Overview of TIMES: Parameters, Primal Variables & Equations

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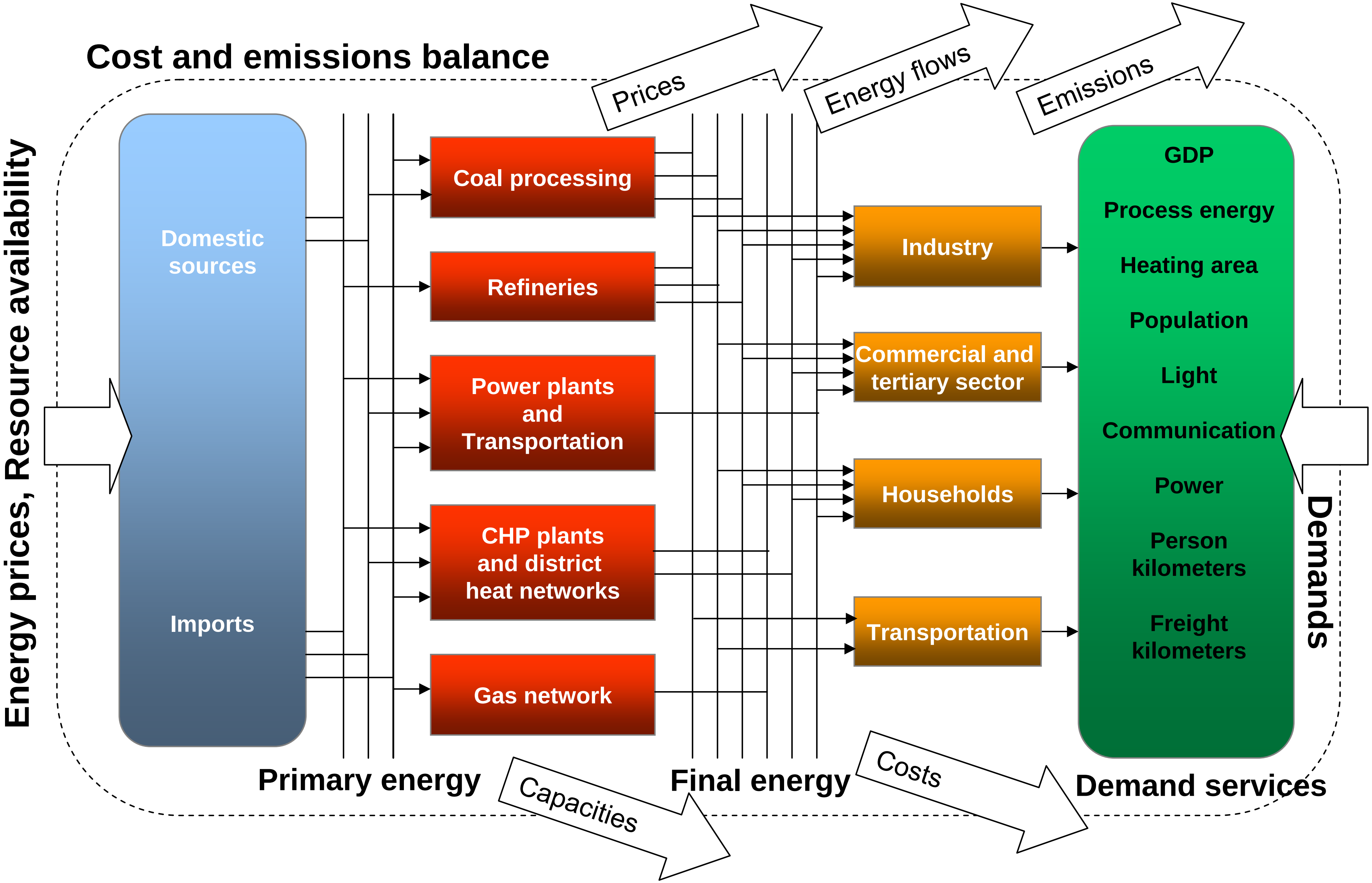
Overview

- Introduction to TIMES
- The Reference Energy System (RES):
  i. Building blocks of the RES
  ii. Characteristics
- Time dimension
  i. Time horizon of model analysis
  ii. Time segments within a year
- Mathematical formulation:
  i. Decision variables.
  ii. Basic equations and related input data
  iii. Objective function


Cost and emissions balance
Prices
Energy flows
Emissions
Energy prices, Resource availability
Domestic sources
Imports
Coal processing
Refineries
Power plants and Transportation
CHP plants and district heat networks
Gas network
Industry
Commercial and tertiary sector
Households
Transportation
GDP
Process energy
Heating area
Population
Light
Communication
Power
Person kilometers
Freight kilometers
Demands
Primary energy
Capacities
Final energy
Costs
Demand services

Development
- By ETSAP
- Implementation in GAMS
- Model generator

Methodology
- Bottom-up Model
- Perfect competition
- Perfect foresight (or myopic variant)
- Optimisation (LP / MIP / NLP)

Min / Max Objective function
s.t.
Equations, Constraints
Decision Variables <=> Solution
Input parameters

TIMES
(The Integrated MARKAL EFOM System)

Features
- Multi-region
- Elastic demands
- Vintaging
- Load curve
- Endogeneous learning
- Discrete capacity expansion
- Macroeconomic linkage
- Stochastic programming
- Trade-off analysis
- Damage functions for external costs of pollutants
- Climate extension

Model formulation of TIMES

Objective function:

Minimizing discounted system costs
=
Sum of
- Import-/Extraction costs,
- variable and fix OM costs,
- Investment costs,
- …

Input data

- Cost data
- Efficiencies
- Full load hours
- Emission factors
- Demand
- …

Model equations:

Transformation relationship
(→ e.g. Efficiency relationship for power plant)

Energy and emission balances

Share constraints on input/output side of technology
(→ e.g. max. ratio of electricity to heat for CHP)

Capacity-activity constraint
(→ e. g. available capacity limits elec gen of power plant)

Cumulated constraints over time
(→ e. g. available fossil resources)

Peaking constraint
(→ Ensuring reserve capacity at peak load)

Load curve equations

Storage equations (e.g. pump storage)

Scenario specific constraints
(→ e. g. bound on CO2 emissions, quota for renewables)

Decision variables

- Process activities
- Energy/Emission flows
- New capacities
- Fundamental prices

Linear programming (LP) model

Optimization problem

Decision variables (positvie, continuous):

- Activity variables (Production level of technologies)
- Energy flows
- Investment decisions

Objective function

$$\text{Min } c_1x_1 + c_2x_2 + \ldots + c_nx_n$$

Model constraints (linear constraints):

- Energy/ emission balances
- Efficiency relationships
- Utilization constraints
- Peaking eqn (reserve capacity)
- GHG mitigation targets, quota for renewables,…

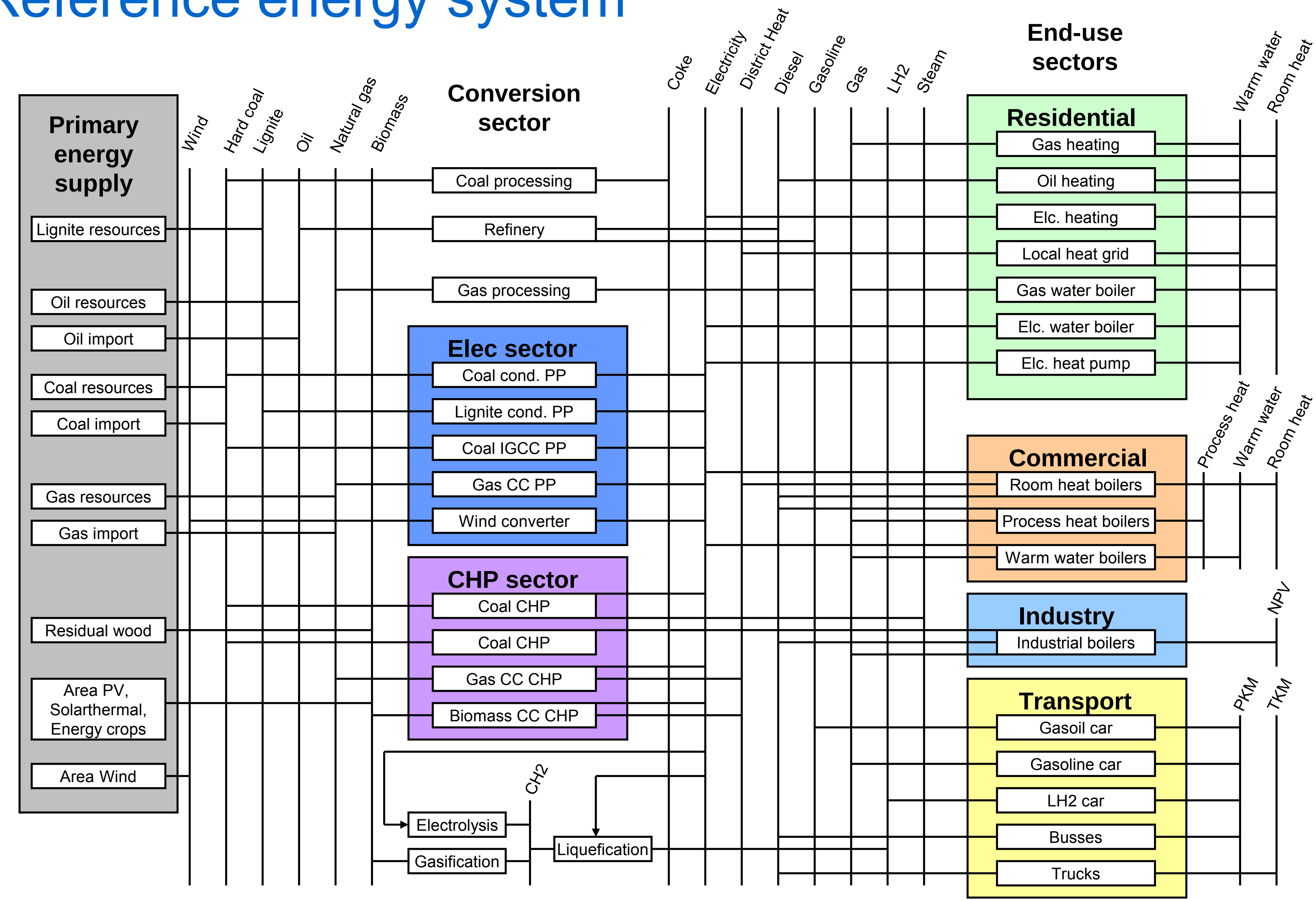
$$\begin{array}{ccccccccc}
a_{11}x_1 & + & a_{12}x_2 & + & \cdots & + & a_{1n}x_n & \geq & b_1 \\
a_{21}x_1 & + & a_{22}x_2 & + & \cdots & + & a_{2n}x_n & \geq & b_2 \\
\vdots & & \vdots & & \ddots & & \vdots & & \vdots \\
a_{i1}x_1 & + & a_{i2}x_2 & + & \cdots & + & a_{in}x_n & \geq & b_i \\
\vdots & & \vdots & & \ddots & & \vdots & & \\
a_{m1}x_1 & + & a_{m2}x_2 & + & \cdots & + & a_{mn}x_n & \geq & b_m \\
 & & & & & & x_j & \geq & 0
\end{array}$$

- Standard TIMES model: Linear programming
- Implemented in modeling environment GAMS (General Algebraic Modeling System) for optimization/equilibrium problems
- Solution by interior point solvers (CPLEX, XPRESS)
- Variants of TIMES:
  - i. Macro economic module -> Non-linear eqns -> Non-linear programming
  - ii. Block-wise capacity expansion -> Binary variables -> Mixed-integer programming

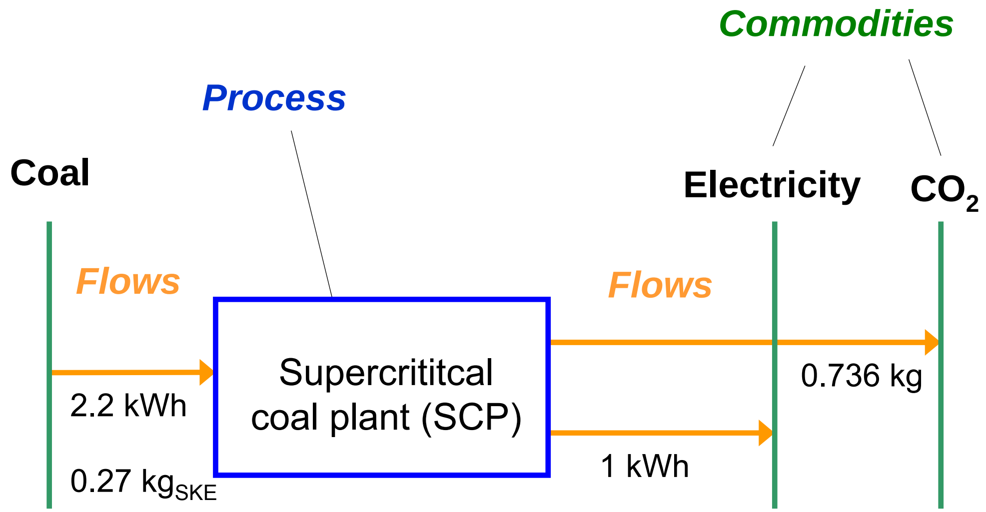
Results of TIMES model run

- All decision variables accessible in a browsable database (*data cube*):
  1. Energy flows, resource extraction, emissions
  2. Activity levels
  3. Total capacities and new investments
  4. Import, export flows
- Energy balance tables constructed from detailed results
- Total system costs, annual costs (discounted + undiscounted) for each technology split-up by cost category (variable, fix O&M, investment, …)
- Price information from so-called dual solution, e.g.
  1. Long-run marginal costs for energy carriers (prices including capital costs)
  2. Necessary subsidy or cost reduction, so that non-competitive technology will be used
  3. Marginal CO_2 abatement costs = CO_2 certificate price

Reference energy system



Representation of a simple technology



Coal PC Supercrit.	Unit	2005	2010	2020	2030
Size	MW_{el}	600	600	600	600
Construction time	Years	3	3	3	3
Lifetime	Years	35	35	35	35
Efficiency (LHV)	%	46	47	48	50
Max. availability	h/a	7500	7500	7500	7500
Spec. Investment costs (overnight)	€/kW_{el}	1175	1175	1140	1140
Fix O&M	€/(kW a)	40.5	40.5	40.5	40.5
Var. O&M	€/MWh_{el}	2.6	2.6	2.6	2.6

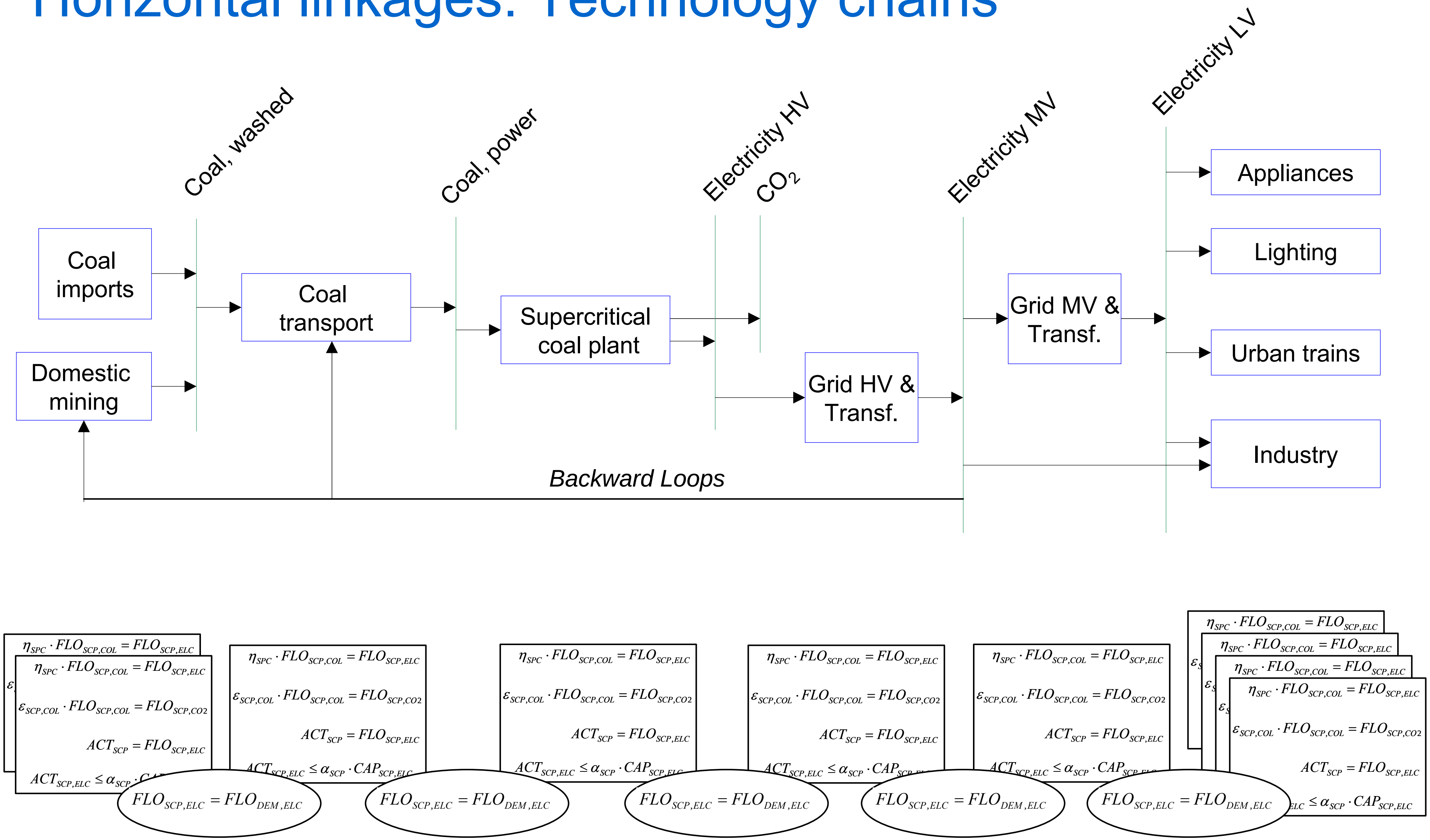
Efficiency eqn $$\eta_{SPC} \cdot FLO_{SCP,COL} = FLO_{SCP,ELC}$$

Emission eqn $$\varepsilon_{SCP,COL} \cdot FLO_{SCP,COL} = FLO_{SCP,CO2}$$

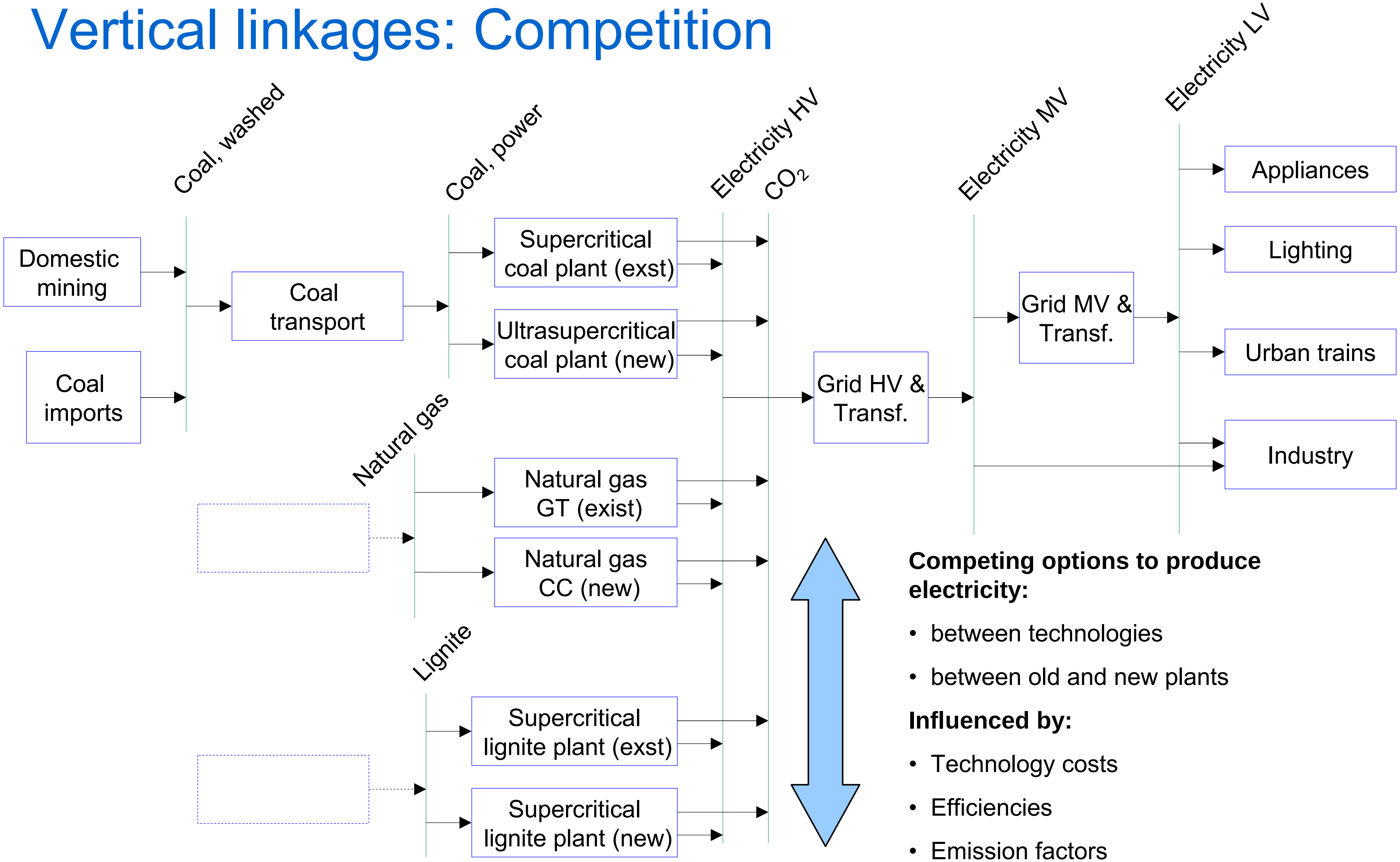
Activity definition $$ACT_{SCP} = FLO_{SCP,ELC}$$

Utilization eqn $$ACT_{SCP,ELC} \leq \alpha_{SCP} \cdot CAP_{SCP,ELC}$$

Horizontal linkages: Technology chains



Vertical linkages: Competition



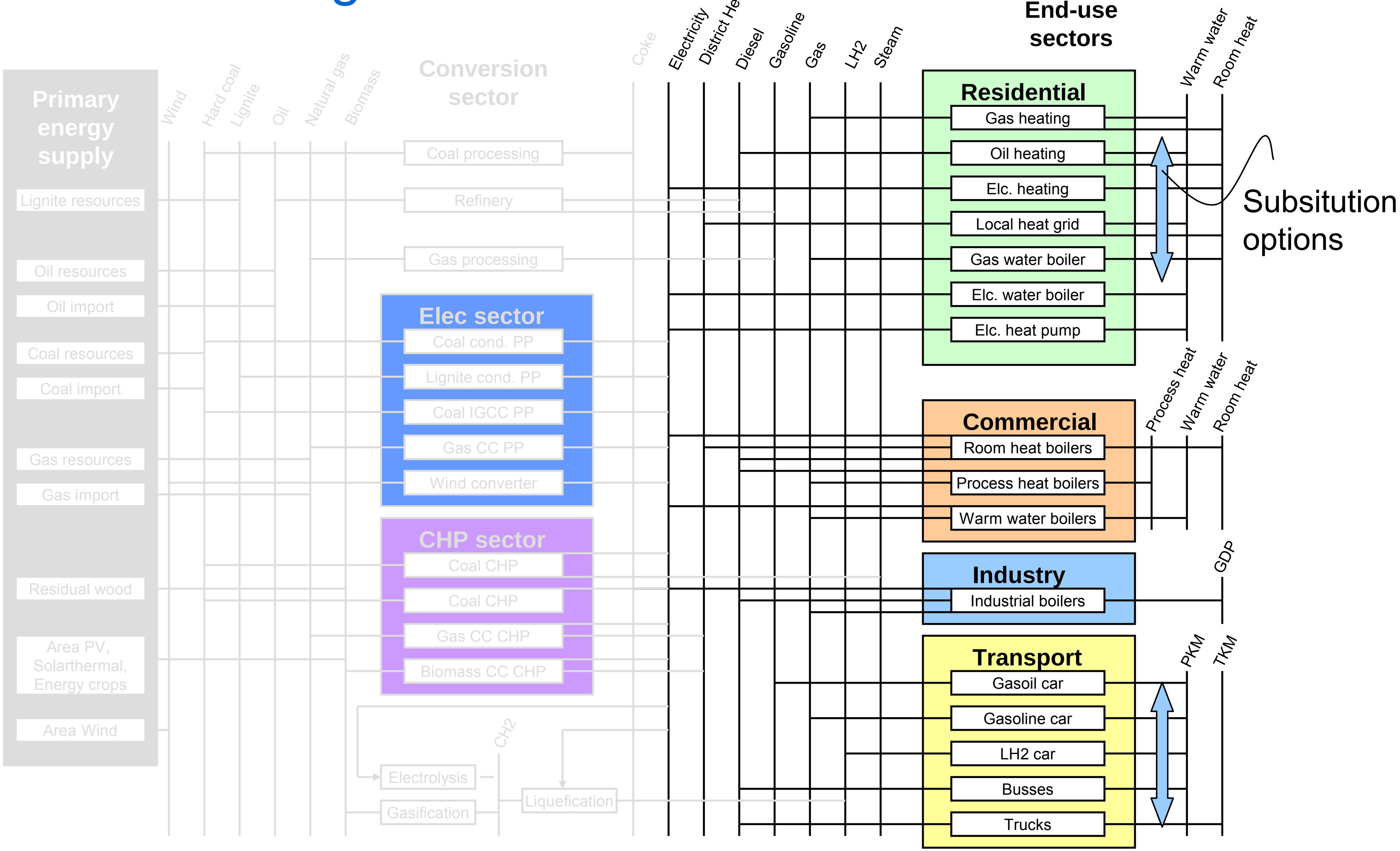
Competing options to produce electricity:

- between technologies
- between old and new plants

Influenced by:

- Technology costs
- Efficiencies
- Emission factors
- Fuel prices…

Vertical linkages: Substitution



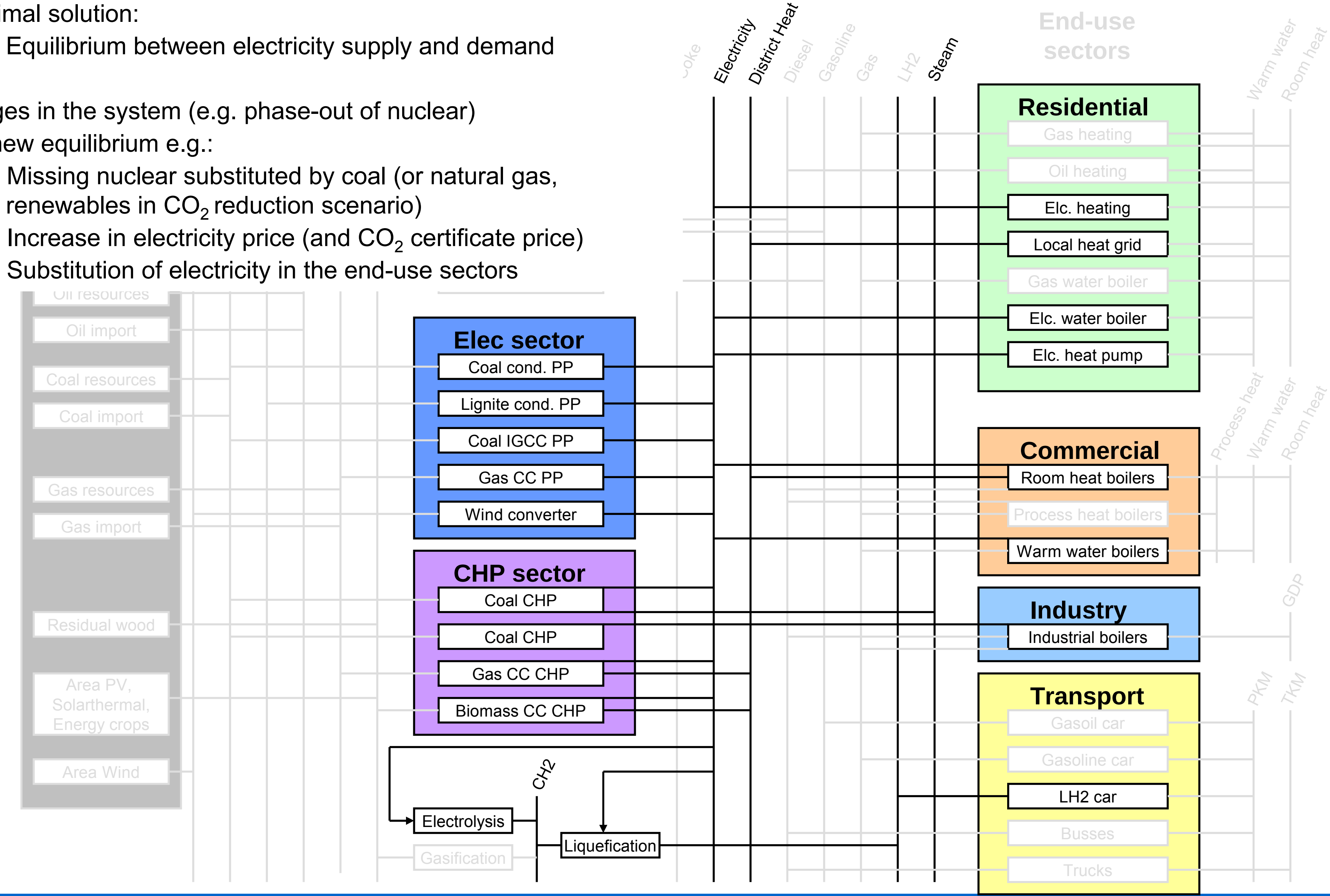
Interdependencies in the energy system

At optimal solution:

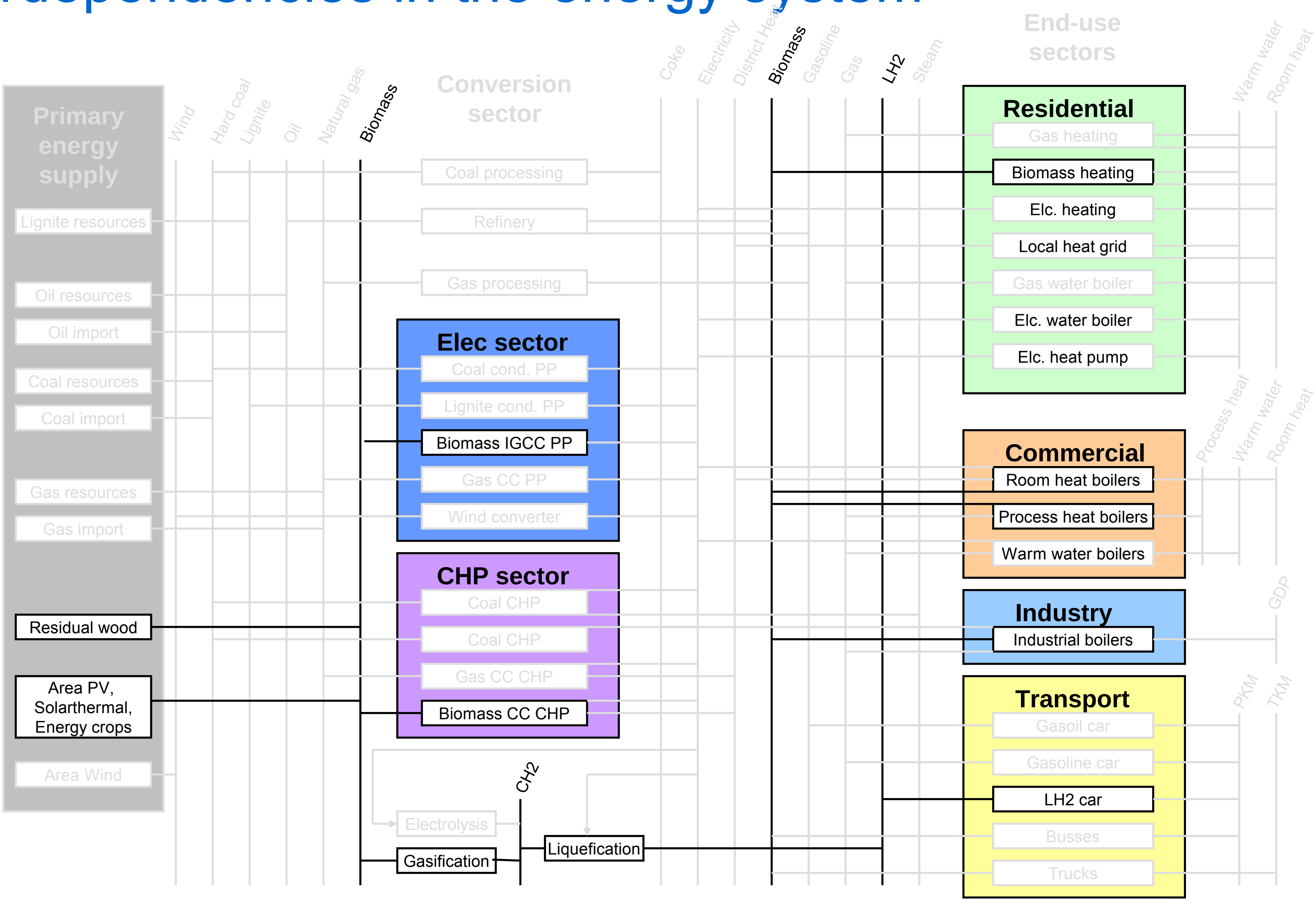
- Equilibrium between electricity supply and demand

Changes in the system (e.g. phase-out of nuclear) yield new equilibrium e.g.:

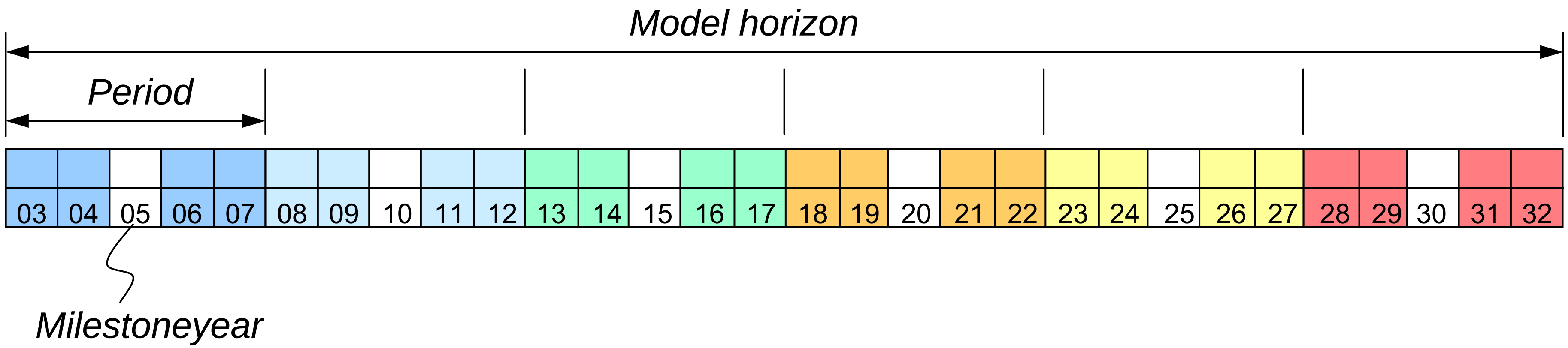
1) Missing nuclear substituted by coal (or natural gas, renewables in CO_2 reduction scenario)
2) Increase in electricity price (and CO_2 certificate price)
3) Substitution of electricity in the end-use sectors

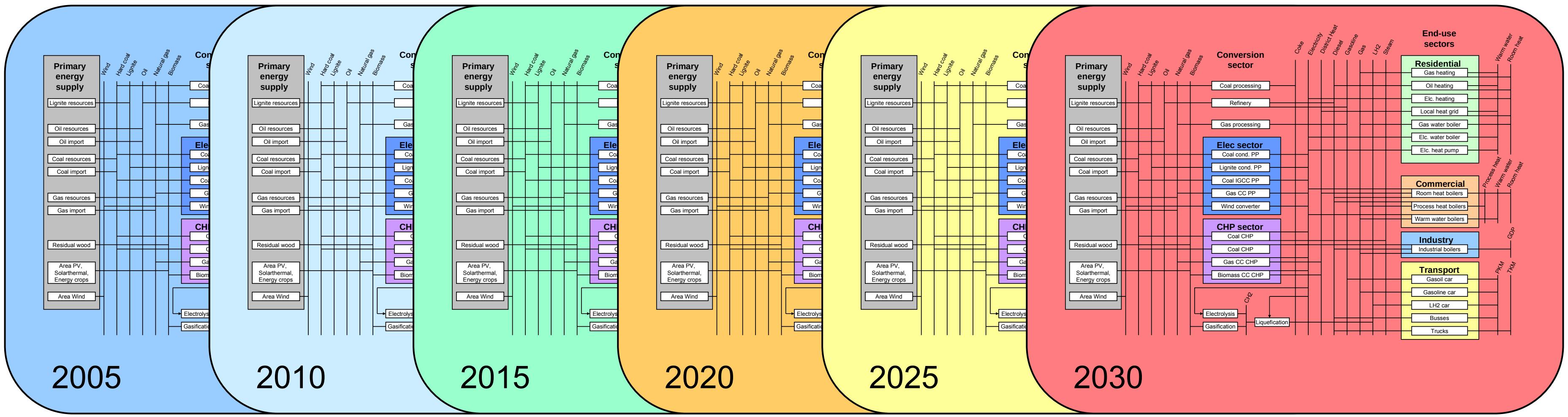


Interdependencies in the energy system

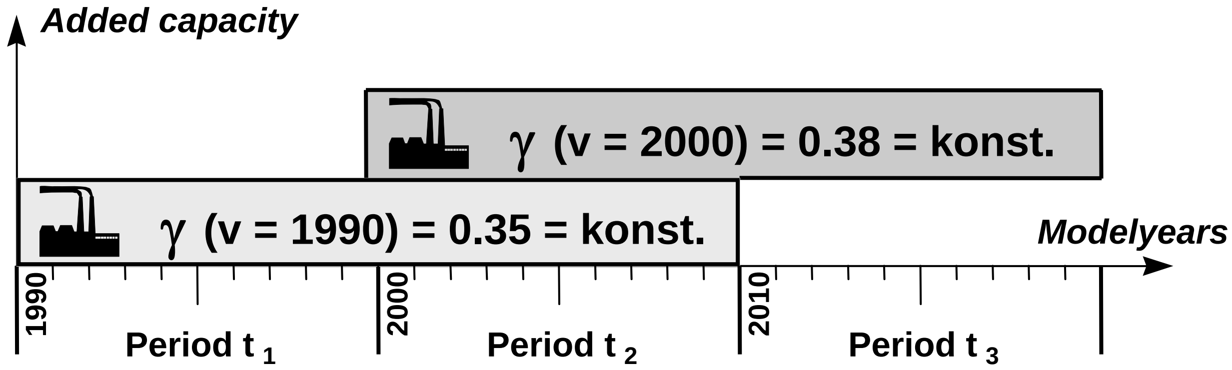


Dynamic model



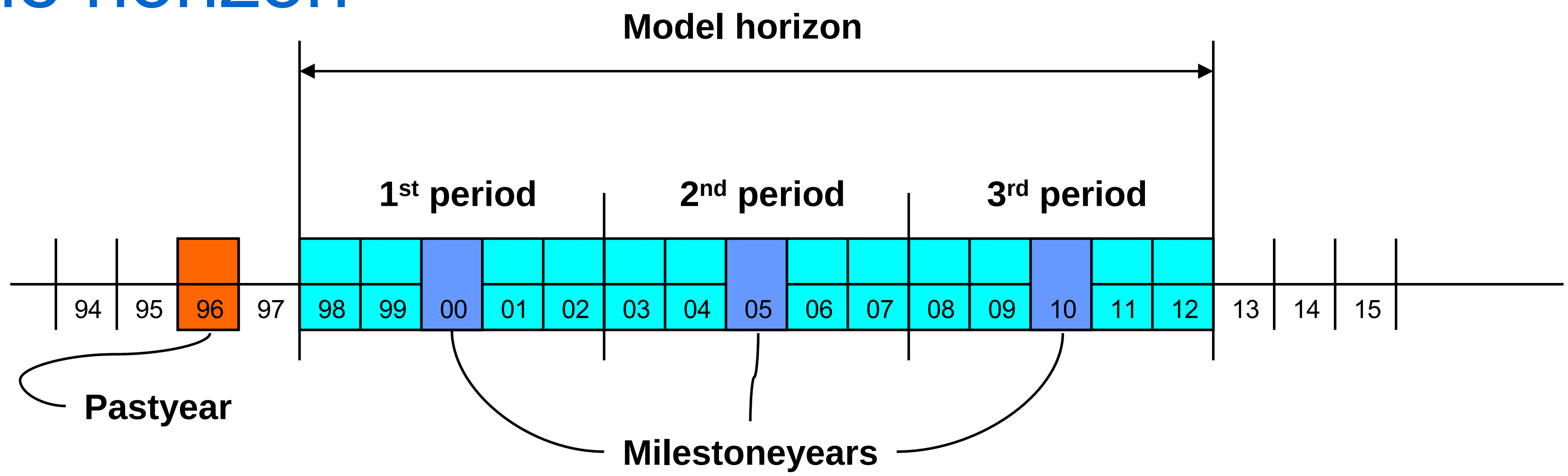


Vintaging



- Process can be specified as vintaged one by entry in set PRC_VINT.
- The characteristics of a vintaged process can be distinguished by its vintage year, e.g. process flow variables have as additional index of the current period *t* the construction period *v*: *VAR_FLO(r,v,t,p,c,s)*

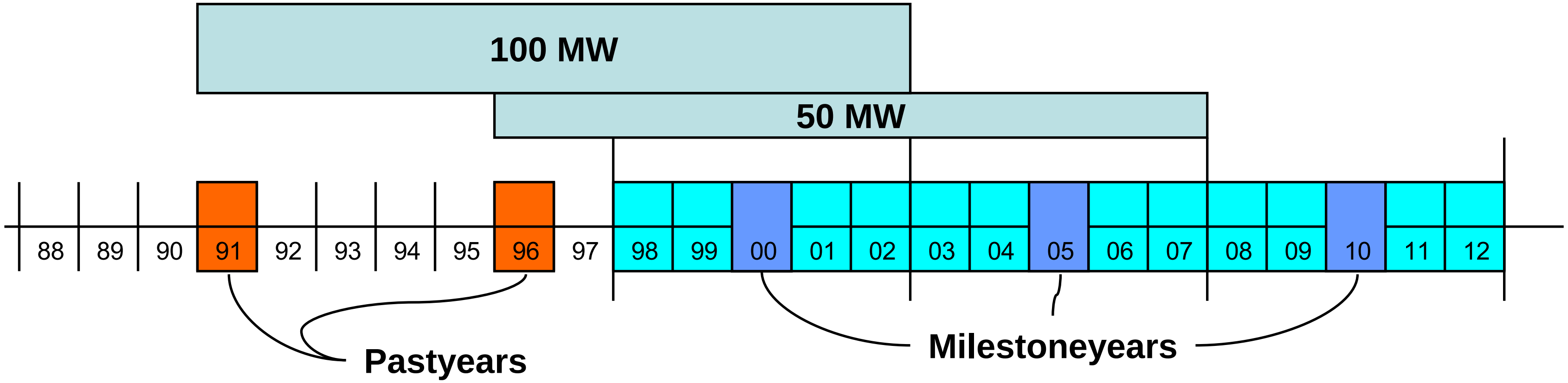
Time horizon



- Different period durations are possible
- Different type of years:
  i. MILESTONYR
  ii. PASTYEAR
  iii. MODLYEAR = MILESTONYR + PASTYEAR
  iv. DATAYEAR: years with input data, input data are inter-/extrapolated to milestoneyears

Past investments

Existing capacity of technology ECOASTM000



- Specification of existing capacity by past investments in their **vintage/past years** (NCAP_PASTI(r,t,prc)):

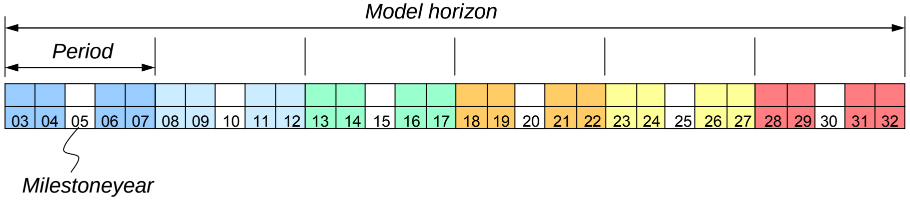
```
PARAMETER NCAP_PASTI(REG,ALLYEAR,PRC)
/         WEU.1991.ECOASTM000   100
          WEU.1996.ECOASTM000    50  /
```

- Alternative specification of residual curve for **Milestoneyears** PRC_RESID(r,t,prc)

```
PARAMETER PRC_RESID(REG,ALLYEAR,PRC)
/         WEU.2000.ECOASTM000   150
          WEU.2005.ECOASTM000    50  /
```

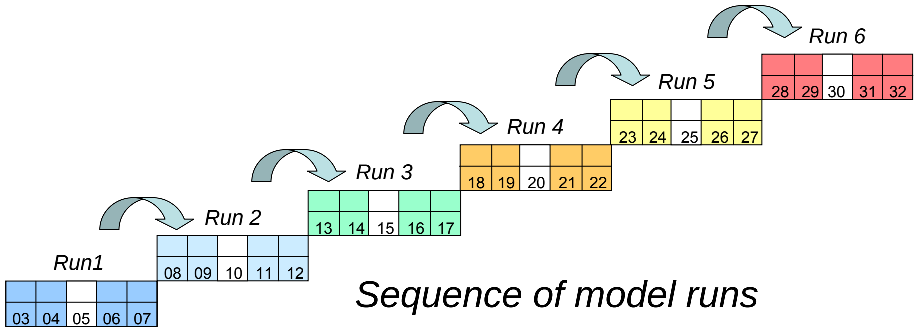
Foresight

Perfect foresight



One optimization run over entire horizon

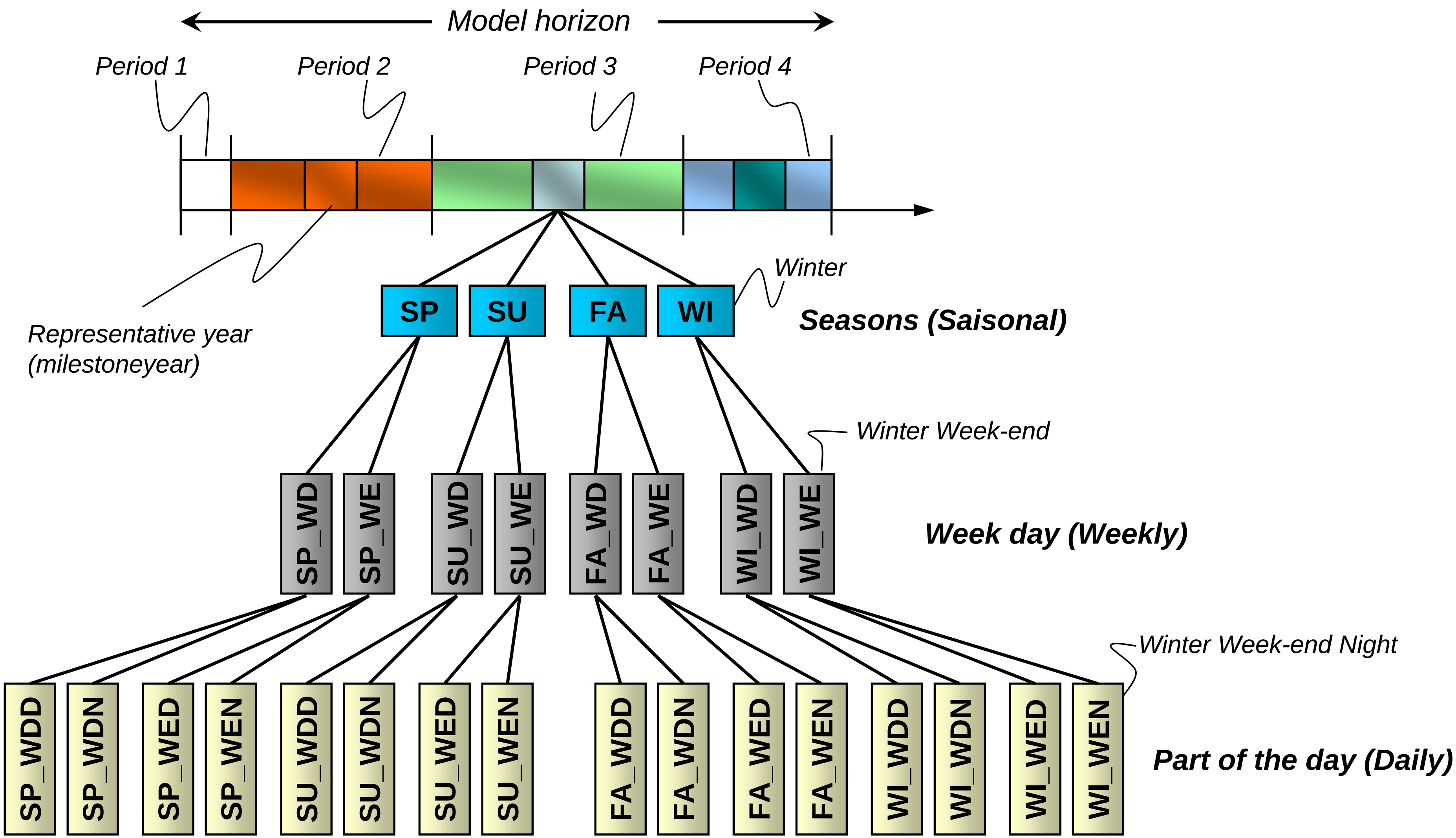
Myopic foresight
(Dynamic-recursive)



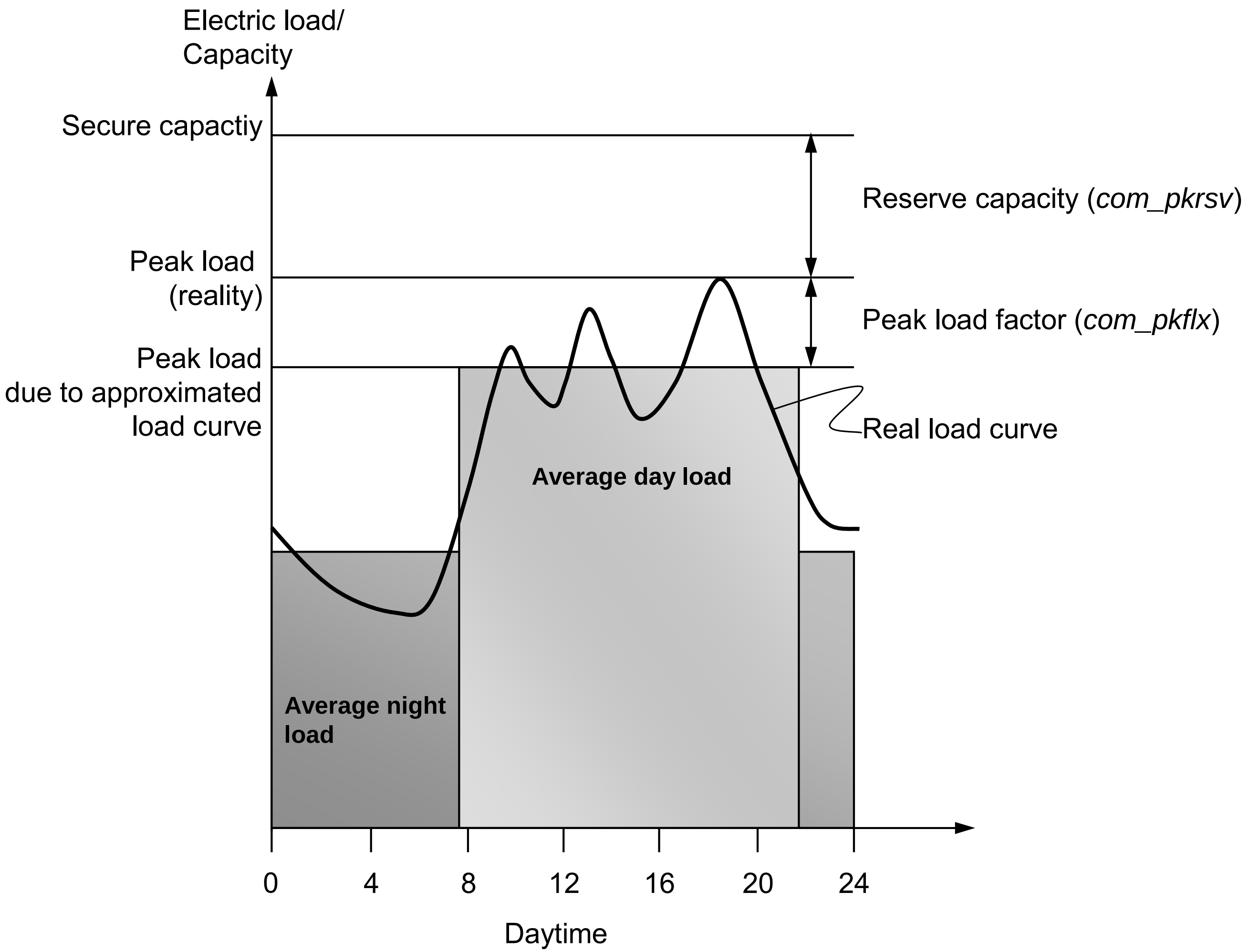
Sequence of model runs

- Perfect foresight:
  i. Decisions take into account entire future model horizon
  ii. Model gives optimal strategy under assumed conditions
- Myopic foresight:
  i. Decisions are based on only limited knowledge of the future
  ii. Implicitly assumed that current conditions will last forever; to some extent ignorant about future

Timeslices

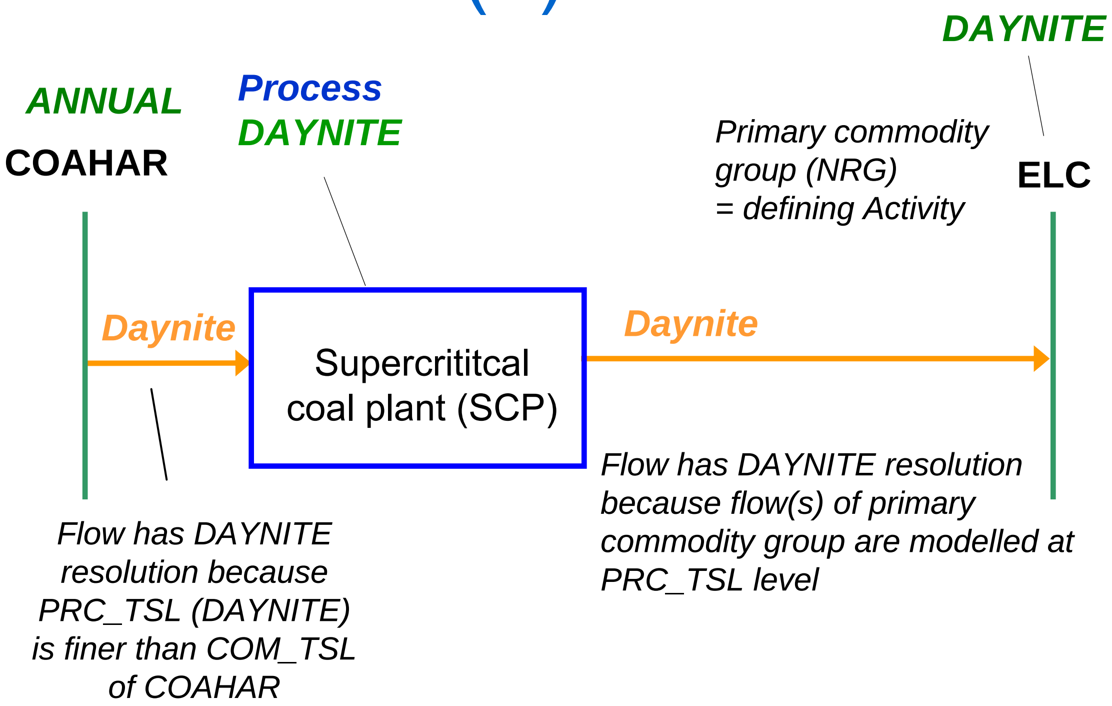

Model horizon
Period 1
Period 2
Period 3
Period 4
Representative year
(milestoneyear)
SP
SU
FA
WI
Winter
Seasons (Saisonal)
Winter Week-end
SP_WD
SP_WE
SU_WD
SU_WE
FA_WD
FA_WE
WI_WD
WI_WE
Week day (Weekly)
Winter Week-end Night
SP_WDD
SP_WDN
SP_WED
SP_WEN
SU_WDD
SU_WDN
SU_WED
SU_WEN
FA_WDD
FA_WDN
FA_WED
FA_WEN
WI_WDD
WI_WDN
WI_WED
WI_WEN
Part of the day (Daily)

Reserve capacity in the power sector



Timeslices (2)

SPG(Shadow Primary Commodity Group) is defined as the group of commodities on the opposite side of the PCG having the same commodity type as the PCG.

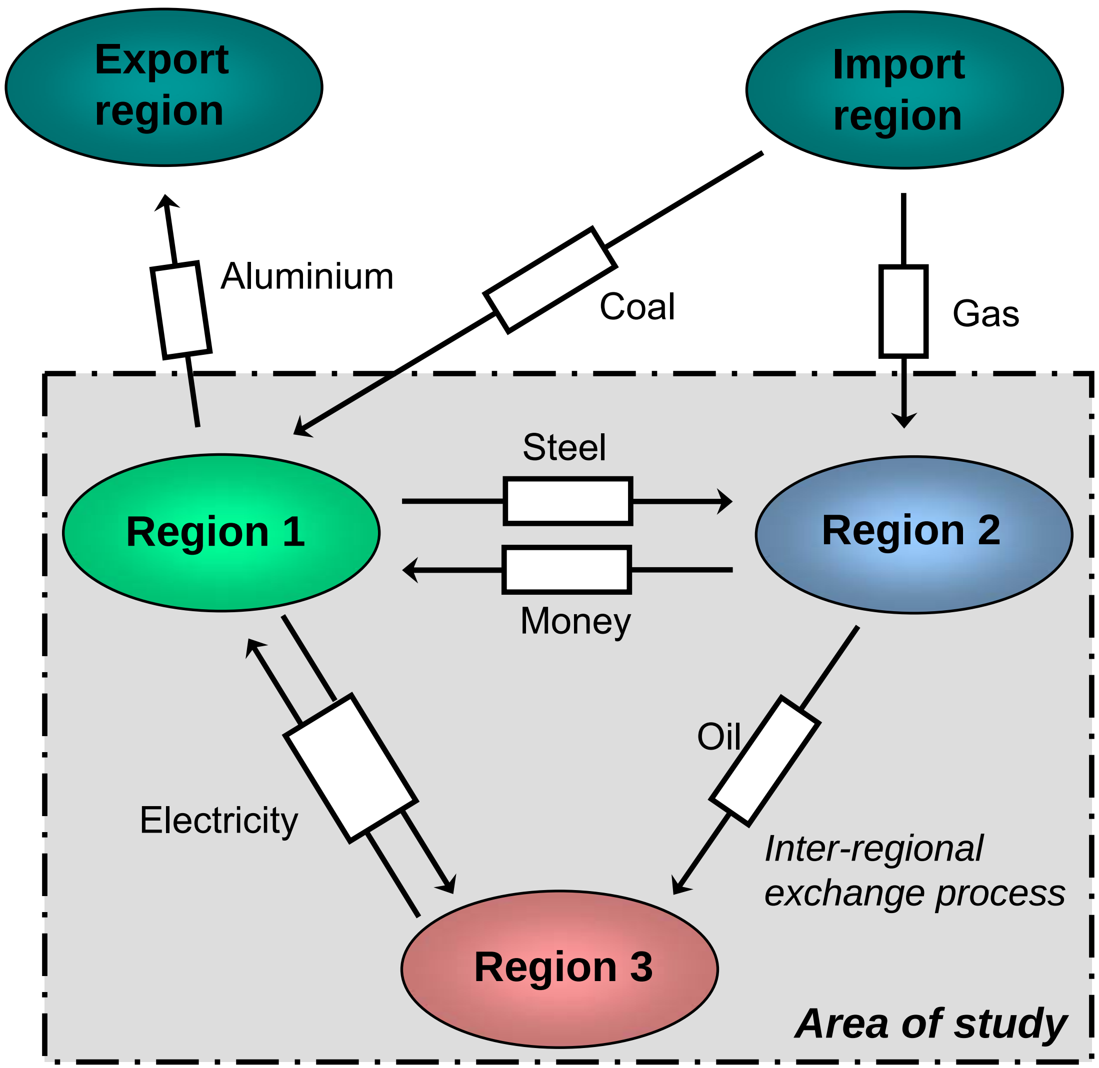



```
SET   COM_TSL
 /
WEU.ELC.DAYNITE
...
WEU.COAHAR.ANNUAL
/
```

```
SET   PRC_TSL
 /
...
WEU.SCP.DAYNITE
...
/
```

- Modeller specifies process and commodity timeslice levels, timeslice levels of commodtiy balances and process flows are deteremined according to the following rules:
  - Commodity timeslice level COM_TSL ⇒ timeslice level of commodity balance equation (default ANNUAL)
  - Process timeslice level PRC_TSL ⇒ timeslice level of activity variable and corresponding flow variables (default ANNUAL)
  - All other flows are modelled at the finest level of COM_TSLevel of the SPG or PRC_TSL.

Multi-regional TIMES model



- Inter-regional exchange process between two internal regions similar to import/export process; thus:
    i. easy linkage of different regions
    ii. modelling of trade
- Trade processes can be described similar to regular technologies, e.g. capacities, investment costs, losses, etc.

Defining processes

```
SET PRC
/
...
SSCCDRFLX00
...
/;
SET TOP (REG,PRC,COM,IO)
/
...
WEU.SSCCDRFLX00.OILCRD.IN
WEU.SSCCDRFLX00.OILDST.OUT
WEU.SSCCDRFLX00.OILLPG.OUT
...
/;
SET COM_GRP
/
...
SSCDRFLX00_NRGO
...
/;

SET COM_GMAP(REG,CG,COM)
/
...
WEU. SSCDRFLX00_NRGO.OILDST
WEU. SSCDRFLX00_NRGO.OILLPG
...
/;

SET PRC_CG(REG,PRC,CG)
/
...
WEU. SSCDRFLX00.SSCDRFLX00_NRGO
...
/;
```

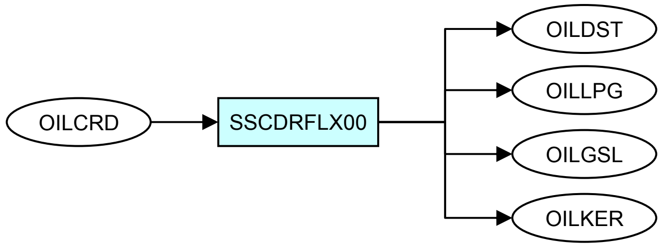
Process name

Topology

User defined commodity group

Members of commodity group

Commodity groups related to SSCCDRFLX00




```
SET PRC_CAPUNT(REG,PRC,CG,UNITS_CAP)
/
...
WEU.SSCCDRFLX00.SSCCDRFLX00_NRGO.PJA
...
/;

SET PRC_ACTUNT(REG,PRC,CG,UNITS_ACT)
/
...
WEU.SSCCDRFLX00.SSCCDRFLX00_NRGO.PJ
...
/;

PARAMETER PRC_ACTFLO(REG,ALLYEAR,PRC,CG)
/
/;

PARAMETER PRC_CAPACT(REG,PRC)
/
WEU.SSCCDRFLX00      1.0
/;
```

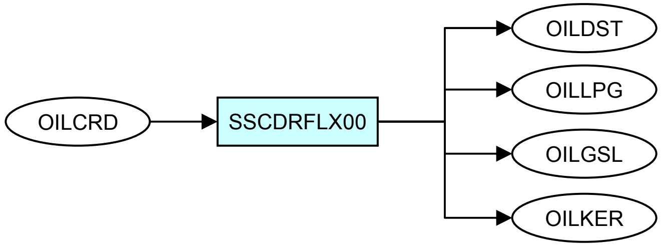
Capacity unit

PCG is SSCCDRFLX00 and activity unit PJ

No Conversion factor needed

Conversion factor is 1

Process definition in VEDA-FE



Activity = sum of all eNRGy output flows

Topology

Capacity unit: PJ/a
Activity unit: PJ

Efficiency from output flows NRGO to crude oil input

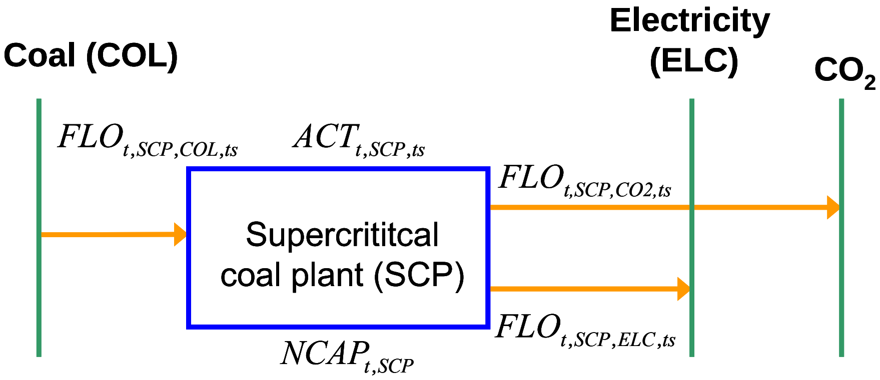
~FI_ST: TCH, PRC, PRE
~FI_UT: TCAP=PJ/a; TACT=PJ

Existing Flexible Refinery

~FI_T

Sets	TechName	TechDesc	Comm-IN	Comm-OUT	Share~UP	EFF~NRGO	Life	BNDACT~UP	BNDACT~UP~2050	ENVACT
\D_TC: PCG=NRGO;	SSCDRFLX00	Flexible Refinery	OILCRD			1.05	50			
				OILLPG	0.5000					
				OILGSL	0.5000					
				OILKER	0.5000					
				OILDST	0.5000					

Basic equations and decision variables



Input parameter

$\eta_{t,SPC,ts}$	*Plant efficiency*
$\varepsilon_{t,SCP,COL,CO2,ts}$	*CO2 Emission factor*
$\alpha_{t,SCP,ts}$	*Availability in time segment ts*
$\alpha_{t,SCP,ANNUAL}$	*Annual availability*
$cap\_past_{t,SCP}$	*Existing capacity*
Δ_{ts}	*Duration of time segment ts*
t	*Index model period*
ts	*Index time segment*

Basic process equations

Efficiency eqn

$$\eta_{t,SPC,ts} \cdot FLO_{t,SCP,COL,ts} = FLO_{t,SCP,ELC,ts}$$

Emission eqn

$$\varepsilon_{t,SCP,COL,CO2,ts} \cdot FLO_{t,SCP,COL,ts} = FLO_{t,SCP,CO2,ts}$$

Activity definition

$$ACT_{t,SCP,ts} = FLO_{t,SCP,ELC,ts}$$

Capacity-Activity constraints

$$\sum_{ts} ACT_{t,SCP,ts} \leq \alpha_{t,SCP,ANNUAL} \cdot CAP_{t,SCP}$$

$$ACT_{t,SCP,ts} \leq \alpha_{t,SCP,ts} \cdot CAP_{t,SCP} \cdot \Delta_{ts}$$

Capacity definition

$$CAP_{t,SCP} = cap\_past_{t,SCP} + \sum_{v<t} cptyr_{v,t,SCP} \cdot NCAP_{v,SCP}$$

Decision variables

Process flows

$FLO_{t,SCP,COL,ts}$, $FLO_{t,SCP,ELC,ts}$, $FLO_{t,SCP,CO2,ts}$

Activity $ACT_{t,SCP,ts}$

New capacity

$NCAP_{t,SCP}$

Total capacity

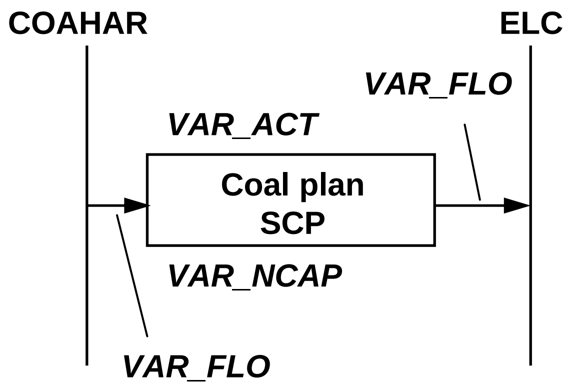
$CAP_{t,SCP}$

Variables

Associated bound parameters

region · *vintage period* · *actual period* · *process* · *timeslice*

- Process oriented:
  i. VAR_ACT(r,v,t,p,s): activity of a process — *lo,up or fx* — ACT_BND(r,t,p,s,l)



  ii. VAR_CAP(r,v,p): installed capacity = previous investments + new investments + past investments still existing — CAP_BND(r,v,p,l)
  iii. VAR_NCAP(r,v,p): new investment in period v — NCAP_BND(r,v,p,l)

- Flow oriented:
  i. VAR_FLO(r,v,t,p,c,s): flow level of commodity c linked to process p
  ii. VAR_IRE(all_reg,v,t,p,c,s,ie): inter-regional exchange variable (*imp or exp*) — IRE_BND(r,t,c,s,all_reg,ie,l), IRE_XBND(all_reg,t,c,s,ie,l)
  iii. VAR_SIN / VAR_SOUT(r,v,t,p,c,s): flows entering/leaving a process p storing a commodity c — STG_IN/OUTBND(r,t,c,s,all_reg,ie,l)

Variables contd.

Associated bound parameters

- Commodity oriented (only created if bound provided):

  i. VAR_COMPRD(r,t,c,s): total production of a commodity — COM_BNDPRD(r,t,c,s,l)

  ii. VAR_COMCON(r,t,c,s): total consumption of a commodity — COM_BNDCON(r,t,c,s,l)

  iii. VAR_COMNET(r,t,c,s): net level of a commodity (production – consumption) — COM_BNDNET(r,t,c,s,l)

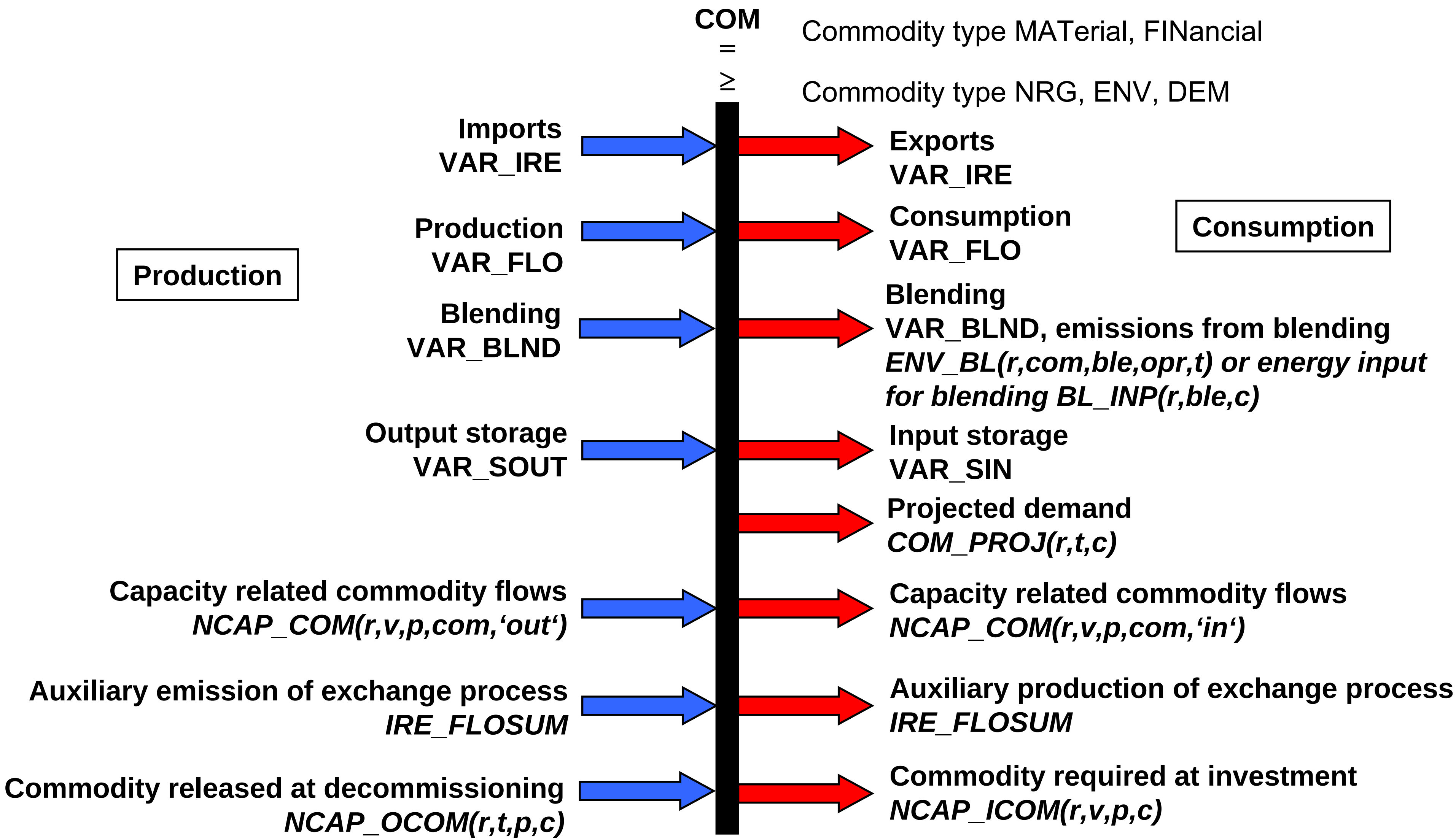
- Blending variables

  i. VAR_BLND(r,t,ble,opr): amount of blending stock opr needed for the production of blending product ble

Basic equations

- *EQ(l)_COMBAL* $_{r,t,c,s}$ — Commodity balance
- *EQ_ACTFLO* $_{r,v,t,p,s}$ — Definition of activity variable
- *EQ_CAPACT* $_{r,v,t,p,s}$ — Utilization constraint
- *EQ_PTRANS* $_{r,v,t,p,cg1,cg2,s}$ — Transformation equation
- *EQ(l)_INSHR/OUTSHR* $_{r,t,p,c,cg,s}$ — Share constraints on in/output side of process
- *EQ_OBJ* — Objective function

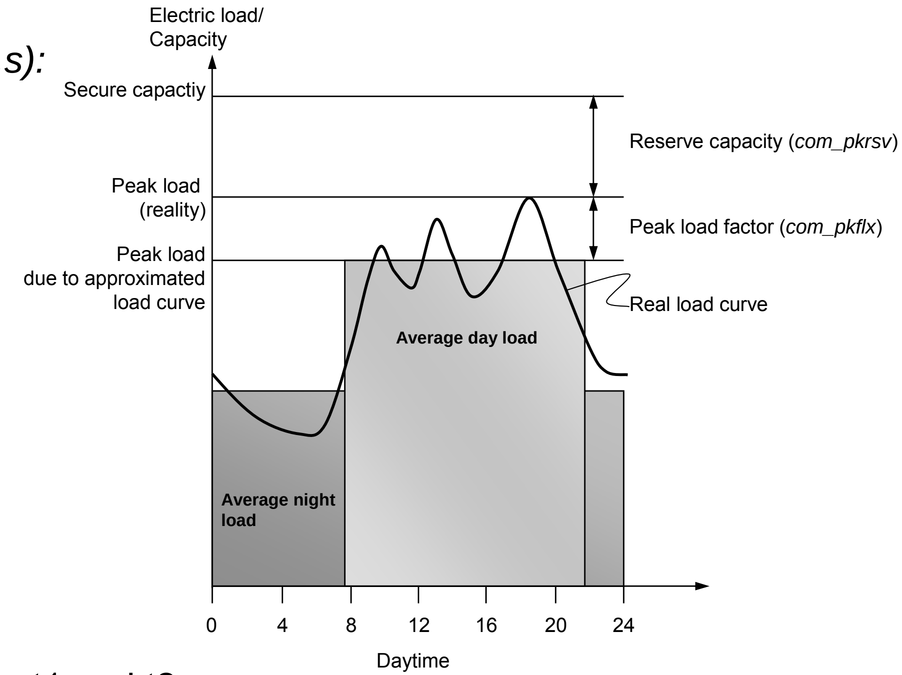
Commodity balance equation



Commodity balance equation contd.

- Commodity balance is created for timeslices on timeslice level specified by *COM_TSL* or individual timeslices given by *COM_TS* (note: then commodity is only available in *COM_TS* timeslices)
- Commodity efficiency *COM_IE*: $Commodity\ production \times COM\_IE \geq Commodity\ consumption$
- Annual demand given by *COM_PROJ(r,t,c)*
- Load curve of demand described by *COM_FR(r,t,c,s):*

```
PARAMETER COM_FR
/
  WEU.2000.RH.ID      0.12000000
  WEU.2000.RH.IN      0.06000000
  WEU.2000.RH.SD      0
  WEU.2000.RH.SN      0
  WEU.2000.RH.WD      0.54670000
  WEU.2000.RH.WN      0.27330000
/
```

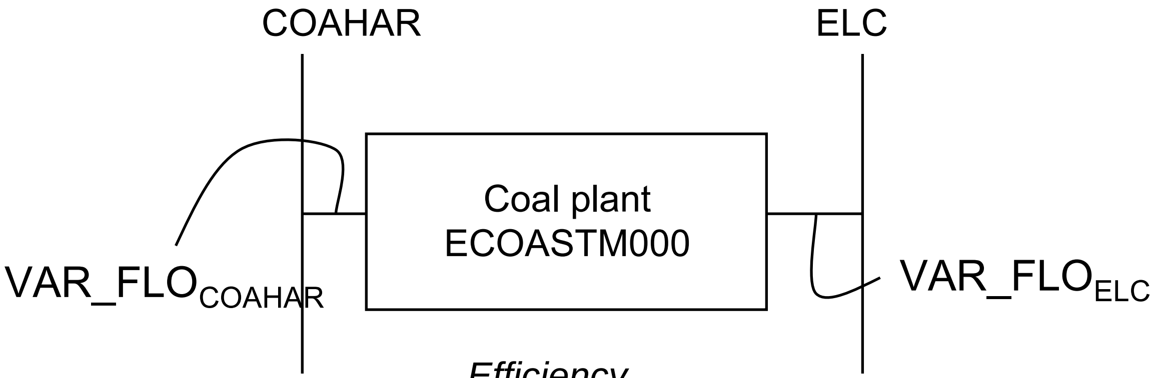


- Cumulative commodity bounds between two periods t1 and t2:
  - *COM_CUMNET(r,t1,t2,c,l)* limit on net amount of commodity
  - *COM_CUMPRD (r,t1,t2,c,l)* limit on production of commodity

Transformation equation

- Transformation equations establishes relationship between the flows of two commodity groups.

- Example 1: Efficiency of coal plant ECOASTM000



Efficiency

$$FLO\_FUNC_{r,t,ECOASTM000,COAHAR,ELC,s} = 0.33$$

Transformation equation

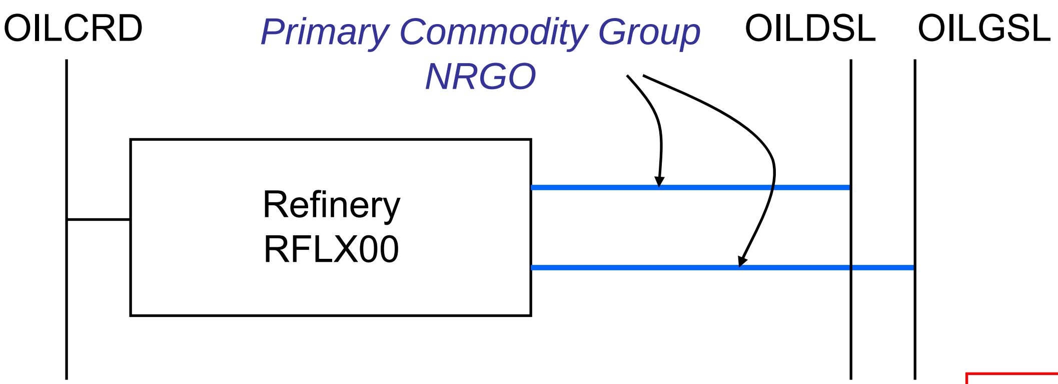
$$EQ\_PTRANS_{r,v,t,ECOASTM000,COAHAR,ELC,s}$$

$$FLO\_FUNC_{r,t,ECOASTM000,COAHAR,ELC,s} \times VAR\_FLO_{r,v,t,ECOASTM000,COAHAR,s} = VAR\_FLO_{r,v,t,ECOASTM000,ELC,s}$$

Process — *1st commodity group* — *2nd commodity group*

Transformation equation contd.

- Example 2: Simple refinery RFLX00



Efficiency $FLO\_FUNC_{r,t,RFLX00,NRGO,OIL,s} = 1$

1st commodity is now on the output side: FLO_FUNC appears always on the side of the process indicated by the first commodity group!!

Transformation equation

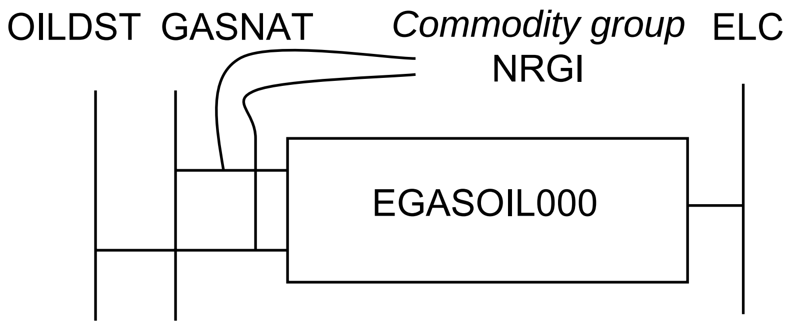
$$EQ\_PTRANS_{r,v,t,RFLX00,NRGO,OILCRD,s}$$

$$FLO\_FUNC_{r,t,RFLX00,NRGO,OILCRD,s} \times \left(VAR\_FLO_{r,v,t,RFLX00,OILDSL,s} + VAR\_FLO_{r,v,t,RFLX00,OILGSL,s}\right) = VAR\_FLO_{r,v,t,RFLX00,OILCRD,s}$$

Process — *1st commodity group* — *2nd commodity group*

Transformation equation contd.

- Example 3: Oil/Gas power plant



Overall Efficiency

$$FLO\_FUNC_{r,t,EGASOIL000,NRGI,ELC,s} = 1$$

Fuel-dependent Efficiency

$$FLO\_SUM_{r,t,EGASOIL000,NRGI,OILDST,ELC,s} = 0.35$$

$$FLO\_SUM_{r,t,EGASOIL000,NRGI,GASNAT,ELC,s} = 0.32$$

Process

1st commodity group

Member of 1st commodity group

2nd commodity group

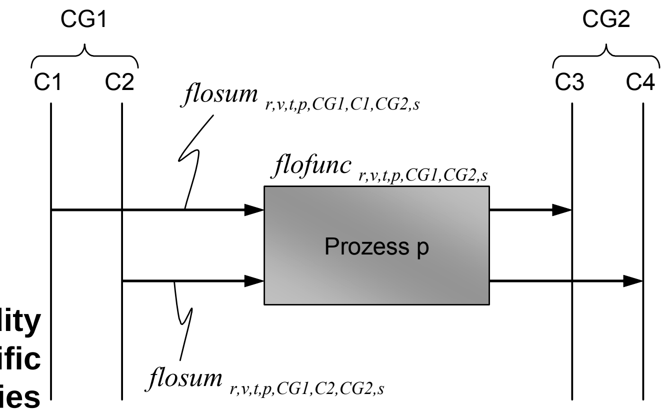
Transformation equation

$$EQ\_PTRANS_{r,v,t,EGASOIL000,NRGI,ELC,s}$$

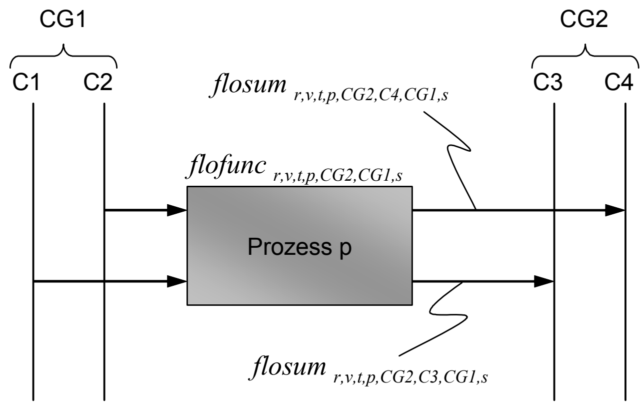
$$FLO\_FUNC_{r,t,EGASOIL000,NRGI,ELC,s} \times \begin{pmatrix} VAR\_FLO_{r,v,t,EGASOIL000,ELC,s} \times FLO\_SUM_{r,t,EGASOIL000,NRGI,OILDST,ELC,s} \\ + VAR\_FLO_{r,v,t,EGASOIL000,ELC,s} \times FLO\_SUM_{r,t,EGASOIL000,NRGI,GASNAT,ELC,s} \end{pmatrix} = VAR\_FLO_{r,v,t,EGASOIL000,ELC,s}$$

Transformation equation contd.

- Two possible cases:



Commodity specific efficiencies on the input side



Commodity specific efficiencies on the output side

$$flofunc_{r,v,t,p,CG1,CG2,s}\begin{pmatrix} flosum_{r,v,t,p,CG1,C1,CG2,s}FLO_{r,v,t,p,C1,s} \\ + flosum_{r,v,t,p,CG1,C2,CG2,s}FLO_{r,v,t,p,C2,s} \end{pmatrix} = FLO_{r,v,t,p,C3,s} + FLO_{r,v,t,p,C4,s}$$

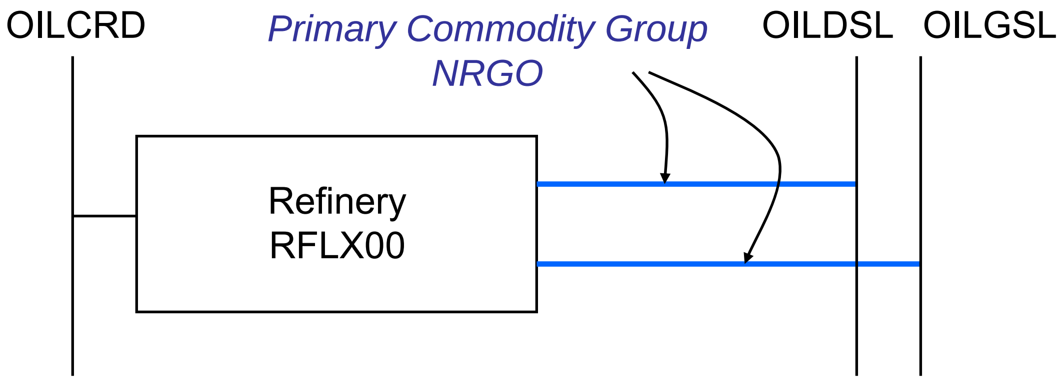
$$FLO_{r,v,t,p,C1,s} + FLO_{r,v,t,p,C2,s} = flofunc_{r,v,t,p,CG2,CG1,s}\begin{pmatrix} flosum_{r,v,t,p,CG1,C3,CG2,s}FLO_{r,v,t,p,C3,s} \\ + flosum_{r,v,t,p,CG1,C4,CG2,s}FLO_{r,v,t,p,C4,s} \end{pmatrix}$$

- It is not possible to use commodity specific efficiencies on both sides of the process at the same time!
- *EQ_PTRANS* is created on the finer timeslice level of SPG or PRC_TSL. SPG (Shadow Primary Commodity Group) is defined as the group of commodities on the opposite side of the PCG having the same commodity type as the PCG.

Definition of activity variable

- Activity of a process equals the sum of the flows specified in the Primary Commodity Group (PRC_ACTUNT).

- Activity variable is created on the timeslice level specified by PRC_TSL.



$$EQ\_ACTFLO_{r,v,t,RFLX00,s}$$

$$=$$

$$VAR\_ACT_{r,v,t,RFLX00,s} = VAR\_FLO_{r,v,t,RFLX00,OILDSL,s} + VAR\_FLO_{r,v,t,RFLX00,OILGSL,s}$$

Capacity utilization constraint

EQ(l)_CAPACT $_{r,v,t,p,s}$

VAR_ACT(r,v,t,p,s) ≤ = Available capacity of process p in period t and timeslice s

timeslice s member of PRC_TSL

Capacity:

- Past investments before model horizon: NCAP_PASTI
- New investments from previous periods
- New investments in actual period t

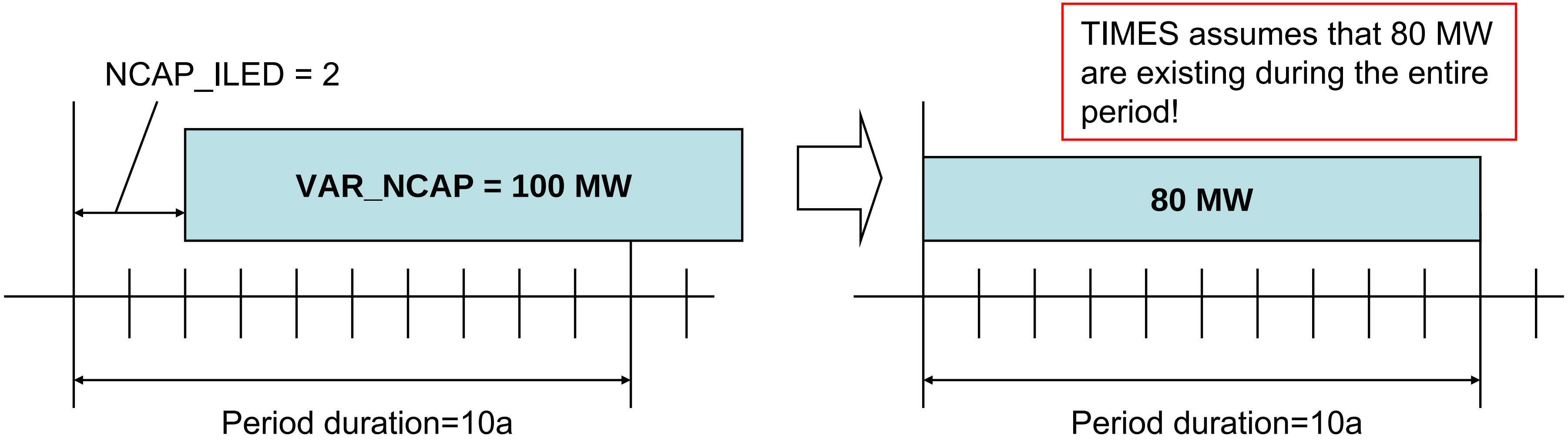
Three availabilities:

- NCAP_AFA(r,v,p,l) : Annual availability
- NCAP_AFS(r,v,p,s,l) : Seasonal availability
- NCAP_AF(r,v,p,s,l) : Availability in timeslices

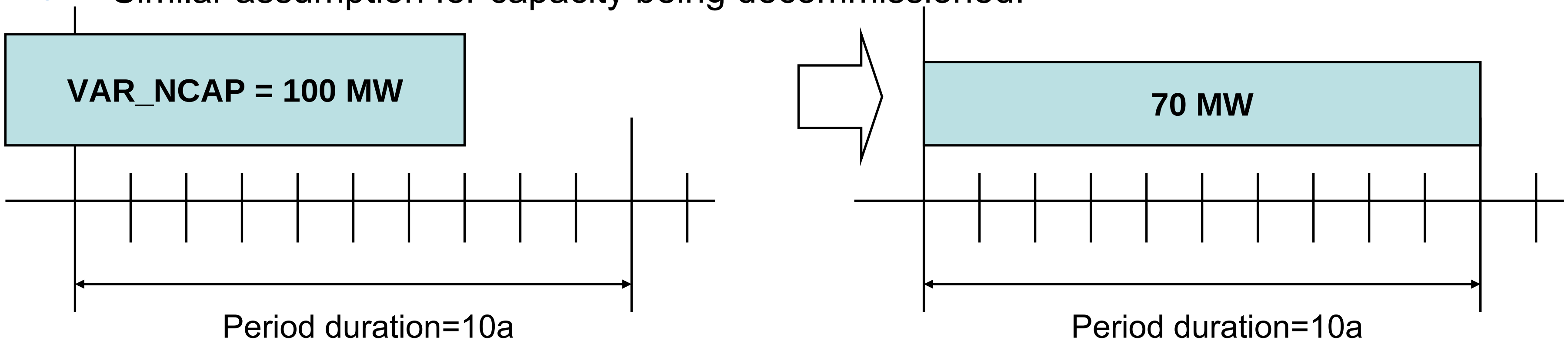
which can be combined.

Capacity utilization constraint contd.

- Effective capacity of a new investment with construction time in construction period:

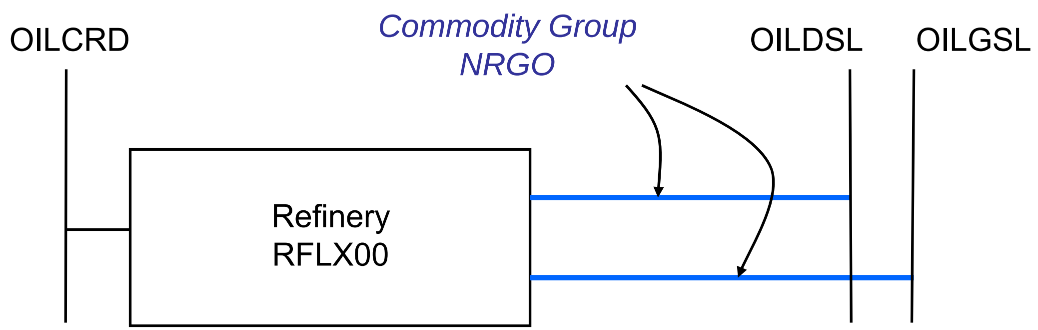


- Similar assumption for capacity being decommissioned:



Share constraints on the input/output of a process

- Possibility to limit the share of a commodity flow within a commodity group on the input or output side of a process.
- Example



$$FLO\_SHAR_{r,t,FRLX00,NRGO,OILDSL,s,UP} = 0.3$$

Process — *Commodity group defining the total flow* — *Commodity*

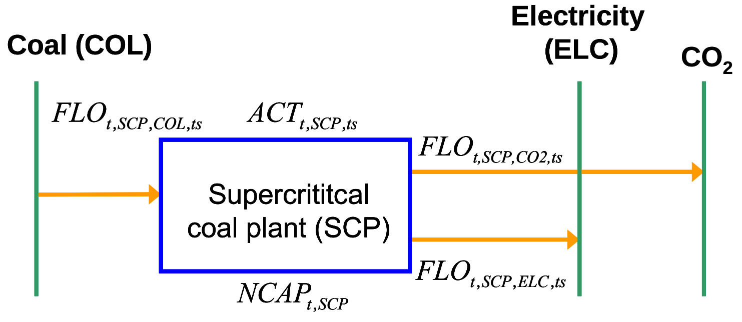
- Fixed, upper or lower bounds may be specified.
- Commodity group must not necessarily compromise all output/input flows, one can identify a subgroup as commodity group.

EQ(l)_IN/OUTSHR

$$\frac{\sum_{v} VAR\_FLO_{r,v,t,RFLX00,OILDSL,s}}{\sum_{v} \left(VAR\_FLO_{r,v,t,RFLX00,OILDSL,s} + VAR\_FLO_{r,v,t,RFLX00,OILGSL,s} \right)} \leq FLO\_SHAR_{r,t,RFLX00,NRGO,OILDSL,s,UP}$$

Objective function: Minimizing total system costs

- Objective function = total discounted energy system costs over the entire model horizon
- Typical cost components in the objective function:



i. Variable O&M costs in period t

$$\ldots + varom_{t,SCP} \cdot ACT_{t,SCP,ts} \cdot \Delta t + \ldots$$

ii. Fixed O&M costs in period t

$$\ldots + fixom_{t,SCP} \cdot CAP_{t,SCP,ts} \cdot \Delta t + \ldots$$

iii. Levelized investment costs in period t (capital recovery factor *crf* depends on economic lifetime and/or technology specific discount rate)

$$\ldots + crf_{t,SCP} \cdot invcost_{t,SCP} \cdot NCAP_{t,SCP,ts} + \ldots$$

iv. Costs/Revenues from imports/exports in period t

$$\ldots + price_{t,COL,IMP} \cdot IMP_{t,COL} \cdot \Delta t + \ldots$$

- Costs in real terms
- General discount rate used to discount costs from different periods to base year
- Investment costs spread over construction time to mimick interest cost during construction

Objective function

- **Discounted sum of the annual costs minus revenues:**

Construction

+ Investment costs
+ Costs for sunk material during construction time

Operation

+ Variable costs
+ Fix operating and maintenance costs
+ Imports
+ Taxes

Decommissioning

+ Surveillance costs
+ Decommissioning costs

Operation

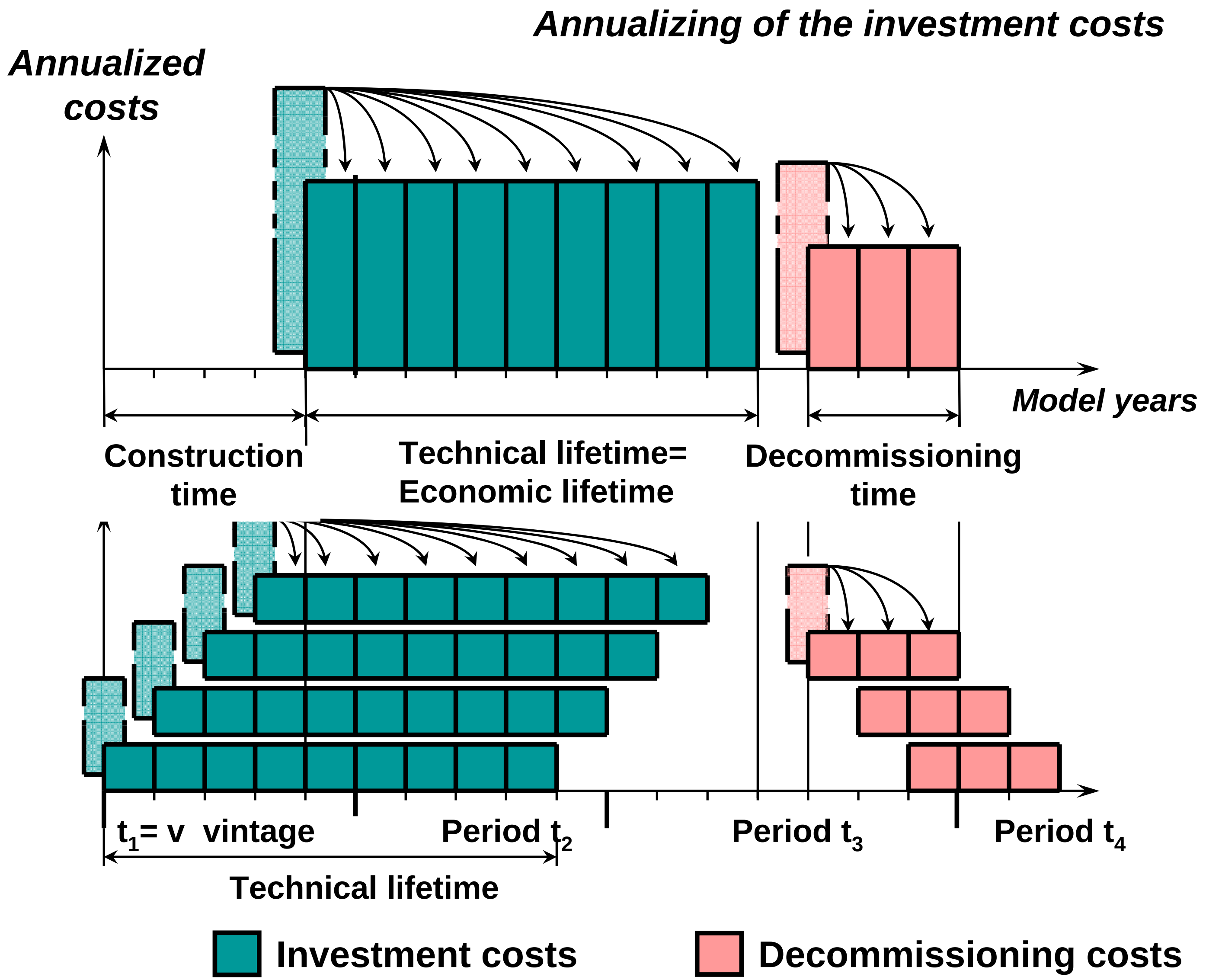
- Subsidies
- Exports

Decommissioning

- Recuperation of sunk material
- Salvage value

- Distinction between technical and economic lifetime
- General discount rate (discounting to base year) and technology specific discount rate (calculating annuities)
- Investment and decommissioning lead-times

Objective function



Summary of basic model equations

- Objective function

$$Min \sum_{y} disc_{y} \left[\begin{array}{l} \sum_{p}\sum_{ts} \cdot varom_{y,p,ts} \cdot ACT_{y,p,ts} + \sum_{p} crf_{y,p} \cdot invcost_{y,p} \cdot NCAP_{y,p} + \sum_{p} fixom_{y,p} \cdot CAP_{y,p} \\ + \sum_{c}\sum_{ts} impprice_{y,c,ts} \cdot IMP_{y,c,ts} - \sum_{c}\sum_{ts} expprice_{y,c,ts} \cdot EXP_{y,c,ts} + \sum_{c}\sum_{p}\sum_{ts} flocost_{y,p,c,ts} \cdot FLO_{y,p,c,ts} \end{array} \right]$$

- Commodity balance

$$\sum_{p \in Production} \sum_{ts} FLO_{t,p,c,ts} + \sum_{ts} IMP_{t,c,ts} = \sum_{p \in Consumption} \sum_{ts} FLO_{t,p,c,ts} + \sum_{ts} EXP_{t,c,ts}$$

- Transformation equation

$$\eta_{t,p,cin,cout,ts} \cdot FLO_{t,p,cin,ts} = FLO_{t,p,cout,ts}$$

- Input/Output shares on process flows

$$\frac{FLO_{t,p,com,ts}}{\sum_{c \in cg} FLO_{t,p,c,ts}} \leq (=, \geq) floshar_{t,p,com,cg,ts,bd}$$

- Activity definition

$$ACT_{t,p,ts} = FLO_{t,p,c,ts}$$

- Utilization constraints

$$ACT_{t,p,ts} \leq \alpha_{t,p,ts} \cdot CAP_{t,p}$$

- Market share constraints

$$\frac{\sum_{ts} FLO_{t,p,c,ts}}{\sum_{p \in Production/Consumption} \sum_{ts} FLO_{t,p,c,ts}} \leq (=, \geq) mrkshr_{t,p,c,bd}$$

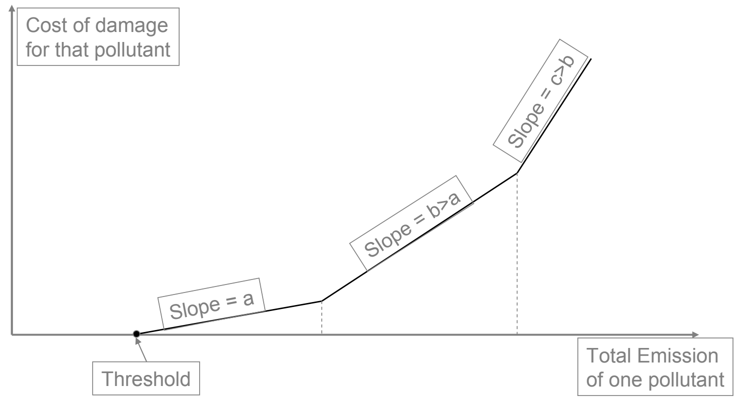
Further model equations

- Description of exchange processes in multi-regional models
- Elastic demands
- Product/market share constraints, e.g. share of hydrogen cars in total person kilometer demand
- Peaking equation: Ensures enough available secure capacity during peak demand
- Storage equation: Modeling of storage between timeslices (e.g. pump storage) or between periods (e.g. stockpiling)
- Commodity-specific availabilities, e.g. full load hours of CHP plant in backpressure and condensing mode
- User constraints: Flexible framework to formulate constraints being not part of the standard portfolio of TIMES equations, e.g. growth constraints, renewable quota

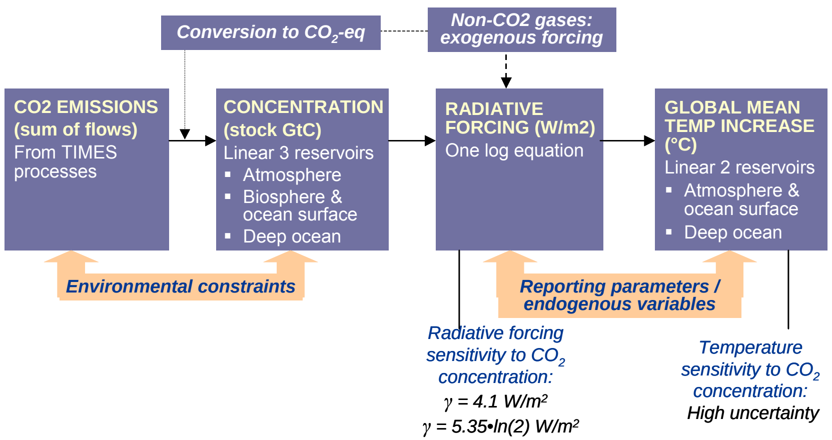
Model variants and extensions

- Block-wise formulation of new investments (lumpy investments)
- Endogenous technological learning
- Damage functions for external costs of pollutants
- Sensitivity analysis algorithm
- Stochastic programming
- MACRO economic extension
- Climate module

Damage functions



Climate Module – Main features



Stochastic TIMES – Example