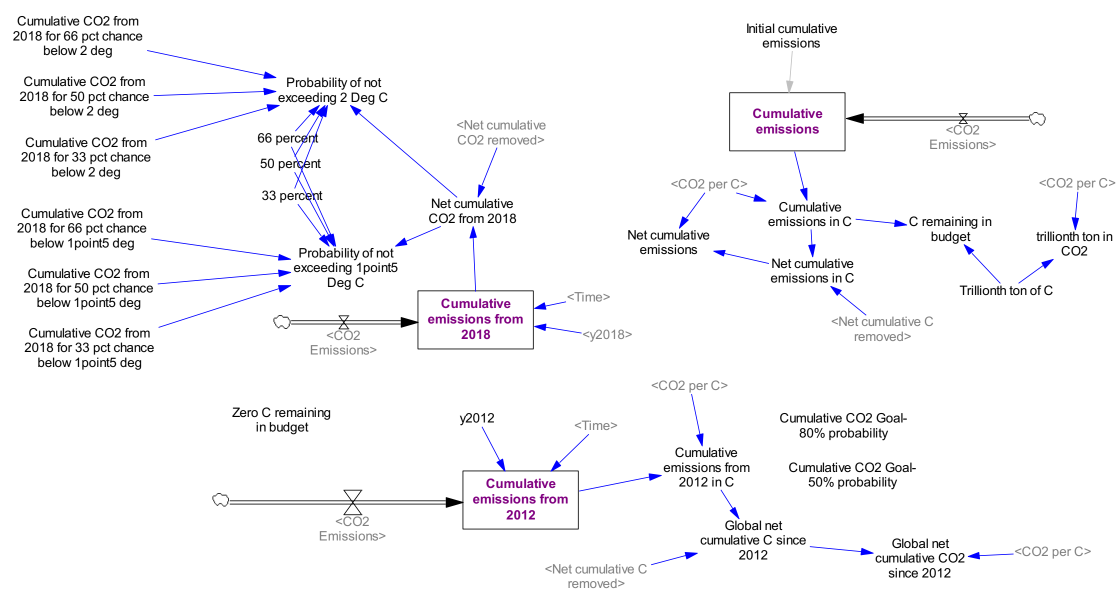


Table 8-7 Cumulative CO_2 Emissions Input Parameters

Parameter	Definition	Units
Initial cumulative emissions	1870 value from C-ROADS CP with start time set to 1870. 1097	GtonsCO2
trillionth ton	1000	GtonsC
Cumulative CO2 from 2018 for 66 pct chance below 2 deg	1170	GtonsCO2
Cumulative CO2 from 2018 for 50 pct chance below 2 deg	1500	GtonsCO2
Cumulative CO2 from 2018 for 33 pct chance below 2 deg	2030	GtonsCO2
Cumulative CO2 from 2018 for 66 pct chance below 1point5 deg	420	GtonsCO2
Cumulative CO2 from 2018 for 50 pct chance below 1point5 deg	580	GtonsCO2
Cumulative CO2 from 2018 for 33 pct chance below 1point5 deg	840	GtonsCO2
"Cumulative CO2 Goal- 80% probability"	Threshold from 2012. 565	GtonsCO2
"Cumulative CO2 Goal- 50% probability"	Threshold from 2012. 1100	GtonsCO2

Table 8-8 Cumulative CO_2 Emissions Calculated Parameters

Parameter	Definition	Units
Cumulative emissions	The cumulative CO2 emissions at each time. INTEG(CO2 Emissions, Initial cumulative emissions)	GtonsCO2
Cumulative emissions in C	Cumulative emissions/CO2 per C	GtonsC
trillionth ton in CO2	trillionth ton*CO2 per C	GtonsCO2
C remaining in budget	Amount of cumulative C left until the trillionth ton is reached Trillionth ton of C-Cumulative emissions in C	GtonsC
Cumulative emissions from 2018	The cumulative CO2 emissions at each time starting at 2018 to assess how much more CO2 is entering the atmosphere moving forward. To be compared to the cumulative CO2 for 33%, 50%, and 66% likelihood of exceeding 1.5 and 2 deg C. INTEG(IF THEN ELSE(Time<y2018, 0, CO2 Emissions), 0)	GtonsCO2
Cumulative emissions from 2018 in C	Cumulative emissions from 2012/CO2 per C	GtonsC
Net cumulative CO2 from 2018	Cumulative emissions from 2018-Net cumulative CO2 removed	GtonsC
Cumulative CO2 from 1870 for 66 pct chance below 2 deg	Cumulative CO2 from 2018 for 66 pct chance below 2 deg+Cumulative emissions from 1870 in 2018	GtonsCO2
Cumulative CO2 from 1870 for 66 pct chance below 1point5 deg	Cumulative CO2 from 2018 for 66 pct chance below 1point5 deg+Cumulative emissions from 1870 in 2018	GtonsCO2
Cumulative emissions from 2012	The cumulative CO2 emissions at each time starting at 2012 to assess how much more CO2 is entering the atmosphere moving forward. To be compared to the cumulative CO2 for 50% and 80% of limiting temperature change to 2 deg C. INTEG(IF THEN ELSE(Time<y2012, 0, CO2 Emissions), 0)	GtonsCO2
Cumulative emissions from 2012 in C	Cumulative emissions from 2012/CO2 per C	GtonsC

Table 8-8 Cumulative CO_2 Emissions Calculated Parameters

Parameter	Definition	Units
Global net cumulative C since 2012	Cumulative emissions from 2012 in C-Net cumulative C removed	GtonsC
Probability of not exceeding 2 Deg C	IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 66 pct chance below 2 deg, "66 percent", IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 50 pct chance below 2 deg, "50 percent", IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 33 pct chance below 2 deg, "33 percent", 0)))	Percent
Probability of not exceeding 1point5 Deg C	IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 66 pct chance below 1point5 deg, "66 percent", IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 50 pct chance below 1point5 deg, "50 percent", IF THEN ELSE(Net cumulative CO2 from 2018<Cumulative CO2 from 2018 for 33 pct chance below 1point5 deg, "33 percent", 0)))	Percent

9. Climate

9.1 Introduction

Like the carbon cycle, the climate sector is adapted from the FREE model, which used the DICE climate sector without modification (Nordhaus 1994). The DICE structure in turn followed Schneider and Thompson (1981).

The model has been recast in terms of stocks and flows of heat, rather than temperature, to make the physical process of accumulation clearer to users. However, the current model is analytically equivalent to the FREE and DICE versions.

FREE and DICE used exogenous trajectories for all non-CO_2 radiative forcings. This version adds explicit forcings from CH_4 and N_2O.

9.2 Structure

The model climate is a fifth-order, linear system, with three negative feedback loops. Two loops govern the transport of heat from the atmosphere and surface ocean, while the third represents warming of the deep ocean. Deep ocean warming is a slow process, because the ocean has such a large heat capacity. If the deep ocean temperature is held constant, the response of the atmosphere and surface ocean to warming is first-order.

Temperature change is a function of radiative forcing (RF) from greenhouse gases and other factors, feedback cooling from outbound longwave radiation, and heat transfer from the atmosphere and surface ocean to the deep ocean layer (Figure 9-3 and Eq. 7 & 8).

Eq. 7

$$T_{surf} = Q_{surf}/R_{surf}$$

$$T_{deep} = Q_{deep}/R_{deep}$$

$$Q_{surf} = \int (RF(t) - F_{out}(t) - F_{deep}(t))dt + Q_{surf}(0)$$

$$Q_{deep} = \int F_{deep}(t)\, dt + Q_{deep}(0)$$

T = Temperature of surface and deep ocean boxes *F_{deep} = heat flux to deep ocean*
Q = heat content of respective boxes *RF = radiative forcing*
R = heat capacity of respective boxes *F_{out} = outgoing radiative flux*

Eq. 8

$$F_{out}(t) = \lambda\, T_{surf}$$

$$F_{deep}(t) = R_{deep}*(T_{surf}-T_{deep})/\tau$$

λ = climate feedback parameter *τ = heat transfer time constant*

Radiative forcing from CO_2 is logarithmic of the atmospheric CO_2 concentration (IPCC AR5, 2014; NOAA, 2020). Forcing from CH_4 and N_2O is less than the sum of RF from each individually to account for interactions between both gases. Forcing from each F-gas is the

product of its concentration and its radiative forcing coefficient; the total forcings of F-gases is the sum of these products, as are the forcings from MP gases derived. The sum of other forcings, which include those from aerosols (black carbon, organic carbon, sulfates), tropospheric ozone, defaults to an exogenous time-varying parameter. The values use a composite of Meinshausen et. al (2011) history 1765-2005 and their projections for RCP6.0 through 2100.

The equilibrium temperature response to a change in radiative forcing is determined by the radiative forcing coefficient, κ, and the climate feedback parameter, λ. Equilibrium sensitivity to $2xCO_2eq$ forcing is 3C in the base case.

$$T_{equil} = \frac{\kappa \ln\left(\frac{C_a}{C_{a,0}}\right)}{\lambda \ln(2)} \qquad \text{Eq. 9}$$

T_{equil} = equilibrium temperature
C_a = atmospheric CO_2 concentration
$C_{a,o}$ = preindustrial atmospheric CO_2 concentration
κ = radiative forcing coefficient
λ = climate feedback parameter

Figure 9-1 Equilibrium Temperature Response

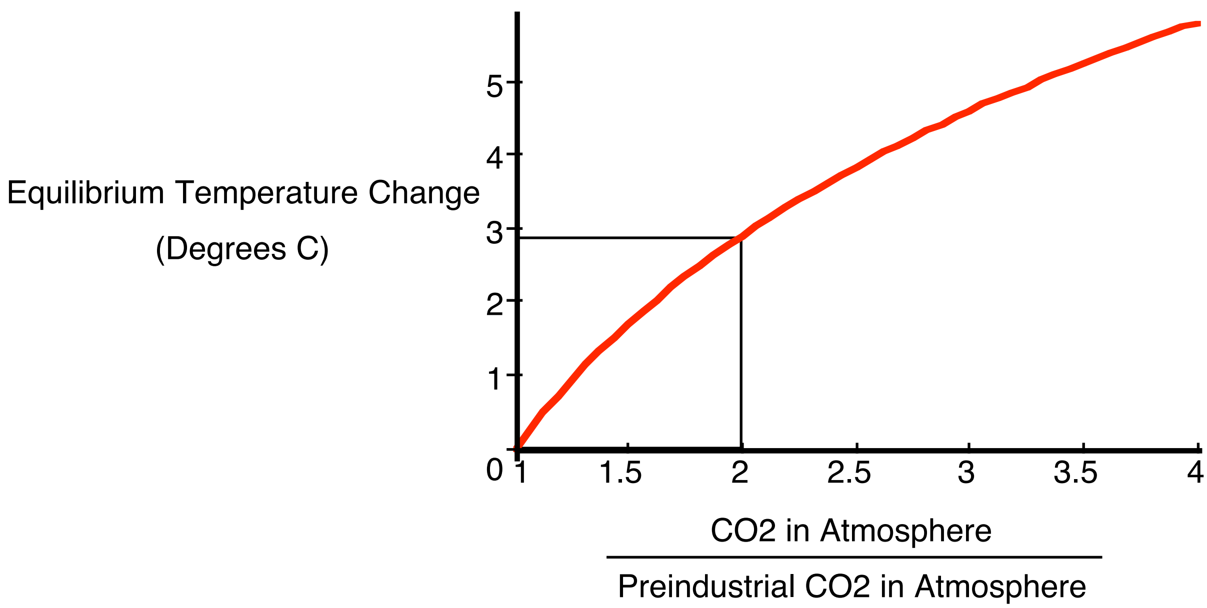


Figure 9-2 Radiative Forcings

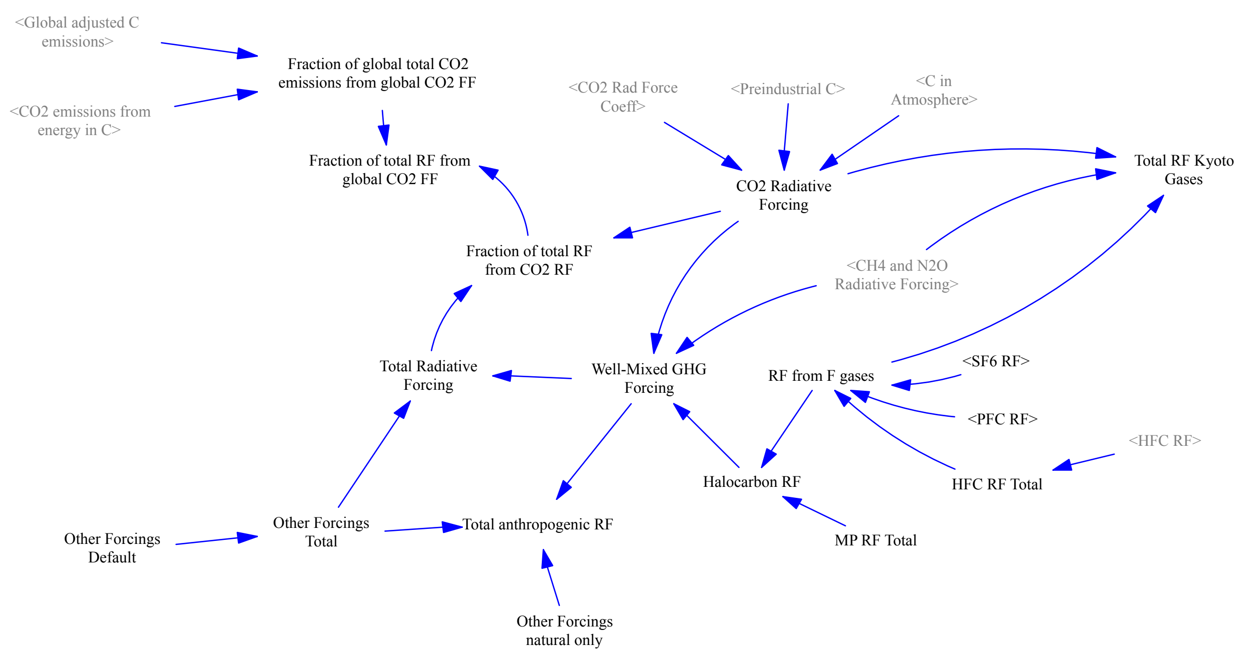


Figure 9-3 Climate Sector

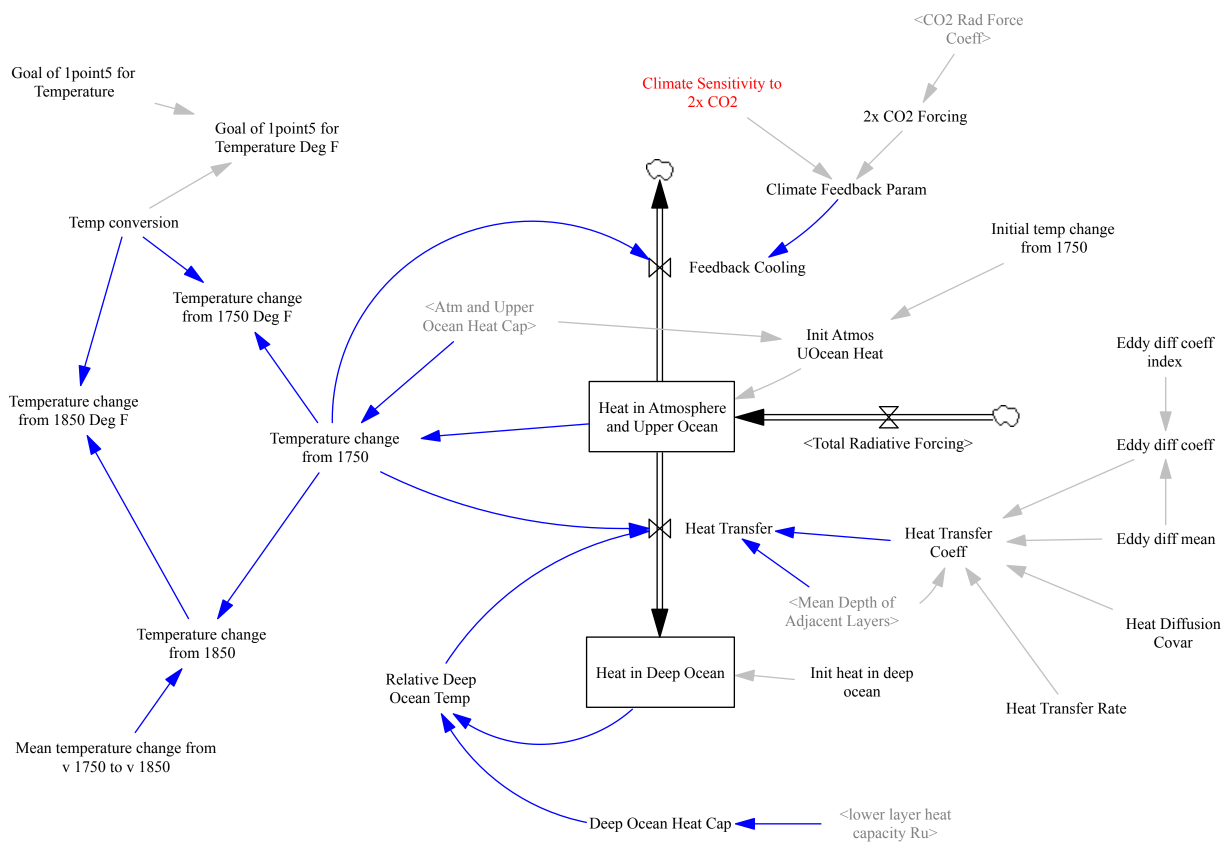


Table 9-1 Radiative Forcing and Temperature Parameter Inputs

Parameter	Definition	RS	Units	Source
Climate Sensitivity to 2x CO_2	Equilibrium temperature change in response to a 2xCO2 equivalent change in radiative forcing. According to AR5, high confidence that value likely between 1.5 and 4.5, with high confidence that extremely unlikely less than 1 and medium confidence that extremely unlikely greater than 6. Changed from AR4, for which lower likely limit was 2.	3	Degrees C	AR5, 2014.
CO_2 Rad Force Coeff	Coefficient of Radiative Forcing from CO2	5.35	Watt/meter^2	IPCC
Preindustrial CO_2	CO_2 content of atmosphere in 1750	590	GtonsC	
Initial temp change from 1750	Average of GISS (2020) and HADCRUT5 (2020) temp anomaly adjusted to v 1750 in 1990	0.77	Deg C	GISS (2020); Hadley (2020)
Init Heat in Deep Ocean[layers]	Initial deep ocean heat (relative to preindustrial). Data input from 1990 value in C-ROADS.		watt*Year/ meter^2	Based on 1990 levels in C-ROADS.
Heat Transfer Rate	Rate of heat transfer between the surface and deep ocean.	1.23	watt/meter^2/ DegreesC	Schneider & Thompson (1981), calibrated to more closely reflect MAGICC 5.3 results..
Area	Global surface area.	5.1e+014	Meter^2	

Table 9-1 Radiative Forcing and Temperature Parameter Inputs

Parameter	Definition	RS	Units	Source
Land thickness	Effective land area heat capacity, expressed as equivalent water layer thickness	8.4	Meter	Schneider & Thompson (1981)
land area fraction	Fraction of global surface area that is land.	0.292	Dmnl	Schneider & Thompson (1981)
watt per J s	Converts watts to J/s.	1	watt/(J/s)	
days per year	Converts years to days.	365	days/year	
sec per day	Converts days to seconds.	86,400	S/day	
mass heat cap	Specific heat of water, i.e., amount of heat in Joules per kg water required to raise the temperature by one degree Celsius.	4186	J/kg/Degrees C	
Density	Density of water, i.e., mass per volume of water.	1000	kg/meter^3	
Goal for Temperature	Assumed threshold of temperature change above which irreversible climate changes may occur	2	Degrees C	
J per W Yr	365*24*60*60/1e+022; converts Joules*1e22 to watts*year	3.1536e-015	JoulesE22/watt/year	
Offset 700m heat	Calibration offset.	-16	JoulesE22	
Mean temperature change from v 1750 to v 1850	Estimate of 0.05 Degrees C from 1750 to 1850 from https://journals.ametsoc.org/view/journals/bams/98/9/bams-d-16-0007.1.xml and calculated from Moberg data.	0.05	Degrees C	GISS (2020); Hadley (2020); Moberg

Table 9-2 RF and Temperature Calculated Parameters

Parameter	**Definition**	**Units**
Radiative Forcing	Total Radiative Forcing from components: "Well-Mixed GHG Forcing"+Other Forcings Total	Watt/(meter^2)
Total anthropogenic RF	Other Forcings Total - Other Forcings natural only + "Well-Mixed GHG Forcing"	Watt/(meter^2)
CO2 Radiative Forcing	Radiative forcing from CO2 in the atmosphere relative to 1750. See Equation 9.	Watt/(meter^2)
CH4 and N2O Radiative Forcing	Adjusts total RF from CH4 and N2O to be less than the sum of RF from each individually to account for interactions between both gases, relative to 1750. See Section 8.2.	Watt/(meter^2)
Halocarbon RF	RF from F gases+MP RF Total, relative to 1750. See Section 8.2.	Watt/(meter^2)
MP RF	Radiative forcing due to Montreal Protocol gases, based on the concentration of each gas multiplied by its radiative forcing coefficient, relative to 1750. See Section 8.2. Data variable En-ROADS Data model	Watt/(meter^2)
RF from F gases	Radiative forcing due to fluorinated gases, based on the concentration of each gas multiplied by its radiative forcing coefficient. The RF of HFCs is the sum of the RFs of the individual HFC types, relative to 1750. See Section 8.2. PFC RF+SF6 RF+HFC RF total	Watt/(meter^2)
HFC RF total	SUM(HFC RF[HFC type!])	Watt/(meter^2)
Other Forcings Total	Composite time series of Meinshausen et. al (2011) history 1765-2005 and their projections for RCP6.0 through 2100. An adjustment shifts the total down by of 0.1 watts/meter^2 to reflect the average of natural forcings (volcano and solar) pre-1800.	Watt/(meter^2)
Heat in Deep Ocean		watt*Year/(meter^2)

Table 9-2 RF and Temperature Calculated Parameters

Parameter	Definition	Units
[upper]	Heat in each layer except for the bottom. INTEG(Heat Transfer[upper]-Heat Transfer[lower], Init Deep Ocean Temp*Deep Ocean Heat Cap[upper])	
[bottom]	Heat in the bottom layer. INTEG(Heat Transfer[bottom], Init Deep Ocean Temp*Deep Ocean Heat Cap[bottom])	
Relative Deep Ocean Temp[layers]	Temperature of each layer of the deep ocean. Heat in Deep Ocean[layers]/Deep Ocean Heat Cap[layers]	Degrees C
2x CO2 Forcing	Radiative forcing at 2x CO2 equivalent CO2 Rad Force Coeff*LN(2)	Watt/meter^2
Equilibrium Temperature	Ratio of Radiative Forcing to the Climate Feedback Parameter Radiative Forcing/Climate Feedback Param	Degrees C
Feedback Cooling	Feedback cooling of atmosphere/upper ocean system due to blackbody radiation. Temperature change from 1750*Climate Feedback Param	Watt/meter^2
Climate Feedback Param	Climate Feedback Parameter - determines feedback effect from temperature increase. "2x CO2 Forcing"/Climate Sensitivity to 2x CO2	Watt/meter^2/Degrees C
Init Atmos UOcean Heat	Initial temp change * Atm and Upper Ocean Heat Cap	watt*Year/(meter*meter)

Table 9-2 RF and Temperature Calculated Parameters

Parameter	**Definition**	**Units**
Heat Transfer[layers]	Heat Transfer from the atmosphere & upper ocean to the first layer of the deep ocean and from each layer of the deep ocean to the layer below it. Temp Diff*Deep Ocean Heat Cap/Heat Transfer Time	Watt/meter^2
Heat Transfer[layer1]	(Temperature change from 1750-Relative Deep Ocean Temp[layer1])*Heat Transfer Coeff/Mean Depth of Adjacent Layers[layer1]	
Heat Transfer[lower]	(Relative Deep Ocean Temp[upper]-Relative Deep Ocean Temp[lower])*Heat Transfer Coeff/Mean Depth of Adjacent Layers[lower]	
Heat Transfer Coeff	The ratio of the actual to the mean of the heat transfer coefficient, which controls the movement of heat through the climate sector, is a function of the ratio of the actual to the mean of the eddy diffusion coefficient, which controls the movement of carbon through the deep ocean. INITIAL((Heat Transfer Rate*Mean Depth of Adjacent Layers[layer1])*(Heat Diffusion Covar*(Eddy diff coeff/Eddy diff mean)+(1-Heat Diffusion Covar)))	watt/meter^2/(DegreesC/meter)
upper layer volume Vu	Water equivalent volume of the upper box, which is a weighted combination of land, atmosphere,and upper ocean volumes. area*(land area fraction*land thickness+(1-land area fraction)*Mixed Depth)	meter^3
lower layer volume Vu[layers]	Water equivalent volume of the deep ocean by layer. area*(1-land area fraction)*Layer Depth[layers]	meter^3

Table 9-2 RF and Temperature Calculated Parameters

Parameter	Definition	Units
volumetric heat capacity	Volumetric heat capacity of water, i.e., amount of heat in watt*year required to raise 1 cubic meter of water by one degree C. mass heat cap*watt per J s/sec per yr*density	watt*year/meter^3/DegreesC
Atm and Upper Ocean Heat Cap	Volumetric heat capacity for the land, atmosphere, and, upper ocean layer, i.e., upper layer heat capacity Ru; based on 70% 100m ocean layer and 30% 8.4m equiv land layer. INITIAL(upper layer volume Vu*volumetric heat capacity/area)	watt*year/DegreesC/meter^2
Deep Ocean Heat Cap[layers]	Volumetric heat capacity for the deep ocean by layer, i.e., lower layer heat capacity Ru. INITIAL(lower layer volume Vu[layers]*volumetric heat capacity/area)	watt*year/DegreesC/meter^2
Temperature change from 1750	Heat in Atmosphere and Upper Ocean/Atm and Upper Ocean Heat Cap	Degrees C
Temperature change from 1750 Deg F	Temperature change from 1750*temp conversion	Degrees F
Temp conversion	1.8	Degrees F/Degrees C
Temperature change from 1850	Temperature change from 1750 - Mean temperature change from v 1750 to v 1850	Degrees C
Temperature change from 1850 Deg F	Temperature change from 1850* Temp conversion	Degrees F

Table 9-2 RF and Temperature Calculated Parameters

Parameter	**Definition**	**Units**
Heat to 700m	Sum of the heat in the atmosphere and upper ocean and that in the top two layers of the deep ocean. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean and 300 m each for layers 1 and 2. Heat in Atmosphere and Upper Ocean*(1-land share) +Heat in Deep Ocean[layer1]+Heat in Deep Ocean[layer2]	watt*year/meter^2
Heat to 2000m	Heat to 2000m in deep ocean. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean, 300 m each for layers 1 and 2, and 1300 m for layer 3. Heat to 700m+Heat in Deep Ocean[layer3]	watt*year/meter^2
Heat to 700m J	Heat to 700 m in Joules*1e22 for the area covered by water. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean and 300 m each for layers 1 and 2. Heat to 700m*J per W Yr*(area*(1-land area fraction))+Offset 700m heat	JoulesE22
Heat to 2000m J	Heat to 2000 m in Joules*1e22 for the area covered by water. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean, 300 m each for layers 1 and 2, and 1300 m for layer 3. Heat to 2000m*J per W Yr*(area*(1-land area fraction))	JoulesE22

9.3 Sea Level Rise

SLR, the structure shown in Figure 9-4, is modeled using the Vermeer and Rahmstorf (2009) semi-empirical model in which the increase in SLR rises with mean global surface temperature and falls with faster rates of warming (to capture the delay in the response of ice sheet melt to temperature change). That model is estimated from historical data 1880-2000, a period with low levels of warming that therefore likely underestimates future sea level rise from the faster-than-historical rates of melt of the Greenland and Antarctic ice sheets, other glaciers, and in the mean size of winter snowpack now being experienced. The slider "Additional SLR from Ice Melt" allows users to capture these effects. Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. The sensitivity to ice sheet melting does not affect the historic period.

Figure 9-4 Structure of Sea Level Rise

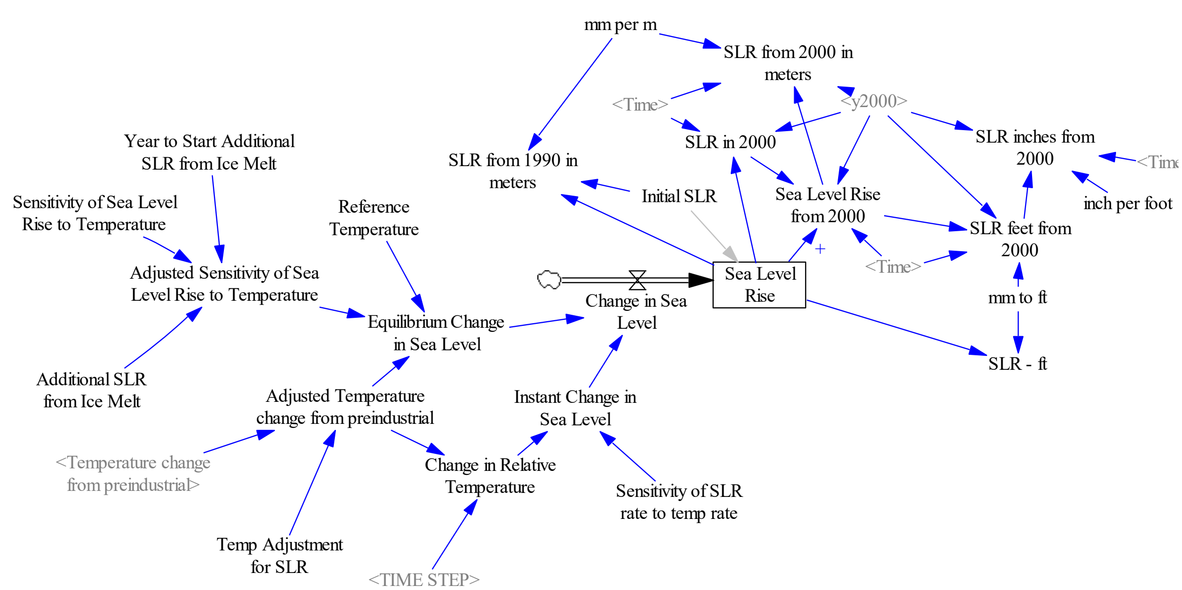


Table 9-3 Sea Level Rise Parameter Inputs

Parameter	Definition	Range	Default	Units
Init Sea Level Rise	Sea level rise in the initial simulation year. Data input from 1990 value in C-ROADS			mm
Sensitivity of Sea Level Rise to Temperature	Sensitivity of sea level rise to temperature anomaly. From V&R (2009) supplement, table S1. Rahmstorf (2007) uses 3.4	5.6	5.6	(mm/year) /degrees C
Additional SLR from Ice Melt	Allows users to capture the effects of future sea level rise from of the melt of Greenland and Antarctic ice sheets and other glaciers, and in the mean size of winter snowpack now being experienced, all of which are likely underestimated by the semi-empirical Vermeer and Rhamstorf 2009 model. Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. Does not affect the historic period.	0-5	0	(mm/year) /degrees C
Temp Adjustment for SLR	Adjustment to global surface temperature that is relative to pre-industrial levels from the average of the 1951-1980 data that Vermeer and Rahmstorf (2009) used based on GISTEMP. See V&R 2009 supplement.		0.2418	Degrees C
Reference Temperature	V&R (2009) temperature change at reference, to be subtracted from temperature change at each time.		-0.41	Degrees C
Sensitivity of SLR rate to temp rate	Slope of instantaneous temperature change - sea level change relationship (Vermeer & Rahmstorf, 2009) From V&R (2009) supplement, table S1. Rahmstorf (2007) uses 0 (i.e. term is missing)		-49	mm/DegreesC

Table 9-4 Sea Level Rise Calculated Parameters

Parameter	Definition	Units
Sea Level Rise	Estimated Sea Level Rise (from initial level) is the accumulation of the rate of sea level rise. Source: Vermeer and Rahmstorf (2009). INTEG(Change in Sea Level, Initial SLR)	mm
SLR in 2000	SLR until 2000, then caps at that level. SAMPLE IF TRUE(Time<=y2000 0, Sea Level Rise, Sea Level Rise)	mm
Sea Level Rise from 2000	Sea Level Rise indexed to zero in the year 2000. IF THEN ELSE(Time<y2000 0, :NA:, Sea Level Rise-SLR in 2000)	mm
Change in Sea Level	Proportional to the temperature difference (around a base year, defined here to be 1800). Equilibrium Change in Sea Level+Instant Change in Sea Level	mm/year
Adjusted Sensitivity of Sea Level Rise to Temperature	SLR is modeled using the Vermeer and Rahmstorf (2009) semi-empirical model in which the increase in SLR rises with mean global surface temperature and falls with faster rates of warming (to capture the delay in the response of ice sheet melt to temperature change). That model is estimated from historical data 1880-2000, a period with low levels of warming that therefore likely underestimates future sea level rise from the faster-than-historical rates of melt of the Greenland and Antarctic ice sheets, other glaciers, and in the mean size of winter snowpack now being experienced. The slider Additional SLR from Ice Melt allows users to capture these effects. Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. Does not affect the historic period. Sensitivity of Sea Level Rise to Temperature+STEP(Additional SLR from Ice Melt,Year to start additional SLR from ice melt)	mm/(year* DegreesC)

Table 9-4 Sea Level Rise Calculated Parameters

Parameter	Definition	Units
Equilibrium Change in Sea Level	Vermeer & Rahmstorf (2009) sea level rise rate (open loop approx to initial transient). Rahmstorf (2007) is recovered when Sensitivity of SLR rate to temp rate = 0. Adjusted Sensitivity of Sea Level Rise to Temperature*(Adjusted Temperature change from 1750-Reference Temperature)	mm/year
Adjusted Temperature change from 1750	Temperature change from 1750 levels adjusted to the model generated average global surface temperature that is used in the calculation of sea level rise from the Vermeer and Rahmstorf (2009) model. Temperature change from 1750-Temp Adjustment for SLR	DegreesC
Change in Relative Temperature	Approximates dT/dt (Adjusted Temperature change from 1750-SMOOTH(Adjusted Temperature change from 1750,TIME STEP))/TIME STEP	DegreesC/year
Instant Change in Sea Level	Vermeer & Rahmstorf (2009) instantaneous sea level rise rate on the time scales under consideration. Rahmstorf (2007) is recovered when Sensitivity of SLR rate to temp rate = 0. Sensitivity of SLR rate to temp rate*Change in Relative Temperature	mm/year

9.4 pH

Figure 9-5 shows the structure of the pH sector of C-ROADS, which reflects the empirical function presented by Bernie *et al.* (2010). Variable definitions and equations are presented in Table 9-5. As the atmospheric concentration in the atmosphere increases, the pH of the ocean decreases by a third order response. Figure 9-6 depicts the historical pH and projected pH for the default RS and the four RCP scenarios.

Figure 9-5 Structure of pH

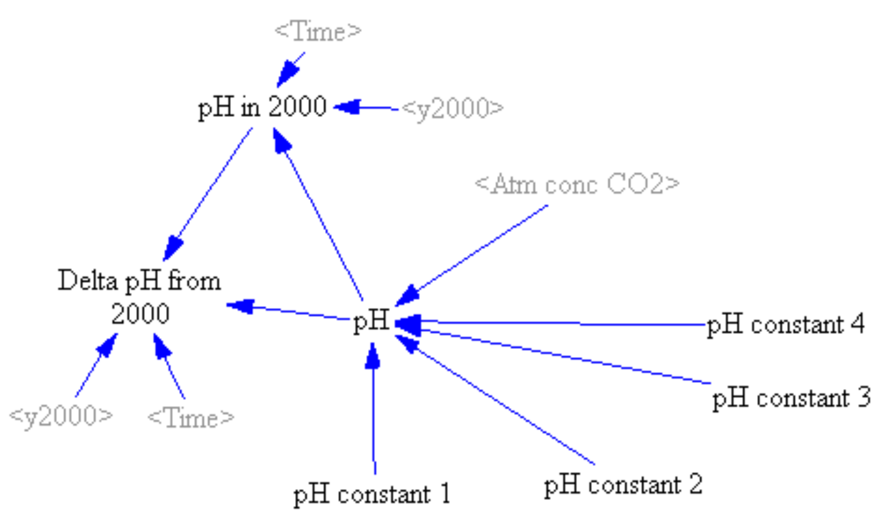
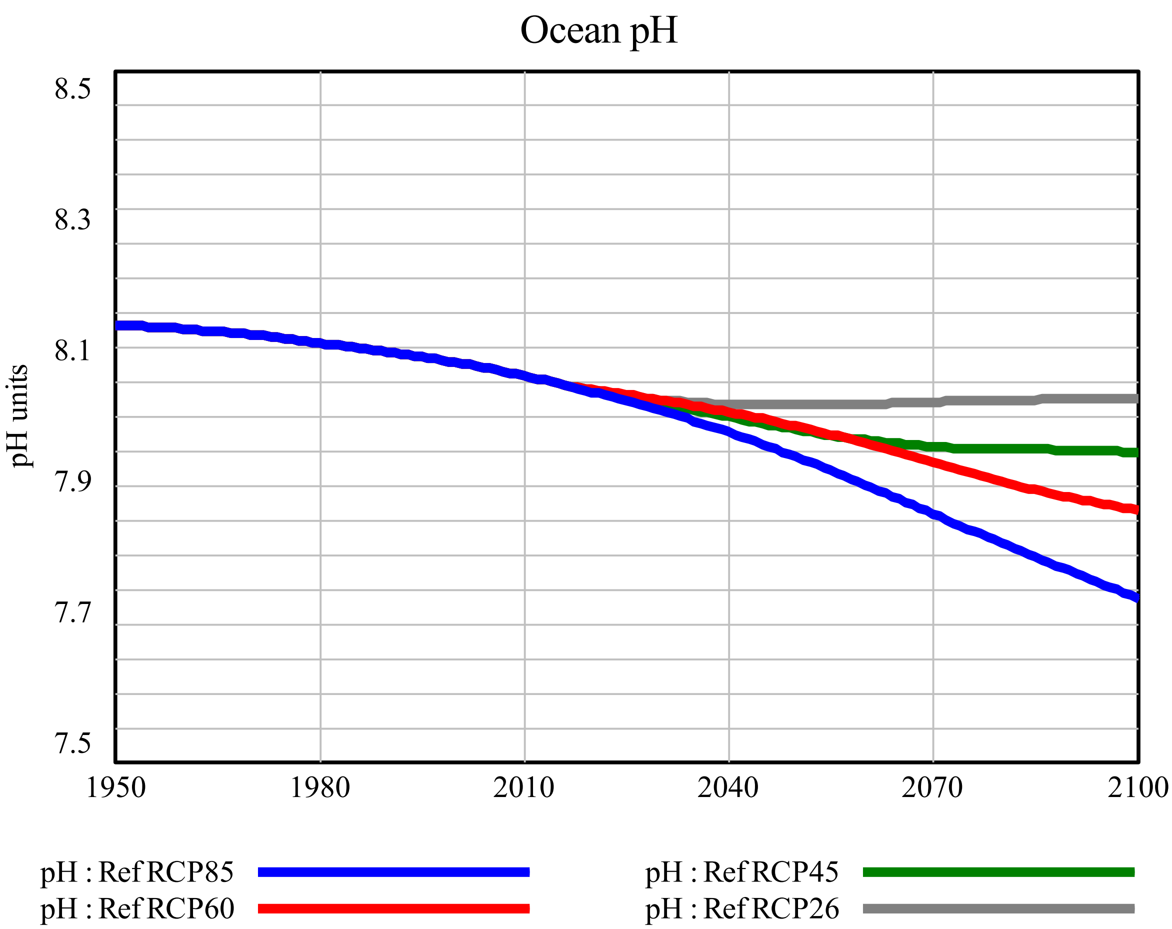


Table 9-5 pH Parameters

Parameter	Definition	Units	Source
pH	Estimated pH as a function of atmospheric CO2 concentration. pH constant 1-pH constant 2*Atm conc CO2+pH constant 3*Atm conc CO2^2-pH constant 4*Atm conc CO2^3	pH units	Bernie *et al.*, 2010
pH constant 1	8.5541	pH units	
pH constant 2	0.00173	1/(ppm)	
pH constant 3	1.3264e-006	1/(ppm*ppm)	
pH constant 4	4.4943e-010	1/(ppm*ppm*ppm)	
pH in 2000	SAMPLE IF TRUE(Time<=y2000, pH, pH)	pH units	
Delta pH from 2000	IF THEN ELSE(Time<y2000, :NA:, pH-pH in 2000)	pH units	

Figure 9-6 Ocean pH



9.5 Damage to GDP

9.5.1 Literature on damage function

In the scientific literature, aggregate economic impact of climate change is expressed as a fraction of 'annual income', global GDP or GDP per capita. It is formulated as an increasing function of global mean temperature change from preindustrial times. Figure 9-7 shows the main damage and damage function estimates in the literature, which are briefly described in the rest of this section.

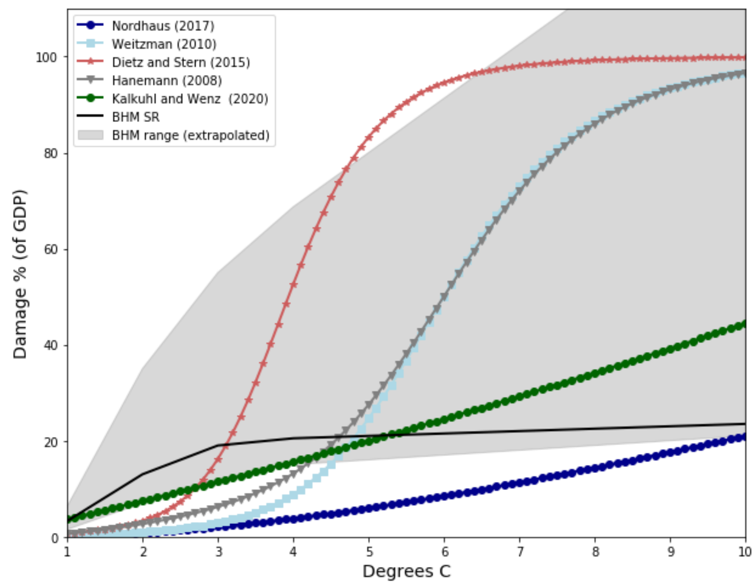


Figure 9-7: Damage function in the literature

9.5.1.1 IPCC AR5 (2014)[1]

Acknowledging the incompleteness of estimates, 0.2-2% loss of global annual income is expected at 2 °C warming (medium evidence, medium agreement). Losses are more likely to be greater, rather than smaller (limited evidence, high agreement). There are only a few quantitative estimates [at the time of the report] for additional warming around 3°C or above. Still, estimates of the incremental economic impact of emitting CO_2 lie between a few dollars and several hundreds of dollars per tonne of carbon (robust evidence, medium agreement).

9.5.1.2 Nordhaus

In 2007, Nordhaus estimated the damage to be 1.7% of output at 2.5°C warming [2]. This was formulated by Ackerman and Stanton[3] as

$$D(t) = 1 - \frac{1}{1 + \left(\frac{T(t)}{18.8}\right)^2} \quad (1)$$

In DICE-2013[4], Nordhaus defined a quadratic damage function as in Eq. 2, where T_{AT} is the atmospheric temperature change.

$$\Omega(t) = \Psi_1 T_{AT}(t) + \Psi_2 [T_{AT}(t)]^2 \quad (2)$$

This damage function was incorporated in the global output (*Q*) formulation with the term $1/\left(1 + \Omega(t)\right)$ as in Eq. 3 where Q^* is the pre-damage output.

$$Q(t) = \frac{Q^*(t)}{1 + \Omega(t)} \quad (3)$$

In 2013, Nordhaus calibrated the damage function as in Figure 9-8 based on the survey of Tol (2009)[5], resulting in less than 1% damage at 2°C warming and around 3.5% damage at 4°C. Due to the mistakes in the survey, Nordhaus updated the damage function calibration in 2016, keeping the function form the same. This new calibration resulted in the following estimates: "Including all factors, the final estimate is that the damages are **2.1% of global income at a 3 °C** warming, and **8.5% of income at a 6 °C** warming."[6]. Figure 9-9 depicts the changes over time in Nordhaus's damage functions, as illustrated by Keen (2020)[7].

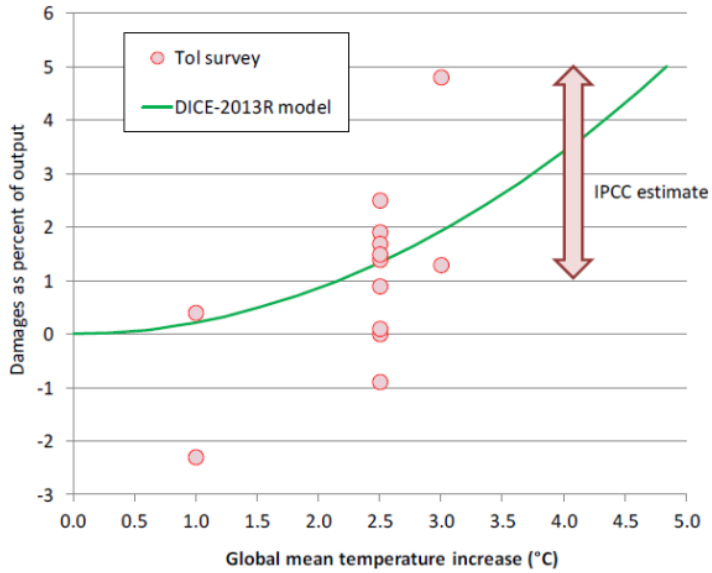


Figure 9-8: Damage function in DICE-2013

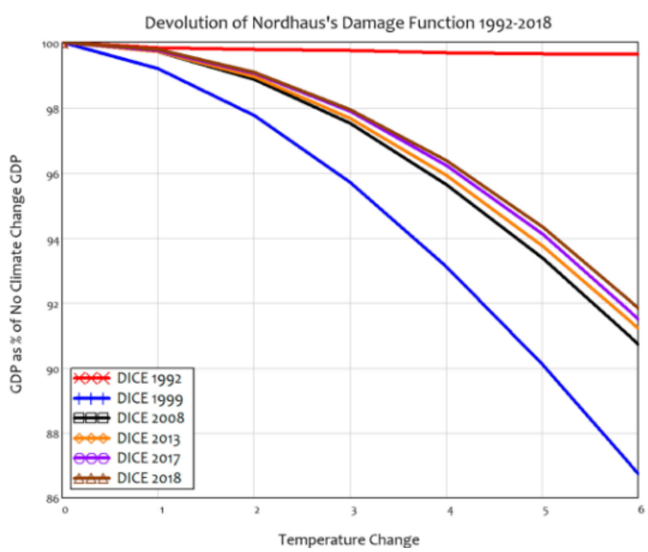


Figure 9-9: Nordhaus's revisions to the damage function. Source: Keen (2020)[7]

9.5.1.3 Weitzman

Weitzman's damage function[8] matches Nordhaus for low temperatures, and creates higher damage values at higher temperatures. Therefore, Weitzman's formulation resembles Eq. 1, but includes an additional term with a higher power of T, as in Eq. 4.

$$D(t) = 1 - \frac{1}{1 + \left(\frac{T(t)}{20.46}\right)^2 + \left(\frac{T(t)}{6.08}\right)^{6.754}} \qquad (4)$$

Note that Dietz and Stern add a linear term to this, attributed to Weitzman, when they cite Weitzman. Eq. 4 is the original formulation from Weitzman's own article.

9.5.1.4 Hanemann (as cited by Ackerman and Stanton)

Following Nordhaus and Weitzman, Hanemann estimated higher damages both at lower temperatures and higher temperatures. Ackerman and Stanton calibrated Weitzman's damage function to his damage estimates[9] as in Eq. 5:

$$D(t) = 1 - \frac{1}{1 + \left(\frac{T(t)}{12.2}\right)^2 + \left(\frac{T(t)}{6.24}\right)^{7.02}} \qquad (5)$$

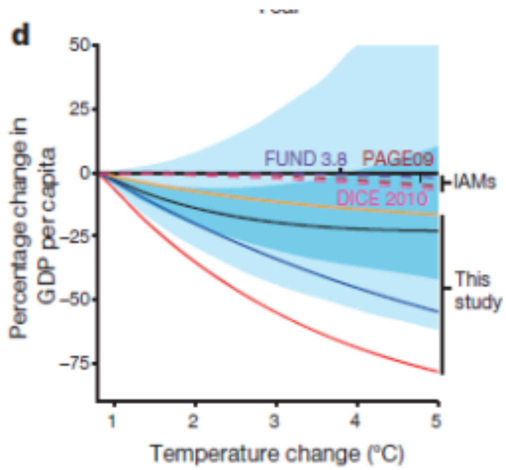
9.5.1.5 Dietz and Stern

Dietz and Stern[10] follow the formulation of Weitzman, yet assume 50% damage at 4 °C, which results in the following parameterization of the damage function:

$$D(t) = 1 - \frac{1}{1 + \left(\frac{T(t)}{12.2}\right)^2 + \left(\frac{T(t)}{4}\right)^{7.02}} \qquad (6)$$

9.5.1.6 Burke et al.

Burke et al. (2015)[11] estimate the macro impacts of climate change from micro impacts based on an extensive empirical study (e.g. daily temperature effect on labor productivity per person scaled up to annual and global). Unlike the previous economists, they do not define a damage function. They conclude that, taking nonlinearities into account, the damage is much higher than the earlier estimates, which is **21% of GDP per capita by 2100** on average. Wealthy countries are not unaffected. Figure 9-10 shows their estimates for the damage on GDP per capita compared to three IAMs (DICE, FUNC and PAGE). Blue shaded areas show the interquartile range and 5^{th}-95^{th} percentiles. Their estimates take different responses by countries into account. In the 'pooled response' formulation, rich and poor countries are assumed to respond identically to the temperature change. Short run estimates account for 1 year of temperature, whereas long run estimates account for 5 years of temperature change.



	Pooled response	Differentiated response
Short run	**Black line**	**Yellow line**
Long run	**Red line**	**Blue line**

Figure 9-10: Damage estimates of Burke et al. (BHM)[11]

In their 2018 study[12] where they focus on the impact of mitigation targets, they estimate 15%–25% loss in GDP per capita by 2100 for 2.5–3°C warming, and more that 30% for 4°C. BHM damage function is widely used in recent studies that analyze the social cost of carbon[13–15].

9.5.1.7 Kalkuhl and Wenz

Based on a new dataset of historical GDP and temperature values of >1500 regions and 77 countries, they estimate 7-14% reduction in global GDP by 2100 for 3.5°C warming. They update Nordhaus's damage function as in Eq. 7 where T_0 is the initial temperature (i.e. preindustrial). They estimate β=-0.0018, and α=-0.0373 for population weighted global damages. (Their model is on a regional basis, so they estimate the global damage with population-weighting).

$$D(t) - 1 = (\alpha + \beta T_0)T(t) + \frac{\beta}{2}T(t)^2 \qquad (7)$$

9.5.1.8 Keen

Keen[7] provides a critique of Nordhaus and other neoclassical economists' damage functions, rather than suggesting a new approach. The figure he composed based on several damage estimates (Figure 9-11) shows a wide range.

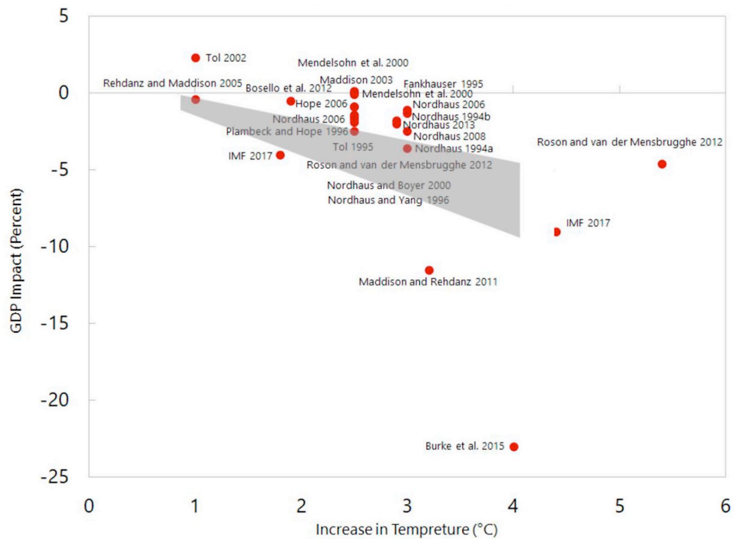


Figure 9-11: Collection of different damage estimates and the linear extrapolation of GDP-temperature relationship between 1960 and 2014 (grey area) Source: Keen (2020)[7]

9.5.2 Modelling the damage function in En-ROADS

The literature has a variety of damage function forms and values. In En-ROADS, we would like to capture all these, and to allow users explore a wider variety of damage values while keeping the model robust. Specifically, we look for a function form that

- captures the damage function shapes and values presented in the literature
- allows parameterization based on easily understandable user inputs (sliders) such as "the damage % at 2°C warming" and/or the "maximum damage"
- saturates at the maximum damage value entered by the users or at 100% so that the damage and GDP values are kept in realistic ranges for extreme temperatures that can be generated by the model
- starts from a small value around 0 at the current warming value (1.1°C) so that we don't need to take past damages into account and re-calibrate the model for damage-inclusive GDP values.

These criteria are met by a logistic function. We use a logistic function formulation with three parameters, L, k and x_0, as in Equation 8, where L is the maximum damage, k refers to the steepness of the damage curve and x_0 is the inflection point.

$$D(t) = \frac{L}{1 + e^{-k(T(t) - x_0)}} \tag{8}$$

9.5.3 User inputs

The damage function is defined by two user inputs: **Reduction in GDP at 2°C from climate impacts** (D_2) and **Maximum reduction in GDP** (L). We need another point on the curve to be

able to define this function, and it is D_1, the damage at a reference temperature (T_{ref}). If the reference temperature is set to the current warming value (1.1°C[4]) and D_1 is set to a small damage value, for instance 0.5% or 0%, we ensure that the damage curve will start from almost zero in 2020. In other words, we will observe a gradually increasing damage from 2020 on in the simulations. Figure 9-12 illustrates these user inputs on an exemplary damage curve.

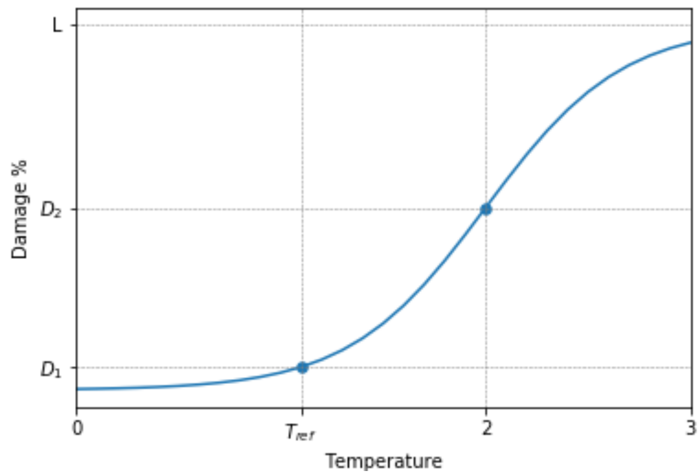


Figure 9-12: User inputs for the logistic damage function

The point D_1 is assumed to be fixed at a certain value, such as 0.5% at 1.1°C warming. Therefore, with the inputs *L and* D_2, the logistic function becomes

$$\frac{L}{1+e^{-k(T_{ref}-x_0)}} = D_1 \qquad (9)$$

$$\frac{L}{1+e^{-k(2-x_0)}} = D_2 \qquad (10)$$

From Equations 9 and 10, the parameters k and x_0 of the logistic function are derived as:

$$k = \frac{\ln\left(\frac{L-D_1}{D_1}\right) - \ln\left(\frac{L-D_2}{D_2}\right)}{2 - T_{ref}}, \qquad D_1, D_2 > 0, \qquad L > D_2, D_1 \qquad (11)$$

$$x_0 = \frac{T_{ref}\left(\frac{2}{T_{ref}}\ln\left(\frac{L-D_1}{D_1}\right) - \ln\left(\frac{L-D_2}{D_2}\right)\right)}{\ln\left(\frac{L-D_1}{D_1}\right) - \ln\left(\frac{L-D_2}{D_2}\right)} \qquad (12)$$

If the users enter an L value equal to D_2, the equations below are undefined because logarithm of 0 is undefined. In such cases, L is replaced by a slightly higher (10%) value in Equations 11 and 12, yet the damage function is capped at the L value entered by the user.

[4] The global mean temperature change from the preindustrial times is reported as 1.1°C by the World Meteorological Organization, and as 1.2°C by NASA.

9.5.4 Calibration of the EN-ROADS damage function to the literature

The logistic function given in Eq. 8 and modified with the parameter formulations in Eq. 11 and 12 can be calibrated to fit to the existing damage functions. For this purpose, we create the damage curves for the literature functions (Nordhaus, Weitzman, Dietz&Stern and Burke) for the range of 0 - 10 °C. Using the *curve_fit* function of Python package *scipy,* which uses a least squares approach for optimization, we find the input values that replicate the literature functions. Below, we present the calibration results for a logistic curve defined by two parameters: $\boldsymbol{D_2}$ *(damage at 2*°C*)* and ***L*** *(maximum damage)*, keeping $D_1=0.5$ (damage at T_{ref}) . The calibrated values of D_2 and L show what users can enter to replicate the literature functions, when we present them with two sliders only. For the Nordhaus, Weitzman and Dietz&Stern functions, we achieve a good fit to the original functions. For Burke, the difference is high especially for low temperatures since we set D_1 constant at 0.5% and the Burke et al.'s value for the damage at 1.1°C is around 4%. The literature functions can be better replicated if D_1 is a variable. However, we chose to keep it as a constant for simplicity of the user interface with only to inputs.

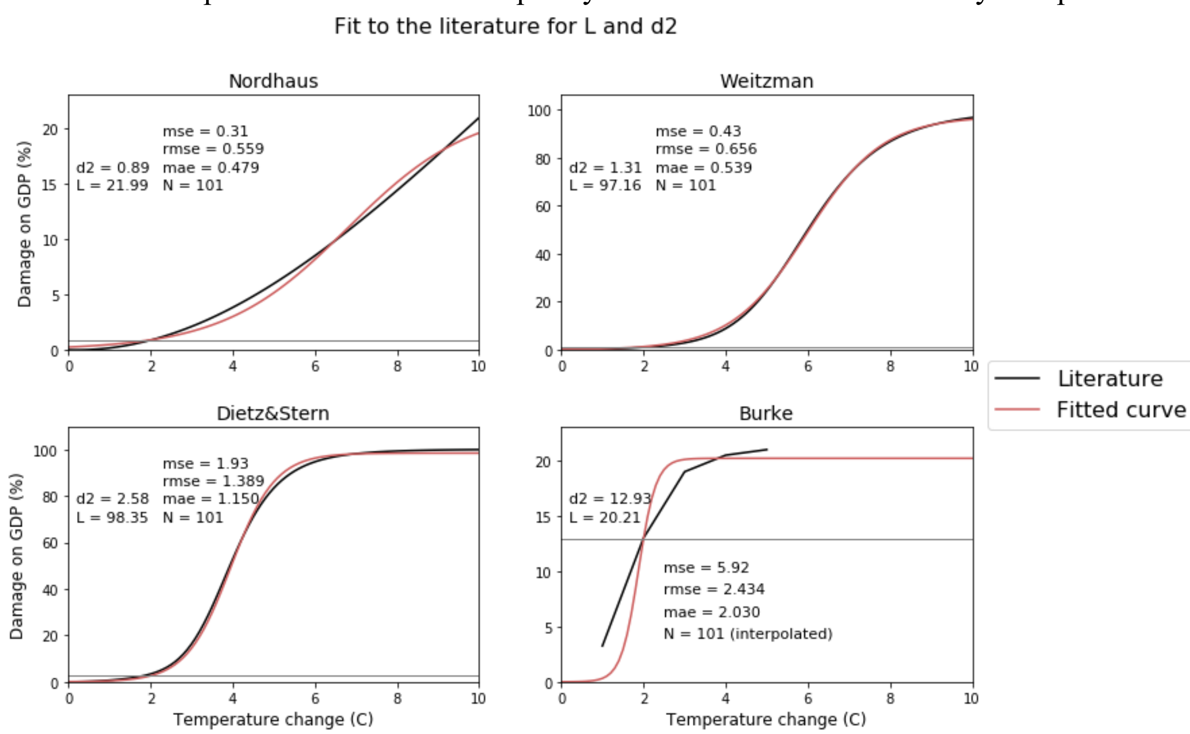


Figure 9-13: Calibration of the logistic damage function to the literature functions using two parameters. L and d2 stand for the maximum damage and the damage at 2°C. Metrics of the fit are shown on the figure, where *mse* is the mean squared error, *rmse* is the root mean squared error, *mae* is the mean absolute error, and *N* is the number of data points in the 0-10℃ range. For the damage function of Burke et al., we use a curve defined by 5 discrete points, and we interpolate it for calibration.

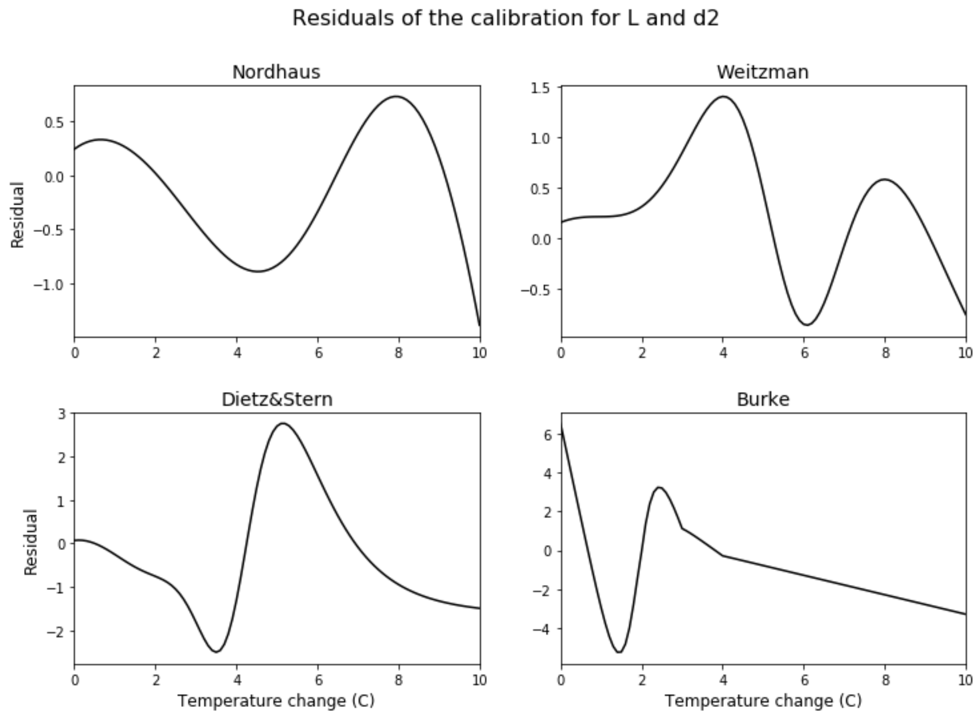


Figure 9-14: Residuals (model - data) of calibrating the 2-parameter logistic curve to the literature functions

9.5.5 Damage Function References

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9.6 Other Impacts

Section 9.5 shows the structure of other impacts; these are all determined through interpolation and extrapolation from literature as noted in Table 9-6.

Figure 9-15 Other Impacts

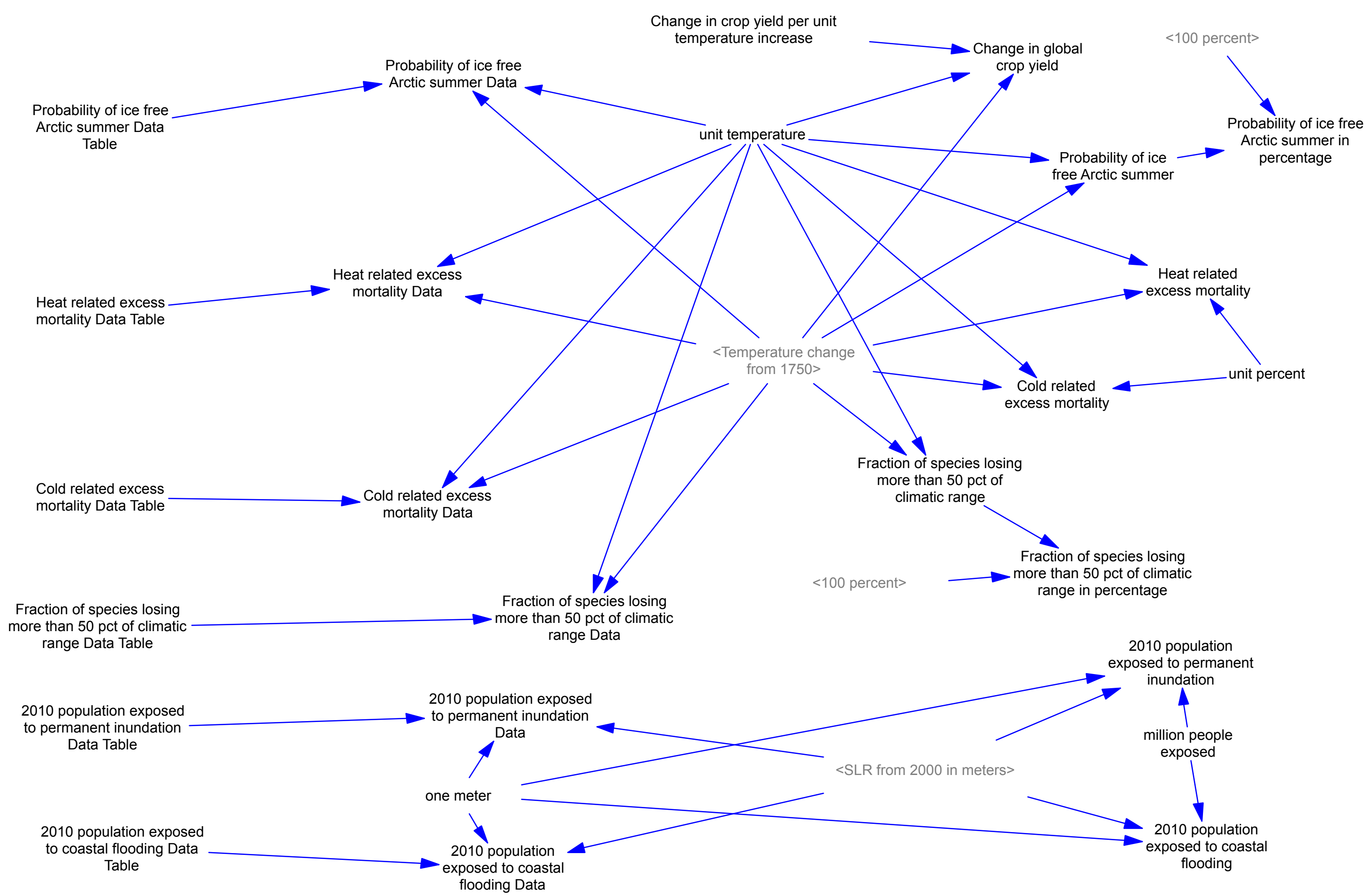


Table 9-6 Other Impacts Parameters

Parameter	Definition	Units
Probability of ice free Arctic summer	Probability of ice free Arctic summer Data Table (Temperature change from 1750 / unit temperature) Source: Sigmond, Michael, John C. Fyfe, and Neil C. Swart. "Ice-free Arctic projections under the Paris Agreement." Nature Climate Change 8.5 (2018): 404-408	1/Year
Heat related excess mortality[Extreme Temp Region]	Heat related excess mortality Data Table[Extreme Temp Region] (Temperature change from 1750 / unit temperature) Function of Temperature change from 1750. Source: Vicedo-Cabrera, Ana Maria, et al. "Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios." Climatic change 150.3-4 (2018): 391-402	Dmnl
Cold related excess mortality[Extreme Temp Region]	Cold related excess mortality Data Table[Extreme Temp Region] (Temperature change from 1750 / unit temperature) Function of Temperature change from 1750. Source: Vicedo-Cabrera, Ana Maria, et al. "Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios." Climatic change 150.3-4 (2018): 391-402	People
Fraction of species losing more than 50 pct of climatic range Data[Species]	Fraction of species losing more than 50 pct of climatic range Data Table[Species] (Temperature change from 1750 / unit temperature) Function of Temperature change from 1750. Source: Warren, R., et al. "The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 C rather than 2 C." Science 360.6390 (2018): 791-79	person*days/Year
Change in crop yield per unit temperature increase[Crop]	Change in crop yield per unit temperature increase[Crop] * Temperature change from 1750 / unit temperature Function of Temperature change from 1750. Change in global yields per 1 C temperature increase:(a) wheat - down by 6.0%; (b) rice - down by 3.2%; (c)	Percent

Table 9-6 Other Impacts Parameters

Parameter	Definition	Units
	maize - down by 7.4%; (d) soybean - down by 3.1% Source: Zhao, Chuang, et al. "Temperature increase reduces global yields of major crops in four independent estimates." Proceedings of the National Academy of Sciences 114.35 (2017): 9326-9331	
Probability of ice free Arctic summer	Function of Temperature change from 1750. Trend: y = 0.0762x2 + 0.0595x - 0.2345 (R^2 = 1) Ice-free Arctic summer occurs when the average September sea-ice extent (SSIE) is less than one-million km-square, the threshold below which the Arctic ocean is virtually ice free with some multiyear ice remaining in the Canadian Arctic Archipelago and along the northern coasts of Greenland and Ellesmere Island. Source: Sigmond, Michael, John C. Fyfe, and Neil C. Swart. "Ice-free Arctic projections under the Paris Agreement." Nature Climate Change 8.5 (2018): 404-408	Dmnl
Heat related excess mortality[Extreme Temp Region]	North America: y = 0.1107x2 + 0.1821x + 0.1195 Central America y = 0.2626x2 - 0.0549x + 0.1425 South America: y = 0.2615x2 + 0.1426x + 0.5729 North Europe: y = 0.1356x2 - 0.1063x + 0.3773 Central Europe: y = 0.3533x2 - 0.2228x + 1.122 South Europe: y = 0.2875x2 + 0.8567x + 0.2203 East Asia: y = 0.1064x2 + 0.1226x + 0.1946 Southeast Asia: y = 0.6575x2 - 0.1283x + 1.2453 Australia y = 0.0147x3 - 0.002x2 + 0.2713x + 0.188 Function of Temperature change from 1750. Source: Vicedo-Cabrera, Ana Maria, et al. "Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios." Climatic change 150.3-4 (2018): 391-402	Percent
Cold related excess mortality[Extreme Temp Region]	North America: y = 0.0248x2 - 0.6268x + 5.8839 Central America y = 0.1673x2 - 1.8584x + 6.5586 South America: y = 0.0868x2 - 1.0221x + 3.9396 North Europe: y = 0.0329x2 - 0.9097x + 8.0109 Central Europe: y = 0.0214x2 - 0.7941x + 8.7652 South Europe: y = 0.0721x2 - 1.1036x + 7.1286 East Asia: y = 0.0823x2 - 1.3335x + 10.255 Southeast Asia: y = 0.2095x2 - 1.8487x + 4.8161 Australia y = 0.0573x2 - 1.4018x + 9.2197	Percent

Table 9-6 Other Impacts Parameters

Parameter	Definition	Units
	Function of Temperature change from 1750. Source: Vicedo-Cabrera, Ana Maria, et al. "Temperature-related mortality impacts under and beyond Paris Agreement climate change scenarios." Climatic change 150.3-4 (2018): 391-402	
Fraction of species losing more than 50 pct of climatic range[Species]	Invertebrates: y = -0.0326x2 + 0.4065x - 0.4861 Vertebrates y = 0.0055x2 + 0.1039x - 0.1362 Insects: y = -0.035x2 + 0.4178x - 0.4981 Plants: y = -0.0081x2 + 0.2502x - 0.2884 Mammals: y = 0.01x2 + 0.0647x - 0.0833 Birds : y = 0.0085x2 + 0.0778x - 0.1209 Butterflies and moths: y = -0.0101x2 + 0.248x - 0.3264 Dragonflies and damselflies: y = 0.0116x2 - 0.0017x - 0.0172 Function of Temperature change from 1750. Source: Warren, R., et al. "The projected effect on insects, vertebrates, and plants of limiting global warming to 1.5 C rather than 2 C." Science 360.6390 (2018): 791-79	Dmnl
2010 population exposed to permanent inundation	Trend: y = -10.368x2 + 185.16x + 101.14 (R^2 = 1) 2010-population exposed to permanent inundation due to sea level rise. Data (SLR, fraction of population exposed): (0.048, 110), (0.38, 170), (1.21, 310) Function of SLR. Source: Kulp, Scott A., and Benjamin H. Strauss. "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding." Nature communications 10.1 (2019): 1-12	Million people
"2010 population exposed to coastal flooding"	Trend: y = -72.579x2 + 272.03x + 237.11 (R^2 = 1) 2010-population exposed to permanent inundation due to sea level rise. Data (SLR, fraction of population exposed): (0.048, 250), (0.38, 330), (1.21, 460) Function of SLR. Source: Kulp, Scott A., and Benjamin H. Strauss. "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding." Nature communications 10.1 (2019): 1-12	Million people
"2010 population exposed to permanent inundation Data"	"2010 population exposed to permanent inundation Data Table" (SLR from 2000 in meters / one meter)	People

Table 9-6 Other Impacts Parameters

Parameter	Definition	Units
	Function of SLR. Source: Kulp, Scott A., and Benjamin H. Strauss. "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding." Nature communications 10.1 (2019): 1-12 Adapted from the source population exposure data using En-ROADS' 2010 population simulation.	
"2010 population exposed to coastal flooding Data"	"2010 population exposed to coastal flooding Data Table" (SLR from 2000 in meters / one meter) Function of SLR. Source: Kulp, Scott A., and Benjamin H. Strauss. "New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding." Nature communications 10.1 (2019): 1-12 Adapted from the source population exposure data using En-ROADS' 2010 population simulation.	Percent

10. Formulation of Air Quality–PM2.5

10.1 Air Quality–PM2.5

The **air quality sector** simulates annual global emissions of PM2.5. En-ROADS estimates annual global emissions from three sources: energy generation (electricity), energy generation (non electricity), and other sources (including agriculture and open fires).

Ambient PM2.5 is considered the leading environmental health risk factor globally and is a top 10 risk factor in countries across the economic development spectrum. PM2.5 is fine particulate matter as defined by the mass per cubic meter of air of particles with a diameter of <=2.5 micrometres (µm).

The components of PM2.5 are solid and liquid particles small enough to remain airborne and are defined as two forms:

1. Solids/liquid particles directly emitted to the atmosphere (primary PM)
2. Solids/liquid particles formed from gaseous precursors (secondary PM).

Components of PM2.5 may include (some of) the following:

- Carbons
- Sulfates
- Nitrates
- Chlorides
- Iron
- Calcium
- Other Organics (solid/liquid)

10.2 Sources of PM2.5 in En-ROADS – Overview

PM2.5 is generated from multiple sources. Figure 10-1 shows the % of emissions (2015) from various sources. The chart was from research *Global Sources of Fine Particulate Matter: Interpretation of PM2.5 Chemical Composition Observed by SPARTAN using a Global Chemical Transport Model* (Weagle et al).

En-ROADS aggregates these sources into the following sources:

1. *Energy-generation*
   a. Electricity production
   b. Energy (non electricity) production
2. *Non energy-generation*

Non energy sources includes: agriculture, open fires, and other sources.

10.3 PM2.5 from Energy Generation

En-ROADS calculates energy generated PM2.5 emissions by applying an emissions factor (million metric tons emitted per exajoule–by fuel source–expressed as MMT/EJ) to the annual rate of energy produced (EJ/Year–by fuel source).

For example, the calculation for PM2.5 from coal used in electricity production is:

PM2.5/Year from electricity (Coal) =PM2.5 EF Electricity(Coal) x EJ/Year Electricity(Coal)

where PM2.5 Emissions Factor (EF) Electricity(Coal)=MMT/EJ Electricity(Coal)
MMT=million metric tons

Figure 10-2 shows the general structure of PM2.5 emissions from energy generation. EFs for each fuel source are multiplied by the exajoules of energy generated (by source).

10.3.1 PM2.5 Emissions Factors (EFs)

Emissions factors (EFs) for fuel sources are calculated in several input-output models. En-ROADS applies EFs estimated from analysis by the International Institute for Applied Systems Analysis (IIASA). The EFs for coal, oil and gas were calculated using the GAINS model (IIASA) to estimate emissions/year from G20 countries/regions and then averaged. Countries included the United States, several EU countries, India (2 regions) and China (3 different regions). The EF for bio was calculated from the RAINS model (IIASA).

Estimates for EFs were not significantly different between electricity and non electricity (which includes industry). En-ROADS applies the same EFs to electricity and non electricity. Users can vary the EF assumption across a range (by source), with a range of 50% to 150% of the base EF (shown in the table below).

MMT/EJ	**Electricity**	**Non electricity**
COAL	0.1200	0.1200
OIL	0.0050	0.0050
GAS	0.0001	0.0001
BIO	0.0400	0.0400

10.3.2 PM2.5 Business as Usual Comparison

In order to compare a simulation scenario where energy generation by source is different from the business as usual (BAU) scenario, En-ROADS simultaneously calculates the BAU scenario using the equation logic inFigure 10-3. The BAU equations calculate the PM2.5 emissions MMT/Year (energy generated) that occurs under the BAU scenario by applying EFs to the BAU energy scenario (energy generation under the business as usual, no change of assumptions scenario). The BAU PM2.5 MMT/Year (energy generated) results are then compared to results generated from the equations in Table 10-2

The structure in Figure 10-3 applies look up tables that contain estimates from the BAU energy scenario.

10.4 PM2.5 from Non Energy Sources

Non energy sources of PM2.5 are estimated by applying a per capita EF to global population. The per capita EF is set at the start of the scenario year.

10.4.1 PM2.5 Emissions per Capita (E/Pop)

In 2015, non energy sources of PM2.5 accounted for 35% total PM2.5 emissions (MMT/Year). Prior to 2015, En-ROADs estimates non energy contribution to total as PM2.5 MMT/Year (non energy generated) is exactly 35% of total PM2.5 emissions.

The per capita PM2.5 MMT/Year/Billion People is calculated in 2015 (Scenario Year) by dividing global PM2.5 MMT/Year (non energy) by global population in billions (2015). For 2015 and remaining simulated years, PM2.5 MMT/Year (non energy) is calculated by multiplying global population (billions) by the 2015 emissions factor (per capita PM2.5 MMT/Year/Billion.)

Figure 10-4 diagrams the equation logic for PM2.5 emissions MMT/Year (non energy).

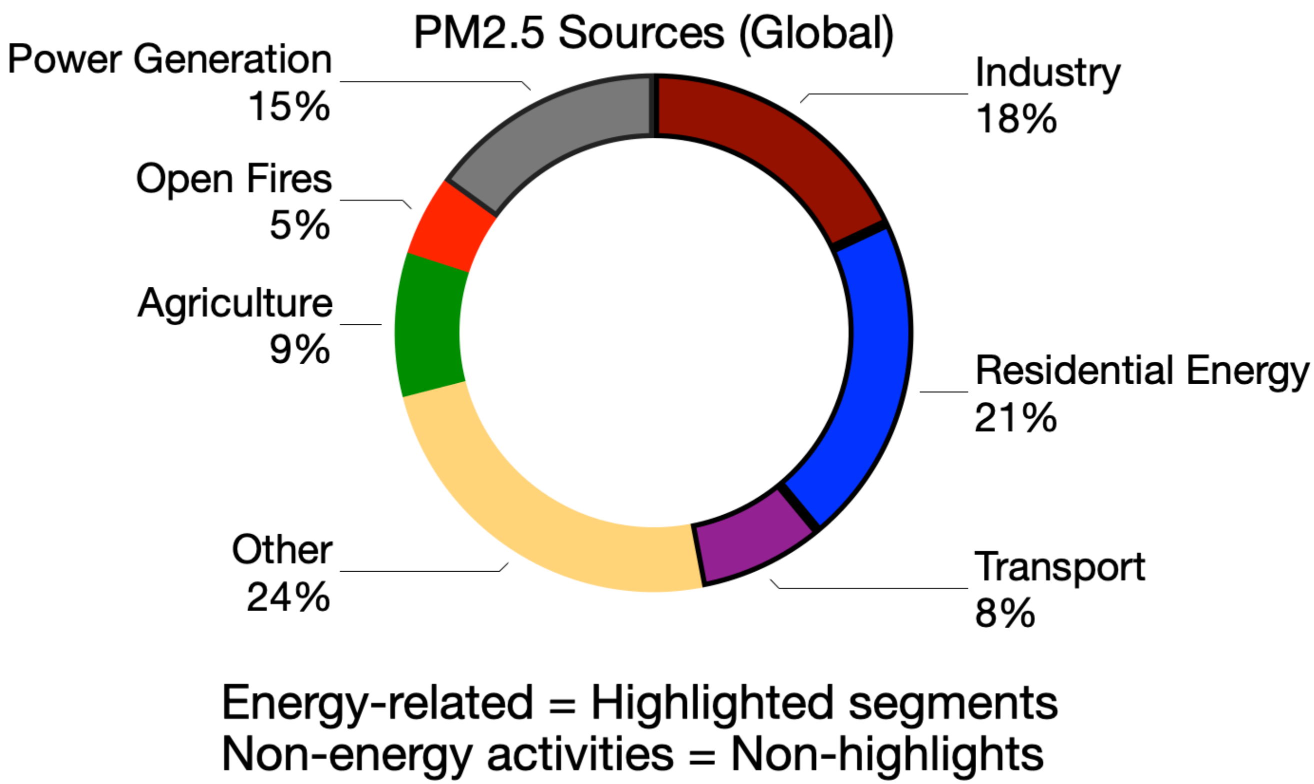
10.4.2 PM2.5 Business as Usual Comparison

Because non energy PM2.5 emissions are based on per capita MMT/Year/Billion, changes in population growth assumptions will change future estimates of PM2.5 MMT/Year (non energy sources).

In order to compare a simulation scenario where PM2.5 emissions (non energy generation by source) differs from the business as usual (BAU) scenario, En-ROADS simultaneously calculates the BAU scenario using the equation logic in Figure 10-5. The BAU equations calculate the PM2.5 emissions MMT/Year (non energy generated) that occurs under the BAU scenario (no changes in population growth assumptions)by applying EFs to the BAU emissions scenario (non energy generation under the business as usual, no change of population assumptions). The BAU PM2.5 MMT/Year (non energy generated) results are then compared to results generated from the equations in Table 10-6.

The structure in Figure 10-5 applies look up tables that contain results from a BAU analysis.

Figure 10-1 Sources of PM2.5 Emissions



Weagle et al, *Global Sources of Fine Particulate Matter: Interpretation of PM2.5 Chemical Composition Observed by SPARTAN using a Global Chemical Transport Model*, DOI: 10.1021/acs.est.8b01658, Environ. Sci. Technol. 2018, 52, 11670−11681

Figure 10-2 Structure of PM2.5 Emissions – Energy

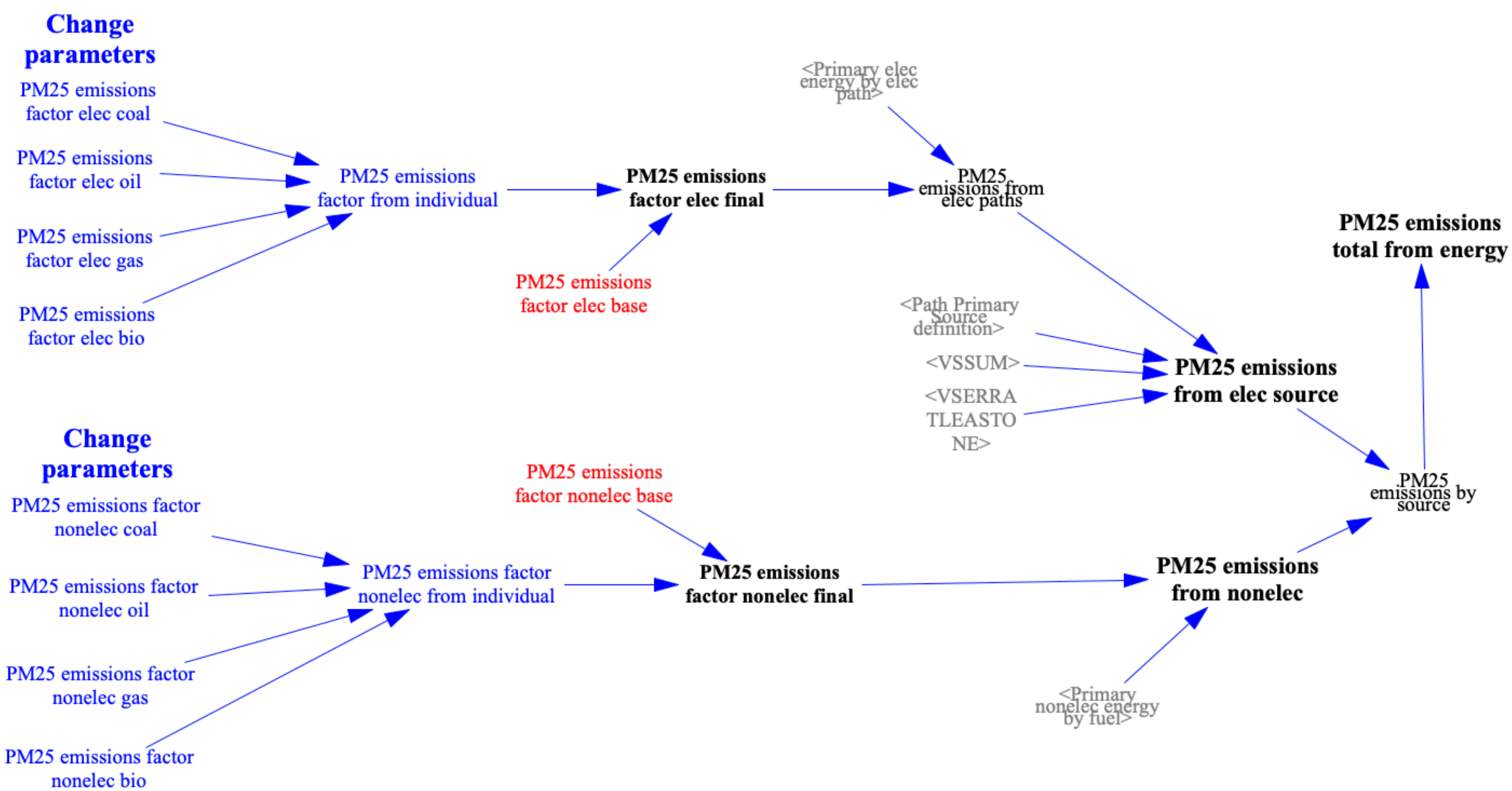


Figure 10-3 Structure of PM2.5 Emissions BAU – Energy

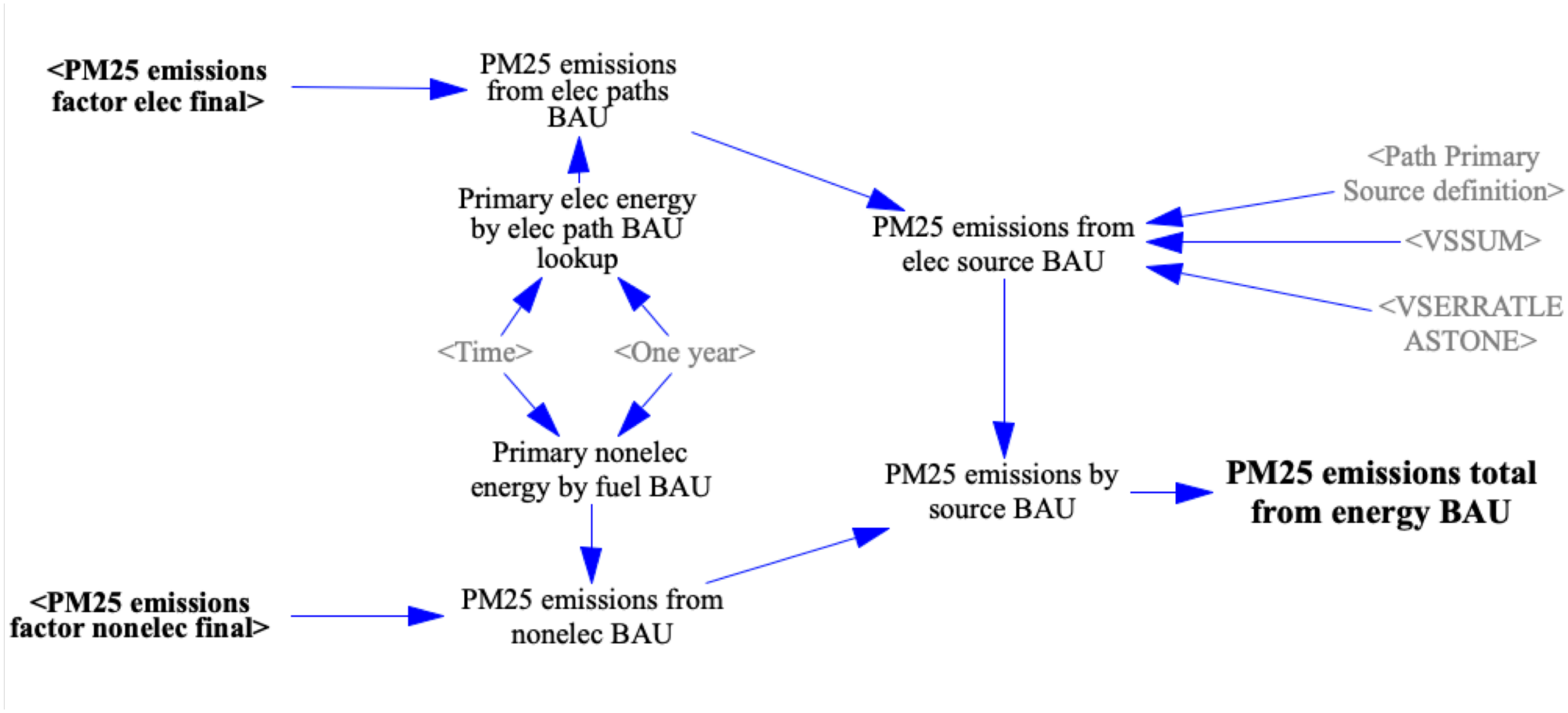


Figure 10-4 Structure of PM2.5 Emissions– Non Energy

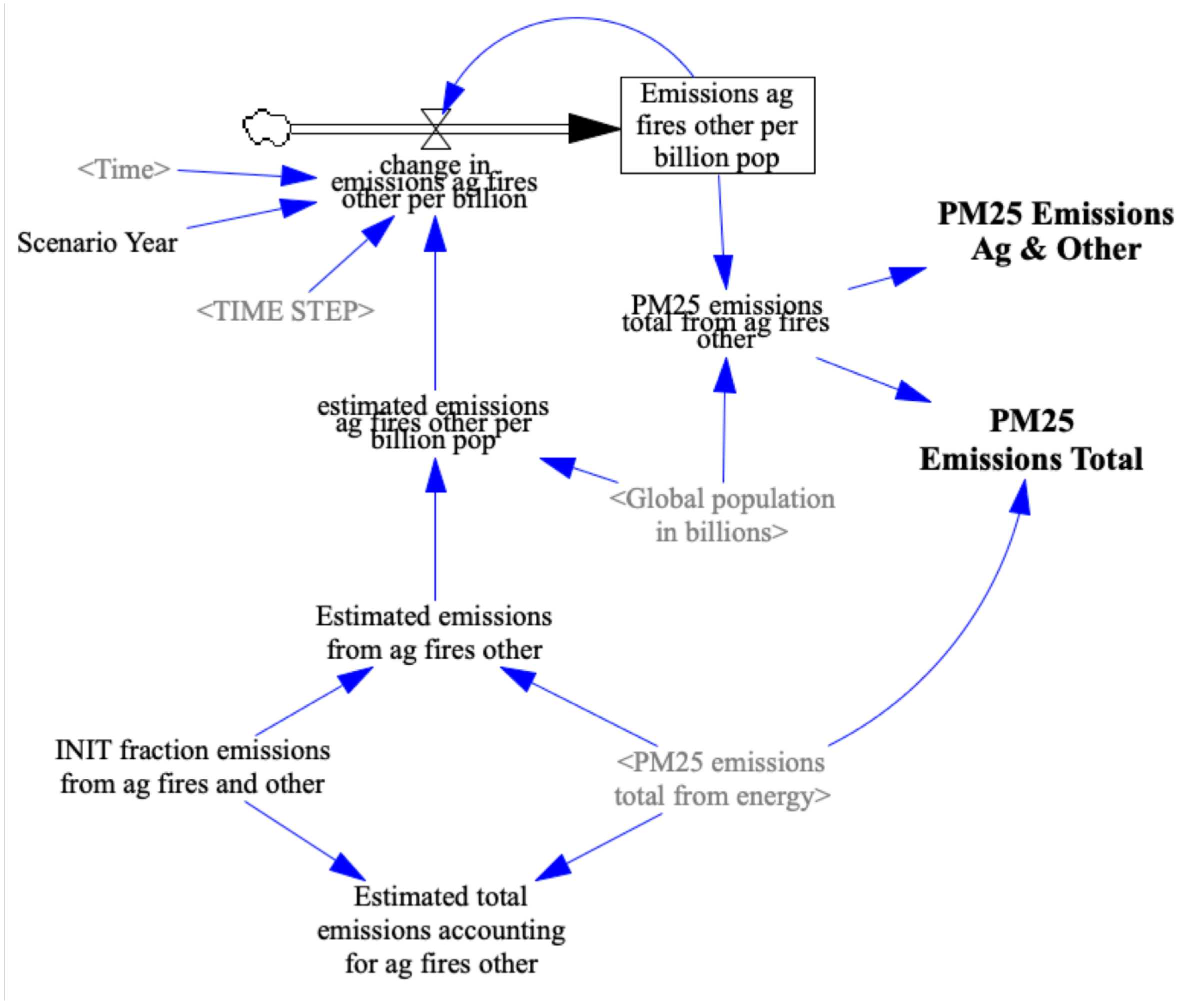


Figure 10-5 Structure of PM2.5 Emissions BAU – Non Energy

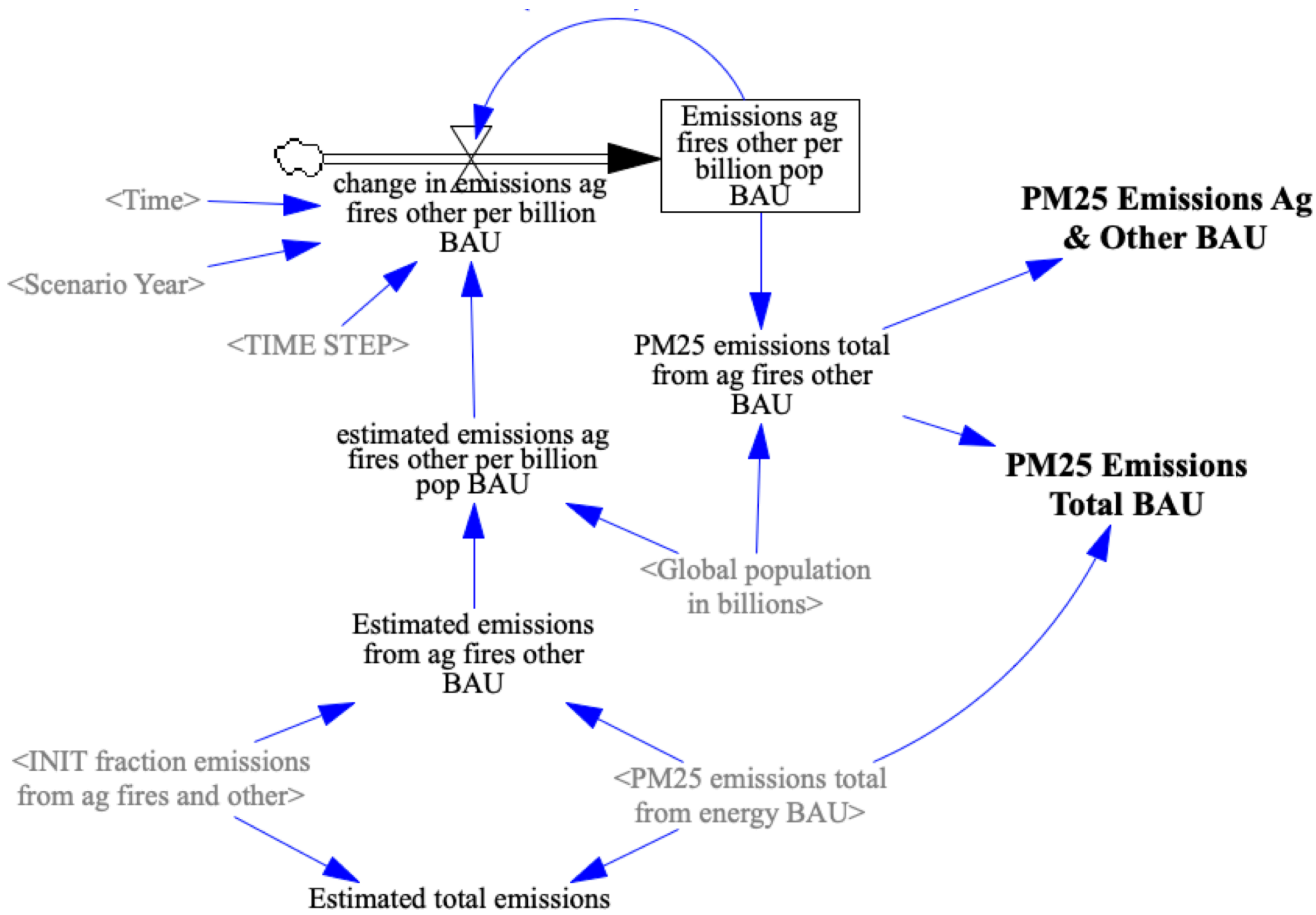


Table 10-1 PM2.5 Energy Generation Parameter Inputs

Parameter	Definition	Range	Default Values	Units
PM25 emissions factor elec base[Primary Fuels]	The sum of PM2.5 emissions from generating electricity.	0-.12		MMT/EJ
[PCoal]			0.12	MMT/EJ
[POil]			0.005	MMT/EJ
[PGas]			0.0001	MMT/EJ
[PBio]			0.04	MMT/EJ
PM25 emissions factor nonelec base[Primary Fuels]	The sum of PM2.5 emissions from generating energy (non electricity).	0-.12		MMT/EJ
[PCoal]			0.12	MMT/EJ
[POil]			0.005	MMT/EJ
[PGas]			0.0001	MMT/EJ
[PBio]			0.04	MMT/EJ
PM 25 emissions factor from individual[Primary Fuels]	Sum up into subscripted variable.			MMT/EJ
PM25 emissions factor elec coal	Individual EF for control panel input.		0.12	MMT/EJ
PM25 emissions factor elec oil	Individual EF for control panel input.		0.005	MMT/EJ
PM25 emissions factor elec gas	Individual EF for control panel input.		0.0001	MMT/EJ
PM25 emissions factor elec bio	Individual EF for control panel input.		0.04	
PM 25 emissions factor nonelec from individual[Primary Fuels]	Sum up into subscripted variable.			MMT/EJ
PM25 emissions factor nonelec coal	Individual EF for control panel input.		0.12	MMT/EJ
PM25 emissions factor nonelec oil	Individual EF for control panel input.		0.005	
PM25 emissions factor nonelec gas	Individual EF for control panel input.		0.0001	MMT/EJ

Table 10-1 PM2.5 Energy Generation Parameter Inputs

Parameter	Definition	Range	Default Values	Units
PM25 emissions factor nonelec bio	Individual EF for control panel input.		0.04	MMT/EJ
PM25 emissions factor elec final[Primary Fuels]	IF THEN ELSE (PM25 emissions factor from individual[Primary Fuels] = PM25 emissions factor elec base[Primary Fuels] , PM25 emissions factor elec base[Primary Fuels] , PM25 emissions factor from individual[Primary Fuels])			MMT/EJ
PM25 emissions factor nonelec final[Primary Fuels]	IF THEN ELSE (PM25 emissions factor nonelec from individual[Primary Fuels] = PM25 emissions factor nonelec base[Primary Fuels] , PM25 emissions factor nonelec base[Primary Fuels] , PM25 emissions factor nonelec from individual[Primary Fuels])			MMT/EJ

Table 10-2 PM2.5 Energy Generation Calculated Parameters

Parameter	Definition	Units
PM25 emissions total from energy	The sum of PM2.5 emissions from fuel sources. SUM (PM25 emissions by source[Primary Fuels!])	MMT/Year
PM25 emissions by source[Primary Fuels]	The sum of PM2.5 emissions from electricity and non electricity energy generation sources, by fuel source. PM25 emissions from nonelec[Primary Fuels] + PM25 emissions from elec source[Primary energy fuel sources]	MMT/Year
PM25 emissions from elec source[Primary Energy Sources]	VECTOR SELECT (Path Primary Source definition[Primary Energy Sources,Elec Paths!] , PM25 emissions from elec paths[Elec Paths!] , 0, VSSUM , VSERRATLEASTONE)	MMT/Year
PM25 emissions from elec paths [Elec thermal plus CCS]	The sum of PM2.5 emissions from electricity generation, by fuel source. PM25 emissions factor elec[Primary Fuels] * Primary elec energy by elec path[Elec thermal plus CCS]	MMT/Year
PM25 emissions from nonelec [Primary Fuels]	The sum of PM2.5 emissions from energy generation (non electricity), by fuel source. PM25 emissions factor nonelec[Primary Fuels] * Primary nonelec energy by fuel[Primary Fuels]	MMT/Year
PM25 emissions factor elec final[Primary Fuels]	IF THEN ELSE (PM25 emissions factor from individual[Primary Fuels] = PM25 emissions factor elec base[Primary Fuels] , PM25 emissions factor elec base[Primary Fuels] , PM25 emissions factor from individual[Primary Fuels])	MMT/EJ

Table 10-2 PM2.5 Energy Generation Calculated Parameters

Parameter	Definition	Units
PM25 emissions factor nonelec final[Primary Fuels]	IF THEN ELSE (PM25 emissions factor nonelec from individual[Primary Fuels] = PM25 emissions factor nonelec base[Primary Fuels] , PM25 emissions factor nonelec base[Primary Fuels] , PM25 emissions factor nonelec from individual[Primary Fuels])	MMT/EJ

Table 10-3 PM2.5 Energy BAU Calculation Parameter Inputs

Parameter	Definition	Units
PM25 emissions total from energy BAU[Primary Fuels]	SUM (PM25 emissions by source BAU[Primary Fuels!])	MMT/Year
PM25 emissions by source BAU[Primary Fuels]	PM25 emissions from nonelec BAU[Primary Fuels] + PM25 emissions from elec source BAU[Primary energy fuel sources]	MMT/EJ
PM25 emissions from elec source BAU[Primary Energy Sources]	VECTOR SELECT (Path Primary Source definition[Primary Energy Sources,Elec Paths!] , PM25 emissions from elec paths BAU[Elec Paths!] , 0, VSSUM , VSERRATLEASTONE)	MMT/Year
PM25 emissions from nonelec BAU[Primary Fuels]	PM2.5 emissions (BAU) from electricity calculated from multiplying BAU exajoules (energy) by PM2.5 emissions factors for fuel source. PM25 emissions factor nonelec[Primary Fuels] * Primary nonelec energy by fuel BAU[Primary Fuels]	MMT/Year
PM25 emissions from elec paths BAU[Elec thermal plus CCS]	PM2.5 emissions (BAU) from electricity calculated from multiplying BAU exajoules (energy) by PM2.5 emissions factors for fuel source. PM25 emissions factor elec[Primary Fuels] * Primary elec energy by elec path BAU lookup[Elec thermal plus CCS]	MMT/Year
Primary elec energy by elec path BAU lookup[Primary Energy Sources]	Lookup variable. Table calculated from En-ROADS BAU simulated energy by elect path for BAU scenario.	EJ/Year

Table 10-3 PM2.5 Energy BAU Calculation Parameter Inputs

Parameter	Definition	Units
Primary nonelec energy by fuel BAU[Primary Fuels]	Lookup variable. Table calculated from En-ROADS BAU simulated energy by non electric for BAU scenario.	EJ/Year

Table 10-4 PM2.5 Non Energy Generation Parameter Inputs

Parameter	Definition	Range	Default Values	Units
INIT fraction emissions from ag fires and other	The initial fraction of global emissions produced by non energy sources. Weagle et al, *Global Sources of Fine Particulate Matter: Interpretation of PM2.5 Chemical Composition Observed by SPARTAN using a Global Chemical Transport Model*, DOI: 10.1021/acs.est.8b01658, Environ. Sci. Technol. 2018, 52, 11670-11681	0-1	.35	Dmnl
Scenario Year	The year to stop adjusting per capita PM2.5 emissions from non energy sources.	1990-2100	2015	Year

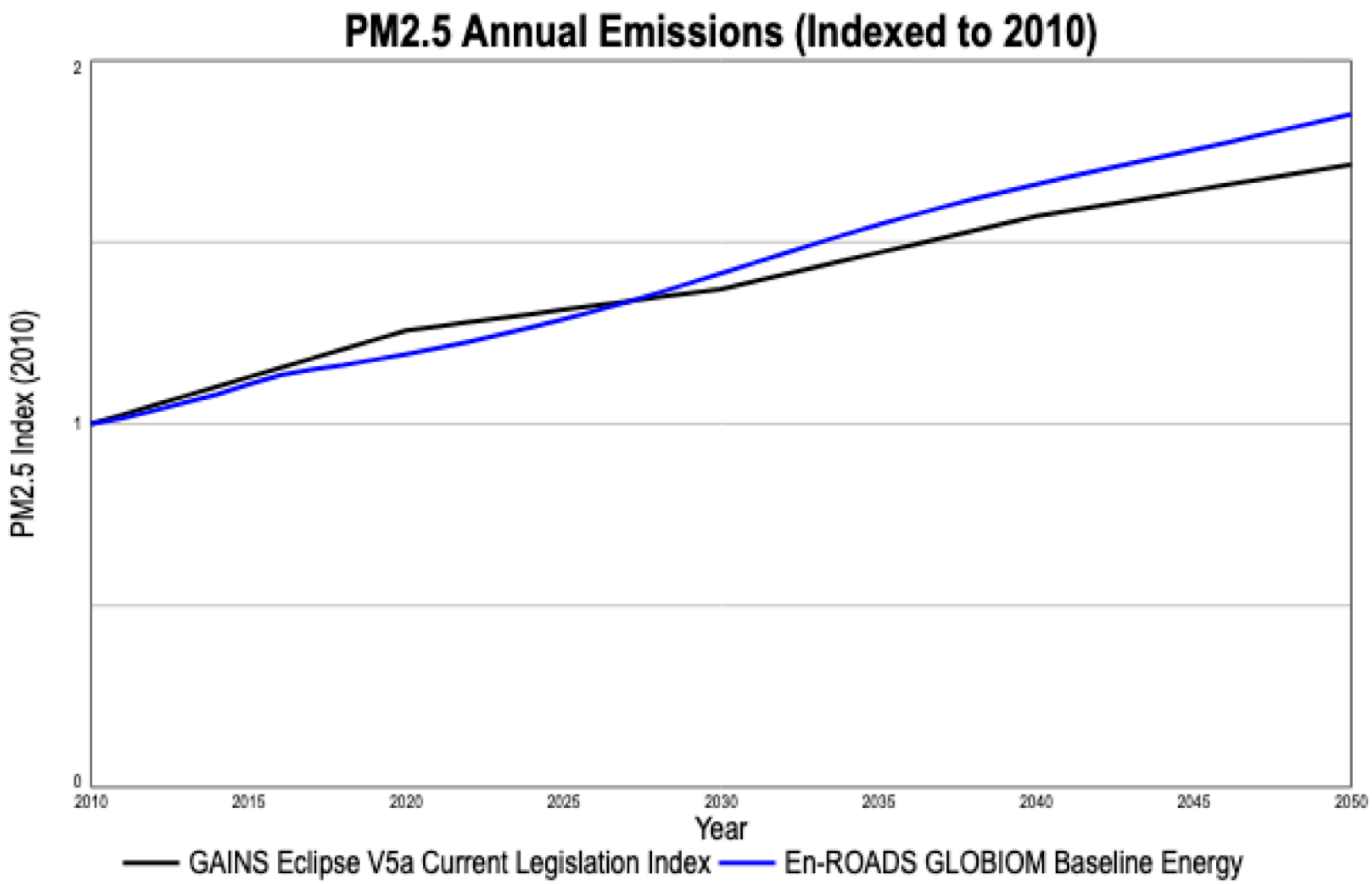
Table 10-5 PM2.5 Non Energy Generation Parameter Inputs

Parameter	Definition	Units
Emissions ag fires other per billion pop	Per capita annual emissions of PM2.5 generated from agriculture, fires, and other sources per billion (population). Parameter updates until Scenario Year. INTEG(change in emissions ag fires other per billion, 0)	MMT/Billion/Year
change in emissions ag fires other per billion	IF THEN ELSE (Time >= Scenario Year , 0, (estimated emissions ag fires other per billion pop - Emissions ag fires other per billion pop) / TIME STEP)	MMT/Billion/Year
Estimated total emissions accounting for ag fires other	PM2.5 emissions (BAU) from all sources (electricity, non electricity, non energy). PM25 emissions total from energy / (1 - INIT fraction emissions from ag fires and other)	MMT/Year
Estimated emissions from ag fires other	PM2.5 emissions (BAU) from non energy based on emissions from energy sources. Used to calculate per capita emisions prior to Scenario Year. (PM25 emissions total from energy / (1 - INIT fraction emissions from ag fires and other)) * INIT fraction emissions from ag fires and other	MMT/Year
PM25 emissions total from ag fires other	Global population in billions * Emissions ag fires other per billion pop	MMT/Year
PM25 Emissions Total	PM25 emissions total from energy + PM25 emissions total from ag fires other	MMT/Year
"PM25 Emissions Ag & Other"	PM25 emissions total from ag fires other	MMT/Year

Table 10-6 PM2.5 Non Energy BAU Calculation Parameter Inputs

Parameter	Definition	Units
Emissions ag fires other per billion pop BAU	Business as Usual (BAU)per capita annual emissions of PM2.5 generated from agriculture, fires, and other sources per billion (population). Parameter updates until Scenario Year. INTEG(change in emissions ag fires other per billion BAU, 0)	MMT/Billion/Year
change in emissions ag fires other per billion BAU	IF THEN ELSE (Time >= Scenario Year , 0, (estimated emissions ag fires other per billion pop BAU - Emissions ag fires other per billion pop BAU) / TIME STEP)	MMT/Billion/Year
estimated emissions ag fires other per billion pop BAU	Estimated emissions from ag fires other BAU / Global population in billions	MMT/Year
Estimated emissions from ag fires other BAU	(PM25 emissions total from energy BAU / (1 - INIT fraction emissions from ag fires and other)) * INIT fraction emissions from ag fires and other	MMT/Year
Estimated total emissions accounting for ag fires other BAU	PM25 emissions total from energy BAU / (1 - INIT fraction emissions from ag fires and other)	MMT/Year
PM25 emissions total from ag fires other BAU	Global population in billions * Emissions ag fires other per billion pop BAU	MMT/Year
PM25 Emissions Total BAU	PM25 emissions total from energy BAU + PM25 emissions total from ag fires other BAU	MMT/Year
“PM25 Emissions åg & Other BAU”	PM25 emissions total from ag fires other BAU	MMT/Year

Figure 10-6 Structure of PM2.5 Emissions BAU – Non Energy



10.5 Calibration and Initialization

PM2.5 emissions calculations were calibrated using GAINS model from the International Institute for Applied Systems Analysis (IIASA). IIASA regularly updates the GAINS model; the Eclipse V5a scenario is the latest GAINS analysis. V5a simulates a “current legislation” scenario that simulates PM2.5 emissions over the 2005-2050 range. The current legislation simulation applies the climate legislation and policies commitments (2015) to estimate global fossil fuel and land practices and resulting impacts.

For calibration, the Eclipse V5a current legislation scenario was indexed (2010 index year) and plotted against a similar index from En-ROADS (2010 index). For more reliable comparison, both indices excluded non energy related emissions. To approximate a current legislation scenario, the En-ROADS emissions were generated using the GLOBIOM 2.6 Baseline assumptions (calibration described in Section 10 of this document).

Figure 10-6 shows the comparison of the two indices through 2050.

11. Initialization, Calibration, Model Testing

En-ROADS initializes and calibrates to available historical data, primarily provided by the following sources:

Energy and CO2 Emissions

- Energy Information Administration (EIA) (2019)
- International Energy Agency (IEA) WEO (2020)
- British Petroleum (BP) Statistical Review of World Energy (2020)
- Shell (2018)
- Global Carbon Budget (2020) (CO2 Energy Emissions only)
- PRIMAP 2.1 (2019) (Non-CO2 GHG Emissions only)
- Houghton and Nassikas (2017) (CO2 Land Use only)

GHG Concentrations, Temperature Change, Sea Level Rise

- GISS Global Mean Estimates based on Land and Ocean Data 1880-2019 (2020)
- HadCRUT5 1850-2020 (2020)
- University of Colorado Sea Level Research Group (2018)

En-ROADS calibrates to projected values provided by the following sources:

- International Energy Agency (IEA) WEO (2018 and 2020)
- Shell (Mountain Scenario) (2013)
- SSP Version 2.0 scenarios (2018 - Available at: https://tntcat.iiasa.ac.at/SspDb)
    - Netherlands Environmental Assessment Agency (PBL). Integrated Model to Assess the Global Environment (IMAGE): Detlef van Vuuren, David Gernaat, Elke Stehfest
    - International Institute for Applied Systems Analysis (IIASA). Model for Energy Supply Strategy Alternatives and their General Environmental Impact - GLobal BIOsphere Management (MESSAGE-GLOBIOM): Keywan Riahi, Oliver Fricko, Petr Havlik
    - National Institute for Environmental Studies (NIES). Asia-Pacific Integrated Model (AIM): Shinichiro Fujimori
    - Pacific Northwest National Laboratory (PNNL). Global Change Assessment Model (GCAM): Kate Calvin and Jae Edmonds
    - Potsdam Institute for Climate Impact Research (PIK). REMIND-MAGPIE: Elmar Kriegler, Alexander Popp, Nico Bauer

  - European Institute on Economics and the Environment (EIEE). World Induced Technical Change Hybrid-GLobal BIOsphere Management (WITCH-GLOBIOM): Massimo Tavoni, Johannes Emmerling
- Network for Greening the Financial System (2020)
  - GCAM 5.2 (U.S.)
  - MESSAGEix-GLOBIOM 1.0 (IIASA)
  - REMIND-MAgPIE 1.7-3.0 (Germany)
- EMF27 models (2014)
  - AIM/End Use (Japan)
  - BET (Japan)
  - DNE21+ (Japan)
  - EC-IAM (Canada)
  - ENV-Linkages (OECD)
  - FARM (U.S./Germany)
  - GCAM (U.S.)
  - GCAM-IIM (U.S./India)
  - GRAPE (Japan)
  - IMACLIM (France)
  - IMAGE (Netherlands)
  - MERGE (U.S.)
  - MESSAGE (IIASA)
  - Phoenix (U.S.)
  - POLES (France)
  - REMIND (Germany)
  - TIAM-World (Canada)
  - WITCH (Italy)

"Calibration and validation comparisons.xlsx" and "Calibration and validation comparisons.pptx" provide output and figures demonstrating the strong fit to history and other modeling groups' projections. Key comparison measures include GDP, total and source energy use and cost measures, GHG emissions and concentrations, and temperature change. Noteworthy, comparisons of primary energy of renewables are depend on conversion assumptions which vary dramatically between sources.

Our default settings are guided primarily by history, WEO Current Policies, and SSP2 Baseline projections, although energy demand for renewables is much greater and that for coal is much less in our baseline than for SSP2.

Importing as data variables, En-ROADS Development also uses various scenario projections for model validation. Accordingly, there are necessary files, generated from data models, which must accompany the model. The development version allows SSP comparisons against the output of 6 models for 5 SSP scenarios, each with up to 6 radiative forcing options, i.e., 1.9, 2.6, 3.4, 4.5, 6.0, and Baseline. To test our behavior against SSP behavior for all SSP storylines, we set population, and GDP per capita controls to follow the given SSP baseline trajectories and exogenously use the average of the models' carbon price values for the given SSP scenario for the given radiative forcing level, and assess the model outout versus SSP results. An important caveat is that SSP assumptions other than carbon pricing are unknown. Accordingly, we force CDR and other GHG action to align with the SSP projections for carbon removal and other GHG emissions. Reliably, for each SSP storyline and RF level, the model captures the key dynamics of the SSP models.

Comparably, model output calibrates well with the EMF27 Reference scenario for the same measures, albeit our results are on the lower end of theirs.

Sensitivity analyses provide insight into model robustness. Using a Latin grid, two tests for extreme conditions, one with standard controls and another with advanced controls, varied key actions as listed in Table 11-1. Output measures, listed in Table 11-2, for each simulation were exported as a .csv file and assessed using an Excel workbook created to confirm reasonable model behavior. Additionally, using random triangular distribution, another set of sensitivity analyses tested the effects of varying key assumptions with actions. Results indicate that, regardless of these assumptions, the relative effect these actions have on the system are robust.

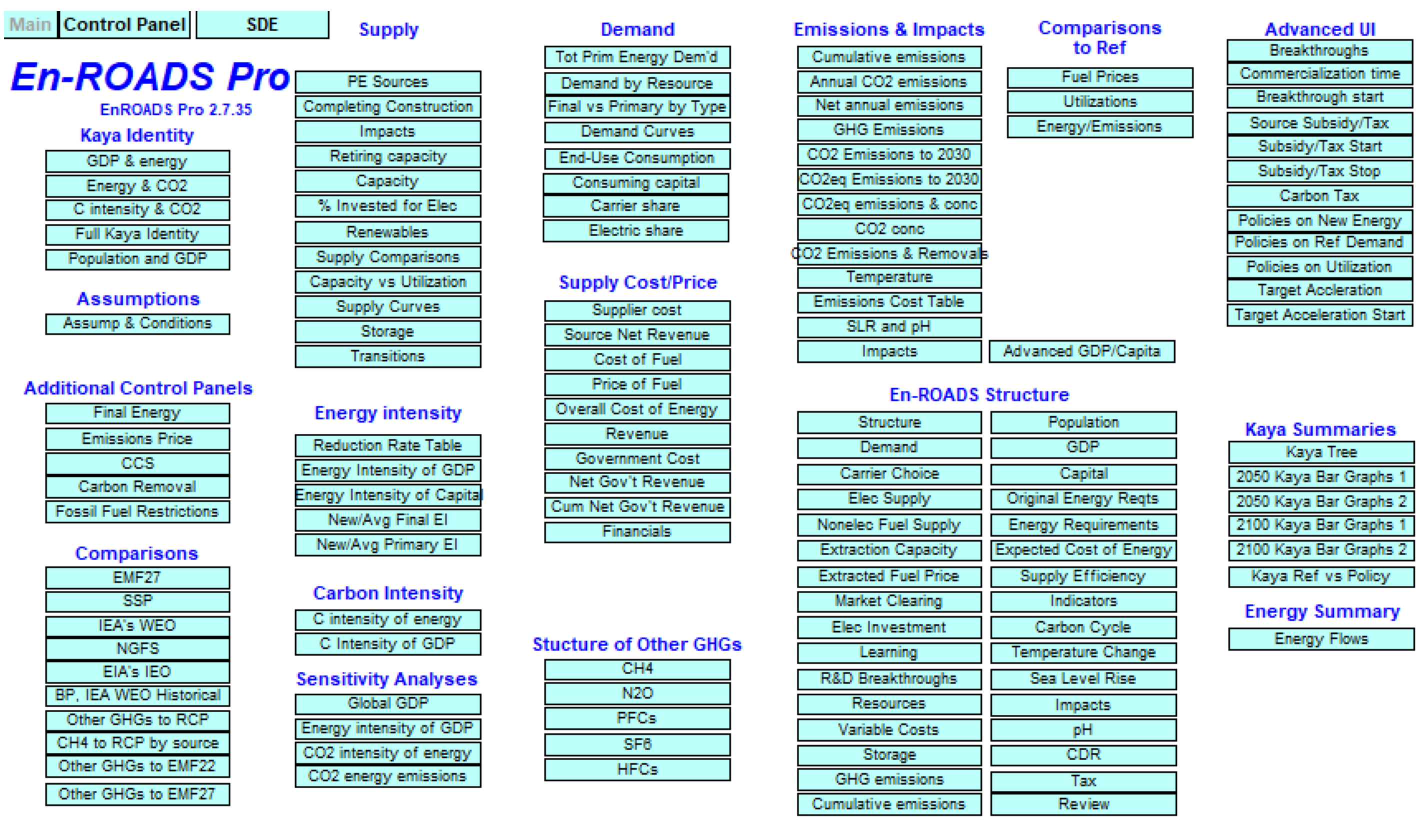
Table 11-1 Sensitivity Analysis Definition

Variable	Min	Max
Basic Controls		
Source subsidy delivered coal tce	0	110
Source subsidy delivered oil boe	0	100
Source subsidy delivered gas MCF	0	5
Source subsidy delivered bio boe	0	30
Source subsidy renewables kWh	-0.03	0
Source subsidy nuclear kWh	-0.07	0
New tech breakthrough setting	0	2
Carbon tax initial target	0	250
Annual improvement to energy efficiency of new capital stationary	1.2	5
Annual improvement to energy efficiency of new capital transport	0.5	5
Electrify new stationary	0	5
Electrify new transport	0	5
Advanced Controls		
Target accelerated retirement rate electric coal	0	10
Breakthrough cost reduction electric coal CCS	0	50
Breakthrough cost reduction electric gas CCS	0	50
Breakthrough cost reduction renewables	0	50
Breakthrough cost reduction nuclear	0	50
Breakthrough cost reduction electric bio CCS	0	50
Source subsidy electric coal CCS kWh	-0.03	0
Non afforestation Percent of max CDR achieved	0	100
Carbon tax final target	0	850
No new FF	0	1
% Reduction in FF utilization	0	100

Table 11-2 Output Variables for Sensitivity Analyses

Variable
Total Primary Energy Demand
Primary energy demand of coal
Primary energy demand of oil
Primary energy demand of gas
Primary energy demand of bio
Primary energy demand of nuclear
Primary energy demand of renewables
Primary energy demand of hydro
Market price of electricity
Market price of delivered fuels for nonelec carriers[Primary Fuels]
Adjusted cost of energy per GJ
Percent share of final consumption that is electric[Transport]
Percent share of final stationary consumption that is electric

Figure 11-1 Main Control Panel



12. References

Climate Interactive Data Files:

Data.vdfx, Created from En-ROADS data model (Data for ESS 68.mdl), dated 01/07/2021.
EnROADS Calc.vdf, Created from (En-ROADS RS v35.mdl), dated 09/11/2020.
SSP v2 Global Data, Created from SSP v2 data model, dated 11/08/2019;
EMF27 v1.vdf, Created from EMF27 data model, dated 06/20/2014;
Global RS GHG.vdf, from C-ROADS v5.005, dated 01/07/2021

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