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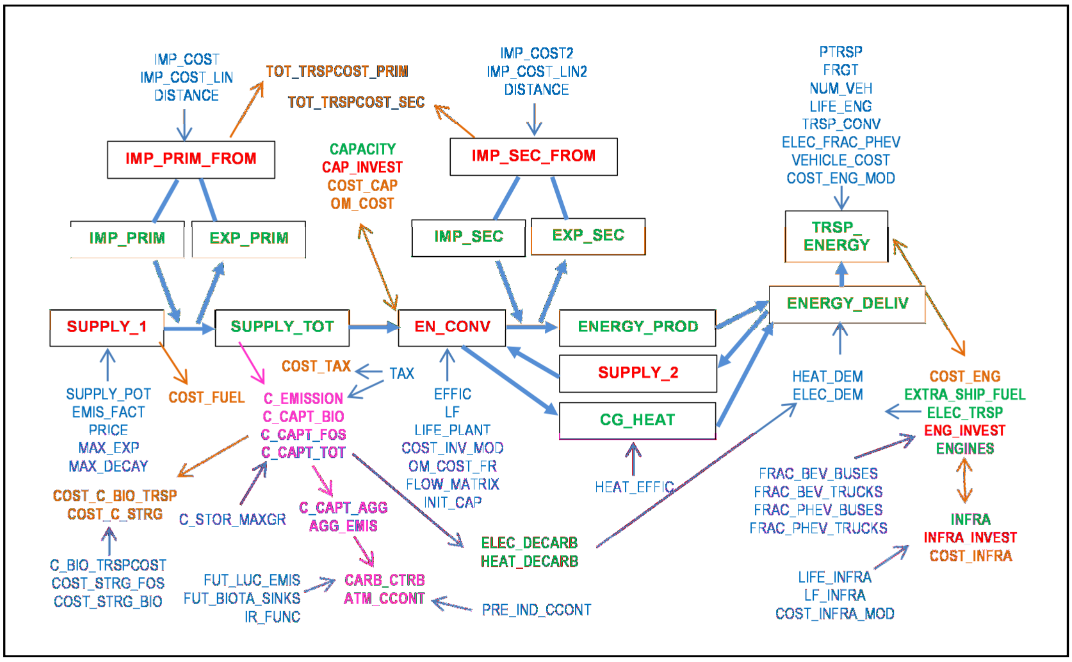

Description of the global energy systems model GET-RC 6.1

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2013
Report No. FRT-2013:10

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Keywords:
Linear Programming, Cost-minimizing, Sustainable mobility, Carbon emissions, Energy scenarios

Suggestion on how to cite this report
Grahn, M., Klampfl, E., Whalen, M.J., Wallington, T.J., Lindgren, K. (2013). Description of the global energy systems model GET-RC 6.1. Report No: FRT 2013:10. Physical Resource Theory, Chalmers, Sweden.

1. Introduction

To provide a tool for decision makers to understand meeting global energy demand with global energy supply at a minimum cost and in a sustainable way, we have developed a global energy model (GET-RC 6.1) that includes a detailed description of passenger vehicle technology options. The model can be used to better understand the fuel and vehicle technology choices available for passenger vehicles and how these fit into the larger global energy system, where different energy sectors compete for the same limited primary energy sources. The original linear programming Global Energy Transition (GET) model, was developed in the late 1990s (Azar et al, 2000) and is designed to meet exogenously given energy demand levels, subject to a CO_2 constraint, at the lowest global energy system cost (all costs are in US$).

The GET model is being developed and extended to address research questions related to the sustainable development of the global energy system. Several different versions of the GET model are available. The *aim* of this report is to describe the version used in a collaboration between staff at Ford Motor Company and Chalmers University of Technology during the period 2008-2013. The model version used, GET-RC 6.1, was developed to address research questions related to light duty passenger vehicles, where R stands for regionalized and C for cars. This model version has been used to generate results published in e.g., Grahn et al (2009a, 2009b, 2009c, 2013), and Wallington et al. (2010, 2012). Background information (e.g., rationale for data chosen) can be found in the joint Ford-Chalmers publications, mentioned above, and in earlier Chalmers publications, e.g., Azar et al (2000, 2003, 2006), and Grahn (2009).

The general structure of GET-RC 6.1 can be described as follows. The world is treated as ten distinct regions with unimpeded movement of energy resources between regions (with the exception of electricity) and with costs ascribed to such movement. We aggregate regional solutions to supply global results and constrain global CO_2 emissions as annual maximum upper limits following emission-curves towards a specific stabilization of atmospheric CO_2 concentration. The model does not consider greenhouse gases other than CO_2. The model time period is 1990-2140 with 10-year time steps: we present and discuss the results for time period 2010-2100. Energy demand is divided into three sectors: (i) electricity, (ii) transportation, and (iii) ”heat”. Heat comprises all stationary uses of energy except for those associated with generating electricity or transportation fuels. The current study emphasizes personal transportation in light-duty vehicles. We assume mature technology costs throughout the time period considered. We further assume that all technologies are available in all regions. All prices and costs are in real terms as future inflation is not considered. A global discount rate of 5% per year was used for the net present value calculations.

It is important to remember that energy systems cost-minimizing models do not predict the future and are not designed to forecast the future development of the energy system. Instead, they provide a tool to understand system behavior, interactions and connections among energy technology options in different sectors.

The report is structured as follows; in Section 2–4 we describe the settings that are defined in the model, i.e., the sets, parameters and variables. Note that the names of the types of entities may differ among modelers. For example, economists use the terms exogenous variable and endogenous variable for given data and decision variables, respectively. In the programming language GAMS, where the GET-model is developed, the terminology adopted is as follows: indices are called sets, given data are called parameters, decision variables are called variables, and constraints as well as the objective function are called equations (GAMS user guide, 2012). In this report, we use the terms defined for models coded in GAMS. The equations used in the model are explained in Section 5. The output code is presented in Section 6, and inspiration for how to implement the model step by step can be found in Section 7. Appended to this report are tables presenting the data (Appendix 1), a compact version of the model code (Appendix 2), calculation of one of the parameters, IR-func (Appedix 3), and the mathematical description of the model (Appendix 4).

2. Sets

In this section, the different sets (indices) are presented. For a compact description of the sets in alphabetic order, see Appendix 2.

2.1 Time

The model's time period is 1990-2140 and is divided into 10 year steps. Results are presented for the 2010-2100 period. The set "t_h" includes historical time steps used for the carbon cycle calculations and for plotting a long-term figure of historical emissions combined with model results. In GAMS, it is sometimes necessary to have more than one name for the same set, e.g. when emissions one year affect emission concentration another year. Here the set "T_all_copy" includes all time step and is identical to "T_all". The timeset "t_2010_2140" is used when fixing a specific value for the result from year 2010 and beyond, e.g. the use of nuclear.

T_all	1800, 1810, 1820, 1830, 1840, 1850, 1860, 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980, 1990, 2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, 2120, 2130, 2140
T_all_copy $\subseteq$ T_all	1800, 1810, 1820, 1830, 1840, 1850, 1860, 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980, 1990, 2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, 2120, 2130, 2140
t_h $\subseteq$ T_all	1800, 1810, 1820, 1830, 1840, 1850, 1860, 1870, 1880, 1890, 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980
t $\subseteq$ T_all	1990, 2000, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, 2120, 2130, 2140
t_2010_2140 $\subseteq$ t	2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110, 2120, 2130, 2140
init_year $\subseteq$ t	1990

2.2 Energy supply

Here we describe the sets for the model's energy options, both primary energy sources, which contains the ingoing sources used in the energy conversion plants (e_in) and the secondary energy carriers, which are the final energy products, i.e., energy carriers coming out from the energy conversion plants (e_out), all listed in the set E.

The set of options that are allowed to enter the energy conversion module as incoming energy (e_in) has the following acronyms. Primary energy options are: natural gas (NG), oil (OIL), coal (COAL), nuclear (NUCLEAR), biomass (BIO), hydro power (HYDRO), wind power (WIND), concentrating solar power (SOLAR_CSP), and finally other solar energy technologies, i.e. solar-PV, solar-heat and solar-hydrogen (SOLAR). The energy carriers that can be converted a second time are: hydrogen (H2) and electricity (ELEC), i.e. electricity can be converted to heat or hydrogen, and hydrogen can be converted to heat or electricity. In this model version, the technology CSP can be viewed as a new energy technology generating inexpensive electricity with low CO_2 emissions, and can therefore act as a proxy for any future inexpensive electricity with low CO_2 emissions, e.g., advanced fission, fusion, wave energy, or geothermal energy.

The set of energy carriers, converted from primary energy sources, (e_out) has the following acronyms: all stationary use that not are electricity nor transportation fuels, e.g., industrial process heat, district heating and feedstock (HEAT), electricity (ELEC), biomass-to-liquid, which is biomass based synthetic fuels assuming cost assumptions from bio-based methanol via gasification (BTL), coal-to-liquid and gas-to-liquid, both using cost assumptions from methanol production (CTL/GTL), hydrogen (H2), natural gas (NG), petroleum based gasoline/diesel/kerosene (PETRO), synthetic fuels for aviation (AIR_FUEL). Since the energy carriers hydrogen (H2) and electricity (ELEC) can be converted a second time are these are both ingoing (e_in) and outgoing (e_out) energy sources.

E	bio, hydro, wind, solar, solar_CSP, NG, oil, coal, nuclear, BTL, CTL/GTL, H2, heat, elec, petro, air_fuel
e_in $\subseteq$ E	bio, hydro, wind, solar, solar_CSP, NG, oil, coal, nuclear, H2, elec
e_out $\subseteq$ E	heat, elec, BTL, CTL/GTL, H2, NG, petro, air_fuel

The following are different subsets of the energy sources and carriers used in some equations. The acronym used below (cg) stands for co-generation of heat and electricity from the same conversion process.

cg_e_in $\subseteq$ e_in	bio, NG, oil, coal, H2
cg_e_out $\subseteq$ e_out	elec, BTL, CTL/GTL, H2
primary $\subseteq$ e_in	bio, hydro, wind, solar, solar_CSP, NG, oil, coal, nuclear
second_in $\subseteq$ e_in	H2, elec
sec $\subseteq$ e_out	BTL, CTL/GTL, H2
nontrade_sec $\subseteq$ e_out	heat, elec, NG, petro, air_fuel
fuels $\subseteq$ primary	bio, coal, oil, NG, nuclear
nonfuels $\subseteq$ primary	hydro, wind, solar, solar_CSP
fossil $\subseteq$ fuels	coal, oil, NG

2.3 Type of conversion plant

The energy conversion plants can be of different types. In this model, energy conversion plants can use conventional technology (0) or co-generation plants where both electricity and heat are produced (cg) or plants where carbon capture and storage technologies (CCS) are applied. The subset c_capt includes the two plant type options that can capture carbon, either with or without co-generation of electricity and heat. The subset CG_type includes the two plant type options that produce co-generated heat and electricity either with or without CCS.

type	0, cg, CCS, cg_CCS
c_capt $\subseteq$ type	CCS, cg_CCS
CG_type $\subseteq$ type	cg, cg_CCS

2.4 Fuels for transport

There are several fuel options that can be used in the transportation sector, i.e. biomass-based liquid fuels (BTL), coal to liquid (CTL), gas to liquid (GTL), petroleum-based fuels such as gasoline, diesel and kerosene (PETRO), electricity (ELEC), hydrogen (H2), natural gas (NG), and synthetic fuels for aviation (AIR_FUEL). The different subsets are used in equations only valid for some specific fuels.

trsp_fuel $\subseteq$ e_out	BTL, CTL/GTL, petro, elec, H2, NG, air_fuel
trsp_fuel_nonel $\subseteq$ trsp_fuel	BTL, CTL/GTL, petro, H2, NG, air_fuel
synfuel_gas $\subseteq$ trsp_fuel_nonel	BTL, CTL/GTL, H2, NG
road_fuel $\subseteq$ trsp_fuel	BTL, CTL/GTL, petro, elec, H2, NG
road_fuel_liquid $\subseteq$ road_fuel	BTL, CTL/GTL, petro

2.5 Vehicle technologies

There are five different vehicle technologies (e-type) available in the model, i.e., conventional internal combustion engine vehicles (0), fuel cell vehicles (FC), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV). The different subsets are declared to be used in equations only valid for some specific vehicle technologies. Note that the set “0” again define current conventional technology, this time internal combustion engine vehicles, whereas it in Section 2.3

is used to define conventional energy conversion plant technologies. The two sets denoted "0" can never be mixed up since a set always are connected to certain variables.

e_type	0, FC, HEV, PHEV, BEV
ic_fc ⊆ e_type	0, FC
hybrids ⊆ e_type	HEV, PHEV
hev_phev_bev ⊆ e_type	HEV, PHEV, BEV
non_phev ⊆ e_type	0, FC, HEV, BEV

2.6 Transport modes

The energy demand in the transportation sector is divided between nine different transport modes (trsp_mode), i.e., light duty passenger vehicles (p_car), airplanes for passenger travel (p_air), buses (p_bus), passenger rail (p_rail), and the following freight road types: trucks (f_road), freight aviation (f_air), freight coastal shipping (f_sea), and freight international shipping (f_isea).

trsp_mode	p_car, p_air, p_bus, p_rail, f_road, f_air, f_sea, f_isea, f_rail
vehicle ⊆ trsp_mode	p_car, f_road
ptrs_mode ⊆ trsp_mode	p_car, p_air, p_bus, p_rail
frgt_mode ⊆ trsp_mode	f_road, f_air, f_sea, f_isea, f_rail
ship_mode ⊆ trsp_mode	f_sea, f_isea

2.7 Regions

In GET-RC 6.1, the world is treated as 10 distinct regions: North America (NAM), Europe (EUR), the Former Soviet Union (FSU), OECD countries in the Pacific Ocean (PAO), Latin America (LAM), the Middle East (MEA), Africa (AFR), Centrally Planned Asia – mainly China (CPA), South Asia – mainly India (SAS) and Pacific Asia (PAS). All regions can export and import, and the the minimum cost selection determines the trade. In GAMS, it is sometimes necessary to have more than one name for the same set, e.g. when energy carriers are traded between two regions. Here the set "R_exp" includes all regions that can export and is identical to "R_imp" that includes the regions that can import.

R	NAM, EUR, PAO, FSU, AFR, PAS, LAM, MEA, CPA, SAS
R_exp ⊆ R	NAM, EUR, PAO, FSU, AFR, PAS, LAM, MEA, CPA, SAS
R_imp ⊆ R	NAM, EUR, PAO, FSU, AFR, PAS, LAM, MEA, CPA, SAS

3. Scalars and parameters

In this section, we present the names of all used scalars and parameters (given data). All scalars and parameters are written in blue throughout this report. The chosen data values can be found in Appendix 1. For a compact description of the scalars and parameters in alphabetic order, see Appendix 2.

3.1 Scalars

In this Section, the names of the scalars are presented. We define scalars as a parameter with one specific value only. As soon as the parameter depends on one or more sets they are presented as a parameter; see Section Parameters. In this report, we always present scalars and parameters in blue text to indicate that they are known values.

3.1.1 Basic scalars

The scalars presented here are the amount of million seconds per year (Msec_per year), which together with a plant specific capacity factor, is used when converting from an energy conversion plant's effect expressed in kW into the amount of energy that comes out of the plant (GJ/yr). The discount rate (r) accounts for the valuation of future costs and is in the base case set to 5%. Also, the interest rate applied to investments (r_invest) is set to 5% in the base case runs.

Msec_per_year	= 31.6	Number of seconds per year expressed in millions	[Ms]
t_step	= 10	Number of year within each time step	[yr]
r	= 0.05	Discount rate	[-]
r_invest	= 0.05	Interest rate applied to investments	[-]
pre_ind_ccont	= 280	Pre-industrial atmospheric CO_2 concentration	[ppm]

3.1.2 Maximum growth and depreciation

Constraints have been added to the model to avoid solutions that are obviously unrealistic, such as constraints on how fast changes can be made in the energy system. This includes constraints on the maximum expansion rates of new technologies (in general it is set so that it takes 50 years to change the entire energy system), as well as annual or total extraction limits on the different available energy sources. The growth is limited by both relative and absolute values. First, we list the relative values below, where all limitations on growth from one timestep to another are maximized to 20% in base case runs. The depreciation, limitations of the minimum fraction remaining in a timestep (compared to previous timestep), is set to 75% for a certain energy technology, 70% for a certain vehicle technology and minimum 20% for the phase out of oil.

cap_g_lim	= 0.2	maximum growth of capacity in energy conversion plants	[-]
supply_g_lim	= 0.2	maximum growth of primary energy extraction	[-]
infra_g_lim	= 0.2	maximum growth of infrastructure capacity	[-]
eng_g_lim	= 0.2	maximum growth of vehicle technologies	[-]
en_conv_decr_lim	= 0.75	minimum fraction of previous timestep's energy technology	[-]
mx_decay_frac	= 0.7	minimum fraction of previous timestep's vehicle technology	[-]
mx_decay_frac_oil	= 0.2	minimum fraction of previous timestep's oil use	[-]

The following scalars present the absolute values. Some scalars are first defined as a global static value and then regionalized and made dynamic in calculations included in the model, overwriting the global values: see Section 3.2.4 Growth and depreciation. The global values are presented here since they only consist of one value (scalars). We use "kick-start" to refer to a small starting value required when something new, like a new infrastructure, is introduced (otherwise any percentage growth will still equal zero if the starting value, in 1990, is zero), We use "final tail" to refer to the last part when something old is phased out (otherwise an old technology will never be totally phased out if always decreased by a certain percentage).

global_max_exp_p	= 2	Global maximum expansion of conversion plants	[TW/decade]
global_max_exp	= 60	Global maximum expansion for energy sources except biomass	[EJ/decade]
global_max_exp_b	= 32	Global maximum expansion for biomass production	[EJ/decade]
global_max_exp_i	=1	Global maximum expansion for infrastructure investments	[TW/decade]
global_init_i	= 0.05	"kick-start" value when a new infrastructure is introduced	[TW]
global_init_e	= 0.1	"kick-start" value when a new engine is introduced	[Gvehicles]
global_init_p	= 0.3	"kick-start" value when a new conversion plant is introduced	[TW]
global_init_s	= 0.3	"kick-start" value when a new energy source is introduced	[EJ]
global_en_conv_dis	= 5	Final "tail" of a certain energy conversion	[EJ]
global_mx_decay	= 6	Final "tail" of a certain transportation energy	[EJ]
global_mx_decay_oil	=10	Final "tail" of oil use in primary energy values	[EJ]
t_tech_plant	=50	Inertia. Minimum of years for a total change (0-100% of the market) for new conversion technologies	[yr]
t_tech_eng	=50	Inertia. Minimum of years for a total change (0-100% of the market) for new vehicle technologies	[yr]
t_tech_effic	=30	Inertia. How fast energy efficiency may change from current level to mature level	[yr]

3.1.3 Energy conversion

The following scalars are used in energy conversion equations including intermittency limitations, co-generation, and CCS.

fos_capt_effic	= 0.9	carbon capture efficiency from fossil CCS	[-]
bio_capt_effic	= 0.9	carbon capture efficiency from bioenergy CCS	[-]
c_capt_heat_fr	= 0.3	max fraction of heat sector using CCS	[-]
c_stor_maxgr	= 100	global annual growth limit on carbon storage capacity	[MtC/decade]
cogen_fr_e	= 0.2	max fraction of electricity demand from co-generation	[-]
cogen_fr_h	= 0.2	max fraction of heat demand that can come from co-generation	[-]
interm_fr	= 0.3	max fraction of intermittent electricity (wind + solar-elec)	[-]

3.1.4 Transport

Below we introduce the scalars used in the transportation module. We assume that a maximum of 20% of all trucks and 50% of all buses can run on electricity as plugin-hybrids (PHEVs) or as pure battery electric vehicles (BEVs).

frac_phev_trucks	= 0.2	share of trucks that can be PHEV	[-]
frac_phev_buses	= 0.5	share of buses that can be PHEV	[-]
frac_bev_trucks	= 0.2	share of trucks that can be BEV	[-]
frac_bev_buses	= 0.5	share of buses that can be BEV	[-]

3.1.5 Cost

The following scalars are used when calculating costs. The reason that the storage cost differs between carbon from fossil fuels and carbon from bioenergy is that bioenergy conversion plants typically are smaller in size compared to fossil fuel conversion plants. The cost for distributing the carbon from larger conversion plants will benefit from the economics of scale.

cost_strg_fos	= 0.037	carbon storage cost from fossils (equivalent to 10 USD/tCO_2)	[GUSD/MtC]
cost_strg_bio	= 0.073	carbon storage cost from bioenergy (equivalent to 20 USD/tCO_2)	[GUSD/MtC]
c_bio_trspcost	= 0.5	additional transportation cost applied to bioenergy CCS	[GUSD/EJ]

3.2 Parameters

In this section, all parameters (given data) used in the model are presented, and we identify in parenthesis on what sets the parameter values depend. Data for the base case runs are given in Appendix 1. For a compact description of parameters in alphabetic order, see Appendix 2.

3.2.1 Supply potential and energy demand

supply_pot (primary, R, t)	Annual upper limit on supply potential (non-fossil sources)	[EJ]
supply_pot_0 (primary, R)	Aggregated upper limit on fossil supply potential.	[EJ]
heat_dem_reg (R, t)	Heat demand	[EJ]
elec_dem_reg (R, t)	Electricity demand	[EJ]
ptrsp (R, ptrs_mode, t)	Energy demand for passenger transport	[EJ]
frgt (R, frgt_mode, t)	Energy demand for freight transport	[EJ]
trsp_dem (R, trsp_mode, t)	Energy demand for each transportation mode	[EJ]

The input data for energy demand for the transportation sector, parameter trsp_dem, is presented in two tables in Appendix 1, where Table ptrsp_all includes demand for passenger transport modes, and Table frgt_all includes demand for the freight transport modes. The input data in earlier model versions assume an overall energy efficieny improvement of 0.7% per year year (equivalent to a doubling of efficiency over 100 years). In this model version, we assume that energy savings of 0.3% per year can be achieved through improved rolling and air resistance and eco-diving, which is assumed to be equal for all types of road and sea based vehicle and ship technologies. The annual improvement on drivetrains, however, are assumed to be technology dependent, i.e., higher for internal combustion engines and fuel cell engines compared to electric vehicles. Therefore, the input data for parameter trsp_dem on p_car, p_bus, f_road, f_sea, and f_isea first need to be adjusted by a factor of 1.004, which in GAMS are made by the following code:

```
trsp_dem (R, "p_rail", t) = ptrsp_all(R, "p_rail", t);
trsp_dem (R, "p_air", t) = ptrsp_all(R, "p_air", t);
trsp_dem (R, "p_car", t) = ptrsp_all(R, "p_car", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "p_bus", t) = ptrsp_all(R, "p_bus", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_rail", t) = frgt_all(R, "f_rail", t);
trsp_dem (R, "f_air", t) = frgt_all(R, "f_air", t);
trsp_dem (R, "f_road", t) = frgt_all(R, "f_road", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_sea", t) = frgt_all(R, "f_sea", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_isea", t) = frgt_all(R, "f_isea", t)*1.004**(t_step*(ord(t)-1));
```

Note that "ord" is a GAMS operator that generates integers from the position in the set, e.g. ord(1990)=1 and ord(2000)=2.

The following expression initializes all static values on supply potential in each time period to be the supply potential presented in Table "supply_pot_0". That means all values presented in the table will be the upper limit for each time step. This will of course lead to unrealisticly high annual upper limits on fossil sources, but equation (2), corrects for that.

supply_pot (primary, R, t) = supply_pot_0 (primary, R); [EJ]

3.2.2 Energy conversion plants, CCS and infrastructure

effic (e_in, type, e_out, t)	Time dependent energy conversion efficiency	[-]
effic_current (e_in, type, e_out)	Near-term energy conversion efficiency	[-]
effic_0 (e_in, type, e_out)	Ideal conversion efficiency assumed available in 2020-2050	[-]
heat_effic (cg_e_in, cg_type, cg_e_out)	Heat efficiency for cogeneration of electricity and heat	[-]
lf (e_in, type, e_out, R)	Load factor (capacity factor) for energy conversion plants, i.e., the share of maximum capacity that is used per year	[-]
lf_infra (synfuel_gas)	Load factor infrastructure	[-]
life_plant (e_in, e_out, type)	Life time on energy conversion plants	[yr]
life_infra (synfuel_gas)	Life time for infrastructure	[yr]
dec_elec (e_in)	Electricity requirements when using CCS (fraction of en_conv)	[-]
init_cap (e_in, e_out, type, R)	Capacity in energy conversion plants for the initial year	[TW]

Calculation of some of the parameters listed above

In this model version, we use time dependent energy efficiency. Energy conversion efficiency in near term "effic_current" is assumed to be 0.1 lower than the ideal energy efficiency "effic_0". It is of course not possible to know exactly when in time the ideal efficiency can become reality. However, we make an assumption that it can be fulfilled sometime between 2020 and 2050.

The model chooses the lowest value on "effic" from two linear functions. Values for effic will therefore be lower in the first timesteps and increase over time until the two curves intersect. From the timestep when they intersect, the values on effic will be stabilized at a so called mature level.

effic_current (e_in, type, e_out) = effic_0 (e_in, type, e_out) – 0.1

effic (e_in, type, e_out, t) =
min (effic_0 (e_in, type, e_out), (effic_0 (e_in, type, e_out) – effic_current (e_in, type, e_out))/
t_tech_effic (e_in, type, e_out)*((ord(t)-1)* t_step) + effic_current (e_in, type, e_out))

As an illustration of the two linear functions that determines parameter "effic", the example of conversion efficiency for biomass based electricity is presented in Figure 1.

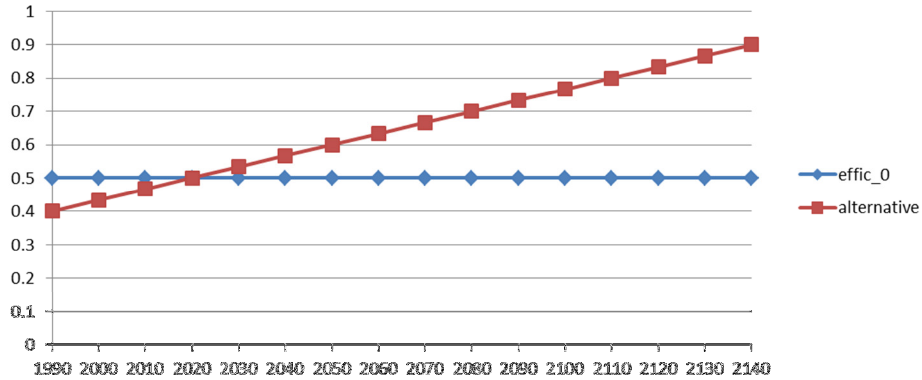

Figure 1. The example of biomass based electricity to illustrate the two equations used for the time dependent energy efficiency parameter "effic". For each time step the model always picks the lowest values.

3.2.3 Transportation sector

num_veh (R, vehicle, t)	Number of vehicles	[Gvehicles]
life_eng (trsp_fuel, e_type, vehicle)	Life time of vehicle engines	[yr]
trsp_conv_st (trsp_fuel, e_type, trsp_mode)	A factor that relates the energy efficiency to conventional ICEV. Valid for aviation and rail.	[-]
trsp_conv (trsp_fuel, e_type, trsp_mode, t)	Time dependent trsp-conv	[-]
elec_frac_phev (vehicle)	Fraction of time that a PHEV operates in battery mode. We assume that BTL/CTL/GTL and Petro PHEVs have the same electricity fraction.	[-]
high_speed_train (R, t)	Fraction of aviation sector substituted with high speed trains run on electricity	[-]

3.2.4 Growth and depreciation

max_exp_p (e_in, e_out, type, R, t)	Growth limit on energy conversion plants	[TW/decade]
max_exp (R, t)	Primary fuel supply growth limit	[EJ/decade]
max_exp_bio (R, t)	Bio energy growth limit	[EJ/decade]
max_inv_infra (R, t)	Infrastructure growth limit	[TW/decade]
en_conv_dis (R, t)	The final "tail" of a certain energy conversion	[EJ]
mx_decay_abs (R, t)	The final "tail" of a certain transportation energy	[EJ]
mx_decay_abs_oil (R, t)	The final "tail" of oil use in primary energy values	[EJ]
init_infra (R)	"kick-start" value when a new infrastructure is introduced	[TW]
init_eng (R)	"kick-start" value when a new engine is introduced	[Gvehicles]
init_plant (R)	"kick-start" value when a new conversion plant is introduced	[TW]
init_supply (R)	"kick-start" value when a new energy source is introduced	[EJ]

Calculations of regionalized growth and depreciation parameters listed above

Below we describe the calculation of regionalized parameters using the global scalars presented in Section "Scalars." The scalars are transferred into dynamic parameters, i.e., changed into time dependent values depending on the regional energy demand in each time step. Note that the global maximum expansion values were presented in TW whereas the regionalized values are presented in EJ (adjusted using Msec_per_year*t_step).

max_exp (R, t) =

((elec_dem_reg (R, t) + heat_dem_reg (R, t) + $\Sigma_{\text{trsp\_mode}}$ (trsp_dem (R, trsp_mode, t))) /

(Msec_per_year*t_step))* global_max_exp;

max_exp_p (e_in, e_out, type, R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_p};$

max_exp_bio (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_b};$

max_inv_infra (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_i};$

init_eng (R) =
$((\text{elec\_dem\_reg}(R, \text{"2000"}) + \text{heat\_dem\_reg}(R, \text{"2000"}) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_e};$

init_infra (R) =
$((\text{elec\_dem\_reg}(R, \text{"2000"}) + \text{heat\_dem\_reg}(R, \text{"2000"}) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_i};$

init_plant (R) =
$((\text{elec\_dem\_reg}(R, \text{"2000"}) + \text{heat\_dem\_reg}(R, \text{"2000"}) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_p};$

init_supply (R) =
$((\text{elec\_dem\_reg}(R, \text{"2000"}) + \text{heat\_dem\_reg}(R, \text{"2000"}) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_s};$

As an alternative to the last four calculations above, the values can instead be inserted as an input data table with the values presented in Table 1.

Table 1. Regional values for the four parameters acting as "kick-start" values when a new tecnology is introduced in model scenarios. These regional values can be used instead of the calculations where a regional value is generated from a global value.

	init_eng (R)	init_infra (R)	init_plant (R)	init_supply (R)
NAM	0.025	0.013	0.076	0.076
EUR	0.018	0.009	0.054	0.054
PAO	0.008	0.004	0.023	0.023
FSU	0.008	0.004	0.024	0.024
AFR	0.005	0.003	0.015	0.015
PAS	0.004	0.002	0.013	0.013
LAM	0.005	0.002	0.015	0.015
MEA	0.004	0.002	0.011	0.011
CPA	0.011	0.005	0.033	0.033
SAS	0.006	0.003	0.019	0.019

en_conv_dis (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \sum_{trsp\_mode}(\text{trsp\_dem}(R, trsp\_mode, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_en\_conv\_dis};$

mx_decay_abs (R, t) =
((elec_dem_reg (R, t)+ heat_dem_reg (R, t)+ Σ_{trsp_mode} (trsp_dem (R, trsp_mode, t))) /
(Msec_per_year*t_step))* global_mx_decay;

mx_decay_abs_oil (R, t) =
((elec_dem_reg (R, t)+ heat_dem_reg (R, t)+ Σ_{trsp_mode} (trsp_dem (R, trsp_mode, t))) /
(Msec_per_year*t_step))* global_mx_decay_oil;

3.2.5 Emissions and carbon taxes

CO_2 emissions are incurred whenever fossil primary energy sources are used in the model. The emissions differ between the fossil energy sources depending on the emission factor (emis_fact). An emission factor is also given for biomass since carbon can be stored by using carbon capture and storage technology. Since it is possible to import and export fossil synthetic fuels, the emissions from the production of CTL/GTL is assigned to the region before exporting the fuel, and the emissions from combusting the fuel is assigned to the region using the fuel. A special emission factor is therefore needed for the combustion of synthetic fuels (emis_fact_syn).

To convert the CO_2 emissions into atmotsperic CO_2 concentration, a carbon cycle module is included. Parameters used in the carbon cycle module are also presented here.

emis_fact (fuels)	Carbon dioxide emission factors	[MtC/EJ]
emis_fact_syn	Carbon dioxide emission factor from the use of CTL/GTL	[MtC/EJ]
c_tax (R, t)	Carbon tax	[GUSD/MtC]
hist_fos_emis (t_h)	Historical fossil emissions	[MtC]
fut_luc_emis (T_all)	Prognos for future emissions from land use change	[MtC]
fut_biota_sinks (T_all)	Estimation of the contribution of natural CO_2 sinks	[MtC]
IRfunc (T_all, T_all_copy)	Impulse Response function. Determines annual contribution to atmospheric carbon from each year's CO_2 emissions.	[-]

The impulse response function, IRfunc, is a declining function representing the annual contribution to atmospheric CO_2 from each emission impulse. The contribution is highest in tipesteps directly after the emission but will contribute to the atmospheric CO_2 for many decades after it is emitted. The impulse response function used in GET is taken from Maier-Reimer and Hasselmann (1987), and in their paper the function is named G(t). In this model version the values of IRfunc are included as a parameter (table) with given data (and not calculated during the run). Values for parameter IRfunc can be found in Appendix 1 and more details on IRfunc can be found in Appendix 3.

3.2.6 Prices and costs

Here we present parameters used when calculating costs in the model. Some costs are calculated in the model from a starting base cost. The cost is thereafter made time dependent and modified by interest rate and discount rate. A base cost for a theoretical standard vehicle run on petroleum based fuel (for cars a gasoline TDI) is first defined (vehicle_cost). For more advanced vehicle technology and fuel options, we add an incremental cost relative to the conventional vehicle (car and truck), see Appendix 1, for chosen data. The investment costs are then modified with an interest rate and a discount rate (cost_inv_mod).

price (fuels, R)	Basic fuel price (without scarcity rent[1] or carbon tax[2])	[GUSD/EJ]

[1] In reality prices will increase, with a so called scarcity rent, when demand is higher than the supply of goods. In the model demand is typically higher than the supply for oil, natural gas and biomass. The scarcity rent will increase with time, on oil and natural gas along with that oil and natural gas become more scarce and on biomass the more stringent the CO_2 restriction is since biomass is a cost-effective substitute for all fossil fuel use. In the model, as an approximation for the real world scarcity rent, we use the marginal values (shadow prices) on the supply constraint.

OM_cost_fr (e_in, e_out)	Operation & maintenance cost as fraction of capacity cost	[-]
cost_inv_base (e_in, type, e_out)	Basic investments cost for energy conversion plants	[GUSD/TW]
cost_inv (e_in, e_out, type, t)	A fourth dimension, the set t (time) is added to the parameter	[GUSD/TW]
cost_inv_mod (e_in, e_out, type, t)	Adjusted plant investment cost (if assuming different investment interest rate and discount rate)	[GUSD/TW]
vehicle_cost (vehicle)	Basic cost for a car and a truck using conventional fuels	[GUSD/Gvehicle]
cost_eng_base (road_fuel, e_type, vehicle)	Additional cost above standard "petro-vehicle"	[GUSD/Gvehicle]
cost_eng (road_fuel, e_type, vehicle, t)	Time dependent vehicle investment cost	[GUSD/Gvehicle]
cost_eng_mod (road_fuel, e_type, vehicle, t)	Vehicle investment cost adjusted if assuming different investment interest rate and discount rates	[GUSD/Gvehicle]
cost_infra (synfuel_gas)	Investment cost for infrastructure	[GUSD/TW]
cost_infra_mod (synfuel_gas)	Adjusted plant investment cost (if assuming different investment interest rate and discount rate)	[GUSD/TW]
imp_cost (fuels)	Cost for transportation of primary energy sources when trading between regions, regardless of the distance.	[GUSD/EJ]
imp_cost2 (sec)	Cost for transportation of secondary energy carriers when trading between regions, regardless of the distance.	[GUSD/EJ]
imp_cost_lin (fuels)	Additional cost, dependent on distance, for transportation when trading primary energy sources.	[GUSD/EJ]
imp_cost_lin2 (sec)	Additional cost, dependent on distance, for transportation when trading secondary energy carriers.	[GUSD/EJ]

Calculation of some parameters listed above
Time is added as a fourth dimension to the investment cost of energy conversion plants and vehicles. Originally we planned to introduce time dependent investment costs, but in this model version, we use identical investment costs for each time step.

cost_inv (e_in, e_out, type, t) = cost_inv_base (e_in, type, e_out);

cost_eng (road_fuel, e_type, vehicle, t) = cost_eng_base (road_fuel, e_type, vehicle) + vehicle_cost (vehicle);

The investment costs will in reality be perceived different if the discount rate (r) differs from the investment interest rate (r_invest). In the model we try to capture this effect by introducing the parameter cost_inv_mod which will adjust the basic investment cost according to these differences. In this model version, we assign r and r_invest the same value, i.e. both set to 0.05. Therefore, the three calculations below do not currently contribute to the result but are useful if performing different tests to determine the effect of assuming that the discount rate and investment rates are not identical.

cost_inv_mod (e_in, e_out, type, t) =
cost_inv (e_in, e_out, type, t) * (r_invest + 1/life_plant (e_in, e_out, type))/(r+1/life_plant (e_in, e_out, type));

cost_eng_mod (road_fuel, e_type, vehicle, t) =
cost_eng (road_fuel, e_type, vehicle, t) * (r_invest + 1/life_eng (road_fuel, e_type, vehicle))/
(r+1/life_eng (road_fuel, e_type, vehicle));

cost_infra_mod (synfuel_gas) =
cost_infra (synfuel_gas) * (r_invest + 1/life_infra (synfuel_gas)) / (r + 1/life_infra (synfuel_gas));

3.2.7 Miscellaneous

distance (R_imp, R_exp)	Table of rough distances between regions	[km]
flow_matrix (e_in, type, e_out)	Table presenting which energy conversions that are allowed	[-]
population (R, t)	Population	[Gpeople]

[2] As an approximation for carbon taxes (if running the model with emission constraints instead of given carbon taxes) we use the marginal value on the emission constraint.

The table flow_matrix is a matrix containing “0” or “1” depending on if an energy conversion, from a primary energy source to an energy carrier, is allowed (=”0”) or not (=”1”), see equation 29.

4. Variables

In this section, the variables are presented with a short explanation including units. Variables written in red indicate main variables, i.e. that the variables are not calculated from any other decision variables. The green variables are calculations of the red variables and can therefore theoretically be excluded from the model, but are useful when analyzing model results, since they can be compared to real statistics and trends. All variables are of type continuous. For a compact description of the variables in alphabetic order, see Appendix 2.

4.1 Balancing energy flows

The energy flows in the model are simplified in many ways, but capture the most important flows in a real global energy system, see Figure 2 for an overview.

4.1.1 Energy conversion

The energy flow, from primary energy extraction until final energy use, is divided into different steps. The following variables are nodes in the total energy flow, see Figure 2.

supply_1 (R, primary, t)	The amount of primary energy extracted in each region and time period	[EJ/yr]
supply_tot (R, primary, t)	The amount of primary energy used in a region and time period after import/export	[EJ/yr]
en_conv (R, e_in,e_out, type,t)	The amount of energy in each region converted from e_in to e_out expressed in primary energy terms in each time period.	[EJ/yr]
supply_2 (R, second_in, t)	The amount of energy in each region that goes back into the energy conversion box to be converted a second time in each period (H2 och ELEC).	[EJ/yr]
energy_prod (R, e_out, t)	The amount of energy carriers coming out of the conversion module in secondary energy (demand) terms, i.e. after energy losses, in every region and time period.	[EJ/yr]
energy_deliv (R, e_out, t)	The amount of energy that meets the exogenously given energy demand (after import/export of H2, CTL/GTL, BTL) in every region and period.	[EJ/yr]
cg_heat (R, t)	The amount of heat produced in each region and time period using co-generation technologies	[EJ/yr]
heat_decarb (R, t)	Additional heat demand in each region and time period if the model chooses to use CCS	[EJ/yr]
elec_decarb (R, t)	Additional electricity demand in each region and time period if the model chooses to use CCS	[EJ/yr]
tot_CSP (t)	Total amount of energy in each time period from concentrating solar power (CSP)	[EJ/yr]

4.1.2 Import and export

There are two steps along the entire energy flow where regions can trade with each other. The primary energy sources “fuels” (bio, coal, oil, NG, and uranium for nuclear) can be traded before the primary energy sources are converted to secondary energy carriers, i.e., between the variables supply_1 and supply_tot in the energy flow. The energy carriers “sec” (BTL, CTL/GTL, H2) can be traded between the variables energy_prod and energy_deliv, see Figure 2. The following variables are used to balance the energy flow that is imported and exported between regions.

imp_prim (R, fuels, t)	Amount of primary energy sources imported to a region in a period	[EJ/yr]
imp_sec (R, sec, t)	Amount of secondary energy sources imported to a region in a period	[EJ/yr]
exp_prim (R, fuels, t)	Amount of primary energy sources exported from a region in a period	[EJ/yr]
exp_sec (R, sec, t)	Amount of secondary energy sources exported from a region in a period	[EJ/yr]
imp_prim_from (R_imp, R_exp, fuels, t)	Primary energy trading flows	[EJ/yr]
imp_sec_from (R_imp, R_exp, sec, t)	Secondary energy trading flows	[EJ/yr]

4.1.3 Transportation

The main energy flow within the transportation sector is captured in the variable trsp_energy. To keep track of the amount of electricity that is used in the transportation sector, the variable elec_trsp is introduced. The amount of energy in elec_trsp will then be added to the total electricity demand (see eq 15). Fuels for buses as well as fuels for ships are calculated from mirroring the shares of fuels and technologies used for trucks. Ships, however, are assumed to not be able to run on electricity, i.e., no HEVs and PHEVs are allowed in the shipping sector. If HEVs and PHEVs are used for trucks, there will be a gap in the fuel use for ships. This gap is assumed to be filled with additional ship fuels by extending the shares equally much in variable extra_ship_fuel.

trsp_energy (R, trsp_fuel, e_type, trsp_mode, t)	Amount of energy used for transport in each region and time period	[EJ/yr]
elec_trsp (R, t)	Demand of electricity for the transportation sector in each time period and region	[EJ/yr]
extra_ship_fuel (R, trsp_fuel, ic_fc, ship_mode, t)	Additional ship fuel required in each region and time period since ships cannot run on electricity	[EJ/yr]

4.2 Calculating investments and capacity

cap_invest (R, e_in, e_out, type, t)	New investments in energy conversion technologies in each region and time period	[TW]
eng_invest (R, trsp_fuel, e_type, vehicle, t)	New investments in engines/vehicles technologies in each region and time period	[Gvehicles]
infra_invest (R, trsp_fuel, t)	New investments in infrastructure for fuel used in transportation in every region and time period	[TW]
capacity (R, e_in, e_out, type, t)	Aggregated capacity of energy conversion technology in every region and time period	[TW]
engines (R, trsp_fuel, e_type, vehicle, t)	Aggregated capacity of engines/vehicles using different fuel types in every region and time period	[Gvehicles]
infra (R, synfuel_gas, t)	Aggregated capacity of infrastructure for synthetic fuels in every region and time period	[TW]

4.3 Calculating emissions and CCS

agg_emis	Total emissions	[MtC]
c_emission_global (t)	Annual global emissions	[MtC]
c_emission (R, t)	Annual emissions per region	[MtC]
c_capt_fos (R, t)	Annual amount of carbon captured from fossil fuels per region	[MtC]
c_capt_bio (R, t)	Annual amount of carbon captured from biomass per region	[MtC]
c_capt_tot (R, t)	Annual amount of carbon captured fr fossil fuels and biomass per region	[MtC]
c_capt_agg	Total amount of captured carbon for all regions and time steps	[MtC]
carb_ctrb (T_all, T_all_copy)	Carbon contribution to the atmosphere from emissions made a specific time period (emitted CO_2 remains in the atmosphere for many decades)	[MtC]
atm_ccont (T_all)	Atmospheric CO_2 concentration in each time period	[ppm]

4.4 Calculating costs

cost_fuel (R, t)	Cost for extracting primary energy sources per time period and region	[GUSD]
tot_trspcost_prim (R, t)	Cost for trading primary energy sources per time period and region	[GUSD]
tot_trspcost_sec (R, t)	Cost for trading secondary energy carriers per time period and region	[GUSD]
cost_cap (R, t)	Investment cost for energy conversion technology per time period and region	[GUSD]
OM_cost (R, t)	Operation and maintenance cost per time period and region	[GUSD]
cost_c_bio_trsp (R, t)	Additional transportation cost if applying CCS on bioenergy per time period and region	[GUSD]

cost_c_strg (R, t)	Cost for storing carbon per time period and region	[GUSD]
tax (R, t)	Cost if applying carbon taxes to the model per time period and region	[GUSD]
annual_cost (R, t)	Sum of all annual costs in the model per time period and region	[GUSD]
tot_cost	Total cost for the entire energy system	[GUSD]

5. Equations

In this section, we describe the equations (constraints and the objective function). The equations drive the model to fulfill all energy balances, keep track of used energy sources and generated emissions, and calculate all costs. The major energy flows in GET-RC 6.1 are illustrated in Figure 2. Note that cost and emission variables are not included in Figure 2.See Figure 21 for a more complete model illustration.

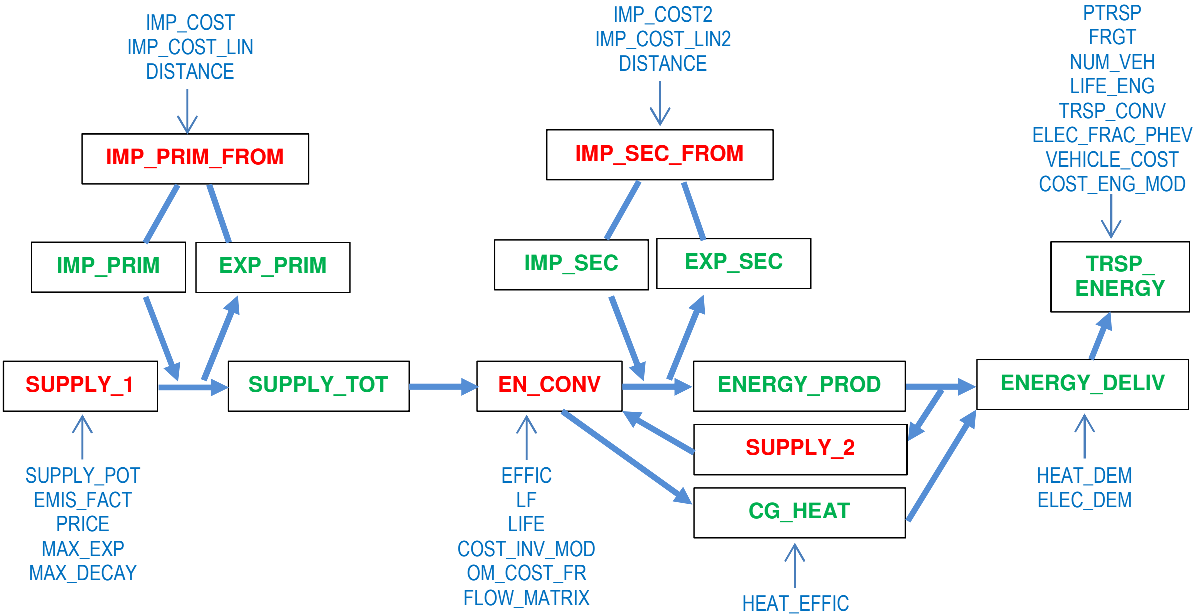

Figure 2. Illustration of how the different energy flow variables connect to each other in GET-RC 6.1 from the extraction of primary energy sources until final energy carriers are produced and used. Variables are shown in boxes whereas parameters giving input to the variables are presented without boxes.

5.1 Balancing energy flows

The following equations balance the energy flow from the primary energy sources through the energy conversion until the produced energy carriers meet the energy demand.

5.1.1 Primary energy supply

The exogenously given annual supply potential (supply_pot) must be greater than or equal to the amount of primary energy sources extracted in a region (supply_1). In other words, the amount extracted of primary energy sources in any time period and region cannot exceed the supply available in that region and time period. Equation (1) balances the renewable energy sources that have an annual supply limit.

$$\text{supply\_pot (primary, R, t)} \geq \text{supply\_1 (R, primary, t)}; \quad (1)$$

The aggregated extracted fossil fuels in a region (supply_1) must be less than or equal to the exogenously given total fossil supply potential (supply_pot_0). Values can be found in Table 26.

$$\Sigma_t \left(\text{t\_step*supply\_1 (R, fossil, t)}\right) \leq \text{supply\_pot\_0 (fossil, R)}; \quad (2)$$

5.1.2 Primary energy supply after trade

These equations balance the energy flow from the variable supply_1 to supply_tot, where supply_tot includes the total amount of primary energy sources in a region after import and export. Note that only the set "fuels" among the primary energy sources can be traded. Therefore, this balance is divided into two equations. One with the set “fuels” and one with “nonfuels” that together cover the set "primary".

supply_tot (R, fuels, t) = supply_1 (R, fuels, t) + imp_prim (R, fuels, t) –
exp_prim (R, fuels, t); (3)

supply_tot (R, nonfuels, t) = supply_1 (R, nonfuels, t); (4)

5.1.3 Energy conversion

The primary energy sources available in a region after import and export (supply_tot) must be exactly the same amount that is used in the energy conversion (en_conv) box, for each region, for each time step but regardless of energy conversion type or produced energy carrier. Note that results in en_conv are expressed in primary energy units (before energy losses).

supply_tot (R, primary, t) = $\Sigma_{\text{type, e\_out}}$ (en_conv (R, primary, e_out, type, t)); (5)

To be able to constrain solar_CSP we use the following equation to summarize all global CSP-production.
tot_CSP (t) = Σ_{R} (supply_1 (R, "solar_csp", t)); (6)

5.1.4 Produced energy carriers after trade

The following equations balance the energy flow from the conversion module (en_conv) into secondary energy carriers (energy_prod). The energy carriers from the energy conversion module are expressed in secondary energy units (primary energy sources multiplied by the energy conversion efficiency depending on type of conversion plant (effic)). Directly after the energy carrier have been produced, it is also possible to import and export the energy carriers, i.e. H2, BTL and CTL/GTL. Note that trading electricity over regions is currently not allowed. In reality, trade of electricity will take place between neighbor countries. However, we have assumed that in a model where the world is divided in ten large regions, the majority of electricity trade will occur within the regions, and the trade between regions is minor as well as in both directions and therefore assumed to be cancelled out.

The balance has been divided in two equations, one handling the tradable energy carriers and the other handling the non-tradable energy carriers.

energy_prod (R, nontrade_sec, t) = $\Sigma_{\text{type, e\_in}}$ (en_conv (R, e_in, nontrade_sec, type, t) *
effic (e_in, type, nontrade_sec, t)); (7)

energy_prod (R, sec, t) = $\Sigma_{\text{type, e\_in}}$ (en_conv (R, e_in, sec, type, t) *
effic (e_in, type, sec, t)) + imp_sec (R, sec, t) – exp_sec (R, sec, t); (8)

5.1.5 Energy carriers that can be converted to other energy carriers

Hydrogen and electricity are two energy carriers that can be converted to other energy carriers, e.g., heat. They are therefore allowed to “loop back into the energy conversion module (supply_2),” i.e., coverted a second time. The following equations balance the energy flow in supply_2. These equations only apply to the set “second_in” (H2 and ELEC).

Eq (9) show that the energy carriers in supply_2 can be used as an incoming source in en_conv. The incoming H2 and ELEC must be greater than or equal to the amount of H2 and ELEC used in en_conv to produce other energy carriers, for each region and time step, regardless of the plant type.

supply_2 (R, second_in, t) $\geq \Sigma_{\text{type, e\_out}}$ (en_conv (R, second_in, e_out, type, t)); (9)

The new produced energy carriers, produced from H2 and ELEC, will not be delivered to the variable energy_prod and can therefore not be traded or looped back more than once. The new produced energy carriers are instead directly delivered to the next node in the model energy flow called energy_deliv. The following equations make sure that the amount of H2 and ELEC that goes back into en_conv is less than or equal to the difference between energy_prod and energy_deliv.

supply_2 (R, "H2", t) $\leq$ energy_prod (R, "H2", t) – energy_deliv (R, "H2", t); (10)

supply_2 (R,"elec", t) $\leq$ energy_prod (R,"elec", t) – energy_deliv (R,"elec", t); (11)

5.1.6 Total amount of energy carriers

The total amount of energy carriers that are available to meet the energy demand (energy_deliv) contains the energy carriers produced in en_conv after import and export as well as after the loop where hydrogen and electricity could be converted into other energy carriers. Additional heat can also be added to energy_deliv if heat has been produced in combined heat and power production plants. This heat (cg_heat) is not seen in the node energy_prod but goes directly from en_conv to energy_deliv (which also was the case for the new produced energy carriers from looping back H2 and ELEC). Recall the energy flow, nodes and variable names by looking at Figure 2. The following equations balance the production of cg_heat.

The amount of cg_heat equals all production where cogeneration types of energy conversion plants have been used in en_conv multiplied with the conversion efficiency.

cg_heat (R, t) = $\Sigma_{\text{cg\_e\_in, cg\_type, cg\_e\_out}}$ (en_conv (R, cg_e_in, cg_e_out, cg_type, t) * heat_effic (cg_e_in, cg_type, cg_e_out)); (12)

The heat produced in combined heat and power plants is added to energy_deliv in the following equation, i.e. that energy_deliv must be less than or equal to the energy_prod plus the cg_heat. The equation (13) only applies to the energy carrier "heat".

energy_deliv (R, "heat", t) $\leq$ energy_prod (R, "heat", t) + cg_heat (R, t); (13)

5.1.7 Balancing heat and electricity demand

The final part of the energy flow is to balance the energy carriers to the exogenously given demand. For heat and electricity demand, this is done in the following direct equations (whereas it is more complex for the transportation demand).

The total amount of heat available (energy_deliv) must be greater than or equal to the exogenously given heat demand plus the additional heat needed if the model chooses to use CCS.

energy_deliv (R,"heat", t) $\geq$ heat_dem_reg (R, t) + heat_decarb (R, t); (14)

The total amount of electricity available (energy_deliv) must be greater than or equal to the exogenously given electricity demand plus the additional electricity needed if the model chose to use CCS as well as the additional electricity needed if the model chose to use PHEVs or BEVs.

energy_deliv (R,"elec", t) $\geq$ elec_dem_reg (R, t) + elec_decarb (R, t) + elec_trsp (R, t); (15)

5.1.8 Balancing demand on fuels for transport

Since the energy needed for different engine types differs depending on technology specific energy efficiency, the energy flows within the transportation sector has to be separated.

The energy carriers are transferred to a variable node called trsp_energy. For the non-electric vehicles, the following equation balances the energy flow between energy_deliv and trsp_energy, i.e, regardless of transportation mode or engine type the trsp_energy equals energy_deliv for non-electric vehicles.

$\Sigma_{\text{trsp\_mode, e\_type}}$ (trsp_energy (R, trsp_fuel_nonel, e_type, trsp_mode, t)) =
energy_deliv (R, trsp_fuel_nonel, t); (16)

The following equation balances the electricity used in the transportation sector. The total electricity demand (elec_trsp) for the transportation sector (i.e., freight rail, passenger rail, high speed passenger rail, PHEVs and BEVs) equals the amount of electricity delivered into the model node trsp_energy.

elec_trsp (R, t) = $\Sigma_{\text{trsp\_mode, e\_type}}$ (trsp_energy (R,"elec", e_type, trsp_mode, t)); (17)

The following equation balances fuels to each transport mode demand. The total fuel demand (trsp_dem) equals the fuels delivered into trsp_energy multiplied with the engine type conversion factor (trsp_conv). The engine type conversion factor is needed to correct the energy demand since different engine types require different amount of energy, e.g, a fuel cell engine is more efficient than an internal combustion engine and thus needs less energy for the same travelled distance).

trsp_dem (R, trsp_mode, t) = $\Sigma_{\text{trsp\_fuel, e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t) *
trsp_conv (trsp_fuel, e_type, trsp_mode, t)); (18)

5.1.9 Fuel fractions for PHEVs

The following equation balances fuels for the plugin-hybrids since they use both a liquid fuel and electricity. The electricity driving fraction in PHEVs is the exogenously given share the vehicle is assumed to drive in electricity mode. We assume that BTL/CTL/GTL and Petro PHEVs have the same elec_frac. As a base case, it is assumed that PHEV cars operate in battery mode 65% of its driving distance (elec_frac_phev).

The fuel delivered into trsp_energy attended for PHEVs multiplied with the engine type liquid fuel conversion factor (trsp_conv) divided by the share that the vehicle runs on fuels (35% for PHEV cars) equals the electricity in trsp_energy attended for PHEVs multiplied by the engine type electricity conversion factor (trsp_conv) divided by the share that the vehicle runs on electricity (65% for PHEV cars).

$\Sigma_{\text{road\_fuel\_liquid}}$ (trsp_energy (R, road_fuel_liquid, "phev", vehicle, t) *
trsp_conv (road_fuel_liquid, "phev", vehicle, t)) / (1 – elec_frac_phev (vehicle)) =
trsp_energy (R, "elec", "phev", vehicle, t)* trsp_conv ("elec", "phev", vehicle, t) /
(elec_frac_phev (vehicle)); (19)

5.1.10 Fuels matching the number of cars and trucks

The following equation balances the fuel demand to the number of vehicles (the model must invest in at least as many vehicles as there is fuel intended for different engine types). The fuel delivered into trsp_energy must be less than or equal to the annual capacity stock of vehicles (engines) divided by the exogenously given total number of vehicles (which generates a share of engine types) multiplied by the exogenously given transportation demand (trsp_dem) divided by the engine type conversion factor (to compensate for that the demand depend on which engine type is chosen). This equation applies to all engine types except PHEVs, because fuel use depends on the electricity driving fraction (see below).

trsp_energy (R, road_fuel, non_phev, vehicle, t) ≤
engines (R, road_fuel, non_phev, vehicle, t) / num_veh (R, vehicle, t) *
trsp_dem (R, vehicle, t) / (trsp_conv (road_fuel, non_PHEV, vehicle, t) + 0.001); (20)

The following equation balances the liquid fuel demand to the number of PHEVs. As base case it is assumed that PHEV cars operate in battery mode 65% of its driving distance (elec_frac_phev). The fuel delivered into trsp_energy must be less than or equal to the annual capacity stock of vehicles (engines) divided by the exogenously given total number of vehicles (which generates a share of engine types) multiplied by 35% of the exogenously given transportation demand (trsp_dem) divided by the engine type conversion factor. This equation applies to PHEVs.

trsp_energy (R, road_fuel_liquid, "phev", vehicle, t) ≤
engines (R, road_fuel_liquid, "phev", vehicle, t) / num_veh (R, vehicle, t) *
(1 – elec_frac_phev (vehicle)) * trsp_dem (R, vehicle, t) /
(trsp_conv (road_fuel_liquid, "phev", vehicle, t) + 0.001); (21)

5.1.11 Fuels to buses and ships

The investment cost for different engine technologies is an important part of the entire fuel and vehicle technology cost. However, investment costs for different engine technologies are only assumed for the demand categories “cars” and “trucks.” Fuel changes within the demand categories “buses” and “ships” are thus not connected to any additional vehicle investment cost, in this model version. Instead, the mix of fuel choices generated for trucks are directly transferred to buses and ships. Since buses, but not ships, can use HEVs, PHEVs, and BEVs, there are different equations relating fuels to buses and ships.

The fuel delivered into trsp_energy for buses equals the fuels in trsp_energy for trucks (f_road) multiplied by the transportation demand for buses divided by the transportation demand for trucks to get the same fraction of each fuel.

trsp_energy (R, trsp_fuel, e_type,"p_bus", t) =
trsp_energy (R, trsp_fuel, e_type, "f_road", t) * trsp_dem (R,"p_bus", t) /
trsp_dem (R,"f_road", t); (22)

Since the electric engine options cannot be used for ships, the fuel mix for ships differs from the fuel mix used in trucks and buses. The share of fuels for ships is still related to trucks (f_road) to give ships the same fraction of e_types and trsp_fuels as chosen for trucks, except for fuels used for HEVs, PHEVs, and BEVs. When these options are chosen in the truck demand category, additional fuels will be needed for ships (extra_ship_fuel). This extra ship-fuel is spread across conventional technologies and fuel cells, see below.

The fuel delivered into trsp_energy for ships equals the fuels in trsp_energy for trucks (f_road) plus the addditional ship fuel needed if electric option has been chosen for trucks, multiplied by the transportation demand for ships divided by the transportation demand for trucks.

trsp_energy (R, trsp_fuel, ic_fc, ship_mode, t) =
(trsp_energy (R, trsp_fuel, ic_fc, "f_road", t) + extra_ship_fuel (R, trsp_fuel, ic_fc, ship_mode, t)) *
trsp_dem (R, ship_mode, t) / trsp_dem (R,"f_road", t); (23)

The following equation calculates the additional amount of ship-fuel, which is equivalent to the fuel used in HEV, PHEV, and BEV trucks.The additional amount of ship-fuel (extra_ship_fuel) equals the trsp_energy used for HEV+PHEV+BEV in the truck demand category.

$$\Sigma_{\text{trsp\_fuel, ic\_fc}} (\text{extra\_ship\_fuel}(R, \text{trsp\_fuel}, \text{ic\_fc}, \text{ship\_mode}, t)) = \Sigma_{\text{trsp\_fuel, hev\_phev\_bev}} (\text{trsp\_energy}(R, \text{trsp\_fuel}, \text{hev\_phev\_bev}, \text{"f\_road"}, t)); \quad (24)$$

5.1.12 Limitations on heavy electric vehicles

In this version of the GET-model, we have assumed that electric engine options (PHEVs and BEVs) cannot be used for long-distance trucks but only for local distribution trucks. Also HEVs are assumed to play a limited role in the long-distance freight category. Long-distance trucks usually run on optimal RPM and do not brake that often, i.e. not much “spare energy” to charge HEV-batteries. As a base case we assume that a maximum of 20% of the truck demand category can be fulfilled with PHEVs and a maximum of 20% of HEVs (frac_phev_trucks=0.20). The fraction of BEVs (frac_bev_trucks) is set to zero.

$$\Sigma_{\text{road\_fuel\_liquid}} (\text{trsp\_energy}(R, \text{road\_fuel\_liquid}, \text{hybrids}, \text{"f\_road"}, t) * \text{trsp\_conv}(\text{road\_fuel\_liquid}, \text{hybrids}, \text{"f\_road"}, t) / (1 - \text{elec\_frac\_phev}(\text{"f\_road"}))) \leq \text{frac\_phev\_trucks} * \text{trsp\_dem}(R, \text{"f\_road"}, t); \quad (25)$$

$$\text{trsp\_energy}(R, \text{"elec"}, \text{"BEV"}, \text{"f\_road"}, t) * \text{trsp\_conv}(\text{"elec"}, \text{"BEV"}, \text{"f\_road"}, t) \leq \text{frac\_bev\_trucks} * \text{trsp\_dem}(R, \text{"f\_road"}, t); \quad (26)$$

For buses we have assumed that HEVs and PHEVs cannot be used for long-distance buses but only for buses running local routes. As base case, we assume that a maximum of 60% of the bus demand category can be fulfilled with HEVs and PHEVs. The fraction of BEVs (frac_bev_buses) is set to zero.

$$\Sigma_{\text{road\_fuel\_liquid}} (\text{trsp\_energy}(R, \text{road\_fuel\_liquid}, \text{hybrids}, \text{"p\_bus"}, t) * \text{trsp\_conv}(\text{road\_fuel\_liquid}, \text{hybrids}, \text{"p\_bus"}, t) / (1 - \text{elec\_frac\_phev}(\text{"f\_road"}))) \leq \text{frac\_phev\_buses} * \text{trsp\_dem}(R, \text{"p\_bus"}, t); \quad (27)$$

$$\text{trsp\_energy}(R, \text{"elec"}, \text{"BEV"}, \text{"p\_bus"}, t) * \text{trsp\_conv}(\text{"elec"}, \text{"BEV"}, \text{"p\_bus"}, t) \leq \text{frac\_bev\_buses} * \text{trsp\_dem}(R, \text{"p\_bus"}, t); \quad (28)$$

5.1.13 Allowed energy conversion paths

Not all theoretical energy conversions options are allowed, i.e. wind can produce electricity but not heat, petro or BTL/CTL/GTL. The matrix flow_matrix controls which paths are allowed, where zeros in the matrix represent allowed paths. The following equation can, thus, only be fulfilled for zero marked paths.

$$\Sigma_{R, t} (\text{en\_conv}(R, \text{e\_in}, \text{e\_out}, \text{type}, t)) * \text{flow\_matrix}(\text{e\_in}, \text{type}, \text{e\_out}) = 0; \quad (29)$$

Instead of equation (29), another option to make sure that the model will not use any of the forbidden conversion paths is to make sure that the conversion efficiencies for these paths are exactly zero. Currently, when the conversion efficiencies are time dependent and initially 0.1 higher than mature level, we have found it easier to use this flow matrix constraint to be sure that the model only uses allowed conversion paths.

5.2 Import and export balances

The following equations balance the import and export flows of both primary energy sources and secondary energy carriers.

The import of primary energy sources (imp_prim) to one region must be exactly the same as has been exported from all other regions to the specific region (imp_prim_from).

imp_prim (R_imp, fuels, t) = Σ_{R_exp} (imp_prim_from (R_imp, R_exp, fuels, t)); (30)

The same applies to the export, where the export of primary energy sources (exp_prim) from one region must be exactly the same as has been imported to all other regions from the specific region (imp_prim_from).

exp_prim (R_exp, fuels, t) = Σ_{R_imp} (imp_prim_from (R_imp, R_exp, fuels, t)); (31)

The import and export equations are here repeated for the secondary energy carriers

imp_sec (R_imp, sec, t) = Σ_{R_exp} (imp_sec_from (R_imp, R_exp, sec, t)); (32)

exp_sec (R_exp, sec, t) = Σ_{R_imp} (imp_sec_from (R_imp, R_exp, sec, t)); (33)

5.3 Investments and depreciation

In this section, equations balancing the investments are presented. Investments are available directly, i.e., investments can be used in the same time step as the model decide on investing in additional or new vehicles or energy conversion plants. New investments will add to the aggregated capacity stock, and every year the capacity stock also depreciates following the investment's life time.

The initial capacity, for the energy conversion plants, is exogenously given for year 1990, as seen in the following equation, i.e. capacity year 1990 (init_year) equals the exogenously given initial capacity (init_cap) plus 10 times the new investments made in 1990. The multiplication with t_step (10 years) is to scale up the investments done in one year over the coming 10 years, since we have 10 year time steps in the model.

capacity (R, e_in, e_out, type, init_year) =
init_cap (e_in, e_out, type, R) + t_step * cap_invest (R, e_in, e_out, type, init_year); (34)

The following three equations balance the aggregated capacity (for all time steps except 1990), for the energy conversion plants, for the vehicle engines, as well as for the infrastructure. The capacity in year t+1 equals 10* the new investments done in year t+1 plus the existing capacity (in year t) multiplied with the depreciation formula. In GAMS "exp" means the number "e" followed by an exponent and "log" means the natural logarithm, "ln". If a plant's lifetime is 25 years, then the depreciation formula is

$$e^{(10\cdot\ln(1-\frac{1}{25}))}$$

capacity (R, e_in, e_out, type, t+1) =
t_step * cap_invest (R, e_in, e_out, type, t+1) + capacity (R, e_in, e_out, type, t)*
exp (t_step*log (1 – 1/life_plant (e_in, e_out, type))); (35)

engines (R, trsp_fuel, e_type, vehicle, t+1) =
t_step * eng_invest (R, trsp_fuel, e_type, vehicle, t+1) + engines (R, trsp_fuel, e_type, vehicle, t) *
exp (t_step * log (1 – 1/life_eng (trsp_fuel, e_type, vehicle))); (36)

infra (R, synfuel_gas, t+1) =
t_step * infra_invest (R, synfuel_gas, t+1) + infra (R, synfuel_gas, t) *
exp (t_step * log (1 – 1/life_infra (synfuel_gas))); (37)

5.3.1 Use limited by capacity

The following equations balance the amount of capacity to the use of energy conversion plants and use of infrastructure (the model must invest in at least as much capacity as there is energy flows in different types of facilities).

For the energy conversion plants, the energy converted in different type of plants (en_conv) multiplied by the conversion efficiency (effic) must be less than or equal to the aggregated capacity stock multiplied by the capacity factor (generally 0.75) multiplied by the number of seconds per year (31.6 Ms/yr). The capacity factor (lf) and number of seconds per year (Msec_per_year) is needed to convert capacity expressed in Watt into energy Joule/yr.

en_conv (R, e_in, e_out, type, t) * effic (e_in, type, e_out, t) ≤
capacity (R, e_in, e_out, type, t) * lf (e_in, type, e_out, R) * Msec_per_year; (38)

For the infrastructure, the delivered energy (energy_deliv) must be less than or equal to the aggregated capacity stock of infrastructure multiplied by the capacity factor (lf_infra) multiplied by the number of seconds per year (31.6 Ms/yr). This is to convert the capacity expressed in Watt into energy expressed in Joule/yr.

energy_deliv (R, synfuel_gas, t) ≤
infra (R, synfuel_gas, t)* lf_infra (synfuel_gas) * Msec_per_year; (39)

5.4 Emission calculations

If the model chooses to use fossil fuels, the CO_2 emissions will be registered using emissions factors (emis_fact) from the Swedish EPA (Naturvårdsverket, 2013). The model does not include greenhouse gases other than CO_2.

5.4.1 Emissions

The CO_2 emissions are based on the energy flow in the variable node supply_tot, which is the amount of primary energy sources used in a region after import and export. This means that all CO_2 are emitted in the region that uses the primary energy source. For tradable secondary energy carriers that contain carbon in the fuel (i.e. CTL and GTL), the emissions are separated between the producing and using region. That is, emissions originating from the energy conversion process are registered in the "production region," and the emissions from combusting the fuel are registered in the "using region" after import/export of secondary energy carriers. Captured emissions from applying CCS (c_capt_tot) are subtracted from the total emission (c_emission).

c_emission (R, t) = Σ_{fossil} (emis_fact (fossil) * supply_tot (R, fossil, t)) –
c_capt_tot (R, t) – exp_sec (R,"CTL/GTL", t) * emis_fact_syn +
imp_sec (R,"CTL/GTL", t) * emis_fact_syn; (40a)

c_emission_global (t) = Σ_R (R, c_emission (R, t)); (40b)

Σ_R (c_emission (R, t_h)) = hist_fos_emis (t_h); (40c)

The emissions can be constrained using different kinds of strategies. In the GET model, we have four different options: (i) apply a carbon tax, (ii) set a constraint on the maximum atmospheric CO_2 concentration that will be met through the carbon cycle module in the model, (iii) limit the global emissions per time step following e.g., the WRE-curves (Wigley et al, 1996), or (iv) set an upper limit on the aggregated emissions over a certain time period. To use the latter option, we need an equation calculating the aggregated emissions, which is done in eq (41) where the emissions made during time period t (1990-2149) are summed up.

$$\text{agg\_emis} = \sum_{R,t} \left(\text{t\_step} * \text{c\_emission}(R,t)\right); \qquad (41)$$

5.4.2 Carbon capture and storage (CCS) and limitations

The model allows for applying CCS technologies on fossil fuels as well as on biomass. In this model version, CCS can be applied to the stationary energy sector (heat and electricity) but not to the production of transportation fuels. In base case, it is assumed that 90% of the carbon in fossil fuels can be captured (fos_capt_effic=0.9). We further assume negligible leakage of stored CO_2, i.e. zero leakage in the model.

The following equation calculates the annual total amount of carbon (c_capt_fos) that has been captured from fossil fuels, which equals the energy flow passing the energy conversion module (en_conv) using the plant type "c_capt" multiplied by the exogenously given emissions factors. The reason for using "less than or equal" instead of "equal" in the equation is that when using "less than or equal," the regions have the possibility of investing in CCS-technology but can wait a decade or so before using it.

$$\text{c\_capt\_fos}(R,t) \leq \sum_{\text{fossil, e\_out, c\_capt}} \left(\text{en\_conv}(R, \text{fossil}, \text{e\_out}, \text{c\_capt}, t) * \text{emis\_fact}(\text{fossil}) * \text{fos\_capt\_effic}\right) \qquad (42)$$

Also when applying CCS on biomass heat and electricity production, we have assumed that 90% of the carbon in the biomass can be captured (bio_capt_effic=0.9).

$$\text{c\_capt\_bio}(R,t) = \sum_{\text{e\_out, c\_capt}} \left(\text{en\_conv}(R, \text{"bio"}, \text{e\_out}, \text{c\_capt}, t) * \text{emis\_fact}(\text{"bio"}) * \text{bio\_capt\_effic}\right); \qquad (43)$$

The following equation adds the two CCS options described above together.

$$\text{c\_capt\_tot}(R,t) = \text{c\_capt\_bio}(R,t) + \text{c\_capt\_fos}(R,t); \qquad (44)$$

The following equation calculates the aggregated captured carbon over the entire time period, 1990-2149. The c_capt_agg is then constrained to an upper limit to maximize the use of CCS due to carbon storage capacity. In base case, the global c_capt_agg is maximized to 600 GtC. Although it is a global limitation (and thereby indicate that CCS is not restricted to storage locations), we assume that it will be possible to find local storage for all new built CCS-plants up until the global upper limit is reached (the CCS costs are based on local storage).

$$\text{c\_capt\_agg} = \sum_{R,t} \left(\text{c\_capt\_tot}(R,t) * \text{t\_step}\right); \qquad (45)$$

The expansion of CCS is also limited to an annual growth limit. In our base case, we have assumed a maximum expansion rate (c_stor_maxgr) of 100 MtC/decade.

The following equation limits the expansion of CCS as follows: all captured carbon (c_capt_tot) in year t+1 should be less than or equal to the amount of captured carbon in year t plus 100*10.

$$\Sigma_{R} \left(c\_capt\_tot(R, t+1)\right) \leq \Sigma_{R} \left(c\_capt\_tot(R, t)\right) + c\_stor\_maxgr * t\_step; \quad (46)$$

CCS cannot be applied to all kinds of stationary energy use. In the base case, we have assumed that a maximum of 30% of the entire heat demand can be fulfilled by CCS facilities (c_capt_heat_fr=0.30).

$$\Sigma_{fuels,\, c\_capt} \left(en\_conv(R, fuels, \text{"heat"}, c\_capt, t)\right) \leq c\_capt\_heat\_fr * heat\_dem\_reg(R, t); \quad (47)$$

When applying CCS, the electricity use increases since additional electricity is needed in these energy conversion plants compared to conventional plants. This additional electricity (elec_decarb) is calculated in eq (48) and added to the total electricity demand in eq (15). The parameter dec_elec is calculated as a fraction of variable en_conv and differs for different CCS facilities but lies in a range of 0.025–0.04. Note that the following equation only runs over the final energy carrier "heat", i.e. when CCS is applied on heat generation plants. When CCS is applied to plants producing electricity, the additional electricity needed is accounted for directly by lowering the energy efficiency for the electricity production. Note also that we assume that negligible additional heat is needed when applying CCS.

$$elec\_decarb(R, t) = \Sigma_{fuels} \left(en\_conv(R, fuels, \text{"heat"}, \text{"CCS"}, t) * dec\_elec(fuels)\right); \quad (48)$$

5.4.3 Carbon cycle model

The GET model uses a carbon cycle model to convert the CO_2 emissions into an atmospheric CO_2 concentration. The carbon contribution (carb_ctrb) depends on the CO_2 emissions registered when using fossil fuels during the model runs (c_emission), as well as estimated future emissions from land use changes (fut_luc_emis) and estimated future biota sinks (fut_biota_sinks) times the factor given by the impulse response function (IRfunc). Read more about IRfunc in Section 3.2.5 Emissions and carbon taxes and in Appedix 4.

$$carb\_ctrb(T\_all, T\_all\_copy) = \left(fut\_luc\_emis(T\_all\_copy) - fut\_biota\_sinks(T\_all\_copy) + \Sigma_{R}\, c\_emission(R, T\_all\_copy)\right) * IRfunc(T\_all, T\_all\_copy) \quad (49)$$

The multiarray carbon contribution (carb_ctrb) is then summarized over T_copy to generate the annual carbon contribution and transferred into an atmospheric carbon concentration in ppm (by multiplying with 0.28/600*10) and added to the pre-industrial carbon concentration (pre_ind_ccont=280 ppm).

$$atm\_ccont(T\_all) = pre\_ind\_ccont + \left(\Sigma_{T\_all\_copy}\, carb\_ctrb(T\_all, T\_all\_copy)\right) * 0.28/600*10 \quad (50)$$

5.5 Cost accounting

In this section, the equations calculating the costs are presented.

5.5.1 Extraction cost on primary energy sources

When using the primary energy sources denoted "fuels", which contains biomass, coal, oil, natural gas and uranium (supply_1), it comes with an extraction cost. The primary energy prices are exogenously given (price). This primary energy cost is charged to the region that extracts the source.

$$cost\_fuel(R, t) = \Sigma_{fuels} \left(supply\_1(R, fuels, t) * price(fuels, R)\right) \quad (51)$$

5.5.2 Investment cost and O&M cost

The total annual investment cost (cost_cap) is an addition of the calculated cost for new installed capacity in energy conversion plants (cap_invest), new vehicles (eng_invest), and new installed infrastructure (infra_invest).

cost_cap (R, t) =
$\Sigma_{\text{e\_in, e\_out, type}}$ (cap_invest (R, e_in, e_out, type, t) * cost_inv_mod (e_in, e_out, type, t)) +
$\Sigma_{\text{road\_fuel, e\_type, vehicle}}$ (eng_invest (R, road_fuel, e_type, vehicle, t) *
cost_eng_mod (road_fuel, e_type, vehicle, t)) +
$\Sigma_{\text{synfuel\_gas}}$ (infra_invest (R, synfuel_gas, t) * cost_infra_mod (synfuel_gas)); (52)

The operation and maintenance (O&M) cost is calculated as a fraction (OM_cost_fr) of the investment costs. The parameter OM_cost_fr is in general 0.04. The parameter cost_inv_mod is the initial plant investment cost adjusted for different investment and discount rates, calculated as cost_inv_mod(e_in, e_out, type, t) = cost_inv(e_in, e_out, type, t) * (r_invest + 1/life_plant(e_in, e_out, type)) /(r+1/life_plant(e_in, e_out, type)). The fraction of the modified investment cost is multiplied by the energy flow in the energy conversion module (en_conv), multiplied by the energy efficiency, and divided by 31.6 Ms/yr and the capacity factor (lf) generalized to 0.7, see eq (53).

OM_cost (R, t) = $\Sigma_{\text{e\_in, e\_out, type}}$ (OM_cost_fr (e_in, e_out) * cost_inv_mod (e_in, e_out, type, t) *
en_conv (R, e_in, e_out, type, t) * effic (e_in, type, e_out, t) / Msec_per_year/0.7); (53)

5.5.3 Costs for carbon storage and carbon tax

When CCS is used, an additional cost will come on the distribution and storage of the carbon. Total captured fossil carbon (c_capt_fos) is multiplied by the storage cost (cost_strg_fos) plus the same for bioenergy CCS.

cost_c_strg (R, t) = c_capt_fos (R, t) * cost_strg_fos +
c_capt_bio (R, t) * cost_strg_bio; (54)

Biomass-based heat and electricity facilities are typical smaller than the fossil based options. Distributing the captured carbon from bioenergy CCS plants will therefore be slightly more costly. The following equation calculated this additional cost.

cost_c_bio_trsp (R, t) = $\Sigma_{\text{e\_out, c\_capt}}$ (en_conv (R, "bio", e_out, c_capt, t)) *
c_bio_trspcost; (55)

In the GET model, there are different possibilities to reduce the CO_2 emissions. If applying a carbon tax, the cost of this tax will be calculated in the following equation.

tax (R, t) = c_emission (R, t)*c_tax (R, t); (56)

5.5.4 Import costs

The following equation calculates the cost for transportation when importing primary energy sources. The transportation cost contains of a fixed part (imp_cost) and a linear cost (imp_cost_lin) depending on the distance.

tot_trspcost_prim (R, t) = $\Sigma_{\text{fuels, R\_exp}}$ (imp_prim_from (R_imp, R_exp, fuels, t) *
(imp_cost (fuels) + distance (R_imp, R_exp) * imp_cost_lin (fuels))); (57)

The following equation calculates the cost for transportation when importing secondary energy carriers. The transportation cost contains of a fixed part (imp_cost2) and a linear cost depending on the distance (imp_cost_lin2).

tot_trspcost_sec (R, t) = $\Sigma_{\text{sec, R\_exp}}$ (imp_sec_from (R_imp, R_exp, sec, t) * (imp_cost2 (sec) + distance (R_imp, R_exp) * imp_cost_lin2 (sec))); (58)

5.5.5 Total annual costs

The following equation calculates the total annual cost (annual_cost) by adding the different annual costs together, i.e. the cost of primary energy sources (cost_fuel), the investment costs (cost_cap), the O&M costs (OM_cost), the carbon storage cost (cost_c_strg), the additional bio-CCS distribution cost (cost_c_bio_trsp), the transportation costs when importing primary energy sources (tot_trspcost_prim) as well as secondary energy carriers (tot_trspcost_sec), and the eventual carbon tax (tax).

annual_cost (R, t) = cost_fuel (R, t) +cost_cap (R, t) + OM_cost (R, t) + cost_c_strg (R, t) + cost_c_bio_trsp (R, t) +tot_trspcost_prim (R, t) + tot_trspcost_sec (R, t) + tax (R, t) ; (59)

5.5.6 Total aggregated costs and objective function

The following expression shows the discounting factor used in this model:

$$(1+r)^{10\cdot(ORD(t)-1)}$$

Note that "ORD" is a GAMS operator which generates integers from the position in the set, e.g. ORD(1990)=1 and ORD(2000)=2.

The following equation calculates the total aggregated cost for the entire global energy system over the time period 1990-2149. This is the variable that is minimized in the objective function, see eq (61). The total cost (tot_cost) equals 10 times the annual cost divided by the discount factor:

tot_cost = $\Sigma_{\text{R, t}}$ (t_step * annual_cost (R, t)/ ((1+r)^(t_step*(ORD (t) – 1)))); (60)

Finally, the following is the objective function:

Minimize tot_cost (61)

5.6 Restrictions, limitations and adjustments

In this section, various constraints, restrictions, and limitations are presented in order to get the model to generate results that are closer to reality or in order to force the model to generate a specific scenario.

5.6.1 Choosing CCS/CSP scenarios

In GET-RC 6.1, we analyze how technology development in the stationary energy sector impacts cost-effective fuel and technology use in the transportation sector. We have chosen to run 4 technology scenarios, i.e. (A) neither CCS nor CSP available, (B) only CCS available, (C) only CSP available, or (D) CCS and CSP both available. To switch between the four scenarios we activate and deactivate the following two restrictions.

This restriction should be activated when running scenarios where CSP is assumed to not make it as a future low cost renewable electricity option.

tot_CSP.up (t) = 0; (62)

The variable c-capt_tot is set to zero if CCS is assumed to not be large scale available in future.

c_capt_tot.up (R, t) = 0; (63)

5.6.2 Limitations on co-generation and intermittent energy

Co-generation plants, where both electricity and heat is generated, are assumed to not be a realistic option in all cities all over the world. Therefore, we have included an upper limitation of how much of the electricity and heat demand that can come from co-generation plants. In this model version, both fractions (cogen_fr_e and cogen_fr_h) are set to 20%.

$\Sigma_{cg\_e\_in,\ cg\_type}$ (en_conv (R, cg_e_in, "elec", cg_type, t) *
effic (cg_e_in, cg_type, "elec", t)) ≤ cogen_fr_e * elec_dem_reg (R, t); (64)

$\Sigma_{cg\_e\_in,\ cg\_type,\ cg\_e\_out}$ (en_conv (R, cg_e_in, cg_e_out, cg_type, t) *
heat_effic (cg_e_in, cg_type, cg_e_out)) ≤ cogen_fr_h * heat_dem_reg (R, t); (65)

Electricity from intermittent energy sources (wind and direct solar), without electricity storage such as hydrogen production, is maximized to 30% of total electricity production.

en_conv (R,"solar", "elec", "0", t) + en_conv (R,"wind", "elec", "0", t) ≤
interm_fr * energy_deliv (R, "elec", t); (66)

5.6.3 Initialization of capacity

The following restrictions set the initial level on capacity. The added small number that increases the number of vehicles in 1990 is only there to avoid infeasible solution when initial capacity for petroleum production should match the amount of vehicles for 1990. It is extremely difficult in a rough model to find the exact match. Increasing the number of vehicles for 1990 will not affect the result on cost-effective fuel and vehicle technology solution but the larger the added value the lower the overall cost (lower the need to invest in conventional petroleum vehicles in 2000).

infra.fx (R, synfuel_gas, init_year) = 0; (67)

engines.fx (R, trsp_fuel, e_type, vehicle, init_year) = 0; (68)

engines.fx (R,"petro", "0", "p_car", init_year) =
num_veh (R,"p_car", init_year) + 0.001; (69)

engines.fx (R,"petro", "0", "f_road", init_year) =
num_veh (R,"f_road", init_year) + 0.001; (70)

5.6.4 Limitations on technology growth and depreciation

To capture natural global energy system inertia, we have included limitations on how fast new (as well as conventional) technology can grow. Growth is restricted in both relative and absolute senses. The growth limitations on energy conversion plants are given below. Note that "log" refers to natural logarithm, sometimes denoted "ln".

capacity (R, e_in, e_out, type, t+1) ≤
capacity (R, e_in, e_out, type, t) * exp (t_step*log (1+cap_g_lim)) + init_plant (R); (71)

capacity (R, e_in, e_out, type, t+1) ≤ capacity (R, e_in, e_out, type, t) +
max_exp_p (e_in, e_out, type, R, t) / (lf (e_in, type, e_out, R) + 0.0001); (72)

The following two equations limit the growth on infrastructure:

infra (R, synfuel_gas, t+1) ≤
infra (R, synfuel_gas, t) * exp (t_step* log (1+infra_g_lim))+ init_infra (R); (73)

infra (R, synfuel_gas, t+1) ≤ infra (R,synfuel_gas, t) + max_inv_infra (R, t)/
lf_infra (synfuel_gas); (74)

The following equation limits the growth on engines (number of engines equal number of vehicles). Vehicle growth is not restricted by absolute numbers.

engines (R, trsp_fuel, e_type, vehicle, t+1) ≤
engines (R, trsp_fuel, e_type, vehicle, t)* exp (t_step * log (1+ eng_g_lim))+
init_eng (R); (75)

Growth expansion rates are also applied on the extraction of fossil energy sources as well as biomass production. First, a relative limitation followed by two equations that limit the growth on fossil fuels as well as biomass in absolute numbers.

supply_1 (R, fuels, t+1) ≤ supply_1 (R, fuels, t) * exp (t_step * log (1+ supply_g_lim)) +
init_supply (R) * Msec_per_year; (76)

supply_1 (R, fossil, t+1) ≤ supply_1 (R, fossil, t) + max_exp (R, t); (77)

supply_1 (R,"bio", t+1) ≤ supply_1 (R,"bio", t) + max_exp_bio (R, t); (78)

Although the maximum expansion constraints above, wind power increases unrealisticly rapidly, therefore we added a constraint on wind power that each 10-year timestep may not exceed a 200% increase.

$\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, t+1)) ≤
3* $\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, t)); (79)

In the real world, there is also inertia on how fast technologies will be phased out. In cost-minimizing models, technologies will most often be used their entire life time, i.e. a sufficient representation of natural interia. However, for the fuel "petro" as well as for all engine types, we have chosen to include two decay limitations, see eq (80) and (81). Petroleum based fuels in a specific time step can never be lower than 70% of the previous time step (mx_decay_frac_oil). To be able to reach zero, the equation also include an absolute number (mx_decay_abs_oil) of x EJ, depending on the time step and region, that subtracts the final "tail" of the out-going fuel usage.

en_conv (R, "oil", "petro", "0", t+1) ≥
en_conv (R, "oil", "petro", "0", t) * mx_decay_frac_oil – mx_decay_abs_oil (R, t); (80)

$\Sigma_{\text{e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t+1)) ≥
$\Sigma_{\text{e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t)) *
mx_decay_frac – mx_decay_abs (R, t); (81)

For all energy conversion paths, there is also a restriction that at least 75% (en_conv_decr_lim) of the energy conversion in the earlier time step will be used. To cut the last tail of an out-going path, a small constant value in EJ (en_conv_dis) will be subtracted.

en_conv (R, e_in, e_out, type, t+1) ≥
en_conv_decr_lim * en_conv (R, e_in, e_out, type, t) – en_conv_dis (R, t); (82)

5.6.5 Technology limitations, restrictions and adjustments

In this section, we have presented different technology limitations, restrictions, and adjustments used in the model.

The following restriction forces a highspeed train to run on electricity. A high speed train is otherwise a fraction of the demand for passenger aviation.

trsp_energy.fx (R,"elec", "0", "p_air", t) =
high_speed_train (R, t)* trsp_dem (R,"p_air", t) / trsp_conv ("elec", "0", "p_air", t); (83)

The upper limit on storage capacity for carbon capture is set to 600,000 MtC.

c_capt_agg.up = 600000; (84)

To make sure that the model does not use CCS before 2010, we have added the following restriction:

c_capt_tot.up (R, t_1990_2010) = 0; (85)

Also to make sure that the model does not use alternative fuels for aviation before year 2010, we have added the following restriction:

energy_deliv.fx (R,"air_fuel", t_1990_2010 = 0; (86)

In all model runs, the following restriction is activated, i.e. we assume that hydrogen will not be available as a fuel for aviation.

en_conv.up (R, "h2", "air_fuel", type, t) = 0; (87)

Fuel cells will not enter the scenarios until fossil conventional technologies have reached a high cost. Usually fuel cells will enter sometimes between 2050 and 2100 in our model runs. However, to be sure that the model does not generate unrealistic results, we have included the following restriction, which forbids fuel cells (fc) to enter the scenarios before 2030.

trsp_energy.up (R, trsp_fuel, "fc", trsp_mode, ”1990”) = 0;
trsp_energy.up (R, trsp_fuel, "fc", trsp_mode, ”2000”) = 0;
trsp_energy.up (R, trsp_fuel, "fc", trsp_mode, ”2010”) = 0;
trsp_energy.up (R, trsp_fuel, "fc", trsp_mode, ”2020”) = 0; (88)

To make sure that the model does not invest in HEVs or PHEVs before 2010, we have added the following restriction:

engines.fx(R, trsp_fuel, hybrids, vehicle, t_1990_2010) = 0; (89)

In this model version, we assume that the contribution of nuclear power (in EJ) will remain at 2010 year level in all regions. In GAMS, this is constrained using the command “.fx”, see eq (90).

supply_tot.fx (R, "nuclear", t_2010_2140) =

R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
EJ	9.53	11	4.03	2.74	0.14	0.25	0.23	0	0.47	0.38

(90)

Solar based heat is limited in absolute numbers (EJ/region) following eq (91).

en_conv.up (R,"solar", "heat", "0", t) =

R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
EJ	0.32	0.52	0.13	0.28	0.56	0.49	0.49	0.31	1.42	1.29

(91)

To simulate actual use of traditional biomass in India (SAS) and China (CPA), the following restrictions have been included, defining the minimum amount of biomass based heat, see eq (92) and (93).

en_conv.lo ("SAS","bio","heat","0", t) =

t	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120
EJ	15	15	15	15	15	15	15	12	10	8	6	4	2

(92)

en_conv.lo ("CPA","bio","heat","0", t) =

t	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120
EJ	15	15	15	15	15	15	15	12	10	8	6	4	2

(93)

When analyzing the results, we have identified those that are too unlikely to occur. The following four restrictions adjust results on oil, gas, wind, and hydro for year 2010.

When the model was coded, it was only four years from 2010, and a huge decrease on oil and gas were not seen to be likely. Therefore, we assumed that the decrease on oil and gas use between year 2000 and 2010 may not exceed 10%.

supply_tot (R, "oil", "2010") $\geq$ 0.9 * supply_tot (R, "oil", "2000"); (94)

supply_tot (R, "NG", "2010") $\geq$ 0.9 * supply_tot (R, "NG", "2000"); (95)

For wind and hydro use, the results for year 2010 show an increase that is unlikely to occur. Therefore, we have added a restriction that the increase on wind power between year 2000 and 2010 may not exceed 100%.

$\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, "2010")) $\leq$
2* $\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, "2000")); (96)

The increase on hydro power between year 2000 and 2010 may not exceed 50%.

$\Sigma_{\text{type, e\_out}}$ (en_conv (R,"hydro", e_out, type, "2010")) $\leq$
1.5* $\Sigma_{\text{type, e\_out}}$ (en_conv (R,"hydro", e_out, type, "2000")); (97)

For the two largest biomass producing regions, Latin America (LAM) and Africa (AFR), the maximum expansion constraint is shown to be too hard. If not adjusted, the biomass production in these regions will not reach their given upper supply potential until after year 2100. Following the literature, it is possible for these regions to reach their maximum supply potential around year 2050-2060 (see e.g., Johansson et al, 1993; Hoogwijk, 2004). We have therefore increased the "max_exp_bio" with a factor of four for LAM and a factor of two for AFR; see the two following adjustments.

max_exp_bio ("LAM", t) = 4* ((elec_dem_reg ("LAM", t) +
heat_dem_reg ("LAM", t) + $\Sigma_{\text{trsp\_mode}}$ (trsp_dem ("LAM", trsp_mode, t))) /
(Msec_per_year*t_step)) * global_max_exp_b; (98)

max_exp_bio ("AFR", t) = 2* ((elec_dem_reg ("AFR", t) +
heat_dem_reg ("AFR", t) + $\Sigma_{\text{trsp\_mode}}$ (trsp_dem ("AFR", trsp_mode, t))) /
(Msec_per_year*t_step)) * global_max_exp_b; (99)

5.6.6 Correcting results for 1990 and 2000

To correct for actual emissions (MtC) in the four industrialized regions, we have included the following restrictions.

c_emission.fx (R, t) =

t \ R	NAM	EUR	PAO	FSU
1990	1596	1256	464	999
2000	1931	1247	603	690
2010	1875	1271	508	854

(100)

To correct for actual use of primary energy sources (following IEA B2020), we have included the following restrictions for year 1990 and 2000.

supply_tot.lo (R, e_in, "1990") =

e_in \ R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
coal	20	20	5.5	12	3.1	2.8	0.7	0.13	22.9	4.1
oil	38	28	14	17	3.8	3.4	6.6	6.1	4.8	5.1
NG	21	12	2.5	23	1.3	1	2.3	3.2	0.66	1.4
nuclear	7.5	8.8	2.8	2.3	0.09	0.17	0.1	0	0	0.26
hydro	2.1	1.7	0.4	0.8	0.2	0.22	1.3	0.05	0.46	0.32
bio	3.2	2.2	0.4	0.8	8.1	5.1	3.2	0.04	8.4	7.6

(101)

supply_tot.lo (R, e_in, "2000") =

e_in \ R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
coal	24	14.8	7.5	7	3.75	4.17	0.9	0.33	27.6	6.26
oil	45	30	17	8	4.55	5.74	9.1	9.46	9.65	8.6
NG	27	17.3	4.5	20	2.16	2.12	3.6	6.74	1.18	3.17
nuclear	9.5	10.5	4	2.4	0.14	0.25	0.13	0	0.18	0.38
hydro	2.3	2.1	0.5	0.8	0.26	0.24	1.99	0.05	0.8	0.36
bio	3.9	3.1	0.7	0.5	10.37	5.88	3.26	0.04	8.98	8.82

(102)

We have also decided to adjust the main oil trade (EJ) for some years, regions, and initial years, following BP statistical review (BP, 2009). For some regions, we have set a lower bound and for others we have set an upper bound.

imp_prim.lo (R,"oil", t) =

t \ R	NAM	EUR	PAO
2000	13	18	9.5
2010	17	24	10
2020	17		

(103)

exp_prim.lo (R,"oil", t) =

t \ R	MEA
2000	44.5
2010	49

(104)

exp_prim.up (R,"oil", t) =

t \ R	NAM	EUR	PAO
2000	0	0	0
2010	0	0	0

(105)

5.6.7 Carbon emission scenarios

There are four ways of constraining CO_2 emissions in this model version. We can (1) put an upper limit on the entire carbon budget, i.e. summarized over all regions and all time steps, (2) put upper limits on each time step's CO_2 emission, (3) set an upper limit on the CO_2 concentration in ppm, or (4) apply a carbon tax.

In this model version, we have not used carbon taxes and therefore eq (106) is set to zero.
c_tax (R, t) = 0; (106)

To constrain the CO_2 emissions, we have chosen to apply upper limits on each time step's global CO_2 emission (MtC), following so called WRE-curves (Wigley et al, 1996). When running different scenarios, one of the following four WRE curves (400, 450 500 or 550 ppm) will be activated.

c_emission_global.up (t) =

t	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
400	8936	8063	6463	4804	3525	2705	2240	1994	1878	1826	1824	1822	1820
450	8780	8297	7443	6467	5556	4770	4121	3596	3181	2849	2658	2502	2371
500	9072	9292	9092	8551	7812	6992	6195	5469	4837	4298	3886	3541	3250
550	9364	10287	10741	10635	10086	9214	8269	7342	6492	5746	5114	4580	4129

(107)

The following restriction can be activated if a global carbon budget will be used as method to constrain the CO_2 emissions. This restriction is NOT activated in this model version.

agg_emis.up = 360000; (-)

The following restriction can be activated if a global CO_2 concentration (ppm) will be used as method to constrain the CO_2 emissions. This restriction is NOT activated in this model version.

atm_ccont.up (”2100”) = 450; (-)

6. Output

To analyze the model results, we plot a selection of variables and present them in figures. When verifying that the model runs properly, hundreds of different figures are generated and compared. In scientific papers, we have focused on presenting results on cost-effective fuel and technology choices for passenger cars (Figure H in the code below). In this section, we present the model code for the thirteen most interesting and relevant figures. These 13 figures are presented from a run assuming that both CCS and CSP are available technologies and the CO_2-scenario is 450 ppm in 2100 (see Figures 3-15).

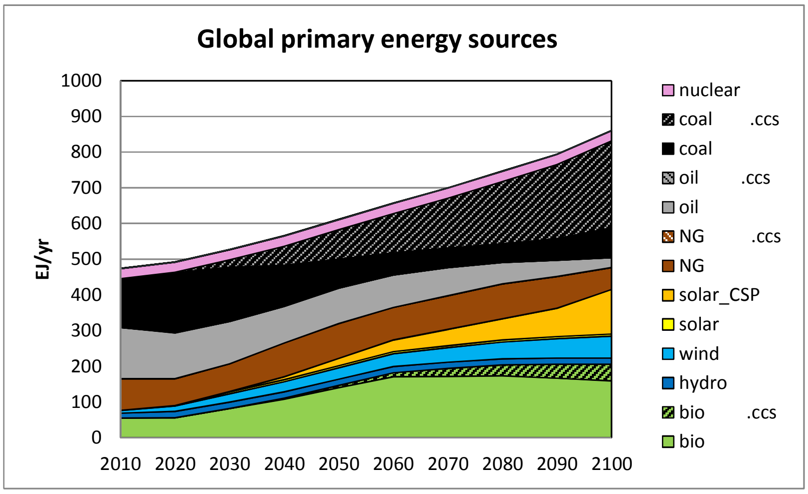

Figure 3. Results on primary energy sources. The figure is called "Figure A" in the GAMS output code below.

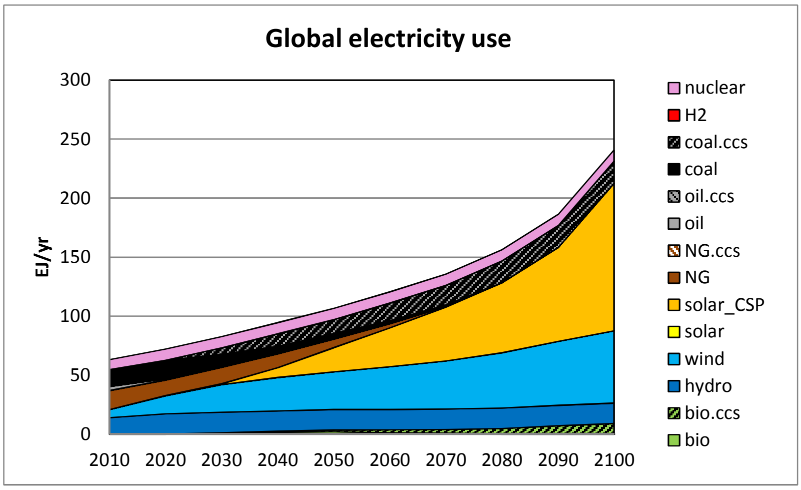

Figure 4. Results on electricity use with values expressed in secondary energy terms. The figure is called "Figure B" in the GAMS output code below.

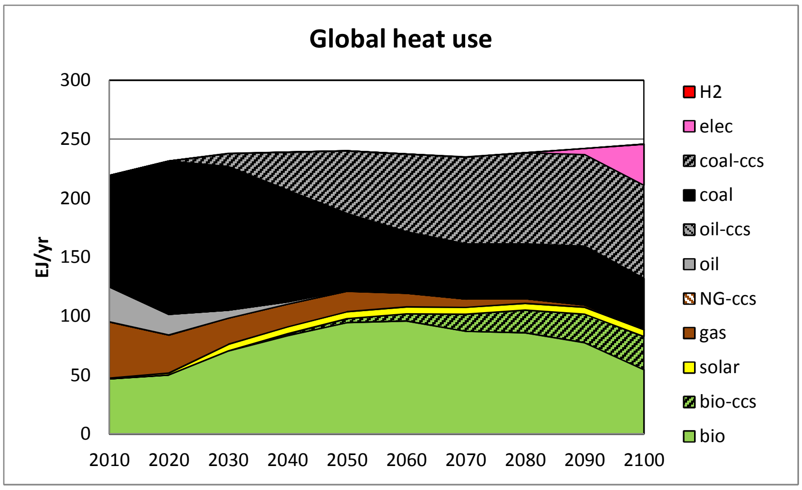

Figure 5. Results on heat production with values expressed in secondary energy terms. The figure is called "Figure C" in the GAMS code below.

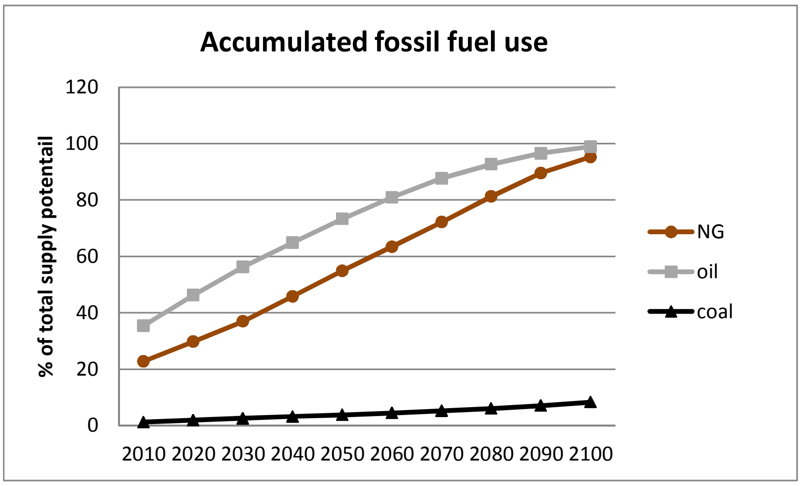

Figure 6. Results on fossil fuels with values expressed in secondary energy terms. The figure is called "Figure D" in the GAMS code below.

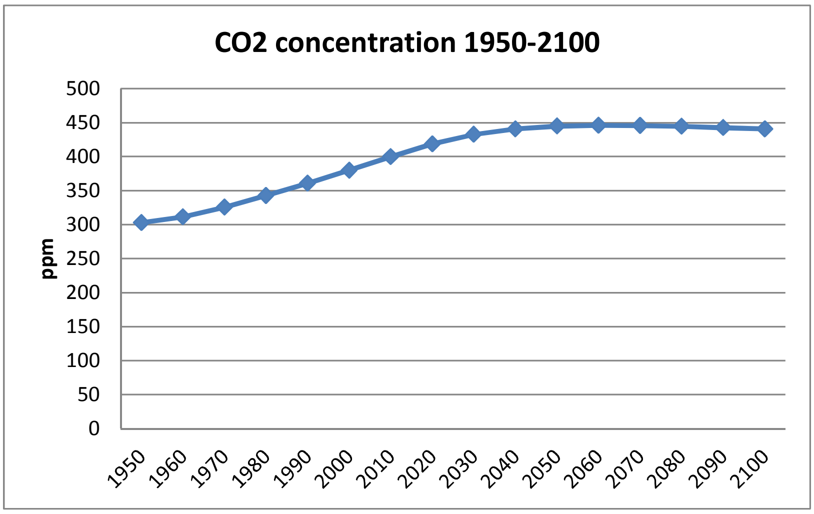

Figure 7. Results on CO_2 concentration. The figure is called "Figure E" in the GAMS code below.

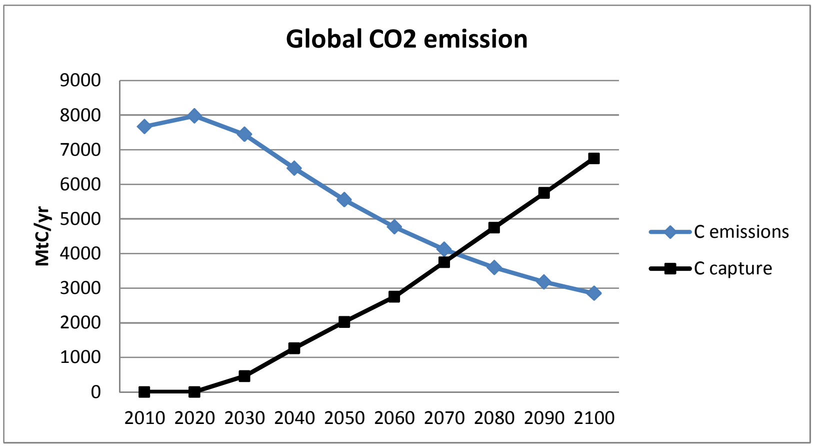

Figure 8. Results on CO_2 emission and CCS. The figure is called "Figure F" in the GAMS code below.

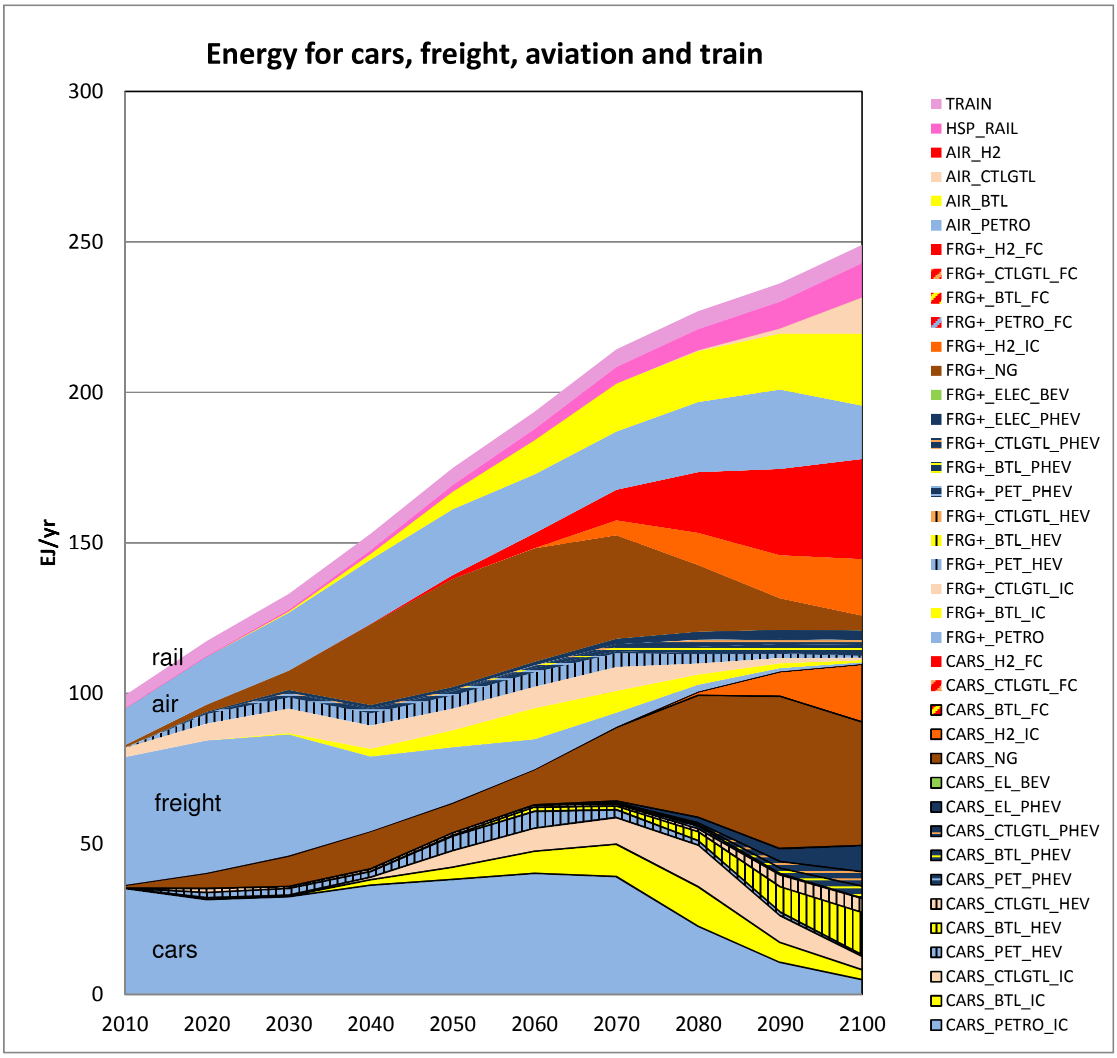

Figure 9. Results on fuel and technology choices for different transport modes with values expressed in secondary energy terms. The figure is called "Figure G" in the GAMS code below.

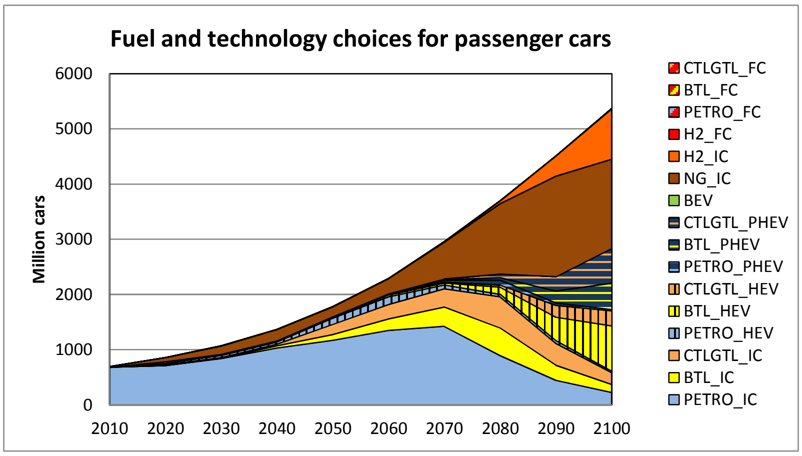

Figure 10. Results on fuel and technology choices for cars with values expressed in secondary energy terms. The figure is called "Figure H" in the GAMS code below. This is the most frequently used figure in our scientific papers.

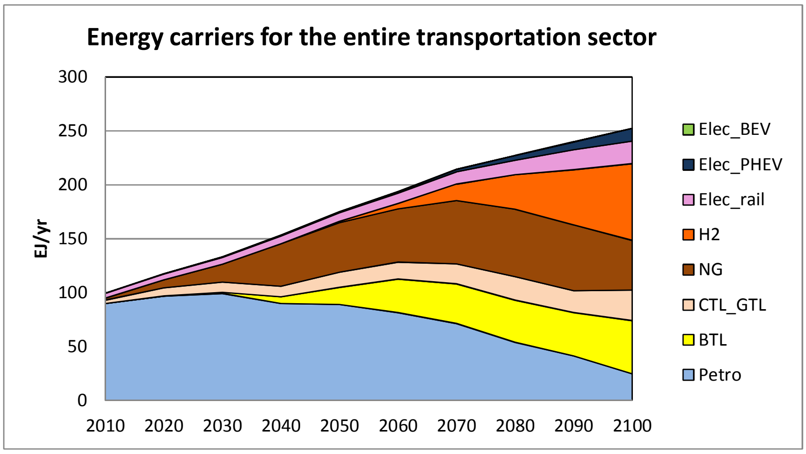

Figure 11. Results on energy carriers for the transport sector with values expressed in secondary energy terms. The figure is called "Figure I" in the GAMS code below.

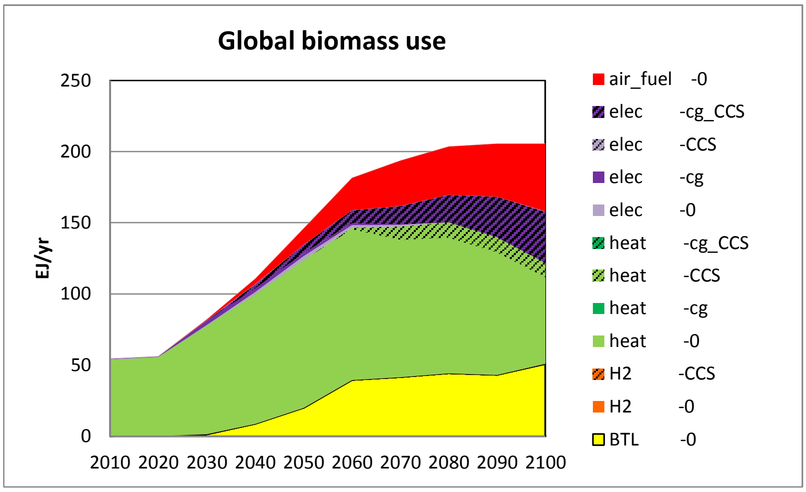

Figure 12. Results on biomass use with values expressed in secondary energy terms. The figure is called "Figure J" in the GAMS code below.

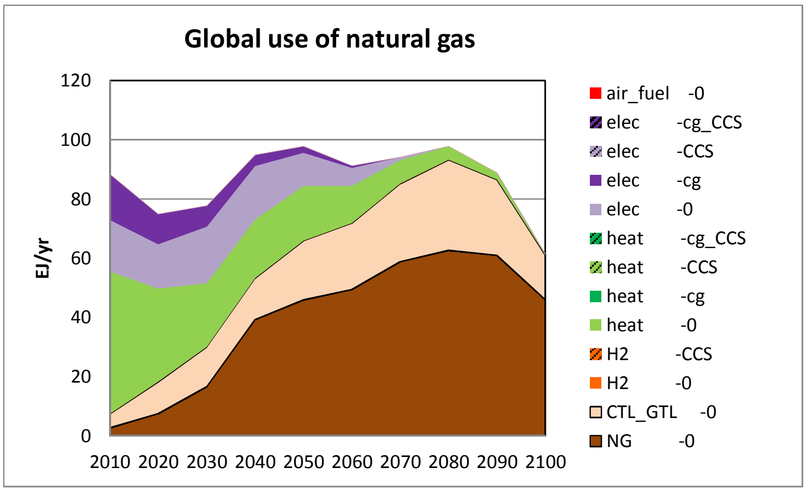

Figure 13. Results on NG use with values expressed in secondary energy terms. The figure is called "Figure K" in the GAMS code below

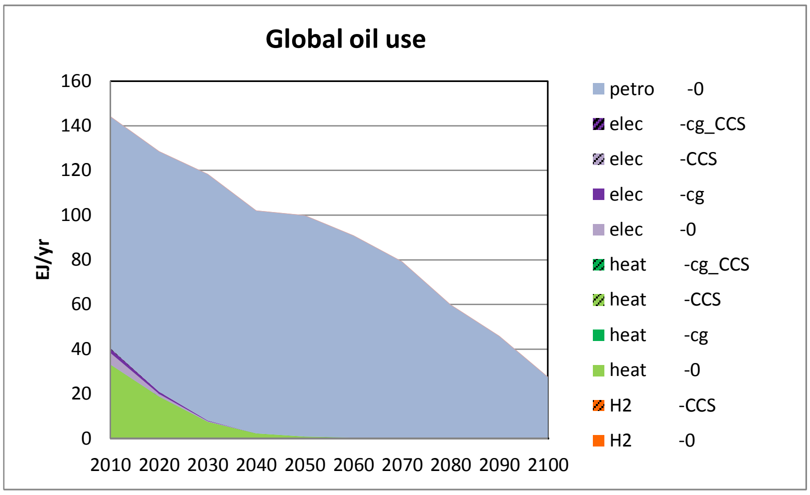

Figure 14. Results on oil use with values expressed in secondary energy terms. The figure is called "Figure L" in the GAMS code below.

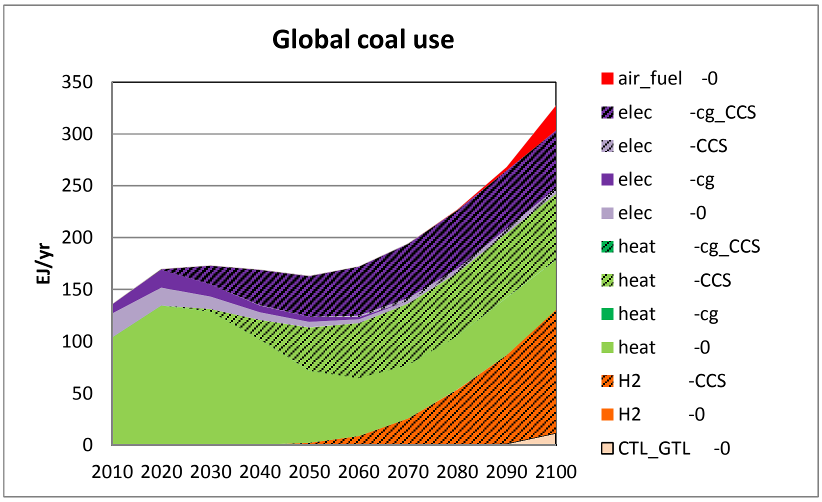

Figure 15. Results on coal use with values expressed in secondary energy terms. The figure is called "Figure M" in the GAMS code below.

There are several ways of plotting results from GAMS. We present a way via a "dat-file" into an Excel-file. The figures are made once as master figures in an Excel-file, and links are made to the dat-file.

In the GAMS code, we first need to write a command for creating a "dat-file", here called "output_data.dat". Since the model output sometimes contains a lot of information per row, we have added a command "RES.pw" to increase the upper amount of letters per row.

The output loops are specifically coded to generate the figures of interest. Currently, no additional sets are introduced, which is otherwise an option to be able to code the output loops more efficiently. The loops are therefore sometimes very long, very specific, and not that flexible. If for example new fuels or technologies are introduced to the model, the output loops must be rewritten. Readers of this report can likely create more efficient and flexible output commands in their optimization tools.

Some of the commands in the code are here explained:

.L	The variables' "normal result"(another choice is e.g. .M for marginal values).
.TL	In each run of the loop the next element in a set will be printed out.
:7:2;	The result will be presented as maximum 7 digits rounded to maximum 2 decimals.
/;	New row.
sum	Summation. The sets presented before the comma will be summarized. If sum over two or more sets the sets will be presented in a parenthesis.
*	A row starting with an asterix will not be printed.

As before, the GAMS program does not distinguish between capital or lower case letters. Here is the GAMS code, creating the 13 most relevant figures (see Figure 3-15):

```
************************************************************************************
file RES / output_data.dat /;
put RES;
RES.pw = 600;
************************************************************************************
*Figure A
*SUPPLY_TOT GLOBAL (EJ) - the amout of primary energy sources used (with CCS marked in the figure)
 put "the amount of primary energy sources used (with CCS marked)"; put /;
 put "GLOBAL (EJ)"; put /;
 put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
 loop ( primary,
   put primary.TL;
   loop (t,
      put ";";
      put sum ((R,e_out), (en_conv.L(R, primary, e_out, "0", t)+
            en_conv.L(R, primary, e_out, "cg", t))):7:2;
      ); put /;
    );
 loop ( primary,
   put primary.TL; put ".ccs";
   loop (t,
      put ";";
      put sum ((R,e_out), (en_conv.L(R, primary, e_out, "ccs", t)+
                        en_conv.L(R, primary, e_out, "cg_ccs", t))):7:2;
      ); put /;
   ); put /; put /; put /;
****************************************************************************************
*Figure  B
*GLOBAL ELECTRICITY USE - the amount of electricity used globally expressed in secondary energy terms (CCS separated).
 put "GLOBAL (EJ)";   put "electricity use - secondary energy"; put /;
 put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
 loop ( e_in,
   put e_in.TL;
   loop (t,
      put ";";
      put sum(R,(effic (e_in, "0", "elec",t)* en_conv.L(R, e_in, "elec", "0", t)+
               effic (e_in, "cg", "elec",t)* en_conv.L(R, e_in, "elec", "cg", t))):7:2;
```

```
      ); put /;
   );
   put "coal.ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("coal", "ccs", "elec",t)* en_conv.L(R, "coal", "elec", "ccs", t)+
                  effic ("coal", "cg_ccs", "elec",t)* en_conv.L(R, "coal", "elec", "cg_ccs", t))):7:2;
      ); put /;
   put "oil.ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("oil", "ccs", "elec",t)* en_conv.L(R, "oil", "elec", "ccs", t)+
                  effic ("oil", "cg_ccs", "elec",t)* en_conv.L(R, "oil", "elec", "cg_ccs", t))):7:2;
      ); put /;
   put "NG.ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("NG", "ccs", "elec",t)* en_conv.L(R, "NG", "elec", "ccs", t)+
                  effic ("NG", "cg_ccs", "elec",t)* en_conv.L(R, "NG", "elec", "cg_ccs", t))):7:2;
      ); put /;
   put "bio.ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("bio", "ccs", "elec",t)* en_conv.L(R, "bio", "elec", "ccs", t)+
                  effic ("bio", "cg_ccs", "elec",t)* en_conv.L(R, "bio", "elec", "cg_ccs", t))):7:2;
      ); put /; put /; put/;
*****************************************************************************************
*Figure  C
*GLOBAL HEAT - the amount of heat used globally (CCS separated).
 put "heat - secondary energy"; put /;
 put "GLOBAL (EJ)"; put /;
 put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
 put "bio";
   loop (t,
      put ";";
      put sum(R,(effic ("bio", "0", "heat",t)* en_conv.L(R, "bio", "heat", "0", t)+
                  heat_effic ("bio", "cg", "elec")* en_conv.L(R, "bio", "elec", "cg", t))):7:2;
   );  put /;
 put "bio-ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("bio", "ccs", "heat",t)* en_conv.L(R, "bio", "heat", "ccs", t)+
                  heat_effic ("bio", "cg_ccs", "elec")* en_conv.L(R, "bio", "elec", "cg_ccs", t))):7:2;
   );  put /;
 put "solar";
   loop (t,
      put ";";
      put sum(R,(effic ("solar", "0", "heat",t)* en_conv.L(R, "solar", "heat", "0", t))):7:2;
   );  put /;
 put "gas";
   loop (t,
      put ";";
      put sum(R,(effic ("NG", "0", "heat",t)* en_conv.L(R, "NG", "heat", "0", t)+
                  heat_effic ("NG", "cg", "elec")* en_conv.L(R, "NG", "elec", "cg", t))):7:2;
   );  put /;
 put "NG-ccs";
   loop (t,
      put ";";
      put sum(R,(effic ("NG", "ccs", "heat",t)* en_conv.L(R, "NG", "heat", "ccs", t)+
                  heat_effic ("NG", "cg_ccs", "elec")* en_conv.L(R, "NG", "elec", "cg_ccs", t))):7:2;
   );  put /;
 put "oil";
   loop (t,
      put ";";
      put sum(R,(effic ("oil", "0", "heat",t)* en_conv.L(R, "oil", "heat", "0", t)+
                  heat_effic ("oil", "cg", "elec")* en_conv.L(R, "oil", "elec", "cg", t))):7:2;
   );  put /;
```

```
 put "oil-ccs";
  loop (t,
      put ";";
      put sum(R,(effic ("oil", "ccs", "heat",t)* en_conv.L(R, "oil", "heat", "ccs", t)+
                    heat_effic ("oil", "cg_ccs", "elec")* en_conv.L(R, "oil", "elec", "cg_ccs", t))):7:2;
  );  put /;
 put "coal";
  loop (t,
      put ";";
      put sum(R,(effic ("coal", "0", "heat",t)* en_conv.L(R, "coal", "heat", "0", t)+
                    heat_effic ("coal", "cg", "elec")* en_conv.L(R, "coal", "elec", "cg", t))):7:2;
  );  put /;
 put "coal-ccs";
  loop (t,
      put ";";
      put sum(R,(effic ("coal", "ccs", "heat",t)* en_conv.L(R, "coal", "heat", "ccs", t)+
                    heat_effic ("coal", "cg_ccs", "elec")* en_conv.L(R, "coal", "elec", "cg_ccs", t))):7:2;
  );  put /;
 put "elec";
  loop (t,
      put ";";
      put sum(R,(effic ("elec", "0", "heat",t)* en_conv.L(R, "elec", "heat", "0", t))):7:2;
  );  put /;
 put "H2";
  loop (t,
      put ";";
      put sum(R,(effic ("H2", "0", "heat",t)* en_conv.L(R, "H2", "heat", "0", t)+
                    heat_effic ("H2", "cg", "elec")* en_conv.L(R, "H2", "elec", "cg", t))):7:2;
  ); put /; put /; put /;
*************************************************************************************
*Figure  D
*The accumulated used of fossil fuels as percentage of entire supply potential
put "accumulated percentage of global fossil fuel used in each time step"; put /;
put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
 loop ( fossil,
  put fossil.TL;
  put ";";
  put ((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100))
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100))
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100))
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100))
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100))
  put ";";
  put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
      +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
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    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2100")))/(sum (R, supply_pot_0 (fossil, R)))*100))
put ";";
put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
    +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
```

```
     +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2100")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2110")))/(sum (R, supply_pot_0 (fossil, R)))*100))
   put ";";
   put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2100")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2110")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2120")))/(sum (R, supply_pot_0 (fossil, R)))*100))
   put ";";
   put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2100")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2110")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2120")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2130")))/(sum (R, supply_pot_0 (fossil, R)))*100))
   put ";";
   put (((sum(R, t_step*supply_1.L(R, fossil, "1990")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2000")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2010")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2020")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2030")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2040")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2050")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2060")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2070")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2080")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2090")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2100")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2110")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2120")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2130")))/(sum (R, supply_pot_0 (fossil, R)))*100)
     +((sum(R, t_step*supply_1.L(R, fossil, "2140")))/(sum (R, supply_pot_0 (fossil, R)))*100)):7:2;
   put /;
   ); put /; put /; put /;
*****************************************************************************************
*Figure  E
*CO2 CONCENTRATION
put "CO2 conc"; put /;
put
";1800;1810;1820;1830;1840;1850;1860;1870;1880;1890;1900;1910;1920;1930;1940;1950;1960;1970;1980;1990;2000;2010;2
020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";
put /;
   put "CO2";
   loop (T_all,
     put ";";
```

```
      put ATM_CCONT.L(T_all):7:2;
   ); put /; put /;  put /;
*******************************************************************************************
*Figure  F
* GLOBAL CO2 EMISSIONS
  put "CO2 emissions"; put /;
  put "GLOBAL"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";
  put /;
  put "C emissions";
    loop (t,
      put ";";
      put sum(R, c_emission.L(R, t)):9:2;
   );  put /;
  put "C capture";
    loop (t,
      put ";";
      put sum(R, C_capt_tot.L(R, t)):9:2;
   ); put /; put /; put /;
*******************************************************************************************
*Figure  G
*GLOBAL FIGURE TRSP SEPARATED IN FIVE GROUPS: CARS, FRG+ (trucks+bus+shipping), AVIATION, TRAIN and
HSP-rail (a fraction of p_air)
put "GLOBAL (EJ)"; put " global transportation secondary energy for different trsp mode - five groups"; put /;
put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
PUT "CARS_PETRO_IC"; LOOP (t,
            PUT ";"; PUT sum(R, trsp_energy.L(R, "petro", "0", "p_car", t)):7:2; ); PUT /;
PUT "CARS_BTL_IC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "BTL", "0", "p_car", t)):7:2; ); PUT /;
PUT "CARS_CTLGTL_IC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "CTL_GTL", "0", "p_car", t)):7:2; ); PUT /;
PUT "CARS_PET_HEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "petro", "HEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_BTL_HEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "BTL", "HEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_CTLGTL_HEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "CTL_GTL", "HEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_PET_PHEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "petro", "PHEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_BTL_PHEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "BTL", "PHEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_CTLGTL_PHEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_EL_PHEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "elec", "PHEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_EL_BEV"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "elec", "BEV", "p_car", t)):7:2; ); PUT /;
PUT "CARS_NG";   LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "NG", "0", "p_car", t)):7:2; ); PUT /;
PUT "CARS_H2_IC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "H2", "0", "p_car", t)):7:2; ); PUT /;
PUT "CARS_PETRO_FC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "petro", "FC", "p_car", t)):7:2; ); PUT /;
PUT "CARS_BTL_FC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "BTL", "FC", "p_car", t)):7:2; ); PUT /;
PUT "CARS_CTLGTL_FC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "CTL_GTL", "FC", "p_car", t)):7:2; ); PUT /;
PUT "CARS_H2_FC"; LOOP (t,
            PUT ";"; PUT sum(R,trsp_energy.L(R, "H2", "FC", "p_car", t)):7:2; ); PUT /;
PUT "FRG+_PETRO";LOOP (t,
            PUT ";"; PUT (sum(R,trsp_energy.L(R, "petro", "0", "p_bus", t)+
                    trsp_energy.L(R, "petro", "0", "f_road", t)+
                    trsp_energy.L(R, "petro", "0", "f_sea", t)+
                    trsp_energy.L(R, "petro", "0", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_BTL_IC";LOOP (t,
            PUT ";"; PUT (sum(R,trsp_energy.L(R, "BTL", "0", "p_bus", t)+
                    trsp_energy.L(R, "BTL", "0", "f_road", t)+
```

```
                    trsp_energy.L(R, "BTL", "0", "f_sea", t)+
                    trsp_energy.L(R, "BTL", "0", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_CTLGTL_IC";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "CTL_GTL", "0", "p_bus", t)+
                    trsp_energy.L(R, "CTL_GTL", "0", "f_road", t)+
                    trsp_energy.L(R, "CTL_GTL", "0", "f_sea", t)+
                    trsp_energy.L(R, "CTL_GTL", "0", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_PET_HEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "petro", "HEV", "p_bus", t)+
                    trsp_energy.L(R, "petro", "HEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_BTL_HEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "BTL", "HEV", "p_bus", t)+
                    trsp_energy.L(R, "BTL", "HEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_CTLGTL_HEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "CTL_GTL", "HEV", "p_bus", t)+
                    trsp_energy.L(R, "CTL_GTL", "HEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_PET_PHEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "petro", "PHEV", "p_bus", t)+
                    trsp_energy.L(R, "petro", "PHEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_BTL_PHEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "BTL", "PHEV", "p_bus", t)+
                    trsp_energy.L(R, "BTL", "PHEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_CTLGTL_PHEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "CTL_GTL", "PHEV", "p_bus", t)+
                    trsp_energy.L(R, "CTL_GTL", "PHEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_ELEC_PHEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "elec", "PHEV", "p_bus", t)+
                    trsp_energy.L(R, "elec", "PHEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_ELEC_BEV";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "elec", "BEV", "p_bus", t)+
                    trsp_energy.L(R, "elec", "BEV", "f_road", t))):7:2; ); PUT /;
PUT "FRG+_NG";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "NG", "0", "p_bus", t)+
                    trsp_energy.L(R, "NG", "0", "f_road", t)+
                    trsp_energy.L(R, "NG", "0", "f_sea", t)+
                    trsp_energy.L(R, "NG", "0", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_H2_IC";;LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "H2", "0", "p_bus", t)+
                    trsp_energy.L(R, "H2", "0", "f_road", t)+
                    trsp_energy.L(R, "H2", "0", "f_sea", t)+
                    trsp_energy.L(R, "H2", "0", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_PETRO_FC";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "petro", "FC", "p_bus", t)+
                    trsp_energy.L(R, "petro", "FC", "f_road", t)+
                    trsp_energy.L(R, "petro", "FC", "f_sea", t)+
                    trsp_energy.L(R, "petro", "FC", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_BTL_FC";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "BTL", "FC", "p_bus", t)+
                    trsp_energy.L(R, "BTL", "FC", "f_road", t)+
                    trsp_energy.L(R, "BTL", "FC", "f_sea", t)+
                    trsp_energy.L(R, "BTL", "FC", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_CTLGTL_FC";LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "CTL_GTL", "FC", "p_bus", t)+
                    trsp_energy.L(R, "CTL_GTL", "FC", "f_road", t)+
                    trsp_energy.L(R, "CTL_GTL", "FC", "f_sea", t)+
                    trsp_energy.L(R, "CTL_GTL", "FC", "f_isea", t))):7:2; ); PUT /;
PUT "FRG+_H2_FC"; LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "H2", "FC", "p_bus", t)+
                    trsp_energy.L(R, "H2", "FC", "f_road", t)+
                    trsp_energy.L(R, "H2", "FC", "f_sea", t)+
                    trsp_energy.L(R, "H2", "FC", "f_isea", t))):7:2; ); PUT /;
PUT "AIR_PETRO";  LOOP (t,
          PUT ";"; PUT (sum(R,trsp_energy.L(R, "petro", "0", "p_air", t)+
                    trsp_energy.L(R, "petro", "0", "f_air", t))):7:2; ); PUT /;
PUT "AIR_BTL";  LOOP (t,
          PUT ";"; PUT (sum(R,en_conv.L(R, "bio", "air_fuel", "0", t)*
                    effic ("bio", "0", "air_fuel",t))):7:2; ); PUT /;
```

```
PUT "AIR_CTLGTL";  LOOP (t,
              PUT ";"; PUT (sum(R,en_conv.L(R, "NG", "air_fuel", "0", t)*
                        effic ("NG", "0", "air_fuel",t)+
                        en_conv.L(R, "coal", "air_fuel", "0", t)*
                        effic ("coal", "0", "air_fuel",t))):7:2; ); PUT /;
PUT "AIR_H2";  LOOP (t,
              PUT ";"; PUT (sum(R,en_conv.L(R, "H2", "air_fuel", "0", t)*
                        effic ("H2", "0", "air_fuel",t))):7:2; ); PUT /;
PUT "HSP_RAIL";  LOOP (t,
              PUT ";"; PUT (sum(R,trsp_energy.L(R, "elec", "0", "p_air", t))):7:2; ); PUT /;
PUT "TRAIN";  LOOP (t,
              PUT ";"; PUT (sum(R,trsp_energy.L(R, "elec", "0", "p_rail", t)+
                        trsp_energy.L(R, "elec", "0", "f_rail", t))):7:2; ); PUT /;
PUT/; PUT/;
*************************************************************************************
*Figure  H
*GLOBAL Figures on the number of CARS for each region that runs on a specific fuel
 put "number of cars running on a spcific fuel"; put /;
 put "GLOBAL (million cars)"; put /;
 put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
 PUT "PETRO_IC";
  LOOP (t,
    PUT ";"; PUT (sum (R,( trsp_energy.L(R, "petro", "0", "p_car", t)*
           trsp_conv("petro","0","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)) )):7:2;
  ); PUT /;
 PUT "BTL_IC";
  LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "BTL", "0", "p_car", t)*
           trsp_conv("BTL","0","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
  ); PUT /;
 PUT "CTLGTL_IC";
  LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "CTL_GTL", "0", "p_car", t)*
           trsp_conv("CTL_GTL","0","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
  ); PUT /;
 PUT "PETRO_HEV";
  LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "petro", "HEV", "p_car", t)*
           trsp_conv("petro","HEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
  ); PUT /;
 PUT "BTL_HEV";
  LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "BTL", "HEV", "p_car", t)*
           trsp_conv("BTL","HEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
  ); PUT /;
 PUT "CTLGTL_HEV";
  LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "CTL_GTL", "HEV", "p_car", t)*
           trsp_conv("CTL_GTL","HEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)) )):7:2;
  ); PUT /;
*calculating a fraction of the elec-part in PHEVs that should be added to the amount of PHEVs.
 PUT "PETRO_PHEV";
  LOOP (t,
    PUT ";"; PUT (sum(R,(trsp_energy.L(R, "petro", "PHEV", "p_car", t)*
           trsp_conv("petro","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)+
           trsp_energy.L(R, "petro", "PHEV", "p_car", t)/
          (trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)+
           trsp_energy.L(R, "BTL", "PHEV", "p_car", t)+
           trsp_energy.L(R, "petro", "PHEV", "p_car", t)+0.001)*
           (trsp_energy.L(R, "elec", "PHEV", "p_car", t)*
           trsp_conv("elec","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)))) ):7:2;
  ); PUT /;
 PUT "BTL_PHEV";
  LOOP (t,
    PUT ";"; PUT (sum(R,(trsp_energy.L(R, "BTL", "PHEV", "p_car", t)*
           trsp_conv("BTL","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)+
           trsp_energy.L(R, "BTL", "PHEV", "p_car", t)/
```

```
                (trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)+
                 trsp_energy.L(R, "BTL", "PHEV", "p_car", t)+
                 trsp_energy.L(R, "petro", "PHEV", "p_car", t)+0.001)*
                 (trsp_energy.L(R, "elec", "PHEV", "p_car", t)*
                 trsp_conv("elec","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)))) ):7:2;
   ); PUT /;
  PUT "CTLGTL_PHEV";
   LOOP (t,
    PUT ";"; PUT (sum(R,(trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)*
                 trsp_conv("CTL_GTL","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)+
                 trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)/
                (trsp_energy.L(R, "CTL_GTL", "PHEV", "p_car", t)+
                 trsp_energy.L(R, "BTL", "PHEV", "p_car", t)+
                 trsp_energy.L(R, "petro", "PHEV", "p_car", t)+0.001)*
                 (trsp_energy.L(R, "elec", "PHEV", "p_car", t)*
                 trsp_conv("elec","PHEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t)))) ):7:2;
   ); PUT /;
  PUT "BEV";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "elec", "BEV", "p_car", t)*
                 trsp_conv("elec","BEV","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /;
  PUT "NG_IC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "NG", "0", "p_car", t)*
                 trsp_conv("NG","0","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /;
  PUT "H2_IC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "H2", "0", "p_car", t)*
                 trsp_conv("H2","0","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /;
  PUT "H2_FC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "H2", "FC", "p_car", t)*
                 trsp_conv("H2","FC","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /;
  PUT "PETRO_FC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "petro", "FC", "p_car", t)*
                 trsp_conv("petro","FC","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t) ))):7:2;
   ); PUT /;
  PUT "BTL_FC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "BTL", "FC", "p_car", t)*
                 trsp_conv("BTL","FC","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /;
  PUT "CTLGTL_FC";
   LOOP (t,
    PUT ";"; PUT (sum (R,(trsp_energy.L(R, "CTL_GTL", "FC", "p_car", t)*
                 trsp_conv("CTL_GTL","FC","p_car",t)*num_veh(R,"p_car",t)*1000/trsp_dem(R,"p_car",t))) ):7:2;
   ); PUT /; PUT /; PUT /;
*******************************************************************************************'
*Figure  I
*GLOBAL TRANSPORTATION FUELS
  put "GLOBAL (EJ)";
  put "Energy used in transportation sector (cars+freight+aviation)"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140";   put /;
  PUT "Petro";
   LOOP (t,
   PUT ";";
   PUT  sum(R, energy_deliv.L(R, "petro", t)):7:2;
   );  PUT /;
  PUT "BTL";
   LOOP (t,
   PUT ";";
   PUT (sum(R,energy_deliv.L(R, "BTL", t))+
```

```
      sum(R,(en_conv.L(R, "bio", "air_fuel", "0", t)*effic ("bio", "0", "air_fuel",t)))):7:2;
   ); PUT /;
  PUT "CTL_GTL";
   LOOP (t,
   PUT ";";
   PUT (sum(R,energy_deliv.L(R, "CTL_GTL", t))+
      sum(R,(en_conv.L(R, "NG", "air_fuel", "0", t)*effic ("NG", "0", "air_fuel",t)+
         en_conv.L(R, "coal", "air_fuel", "0", t)*effic ("coal", "0", "air_fuel",t)))):7:2;
   ); PUT /;
  PUT "NG";
   LOOP (t,
   PUT ";";
   PUT sum(R,energy_deliv.L(R, "NG", t)):7:2;
   ); PUT /;
  PUT "H2";
   LOOP (t,
   PUT ";";
   PUT (sum(R, energy_deliv.L(R, "h2", t))+
      sum(R,(en_conv.L(R, "H2", "air_fuel", "0", t)*effic ("H2", "0", "air_fuel",t)))):7:2;
   ); PUT /;
  put "Elec_rail";
   loop (t,
    put ";";
    put (sum(R, elec_trsp.L(R, t))-(
       sum(R, trsp_energy.L(R, "elec", "PHEV", "p_car", t))+
       sum(R, trsp_energy.L(R, "elec", "PHEV", "f_road", t))+
       sum(R, trsp_energy.L(R, "elec", "PHEV", "p_bus", t))+
       sum(R, trsp_energy.L(R, "elec", "BEV", "p_car", t))+
       sum(R, trsp_energy.L(R, "elec", "BEV", "f_road", t))+
       sum(R, trsp_energy.L(R, "elec", "BEV", "p_bus", t)) )):7:2
   ); PUT /;
  put "Elec_PHEV";
   loop (t,
    put ";";
    put (sum(R, trsp_energy.L(R, "elec", "PHEV", "p_car", t))+
       sum(R, trsp_energy.L(R, "elec", "PHEV", "f_road", t))+
       sum(R, trsp_energy.L(R, "elec", "PHEV", "p_bus", t)) ):7:2
   ); PUT /;
  put "Elec_BEV";
   loop (t,
    put ";";
    put (sum(R, trsp_energy.L(R, "elec", "BEV", "p_car", t))+
       sum(R, trsp_energy.L(R, "elec", "BEV", "f_road", t))+
       sum(R, trsp_energy.L(R, "elec", "BEV", "p_bus", t)) ):7:2
   ); put /; put /; put /;
*************************************************************************************
*Figure  J
*GLOBAL BIOMASS USE
  put "biomass use - primary energy"; put /;
  put "GLOBAL"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140"; put /;
  loop ( e_out,
   loop ( type,
    put e_out.TL; put "-"; put type.TL;
    loop (t,
     put ";";
     put sum(R,en_conv.L(R, "bio", e_out, type, t)):7:2;
    ); put /;
   );
  ); put /; put /; put /;
*****************************************************************************************
*Figure  K
*GLOBAL NATURAL NG USE
  put "natural NG use - primary energy"; put /;
  put "GLOBAL"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140"; put /;
  loop ( e_out,
```

```
    loop ( type,
      put e_out.TL; put "-"; put type.TL;
      loop (t,
        put ";";
        put sum(R,en_conv.L(R, "NG", e_out, type, t)):7:2;
      ); put /;
    );
  ); put /; put /; put /;
******************************************************************************************
*Figure  L
*GLOBAL OIL USE
  put "oil use - primary energy"; put /;
  put "GLOBAL"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140"; put /;
  loop (e_out,
    loop ( type,
      put e_out.TL; put "-"; put type.TL;
      loop (t,
        put ";";
        put sum(R,en_conv.L(R, "oil", e_out, type, t)):7:2;
      ); put /;
    );
  ); put /; put /; put /;
******************************************************************************************
*Figure  M
*GLOBAL COAL USE
  put "coal use - primary energy"; put /;
  put "GLOBAL"; put /;
  put ";1990;2000;2010;2020;2030;2040;2050;2060;2070;2080;2090;2100;2110;2120;2130;2140"; put /;
  loop ( e_out,
    loop ( type,
      put e_out.TL; put "-"; put type.TL;
      loop (t,
        put ";";
        put sum(R,en_conv.L(R, "coal", e_out, type, t)):7:2;
      ); put /;
    );
  ); put /; put /; put /;
*****************************************************************************************
```

7. Implementation

In this section, we provide suggestions on how to implement the model step by step. In our Ford-Chalmers collaboration, we started with a simple model with only a few sets, parameters, and variables, and then we added parts of the models in five steps until the full model was implemented. We called these incomplete model versions “simple models”. In Figures 16-21, we built up the full model from the "simple models".

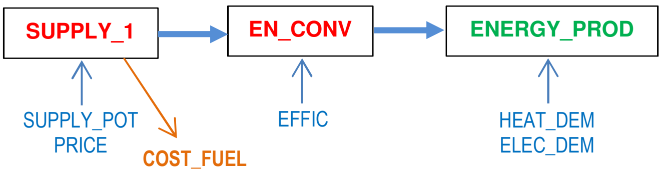

Figure 16. Rough illustration of Simple Model 1. The energy flow is marked in thick blue arrows. Energy flow variables are marked red and green. Cost variables, which are minimized in the objective function, are written in orange. Blue text indicates introduced parameters and points at the variables they impact.

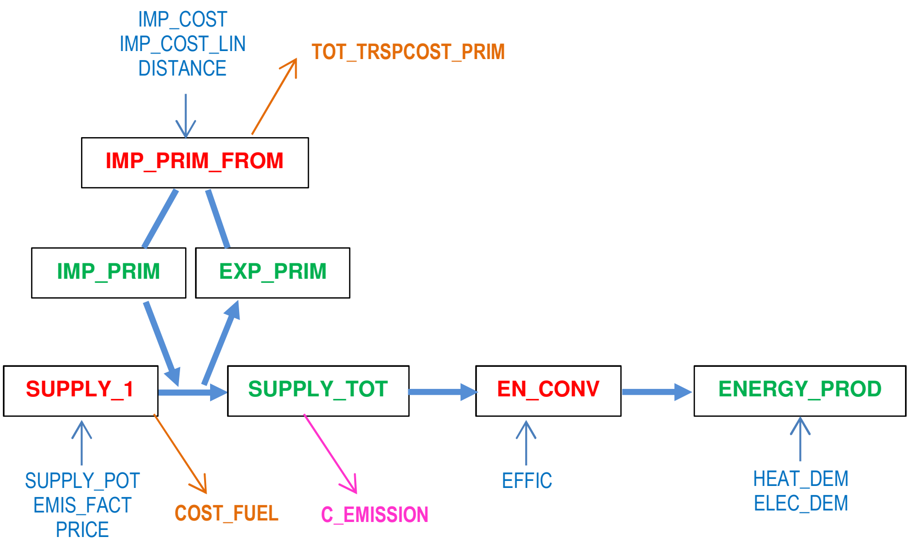

Figure 17. Rough illustration of Simple Model 2. We have here added the features of import and export of primary energy sources where one more cost variable will be included in the objective function. We also introduce the emission calculation.

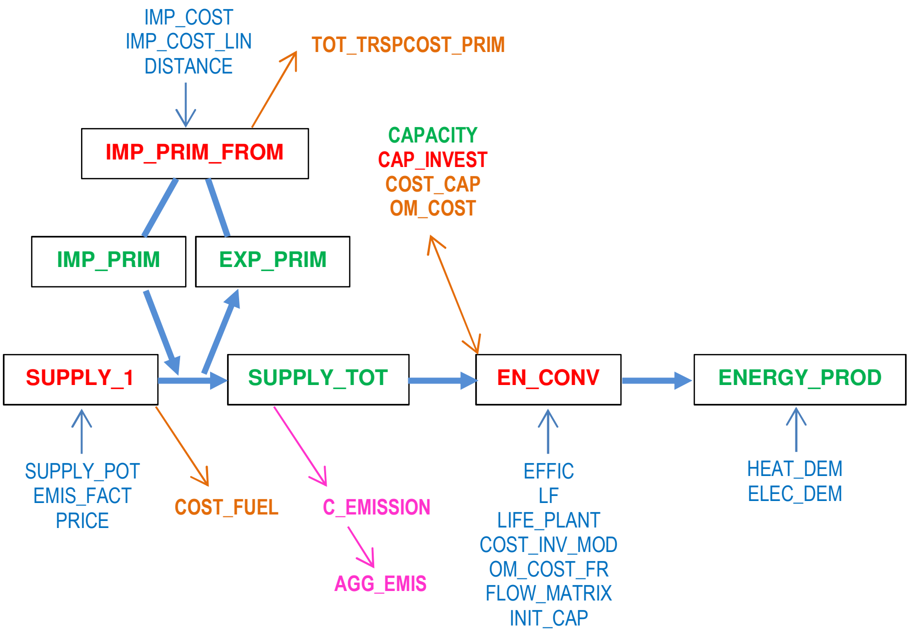

Figure 18. Rough illustration of Simple Model 3. We have here added the variables and parameters connected to the investements of energy conversion plants, where two more cost variables cost_cap and om_cost are included in the objective function. We also add one more variable in the emissions calculation.

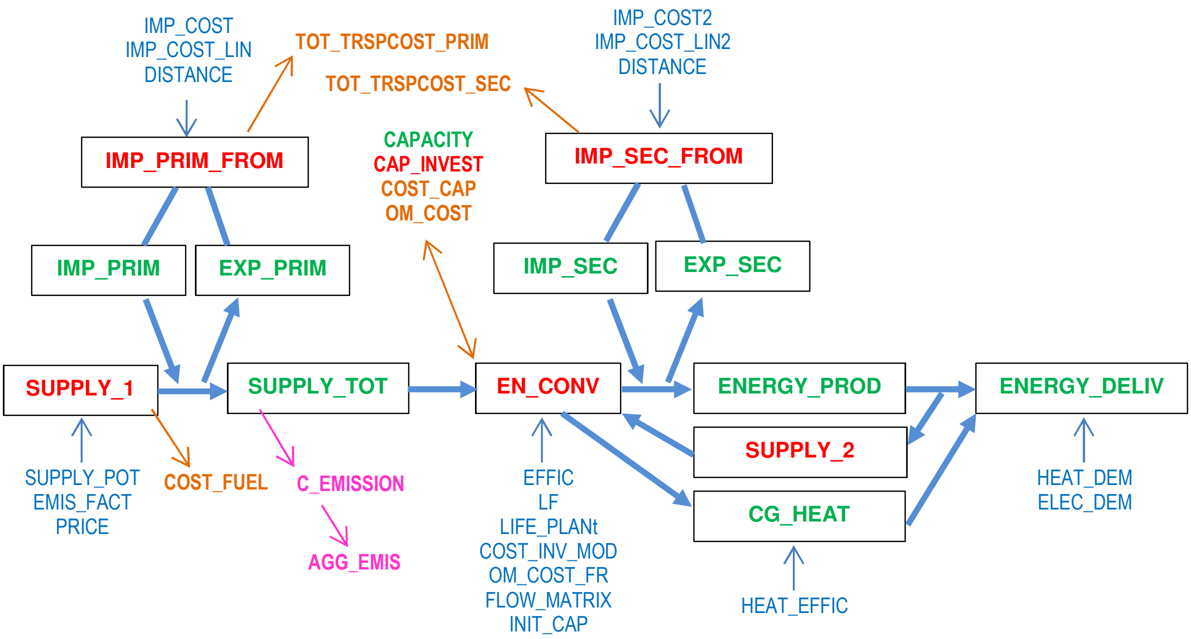

Figure 19. Rough illustration of Simple Model 4. We have here added the variables and parameters connected to import and export of energy carriers, the feature of that some energy carriers can be converted a second time (supply_2), the heat flow from co-generation (cg_heat) and added the variable energy_deliv.

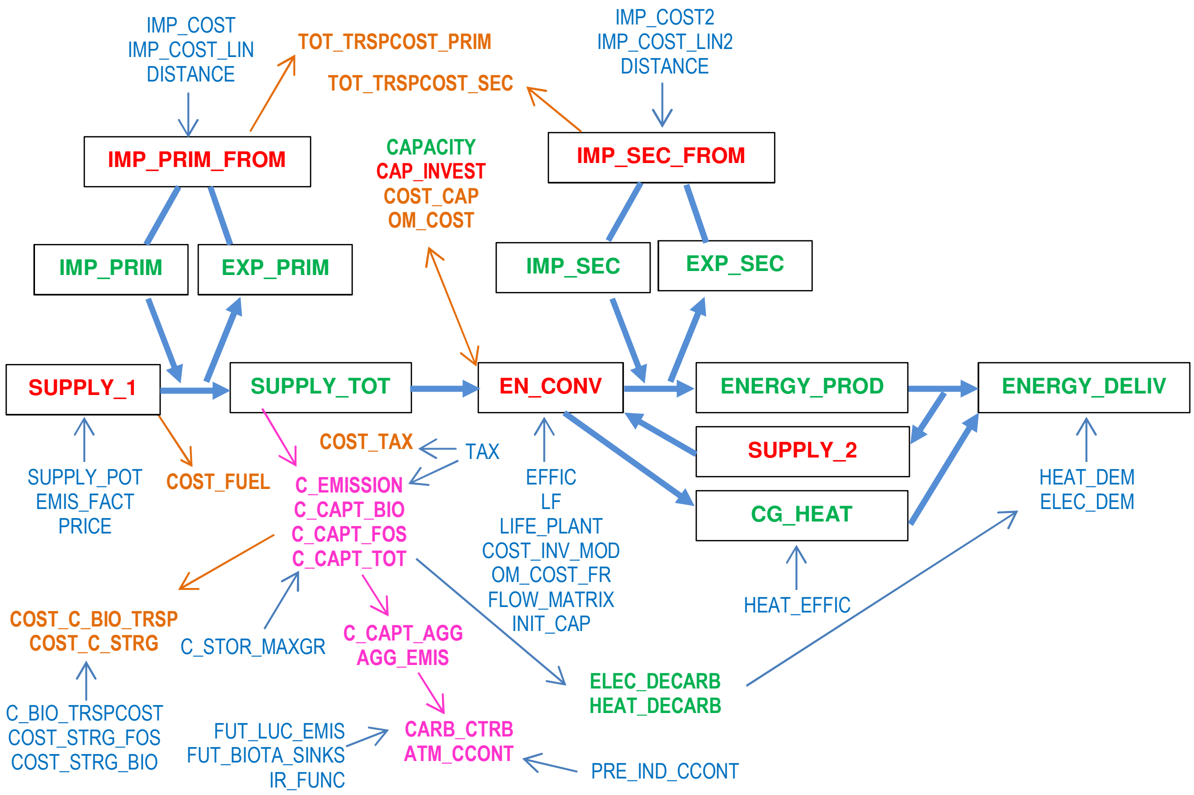

Figure 20. Rough illustration of Simple Model 5. We have here added the variables and parameters connected to CCS and the carbon cycle, including that the additional electricity and heat needed when applying CCS will affect the demand.

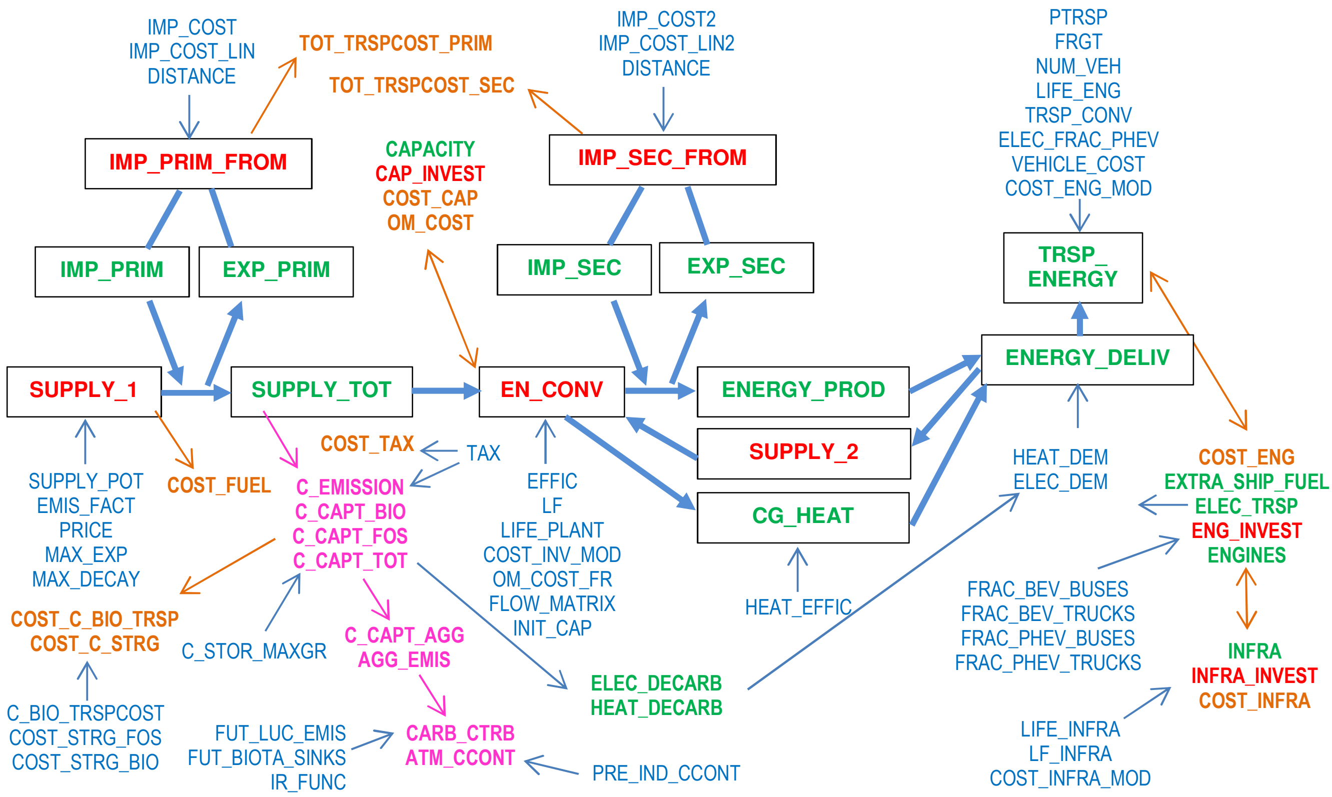

Figure 21. Rough illustration of Simple Model 6, which is equal to the full GET-RC 6.1 model. We have here added the transportation and infrastructure modules. Further, which is difficult to illustrate, also all adjustments, and limitations are added in this final step.

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Appendix 1: Data

Values on parameters in GET-RC 6.1.

Table 2. dec_elec (e_in)

Fuels	[-]
bio	0.04
coal	0.04
oil	0.03
NG	0.025

Table 3. emis_fact (fuels)

Fuels	MtC/EJ
bio	32
coal	24.7
oil	20.5
NG	15.4
emis_fact_syn	19.1

Table 4. hist_fos_emis (t_h)

t_h	MtC/yr
1800	8
1810	10
1820	14
1830	24
1840	33
1850	54
1860	91
1870	147
1880	236
1890	356
1900	534
1910	819
1920	932
1930	1053
1940	1299
1950	1630
1960	2578
1970	4075
1980	5297

Table 5. fut_luc_emis (T_all_copy)

T_all_copy	MtC/yr
1990	1100
2000	1000
2010	800
2020	600
2030	400
2040	200
2050	100
2060	0
2070	0
2080	0
2090	0
2100	0
2110	0
2120	0
2130	0
2140	0

Table 6. fut_biota_sinks (T_all_copy)

T_all_copy	MtC/yr
1990	1000
2000	1000
2010	1000
2020	900
2030	800
2040	800
2050	800
2060	800
2070	800
2080	700
2090	700
2100	600
2110	500
2120	400
2130	300
2140	200

Table 7. init_eng (R)

R	Gvehicles
NAM	0.025
EUR	0.018
PAO	0.008
FSU	0.008
AFR	0.005
PAS	0.004
LAM	0.005
MEA	0.004
CPA	0.011
SAS	0.006

Table 8. init_infra (R)

R	TW
NAM	0.013
EUR	0.009
PAO	0.004
FSU	0.004
AFR	0.003
PAS	0.002
LAM	0.002
MEA	0.002
CPA	0.005
SAS	0.003

Table 9. init_plant (R)

R	TW
NAM	0.076
EUR	0.054
PAO	0.023
FSU	0.024
AFR	0.015
PAS	0.013
LAM	0.015
MEA	0.011
CPA	0.033
SAS	0.019

Table 10. init_supply (R)

R	EJ
NAM	0.076
EUR	0.054
PAO	0.023
FSU	0.024
AFR	0.015
PAS	0.013
LAM	0.015
MEA	0.011
CPA	0.033
SAS	0.019

Table 11. imp_cost (fuels)

Fuels	GUSD/ EJ
bio	2.0
coal	1.0
oil	0.5
NG	1.5
nuclear	0.5

Table 12. imp_cost2 (sec)

sec	GUSD/ EJ
BTL	1.0
CTL/GTL	1.0
H2	2.0

Table 13. imp_cost_lin (fuels)

Fuels	GUSD/ EJ
bio	0.00001
coal	0.00001
oil	0.00001
NG	0.00002
nuclear	0.00001

Table 14. imp_cost_lin2 (sec)

sec	GUSD/ EJ
BTL	0.00001
CTL/GTL	0.00001
H2	0.00002

Table 15. elec_frac_PHEV (vehicle)

vehicle	[-]
p_car	0.65
f_road	0.53

Table 16. life_infra (synfuel_gas)

synfuel_gas	yr
BTL	50
CTL_GTL	50
H2	50
NG	50

Table 17. cost_infra (synfuel_gas)

synfuel_gas	USD/kW
BTL	500
CTL_GTL	500
H2	2000
NG	1500

Table 18. high_speed_train_global (t)

t	[-]
1990	0.04
2000	0.04
2010	0.04
2020	0.04
2030	0.06
2040	0.10
2050	0.14
2060	0.20
2070	0.24
2080	0.26
2090	0.28
2100	0.30
2110	0.30
2120	0.30
2130	0.30
2140	0.30

Table 19. cost_eng_base (road_fuel, e_type, vehicle)

road_fuel, e_type	USD/car	USD/truck
BTL.0	100	100
CTL/GTL.0	100	100
BTL.FC	6000	19400
CTL/GTL.FC	6000	19400
BTL.HEV	1700	5800
CTL/GTL.HEV	1700	5800
BTL.PHEV	5600	21800
CTL/GTL.PHEV	5600	21800
H2.0	2600	10300
H2.FC	6400	21900
petro.0	0	0
petro.FC	6000	19400
petro.HEV	1600	5700
petro.PHEV	5500	21700
NG.0	1400	5200
elec.BEV	15600	62500

high_speed_train (R,t) = high_speed_train_global (t);

cost_infra_mod (synfuel_gas) =
cost_infra (synfuel_gas) * (r_invest + 1/life_infra (synfuel_gas)) / (r + 1/life_infra (synfuel_gas));

lf_infra (synfuel_gas) = 0.7;
life_plant (e_in, e_out, type) = 25;
life_plant ("hydro", "elec", "0") = 40;
life_plant ("solar_CSP", "elec", "0") = 30;
life_eng (trsp_fuel,e_type,vehicle) = 15;
OM_cost_fr (e_in, e_out) = 0.04;
OM_cost_fr ("solar_CSP", "elec") = 0.014;
c_tax (R, t) = 0;

vehicle_cost ("p_car") = 20000;
vehicle_cost ("f_road") = 80000;

cost_eng (road_fuel, e_type, vehicle, t) = cost_eng_base (road_fuel, e_type, vehicle) + vehicle_cost (vehicle);

cost_eng_mod (road_fuel, e_type, vehicle, t) =
cost_eng (road_fuel, e_type, vehicle, t) * (r_invest + 1/life_eng (road_fuel, e_type, vehicle))/ (r+1/life_eng (road_fuel, e_type, vehicle));

Table 20. trsp_conv_static (trsp_fuel, e_type, trsp_mode) [-]

trsp_fuel, e_type	p_rail, f_rail	p_air	f_air
BTL.0	0	0	0
CTL/GTL.0	0	0	0
BTL.FC	0	0	0
CTL/GTL.FC	0	0	0
BTL.HEV	0	0	0
CTL/GTL.HEV	0	0	0
BTL.PHEV	0	0	0
CTL/GTL.PHEV	0	0	0
H2.0	0	0	0
H2.FC	0	0	0
petro.0	0	1	1
petro.FC	0	0	0
petro.HEV	0	0	0
petro.PHEV	0	0	0
NG.0	0	0	0
elec.0	1	2	0
elec.PHEV	0	0	0
elec.BEV	0	0	0
air_fuel.0	0	1	1

Note that high-speed-train is modeled as a share of p_air

trsp_conv (trsp_fuel, e_type, trsp_mode, t) = trsp_conv_static (trsp_fuel, e_type, trsp_mode);

Table 21. trsp_conv_car (trsp_fuel, e_type, t) [-]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140
BTL.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
BTL.FC	1.23	1.28	1.33	1.39	1.44	1.5	1.56	1.63	1.69	1.76	1.83	1.91	1.99	2.07	2.15	2.15
CTL/GTL.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
CTL/GTL.FC	1.23	1.28	1.33	1.39	1.44	1.5	1.56	1.63	1.69	1.76	1.83	1.91	1.99	2.07	2.15	2.15
BTL.HEV	1.25	1.3	1.35	1.41	1.47	1.53	1.59	1.65	1.72	1.79	1.86	1.94	2.02	2.1	2.18	2.18
CTL/GTL.HEV	1.25	1.3	1.35	1.41	1.47	1.53	1.59	1.65	1.72	1.79	1.86	1.94	2.02	2.1	2.18	2.18
BTL.PHEV	1.44	1.5	1.56	1.62	1.69	1.76	1.83	1.91	1.98	2.06	2.15	2.24	2.33	2.42	2.52	2.52
CTL/GTL.PHEV	1.44	1.5	1.56	1.62	1.69	1.76	1.83	1.91	1.98	2.06	2.15	2.24	2.33	2.42	2.52	2.52
H2.0	1.09	1.13	1.18	1.22	1.27	1.33	1.38	1.44	1.49	1.56	1.62	1.68	1.75	1.82	1.9	1.9
H2.FC	1.73	1.8	1.87	1.95	2.03	2.11	2.2	2.29	2.38	2.48	2.58	2.68	2.79	2.91	3.02	3.02
petro.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
petro.FC	1.12	1.17	1.22	1.27	1.32	1.37	1.43	1.49	1.55	1.61	1.68	1.74	1.82	1.89	1.97	1.97
petro.HEV	1.25	1.3	1.35	1.41	1.47	1.53	1.59	1.65	1.72	1.79	1.86	1.94	2.02	2.1	2.18	2.18
petro.PHEV	1.44	1.5	1.56	1.62	1.69	1.76	1.83	1.91	1.98	2.06	2.15	2.24	2.33	2.42	2.52	2.52
NG.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
elec.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
elec.PHEV	3.71	3.75	3.8	3.84	3.89	3.93	3.98	4.03	4.08	4.13	4.18	4.23	4.28	4.33	4.38	4.38
elec.BEV	3.71	3.75	3.8	3.84	3.89	3.93	3.98	4.03	4.08	4.13	4.18	4.23	4.28	4.33	4.38	4.38
air_fuel.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 22. trsp_conv_freight (trsp_fuel, e_type, t) [-]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140
BTL.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
BTL.FC	1.01	1.05	1.1	1.14	1.19	1.24	1.29	1.34	1.39	1.45	1.51	1.57	1.64	1.7	1.77	1.77
CTL_GTL.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
CTL_GTL.FC	1.01	1.05	1.1	1.14	1.19	1.24	1.29	1.34	1.39	1.45	1.51	1.57	1.64	1.7	1.77	1.77
BTL.HEV	1.06	1.1	1.14	1.19	1.24	1.29	1.34	1.4	1.45	1.51	1.58	1.64	1.71	1.78	1.85	1.85
CTL_GTL.HEV	1.06	1.1	1.14	1.19	1.24	1.29	1.34	1.4	1.45	1.51	1.58	1.64	1.71	1.78	1.85	1.85
BTL.PHEV	1.27	1.32	1.38	1.43	1.49	1.55	1.62	1.68	1.75	1.82	1.9	1.97	2.05	2.14	2.22	2.22
CTL_GTL.PHEV	1.27	1.32	1.38	1.43	1.49	1.55	1.62	1.68	1.75	1.82	1.9	1.97	2.05	2.14	2.22	2.22
H2.0	1.09	1.13	1.18	1.22	1.27	1.33	1.38	1.44	1.49	1.56	1.62	1.68	1.75	1.82	1.9	1.9
H2.FC	1.49	1.55	1.62	1.68	1.75	1.82	1.9	1.98	2.06	2.14	2.23	2.32	2.41	2.51	2.61	2.61
petro.0	0.96	1	1.04	1.08	1.13	1.17	1.22	1.27	1.32	1.38	1.43	1.49	1.55	1.61	1.68	1.68
petro.FC	1.05	1.1	1.14	1.19	1.24	1.29	1.34	1.39	1.45	1.51	1.57	1.64	1.7	1.77	1.84	1.84
petro.HEV	1.15	1.2	1.25	1.3	1.35	1.41	1.47	1.52	1.59	1.65	1.72	1.79	1.86	1.94	2.02	2.02
petro.PHEV	1.27	1.32	1.38	1.43	1.49	1.55	1.62	1.68	1.75	1.82	1.9	1.97	2.05	2.14	2.22	2.22
NG.0	0.86	0.9	0.94	0.97	1.01	1.06	1.1	1.14	1.19	1.24	1.29	1.34	1.4	1.45	1.51	1.51
elec.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
elec.PHEV	3.18	3.21	3.25	3.29	3.33	3.37	3.41	3.45	3.5	3.54	3.58	3.62	3.67	3.71	3.76	3.76
elec.BEV	3.18	3.21	3.25	3.29	3.33	3.37	3.41	3.45	3.5	3.54	3.58	3.62	3.67	3.71	3.76	3.76
air_fuel.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

trsp_conv (trsp_fuel, e_type, "p_car", t) = trsp_conv_car (trsp_fuel, e_type, t);
trsp_conv (trsp_fuel, e_type, "p_bus", t) = trsp_conv_freight (trsp_fuel, e_type, t);
trsp_conv (trsp_fuel, e_type, "f_road", t) = trsp_conv_freight (trsp_fuel, e_type, t);
trsp_conv (trsp_fuel, e_type, "f_sea", t) = trsp_conv_freight (trsp_fuel, e_type, t);
trsp_conv (trsp_fuel, e_type, "f_isea", t) = trsp_conv_freight (trsp_fuel, e_type, t);

Table 23. heat_effic (cg_e_in, cg_type, cg_e_out) [-]

cg_e_in, cg_type	elec	BTL	CTL/GTL	H2
bio.cg	0.55	0	0	0
bio.cg_CCS	0.55	0	0	0
NG.cg	0.40	0	0	0
NG.cg_CCS	0.35	0	0	0
oil.cg	0.45	0	0	0
oil.cg_CCS	0.45	0	0	0
coal.cg	0.50	0	0	0
coal.cg_CCS	0.50	0	0	0
H2.cg	0.40	0	0	0

Table 24. price (fuels, R) [GUSD/EJ]

R_imp	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
bio	3.0	4.0	2.0	4.0	2.0	2.0	2.0	2.0	2.0	2.0
coal	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
oil	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
NG	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
nuclear	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 25. distance (R_imp, R_exp) [km]

R_imp	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
NAM	0	6800	9600	7900	10400	13300	8100	10000	10100	12800
EUR	6800	0	9700	2500	4200	9400	8713	3200	8200	7000
PAO	9600	9700	0	7500	12200	4600	17700	9600	2100	6700
FSU	7900	2500	7500	0	5200	7100	11200	2900	5800	5000
AFR	10400	4200	12200	5200	0	9200	7600	2600	10100	6200
PAS	13300	9400	4600	7100	9200	0	16600	7300	3300	3000
LAM	8100	8713	17700	11200	7600	16600	0	9900	16900	13800
MEA	10000	3200	9600	2900	2600	7300	9900	0	7600	4400
CPA	10100	8200	2100	5800	10100	3300	16900	7600	0	4800
SAS	12800	7000	6700	5000	6200	3000	13800	4400	4800	0

Table 26. supply_pot_0 (primary, R) [EJ]

R_imp	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
Bio	18	20	2	13	44	6.5	65	0.25	20	17
Coal	37262	17640	19074	121747	6457	380	1983	633	54649	3756
Oil	1550	864	65	1115	830	96	1144	5362	564	254
NG	1959	1420	155	2348	706	165	665	2578	315	434
Nuclear	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Wind	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Hydro	2.57	2.7	0.5	2.04	1.88	0.50	2.53	0.05	3.28	1.30
Solar	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Solar_CSP	1000	1000	1000	0	1000	1000	1000	1000	1000	1000

supply_pot (primary, R, t) = supply_pot_0 (primary, R);

Table 27. init_cap (e_in, e_out, type, R) [TW]

	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
bio.elec.0	0.0155	0.0053	0.021	0.00384	0	0.00096	0.0024	0.00043	0.00098	0.00096
bio.heat.0	0.13521	0.12215	0.02391	0.03511	0.3796	0.16549	0.14642	0.00358	0.387	0.34
coal.elec.0	0.39	0.24	0.06	0.08	0.0285	0.03	0.005	0.004	0.235	0.05
coal.heat.0	0.08259	0.34336	0.00584	0.37903	0.15683	0.3104	0.27984	0.04344	0.26989	0.3
NG.elec.0	0.08	0.047	0.05	0.18	0.0008	0.008	0.02	0.04	0.0007	0.005
NG.heat.0	0.23354	0.11133	0.09835	0.63462	0.46688	0.0097	0.13464	0.01415	0.3381	0.4
oil.elec.0	0.04	0.057	0.04	0.04	0.003	0.03	0.03	0.044	0.008	0.006
oil.heat.0	0.7237	0.77939	0.16286	0.35523	0.2435	0.04772	0.00784	0.27326	0.15058	0.2
oil.petro.0	1.28615	0.75803	0.20182	0.35448	0.10533	0.14582	0.30928	0.22679	0.18356	0.14197
nuclear.elec.0	0.13212	0.15489	0.03886	0.04098	0.00183	0.0165	0.00266	0	0	0.00107
hydro.elec.0	0.1251	0.10505	0.02777	0.05554	0.00932	0.00785	0.08633	0.00483	0.03575	0.02113

Table 28. cost_inv_base (e_in, type, e_out) [GUSD/kW]

	heat	elec	BTL	CTL/GTL	H2	NG	petro	air_fuel
bio.0	300	1200	1000		800			1300
bio.cg		1300						
bio.dec	500	1700			1000			
bio.cg_dec		1800						
hydro.0		1000						
wind.0		600						
solar.0	400	1200			2000			
solar_CSP.0		3200						
NG.0	100	500		600	300	0		1000
NG.cg		600						
NG.dec	300	900			500			
NG.cg_dec		1000						
oil.0	100	600			400		900	
oil.cg		700						
oil.dec	300	1000			600			
oil.cg_dec		1100						
coal.0	300	1100		1000	700			1300
coal.cg		1200						
coal.dec	500	1500			900			
coal.cg_dec		1600						
nuclear.0		2000						
H2.0	100	500						0
H2.cg		600						
elec.0	100				700			

cost_inv (e_in, e_out, type, t) = cost_inv_base (e_in, type, e_out);

cost_inv_mod (e_in, e_out, type, t) =
cost_inv (e_in, e_out, type, t) * (r_invest + 1/life_plant (e_in, e_out, type))/
(r+1/life_plant (e_in, e_out, type));

Table 29. lf_global(e_in, type, e_out) [-]

	heat	elec	BTL	CTL/GTL	H2	NG	petro	air_fuel
bio.0	0.7	0.7	0.8		0.6			0.8
bio.cg		0.7						
bio.dec	0.7	0.7			0.6			
bio.cg_dec		0.7						
hydro.0		0.7						
wind.0		0.25						
solar.0	0.25	0.25			0.25			
solar_CSP.0		0.6						
NG.0	0.7	0.7		0.8	0.6	0.7		0.8
NG.cg		0.7						
NG.dec	0.7	0.7			0.6			
NG.cg_dec		0.7						
oil.0	0.7	0.7			0.6		0.8	
oil.cg		0.7						
oil.dec	0.7	0.7			0.6			
oil.cg_dec		0.7						
coal.0	0.7	0.7		0.7	0.6			0.8
coal.cg		0.7						
coal.dec	0.7	0.7			0.6			
coal.cg_dec		0.7						
nuclear.0		0.7						
H2.0	0.7	0.7						0.7
H2.cg		0.7						
elec.0	1				0.7			

lf(e_in, type, e_out, R) = lf_global(e_in, type, e_out);

lf("solar", "0", e_out,"LAM") = 0.28;
lf("solar", "0", e_out,"MEA") = 0.28;
lf("solar", "0", e_out,"CPA") = 0.28;
lf("solar", "0", e_out,"AFR") = 0.28;
lf("solar", "0", e_out,"PAS") = 0.28;
lf("solar", "0", e_out,"SAS") = 0.28;
lf("solar", "0", e_out,"NAM") = 0.27;

Table 30. effic_0 (e_in, type, e_out) [-]

	heat	elec	BTL	CTL/GTL	H2	NG	petro	air_fuel
bio.0	0.9	0.5	0.5		0.6			0.5
bio.cg		0.35						
bio.dec	0.8	0.3			0.55			
bio.cg_dec		0.25						
hydro.0		1						
wind.0		1						
solar.0	1	1			1			
solar_CSP.0		1						
NG.0	0.9	0.55		0.7	0.8	1		0.6
NG.cg		0.5						
NG.dec	0.8	0.45			0.75			
NG.cg_dec		0.4						
oil.0	0.9	0.5			0.75		0.9	
oil.cg		0.45						
oil.dec	0.8	0.4			0.7			
oil.cg_dec		0.35						
coal.0	0.9	0.5		0.5	0.65			0.5
coal.cg		0.4						
coal.dec	0.8	0.35			0.6			
coal.cg_dec		0.3						
nuclear.0		0.33						
H2.0	0.9	0.55						0.67
H2.cg		0.5						
elec.0	0.95				0.8			

effic_current (e_in, type, e_out) = effic_0 (e_in, type, e_out) - 0.1;

effic (e_in, type, e_out, t) =
min (effic_0 (e_in, type, e_out), (effic_0 (e_in, type, e_out) - effic_current (e_in, type, e_out))/
t_tech_effic *((ord(t)-1)* t_step) + effic_current (e_in, type, e_out));

Table 31. flow_matrix (e_in, type, e_out) [-]

	heat	elec	BTL	CTL/GTL	H2	NG	petro	air_fuel
bio.0	0	0	0	1	0	1	1	0
bio.cg	1	0	1	1	1	1	1	1
bio.dec	0	0	1	1	0	1	1	1
bio.cg_dec	1	0	1	1	1	1	1	1
hydro.0	1	0	1	1	1	1	1	1
hydro.cg	1	1	1	1	1	1	1	1
hydro.CCS	1	1	1	1	1	1	1	1
hydro.cg_CCS	1	1	1	1	1	1	1	1
wind.0	1	0	1	1	1	1	1	1
wind.cg	1	1	1	1	1	1	1	1
wind.CCS	1	1	1	1	1	1	1	1
wind.cg_CCS	1	1	1	1	1	1	1	1
solar.0	0	0	1	1	0	1	1	1
solar.cg	1	1	1	1	1	1	1	1
solar.CCS	1	1	1	1	1	1	1	1
solar.cg_CCS	1	1	1	1	1	1	1	1
solar_CSP.0	1	0	1	1	1	1	1	1
solar_CSP.cg	1	1	1	1	1	1	1	1
solar_CSP.CCS	1	1	1	1	1	1	1	1
solar_CSP.cg_CCS	1	1	1	1	1	1	1	1
NG.0	0	0	1	0	0	0	1	0
NG.cg	1	0	1	1	1	1	1	1
NG.dec	0	0	1	1	0	1	1	1
NG.cg_dec	1	0	1	1	1	1	1	1
oil.0	0	0	1	1	0	1	0	1
oil.cg	1	0	1	1	1	1	1	1
oil.dec	0	0	1	1	0	1	1	1
oil.cg_dec	1	0	1	1	1	1	1	1
coal.0	0	0	1	0	0	1	1	0
coal.cg	1	0	1	1	1	1	1	1
coal.dec	0	0	1	1	0	1	1	1
coal.cg_dec	1	0	1	1	1	1	1	1
nuclear.0	1	0	1	1	1	1	1	1
nuclear.cg	1	1	1	1	1	1	1	1
nuclear.CCS	1	1	1	1	1	1	1	1
nuclear.cg_CCS	1	1	1	1	1	1	1	1
H2.0	0	0	1	1	1	1	1	0
H2.cg	1	0	1	1	1	1	1	1
H2.CCS	1	1	1	1	1	1	1	1
H2.cg_CCS	1	1	1	1	1	1	1	1
elec.0	0	1	1	1	0	1	1	1
elec.cg	1	1	1	1	1	1	1	1
elec.CCS	1	1	1	1	1	1	1	1
elec.cg_CCS	1	1	1	1	1	1	1	1

Table 32. heat_dem_reg (R, T_all) [EJ]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM	29.61	33.29	31.69	28.7	23.81	20.11	16.42	13.38	10.35	8.86	7.36	5.86	5.75	5.63	5.52
EUR	30.48	29.49	28.68	26.48	24.41	22.06	19.71	17.17	14.62	13.44	12.26	11.09	10.87	10.65	10.44
PAO	9.17	12.04	10.82	9.16	7.34	5.95	4.55	3.94	3.32	3.1	2.88	2.66	2.66	2.66	2.66
FSU	28.23	18.07	27.34	28.36	27.61	26.15	24.69	22.2	19.71	17.55	15.39	13.24	12.97	12.71	12.46
LAM	6.32	7.96	15.28	17.32	18.15	18.35	18.55	17.14	15.73	15.19	14.64	14.1	14.1	14.1	14.1
MEA	4.48	7.13	8.37	10.83	14.06	17.74	21.42	24.82	28.23	30.88	33.52	36.17	36.89	37.63	38.38
AFR	3.15	12.39	15.83	19.13	22.82	25.81	28.8	32.19	35.59	40.78	45.97	51.16	53.72	56.41	59.23
CPA	16.94	25.43	45.09	50.66	55.04	54.19	53.33	49.4	45.46	43.32	41.18	39.05	38.26	37.5	36.75
PAS	4.21	9.89	15.13	16.09	16.83	16.56	16.29	14.8	13.31	12.77	12.23	11.69	11.69	11.69	11.69
SAS	6.31	14.84	20.97	24.75	27.75	32.07	36.39	42.43	48.47	52.58	56.69	60.81	63.85	67.04	70.39

Table 33. elec_dem_reg (R, T_all) [EJ]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM	12.67	16.32	16.93	17.29	17.48	17.15	16.84	15.61	14.41	13.53	12.66	11.78	11.19	10.63	10.1
EUR	8.95	10.61	12.38	13.63	15.02	16.03	17.03	17.06	17.09	16.63	16.18	15.72	15.72	15.72	15.72
PAO	3.75	5.2	5.19	5.28	5.58	5.4	5.23	4.97	4.71	4.65	4.58	4.52	4.52	4.52	4.52
FSU	4.83	3.54	4.94	5	5.22	5.52	5.84	6.21	6.58	6.99	7.4	7.81	7.81	7.81	7.81
LAM	1.6	2.43	3.37	3.98	4.66	5.32	5.98	7.41	8.82	9.71	10.59	11.49	11.49	11.49	11.49
MEA	0.71	1.38	1.85	2.55	3.43	4.78	6.11	8.43	10.73	14.72	18.71	22.7	23.84	25.03	26.28
AFR	0.95	1.29	1.58	2.02	2.44	3.67	4.89	6.62	8.34	13.07	17.81	22.55	24.81	27.29	30.01
CPA	2.87	5.26	6.95	9.1	11.73	14.53	17.34	20.26	23.19	25.13	27.07	29.03	30.48	32	33.6
PAS	0.84	1.54	2.65	4.12	5.48	7.07	8.67	9.92	11.18	11.97	12.78	13.58	13.58	13.58	13.58
SAS	1.23	2.24	2.75	3.53	4.7	6.34	7.99	11.09	14.22	19.21	24.21	29.23	32.15	35.36	38.9

Table 34. ptrsp_all (R, ptrs_mode, t) [EJ]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM.p_car	12.49	14.54	15.4	15.53	15.37	14.52	13.5	12.34	11.07	9.77	8.45	7.17	5.93	4.77	3.68
EUR.p_car	6.64	8.27	9.12	9.56	9.89	9.92	9.86	9.44	8.88	8.36	7.69	6.96	6.21	5.47	4.74
PAO.p_car	1.87	2.59	2.52	2.32	2.29	2.21	2.09	1.95	1.8	1.67	1.53	1.39	1.23	1.06	0.89
FSU.p_car	0.99	0.23	0.24	0.25	0.43	0.73	1.17	1.71	2.45	3.09	3.85	4.7	4.71	4.51	4.23
LAM.p_car	0.99	1.54	3	4.53	5.66	7	8.47	10.1	11.43	12.69	13.29	13.55	13.05	12.29	11.42
MEA.p_car	0.36	0.57	1.11	1.66	2.33	3.49	4.95	6.37	7.84	9.28	11.03	13.14	15.72	16.57	16.41
AFR.p_car	0.47	0.65	1.02	1.38	1.87	2.7	3.75	5.3	7.75	12.87	20.95	32.01	39.86	41.47	43.02
CPA.p_car	0.01	0.05	0.51	0.97	2.23	4.15	7.08	9.54	12.39	14.93	17.19	18.12	18.42	18.47	18.25
PAS.p_car	0.19	0.42	1.45	2.5	3.31	3.97	4.67	5.23	5.86	6.78	7.43	8.15	7.6	6.62	5.42
SAS.p_car	0.12	0.24	0.55	0.86	1.85	4.1	7.3	12.1	18.34	23.59	26.51	27.77	26.78	24.18	21.15
NAM.p_bus	0.22	0.23	0.23	0.22	0.21	0.2	0.19	0.17	0.16	0.15	0.14	0.13	0.12	0.11	0.1
EUR.p_bus	0.44	0.4	0.38	0.36	0.36	0.34	0.3	0.26	0.22	0.18	0.15	0.12	0.11	0.1	0.09
PAO.p_bus	0.13	0.16	0.14	0.12	0.12	0.11	0.11	0.1	0.1	0.09	0.09	0.08	0.08	0.08	0.07
FSU.p_bus	0.59	0.34	0.3	0.25	0.31	0.35	0.36	0.33	0.27	0.19	0.12	0.05	0	0	0
LAM.p_bus	0.25	0.32	0.48	0.65	0.64	0.6	0.56	0.51	0.48	0.46	0.43	0.4	0.36	0.34	0.32
MEA.p_bus	0.23	0.34	0.52	0.71	0.76	0.69	0.57	0.54	0.56	0.55	0.54	0.52	0.48	0.42	0.4
AFR.p_bus	0.17	0.23	0.34	0.44	0.53	0.63	0.76	0.98	1.21	1.32	1.19	1.1	1.01	0.9	0.8
CPA.p_bus	0.09	0.25	0.69	1.16	1.44	1.49	1.5	1.44	1.37	1.28	1.19	1.1	1	0.91	0.82
PAS.p_bus	0.24	0.33	0.47	0.69	0.7	0.7	0.69	0.66	0.62	0.58	0.54	0.5	0.45	0.4	0.35
SAS.p_bus	0.54	0.92	1.32	1.73	1.98	2.12	2.22	2.19	2.09	1.94	1.77	1.58	1.43	1.26	1.13
NAM.p_rail	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.1	0.1	0.1	0.1	0.09	0.09	0.09	0.08
EUR.p_rail	0.24	0.27	0.29	0.29	0.3	0.31	0.33	0.33	0.33	0.34	0.35	0.36	0.36	0.37	0.38
PAO.p_rail	0.07	0.08	0.07	0.06	0.06	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.03	0.03
FSU.p_rail	0.33	0.31	0.27	0.23	0.26	0.29	0.34	0.37	0.4	0.42	0.44	0.46	0.47	0.48	0.5
LAM.p_rail	0	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
MEA.p_rail	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.06	0.07	0.08	0.09	0.1
AFR.p_rail	0.01	0.01	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07	0.08
CPA.p_rail	0.02	0.05	0.12	0.2	0.24	0.26	0.3	0.32	0.35	0.37	0.39	0.42	0.45	0.47	0.5
PAS.p_rail	0	0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.07	0.08	0.09	0.1	0.11
SAS.p_rail	0.05	0.07	0.09	0.12	0.14	0.17	0.2	0.25	0.32	0.38	0.44	0.51	0.55	0.58	0.59
NAM.p_air	2.07	3.38	4.42	5.4	6.41	7.5	8.74	9.58	10.21	10.47	10.58	10.62	10.62	10.62	10.62
EUR.p_air	1.19	2.44	3.28	4.23	5.1	5.75	6.57	7.37	8	8.25	8.51	8.64	8.64	8.64	8.64
PAO.p_air	0.63	0.88	1.07	1.29	1.51	1.72	1.96	2.07	2.32	2.46	2.53	2.56	2.59	2.6	2.6
FSU.p_air	1.27	0.17	0.23	0.34	0.45	0.61	0.82	1.11	1.48	1.85	2.1	2.31	2.44	2.52	2.56
LAM.p_air	0.11	0.57	0.87	1.34	2.01	2.91	4.18	5.07	5.61	5.85	6.01	6.16	6.16	6.16	6.16
MEA.p_air	0.14	0.27	0.36	0.48	0.63	0.78	0.94	1.21	1.65	2.07	2.78	3.78	5.12	6.45	7.1
AFR.p_air	0.06	0.2	0.31	0.47	0.69	0.96	1.31	1.91	2.7	3.92	5.7	8.33	11.37	14.21	15.93
CPA.p_air	0.02	0.37	0.66	1.04	1.5	2.11	2.96	3.64	4.72	5.8	7.28	9.03	11.13	12.6	13.44
PAS.p_air	0.18	0.52	0.78	1.14	1.58	2.18	2.97	3.95	5.23	6.85	8.67	10.09	10.74	11.07	11.07
SAS.p_air	0.08	0.13	0.22	0.35	0.52	0.76	1.09	1.9	3.71	6.3	9.77	14.15	16.1	17.16	17.95

Table 35. frgt_all (R, frgt_mode, t) [EJ]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM.f_road	5.22	6.58	7.25	7.91	8.56	8.91	9.23	9.46	9.65	9.78	9.88	9.95	9.96	9.95	9.91
EUR.f_road	3.55	3.95	4.15	4.14	4.29	4.36	4.43	4.42	4.41	4.41	4.4	4.41	4.35	4.27	4.21
PAO.f_road	1.53	1.97	1.81	1.64	1.65	1.63	1.6	1.56	1.52	1.51	1.49	1.47	1.46	1.44	1.42
FSU.f_road	1.88	2.01	1.71	1.4	1.61	1.82	2.05	2.22	2.4	2.49	2.58	2.66	2.68	2.68	2.69
LAM.f_road	1.46	2.05	3.4	4.85	5.41	5.89	6.4	6.74	7.08	7.35	7.64	7.92	7.87	7.81	7.74
MEA.f_road	1.16	1.7	2.79	3.89	4.57	5.21	5.93	6.54	7.21	7.6	8	8.43	8.79	9.08	9.15
AFR.f_road	0.89	1.2	1.76	2.31	2.8	3.35	3.99	4.74	5.63	6.62	7.77	9.11	10.06	10.43	10.71
CPA.f_road	0.73	1.52	3.86	6.28	7.89	9.22	10.64	11.62	12.59	13.25	13.88	14.47	14.78	15.06	15.29
PAS.f_road	0.57	0.83	1.79	2.76	3.16	3.45	3.76	3.91	4.05	4.23	4.4	4.58	4.69	4.8	4.91
SAS.f_road	1.12	1.75	2.36	2.97	3.45	3.99	4.61	5.37	6.23	6.82	7.45	8.14	8.49	8.76	8.9
NAM.f_rail	1.22	1.37	1.44	1.43	1.42	1.37	1.33	1.26	1.22	1.16	1.11	1.06	1.01	0.95	0.91
EUR.f_rail	0.19	0.2	0.19	0.19	0.18	0.19	0.19	0.18	0.18	0.17	0.17	0.16	0.15	0.15	0.15
PAO.f_rail	0.03	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
FSU.f_rail	0.23	0.23	0.19	0.14	0.15	0.16	0.17	0.17	0.18	0.17	0.17	0.17	0.16	0.16	0.15
LAM.f_rail	0.07	0.09	0.14	0.2	0.21	0.22	0.23	0.24	0.24	0.24	0.24	0.24	0.23	0.22	0.21
MEA.f_rail	0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07
AFR.f_rail	0.03	0.04	0.06	0.07	0.08	0.09	0.1	0.12	0.14	0.15	0.18	0.2	0.22	0.22	0.22
CPA.f_rail	0.32	0.53	0.88	1.33	1.46	1.53	1.59	1.58	1.58	1.54	1.5	1.46	1.4	1.34	1.29
PAS.f_rail	0.06	0.08	0.15	0.23	0.25	0.26	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25
SAS.f_rail	0.08	0.11	0.15	0.18	0.2	0.22	0.25	0.28	0.31	0.32	0.34	0.36	0.36	0.36	0.36
NAM.f_sea	0.51	0.58	0.6	0.6	0.6	0.58	0.56	0.54	0.52	0.5	0.47	0.45	0.42	0.41	0.39
EUR.f_sea	0.1	0.11	0.1	0.1	0.1	0.1	0.09	0.09	0.09	0.08	0.08	0.08	0.07	0.07	0.07
PAO.f_sea	0.12	0.14	0.13	0.11	0.11	0.09	0.09	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.06
FSU.f_sea	0.1	0.11	0.08	0.06	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.07
LAM.f_sea	0.06	0.07	0.11	0.16	0.17	0.18	0.19	0.19	0.19	0.2	0.2	0.2	0.19	0.18	0.17
MEA.f_sea	0.01	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07
AFR.f_sea	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.05
CPA.f_sea	0.1	0.16	0.3	0.45	0.5	0.52	0.54	0.54	0.53	0.52	0.5	0.5	0.48	0.46	0.44
PAS.f_sea	0.02	0.03	0.05	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
SAS.f_sea	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02
NAM.f_air	0.1	0.13	0.14	0.15	0.16	0.16	0.17	0.17	0.18	0.18	0.18	0.18	0.18	0.18	0.18
EUR.f_air	0.09	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.09	0.09
PAO.f_air	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
FSU.f_air	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
LAM.f_air	0.02	0.02	0.04	0.06	0.06	0.07	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09
MEA.f_air	0.02	0.02	0.04	0.05	0.06	0.07	0.08	0.09	0.09	0.1	0.1	0.1	0.1	0.11	0.11
AFR.f_air	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06
CPA.f_air	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06
PAS.f_air	0.01	0.01	0.02	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04
SAS.f_air	0.01	0.01	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.06	0.06	0.06	0.06
NAM.f_isea	2.26	2.67	2.87	3.07	3.27	3.39	3.56	3.68	3.87	3.97	4.04	4.23	4.33	4.46	4.48
EUR.f_isea	0.46	0.5	0.52	0.54	0.57	0.62	0.6	0.65	0.71	0.68	0.74	0.81	0.76	0.8	0.85
PAO.f_isea	0.53	0.66	0.6	0.54	0.57	0.56	0.6	0.58	0.55	0.59	0.64	0.61	0.65	0.69	0.73
FSU.f_isea	0.44	0.5	0.41	0.32	0.4	0.43	0.54	0.58	0.63	0.68	0.74	0.81	0.76	0.8	0.85

LAM.f_isea	0.26	0.34	0.63	0.92	1.03	1.17	1.34	1.44	1.58	1.78	1.93	2.12	2.17	2.17	2.18
MEA.f_isea	0.05	0.09	0.15	0.22	0.23	0.31	0.34	0.43	0.47	0.51	0.55	0.61	0.76	0.8	0.85
AFR.f_isea	0.03	0.04	0.05	0.05	0.12	0.12	0.13	0.22	0.24	0.25	0.37	0.4	0.54	0.57	0.61
CPA.f_isea	0.43	0.74	1.72	2.7	3.15	3.58	4.03	4.32	4.66	4.9	5.14	5.54	5.74	5.84	5.94
PAS.f_isea	0.09	0.12	0.25	0.38	0.46	0.49	0.54	0.58	0.63	0.68	0.74	0.81	0.87	0.92	0.97
SAS.f_isea	0.03	0.04	0.05	0.05	0.06	0.06	0.07	0.07	0.16	0.17	0.18	0.2	0.22	0.23	0.24

```
trsp_dem (R, "p_rail", t) = ptrsp_all (R, "p_rail", t);
trsp_dem (R, "p_air", t) = ptrsp_all (R, "p_air", t);
trsp_dem (R, "p_car", t) = ptrsp_all (R, "p_car", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "p_bus", t) = ptrsp_all (R, "p_bus", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_rail", t) = frgt_all (R, "f_rail", t);
trsp_dem (R, "f_air", t) = frgt_all (R, "f_air", t);
trsp_dem (R, "f_road", t) = frgt_all (R, "f_road", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_sea", t) = frgt_all (R, "f_sea", t)*1.004**(t_step*(ord(t)-1));
trsp_dem (R, "f_isea", t) = frgt_all (R, "f_isea", t)*1.004**(t_step*(ord(t)-1));
```

Table 36. num_cars (R, t) [Gcars]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM	0.1683	0.1764	0.2085	0.2283	0.2423	0.2457	0.2451	0.2401	0.2311	0.2187	0.2032	0.1849	0.1641	0.1415	0.1171
EUR	0.1504	0.1893	0.2418	0.2745	0.3045	0.3258	0.3465	0.3549	0.3575	0.3591	0.3534	0.3423	0.3269	0.3082	0.2859
PAO	0.0433	0.0541	0.067	0.0731	0.0775	0.0799	0.0814	0.0814	0.0803	0.0802	0.0791	0.0769	0.073	0.0677	0.0612
FSU	0.0188	0.004	0.0054	0.0082	0.0143	0.0243	0.0398	0.0597	0.0918	0.1241	0.1657	0.2172	0.2336	0.2398	0.241
LAM	0.0368	0.0556	0.0726	0.0995	0.1333	0.1768	0.2297	0.2936	0.3563	0.4246	0.4771	0.5216	0.5392	0.5445	0.5425
MEA	0.0097	0.0148	0.0225	0.0342	0.0533	0.0882	0.1341	0.1853	0.2446	0.3104	0.3958	0.506	0.6493	0.7341	0.7799
AFR	0.007	0.01	0.0144	0.0208	0.0309	0.0491	0.0749	0.1263	0.2049	0.3339	0.6001	0.9859	1.317	1.4699	1.636
CPA	0.0004	0.0024	0.0082	0.0245	0.0605	0.121	0.2213	0.32	0.4459	0.5762	0.7116	0.805	0.878	0.9442	1.0008
PAS	0.0104	0.0228	0.0426	0.0684	0.0974	0.1254	0.1582	0.1897	0.2287	0.2838	0.3334	0.3923	0.3922	0.3668	0.3221
SAS	0.0041	0.0069	0.0121	0.0236	0.0543	0.1294	0.2473	0.4397	0.715	0.9863	1.1892	1.3365	1.3826	1.3391	1.2569

Table 37. num_trucks (R, t) [Gtrucks]

	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
NAM	0.0211	0.0273	0.0331	0.0387	0.0439	0.0473	0.0509	0.0543	0.0579	0.0613	0.065	0.0688	0.0724	0.0763	0.0802
EUR	0.0142	0.0167	0.0196	0.0219	0.0243	0.0263	0.0285	0.0301	0.0319	0.034	0.0362	0.0385	0.0403	0.0423	0.0443
PAO	0.0038	0.0043	0.0047	0.005	0.0052	0.0054	0.0056	0.0057	0.0058	0.006	0.0063	0.0065	0.0068	0.0072	0.0075
FSU	0.001	0.0036	0.0043	0.0052	0.0066	0.008	0.0097	0.0111	0.0127	0.0139	0.0152	0.0165	0.0175	0.0185	0.0196
LAM	0.0105	0.014	0.0165	0.0201	0.0239	0.0277	0.0321	0.0358	0.0399	0.044	0.0485	0.0534	0.0562	0.0593	0.0624
MEA	0.0064	0.0089	0.0119	0.0153	0.0193	0.0235	0.0287	0.0338	0.0399	0.0449	0.0506	0.0569	0.0635	0.0701	0.0755
AFR	0.0029	0.0042	0.0059	0.0079	0.0104	0.0133	0.0171	0.0217	0.0275	0.0345	0.0432	0.0541	0.0636	0.0702	0.0768
CPA	0.0071	0.0146	0.0209	0.0286	0.0368	0.0435	0.0513	0.0569	0.063	0.0679	0.0732	0.0789	0.0834	0.0882	0.0932
PAS	0.0047	0.0073	0.0101	0.013	0.016	0.0184	0.0213	0.0233	0.0255	0.0281	0.031	0.0341	0.037	0.0401	0.0435
SAS	0.0048	0.007	0.0094	0.0121	0.0153	0.0192	0.0239	0.0299	0.0372	0.0434	0.0505	0.0587	0.065	0.0712	0.0769

```
num_veh (R, "p_car", t) =  num_cars (R, t);
num_veh (R, "f_road", t) = num_trucks (R, t);
```

Table 38. IRfunc (T_all, T_all_copy) [-] (1st half of the table)

	1800	1810	1820	1830	1840	1850	1860	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960
1800	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1810	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1820	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1830	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0
1840	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0
1850	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0
1860	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0
1870	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0
1880	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0
1890	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0
1900	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0
1910	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0
1920	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0
1930	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0
1940	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0
1950	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0
1960	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1
1970	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747
1980	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644
1990	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573
2000	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522
2010	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482
2020	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45
2030	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424
2040	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402
2050	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383
2060	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366
2070	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337	0.35
2080	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325	0.337
2090	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314	0.325
2100	0.221	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304	0.314
2110	0.217	0.221	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295	0.304
2120	0.214	0.217	0.221	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287	0.295
2130	0.211	0.214	0.217	0.221	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279	0.287
2140	0.209	0.211	0.214	0.217	0.221	0.224	0.227	0.231	0.235	0.239	0.244	0.249	0.254	0.259	0.265	0.272	0.279

Table 39. IRfunc (T_all, T_all_copy) [-] (2nd half of the table)

1970	1980	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0	0
0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0	0
0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0	0
0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0	0
0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0	0
0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0	0
0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0	0
0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0	0
0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0	0
0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0	0
0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0	0
0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1	0
0.287	0.295	0.304	0.314	0.325	0.337	0.35	0.366	0.383	0.402	0.424	0.45	0.482	0.522	0.573	0.644	0.747	1

Appendix 2: Compact model description

Here the global energy systems model GET-RC 6.1 is described in a compact version without explanations. All sets, parameters and variables are listed in alphabetic order. The equations are here written in a slightly different way starting with the objective function followed by the constraints, however, using the same equation numbers. Variables written in red indicate main variables, i.e. that the variables are not calculated from any other decision variables. All variables are of type continuous.

Sets

The sets (indices) are here presented in alphabetic order. See Section 2 for contents of each set.

c_capt ⊆ type	Energy conversions plants that can capture carbon	[-]
vehicle ⊆ trsp_mode	The two transportation modes of passenger cars and road-based freight	[-]
cg_e_in ⊆ e_in	Energy sources that can be used for co-generation of heat and electricity	[-]
cg_e_out ⊆ e_out	Energy carriers that can be produced from co-generation	[-]
CG_type ⊆ type	Plants that can be used for co-generation of electricity and heat	[-]
E	All energy sources and carriers	[-]
e_in ⊆ E	Energy sources that can be converted into energy carriers	[-]
e_out ⊆ E	Energy carriers that can come out from the conversion module	[-]
e_type	Type of engine technology	[-]
frgt_mode ⊆ trsp_mode	All freight transportation modes	[-]
fossil ⊆ fuels	Fossil primary energy sources	[-]
fuels ⊆ primary	Primary energy sources that can be traded	[-]
hev_phev_bev ⊆ e_type	Hybrids, plugin-hybrids and battery electric vehicles	[-]
hybrids ⊆ e_type	Hybrids and plugin-hybrids	[-]
ic_fc ⊆ e_type	Internal combustion engines and fuel cells	[-]
init_year ⊆ t	First time steps	[-]
synfuel_gas ⊆ trsp_fuel_nonel	Synthetic and gaseous fuel for transport	[-]
non_phev ⊆ e_type	All types of engine technologies except plugin-hybrids	[-]
nontrade_sec ⊆ e_out	Secondary energy carriers that cannot be traded	[-]
nonfuels ⊆ primary	Primary energy sources that cannot be traded	[-]
primary ⊆ e_in	Primary energy sources	[-]
ptrs_mode ⊆ trsp_mode	All passenger transportation modes	[-]
R	Regions	[-]
R_exp ⊆ R	Exporting regions	[-]
R_imp ⊆ R	Importing regions	[-]
road_fuel ⊆ trsp_fuel	Energy carriers for road transportation sector	[-]
road_fuel_liquid ⊆ road_fuel	Synthetic fuels and petroleum-based fuels for road transport	[-]
second_in ⊆ e_in	Energy carriers that can be converted a second time	[-]
sec ⊆ e_out	Secondary energy carriers	[-]
ship_mode ⊆ trsp_mode	The two transportation modes of sea-based freight	[-]
T_all	All time steps	[-]
T_all_copy ⊆ T_all	Duplicate of "T_all" to be able to code carbon cycle calculations	[-]
t_h ⊆ T_all	Historical time steps used for the carbon cycle calculations	[-]
t ⊆ T_all	Time steps for the modeled time period	[-]
t_2010_2140 ⊆ t	Time steps used when constraining nuclear	[-]
trsp_fuel ⊆ e_out	All energy carriers that can be used in the transportation sector	[-]
trsp_fuel_nonel ⊆ trsp_fuel	Energy carriers for the transportation sector except electricity	[-]
trsp_mode	The different transportation modes	[-]
type	Different types of energy conversion plants	[-]

Scalars

The scalars are here presented in alphabetic order. We define scalars as a parameter (given data) with one specific value only. As soon as the parameter depends on one or more sets they are presented under Section Parameters. See Section 3 for more details.

bio_capt_effic	= 0.9	Carbon capture efficiency from bioenergy CCS	[-]
c_capt_heat_fr	= 0.3	Max fraction of heat sector using CCS	[-]
c_stor_maxgr	= 100	Global annual growth limit on C storage capacity	[MtC/decade]
c_bio_trspcost	= 0.5	Additional transportation cost applied to bioenergy CCS	[USD/GJ]
cap_g_lim	= 0.2	Maximum growth of capacity in energy conversion plants	[-]
cogen_fr_e	= 0.2	Max fraction of electricity demand from co-generation	[-]
cogen_fr_h	= 0.2	Max fraction of heat demand that can come from co-generation	[-]
cost_strg_bio	= 0.073	Carbon storage cost from bioenergy (equals to 20 USD/t CO_2)	[GUSD/MtC]
cost_strg_fos	= 0.037	Carbon storage cost from fossils (equals to 10 USD/t CO_2)	[GUSD/MtC]
en_conv_decr_lim	= 0.75	Minimum fraction of previous time step's en_conv, i.e. limitation of an energy technology decrease	[-]
eng_g_lim	= 0.2	Maximum growth of vehicles	[-]
fos_capt_effic	= 0.9	Carbon capture efficiency from fossil CCS	[-]
frac_bev_buses	= 0.5	Share of buses that can use BEV	[-]
frac_bev_trucks	= 0.2	Share of trucks that can use BEV	[-]
frac_phev_buses	= 0.5	Share of buses that can use PHEV	[-]
frac_phev_trucks	= 0.2	Share of trucks that can use PHEV	[-]
global_en_conv_dis	= 5	The final "tail" of a certain energy conversion	[EJ]
global_init_e	= 0.1	"kick-start" value when a new engine is introduced	[Gvehicles]
global_init_i	= 0.05	"kick-start" value when a new infrastructure is introduced	[TW]
global_init_p	= 0.3	"kick-start" value when a new conversion plant is introduced	[TW]
global_init_s	= 0.3	"kick-start" value when a new energy source is introduced	[EJ]
global_mx_decay_oil	=10	The final "tail" of oil use in primary energy values	[EJ]
global_max_exp	= 60	Global maximum expansion rate for energy sources except biomass	[EJ/decade]
global_max_exp_p	= 2	Global maximum expansion rate for investments in conversion plants	[TW/decade]
global_max_exp_b	= 32	Global maximum expansion rate for biomass production	[EJ/decade]
global_max_exp_i	=1	Global maximum expansion rate for infrastructure investments	[TW/decade]
global_mx_decay	= 6	Final "tail" of a certain transportation energy	[EJ]
infra_g_lim	= 0.2	Maximum infrastructure growth	[-]
interm_fr	= 0.3	Max fraction of intermittent electricity (wind + solar-elec)	[-]
mx_decay_frac	= 0.7	Minimum fraction of previous time step's transport solution	[-]
mx_decay_frac_oil	= 0.2	Minimum fraction of previous time step's oil use	[-]
Msec_per_year	= 31.6	Number of seconds per year expressed in millions	[Ms]
pre_ind_ccont	= 280	Pre-industrial atmospheric CO_2 concentration	[ppm]
r	= 0.05	Discount rate	[-]
r_invest	= 0.05	Interest rate applied to investments	[-]
supply_g_lim	= 0.2	Maximum growth of energy supply	[-]
t_step	= 10	Number of year within each time step	[yr]
t_tech_plant	=50	Inertia. How fast new conversion technologies may totally change	[yr]
t_tech_eng	=50	Inertia. How fast new engine technologies may totally change	[yr]
t_tech_effic	=30	Inertia. How fast energy efficiency may totally change	[yr]

Parameters

In this section, the parameters (given data) used in the model are presented with the sets the parameter depends on in parenthesis and in alphabetical order. See Section 3 for more details. Data used as base case in the model is presented in Appendix 1. Note that parameters calculated during model runs are marked with an asterisk.

c_tax (R, t)	Carbon tax	[GUSD/MtC]
cost_eng* (road_fuel, e_type, vehicle, t)	Time dependent vehicle investment cost	[GUSD/Gvehicle]
cost_eng_base (road_fuel, e_type, vehicle)	Additional cost above standard "petro-vehicle"	[GUSD/Gvehicle]
cost_eng_mod* (road_fuel, e_type, vehicle, t)	Vehicle investment cost adjusted if assuming different investment interest rate and discount rates	[GUSD/Gvehicle]
cost_infra (synfuel_gas)	Investment cost for infrastructure	[GUSD/TW]
cost_infra_mod* (synfuel_gas)	Investment cost for infrastructure adjusted if assuming different investments and discount rates	[GUSD/TW]
cost_inv* (e_in, e_out, type, t)	Time is added to the plant investment costs	[GUSD/TW]
cost_inv_base (e_in, type, e_out)	Investments cost for energy conversion plants	[GUSD/TW]
cost_inv_mod* (e_in, e_out, type, t)	Plant investment cost adjusted if assuming different investment interest rate and discount rates	[GUSD/TW]
dec_elec (e_in)	Electricity requirements when using CCS	[-]
distance (R_imp, R_exp)	Table of rough distances between regions	[km]
effic* (e_in, type, e_out, t)	Energy conversion efficiency in conversion plants	[-]
effic_0 (e_in, type, e_out)	Ideal conversion efficiency assumed available in 2020-2050	[-]
effic_current* (e_in, type, e_out)	Near term energy conversion efficiency	[-]
elec_dem_reg (R, t)	Electricity demand	[EJ]
elec_frac_phev (vehicle)	Fraction of time that a PHEV operates in battery mode	[-]
emis_fact (fuels)	Carbon dioxide emission factors	[MtonC/EJ]
emis_fact_syn	Emission factor from CTL/GTL	[MtonC/EJ]
en_conv_dis* (R, t)	The final "tail" of a certain energy conversion	[EJ]
flow_matrix (e_in, type, e_out)	Table on allowed energy conversions	[-]
frgt (R, frgt_mode, t)	Energy demand for freight transport	[EJ]
fut_biota_sinks (T_all)	Estimation of the contribution of natural CO_2 sinks	[MtC]
fut_luc_emis (T_all)	Prognos for future emissions from land use change	[MtC]
IRfunc (T_all, T_all_copy)	Impulse Response function. Determines annual contribution to atmospheric carbon from each year's CO_2 emissions.	[-]
heat_dem_reg (R, t)	Heat demand	[EJ]
heat_effic (cg_e_in, cg_type, cg_e_out)	Heat efficiency when cogeneration of electricity and heat	[-]
high_speed_train (R, t)	Fraction of aviation substituted with high speed trains	[-]
hist_fos_emis (t_h)	Historical fossil emissions	[MtC]
imp_cost (fuels)	Cost for transportation of primary energy sources when trading between regions, regardless distance.	[GUSD/EJ]
imp_cost2 (sec)	Cost for transportation of secondary energy carriers when trading between regions, regardless distance.	[GUSD/EJ]
init_cap (e_in, e_out, type, R)	Capacity in energy conversion plants 1990	[TW]
init_eng* (R)	"kick-start" value when a new engine is introduced	[Gvehicles]
init_infra* (R)	"kick-start" value when a new infrastructure is introduced	[TW]
init_plant* (R)	"kick-start" value when a new conversion plant is introduced	[TW]
init_supply* (R)	"kick-start" value when a new energy source is introduced	[EJ]
lf (e_in, type, e_out, R)	Load factor (capacity factor) for energy conversion plants, i.e., the share of maximum capacity used per year	[-]
lf_infra (synfuel_gas)	Load factor infrastructure	[-]
life_eng (trsp_fuel,e_type,vehicle)	Life time on vehicle engines	[yr]
life_infra (synfuel_gas)	Life time for infrastructure	[yr]
life_plant (e_in, e_out, type)	Life time on energy conversion plants	[yr]
mx_decay_abs_oil* (R, t)	The final "tail" of oil use in primary energy values	[EJ]
max_exp* (R, t)	Primary fuel supply growth limit	[EJ/decade]
max_exp_bio* (R, t)	Bio energy growth limit	[EJ/decade]
max_exp_p* (e_in, e_out, type, R, t)	Growth limit on energy conversion plants	[TW/decade]
max_inv_infra* (R, t)	Infrastructure growth limit	[TW/decade]
mx_decay_abs* (R, t)	The final "tail" of a certain transportation energy	[EJ]

num_veh (R, vehicle, t)	Number of vehicles	[Gvehicles]
OM_cost_fr (e_in, e_out)	Operation & maintenance cost as fraction of investment cost	[-]
population (R, t)	Population	[Gpeople]
price (fuels, R)	Basic fuel price without scarcity rent or carbon tax	[GUSD/EJ]
ptrsp (R, ptrs_mode, t)	Energy demand for passenger transport	[EJ]
supply_pot (primary, R, t)	Annual maximum supply potential (non-fossil sources)	[EJ]
supply_pot_0 (primary,R)	Total primary energy supply potential (fossil sources)	[EJ]
trsp_conv_st(trsp_fuel,e_type, trsp_mode)	A factor that relates the energy efficiency to conventional ICEV. Valid for aviation and rail.	[-]
trsp_conv(trsp_fuel,e_type, trsp_mode, t)	Time dependent trsp-conv	[-]
trsp_dem (R, trsp_mode, t)	Energy demand for each transportation mode.	[EJ]
imp_cost_lin (fuels)	Additional cost, dependent on distance, for transportation when trading primary energy sources.	[GUSD/EJ]
imp_cost_lin2 (sec)	Additional cost, dependent on distance, for transportation when trading secondary energy carriers.	[GUSD/EJ]
vehicle_cost (vehicle)	Basic cost for vehicles with gasoline IC engine	[GUSD/Gvehicle]

Calculation of the parameters that are defined during the model run

The following calculations are made during the model run to generate values on the parameters listed with an asterisk above. Calculations are listed in alphabetical order following the parameter name. All calculations are however not activated in this model version. In the original global GET model version growth limitation parameters in absolute numbers were given in TW. When regionalizing these global values we have also changed so the values now are expressed in EJ. Therefore all these parameters below, starting with en_conv_dis (R, t) and ending with mx_decay_abs (R, t) have been adjusted using Msec_per_year*t_step. For more information, see Section 3.

cost_eng (road_fuel, e_type, vehicle, t) = cost_eng_base (road_fuel, e_type, vehicle) + vehicle_cost (vehicle);

cost_eng_mod (road_fuel, e_type, vehicle, t) =
cost_eng (road_fuel, e_type, vehicle, t) * (r_invest + 1/life_eng (road_fuel, e_type, vehicle))/
(r+1/life_eng (road_fuel, e_type, vehicle));

cost_infra_mod (synfuel_gas) =
cost_infra (synfuel_gas) * (r_invest + 1/life_infra (synfuel_gas)) / (r + 1/life_infra (synfuel_gas));

cost_inv (e_in, e_out, type, t) = cost_inv_base (e_in, type, e_out);

cost_inv_mod (e_in, e_out, type, t) =
cost_inv (e_in, e_out, type, t) * (r_invest + 1/life_plant (e_in, e_out, type))/(r+1/life_plant (e_in, e_out, type));

effic (e_in, type, e_out, t) =
min (effic_0 (e_in, type, e_out), (effic_0 (e_in, type, e_out) – effic_current (e_in, type, e_out))/
t_tech_effic (e_in, type, e_out)*((ord(t)-1)* t_step) + effic_current (e_in, type, e_out))

effic_current (e_in, type, e_out) = effic_0 (e_in, type, e_out) – 0.1

en_conv_dis (R, t) =
((elec_dem_reg (R, t) + heat_dem_reg (R, t) + Σ_{ptrs_mode} (ptrsp (R, ptrs_mode, t)) +
Σ_{frgt_mode} (frgt (R, frgt_mode, t)))/(Msec_per_year*t_step))* global_en_conv_dis;

init_eng (R) =
((elec_dem_reg (R,"2000")+ heat_dem_reg (R,"2000")+ Σ_{ptrs_mode} (ptrsp (R, ptrs_mode, "2000"))+
Σ_{frgt_mode} (frgt (R, frgt_mode, "2000")))/ (Msec_per_year*t_step))* global_init_e;

init_infra (R) =

$((\text{elec\_dem\_reg}(R,\text{"2000"}) + \text{heat\_dem\_reg}(R,\text{"2000"}) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, \text{"2000"})) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_i};$

init_plant (R) =
$((\text{elec\_dem\_reg}(R,\text{"2000"}) + \text{heat\_dem\_reg}(R,\text{"2000"}) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, \text{"2000"})) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_p};$

init_supply (R) =
$((\text{elec\_dem\_reg}(R,\text{"2000"}) + \text{heat\_dem\_reg}(R,\text{"2000"}) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, \text{"2000"})) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, \text{"2000"}))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_init\_s};$

mx_decay_abs_oil (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_mx\_decay\_oil};$

max_exp (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp};$

max_exp_bio (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_b};$

max_exp_p (e_in, e_out, type, R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_p};$

max_inv_infra (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_max\_exp\_i};$

mx_decay_abs (R, t) =
$((\text{elec\_dem\_reg}(R, t) + \text{heat\_dem\_reg}(R, t) + \Sigma_{\text{ptrs\_mode}}(\text{ptrsp}(R, \text{ptrs\_mode}, t)) + \Sigma_{\text{frgt\_mode}}(\text{frgt}(R, \text{frgt\_mode}, t))) / (\text{Msec\_per\_year} * \text{t\_step})) * \text{global\_mx\_decay};$

supply_pot (primary, R, t) = supply_pot_0 (primary, REGIONS); [EJ]

Variables

The variables are presented in alphabetical order. See Section 4 for more details. Variables written in red indicate main variables, i.e. the variables are not calculated from any other decision variables. All variables are of type continuous.

agg_emis	Total emissions	[MtC]
annual_cost (R, t)	Sum of all annual costs in the model	[GUSD]
atm_ccont (T_all)	Atmospheric CO_2 concentration from the carbon cycle module	[ppm]
c_emission_global (t)	Annual global emissions	[MtC]
c_emission (R, t)	Annual emissions per region	[MtC]
c_capt_fos (R, t)	Annual amount of carbon captured from fossil fuels	[MtC]
c_capt_bio (R, t)	Annual amount of carbon captured from biomass	[MtC]
c_capt_tot (R, t)	Annual amount of carbon captured from fossil fuels and biomass	[MtC]

c_capt_agg	Total amount of captured carbon for all regions and time steps	[MtC]
cap_invest (R, e_in, e_out, type, t)	New investments in energy conversion technologies	[TW]
capacity (R, e_in, e_out, type, t)	Aggregated capacity stock energy conversion techn	[TW]
carb_ctrb (T_all, T_all_copy)	Carbon contribution generated by the carbon cycle module	[MtC]
cg_heat (R, t)	The amount of heat produced using co-generation technologies	[EJ/yr]
cost_c_bio_trsp (R, t)	Additional transportation cost if applying CCS on bioenergy	[GUSD]
cost_c_strg (R, t)	Cost for storing carbon	[GUSD]
cost_cap (R, t)	Cost for investing in energy conversion technologies	[GUSD]
cost_fuel (R, t)	Cost for extracting primary energy sources	[GUSD]
en_conv (R, e_in, e_out, type, t)	The amount of energy converted from e_in to e_out expressed in primary energy terms.	[EJ/yr]
energy_deliv (R, e_out, t)	The amount of energy that meets the demand after import/export of H2, CTL/GTL and BTL.	[EJ/yr]
energy_prod (R, e_out, t)	The amount of energy carriers coming out of the conversion module in secondary energy (demand) terms, i.e. after energy losses.	[EJ/yr]
elec_decarb (R, t)	Additional electricity demand if the model chose to use CCS	[EJ/yr]
elec_trsp (R, t)	Electricity for the transportation sector	[EJ/yr]
eng_invest (R, trsp_fuel, e_type, vehicle, t)	New investments in engines/vehicles	[Gvehicles]
engines (R, trsp_fuel, e_type, vehicle, t)	Aggregated capacity stock engines/vehicles	[Gvehicles]
extra_ship_fuel (R, trsp_fuel, ic_fc, ship_mode, t)	Additional ship fuel since ships cannot run on elec	[EJ/yr]
exp_prim (R, fuels, t)	The amount of primary energy sources exported from a region	[EJ/yr]
exp_sec (R, sec, t)	The amount of secondary energy sources exported from a region	[EJ/yr]
heat_decarb (R, t)	Additional heat demand if the model chose to use CCS	[EJ/yr]
imp_prim (R, fuels, t)	The amount of primary energy sources imported to a region	[EJ/yr]
imp_prim_from (R_imp, R_exp, fuels, t)	Present primary energy trading flows	[EJ/yr]
imp_sec (R, sec, t)	The amount of secondary energy sources imported to a region	[EJ/yr]
imp_sec_from (R_imp, R_exp, sec, t)	Present secondary energy trading flows	[EJ/yr]
infra (R, synfuel_gas, t)	Aggregated capacity infrastructure	[TW]
infra_invest (R, trsp_fuel, t)	New investments in infrastructure	[TW]
OM_cost (R, t)	Operation and maintenance cost	[GUSD]
supply_1 (R, primary, t)	The amount of primary energy extracted in each region	[EJ/yr]
supply_2 (R, second_in, t)	The amount of energy that goes back into the energy conversion box to be converted a second time (H2 och ELEC).	[EJ/yr]
supply_tot (R, primary, t)	The amount of primary energy used in a region after import/export	[EJ/yr]
tax (R, t)	Cost if applying carbon taxes to the model	[GUSD]
tot_cost	Total cost for the entire energy system	[GUSD]
tot_CSP (t)	The total amount of energy from concentrating solar power (CSP)	[EJ/yr]
tot_trspcost_prim (R, t)	Cost for trading primary energy sources	[GUSD]
tot_trspcost_sec (R, t)	Cost for trading secondary energy sources	[GUSD]
trsp_energy (R, trsp_fuel, e_type, trsp_mode, t)	Secondary energy for the transportation sector	[EJ/yr]

Equations and functions

Note that the equations are not presented in the same order in this Appendix as in the main report. All equations do, however, have the same numbers.

Objective function

Minimize $\sum_{R,t}$ (t_step * (cost_fuel (R, t) +cost_cap (R, t) + OM_cost (R, t) + cost_c_strg (R, t) + cost_c_bio_trsp (R, t) +tot_trspcost_prim (R, t) + tot_trspcost_sec (R, t) + tax (R, t)) /

$(1+r)^{10\cdot(ord(t)-1)}$)

(59, 60, 61)

Cost calculations

Extraction cost on primary energy sources

cost_fuel (R, t) = $\sum_{fuels}$ (supply_1 (R, fuels, t) * price (fuels, R)) (51)

Investment cost and O&M cost

cost_cap (R, t) =
Σ $_{\text{e\_in, e\_out, type}}$ (cap_invest (R, e_in, e_out, type, t) * cost_inv_mod (e_in, e_out, type, t)) +
Σ $_{\text{road\_fuel, e\_type, vehicle}}$ (eng_invest (R, road_fuel, e_type, vehicle, t) *
cost_eng_mod (road_fuel, e_type, vehicle, t)) +
Σ $_{\text{synfuel\_gas}}$ (infra_invest (R, synfuel_gas, t) * cost_infra_mod (synfuel_gas)) (52)

OM_cost (R, t) =
Σ $_{\text{e\_in, e\_out, type}}$ (OM_cost_fr (e_in, e_out) * cost_inv_mod (e_in, e_out, type, t) *
en_conv (R, e_in, e_out, type, t) * effic (e_in, type, e_out, t) / Msec_per_year/0.7) (53)

Costs for carbon storage and CO_2 tax

cost_c_strg (R, t) = c_capt_fos (R, t) * cost_strg_fos + c_capt_bio (R, t) *
cost_strg_bio (54)

cost_c_bio_trsp (R, t) = Σ $_{\text{e\_out, c\_capt}}$ (en_conv (R, "bio", e_out, c_capt, t)) *
c_bio_trspcost (55)

tax (R , t) = c_emission (R, t)* c_tax (R, t) (56)

Import costs

tot_trspcost_prim (R, t) =
Σ $_{\text{fuels, R\_exp}}$ (imp_prim_from (R_imp, R_exp, fuels, t) * (imp_cost (fuels) +
distance (R_imp, R_exp) * imp_cost_lin (fuels))) (57)

tot_trspcost_sec (R, t) =
Σ $_{\text{sec, R\_exp}}$ (imp_sec_from (R_imp, R_exp, sec, t) *
(imp_cost2 (sec) + distance (R_imp, R_exp) * imp_cost_lin2 (sec))) (58)

Energy balances

Primary energy supply including import and export of primary energy sources

supply_pot (primary, R, t) ≥ supply_1 (R, primary, t) (1)

Σ $_{\text{t}}$ (t_step*supply_1 (R, fossil, t)) ≤ supply_pot_0 (fossil, R) (2)

supply_tot (R, fuels, t) = supply_1 (R, fuels, t) + imp_prim (R, fuels, t) –
exp_prim (R, fuels, t) (3)

supply_tot (R, nonfuels, t) = supply_1 (R, nonfuels, t) (4)

Energy conversion including import and export of energy carriers

$$\text{supply\_tot}\ (R, \text{primary}, t) = \Sigma_{\text{type, e\_out}} \left(\text{en\_conv}\ (R, \text{primary}, \text{e\_out}, \text{type}, t)\right) \quad (5)$$

$$\text{tot\_CSP}\ (t) = \Sigma_{R} \left(\text{supply\_1}\ (R, \text{"solar\_csp"}, t)\right); \quad (6)$$

$$\text{energy\_prod}\ (R, \text{nontrade\_sec}, t) = \Sigma_{\text{type, e\_in}} \left(\text{en\_conv}\ (R, \text{e\_in}, \text{nontrade\_sec}, \text{type}, t) * \text{effic}\ (\text{e\_in}, \text{type}, \text{nontrade\_sec}, t)\right) \quad (7)$$

$$\text{energy\_prod}\ (R, \text{sec}, t) = \Sigma_{\text{type, e\_in}} \left(\text{en\_conv}\ (R, \text{e\_in}, \text{sec}, \text{type}, t) * \text{effic}\ (\text{e\_in}, \text{type}, \text{sec}, t)\right) + \text{imp\_sec}\ (R, \text{sec}, t) - \text{exp\_sec}\ (R, \text{sec}, t) \quad (8)$$

Energy carriers that can be converted to other energy carriers

$$\text{supply\_2}\ (R, \text{second\_in}, t) \geq \Sigma_{\text{type, e\_out}} \left(\text{en\_conv}\ (R, \text{second\_in}, \text{e\_out}, \text{type}, t)\right) \quad (9)$$

$$\text{supply\_2}\ (R, \text{"H2"}, t) \leq \text{energy\_prod}\ (R, \text{"H2"}, t) - \text{energy\_deliv}\ (R, \text{"H2"}, t) \quad (10)$$

$$\text{supply\_2}\ (R, \text{"elec"}, t) \leq \text{energy\_prod}\ (R, \text{"elec"}, t) - \text{energy\_deliv}\ (R, \text{"elec"}, t) \quad (11)$$

Import and export balances

$$\text{imp\_prim}\ (\text{R\_imp}, \text{fuels}, t) = \Sigma_{\text{R\_exp}} \left(\text{imp\_prim\_from}\ (\text{R\_imp}, \text{R\_exp}, \text{fuels}, t)\right) \quad (30)$$

$$\text{exp\_prim}\ (\text{R\_exp}, \text{fuels}, t) = \Sigma_{\text{R\_imp}} \left(\text{imp\_prim\_from}\ (\text{R\_imp}, \text{R\_exp}, \text{fuels}, t)\right) \quad (31)$$

$$\text{imp\_sec}\ (\text{R\_imp}, \text{sec}, t) = \Sigma_{\text{R\_exp}} \left(\text{imp\_sec\_from}\ (\text{R\_imp}, \text{R\_exp}, \text{sec}, t)\right) \quad (32)$$

$$\text{exp\_sec}\ (\text{R\_exp}, \text{sec}, t) = \Sigma_{\text{R\_imp}} \left(\text{imp\_sec\_from}\ (\text{R\_imp}, \text{R\_exp}, \text{sec}, t)\right) \quad (33)$$

Balancing cogeneration and energy carriers intermediate step

$$\text{cg\_heat}\ (R, t) = \Sigma_{\text{cg\_e\_in, cg\_type, cg\_e\_out}} \left(\text{en\_conv}\ (R, \text{cg\_e\_in}, \text{cg\_e\_out}, \text{cg\_type}, t) * \text{heat\_effic}\ (\text{cg\_e\_in}, \text{cg\_type}, \text{cg\_e\_out})\right) \quad (12)$$

$$\text{energy\_deliv}\ (R, \text{"heat"}, t) \leq \text{energy\_prod}\ (R, \text{"heat"}, t) + \text{cg\_heat}\ (R, t) \quad (13)$$

Balancing heat and electricity demand

$$\text{energy\_deliv}\ (R, \text{"heat"}, t) \geq \text{heat\_dem\_reg}\ (R, t) + \text{heat\_decarb}\ (R, t) \quad (14)$$

$$\text{energy\_deliv}\ (R, \text{"elec"}, t) \geq \text{elec\_dem\_reg}\ (R, t) + \text{elec\_decarb}\ (R, t) + \text{elec\_trsp}\ (R, t) \quad (15)$$

Balancing demand on fuels for transport

$\Sigma_{\text{trsp\_mode, e\_type}}$ (trsp_energy (R, trsp_fuel_nonel, e_type, trsp_mode, t)) =
energy_deliv (R, trsp_fuel_nonel, t) (16)

elec_trsp (R, t) = $\Sigma_{\text{trsp\_mode, e\_type}}$ (trsp_energy (R,"elec", e_type, trsp_mode, t)) (17)

trsp_dem (R, trsp_mode, t) =
$\Sigma_{\text{trsp\_fuel, e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t) *
trsp_conv (trsp_fuel, e_type, trsp_mode, t)) (18)

Transport balances and options

Fuel fraction for PHEVs

$\Sigma_{\text{road\_fuel\_liquid}}$ (trsp_energy (R, road_fuel_liquid, "phev", vehicle, t) *
trsp_conv (road_fuel_liquid, "phev", vehicle, t)) / (1 – elec_frac_phev(vehicle)) =
trsp_energy (R, "elec", "phev", vehicle, t)* trsp_conv ("elec", "phev", vehicle, t) /
(elec_frac_phev (vehicle)) (19)

Balance fuels to the number of cars and trucks

trsp_energy (R, road_fuel, non_phev, vehicle, t) ≤
engines (R, road_fuel, non_phev, vehicle, t) / num_veh (R, vehicle, t) *
trsp_dem (R, vehicle, t) / (trsp_conv (road_fuel, non_phev, vehicle, t) + 0.001) (20)

trsp_energy (R, road_fuel_liquid, "phev", vehicle, t) ≤
engines (R, road_fuel_liquid, "phev", vehicle, t) / num_veh (R, vehicle, t) *
(1 – elec_frac_phev (vehicle)) * trsp_dem (R, vehicle, t) /
(trsp_conv (road_fuel_liquid, "phev", vehicle, t) + 0.001) (21)

Balance fuels to buses and ships

trsp_energy (R, trsp_fuel, e_type,"p_bus", t) =
trsp_energy (R, trsp_fuel, e_type, "f_road", t) * trsp_dem (R,"p_bus", t) /
trsp_dem (R,"f_road", t) (22)

trsp_energy (R, trsp_fuel, ic_fc, ship_mode, t) =
(trsp_energy (R, trsp_fuel, ic_fc, "f_road", t) + extra_ship_fuel (R, trsp_fuel, ic_fc, ship_mode, t)) *
trsp_dem (R, ship_mode, t) / trsp_dem (R,"f_road", t) (23)

$\Sigma_{\text{trsp\_fuel, ic\_fc}}$ (extra_ship_fuel (R, trsp_fuel, ic_fc, ship_mode, t)) =
$\Sigma_{\text{trsp\_fuel, hev\_phev\_bev}}$ (trsp_energy (R, trsp_fuel, hev_phev_bev, "f_road", t)) (24)

Limitations on heavy electric vehicles

$$\Sigma_{\text{road\_fuel\_liquid}} \left(\text{trsp\_energy}(R, \text{road\_fuel\_liquid}, \text{hybrids}, \text{"f\_road"}, t) * \text{trsp\_conv}(\text{road\_fuel\_liquid}, \text{hybrids}, \text{"f\_road"}, t) / \left(1 - \text{elec\_frac\_phev}(\text{"f\_road"})\right)\right) \leq \text{frac\_phev\_trucks} * \text{trsp\_dem}(R, \text{"f\_road"}, t) \quad (25)$$

$$\text{trsp\_energy}(R, \text{"elec"}, \text{"BEV"}, \text{"f\_road"}, t) * \text{trsp\_conv}(\text{"elec"}, \text{"BEV"}, \text{"f\_road"}, t) \leq \text{frac\_bev\_trucks} * \text{trsp\_dem}(R, \text{"f\_road"}, t) \quad (26)$$

$$\Sigma_{\text{road\_fuel\_liquid}} \left(\text{trsp\_energy}(R, \text{road\_fuel\_liquid}, \text{hybrids}, \text{"p\_bus"}, t) * \text{trsp\_conv}(\text{road\_fuel\_liquid}, \text{hybrids}, \text{"p\_bus"}, t) / \left(1 - \text{elec\_frac\_phev}(\text{"f\_road"})\right)\right) \leq \text{frac\_phev\_buses} * \text{trsp\_dem}(R, \text{"p\_bus"}, t) \quad (27)$$

$$\text{trsp\_energy}(R, \text{"elec"}, \text{"BEV"}, \text{"p\_bus"}, t) * \text{trsp\_conv}(\text{"elec"}, \text{"BEV"}, \text{"p\_bus"}, t) \leq \text{frac\_bev\_buses} * \text{trsp\_dem}(R, \text{"p\_bus"}, t) \quad (28)$$

Investments and depreciation

Investments in conversion plants, vehicles and infrastructure

$$\text{capacity}(R, \text{e\_in}, \text{e\_out}, \text{type}, \text{init\_year}) = \text{init\_cap}(\text{e\_in}, \text{e\_out}, \text{type}, R) + \text{t\_step} * \text{cap\_invest}(R, \text{e\_in}, \text{e\_out}, \text{type}, \text{init\_year}) \quad (34)$$

$$\text{capacity}(R, \text{e\_in}, \text{e\_out}, \text{type}, t+1) = \text{t\_step} * \text{cap\_invest}(R, \text{e\_in}, \text{e\_out}, \text{type}, t+1) + \text{capacity}(R, \text{e\_in}, \text{e\_out}, \text{type}, t) * \exp\left(\text{t\_step} * \log\left(1 - 1/\text{life\_plant}(\text{e\_in}, \text{e\_out}, \text{type})\right)\right) \quad (35)$$

$$\text{engines}(R, \text{trsp\_fuel}, \text{e\_type}, \text{vehicle}, t+1) = \text{t\_step} * \text{eng\_invest}(R, \text{trsp\_fuel}, \text{e\_type}, \text{vehicle}, t+1) + \text{engines}(R, \text{trsp\_fuel}, \text{e\_type}, \text{vehicle}, t) * \exp\left(\text{t\_step} * \log\left(1 - 1/\text{life\_eng}(\text{trsp\_fuel}, \text{e\_type}, \text{vehicle})\right)\right) \quad (36)$$

$$\text{infra}(R, \text{synfuel\_gas}, t+1) = \text{t\_step} * \text{infra\_invest}(R, \text{synfuel\_gas}, t+1) + \text{infra}(R, \text{synfuel\_gas}, t) * \exp\left(\text{t\_step} * \log\left(1 - 1/\text{life\_infra}(\text{synfuel\_gas})\right)\right) \quad (37)$$

Use limited by capacity

$$\text{en\_conv}(R, \text{e\_in}, \text{e\_out}, \text{type}, t) * \text{effic}(\text{e\_in}, \text{type}, \text{e\_out}, t) \leq \text{capacity}(R, \text{e\_in}, \text{e\_out}, \text{type}, t) * \text{lf}(\text{e\_in}, \text{type}, \text{e\_out}, R) * \text{Msec\_per\_year} \quad (38)$$

$$\text{energy\_deliv}(R, \text{synfuel\_gas}, t) \leq \text{infra}(R, \text{synfuel\_gas}, t) * \text{lf\_infra}(\text{synfuel\_gas}) * \text{Msec\_per\_year} \quad (39)$$

Carbon capture and storage (CCS) and limitations

$$\text{c\_capt\_fos}(R, t) \leq \Sigma_{\text{fossil, e\_out, c\_capt}} \left(\text{en\_conv}(R, \text{fossil}, \text{e\_out}, \text{c\_capt}, t) * \text{emis\_fact}(\text{fossil}) * \text{fos\_capt\_effic}\right) \quad (42)$$

c_capt_bio (R, t) =
Σ_{e_out, c_capt} (en_conv (R, "bio", e_out, c_capt, t) * emis_fact ("bio") * bio_capt_effic) (43)

c_capt_tot (R, t) = c_capt_bio (R, t) + c_capt_fos (R, t) (44)

c_capt_agg = $\Sigma_{R, t}$ (c_capt_tot (R, t) * t_step) (45)

Σ_R (c_capt_tot (R, t+1)) $\leq$ Σ_R (c_capt_tot (R, t)) + c_stor_maxgr * t_step (46)

Σ_{fuels, c_capt} (en_conv (R, fuels, "heat", c_capt, t)) $\leq$ c_capt_heat_fr * heat_dem_reg (R, t) (47)

elec_decarb (R, t) = Σ_{fuels} (en_conv (R, fuels, "heat", "CCS", t) * dec_elec (fuels)) (48)

Allowed energy conversion paths

$\Sigma_{R, t}$ (en_conv (R, e_in, e_out, type, t))*flow_matrix (e_in, type, e_out) = 0; (29)

Emission calculations

c_emission (R, t) = Σ_{fossil} (emis_fact (fossil) * supply_tot (R, fossil, t)) –
c_capt_tot (R, t) – exp_sec (R,"CTL/GTL", t) * emis_fact_syn +
imp_sec (R,"CTL/GTL", t) * emis_fact_syn; (40a)

c_emission_global (R, t) = Σ_R (R, c_emission (R, t)); (40b)

Σ_R (c_emission (R, t_h)) = hist_fos_emis (t_h); (40c)

agg_emis = $\Sigma_{R, t}$ (t_step * c_emission (R, t)) (41)

Carbon cycle model

carb_ctrb (T_all, T_all_copy) = (fut_luc_emis (T_all_copy) – fut_biota_sinks (T_all_copy) +
Σ_R c_emission (R, T_all_copy)) * IRfunc (T_all, T_all_copy) (49)

atm_ccont (T_all) = pre_ind_ccont +
($\Sigma_{T\_all\_copy}$ carb_ctrb (T_all, T_all_copy)) * 0.28/600*10 (50)

Restrictions, limitations and adjustments

Chose CCS/CSP scenarios (activate when wanted)

tot_CSP.up (t) = 0; (62)

c_capt_tot.up (R, t) = 0; (63)

Limitations on co-generation and intermittent energy

$\Sigma_{\text{cg\_e\_in, cg\_type}}$ (en_conv (R, cg_e_in, "elec", cg_type, t) *
effic (cg_e_in, cg_type, "elec", t)) ≤ cogen_fr_e * elec_dem_reg (R, t); (64)

$\Sigma_{\text{cg\_e\_in, cg\_type, cg\_e\_out}}$ (en_conv (R, cg_e_in, cg_e_out, cg_type, t) *
heat_effic (cg_e_in, cg_type, cg_e_out)) ≤ cogen_fr_h * heat_dem_reg (R, t); (65)

en_conv (R,"solar", "elec", "0", t) + en_conv (R,"wind", "elec", "0", t) ≤
interm_fr * energy_deliv (R, "elec", t); (66)

Initialization of capacity

infra.fx (R, synfuel_gas, init_year) = 0; (67)

engines.fx (R, trsp_fuel, e_type, vehicle, init_year) = 0; (68)

engines.fx (R,"petro", "0", "p_car", init_year) =
num_veh (R,"p_car", init_year) + 0.01; (69)

engines.fx (R,"petro", "0", "f_road", init_year) =
num_veh (R,"f_road", init_year) + 0.01; (70)

Limitations on technology growth and depreciation

capacity (R, e_in, e_out, type, t+1) ≤
capacity (R, e_in, e_out, type, t) * exp (t_step*log (1+cap_g_lim)) + init_plant (R); (71)

capacity (R, e_in, e_out, type, t+1) ≤ capacity (R, e_in, e_out, type, t) +
max_exp_p (e_in, e_out, type, R, t) / (lf (e_in, type, e_out, R) + 0.0001); (72)

infra (R, synfuel_gas, t+1) ≤
infra (R, synfuel_gas, t) * exp (t_step* log (1+infra_g_lim))+ init_infra (R); (73)

infra (R, synfuel_gas, t+1) ≤ infra (R,synfuel_gas, t) +
max_inv_infra (R, t)/ lf_infra (synfuel_gas); (74)

engines (R, trsp_fuel, e_type, vehicle, t+1) ≤
engines (R, trsp_fuel, e_type, vehicle, t)* exp (t_step * log (1+ eng_g_lim))+ init_eng (R); (75)

supply_1 (R, fuels, t+1) ≤
supply_1 (R, fuels, t) * exp (t_step * log (1+ supply_g_lim)) +

init_supply (R) * Msec_per_year; (76)

supply_1 (R, fossil, t+1) $\leq$ supply_1 (R, fossil, t) + max_exp (R, t); (77)

supply_1 (R,"bio", t+1) $\leq$ supply_1 (R,"bio", t) + max_exp_bio (R, t); (78)

$\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, t+1)) $\leq$
3* $\Sigma_{\text{type, e\_out}}$ (en_conv (R,"wind", e_out, type, t)); (79)

en_conv (R, "oil", "petro", "0", t+1) $\geq$
en_conv (R, "oil", "petro", "0", t) * mx_decay_frac_oil – mx_decay_abs_oil (R, t); (80)

$\Sigma_{\text{e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t+1)) $\geq$
$\Sigma_{\text{e\_type}}$ (trsp_energy (R, trsp_fuel, e_type, trsp_mode, t)) *
mx_decay_frac – mx_decay_abs (R, t); (81)

en_conv (R, e_in, e_out, type, t+1) $\geq$
en_conv_decr_lim * en_conv (R, e_in, e_out, type, t) – en_conv_dis (R, t); (82)

Technology limitations, restrictions and adjustments

trsp_energy.fx (R,"elec", "0", "p_air", t) =
high_speed_train (R, t)* trsp_dem (R,"p_air", t) / trsp_conv ("elec", "0", "p_air", t); (83)

c_capt_agg.up = 600000; (84)

c_capt_tot.up (R, t_1990_2010) = 0; (85)

energy_deliv.fx (R,"air_fuel", t_1990_2010 = 0; (86)

en_conv.up (R, "h2", "air_fuel", type, t) = 0; (87)

trsp_energy.up (R, trsp_fuel, "fc", trsp_mode, t_1990_2020) = 0; (88)

engines.fx(R, trsp_fuel, hybrids, vehicle, t_1990_2010) = 0; (89)

supply_tot.fx (R, "nuclear", t_2010_2140) =

R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
EJ	9.53	11	4.03	2.74	0.14	0.25	0.23	0	0.47	0.38

(90)

en_conv.up (R,"solar", "heat", "0", t) =

R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
EJ	0.32	0.52	0.13	0.28	0.49	0.31	0.56	1.42	0.49	1.29

(91)

en_conv.lo ("SAS","bio","heat","0", t) =

t	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120
EJ	15	15	15	15	15	15	15	12	10	8	6	4	2

(92)

en_conv.lo ("CPA","bio","heat","0", t) =

t	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120
EJ	15	15	15	15	15	15	15	12	10	8	6	4	2

(93)

supply_tot (R, "oil", "2010") $\geq$ 0.9 * supply_tot (R, "oil", "2000"); (94)

supply_tot (R, "NG", "2010") $\geq$ 0.9 * supply_tot (R, "NG", "2000"); (95)

$\sum_{type,\ e\_out}$ (en_conv (R,"wind", e_out, type, "2010")) $\leq$
2* $\sum_{type,\ e\_out}$ (en_conv (R,"wind", e_out, type, "2000")); (96)

The increase on hydro power between year 2000 and 2010 may not exceed 50%

$\sum_{type,\ e\_out}$ (en_conv (R,"hydro", e_out, type, "2010")) $\leq$
1.5* $\sum_{type,\ e\_out}$ (en_conv (R,"hydro", e_out, type, "2000")); (97)

max_exp_bio ("LAM", t) = 4* ((elec_dem_reg ("LAM", t) + heat_dem_reg ("LAM", t) +
$\sum_{ptrs\_mode}$ (ptrsp ("LAM", ptrs_mode, t))) + $\sum_{frgt\_mode}$ (frgt ("LAM", frgt_mode, t))) /
(Msec_per_year*t_step)) * global_max_exp_b; (98)

max_exp_bio ("AFR", t) = 2* ((elec_dem_reg ("AFR", t) + heat_dem_reg ("AFR", t) +
$\sum_{ptrs\_mode}$ (ptrsp ("AFR", ptrs_mode, t)) + $\sum_{frgt\_mode}$ (frgt ("AFR", frgt_mode, t))) /
(Msec_per_year*t_step)) * global_max_exp_b; (99)

Correcting results for 1990 and 2000

c_emission.fx (R, t) =

t \ R	NAM	EUR	PAO	FSU
1990	1596	1256	464	999
2000	1931	1247	603	690
2010	1875	1271	508	854

(100)

supply_tot.lo (R, e_in, “1990”) =

e_in \ R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
coal	20	20	5.5	12	3.1	2.8	0.7	0.13	22.9	4.1
oil	38	28	14	17	3.8	3.4	6.6	6.1	4.8	5.1
NG	21	12	2.5	23	1.3	1	2.3	3.2	0.66	1.4
nuclear	7.5	8.8	2.8	2.3	0.09	0.17	0.1	0	0	0.26
hydro	2.1	1.7	0.4	0.8	0.2	0.22	1.3	0.05	0.46	0.32
bio	3.2	2.2	0.4	0.8	8.1	5.1	3.2	0.04	8.4	7.6

(101)

supply_tot.lo (R, e_in, “2000”) =

e_in \ R	NAM	EUR	PAO	FSU	AFR	PAS	LAM	MEA	CPA	SAS
coal	24	14.8	7.5	7	3.75	4.17	0.9	0.33	27.6	6.26
oil	45	30	17	8	4.55	5.74	9.1	9.46	9.65	8.6
NG	27	17.3	4.5	20	2.16	2.12	3.6	6.74	1.18	3.17
nuclear	9.5	10.5	4	2.4	0.14	0.25	0.13	0	0.18	0.38
hydro	2.3	2.1	0.5	0.8	0.26	0.24	1.99	0.05	0.8	0.36
bio	3.9	3.1	0.7	0.5	10.37	5.88	3.26	0.04	8.98	8.82

(102)

imp_prim.lo (R,"oil", t) =

t \ R	NAM	EUR	PAO
2000	13	18	9.5
2010	17	24	10
2020	17		

(103)

exp_prim.lo (R,"oil", t) =

t \ R	MEA
2000	44.5
2010	49

(104)

exp_prim.up (R,"oil", t) =

t \ R	NAM	EUR	PAO
2000	0	0	0
2010	0	0	0

(105)

Carbon emission scenarios

c_tax (R, t) = 0; (106)

c_emission_global.up (t) =

t	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130-2140
400	8936	8063	6463	4804	3525	2705	2240	1994	1878	1826	1824	1822	1820
450	8780	8297	7443	6467	5556	4770	4121	3596	3181	2849	2658	2502	2371
500	9072	9292	9092	8551	7812	6992	6195	5469	4837	4298	3886	3541	3250
550	9364	10287	10741	10635	10086	9214	8269	7342	6492	5746	5114	4580	4129

(107)

agg_emis.up = 360000; (not activated)

atm_ccont.up (”2100”) = 450; (not activated)

Appendix 3: Calculation of IRfunc

Calculating the values for parameter IRfunc

To facilitate the transformation of GET-RC 6.1 from GAMS into IBM ILOG OPL Development Studio, we have exchanged the calculation of parameter IRfunc into presenting the data of IRfunc in a table. For interested readers, we present the initial calculations made in GAMS. The parameter IRfunc determines the annual contribution to atmospheric carbon from each year's CO_2 emissions.

The impulse response function used in the climate module in GET follows a five box diffusion model. The boxes are in IRfunc separated by the set "coeff". The exponential fits (A and tao) to the different boxes are taken from the first row in Table 1 of Maier-Reimer and Hasselmann (1987).

To calculate the data for the parameter IRfunc in GAMS we need to define additional sets and parameters.

Sets

coeff	(0, 1, 2, 3, 4) Steps used in the carbon cycle model to calculate IRfunc.	[-]

Parameters

A (coeff)	Amplitude in IRfunc. Relative capacity of other reservoirs. Exponential fits to the computed impulse response function.	[-]
tao (coeff)	Exponential fits to the computed impulse response function.	[yr]

The following is the expression for how the data in the impulse response function, IRfunc, is calculated

IRfunc (T_all, T_all_copy) =

$$\Sigma_{coeff} \left(\left(\text{SIGN}\left(\text{ord}(T\_all) - \text{ord}(T\_all\_copy) + 1/2\right) + 1\right)/2\right) * A(\text{coeff}) * \exp\left(-10*\left(\left(\text{SIGN}\left(\text{ord}(T\_all) - \text{ord}(T\_all\_copy) + 1/2\right) + 1\right)/2\right) * \left(\text{ord}(T\_all) - \text{ord}(T\_all\_copy)\right) / tao(\text{coeff})\right) \quad [-]$$

SIGN is a GAMS function here used to make sure that atmospheric CO_2 contribution only applies to time steps after the year of a certain CO_2 emission. SIGN(x) returns 1 if x > 0 as well as if x < 0 but returns 0 if x = 0.

When T_all equals T_all_copy, the code "SIGN (ord (T_all) – ord (T_all_copy) + 1/2)" generates 0+1/2 = 0.5 and since 0.5>0 the SIGN function will generate the result 1, which in turn will generate (1+1)/2 =1 when following IRfunc directly after the SIGN function. Further when T_all equals T_all_copy the expression exp(x) will be exp(0)=1. This leads to that when T_all equals T_all_copy the impulse response function will be the sum of all A-values, since
$IRfunc=SUM_{coeff}(1*A_{coeff}*\exp(-10*1*0/tao_{coeff})) = SUM_{coeff}(A_{coeff}) = 0.131+0.201+0.321+0.249+0.098 = 1$

When T_all < T_all_copy for example when T_all=1800 and T_all_copy=1810, i.e. when ord(T_all)=1 and ord(T_all_copy)=2, the code "SIGN (ord (T_all) – ord (T_all_copy) + 1/2)" generate 1-2+1/2 = -0.5 and since SIGN(x) < 0 the SIGN function will generate the result 1. The IRfunction will then become:
$IRfunc=SUM_{coeff}((1+1)/2*A_{coeff}*\exp(-10*1*(-1)/tao_{coeff})) = SUM_{coeff}(A_{coeff}*\exp(10/tao_{coeff}))$.

When T _all > T_all_copy for example when T_all=1810 and T_all_copy=1800 (i.e. when ord(T_all)=2 and ord(T_all_copy)=1 the code "SIGN (ord (T_all) – ord (T_all_copy) + 1/2)" generate 2-1+1/2 = 1.5 and since SIGN(x) > 0 the SIGN function will generate the result 1. The IRfunction will then become:
$IRfunc=SUM_{coeff}((1+1)/2*A_{coeff}*\exp(-10*1*1/tao_{coeff})) = SUM_{coeff}(A_{coeff}*\exp(-10/tao_{coeff}))$.
Remember that exp(-x) will be close to zero and closer the higher the x leading to that the result always will be zero when T_all > T_all_copy. Since the impulse response function is a parameter whose values are calculated in the model run, IRfunc (T_all, T_all_copy) can of course instead be included as a table. We have therefore chosen to use a parameter IRfunc with data presented in Appendix 1.

Data for the parameters tao and A

	0	1	2	3	4
tao (coeff)	10000	363	73.6	17.3	1.9
A (coeff)	0.131	0.201	0.321	0.249	0.098

Appendix 4: Mathematical description

Note that this mathematical description is identical to the version presented in the supporting information to the scientific paper published in the special issue on decarbonised economy in the Journal Sustainability (Grahn et al., 2013). The equation numbers are therefore not identical compared to elsewhere in this report.

1. Mathematical Formulation of Model

This model is formulated as a Linear Program (LP). The objective is to minimize the cost to society based on the available supply and required demand to meet global sustainability targets. Mathematically describing the relationships between energy sources and conversion of these sources to meet the demands from the various sectors involves the introduction of numerous inputs and constraints, as presented below.

1.1. Input

In this section, we introduce the sets and input parameters such as the type of energy supply, the type of energy conversion plants, and the demand from different transportation modes. The parameters capture costs associated with different investments and storage, estimation of future emissions, the amount of energy produced by different sources in different regions, etc.

1.1.1. Sets First we describe the *Energy* sets of all energy options for both primary energy sources and secondary energy carriers.

E = all energy sources and carriers.
$E^I \subset E$ = all energy sources that be converted (both primary and secondary).
$E^{ICG} \subset E^I$ = energy sources that can be used for co-generation of heat and electricity.
$E^{IP} \subset E^I$ = primary energy sources.
$E^{IPT} \subset E^{IP}$ = primary energy sources that can be traded between regions.
$E^{IPF} \subset E^{IP}$ = primary energy sources that are fossil fuels.
$E^O \subset E$ = all energy carriers (i.e. converted from primary energy sources).
$E^{OT} \subset E^O$ = energy carriers that can be traded between regions.
$E^{OCG} \subset E^O$ = energy carriers that can be produced from co-generation.
$E^{OM} \subset E^O$ = energy carriers that can be used in the transportation sector.
$E^{OS} \subset E^{OM}$ = synthetic and gaseous fuels used in the transportation sector.
$E^{OR} \subset E^{OM}$ = energy carriers for the road transportation sector.
$E^{ORL} \subset E^{OR}$ = synthetic fuels and petroleum-based fuels for road transport.

Next, we describe the *Transportation Mode* sets:

M = all transportation modes
$M^P \subset M$ = passenger transportation modes
$M^V \subset M$ = passenger cars and road-based freight
$M^L \subset M$ = heavy road-based transportation modes
$M^F \subset M$ = all freight transportation modes
$M^B \subset M$ = sea-based freight transportation modes

The *Energy Conversion Plant* sets are as follows:

F = energy conversion plant types.
$F^{CC} \subset F$ = energy conversion plant types that can capture carbon.
$F^{CG} \subset F$ = energy conversion plant types that can be used for co-generation of electricity and heat.

The sets for *Engine Technologies* are below:

P = all powertrain technology types.
P^H = all hybrids and plug-in hybrids.
P^B = all internal combustion engines and fuel cells.

The following are the sets for *Regions and Time periods*:

R = all regions.
T^T = all time periods.
T = all time periods excluding the historical time periods.

1.1.2. Parameters

The parameters and their units are described below.

$\alpha^c_{e_i,e_o,f}$ = Life time of energy conversion plants of type $f \in F$ that convert energy in $e_i \in E^I$ to energy out $e_o \in E^O$. [yr]

$\alpha^i_{e_o}$ = Life time of infrastructure for $e_o \in E^{OS}$. [yr]

$\alpha^v_{e_o,p,m}$ = Life time of vehicle powertrains of type $p \in P$ using transportation mode $m \in M^V$ and transportation fuel $e_o \in E^{OM}$. [yr]

$b^c_{e_i,e_o,f,r}$ = Capacity in energy conversion plants of type $f \in F$ in region $r \in R$ that convert energy from $e_i \in E^I$ to $e_o \in E^O$, in the model's initial year. [TW]

$\tilde{b}^p_r$ = Small "kick-start" value when a new primary energy source is introduced in region $r \in R$. $[\frac{\text{EJ}}{\text{decade}}]$

$\tilde{b}^c_r$ = Small "kick-start" value when a new energy conversion technology is introduced in region $r \in R$. $[\frac{\text{TW}}{\text{decade}}]$

$\tilde{b}^i_r$ = Small "kick-start" value when new infrastructure is introduced in region $r \in R$. $[\frac{\text{TW}}{\text{decade}}]$

$\tilde{b}^v_r$ = Small "kick-start" value when a new powertrain technology is introduced in region $r \in R$. $[\frac{\text{Gvehicles}}{\text{decade}}]$

$\beta^c_{e_i,e_o,f,t}$ = Capacity factor (the share of maximum capacity that is used per year) for energy conversion plants of type $f \in F$ converting $e_i \in E^I$ to $e_o \in E^O$ in every time period $t \in T$. [-]

$\beta^i_{e_o}$ = Capacity factor for infrastructure for fuels $e_o \in E^{OS}$. [-]

$\gamma_{e_o,p,m,t}$ = A time $t \in T$ dependent relative powertrain efficiency factor that relates the powertrain $p \in P$ efficiency to conventional ICEV for transportation modes $m \in M$ and fuel $e_o \in E^{OM}$. [-]

$c^p_{e_i,r}$ = Extraction cost for primary energy sources $e_i \in E^{IPT}$ in regions $r \in R$. $[\frac{\text{GUSD}}{\text{EJ}}]$

$c^c_{e_i,e_o,f,t}$ = Investment cost, adjusted if assuming different investment and discount rates, for energy conversion plants of type $f \in F$ that convert $e_i \in E^I$ to $e_o \in E^O$ in time period $t \in T$. $[\frac{\text{GUSD}}{\text{MtC}}]$

$c^i_{e_o}$ = Investment cost, adjusted if assuming different investment and discount rates, for infrastructure distributing energy $e_o \in E^{OS}$. $[\frac{\text{GUSD}}{\text{MtC}}]$

$c^v_{e_o,p,t}$ = Investment cost, adjusted if assuming different investment and discount rates, for vehicles in transportation mode $m \in M^V$ with powertrain $p \in P$ using energy $e_o \in E^{OR}$ in time period $t \in T$. $[\frac{\text{GUSD}}{\text{MtC}}]$

$c^{pt}_{e_i}$ = Cost for transportation of primary energy sources $e_i \in E^{IPT}$ when trading between regions. $[\frac{\text{GUSD}}{\text{EJ}}]$

$c^{st}_{e_o}$ = Cost for transportation of energy carriers $e_o \in E^{OT}$ when trading between regions. $[\frac{\text{GUSD}}{\text{EJ}}]$

$c^{\tilde{pt}}_{e_i}$ = Additional, distance depending, cost for transportation of primary energy sources $e_i \in E^{IPT}$ when trading between regions. $[\frac{\text{GUSD}}{\text{EJ}}]$

$c^{\tilde{st}}_{e_o}$ = Additional, distance depending, cost for transportation of energy carriers $e_o \in E^{OT}$ when trading between regions. $[\frac{\text{GUSD}}{\text{EJ}}]$

c^f = Cost for carbon storage from fossil CCS. $[\frac{\text{GUSD}}{\text{MtC}}]$

c^b = Cost for carbon storage from bioenergy CCS. $[\frac{\text{GUSD}}{\text{MtC}}]$

$c^{\tilde{b}}$ = Additional transportation cost applied to bioenergy CCS. $[\frac{\text{GUSD}}{\text{EJ}}]$

$c^t_{r,t}$ = Cost for emitting CO_2 (carbon tax) in region $r \in R$ and time period $t \in T$. $[\frac{\text{GUSD}}{\text{MtC}}]$

$d^e_{r,t}$ = Electricity demand for region $r \in R$ and time period $t \in T$. [EJ/yr]

$d^h_{r,t}$ = Heat demand for region $r \in R$ and time period $t \in T$. [EJ/yr]

$d^t_{r,m,t}$ = Energy demand for each transportation mode $m \in M$ in every region $r \in R$ and time period $t \in T$. [EJ/yr]

δ_{r_1,r_2} = Table of rough distances between regions $r_1 \in R$ and $r_2 \in R$ [km]

ε_t^b = Estimation of future natural CO_2 sinks in biota time periods $t \in T$. [MtC/yr]
ε_t^l = Estimation of future emissions from land use changes for periods $t \in T$. [MtC/yr]
ε_t^h = Historical fossil emissions for time periods $t \in T$. [MtC/yr]
ζ = Constant used in carbon cycle model. [-]
$\eta_{e_i,e_o,f,t}$ = Energy conversion efficiency when energy is converted from $e_i \in E^I$ to $e_o \in E^O$ in plants of type $f \in F$ in time period $t \in T$. [-]
η^{ccb} = Carbon capture efficiency in bioenergy CCS plants. [-]
η^{ccf} = Carbon capture efficiency in fossil CCS plants. [-]
$\eta_{e_i,e_o,f}^{cg}$ = The share of energy output that is heat when converting $e_i \in E^{ICG}$ to $e_o \in E^{OCG}$ in co-generation plants of type $f \in F^{CG}$. [-]
θ_{e_i} = Carbon dioxide emission factors for $e_i \in E^{IPT}$ $[\frac{\text{MtC}}{\text{EJ}}]$
θ^s = Carbon dioxide emission factor from the use of CTL/GTL. $[\frac{\text{MtC}}{\text{EJ}}]$
$\iota_{r,t}^p$ = Growth limit on extraction of primary energy sources for every region $r \in R$ and time period $t \in T$. $[\frac{\text{EJ}}{\text{decade}}]$
$\iota_{r,t}^b$ = Growth limit on biomass plantation for regions $r \in R$ and periods $t \in T$. $[\frac{\text{EJ}}{\text{decade}}]$
$\iota_{r,e_i,e_o,f,t}^c$ = Growth limit on energy conversion plants of type $f \in F$ that convert $e_i \in E^I$ to $e_o \in E^O$ for every region $r \in R$ and period $t \in T$. $[\frac{\text{TW}}{\text{decade}}]$
$\iota_{r,t}^i$ = Growth limit on infrastructure for regions $r \in R$ and periods $t \in T$. $[\frac{\text{TW}}{\text{decade}}]$
$\iota_{r,t}^{df}$ = Absolute number in order to reach zero when phasing out a transportation fuel for every region $r \in R$ and time period $t \in T$. $[\frac{\text{EJ}}{\text{decade}}]$
$\iota_{r,t}^{dc}$ = Absolute number in order to reach zero when phasing out a conversion technology for every $r \in R$ and time period $t \in T$. $[\frac{\text{EJ}}{\text{decade}}]$
ι^l = Max growth limit, in relative terms, on primary energy extraction, energy conversion capacity, infrastructure capacity, and vehicle stock. [-]
κ = Global growth limit on carbon storage capacity. $[\frac{\text{MtC}}{\text{decade}}]$
μ = Number of seconds per year expressed in millions. [Ms]
ξ^{im} = Max fraction of electricity produced from intermittent energy sources. [-]
ξ^{cge} = Max fraction of electricity produced in co-generation plants. [-]
ξ^{cgh} = Max fraction of heat produced in co-generation plants. [-]
ξ^{cc} = Max fraction of heat produced in CCS plants. [-]
ξ^{dc} = Min fraction of previous time step's energy conversion. [-]
ξ^{df} = Min fraction of previous time step's transportation fuels. [-]
ξ_{e_i,e_o}^{om} = Operation and maintenance cost as fraction of investment cost for energy conversion plants that converts $e_i \in E^I$ to $e_o \in E^O$. [-]
$\xi_{e_i}^e$ = Electricity requirements if applying CCS when converting $e_i \in E^I$ to electricity (fraction on energy converted). [-]
ξ_m^b = Share of heavy road-based transportation modes $m \in M^L$ that can be of powertrain type BEV. [-]
ξ_m^p = Share of heavy road-based transportation modes $m \in M^L$ that can be of powertrain type PHEV. [-]
ξ_m = Fraction of time that a PHEV operates in battery mode for vehicles in transportation modes $m \in M^V$. [-]
$n_{r,m,t}^v$ = Number of vehicles for transportation mode $m \in M^V$ in every region $r \in R$ and time period $t \in T$. $[\frac{\text{Gvehicles}}{\text{yr}}]$
ϕ_{t_1,t_2} = Parameterized Impulse Response Function giving the contribution to the CO_2 concentration in year $t_1 \in T$ as a result of emissions from year $t_2 \in T$. $[\frac{\text{MtC}}{\text{yr}}]$
$\sigma_{e_i,e_o,f}$ = Indicates if energy conversion is allowed at a conversion plant $f \in F$ from a primary energy source $e_i \in E^I$ to an energy carrier $e_o \in E^O$. [-]
ψ = Pre-industrial atmospheric CO_2 concentration. [ppm]

r^d	= Discount rate.	[-]
u^{cc}	= Max storage capacity for global captured carbon.	[MtC]
$u^{y^p}_{e_i,r,t}$	= Annual maximum supply potential (non-fossil sources) of primary energy source $e_i \in E^{IP}$ in every region $r \in R$ and time period $t \in T$.	[EJ/yr]
$\tilde{u}^{y^p}_{e_i,r}$	= Total primary energy supply potential (fossil sources) of energy source $e_i \in E^{IP}$ in every region $r \in R$.	[EJ]

1.1.3. Variables First, we introduce the following continuous variables associated with ***Costs*** and expressed in units [GUSD/yr] each region $r \in R$ and time period $t \in T$.

- $x^p_{r,t} \in \mathbb{R}^+$ is the total cost for extracting primary energy sources.
- $x^c_{r,t} \in \mathbb{R}^+$ is the total cost, aggregated over all investments (e.g. energy conversion capacity, infrastructure, and vehicles).
- $x^{om}_{r,t} \in \mathbb{R}^+$ is the total cost for operation and maintenance.
- $x^{tp}_{r,t} \in \mathbb{R}^+$ is the total transportation cost for importing primary energy sources.
- $x^{ts}_{r,t} \in \mathbb{R}^+$ is the total transportation cost for importing energy carriers.
- $x^{cc}_{r,t} \in \mathbb{R}^+$ is the total cost for storing carbon.
- $x^b_{r,t} \in \mathbb{R}^+$ is the total additional transportation cost if applying CCS on bio-energy
- $x^t_{r,t} \in \mathbb{R}^+$ is the total cost if applying carbon taxes to the model.

Second, we introduce the continuous variables associated with ***Energy*** in units [EJ/yr] for every time period $t \in T$, dividing these into: main energy flow, energy conversion, import and export, and transportation sector. The variables associated with the ***Main Energy Flow*** are as follows:

- $y^p_{r,e_i,t} \in \mathbb{R}^+$ is the amount of primary energy $e_i \in E^{IP}$ extracted in each region $r \in R$.
- $y^{pf}_{r,e_i,t} \in \mathbb{R}^+$ is the amount of primary energy $e_i \in E^{IP}$ used in a region $r \in R$ after import/export has taken place.
- $y^l_{r,e_i,t} \in \mathbb{R}^+$ is the amount of energy $e_i \in E^I \setminus E^{IP}$ that will be converted a second time in each region $r \in R$.
- $y^s_{r,e_o,t} \in \mathbb{R}^+$ is the amount of energy carriers $e_o \in E^O$ produced in each region $r \in R$.
- $y^{sf}_{r,e_o,t} \in \mathbb{R}^+$ The amount of energy carriers $e_o \in E^O$ that meets the demand after import/export in each region $r \in R$.
- $y^{cg}_{r,t} \in \mathbb{R}^+$ is the amount of heat produced using co-generation technologies in each region $r \in R$.
- $y^{cce}_{r,t} \in \mathbb{R}^+$ is the additional electricity, added to the regional demand, if the model choose to use CCS in heat generation plants in each region $r \in R$.
- $y^{csp}_t \in \mathbb{R}^+$ is the total amount of energy from CSP.

The continuous variable associated with ***Energy Conversion*** is $w^c_{r,e_i,e_o,f,t} \in \mathbb{R}^+$, which is the amount of energy converted from $e_i \in E^I$ to $e_o \in E^O$ by plants of type $f \in F$ in each region $r \in R$ and time period $t \in T$ and is in units [EJ/yr] .

The continuous variables associated with ***Import and Export*** are in units of [EJ/yr] for every time period $t \in T$ and are as follows:

- $y^{pet}_{r,e_i,t} \in \mathbb{R}^+$ is the amount of primary energy $e_i \in E^{IPT}$ exported from a region $r \in R$.
- $y^{set}_{r,e_o,t} \in \mathbb{R}^+$ is the amount of energy carriers $e_o \in E^{OT}$ exported from a region $r \in R$.
- $y^{pit}_{r,e_i,t} \in \mathbb{R}^+$ is the amount of primary energy $e_i \in E^{IPT}$ imported to a region $r \in R$.
- $y^{sit}_{r,e_o,t} \in \mathbb{R}^+$ is the amount of energy carriers $e_o \in E^{OT}$ imported to a region $r \in R$.
- $y^{pt}_{r_1,r_2,e_i,t} \in \mathbb{R}^+$ is the amount of primary energy $e_i \in E^{IPT}$ imported from region $r_1 \in R$ to a region $r_2 \in R$.
- $y^{st}_{r_1,r_2,e_o,t} \in \mathbb{R}^+$ is the amount of energy carriers $e_o \in E^{OT}$ imported from region $r_1 \in R$ to a region $r_2 \in R$.

The next couple of continuous variables associated with the ***Transportation Sector*** are in units of [EJ/yr] for every region $r \in R$ and time period $t \in T$ and are as follows: $y^{sm}_{r,e_o,p,m,t} \in \mathbb{R}^+$ is the amount of transportation fuels $e_o \in E^{OM}$ required for powertrain of type $p \in P$ for the transportation mode $m \in M$ and $y^{ev}_{r,t} \in \mathbb{R}^+$ is the amount of electricity used in the transportation sector.

The following continuous variables associated with ***Investment and Capital*** are for every region $r \in R$ and time period $t \in T$:

- $z^c_{r,e_i,e_o,f,t} \in \mathbb{R}^+$ in units $[\frac{\text{TW}}{\text{decade}}]$ is new investments in energy conversion capacity for converting $e_i \in E^I$ to $e_o \in E^O$ in plant type $f \in F$.
- $z^i_{r,e_o,t} \in \mathbb{R}^+$ in units $[\frac{\text{TW}}{\text{decade}}]$ is new investments in infrastructure capacity for distributing energy carrier $e_o \in E^{OM}$.
- $z^v_{r,e_o,p,m,t} \in \mathbb{R}^+$ in units $[\frac{\text{Gvehicles}}{\text{decade}}]$ is new investments in vehicles used in transportation mode $m \in M^V$ with powertrain $p \in P$ running on fuel $e_o \in E^{OM}$.
- $v^c_{r,e_i,e_o,f,t} \in \mathbb{R}^+$ in units [TW] is the aggregated capacity in energy conversion plants for converting $e_i \in E^I$ to $e_o \in E^O$ in plant type $f \in F$.
- $v^i_{r,e_o,t} \in \mathbb{R}^+$ in units [TW] is the aggregated infrastructure capacity for energy carriers $e_o \in E^{OS}$.
- $v^v_{r,e_o,p,m,t} \in \mathbb{R}^+$ in units [Gvehicles] is the aggregated number of vehicles with powertrain $p \in P$ using fuel $e_o \in E^{OM}$ in transportation mode $m \in M^V$.

The next few continuous variables are associated with the ***Carbon Emitted*** and can take on both positive values and negative values when using the strategy of negative emissions (e.g., to reach really low CO_2 targets, the model might want to use CCS on bioenergy): $s^e_{r,t} \in \mathbb{R}$ are the annual emissions in each region $r \in R$ and time period $t \in T^T$ in units [MtC/yr]; $s^g_t \in \mathbb{R}$ are the global annual emissions aggregated over all regions in units [MtC/yr]; and s are the total global emissions aggregated over all time periods and regions in units [MtC].
The following continuous variables are associated with the ***Carbon Captured*** and are in units in units [MtC/yr] for every region $r \in R$ and time period $t \in T^T$: $s^f_{r,t} \in \mathbb{R}^+$ is the annual amount of carbon captured from fossil fuels; $s^b_{r,t} \in \mathbb{R}^+$ is the annual amount of carbon captured from biomass; and $s^t_{r,t} \in \mathbb{R}^+$ is the annual amount of carbon captured from fossil fuels and biomass.
The last two variables are associated with the ***CO_2 Concentration***: $s^c_{t_1,t_2} \in \mathbb{R}$ is the carbon contribution generated by the carbon cycle module in time period $t_1 \in T^T$ from time period $t_2 \in T^T$ in units of [MtC/yr]; and $s^{ac}_t \in \mathbb{R}^+$ is the atmospheric CO_2 concentration, from the carbon cycle module, in every time period $t \in T^T$ in units of [ppm].

1.1.4. Objective Function The objective of this model is to minimize total global energy system cost: the expression in the denominator is the discount factor.

$$\text{Minimize} \sum_{r \in R} \sum_{t \in T} \frac{\tilde{t}\left(x^p_{rt} + x^c_{rt} + x^{om}_{rt} + x^{tp}_{rt} + x^{ts}_{rt} + x^{cc}_{rt} + x^b_{rt} + x^t_{rt}\right)}{(1 + r^d)^{t - t_0}} \quad \forall \ t_0 \in \{1990\}$$

1.1.5. Constraints We have divided the constraints into logical groups around the following: cost, primary energy flow, secondary energy flow, transport balances and limitations, investments and depreciations, and emissions.
Costs
The first set of constraints define the cost decision variables for simplification of notation in the objective function:

- Total cost for extracting primary energy sources for each region and time period:

$$x^p_{rt} = \sum_{e_i \in E^{IPT}} c^p_{e_i r} y^p_{r,e_i,t} \ \ \forall \ r \in R, t \in T \tag{1}$$

- Total cost, aggregated over all investments done (energy conversion capacity, infrastructure, and vehicles) for each region and time period:

$$x^c_{rt} = \sum_{e_i \in E^I} \sum_{e_o \in E^O} \sum_{f \in F} c^c_{e_i e_o f t} z^c_{r e_i e_o f t} + c^i_{e_o} z^i_{r e_o t} + c^v_{e_o p t} z^v_{r e_o p m t} \ \ \forall \ r \in R, t \in T \tag{2}$$

- Total cost for operation and maintenance for each region and time period:

$$x_{rt}^{om} = \sum_{e_i \in E^I} \sum_{e_o \in E^O} \sum_{f \in F} [\xi_{e_i e_o}^{om} c_{e_i e_o f t}^{c} \eta_{e_i e_o f t} / \mu] w_{r e_i e_o f t}^{c} \;\; \forall \; r \in R, t \in T \tag{3}$$

- Total transportation cost for importing primary energy sources in each region and time period:

$$x_{r_1 t}^{pt} = \sum_{e_i \in E^{IPT}} \sum_{r_2 \in R \setminus \{r_1\}} [c_{e_i}^{pt} + \delta_{r_1 r_2} c_{e_i}^{\tilde{pt}}] y_{r_1 r_2 e_i t}^{pt} \;\; \forall \; r_1 \in R, t \in T \tag{4}$$

- Total transportation cost for importing energy carriers in each region and time period:

$$x_{r_1 t}^{st} = \sum_{e_o \in E^{OT}} \sum_{r_2 \in R \setminus \{r_1\}} [c_{e_o}^{st} + \delta_{r_1 r_2} c_{e_o}^{\tilde{st}}] y_{r_1 r_2 e_o t}^{pt} \;\; \forall \; r_1 \in R, t \in T \tag{5}$$

- Total cost for storing carbon (including transportation of CO_2) in every region and time period:

$$x_{rt}^{cc} = c^f s_{rt}^f + c^b s_{rt}^b \;\; \forall \; r \in R, t \in T$$

- Total additional transportation cost for carbon capture and storage from bioenergy conversion plants in every region and time period:

$$x_{rt}^{b} = \sum_{e_o \in E^O} \sum_{f \in F^C C} c^{\tilde{b}} w_{r e_i e_o f t}^{c} \;\; \forall \; r \in R, t \in T \tag{6}$$

- Total cost for each region and time period if applying carbon taxes to the model:

$$x_{rt}^{t} = c_{rt}^{t} s_{rt}^{e} \;\; \forall \; r \in R, t \in T \tag{7}$$

Primary Energy Flow

We first describe the constraints around ***Extraction and Trade***.

- Upper bound on the amount of non-fossil primary energy sources extracted in each region in every time period:

$$y_{re_i t}^{p} \leq u_{re_i t}^{y^p} \;\; \forall \; r \in R, e_i \in E^{IP}, t \in T \tag{8}$$

- Upper bound on the amount of fossil primary energy sources extracted in each region over all time periods:

$$\sum_{t \in T} \tilde{t} y_{re_i t}^{p} \leq \tilde{u}_{re_i}^{y^p} \;\; \forall \; r \in R, e_i \in E^{IP} \tag{9}$$

- The primary energy used in a region must be equal to the primary energy extracted in the region plus the primary energy that has been imported to the region minus the primary energy that has been exported from the region:

$$y_{re_i t}^{pf} = y_{re_i t}^{p} + y_{re_i t}^{pit} - y_{re_i t}^{pet} \;\; \forall \; r \in R, e_i \in E^{IPT}, t \in T \tag{10}$$

- The use of primary energy sources, that can not be traded, must be equal to the primary energy extracted in the region in every time period:

$$y_{re_i t}^{pf} = y_{re_i t}^{p} \;\; \forall \; r \in R, e_i \in E^{IP} \setminus E^{IPT}, t \in T \tag{11}$$

- The import of primary energy sources to one region must equal the sum of all exports from other regions to this specific region:

$$y_{r_i e_i t}^{pit} = \sum_{r_e \in R \setminus \{r_i\}} y_{r_i r_e e_i t}^{pt} \;\; \forall \; r_i \in R, e_i \in E^{IPT}, t \in T \tag{12}$$

• The export of primary energy sources from one region must equal the sum of all imports to other regions from this specific region:

$$y^{pet}_{r_e e_i t} = \sum_{r_i \in R \setminus \{r_e\}} y^{pt}_{r_i r_e e_i t} \ \forall \ r_e \in R, e_i \in E^{IPT}, t \in T \tag{13}$$

The couple of constraints around ***Energy Conversion Balancing Primary Energy Sources*** are itemized below:

• The primary energy used in a region must be equal to the amount of primary energy converted to energy carriers in energy conversion plants, in each region and every time period:

$$y^{pf}_{re_i t} = \sum_{f \in F} \sum_{e_o \in E^O} w^c_{re_i e_o ft} \ \forall \ r \in R, e_i \in E^{IP}, t \in T \tag{14}$$

• Here we define the global use of CSP. In the scenarios where we assume that CSP will not be a large scale available technology, we set the variable y^{csp}_t to zero.

$$y^{csp}_t = \sum_{r \in R} y^p_{re_i t} \ \forall \ e_i \in \{\text{solar\_CSP}\}, t \in T \tag{15}$$

Secondary Energy Flow

We start by introducing the constraints involving ***Energy conversion to energy carriers and trade***.

• For energy carriers that can not be traded between regions, the amount of energy carriers used in a region must be equal to the amount of primary energy sources converted in the region's energy conversion plants times the conversion efficiency in each region and every time period:

$$y^s_{re_o t} = \sum_{f \in F} \sum_{e_i \in E^I} \eta_{e_i e_o ft} w^c_{re_i e_o ft} \ \forall \ r \in R, e_o \in E^O \setminus E^{OT}, t \in T \tag{16}$$

• For energy carriers that can be traded between regions, the amount of energy carriers used in a region equals the amount of primary energy sources converted in the region's energy conversion plants times the conversion efficiency, plus the energy carriers that have been imported to the region minus the energy carriers that have been exported from the region, for each region and every time period:

$$y^s_{re_o t} = \sum_{f \in F} \sum_{e_i \in E^I} \eta_{e_i e_o ft} w^c_{re_i e_o ft} + y^{sit}_{re_o t} - y^{set}_{re_o t} \ \forall \ r \in R, e_o \in E^{OT}, t \in T \tag{17}$$

• The import of energy carriers to one region must equal the sum of all exports from other regions to the specified region:

$$y^{sit}_{r_i e_o t} = \sum_{r_e \in R \setminus \{r_i\}} y^{st}_{r_i r_e e_o t} \ \forall \ r_i \in R, e_o \in E^{OT}, t \in T \tag{18}$$

• The export of energy carriers from one region must equal the sum of all imports to other regions from the specified region:

$$y^{set}_{r_e e_o t} = \sum_{r_i \in R \setminus \{r_e\}} y^{st}_{r_i r_e e_o t} \ \forall \ r_e \in R, e_o \in E^{OT}, t \in T \tag{19}$$

• The amount of heat produced in co-generation with electricity equals the exogenously given share of heat in such conversion plants times the total amount of energy produced in these plants, for each region and every time period:

$$y_{rt}^{cg} = \sum_{e_i \in E^{ICG}} \sum_{e_o \in E^{OCG}} \sum_{f \in F^{CG}} \eta_{e_i e_o f}^{cg} w_{re_i e_o ft}^{c} \ \forall \ r \in R, t \in T \tag{20}$$

• These constraints specify the balance (i.e. transfer) of energy carriers produced, imported, and exported to the next model node where energy carriers meet the demand. The amount of energy carriers meeting each region's demand must be less than or equal to the amount of energy carriers produced and traded for each energy carrier except heat, and for each region and every time period:

$$y_{re_ot}^{sf} \leq y_{re_ot}^{s} \ \forall \ r \in R, e_o \in E^O \setminus \{\text{heat}\}, t \in T \tag{21}$$

• The energy carrier heat is balanced (i.e. transferred) to the next model node where energy carriers meet the demand. The amount of heat meeting the demand in a region must be less than or equal to the amount of heat produced in conventional heat generation plants plus the heat produced in co-generation plants, for each region and every time period:

$$y_{re_ot}^{sf} \leq y_{re_ot}^{s} + y_{rt}^{cg} \ \forall \ r \in R, e_o \in \{\text{heat}\}, t \in T \tag{22}$$

The next group of Secondary Energy Flow Constraints involve the ***Conversion of Energy Carriers to Other Energy Carriers***:

• Some energy carriers (e.g., electricity and hydrogen) can be converted to other energy carriers (e.g., heat). There must be an equal or larger amount of an energy carrier produced in the first energy conversion process than what can be used in this second conversion process, for each of the energy carriers allowed to be converted a second time and for every region and period:

$$y_{re_it}^{l} \geq \sum_{f \in F} \sum_{e_o \in E^O} w_{re_i e_o ft}^{c} \ \forall \ r \in R, e_i \in E^I \setminus E^{IP}, t \in T \tag{23}$$

• The amount of energy carriers converted again must be less than or equal to the difference between the energy carriers produced, including import and export, and the energy carriers meeting the demand for each of the energy carriers allowed to be converted a second time, each region and every time period:

$$y_{re_it}^{l} \leq y_{re_it}^{s} - y_{re_it}^{sf} \ \forall \ r \in R, e_i \in E^I \setminus E^{IP}, t \in T \tag{24}$$

The following group of Secondary Energy Flow Constraints involve ***Balancing Heat and Electricity demand***:

• The total amount of heat generated in a region must be greater than or equal to the exogenously given heat demand in each region and every time period:

$$y_{re_ot}^{sf} \geq d_{rt}^{h} \ \forall \ r \in R, e_o \in \{\text{heat}\}, t \in T \tag{25}$$

• The net amount of electricity generated in a region must be greater than or equal to the exogenously given electricity demand plus the additional electricity needed if the model chooses to apply CCS on heat generation plants, as well as if the model chooses to use electricity in the transportation sector (e.g., for PHEVs and BEVs) in each region and time period:

$$y_{re_ot}^{sf} \geq d_{rt}^{e} + y_{rt}^{cce} + y_{rt}^{ev} \ \forall \ r \in R, e_o \in \{\text{elec}\}, t \in T \tag{26}$$

We group the Secondary Energy Flow Constraints on ***Balancing Demand on Fuels for Transport*** as follows:

• For non-electric vehicles, the amount of transportation fuels produced (except electricity) equals the fuel required for all transportation modes and all powertrain types for each region and time step:

$$y^{sf}_{re_ot} = \sum_{m \in M} \sum_{p \in P} y^{sm}_{re_opmt} \;\; \forall \;\; r \in R, e_o \in E^{OM} \setminus \{\text{elec}\}, t \in T \tag{27}$$

• The total amount of electricity used in a region's transportation sector equals the electricity required for all transportation modes (e.g. passenger rail, freight rail, high speed rail) and all powertrain types (e.g. PHEVs and BEVs) for each region and time step:

$$y^{ev}_{rt} = \sum_{m \in M} \sum_{p \in P} y^{sm}_{re_opmt} \;\; \forall \;\; r \in R, e_o \in \{\text{elec}\}, t \in T \tag{28}$$

• The exogenously given energy demand for the different transportation modes must be equal to the amount of available fuels (for all fuels and powertrain options) times a relative powertrain efficiency factor in each region and time period:

$$d^t_{rmt} = \sum_{e_o \in E^{OM}} \sum_{p \in P} \gamma_{e_opmt} y^{sm}_{re_opmt} \;\; \forall \;\; r \in R, m \in M, t \in T \tag{29}$$

The next group of Secondary Energy Flow Constraints involve ***Limitations on Co-generation and Intermittent Energy***:

• The amount of electricity coming from co-generation plants is limited to a certain share of the electricity demand for all regions and time periods.

$$\sum_{e_i \in E^{ICG}} \sum_{f \in F^{CG}} \eta_{e_ie_oft} w^c_{re_ie_oft} \leq \xi^{cge} d^e_{rt} \;\; \forall \;\; r \in R, e_o \in \{\text{elec}\}, t \in T \tag{30}$$

• The amount of heat coming from co-generation plants is limited to a certain share of the heat demand for all regions and time periods.

$$\sum_{e_i \in E^{ICG}} \sum_{f \in F^{CG}} \sum_{e_o \in E^{OCG}} \eta^{cg}_{e_ie_of} w^c_{re_ie_oft} \leq \xi^{cgh} d^h_{rt} \;\; \forall \;\; r \in R, t \in T \tag{31}$$

• Electricity from intermittent energy sources (e.g., wind and solar) without electricity storage, such as hydrogen production, is maximized to a certain share of total electricity production.

$$w^c_{re_ie_oft} + w^c_{r\tilde{e_i}e_oft} \leq \xi^{im} y^{sf}_{re_ot} \;\; \forall \;\; r \in R, e_i \in \{\text{wind}\}, \tilde{e_i} \in \{\text{solar}\}, e_o \in \{\text{elec}\}, f \in \{0\}, t \in T$$

We group the Secondary Energy Flow Constraints on ***Limitations on Technology Growth and Depreciation*** as follows:

• This limits the relative growth on energy conversion capacity for each combination of primary energy source and energy carrier, type of conversion plant, region, and time period.

$$v^c_{re_ie_oft_2} \leq e^{\tilde{t}\ln(1+\iota^l)} v^c_{re_ie_oft_1} + \tilde{b}^c_r \;\; \forall \;\; r \in R, e_i \in E^I, e_o \in E^O, f \in F, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{32}$$

• This limits the growth on energy conversion capacity, in absolute number, for each energy carrier, region, and time period.

$$v^c_{re_ie_oft_2} \leq v^c_{re_ie_oft_1} + \frac{\iota^c_{re_ie_oft_1}}{\beta^c_{e_ie_oft_1}} \;\; \forall \;\; r \in R, e_i \in E^I, e_o \in E^O, f \in F, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{33}$$

• This limits the relative growth on infrastructure capacity for each energy carrier, region, and time period.

$$v^i_{re_o t_2} \leq e^{\tilde{t}\ln(1+\iota^l)} v^i_{re_o t_1} + \tilde{b}^i_r \;\; \forall \;\; r \in R, e_o \in E^O, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{34}$$

• This limits the growth on infrastructure capacity, in absolute number, for each energy carrier, region, and time period.

$$v^i_{re_o t_2} \leq v^i_{re_o t_1} + \frac{\iota^i_{rt_1}}{\beta^i_{e_o}} \;\; \forall \;\; r \in R, e_o \in E^O, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{35}$$

• This limits the relative growth on vehicles for each combination of powertrain, fuels, transportation mode, region, and time period.

$$v^v_{re_o pmt_2} \leq e^{\tilde{t}\ln(1+\iota^l)} v^v_{re_o pmt_1} + \tilde{b}^v_r \;\; \forall \;\; r \in R, e_o \in E^O, p \in P, m \in M, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{36}$$

• This limits the relative growth on extraction of primary energy sources for each source, region, and time period.

$$y^p_{re_i t_2} \leq e^{\tilde{t}\ln(1+\iota^l)} y^p_{re_i t_1} + \tilde{b}^p_r \;\; \forall \;\; r \in R, e_i \in E^I, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{37}$$

• This limits the growth on extraction of fossil primary energy sources for each source, region, and time period.

$$y^p_{re_i t_2} \leq y^p_{re_i t_1} + \iota^p_{rt_1} \;\; \forall \;\; r \in R, e_i \in E^{IPF}, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{38}$$

• This constraint limits the growth on extraction of biomass for each region and time period.

$$y^p_{re_i t_2} \leq y^p_{re_i t_1} + \iota^b_{rt_1} \;\; \forall \;\; r \in R, e_i \in \{\text{bio}\}, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{39}$$

• This limits the decay to capture energy system inertia when phasing out an energy conversion plant for each primary energy source converted to any energy carrier, in all types of conversion plants, for each region and time period.

$$w^c_{re_i e_o f t_2} \leq \xi^{dc} w^c_{re_i e_o f t_1} - \iota^{dc}_{rt_1} \;\; \forall \;\; r \in R, e_i \in E^I, e_o \in E^O, f \in F, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{40}$$

• This constraint limits the decay when phasing out a transportation fuel technology for each transportation mode, powertrain technology, region, and time period.

$$y^{sm}_{re_o pmt_2} \leq \xi^{df} y^{sm}_{re_o pmt_2} - \iota^{df}_{rt_1} \;\; \forall \;\; r \in R, e_o \in E^{OM}, p \in P, m \in M, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{41}$$

Transport Balances and Limitations
The first grouping is to ***Balance the Number of Cars and Trucks to the Different Fuels.***
• The amount of transportation fuels must be less than or equal to the stock of vehicles for region, time period, and road based fuel and powertrain combination, except for PHEVs, times a conversion and scaling factor. This factor consists of the exogenously given energy demand for transport divided with the exogenously given total amount of vehicles and the relative powertrain efficiency factor:

$$y^{sm}_{re_o pmt} \leq \frac{d^t_{rmt}}{\gamma_{e_o pmt} n^v_{rmt}} v^v_{re_o pmt} \;\; \forall \;\; r \in R, e_o \in E^{OR}, p \in P \setminus \{\text{phev}\}, m \in M^V, t \in T \tag{42}$$

• The amount of liquid fuels for PHEVs must be less than or equal to the stock of PHEVs times a conversion and scaling factor. This factor consists of the exogenously given energy demand for transport multiplied with the non-electric share of energy needed for PHEVs, divided with by the exogenously given total amount of vehicles and the relative powertrain efficiency factor, for each road based fuel, region, and time step:

$$y^{sm}_{re_opmt} \leq \frac{(1-\xi_m)d^t_{rmt}}{\gamma_{e_opmt} n^v_{rmt}} v^v_{re_opmt} \quad \forall\ r \in R, e_o \in E^{ORL}, p \in \{\text{phev}\}, m \in M^V, t \in T \tag{43}$$

The next constraint associated with Transport Balances and Limitations is around ***Non-electric Fuels for PHEVs***:

• This constraint balances the right amount of liquid fuels to complement the electricity in PHEVs:

$$\sum_{e_o \in E^{OM}} \frac{\gamma_{e_opmt}}{1-\xi_m} y^{sm}_{re_opmt} = \frac{\gamma_{\tilde{e}^opmt}}{\xi_m} y^{sm}_{r\tilde{e}^opmt} \quad \forall\ r \in R, \tilde{e}_o \in \{\text{elec}\}, p \in \{\text{phev}\}, m \in M^V, t \in T \tag{44}$$

The next couple of constraints associated with Transport Balances and Limitations are on ***Limitations on Heavy Electric Vehicles***.

• The powertrain technologies HEVs and PHEVs are assumed to play a limited role in future transportation modes. Trucks and Buses are therefore limited to a certain share of energy demand for these modes.

$$\sum_{e_o \in E^{ORL}} \frac{\gamma_{e_opmt}}{1-\xi_m} y^{sm}_{re_opmt} \leq \xi^p_m d^t_{rmt} \quad \forall\ r \in R, m \in M^L, p \in P^H, t \in T \tag{45}$$

• The BEV powertrain technology is assumed to play a limited role in future transportation modes. Trucks and Buses are therefore limited to a certain share of energy demand for these modes:

$$\gamma_{e_opmt} y^{sm}_{re_opmt} \leq \xi^b_m d^t_{rmt} \quad \forall\ r \in R, e_o \in \{\text{elec}\}, p \in \{\text{BEV}\}, m \in M^L, t \in T \tag{46}$$

Investment and Depreciation

The first grouping of constraints is around ***Energy Conversion Plants, Infrastructure, and Vehicles***:

• The initial capacity (for 1990) in energy conversion plants is equal to the exogenously given capacity plus new investments made in 1990.

$$v^c_{re_ie_oft} = b^c_{re_ie_of} + \tilde{t} z^c_{re_ie_oft} \quad \forall\ r \in R, e_i \in E^I, e_o \in E^O, f \in F, t \in \{1990\} \tag{47}$$

• Aggregated capacity in energy conversion plants equals new investments plus the aggregated capacity from the previous time period multiplied by a depreciation factor based on a plant's assumed life time.

$$v^c_{re_ie_oft_2} = \tilde{t} z^c_{re_ie_oft_2} + e^{\tilde{t}\ln(1-1/\alpha^c_{e_ie_of})} v^c_{re_ie_oft_1} \quad \forall\ r \in R, e_i \in E^I, e_o \in E^O, f \in F, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{48}$$

• Aggregated capacity in fuel infrastructure equals new investments plus the aggregated capacity from the previous time period multiplied by a depreciation factor.

$$v^i_{re_ot_2} = \tilde{t} z^i_{re_ot_2} + e^{\tilde{t}\ln(1-1/\alpha^i_{e_o})} v^i_{re_ot_1} \quad \forall\ r \in R, e_o \in E^{OS}, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{49}$$

• The aggregated number of vehicles, with a certain powertrain technology, equals new investments plus the aggregated stock of vehicles from the previous time period multiplied by a depreciation factor.

$$v^v_{re_opmt_2} = \tilde{t} z^v_{re_opmt_2} + e^{\tilde{t}\ln(1-1/\alpha^v_{e_opm})} v^v_{re_opmt_1} \quad \forall\ r \in R, e_o \in E^{OM}, m \in M^V, t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{50}$$

The second grouping of constraints on Investment and Depreciation is around ***Balancing Investments to Energy Flow***:

• The energy flow in energy conversion plants times its conversion efficiency must be less than or equal to the aggregated capacity in energy conversion plants (converted from TW into EJ/yr).

$$\eta_{e_ie_oft} w^c_{re_ie_oft} \leq \beta^c_{e_ie_oft} \mu v^c_{re_ie_oft} \;\; \forall \; r \in R, e_i \in E^I, e_o \in E^O, f \in F, t \in T \tag{51}$$

• The amount of fuels used must be less than or equal to the aggregated capacity in fuel infrastructure (converted from TW into EJ/yr).

$$y^{sf}_{re_ot} \leq \beta^i_{e_o} \mu v^i_{re_ot} \;\; \forall \; r \in R, e_o \in E^{OS}, t \in T \tag{52}$$

The next grouping of constraints on Investment and Depreciation is around ***CCS and Limitations***:

• This limits the total amount of captured carbon from fossil fuels in each region and time period. When using "less than or equal" the regions have the possibility to invest in CCS-technology but wait a decade or so before using it.

$$s^f_{rt} \leq \sum_{e_i \in E^{IPF}} \sum_{e_o \in E^O} \sum_{f \in F^{CC}} \theta_{e_i} \eta^{ccf} w^c_{re_ie_oft} \;\; \forall \; r \in R, t \in T \tag{53}$$

• This limits the total amount of captured carbon from bio-energy in each region and time period.

$$s^b_{rt} \leq \sum_{e_o \in E^O} \sum_{f \in F^{CC}} \theta_{e_i} \eta^{ccb} w^c_{re_ie_oft} \;\; \forall \; r \in R, e_i \in \{\text{bio}\}, t \in T \tag{54}$$

• This sets the total amount of carbon captured in each region and every time period. In the scenarios where we assume that CCS will not be a large scale available technology, we set this variable to zero.

$$s^t_{rt} = s^f_{rt} + s^b_{rt} \;\; \forall \; r \in R, t \in T \tag{55}$$

• This sets the global limitation on carbon storage expansion for every time period.

$$\sum_{r \in R} s^t_{rt_2} \leq \sum_{r \in R} s^t_{rt_1} + \tilde{t}\kappa \;\; \forall \; t_1 \in T, t_2 \in T : t_2 = t_1 + \tilde{t} \tag{56}$$

• This constraint sets the global limitation on carbon storage.

$$\sum_{r \in R} \sum_{t \in T} \tilde{t} s^t_{rt} \leq u^{cc} \tag{57}$$

• This specifies the maximum heat demand that can be fulfilled from CCS facilities for every region and time period.

$$\sum_{e_i \in E^{IPT}} \sum_{f \in F^{CC}} w^c_{re_ie_oft} \leq \xi^{cc} d^h_{rt} \;\; \forall \; r \in R, e_o \in \{\text{heat}\}, t \in T \tag{58}$$

• This specifies the additional electricity needed if the model choose to use CCS in heat generation plants for each region and time period. Note that we assume that negligible additional heat is needed when applying CCS.

$$y^{cce}_{rt} = \sum_{e_i \in E^{IPT}} \xi^e_{e_i} w^c_{re_ie_oft} \;\; \forall \; r \in R, e_o \in \{\text{heat}\}, f \in \{\text{CCS}\}, t \in T \tag{59}$$

The next constraint on Investment and Depreciation is around ***Allowed Energy Conversion Paths***:

• This constraint whether or not energy conversion from a primary energy source to an energy carrier is allowed for each primary energy source, energy carrier, and type of energy conversion plant. When $\sigma_{e_ie_of}=1$, then the constraint guarantees that it is not allowed, as the constraint is then active.

$$\sum_{r\in R}\sum_{t\in T}\sigma_{e_ie_of}w^c_{re_ie_oft}=0\ \forall\ e_i\in E^I,e_o\in E^O,f\in F \tag{60}$$

Emission Calculations

• This constrains the carbon dioxide emissions in each region and time period. The emissions are based on the amount of primary energy sources used in a region after import and export. For tradable secondary energy carriers that contain carbon in the fuel (i.e., CTL and GTL), the emissions are separated between the producing and using region. Captured emissions from applying CCS are subtracted from the total emissions.

$$s^e_{rt}=\sum_{e_i\in E^{IPF}}\theta_{e_i}y^{pf}_{re_it}-s^t_{rt}-\theta^s y^{set}_{re_ot}+\theta^s y^{sit}_{re_ot}\ \forall\ r\in R,e_o\in\{\text{CTL/GTL}\},t\in T \tag{61}$$

• This sets the global carbon dioxide emissions for each time period. When analyzing different CO_2 reduction targets, we vary the upper bounds on variable s^g_t.

$$s^g_t=\sum_{r\in R}s^e_{rt}\ \forall\ t\in T \tag{62}$$

• This sets historical global emissions for each time period.

$$\varepsilon^h_t=\sum_{r\in R}s^e_{rt}\ \forall\ t\in T^T\setminus T \tag{63}$$

• This sets the aggregated global carbon dioxide emissions.

$$s=\sum_{r\in R}\sum_{t\in T}\tilde{t}s^e_{rt} \tag{64}$$

The next couple of constraints involve the ***Carbon Cycle Model***:

• The carbon contribution to the atmospheric CO_2 concentration from one time period to another time period depends on the emissions from fossil fuels, as well as estimated future emissions from land use changes and estimated future biota sinks, times a factor given by the impulse response function.

$$s^c_{t_1t_2}=\phi_{t_1t_2}\left(\sum_{r\in R}s^e_{rt_2}+\varepsilon^l_{t_2}-\varepsilon^b_{t_2}\right)\ \forall\ t_1,t_2\in T^T \tag{65}$$

• This sets the atmospheric CO_2 concentration.

$$s^{ac}_{t_1}=\psi+\zeta\sum_{t_2\in T^T}s^c_{t_1t_2}\ \forall\ t_1\in T^T \tag{66}$$

Note that the mathematical formulation presented in this paper can be modified with different constraints based on the desired scenarios. For example, we could include upper bounds on the use of nuclear energy, assuming no expansion beyond current global capacity or limit the amount of hydrogen used in aviation. The model described in this paper is not meant to be all inclusive but is meant to lay the foundation upon which any modeler can expand based on their specific questions.