Overview of TIMES: Parameters, Primal Variables & Equations

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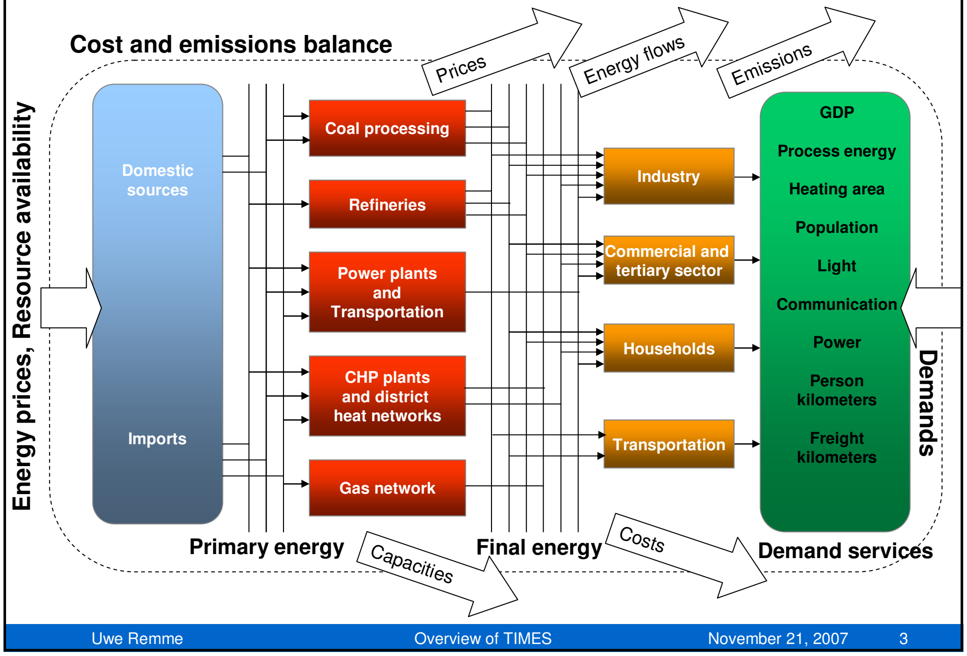
Overview

- 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**

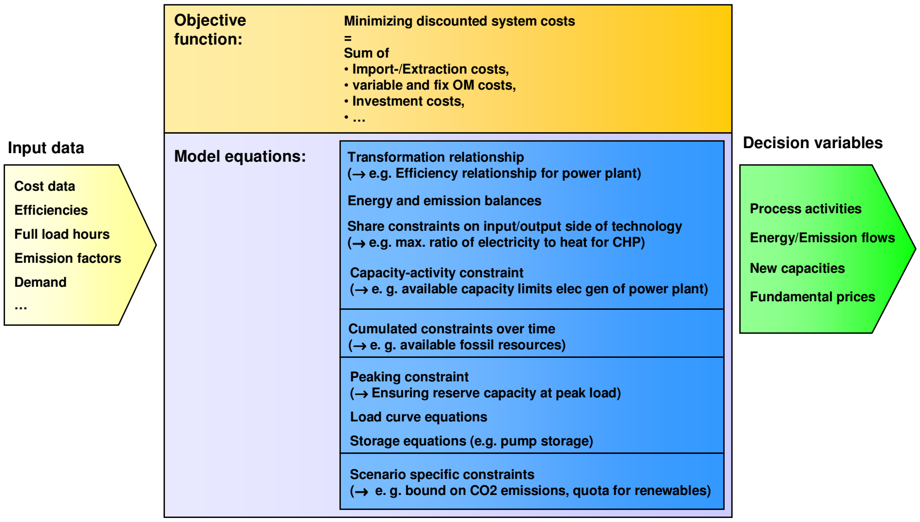
TIMES
(The Integrated MARKAL EFOM System)

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**

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

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*):
  i. Energy flows, resource extraction, emissions
  ii. Activity levels
  iii. Total capacities and new investments
  iv. 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.
  i. Long-run marginal costs for energy carriers (prices including capital costs)
  ii. Necessary subsidy or cost reduction, so that non-competitive technology will be used
  iii. Marginal CO_2 abatement costs = CO_2 certificate price

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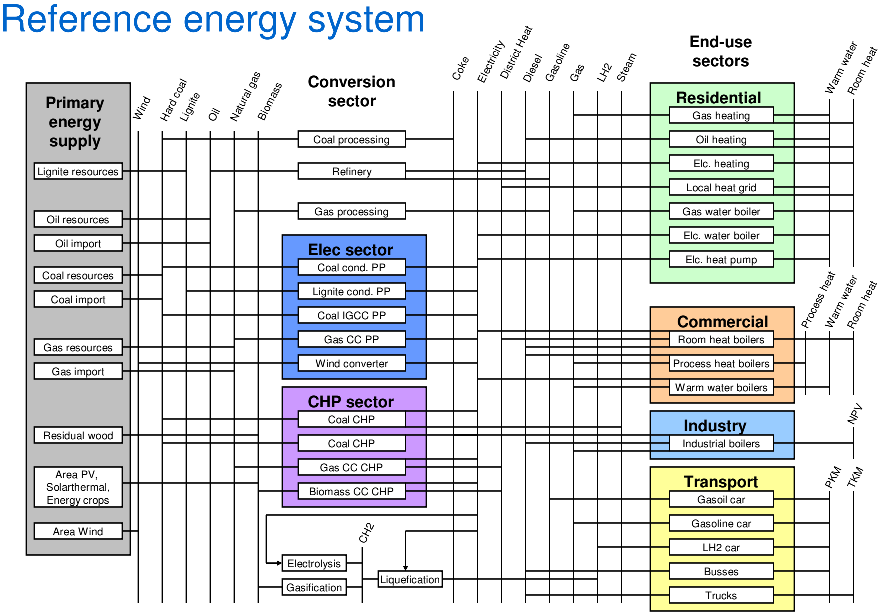
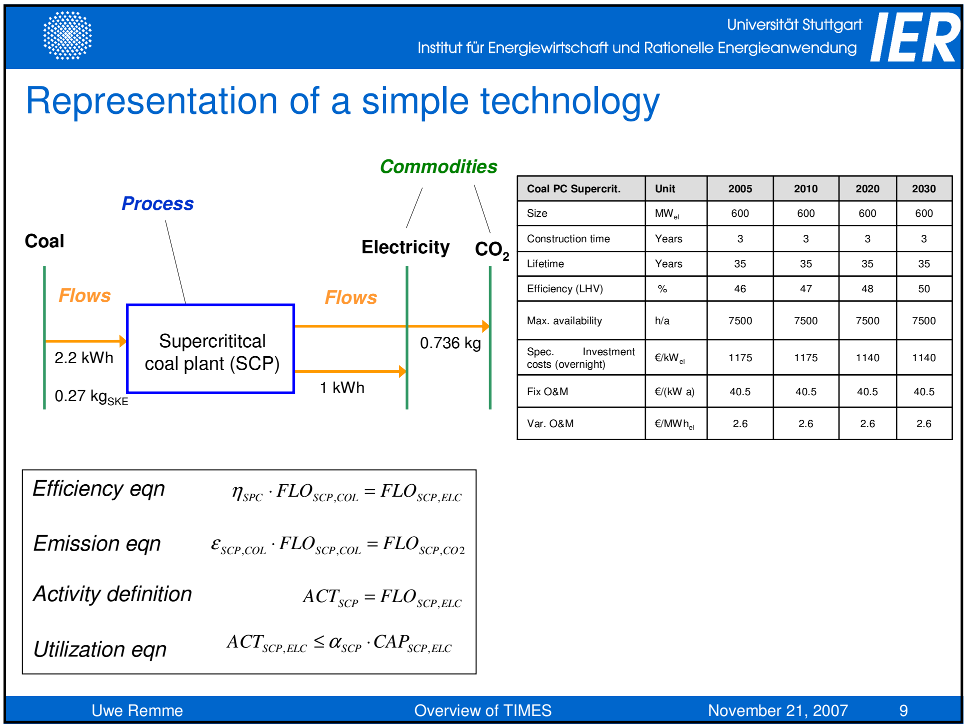
Reference energy system





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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 $ACT_{SCP,ELC} \le \alpha_{SCP} \cdot CAP_{SCP,ELC}$

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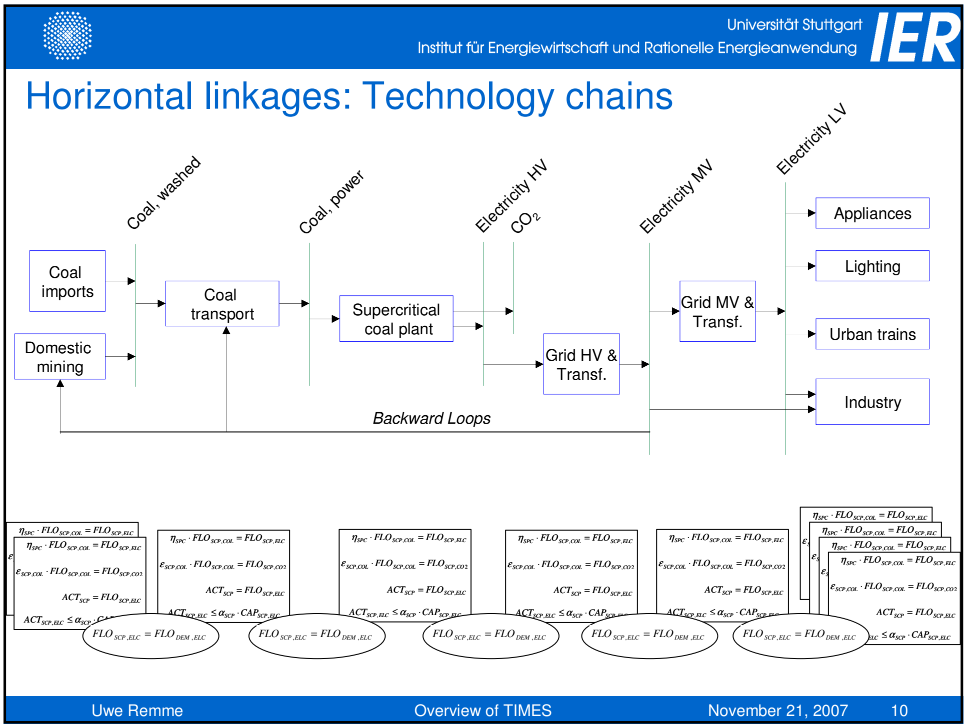

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Horizontal linkages: Technology chains

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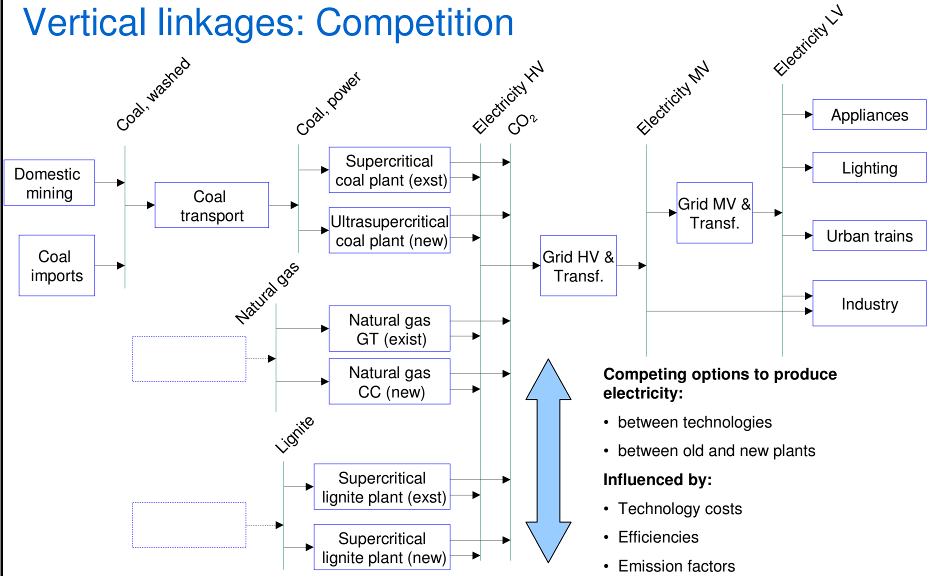
Vertical linkages: Competition



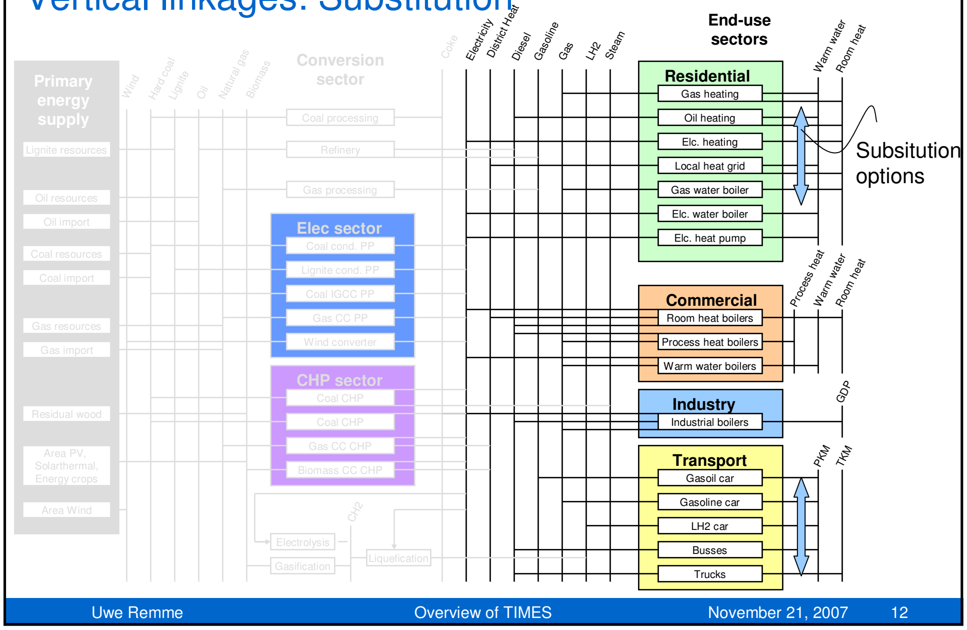
Competing options to produce electricity:

- between technologies
- between old and new plants

Influenced by:

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

Vertical linkages: Substitution



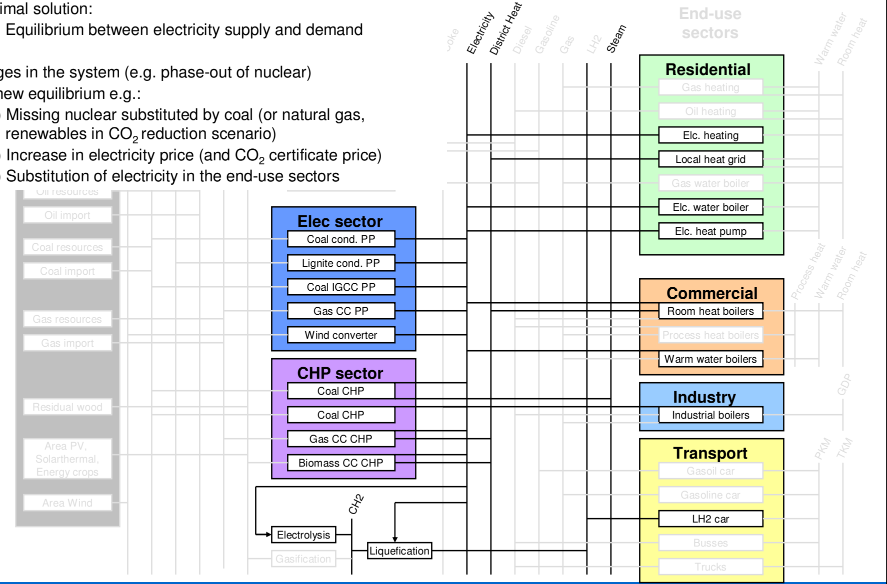
Interdependencies in the energy system

At optimal solution:

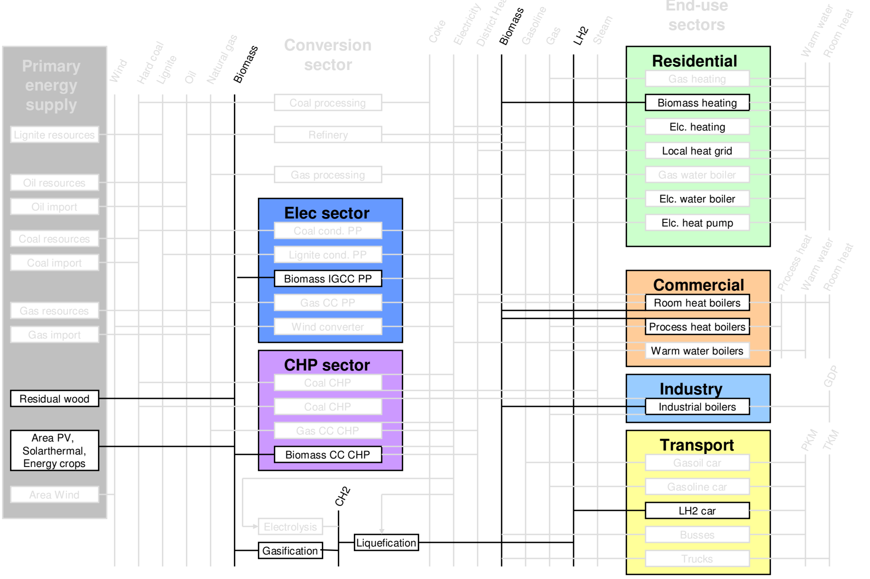
- Equilibrium between electricity supply and demand

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

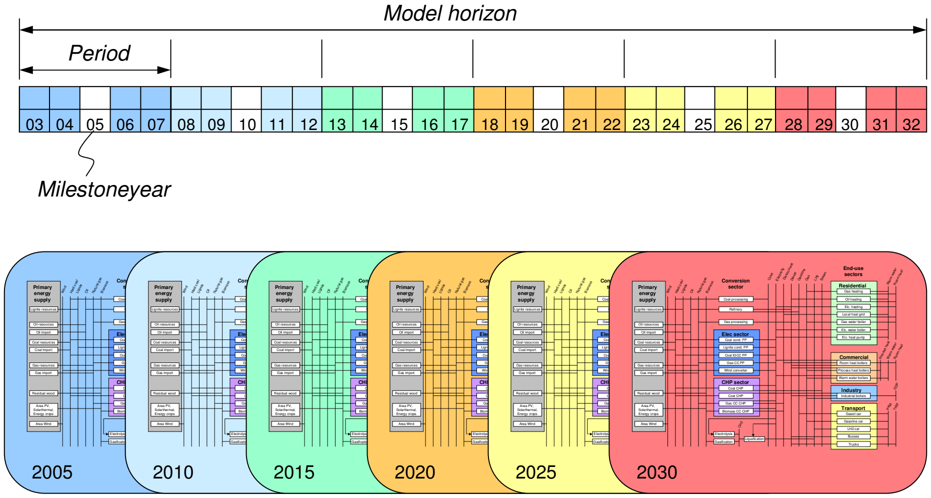
1) Missing nuclear substituted by coal (or natural gas, renewables in CO_2 reduction scenario)
2) Increase in electricity price (and CO_2 certificate price)
3) Substitution of electricity in the end-use sectors



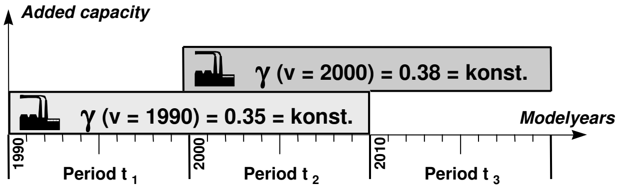
Interdependencies in the energy system



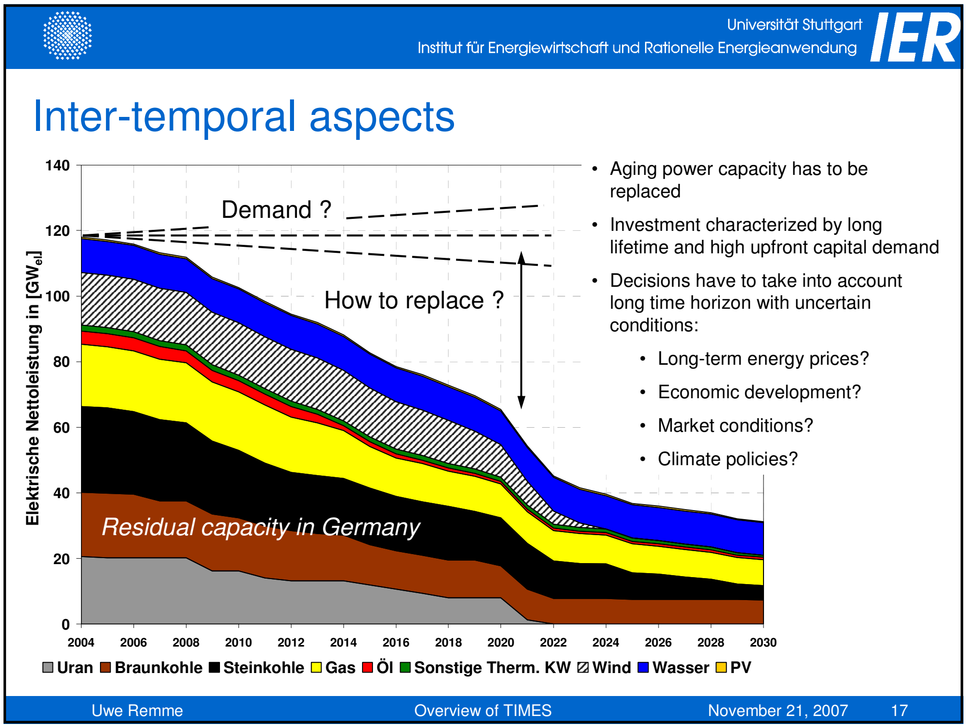
Dynamic model



Vintaging

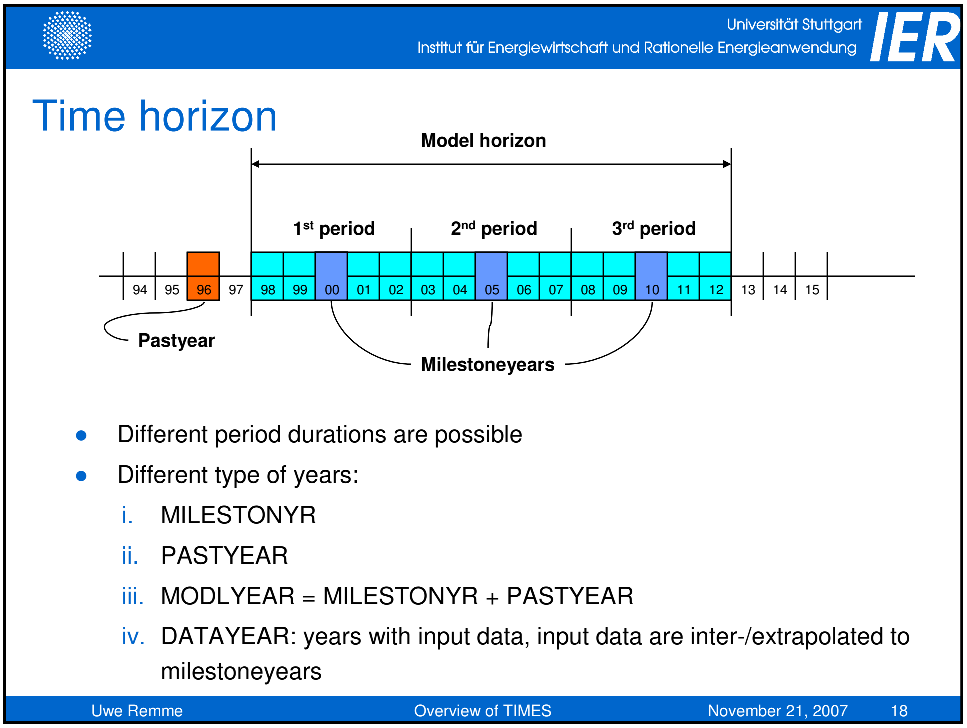


- Process can be specified as vintaged one by entry in set PRC_VINT.
- The characteristics of a vintaged process can be distinguished by its vintage year, e.g. process flow variables have as additional index of the current period *t* the construction period *v*: *VAR_FLO(r,v,t,p,c,s)*



Inter-temporal aspects

- Aging power capacity has to be replaced
- Investment characterized by long lifetime and high upfront capital demand
- Decisions have to take into account long time horizon with uncertain conditions:
  - Long-term energy prices?
  - Economic development?
  - Market conditions?
  - Climate policies?



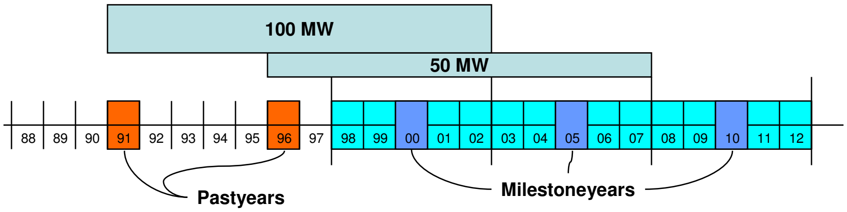
Time horizon

- 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  /
```

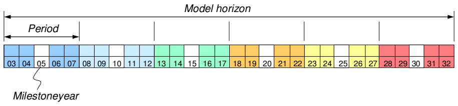
- Alternative specification of residual curve for **Milestoneyears** PRC_RESID(r,t,prc)

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

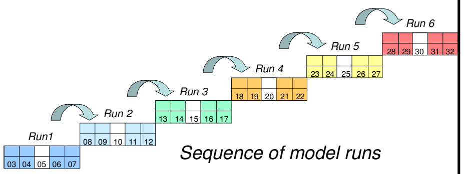
Foresight

Perfect foresight

Myopic foresight
(Dynamic-recursive)



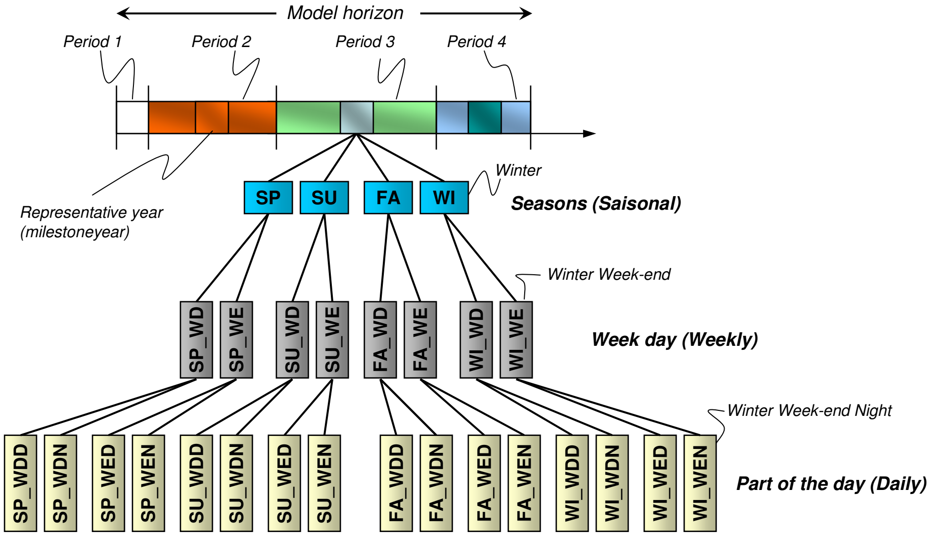
One optimization run over entire horizon



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)

SP_WD
SP_WE
SU_WD
SU_WE
FA_WD
FA_WE
WI_WD
WI_WE

Winter Week-end

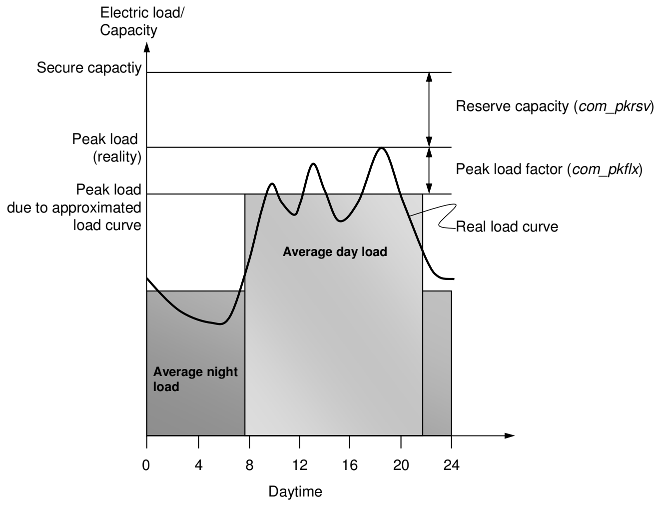
Week day (Weekly)

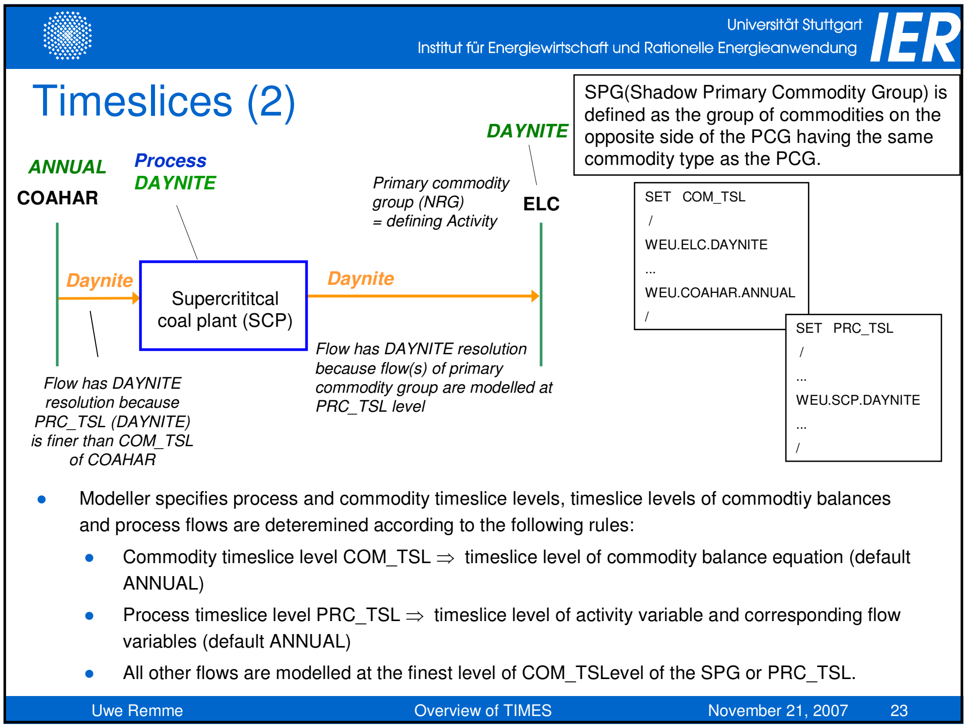
SP_WDD
SP_WDN
SP_WED
SP_WEN
SU_WDD
SU_WDN
SU_WED
SU_WEN
FA_WDD
FA_WDN
FA_WED
FA_WEN
WI_WDD
WI_WDN
WI_WED
WI_WEN

Winter Week-end Night

Part of the day (Daily)

Reserve capacity in the power sector





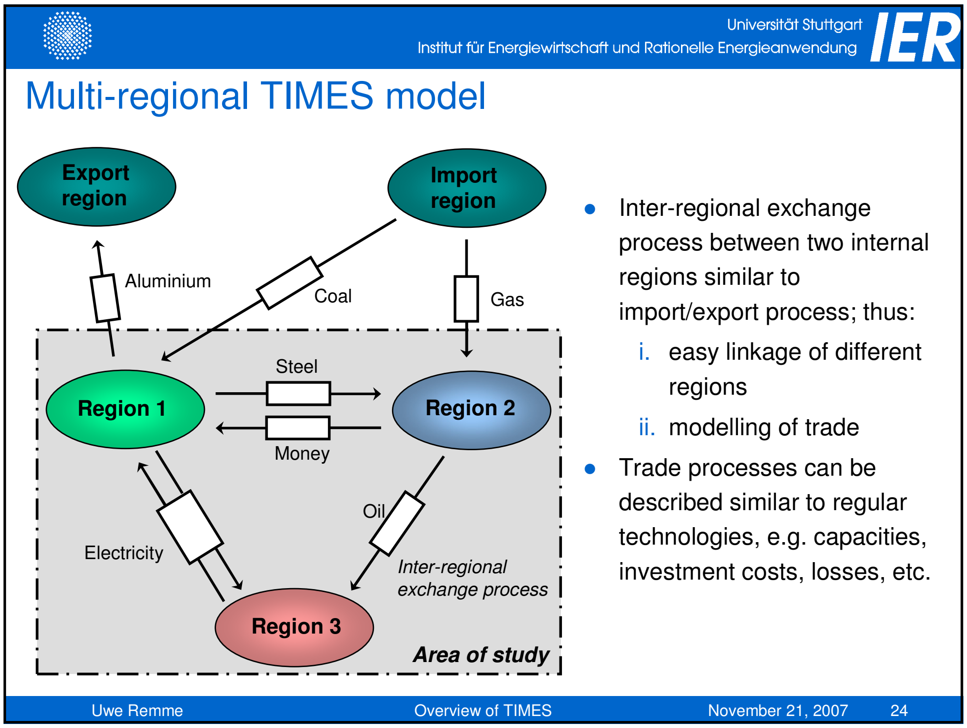
Timeslices (2)

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
…
/
```

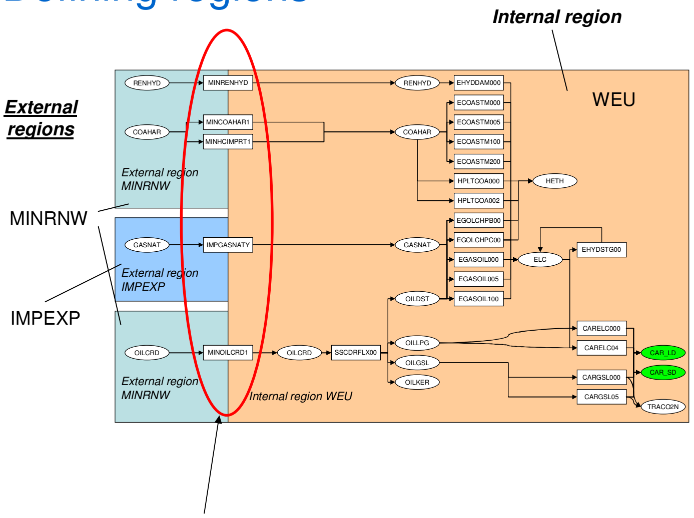
- Modeller specifies process and commodity timeslice levels, timeslice levels of commodtiy balances and process flows are deteremined according to the following rules:
  - Commodity timeslice level COM_TSL ⇒ timeslice level of commodity balance equation (default ANNUAL)
  - Process timeslice level PRC_TSL ⇒ 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:
  1. easy linkage of different regions
  2. modelling of trade
- Trade processes can be described similar to regular technologies, e.g. capacities, investment costs, losses, etc.

Defining regions



All regions

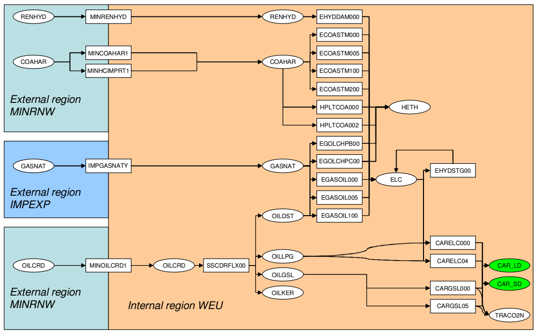
```
SET ALL_REG
/
WEU
IMPEXP
MINRNW
/;
```

Internal region

```
SET REG(ALL_REG)
/
WEU
/;
```

- External and internal regions are linked by exchange processes.

Defining commodities



Commodity groups

```
SET COM_GRP
/
COAHAR
OILCRD
OILLPG
OILGSL
OILKER
OILDST
GASNAT
RENHYD
ELC
HETH
…
/;
```

Commodities

```
SET COM(COM_GRP)
/
COAHAR
OILCRD
OILLPG
OILGSL
OILKER
OILDST
GASNAT
RENHYD
ELC
HETH
…
/;
```

- Each commodity is a commodity group with only one member: the commodity itself.
- Commodity unit must be specified, flows are measured in commodity units.
- Commodity type has to be specified: NRG (energy carrier), DEM (demand), ENV (environmental indicators), FIN (financial)

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. SSCCDRFLX00.SSCDRFLX00_NRGO
...
/;
```

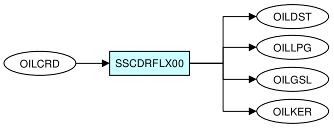
Process name

Topology

User defined commodity group

Members of commodity group

Commodity groups related to SSCCDRFLX00



```
SET PRC_CAPUNT(REG,PRC,CG,UNITS_CAP)
/
...
WEU.SSCDRFLX00.SSCDRFLX00_NRGO.PJA
...
/;

SET PRC_ACTUNT(REG,PRC,CG,UNITS_ACT)
/
...
WEU.SSCDRFLX00.SSCDRFLX00_NRGO.PJ
...
/;

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

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

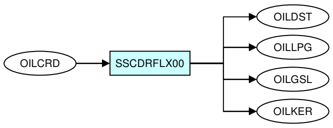
Capacity unit

PCG is SSCCDRFLX00 and activity unit PJ

No Conversion factor needed

Conversion factor is 1

Process definition in VEDA-FE

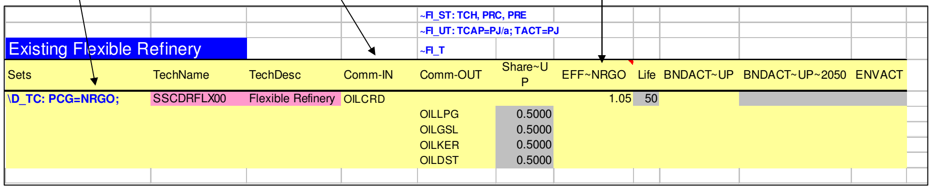


Capacity unit: PJ/a
Activity unit: PJ

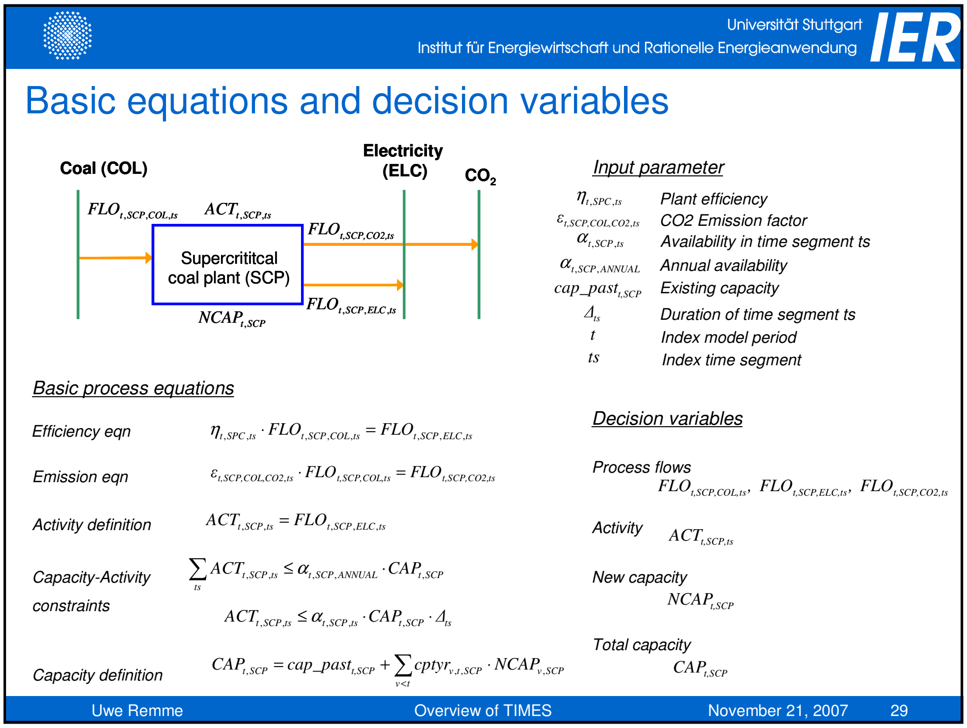
Topology

Activity = sum of all eNRGy output flows

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

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

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

Capacity definition

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

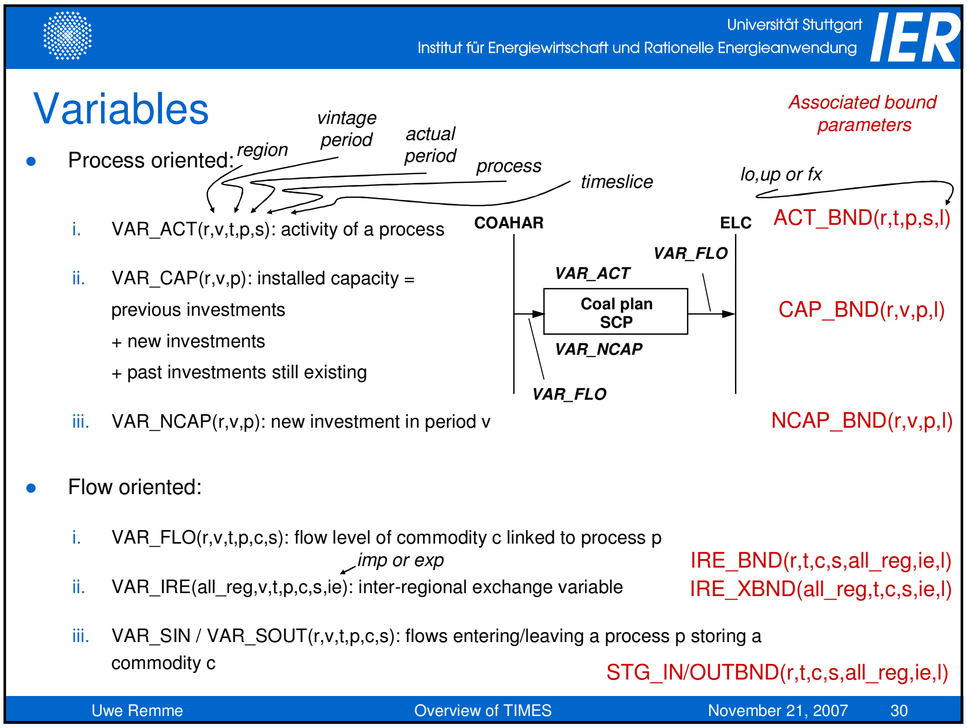
Decision variables

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

- Process oriented:

  i. VAR_ACT(r,v,t,p,s): activity of a process — 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 — IRE_BND(r,t,c,s,all_reg,ie,l)
  IRE_XBND(all_reg,t,c,s,ie,l)

  imp or exp

  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.

- Commodity oriented (only created if bound provided):

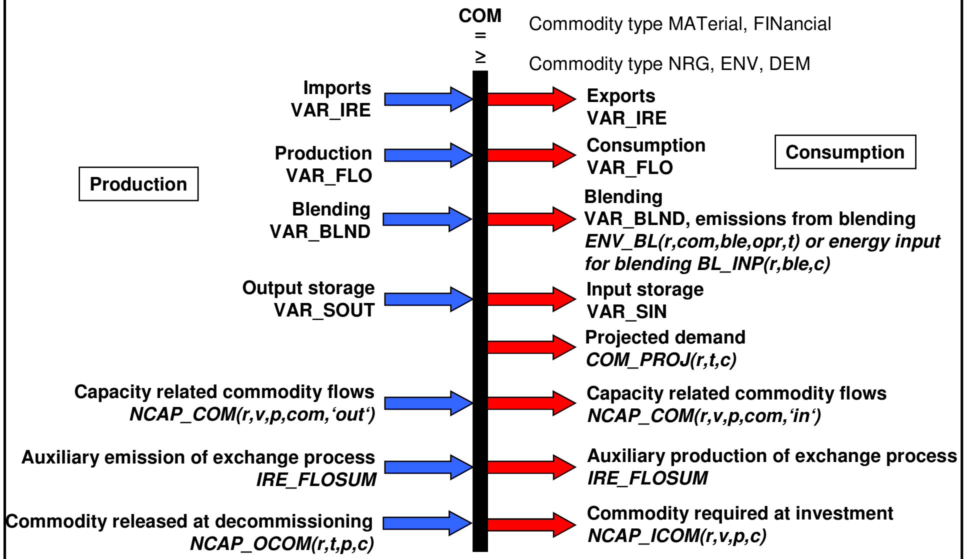
	Associated bound parameters
i. VAR_COMPRD(r,t,c,s): total production of a commodity	COM_BNDPRD(r,t,c,s,l)
ii. VAR_COMCON(r,t,c,s): total consumption of a commodity	COM_BNDCON(r,t,c,s,l)
iii. VAR_COMNET(r,t,c,s): net level of a commodity (production – consumption)	COM_BNDNET(r,t,c,s,l)

- 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



COM = Commodity type MATerial, FINancial

≥ Commodity type NRG, ENV, DEM

Production

Imports
VAR_IRE

Production
VAR_FLO

Blending
VAR_BLND

Output storage
VAR_SOUT

Capacity related commodity flows
NCAP_COM(r,v,p,com,'out')

Auxiliary emission of exchange process
IRE_FLOSUM

Commodity released at decommissioning
NCAP_OCOM(r,t,p,c)

Consumption

Exports
VAR_IRE

Consumption
VAR_FLO

Blending
VAR_BLND, emissions from blending *ENV_BL(r,com,ble,opr,t) or energy input for blending BL_INP(r,ble,c)*

Input storage
VAR_SIN

Projected demand
COM_PROJ(r,t,c)

Capacity related commodity flows
NCAP_COM(r,v,p,com,'in')

Auxiliary production of exchange process
IRE_FLOSUM

Commodity required at investment
NCAP_ICOM(r,v,p,c)

Commodity balance equation contd.

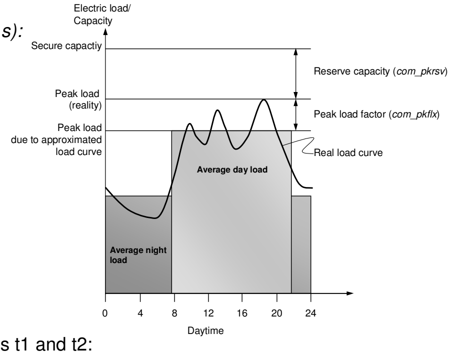
- Commodity balance is created for timeslices on timeslice level specified by *COM_TSL* or individual timeslices given by *COM_TS* (note: then commodity is only available in *COM_TS* timeslices)
- Commodity efficiency *COM_IE*: $Commodity\ production \times COM\_IE \geq Commodity\ consumption$
- Annual 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

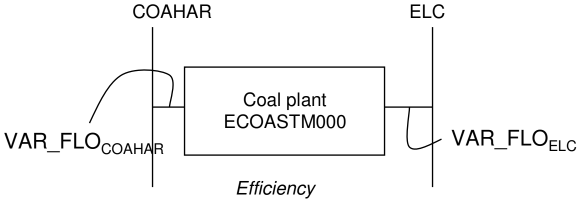
/



- 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



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

Transformation equation

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

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

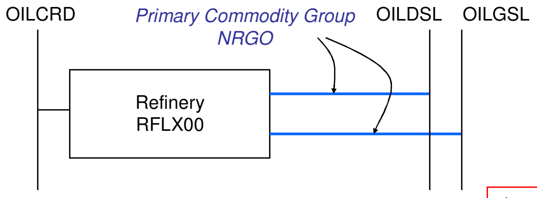
Process

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

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

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

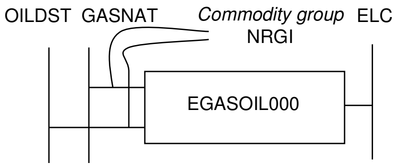
Process

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

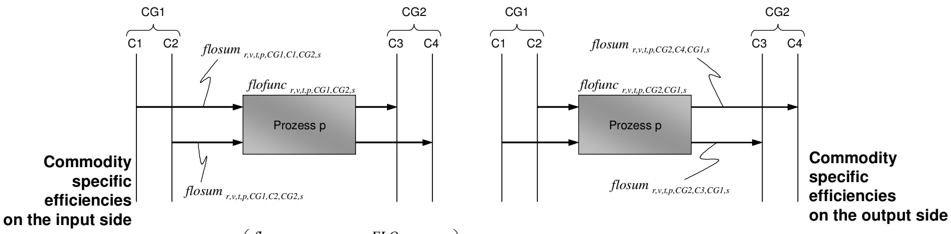
Transformation equation

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

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

Transformation equation contd.

- Two possible cases:



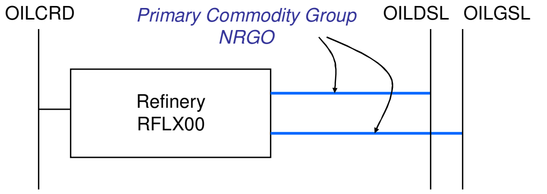
$$flofunc_{r,v,t,p,CG1,CG2,s} \begin{pmatrix} flosum_{r,v,t,p,CG1,C1,CG2,s} FLO_{r,v,t,p,C1,s} \\ + flosum_{r,v,t,p,CG1,C2,CG2,s} FLO_{r,v,t,p,C2,s} \end{pmatrix} = FLO_{r,v,t,p,C3,s} + FLO_{r,v,t,p,C4,s}$$

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

- 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.



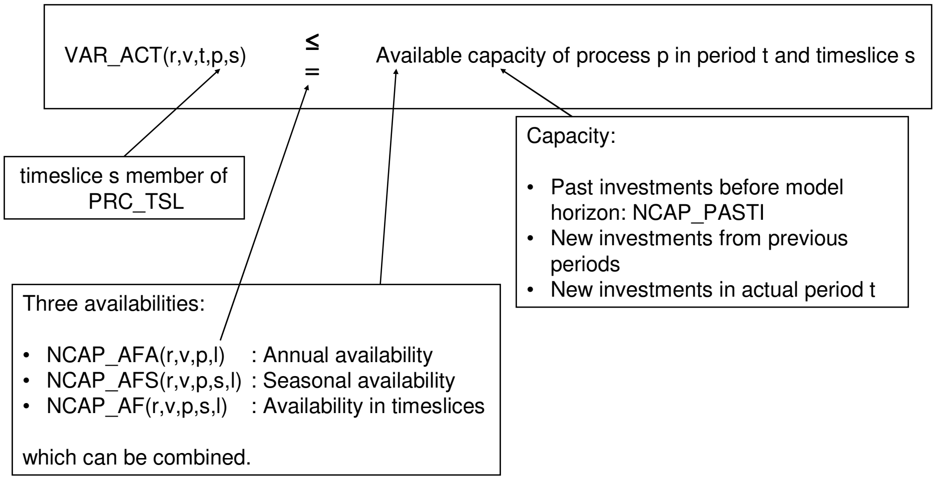
$$EQ\_ACTFLO_{r,v,t,RFLX00,s}$$

$$=$$

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

Capacity utilization constraint

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



VAR_ACT(r,v,t,p,s) $\overset{\le}{=}$ 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

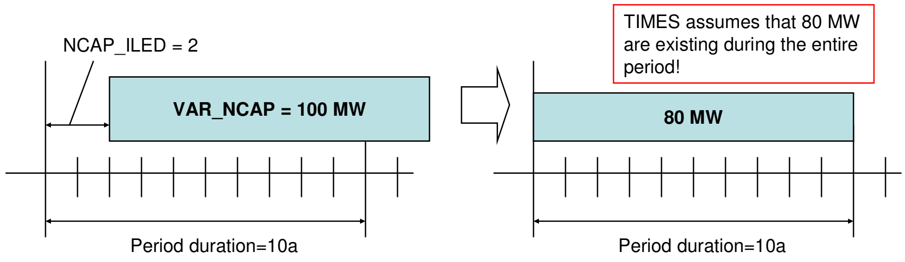
Three availabilities:

- 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.

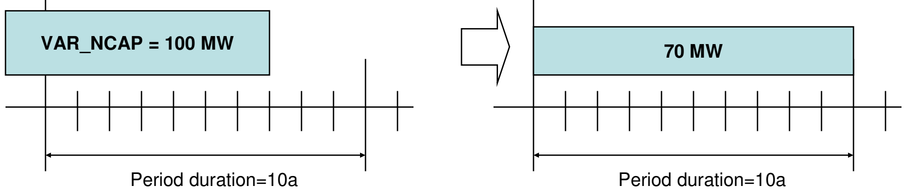
Capacity utilization constraint contd.

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



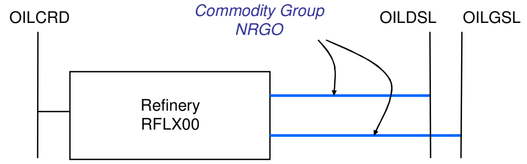
TIMES assumes that 80 MW are existing during the entire period!

- 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

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

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

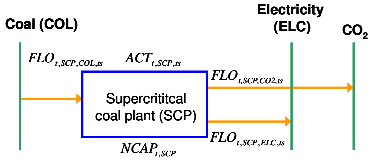
      $$\ldots + fixom_{t,SCP} \cdot CAP_{t,SCP,ts} \cdot \Delta t + \ldots$$

    - 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

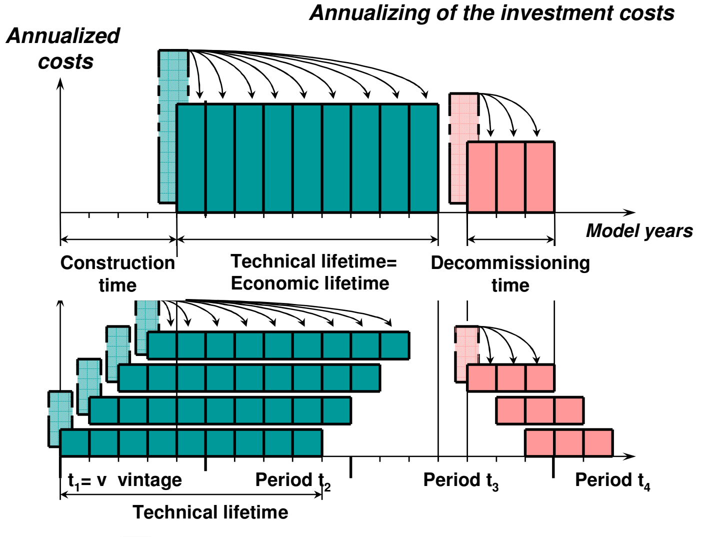
Decommissioning
+ Surveillance costs
+ Decommissioning costs

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

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

- 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

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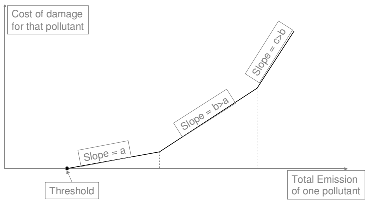
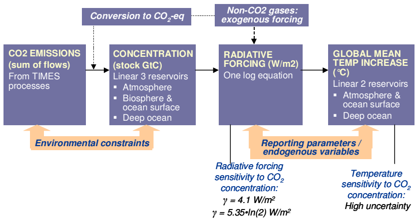
Model variants and extensions

- 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


Conversion to CO_2-eq

Non-CO2 gases: exogenous forcing

CO2 EMISSIONS (sum of flows)
From TIMES processes

CONCENTRATION (stock GtC)
Linear 3 reservoirs
- Atmosphere
- Biosphere & ocean surface
- Deep ocean

RADIATIVE FORCING (W/m2)
One log equation

GLOBAL MEAN TEMP INCREASE (°C)
Linear 2 reservoirs
- Atmosphere & ocean surface
- Deep ocean

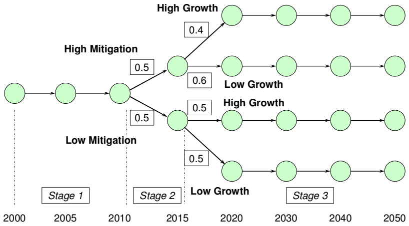
Environmental constraints

Reporting parameters / endogenous variables

Radiative forcing sensitivity to CO_2 concentration:
$\gamma = 4.1$ W/m²
$\gamma = 5.35 \cdot \ln(2)$ W/m²

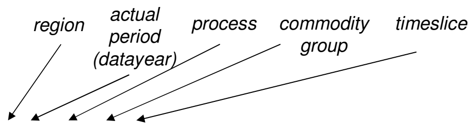
Temperature sensitivity to CO_2 concentration:
High uncertainty

Stochastic TIMES – Example



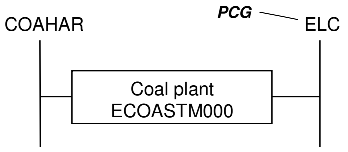
Process transformation parameter VEDA_FLOP

- Syntax:



VDA_FLOP(r, t, prc, cg, s)

- Example 1: Efficiency of coal plant ECOASTM000



- Primary commodity group (PCG) = Definition of activity (PRC_ACTUNT)

  here: Electricity ELC chosen
- Efficiency of 33%:

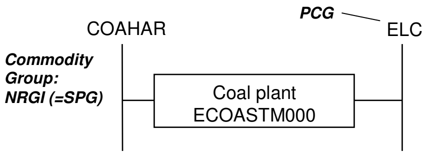
  $VDA\_FLOP_{r,t,ECOASTM000,COAHAR,s} = 3$

- *VDA_FLOP* defined for individual commodities c (input or output side):

  Flow of commodity c per unit of activity (here 3 units coal per 1 unit of electricity)
- Rigid processes can be defined in a similar manner, i.e. relating all commodity flows to the activity by individual *VDA_FLOP*s.

VEDA_FLOP contd.

- Example 2: Efficiency of coal plant ECOASTM000



- Primary commodity group (PCG) = Definition of activity (PRC_ACTUNT)

  here: Electricity ELC chosen
- Shadow primary group (SPG): all commodities of type NRG on the opposite side of the PCG

  here: COAHAR commodity
- Efficiency of 33%: $VDA\_FLOP_{r,t,ECOASTM000,COAHAR,s} = 0.33$

$$VDA\_FLOP_{r,t,ECOASTM000,NRGI,s} = 1$$

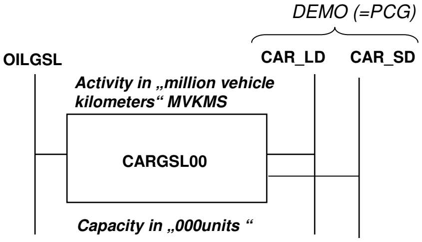
- VDA_FLOP for the shadow primary commodity group (SPG) NGRI of 1 needed to indicate that transformation equation works from the input to the output side

  (actually describes: activity units per one unit of SPG; here: one unit of electricity per unit of coal; corresponds to FLO_FUNC)
- VDA_FLOP for coal commodity defines the actual efficiency of 33% (corresponds to FLO_SUM).

$$\boxed{\begin{aligned}&VDA\_FLOP_{r,t,ECOASTM000,NRGI,s} \times VDA\_FLOP_{r,t,ECOASTM000,COAHAR,s} \times VAR\_FLO_{r,v,t,ECOASTM000,COAHAR,s}\\&= VAR\_FLO_{r,v,t,ECOASTM000,ELC,s}\end{aligned}}$$

VEDA_FLOP contd.

- Example 3: Dual mode car



- Primary commodity group (PCG) = Definition of activity (PRC_ACTUNT)

  here: group of CAR_LD and CAR_SD; called DEMO
- SPG: here OILGSL
- Modal efficiencies:

$$VDA\_FLOP_{r,t,CARGSL,CAR\_LD,s} = 0.8$$

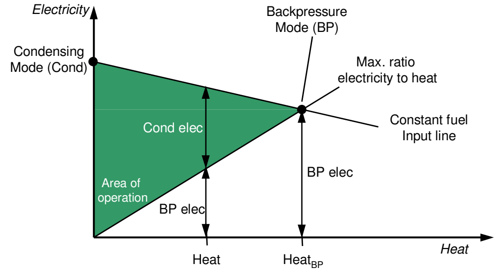
$$VDA\_FLOP_{r,t,CARGSL,CAR\_SD,s} = 1.11$$

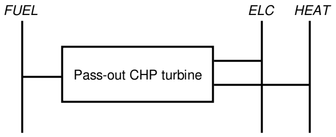
- Overall efficiency from PCG to SPG(optional):

$$VDA\_FLOP_{r,t,CARGSL,DEMO,s} = 1$$

$$\boxed{VAR\_FLO_{r,v,t,CARGSL00,OILGSL,s} = VDA\_FLOP_{r,t,CARGSL,DEMO,s} \times \begin{pmatrix} VDA\_FLOP_{r,t,CARGSL,CAR\_LD,s} \times VAR\_FLO_{r,v,t,CARGSL,CAR\_LD,s} + \\ VDA\_FLOP_{r,t,CARGSL,CAR\_SD,s} \times VAR\_FLO_{r,v,t,CARGSL,CAR\_SD,s} \end{pmatrix}}$$

CHP plants





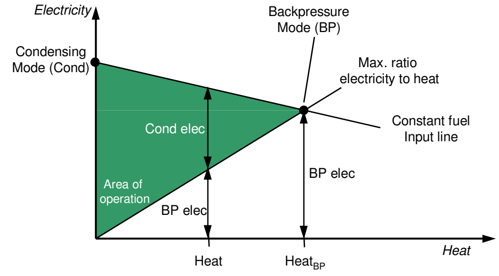
Description of constant fuel input line

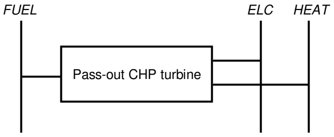
$$VAR\_FLO_{fuel} = \frac{1}{\eta_{cond}} \left(VAR\_FLO_{ELC} + elp \cdot VAR\_FLO_{HEAT} \right)$$

$$reh \geq \frac{VAR\_FLO_{ELC}}{VAR\_FLO_{HEAT}}$$

η_{cond} : Condensing mode efficiency
reh : Max. Ratio of electricity to heat
elp : Electricity loss per heat unit

CHP plants – Input parameters





- Pass-out or extraction turbine:
  1. Parameter VDA_CEH(r,t,prc):
     - a) <= 1: electricity loss per unit of heat gained (moving from condensing to backpressure mode; indicates activity is measured in terms of electricity
     - b) >= 1: heat loss per unit of electricity gained (moving from backpressure to condensing mode); indicates activity is measured in terms of total ouptut (electricity plus heat)
  2. Efficiencies:

     Case a): efficiencies must be specified for condensing point; costs must be specified based on condensing mode (e.g. investment costs)

     Case b): efficiencies must be specified for backpressure point; costs must be specified based on total electricity and heat output at backpressure point (e.g. investment costs)
  3. NCAP_CHPR(r,t,prc,bd): Ratio of heat to power at backpressure point; at least a maximum value is required, but in addition also a minimu value may be specified

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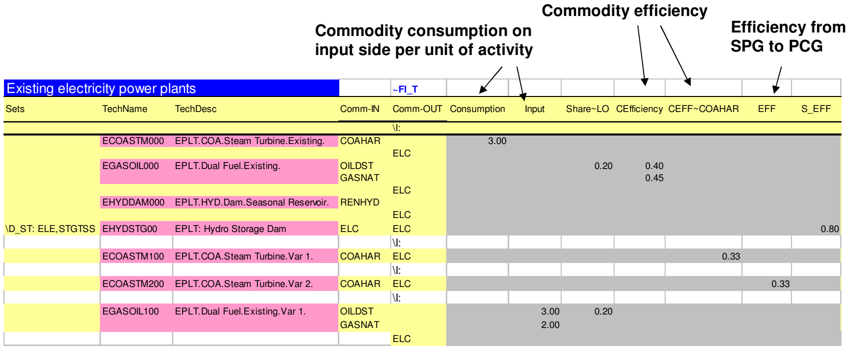
Efficiency parameters in VEDA-FE



Commodity consumption on input side per unit of activity

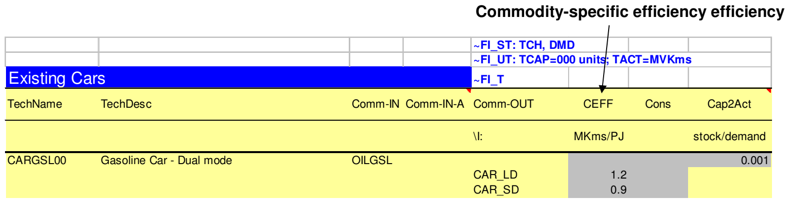
Commodity efficiency

Efficiency from SPG to PCG

Existing electricity power plants

~FI_T

Sets	TechName	TechDesc	Comm-IN	Comm-OUT	Consumption	Input	Share~LO	CEfficiency	CEFF~COAHAR	EFF	S_EFF
				\I:							
	ECOASTM000	EPLT.COA.Steam Turbine.Existing.	COAHAR		3.00						
				ELC							
	EGASOIL000	EPLT.Dual Fuel.Existing.	OILDST				0.20	0.40			
			GASNAT					0.45			
				ELC							
	EHYDDAM000	EPLT.HYD.Dam.Seasonal Reservoir.	RENHYD								
				ELC							
\D_ST: ELE,STGTSS	EHYDSTG00	EPLT: Hydro Storage Dam	ELC	ELC							0.80
				\I:							
	ECOASTM100	EPLT.COA.Steam Turbine.Var 1.	COAHAR	ELC					0.33		
				\I:							
	ECOASTM200	EPLT.COA.Steam Turbine.Var 2.	COAHAR	ELC						0.33	
				\I:							
	EGASOIL100	EPLT.Dual Fuel.Existing.Var 1.	OILDST			3.00	0.20				
			GASNAT			2.00					
				ELC							



Commodity-specific efficiency efficiency

~FI_ST: TCH, DMD

~FI_UT: TCAP=000 units; TACT=MVKms

Existing Cars

~FI_T

TechName	TechDesc	Comm-IN	Comm-IN-A	Comm-OUT	CEFF	Cons	Cap2Act
				\I:	MKms/PJ		stock/demand
CARGSL00	Gasoline Car - Dual mode	OILGSL					0.001
				CAR_LD	1.2		
				CAR_SD	0.9		

Defining processes

- Each process is member of the set PRC.
- Input and output commodities by entries in set TOP
- Primary commodity group (PCG):
  - i. Group of commodity flows defining activity of a process
  - ii. Activity unit has to be given.

  } ⇒Set PRC_ACTUNT (r,prc,cg,units_act)
- Capacity unit has to be specified.
- Commodity units defines flow units.
- Activity and commodity unit of PCG different ⇒ PRC_ACTFLO converting activity units to flow units of PCG
- Capacity unit and activity unit different ⇒ PRC_CAPACT converting capacity units to activity unit
- User is responsible for correct conversion factors!
- All commodity groups (CGs) related to the process ⇒ set PRC_CG

Defining processes contd.

```
SET PRC
/
...
CARGSL00
...
/;
SET TOP (REG,PRC,COM,IO)
/
...
WEU.CARGSL00.OILGSL.IN
WEU.CARGSL00.CAR_LD.OUT
WEU.CARGSL00.CAR_SD.OUT
/;

SET PRC_CG(REG,PRC,CG)
/
...
WEU.CARGSL00.CARGSL00_DEMO
...
/;

SET PRC_CAPUNT(REG,PRC,CG,UNITS_CAP)
/
...
WEU.CARGSL00.CARGSL00_DEMO. 000units
...
/;

SET PRC_ACTUNT(REG,PRC,CG,UNITS_ACT)
/
...
WEU.CARGSL00.CARGSL_DEMO.MVKMS
...
/;
```

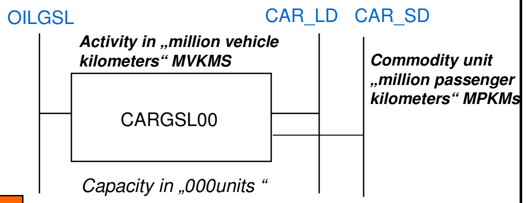
Process name

Topology

Commodity groups related to CAR

Capacity unit

PCG = total demand output and activity unit in MVKMS



Activity in „million vehicle kilometers“ MVKMS

Commodity unit „million passenger kilometers“ MPKMs

Capacity in „000units “

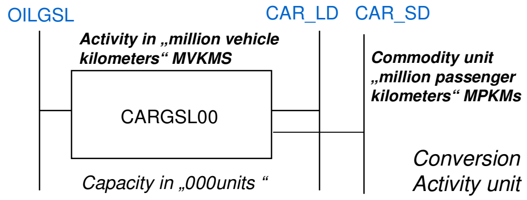
```
PARAMETER PRC_ACTFLO(REG,ALLYEAR,PRC,CG)
/
WEU.1990.CARGSL00.CARGSL00_DEMO
/;

PARAMETER PRC_CAPACT(REG,PRC)
/
WEU.CARGSL00     0.001
/;
```

Persons per car

VKM/car = 1000 VKM/car = 1 MVKM/1000cars

Process definition in VEDA-FE



Activity in „million vehicle kilometers" MVKMS

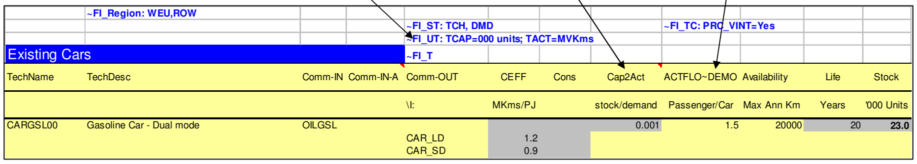
Commodity unit „million passenger kilometers" MPKMs

Capacity in „000units "

Conversion factor
Activity unit to unit of demand
(1 VKm = 1.5 PKm)

Conversion factor
Capacity to Activity
(1000 VKm per car and year)

Capacity unit: number of cars
Activity unit: vehicle kilometers



	~FI_Region: WEU,ROW										
				~FI_ST: TCH, DMD				~FI_TC: PRC_VINT=Yes			
				~FI_UT: TCAP=000 units; TACT=MVKms							
Existing Cars				~FI_T							
TechName	TechDesc	Comm-IN	Comm-IN-A	Comm-OUT	CEFF	Cons	Cap2Act	ACTFLO~DEMO	Availability	Life	Stock
				\I:	MKms/PJ		stock/demand	Passenger/Car	Max Ann Km	Years	'000 Units
CARGSL00	Gasoline Car - Dual mode	OILGSL					0.001	1.5	20000	20	**23.0**
				CAR_LD	1.2						
				CAR_SD	0.9						