The KAPSARC Energy Model for Saudi Arabia

Documentation of the model build called "KEM-SA_v9.16"

Contents

Summary: The KAPSARC Energy Model for Saudi Arabia

The KAPSARC Energy Model for Saudi Arabia (KEM-SA) is a partial economic equilibrium model that characterizes some of the energy and most energy-intensive sectors in the Saudi economy; these are the electric power, petrochemicals, refining, water desalination, oil and gas upstream and cement sectors. Each sector is contained within its own sub-model and acts as an agent that makes decisions on fuel usage, investment and technology to minimize its cost or maximize profit. The model is being expanded to include more sectors from the demand-side in the economy; first by developing a residential electricity use model that is linked with KEM-SA and then a passenger transport model. The sectors and the transfer of physical goods among them are presented in Figure 1 below.

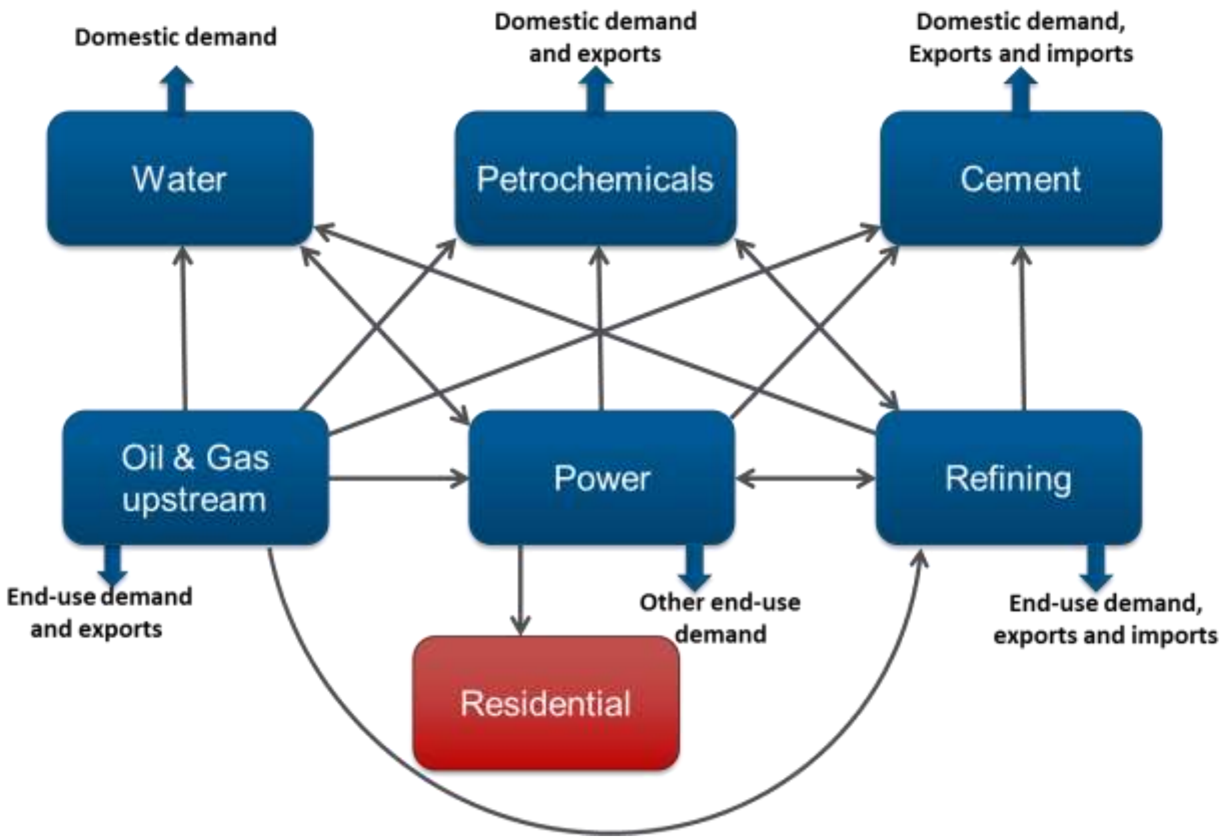


Figure 1 – Sectors in KEM-SA and their modeled interactions

The modeling framework was developed by KAPSARC because Saudi Arabia faces a set of energy issues including growing local demand, limited production of natural gas and a domestic economy that functions with energy prices that are set by the government. Historically, domestic energy prices are administered by the government for two main reasons:

- To support the diversification of the economy through industrialization, and

- To support local residents with low and fixed prices; the low fuel prices are also passed on to the end-consumers of the utilities' and the industrial sectors' products.

However, because the true opportunity costs are not used as prices, the current fuel pricing policy has led to a situation of economic and energy inefficiency within the energy-consuming sectors. KEM-SA is a tool to help estimate the consequences of alternative energy policies that affect energy production and use within Saudi Arabia. Matar et al. (2015a, 2015b, 2015c) and Matar (2016) previously employed the model for exploring the effects of some alternative scenarios.

A mixed-complementarity problem (MCP) formulation is adopted for KEM-SA because it allows us to consider the administered energy prices that permeate the Saudi economy. The workflow has been to first develop the linear program (LP) that represents the operation and investment for the sector, and then specify that as the primal LP problem. From the primal problem, we can, with consideration of mathematical theorems of duality, write a dual LP problem. The primal and dual LPs produce the same objective value, and their respective constraints can be solved together without explicitly including the objective functions; the objective function in one problem is embedded in the other. Murphy et al. (2016) have made the case for the use of MCP in energy policy models and detail the workflow of the KEM-SA.

Running KEM-SA

KEM-SA is developed and run in the General Algebraic Modeling System (GAMS) development environment. A GAMS license for the solver PATH is the only requirement to run the model; KAPSARC aims to provide a virtual environment to run the model so that it is accessible to all users. Everything else, including the data, is contained within the model files.

To begin, a user should first create a project directory in the folder where **Integratedmodel.gms** is stored. The command to create a new project directory can be found in the "file" drop-down menu of the GAMS user interface. The naming of it is up to the user.

Integratedmodel.gms is the main model file. It includes all the model files in the root model directory and the folders KEM and RW; the folder KEM contains all the main model files and the folder RW incorporates the report writing files. When the main model file is opened in GAMS, the internal directories KEM and RW must be called as "idir=kem;rw;" in the command line, as shown in Figure 2 below. Once the command is written, click on the button just left of it (or press F9 on the keyboard) to run the model.

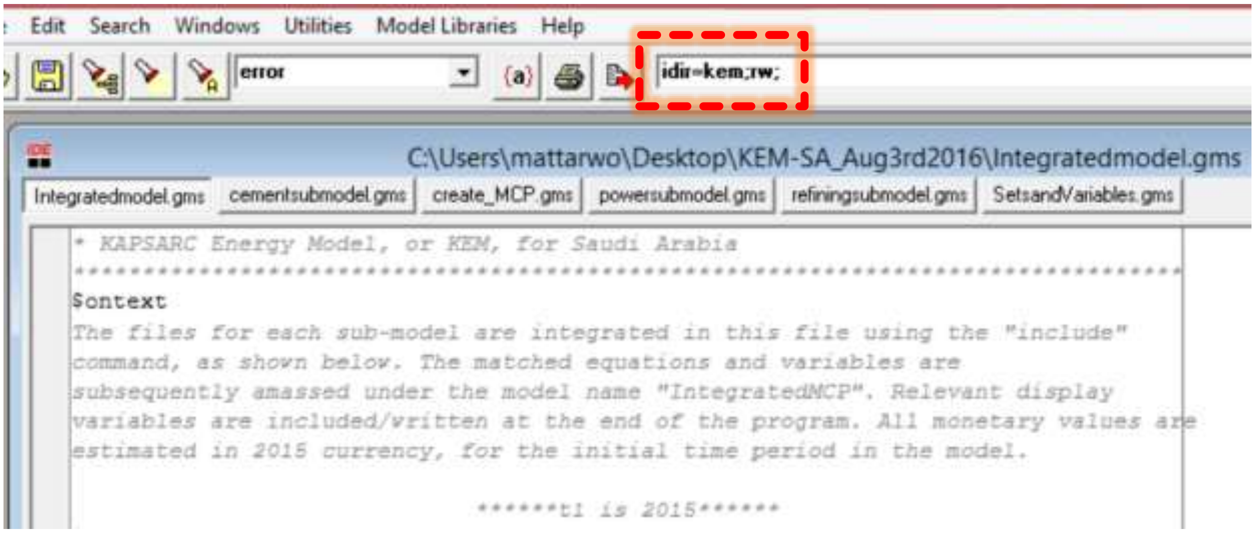


Figure 2 – Writing the command "idir=kem;rw;" for **Integratedmodel.gms** in GAMS

<u>Scenarios and options</u>

By default, KEM-SA includes the ability for the user to choose from six scenarios, as shown in Figure 3 below. The values 1 to 6 are used in the files **solve_MCP.gms** and **solve_MCP_in_recursion.gms** to specify sets and parameters that are pertinent to each scenario. The two files are described in the next section.

In the file **Integratedmodel.gms**, the baseline, or business-as-usual case, has `scenario` set to 1. This scenario calls for fuels to have externally-set administered prices and quotas by sector. Natural gas is supply-constrained in Saudi Arabia and given its low administered price, the government has to specify quotas to each consuming sector.

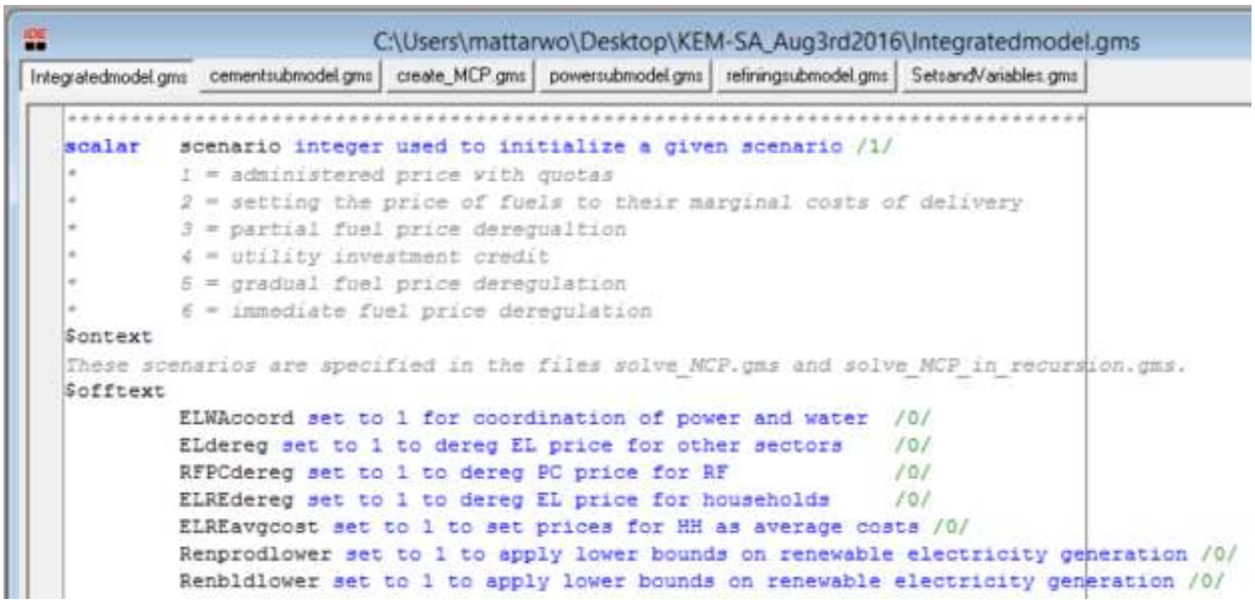
`Scenario` equal to 2 relaxes the fuel supply constraint and sets fuel prices equal to their marginal cost of production and delivery. The production, and thus marginal costs, of refined fuels is dictated by the refining structure, as defined in the Refining Sub-model section. For upstream fuels, the model considers the marginal cost of production and transportation costs, taking the quantity produced exogenously.

`Scenario` equal to 3 is a case where we deregulate fuel prices up to when the power and water utilities reach their budget limits.

`Scenario` equal to 4 combines higher administered fuel prices and investment credits for renewable and nuclear power plants. Both the fuel price and the capital subsidy may be defined by the user.

When running the model in dynamic form, `scenario` equal to 5 gradually deregulates fuel prices over time; for crude oil and refined products, the time it takes to reach their projected world market price. The user can specify the length of time to deregulate.

In `scenario` equal to 6, the model alternatively relaxes the fuel supply constraints to the sectors, and allows natural gas to flow to where it adds the greatest value at the marginal cost of its delivery; the marginal cost is determined as one of the variables by the model. The prices of crude oil and oil products are additionally set to the world market prices.




```
****************************************************************************
scalar   scenario integer used to initialize a given scenario /1/
*        1 = administered price with quotas
*        2 = setting the price of fuels to their marginal costs of delivery
*        3 = partial fuel price deregualtion
*        4 = utility investment credit
*        5 = gradual fuel price deregulation
*        6 = immediate fuel price deregulation
$ontext
These scenarios are specified in the files solve_MCP.gms and solve_MCP_in_recursion.gms.
$offtext
         ELWAcoord set to 1 for coordination of power and water  /0/
         ELdereg set to 1 to dereg EL price for other sectors    /0/
         RFPCdereg set to 1 to dereg PC price for RF             /0/
         ELREdereg set to 1 to dereg EL price for households     /0/
         ELREavgcost set to 1 to set prices for HH as average costs /0/
         Renprodlower set to 1 to apply lower bounds on renewable electricity generation /0/
         Renbldlower set to 1 to apply lower bounds on renewable electricity generation /0/
```

Figure 3 – Scenario and option selection in the default setup of the model

As Figure 3 also shows, the user has the ability to choose between options in conjunction with scenarios. Setting `ELWAcoord` to 1 would have marginal cost prices for electricity between the electricity and water desalination sectors. Currently, the electricity prices between the two sectors are administered. `ELdereg` specifies that all the KEM-SA fuel supply, transformation and industrial sectors purchase electricity at the marginal cost of delivering electricity. `RFPCdereg` sets the price at which the refineries buy methyl tert-butyl ether (MTBE) from the petrochemicals sector to its marginal cost of delivery. Setting `ELREdereg` or `ELREavgcost` to 1 would set electricity prices charged to the households as marginal delivery costs or average generation and distribution costs for the electricity sector. Having `Renprodlower` or `Renbldlower` set to 1 would activate the portions in the model that specify lower bounds for renewable generation or capacity, respectively; by default, the lower bounds are set to 0 for both.

Defining data, equations and variables

Among the first files called in **Integratedmodel.gms** is the file called **SetsandVariables.gms**. It contains all the sets by which all the scalars, parameters, tables, variables and equations are indexed in KEM-SA. For example, if a data set varies by time and region, then it is indexed by the two corresponding sets. The sets that are used in all sectors in KEM-SA are shown below.

```
Sets
time            time period (year) for defining parameters and tables /t1*t30/
trun(time)      final model run time period /t1*t1/
time2(trun)     myopic horizon for hybrid recursive dynamics /t1*t1/
i               time summation index for discounting  /1*100/
t(trun)         dynamic set for time
;
```

The set `time` is used to define all data in the model. The sets `trun(time)` and `time2(trun)` are the time indices that dictate whether the model is run as long-term static (single-year), dynamic perfect foresight over the horizon, recursively dynamic, or a hybrid between the dynamic perfect foresight and the recursively dynamic models; this dynamic approach is described in the next section. A user specifies `trun(time)` as the horizon over which the model is run; if the set has one element, the model is run in a steady state single-year. `time2(trun)`, if defined the same as `trun(time)` and has greater than one element, runs the analysis assuming all the economic agents have perfect foresight for the future. If it is defined to contain just one element and `trun(time)` has more than one element, the model is run recursively, running a long-term static model for every year in the horizon. If `time2(trun)` is defined lower than `trun(time)` but greater than one, then the model is run to hybridize both perfect foresight and recursion until the last time period of `trun(time)`.

Furthermore, the parent set called `allmaterials` consists of all the physical materials in the model. It houses fuels, petrochemicals, intermediate and finished refined products, cement products, atoms and chemical compounds used in their respective sub-models. Materials used in the same processes are allocated to the same sub-sets. For example, the fuels or intermediate refining material in the parent set are separated into the sub-set `f`, as shown below. Then the individual types of fuel are separated into sub-sets of `f` into upstream fuels, types of crude oil, and so on; the elements of the set are defined in subsequent sections.

```
f(allmaterials) fuels /crude,dummyf,u-
235,ethane,methane,NGL,Coal,       propane,naphtha,Gcond,Arabsuper,Arabextra,
Arablight,Arabmed,Arabheavy,hsr-naphtha,lsr-naphtha,hh-naphtha,hl-naphtha,sr-
resid,Asphalt,sr-keros,sr-distill,cc-gasoline,cc-naphtha,lhc-naphtha,lt-
naphtha,a-gasoline,v-gas-oil,hv-gas-oil,v-resid,cc-gas-oil,c-gas-oil,c-
naphtha,ref-gas,fuel-gas,isomerate,h-reformate,l-
reformate,95motorgas,91motorgas,LPG,vis-
```

```
resid,olefingas,petcoke,HFO,Diesel,Butane,Pentane,Jet-fuel,ht-diesel,hc-
diesel,MTBE/
```

As illustrated in Figure 4 below, Saudi Arabia is geographically segregated into 4 regions in KEM-SA; western, southern, central and eastern. Such a representation allows the modeler to distinguish between the regional demands for goods, which are affected by climate conditions and socio-economic differences.

```
r(rall) regions of Saudi Arabia defined in KEM-SA
/west western region,
 sout southern region,
 cent central region,
 east eastern region/
```

Sets pertaining to individual sectors are detailed in the section that details each sub-model. The variables and equations for each sector are defined by these sets.

Figure 4 – Regional disaggregation in KEM-SA (source: KAPSARC)

Projections

The model is presently calibrated to the year 2015; the most recent year that we could obtain data. The user can perform projections running the model in a dynamic setting and using the file **projections.gms**. In this file, the user can specify future growths for items such as oil and natural gas production, prices of fuels, planned or to-be-retired production capacities in the various sectors and demand for the sectors' products.

The dynamic approach in KEM-SA

On one hand, KEM-SA is able to generate a solution for the whole analysis period, `trun(time)` (or `t(trun)`), which would assume the agents know the full set of future information. KEM-SA is also capable of considering a form of bounded rationality known as recursive dynamics; capacity is added with a planning horizon, `time2(trun)`, less than that of the total time period, `trun(time)`, and the model is solved recursively, stepping forward through all of the years in the planning horizon. As the model steps through the forecast years, the planning horizon shrinks when there is less than five years remaining in the analysis period, and eventually, the last year is a single long run period.

Stating recursive dynamics more formally, the model optimizes capacity over the years *t, t+1, …, t+H* and optimizes operating decisions for year *t*. When the year is *t+1*, the capacity decisions made in year *t* for years *t+1, t+2, …, t+H* are dropped, the horizon is extended to year *t+H+1*, and optimized over those years.

In this myopic framework, the cost of adding capacity available in year *t+k* *(k∈{0,…H})* is the present value (in year *t+k*) of the economic depreciation/annualized cost occurring between years *t+k* and *t+H*. Let

i = interest rate

L = useful life of the equipment

I = investment cost measured at the time the facility first operates, including interest paid during construction.

The annualized capital cost is

$$a = \frac{I}{\sum_{l=0}^{L-1} \frac{1}{(1+i)^l}}.$$

At time *t* in KEM-SA the cost of plant and equipment in the *k*th year beyond *t* in the recursion is the present value of the annualized capital cost over the remaining years in the planning horizon,

$$c_{t,k} = a \sum_{j=0}^{H-k} \frac{1}{(1+i)^j}.$$

The agent optimization in each year *t* can therefore be viewed as a multi-period optimization done over *H* years. The only capacity that is retained in year *t+1* in the solution is the capacity added in year *t*. All other years' decisions are discarded as those years' only role in the model is to make the decisions in *t* less myopic. The solution process then moves to finding the equilibrium for the year *t+1* with the new sub-model covering years *t+1* through *t+H+1*. Again, only the results for year *t+1* are retained when solving the model in subsequent years.

The recursive portion of the model is found in **solve_recursive.gms**. **solve_MCP_in_recursion.gms** specifies some sets and parameters differently within the recursion separate from the initial specification in **solve_MCP.gms**. For example, the administered energy prices in Saudi Arabia were changed in 2016, but the sectors did not have that information available to them beforehand. So if we now perform an analysis using KEM-SA, we can run the year of calibration (2015 and earlier, because data is not yet available for 2016) recursively assuming the sectors' decisions in that year are based on old energy prices in the planning horizon, `time2(trun)`. Then, the sectors will be shocked with the new prices and may make different decisions as a result in 2016. As another example, if we want to analyze the effects of a policy change in a future year, we can do so without the sectors able to anticipate the new policy. In both of these cases, they cannot anticipate future information.

The KEM-SA sub-models

Each integrated sector is represented by its own sub-model, described below; the residential electricity use model is detailed by Matar (2016). The integrated model is declared as an MCP in **create_MCP.gms**. The equations and constraints here are directly translated forms of the GAMS equations into standard algebraic notation. We do not include any of the conditions that restrict the generation of rows, columns or coefficients. Those are many and difficult to legibly include in the algebraic equations and constraints. They can be read, however, in the GAMS code.

The model's solve statements are found in **solve_MCP.gms** or **solve_recursive.gms**. If the user wishes to solve over a single year or dynamically with perfect foresight, then the solve statement in **solve_MCP.gms** is automatically run. If the model is run either recursively or a hybrid between perfect foresight and recursion, then the solve statement in **solve_recursive.gms** is activated instead.

Each integrated sector has its own discount rate by which to discount future cash flows. The rates, and the discounting factors, are computed in **discounting.gms**.

Moreover, all the data used in KEM-SA is public with the exception of one set. The existing refining capacities used by the model are obtained from the IHS Midstream Database. For this reason, this data is removed from the model files.

The electric power sector

The electricity sector, defined in the file **powersubmodel.gms**, minimizes the costs of generation, transmission and distribution to the customers. It is the only one displayed here in MCP formulation to illustrate how the MCP is constructed. All the other sectors are displayed as LPs from which the dual constraints are obtained.

The model uses chronological load curves rather than load duration curves to represent the demand for electricity. This was chosen for three reasons. One, we have a multi-regional model with renewables, and one would thus have to know temporal information in the data. If the model chooses to invest in photovoltaics (PV) or wind in a region, load duration curves would distort the time of year that overlaps between regions. In this case, the energy conservation law could be violated.

Two, we have thermal storage for concentrating solar power (CSP), which means we have to account for the hourly information that a load duration curve would not. Three, we have more than one intermittent renewable as a possible technology for investment and therefore, it would be difficult to manage with load duration curves.

To maintain model tractability, an hourly load curve is divided up into 8 load segments, with weekdays distinguished from weekends. The load curve is also broken up into three seasons: winter, summer, with the fall and spring seasons combined into a single season. This generates 6 load curves per region.

The planning reserve margin in the model requires that the model has enough reliable capacity to exceed the expected hourly peak load by 10 percent. This is a default setting and may be changed by the user. If the existing capacity at any point produces less than the required margin, additional capacity that contributes to it would have to be built. Renewable technologies are generally not able to contribute to the margin.

Power plant technologies currently represented are listed in Table 1. They include plants that are already in place and prospective technologies in which the sector can invest. The conversion from open-cycle gas turbines (GT) to combined-cycle (CC) plants is solely an activity, and the resulting converted CC plant may have different operational characteristics than a new investment in a CC power plant. Thermal plants are characterized by heat rates (or net thermal efficiency in percent), variable and fixed operation and maintenance costs, ramping costs and capital costs in the case for new investment.

Steam plants with flue gas desulfurization exhibit slightly different operating characteristics when compared with those without. While we generally restrict the upper bound of HFO use in power generation to the values observed in 2015, this restriction is lifted for plants with desulfurization units. In addition, the increased self-consumption of electricity due to the operation of a desulfurization unit results in lower thermal efficiency for the plant.

Oil- or gas-fired steam
Oil-fired steam plants with desulfurization
Supercritical coal-fired steam
Open-cycle gas turbine
Combined-cycle plants
Conversion of open-cycle GT to CC
Photovoltaic
CSP with thermal energy storage
Nuclear
On-shore wind

Table 1 – Power plant technologies in KEM-SA

The representation of CSP in the current version of KEM is limited to parabolic trough technology with molten salt thermal energy storage. The storage mechanism allows for flexible settings by the user. We can include one, two or however many hours of storage. Figure 5 below illustrates the approach taken to model the operating decisions of a CSP plant. Because of irreversiblilities such as friction effects, we consider a loss in heat between the point of reception and either the storage device or the steam generator; heat transferred out of the solar field may either be used to provide instantaneous heat to the steam generator or be stored for use when it is needed. Using direct normal irradiation (DNI) measurements, the amount of direct solar irradiation on the aperture plane of the collectors is first calculated to determine the rate of energy transfer from the solar field. The file **Macros.gms** contains all the solar irradiance equations.

Single-axis tracking is done by arranging the collectors along the north-south axis and varying their tilt angle from east to west throughout the day. Following Sioshansi and Denholm (2010), the default setting is that CSP plants do not contribute to the planning reserve margin due to limitations in ramping and startup.

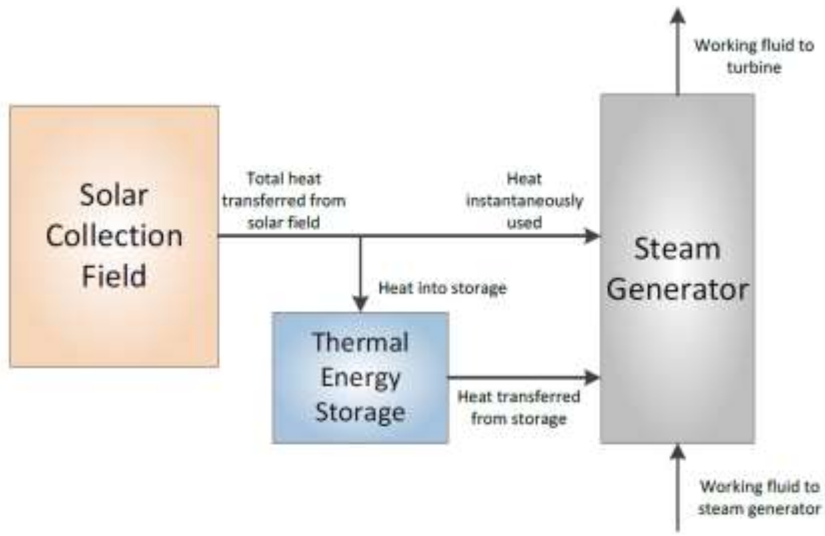


Figure 5 – Heat flows in the CSP plant with thermal storage (source: KAPSARC)

Other power generation technologies included in KEM for Saudi Arabia are photovoltaics (PV) and onshore wind turbines. The power generated by these technologies is generally dependent on the availability of solar radiation and wind speeds.

For PV, we have estimated the power produced for up to 50 GW per region using the regional DNI. Then the model linearly interpolates between 0 GW and 50 GW for existing and newly-built capacity. The representation does not include electricity storage, which would shift the load curve differently. PV also degrade over time as a result of the thermal stresses imposed by cycling through the days; they have been found to degrade faster in harsher climates by Jordan and Kurtz (2012), like that experienced in most of Saudi Arabia. We have included the degradation of PV panels over its life, whether it is run as a single-year static model or multi-period.

For wind turbines, the rate of energy transfer with wind is proportional to turbine speed cubed. Wind turbines are designed to operate only if the wind is between specified cut-in and cutoff speeds, and their power output plateaus once their rated wind speed is observed. For a typical turbine, we consider a cut-in speed of 3 meters per second, a cutoff speed of 25 meters per second and a rated speed of 13 meters per second (Al-Abbadi, 2005).

We could not obtain hourly wind speed data for Saudi Arabia. To bypass this issue, we used the monthly Weibull distribution curves of hourly data presented by Rehman et al. (1994) to estimate profiles of the hourly wind speeds using the season- and region-specific Weibull shape and scale parameters. The shapes of the daily profiles are then calibrated to the distributions' mean values and the resulting average speed variations are graphically presented by Al-Abbadi (2005) and Rehman and Ahmad (2004).

For each region, the power output of the turbine in every load segment is normalized by the maximum annual output, and the decisions to operate any existing capacity or install additional units are made based on the impact the output would have on the load curve.

Due to the intermittent nature of solar radiation availability and wind speeds, the additional costs of operating spinning reserves are also incorporated when operating their capacity. For a given generation during a load segment, the model imposes 20 percent of the generation (in GW) to be met by up-spinning reserves. These reserves are subtracted from the capacity that can be operated and include additional fuel consumption costs that are a fraction of normal consumption costs.

For coal-fired steam power plants, the model allows for imports from South Africa, due to the country's status as one of the world's leading coal exporters and the current use of South African steam coal in other Gulf Cooperation Council (GCC) countries. The coal is imported through Jeddah's Islamic Port in western Saudi Arabia from South Africa's Richards Bay Coal Terminal. Free-on-board (FOB) prices of South African steam coal are first obtained. Freight costs are added to the FOB price based on cape-size coal transportation from Richards Bay to India's west coast, a major coal trade route, and normalized for distance.

Using a net thermal efficiency for the plants and an energy density of 24.7 megajoules per kg for future steam coal exported from South Africa (Eberhard, 2011), we estimate a fuel use rate for the plants of 376.2 metric tonnes per GWh of electricity.

Sets and variable descriptions:

```
Sets
ELp power plant technologies in KEM-SA
                  /Steam steam turbine plants,
                   Stscrub Steam turbine plants with desulfurization,
                   GT open-cycle gas turbine plants,
                   CC combined-cycle plants,
                   CCcon converted gas turbine plants to combined-cycle,
                   GTtoCC the activity of the conversion,
                   CoalSteam supercritical coal-fired steam plants,
                   Nuclear,
                   PV photovoltaics,
                   CSP concentrating solar power with thermal energy storage,
                   Wind on-shore wind turbine plants/

ELpd(ELp) dispatchable technologies /Steam, Stscrub, GT, CC, CCcon, GTtoCC,
Nuclear, CoalSteam/
ELpcom(ELpd) technologies without GTtoCC /Steam, Stscrub, GT, CC, CCcon,
Nuclear, CoalSteam/
ELpnoscrub(ELpd) technologies without scrubber /Steam, GT, CC, CCcon, GTtoCC,
```

```
Nuclear, CoalSteam/
ELpGTtoCC(ELpd) GTtoCC conversion only /GTtoCC/
ELpnuc(ELpd) nuclear power plant /Nuclear/
ELpspin(ELpd) plants used for spinning reserves /GT/

ELpsw(ELp) renewable technologies /PV, CSP, Wind/
ELps(ELpsw) solar technologies /PV, CSP/
ELppv(ELpsw) non-dispatchable solar technologies /PV/
ELpcsp(ELpsw) CSP plants with thermal energy storage /CSP/
ELpw(ELpsw) On-shore wind turbines /Wind/
*GTtoCC is an intermediate process that represents the retrofitting of
existing GT plants into CC plants.

ELstorage thermal storage technologies /moltensalt/

ELl load segments in a 24-hour period /L1*L8/
ELlpeak(ELl) peak load segments /L4*L6/
ELloffpeak(ELl) off-peak load segments /L1*L3,L7*L8/

ELs seasons /sums summer, wint winter, spfa spring and fall/
ELday types of day /wday weekday, wendhol weekend/holiday/
coord geographical coordinates /lat latitude,long longitude/

ELf(f) /Arablight Arabian Light crude oil,
        HFO heavy fuel oil,
        diesel diesel,
        methane natural gas,
        u-235 uranium fuel,
        Coal steam coal from South Africa/
ELfref(ELf) refined petroleum fuels /HFO, diesel/
ELfup(ELf) upstream fuels /Arablight,methane,u-235,Coal/
ELfspin(ELf) fuels used for up spinning capacity /diesel,methane/
ELfnoHFO(ELf) fuels except HFO

v plant vintage /old old vintage (2015 and before),
                 new new vintage (2016 and after)/
vo(v) old vintage /old/
vn(v) new vintage /new/
;

ELfnoHFO(ELf) = yes;
ELfnoHFO('HFO') = no;

alias (r,rr), (ELpd,ELpp), (ELs,ELss), (ELl,ELll), (ELday,ELdayy);

Variables
DELpurchbal(trun) free dual variable of the equipment capital purchasing
                  equation
DELcnstrctbal(trun) free dual variable of the construction capital purchasing
```

```
                    equation
DELopmaintbal(trun) free dual variable of the O&M cost equation
DELnucconstraint(ELl,ELs,Elday,trun,r) free dual variable of the nuclear
                 operation constraint
DELstorenergybal(ELl,ELs,ELday,trun,r) free dual variable of the thermal
                                       energy storage balance equation
DELstorenergyballast(ELl,ELs,ELday,trun,r) free dual variable of the thermal
                                           energy storage balance equation
DELCSPcaplim(ELpsw,v,ELl,ELs,ELday,trun,r) free dual variable of the CSP
                                           operational limit equation
;

Positive variables
ELbld(ELpd,v,trun,r) annual capacity built of dispatchable plants by region
                     in GW
ELrenbld(ELpsw,v,trun,r) annual capacity built of non-dispatchable renewable
                         plants by region in GW
ELexistcp(ELpd,v,trun,r) existing capacity of dispatchable plants in trun by
                         region in GW
ELrenexistcp(ELpsw,v,trun,r) existing capacity of non-dispatchable renewable
                             plants in trun by region in GW
ELop(ELpd,v,ELl,ELs,ELday,ELf,trun,r) electrical generation by disptachable
                                      plants by vintage, time and type-of-
                                      day, season, fuel, time and region in
                                      TWh
ELsolop(ELpsw,v,ELl,ELs,ELday,trun,r) electrical generation by non-
                                      disptachable solar PV plants by
                                      vintage, time and type-of-day, season,
                                      time and region in TWh
ELsoloplevel(ELppv,v,trun,r) interpolation variable to assign solar PV
                             operation from 0 GW to 50 GW per region
ELgttocc(Elpd,v,trun,r) GT capacity available in trun to upgrade to CC in GW
ELupspincap(ELpd,v,ELl,ELs,ELday,ELf,trun,r) capacity of up-spinning reserves
                                             in GW; only gas turbines using
                                             methane or diesel are eligible
ELrampupcst(ELpd,ELl,ELs,ELday,trun,r) cost of ramping up dispatchable plants
                                       in each time segment in the day in
                                       millions of USD
ELrampdncst(ELpd,ELl,ELs,ELday,trun,r) cost of ramping down dispatchable
                                       plants in each time segment in the day
                                       in millions of USD
ELCSPlandarea(trun,r) land collection area used for CSP in square km
ELheatstorin(ELl,ELs,ELday,trun,r) amount of heat into the storage device in
                                   TWh (for CSP)
ELheatstorout(ELl,ELs,ELday,trun,r) amount of heat out of the storage device
                                    in TWh (for CSP)
ELheatstorage(ELl,ELs,ELday,trun,r) amount of heat stored in the storage
                                    device in TWh (for CSP)
ELheatinstant(ELl,ELs,ELday,trun,r) amount of heat instanteously used to
                                    generate power in TWh (for CSP)
ELwindoplevel(ELpw,v,trun,r) interpolation variable to assign on-shore wind
                             operation from 0 GW to 50 GW per region
ELwindop(ELpsw,v,ELl,ELs,ELday,trun,r) electrical generation by non-
```

```
                                        disptachable wind turbine plants by
                                        vintage, time and type-of-day, season,
                                        time and region in TWh
ELtrans(ELl,ELs,ELday,trun,r,rr) electrical energy transmitted between
                                 intra-regionally and inter-regionally in TWh
ELtransbld(trun,r,rr)  built electricity transmission capacity between
                       regions in GW
ELtransexistcp(trun,r,rr) existing electricity transmission capacity between
                          regions in GW
ELImports(trun) equipment purchased costs in trun in millions of USD
                (typically imported)
ELConstruct(trun) construction capital costs in trun in millions of USD
ELOpandmaint(trun) O&M costs in trun in millions of USD
ELfconsump(ELpd,f,trun,r)  Fuel consumption by power plants in the units of
                           the fuel, time and region; crude oil is in
                           millions of barrels, natural gas is in trillion
                           BTU and refined oil products are in millions of
                           metric tonnes
```

Below are the dual variables restricted to be zero or positive for each of the primal inequalities (not equations) described hereafter:

```
DELcapbal(Elpd,v,trun,r)
DELrencapbal(ELpsw,v,trun,r)
DELgtconvlim(ELpd,v,trun,r)
DELcaplim(ELpd,v,ELl,ELs,ELday,trun,r)
DELsolcaplim(ELpsw,v,trun,r)
DELsolutil(ELpsw,v,ELl,ELs,ELday,trun,r)
DELsolcapsum(trun,r)
DELupspinres(ELpd,ELl,ELs,ELday,trun,r)
DELdnspinres(ELpd,ELl,ELs,ELday,trun,r)
DELCSPutil(ELl,ELs,ELday,trun,r)
DELsup(ELl,ELs,ELday,trun,r)
DELdem(ELl,ELs,ELday,trun,r)
DELrsrvreq(trun,r)
DELtranscapbal(trun,r,rr)
DELtranscaplim(ELl,ELs,ELday,trun,r,rr)
DELfcons(ELpd,ELf,trun,r)
DELfavail(ELf,trun,r)
DELfavailcr(ELf,trun,r)
DELsolenergybal(ELl,ELs,ELday,trun,r)
DELCSPcaplim(ELpsw,v,ELl,ELs,ELday,trun,r)
DELCSPlanduselim(trun,r)
DELwindcaplim(ELpsw,v,trun,r)
DELwindutil(ELpw,v,ELl,ELs,ELday,trun,r)
DELwindcapsum(trun,r)
DELrenprodreq(ELpsw,v,trun)
DELnucprodreq(ELpd,v,trun)
DELrenbldreq(ELpsw,v,trun)
DELbldreq(trun)
DELstorlim(ELpsw,ELl,ELs,ELday,trun,r)
DELrampupbal(ELpd,ELl,ELs,ELday,trun,r)
```

```
        DELrampdnbal(ELpd,ELl,ELs,ELday,trun,r)
;
```

$ELbld_{ELpd,v,t,r}$ and $ELrenbld_{ELpsw,v,t,r}$ are restricted to new-vintage plants and only appear if the time difference between the current and first year of analysis is larger than the technologies' lead time.

Accumulates all equipment capital costs:
Note: $\gamma_{capital\ credit}$ is set to zero except for investment credit scenarios.
$ELpurcst_{ELp,t}$ and $ELtranspurcst_{t,r,rr}$ are the portion of the capital costs attributed to purchasing the equipment.

$$\sum_{ELpd}\sum_{v}\sum_{r}\left\{\left[ELpurcst_{ELpd,t}\left(1-\gamma_{capital\ credit_{ELpd}}\right)\right]ELbld_{ELpd,v,t,r}\right\}$$
$$+\sum_{ELpsw}\sum_{v}\sum_{r}\{[ELpurcst_{ELpsw,t}(1-\gamma_{capital\ credit_{sw}})]ELrenbld_{ELpsw,v,t,r}\}$$
$$+\sum_{r}\sum_{rr}[ELtranspurcst_{t,r,rr}ELtransbld_{t,r,rr}] = ELImports_{t}$$

Accumulates all construction capital costs:
Note: $\gamma_{capital\ credit}$ is set to zero except for investment credit scenarios.
$ELconstcst_{ELp,t}$ and $ELtransconstcst_{t,r,rr}$ are the portion of the capital costs attributed to construction and purchasing land.

$$\sum_{ELpd}\sum_{v}\sum_{r}\left\{\left[ELconstcst_{ELpd,t}\left(1-\gamma_{capital\ credit_{ELpd}}\right)\right]ELbld_{ELpd,v,t,r}\right\}$$
$$+\sum_{ELpsw}\sum_{v}\sum_{r}\{[ELconstcst_{ELpsw,t}(1-\gamma_{capital\ credit_{sw}})]ELrenbld_{ELpsw,v,t,r}\}$$
$$+\sum_{r}\sum_{rr}[(ELtransconstcst_{t,r,rr})ELtransbld_{t,r,rr}] = ELConstruct_{t}$$

Accumulates all non-fuel variable and fixed operations and maintenance costs:
$ELomcst_{ELp,v,r}$ *and* $ELfixedOMcst_{ELp,t}$ are the variable and fixed operation and maintenance (O&M) costs for the various power plants. $ELstoromcst_{r}$ and $ELtransomcst_{r,rr}$ are the O&M costs of the thermal storage unit in a CSP plant and transmission and distribution, respectively. $ELrampupcst_{ELpd,ELl,ELs,ELday,t,r}$ and $ELrampdncst_{ELpd,ELl,ELs,ELday,t,r}$ are the costs of varying output from one load segment to the next.

$$\sum_{ELpd}\sum_{v}\sum_{r}\sum_{ELf}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[ELomcst_{ELpd,v,r}ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r}\right]$$
$$+\sum_{ELps}\sum_{v}\sum_{r}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[ELomcst_{ELps,v,r}ELsolop_{ELps,v,ELl,ELs,ELday,t,r}\right]$$
$$+\sum_{ELpw}\sum_{v}\sum_{r}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[ELomcst_{ELpw,v,r}ELwindop_{ELpw,v,ELl,ELs,ELday,t,r}\right]$$
$$+\sum_{ELpd}\sum_{v}\sum_{r}ELfixedOMcst_{ELpd,t}\left(ELexistcp_{ELpd,v,t,r}\right.$$
$$\left.+\sum_{ELpp}ELcapadd_{ELpp,ELpd}ELbld_{ELpd,v,t,r}\right)$$
$$+\sum_{ELpsw}\sum_{v}\sum_{r}ELfixedOMcst_{ELpsw,t}\left(ELexistcp_{ELpsw,v,t,r}+ELbld_{ELpsw,v,t,r}\right)$$
$$+\sum_{ELl}\sum_{ELs}\sum_{ELday}\sum_{r}\left[ELstoromcst_{r}ELheatstorage_{ELl,ELs,ELday,t,r}\right]$$
$$+\sum_{r}\sum_{rr}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[ELtransomcst_{r,rr}ELtrans_{ELl,ELs,ELday,t,r,rr}\right]$$
$$+\sum_{ELd,ELl,ELs,ELday,r}(ELrampupcst_{ELpd,ELl,ELs,ELday,t,r}$$
$$+ELrampdncst_{ELpd,ELl,ELs,ELday,t,r})=ELOpandmaint_{t}$$

Enforces fuel availability, if supply is limited:
$ELfconsumpmax_{ELf,t,r}$ are the supply limits for fuel use by the power sector. For most fuels, this parameter is set as infinite. For natural gas, however, the government has historically enforced quotas for all consuming sectors.

$$-\sum_{ELpd}ELfconsump_{ELpd,ELf,t,r}\geq -ELfconsumpmax_{ELf,t,r}$$

Accumulates fuel consumption:
Note: ELpspin is a subset of ELpd that only includes plants used for spinning reserves.

$ELfuelburn_{ELpd,v,ELf,r}$ are the heat rates of the power plants in fuel units per GWh of electricity generated. For natural gas it is in the units of MMBTU per GWh and for crude oil it is in barrels per GWh. For refined oil products it is in tonnes because we deal with mass relationships in the refining sub-model.

$ELUSRfuelfrac$ is the fuel rate used in the up-spinning reserves as a fraction of normal consumption rate. $ELlchours_{ELl}$ are the number of hours in each load segment in the load curve. $ELdaysinseason_{ELs,ELday}$ are the numbers of days in each seasonal period and type of day.

$$ELfconsump_{ELpd,ELf,t,r} - \sum_{v}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[ELfuelburn_{ELpd,v,ELf,r}ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r}\right]$$
$$- \sum_{v}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[(ELUSRfuelfrac)ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELfuelburn_{ELpd,v,ELf,r}ELupspincap_{ELpd,v,ELl,ELs,ELday,ELf,t,r}\right]$$
$$\geq 0$$

Capacity balance for dispatchable technologies:

Note: $ELaddition_{ELpd,v,t+1,r}$ and $ELretirement_{ELpd,v,t+1,r}$ are parameters to add plants already under construction and set rules for retirement, respectively. We conservatively assume additions and retirements take place at the end of time period, t.

$$ELexistcp_{ELpd,v,t,r} + ELaddition_{ELpd,v,t+1,r} - ELretirement_{ELpd,v,t+1,r} + \sum_{ELpp} ELcapadd_{Elpp,ELpd}\, ELbld_{ELpp,v,t,r} - ELexistcp_{ELpd,v,t+1,r} \geq 0$$

Capacity balance for renewable plants:

Note: PVdegrade only applies to PV plants.

$$ELrenexistcp_{ELpsw,v,t,r}(1 - PVdegrade) + ELrenbld_{ELpsw,v,t,r}(1 - PVdegrade) - ELrenexistcp_{ELpsw,v,t+1,r} \geq 0$$

Conversion limit for existing single-cycle GT to CCGT (restricted to old-vintage plants):

$$-ELGTtoCC_{ELpgttocc,vo,t+1,r} - ELbld_{ELpgttocc,vo,t,r} + ELGTtoCC_{ELpgttocc,vo,t,r} \geq 0$$

Ensures generation by conventional dispatchable technologies does not exceed their capacity:
$ELcapfactor_{ELpd}$ accounts for duration of time that plants have scheduled maintenance. It is a unitless value. $ELcapadd_{Elpp,ELpd}$ is a table to subtract the capacity of the upgraded GT plants by the model, and add 50 percent higher capacity to it in the form of converted CC plants.

$$ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELcapfactor_{ELpd}\left[ELexistcp_{ELpd,v,t,r} + \sum_{ELpp} ELcapadd_{Elpp,ELpd}\, ELbld_{ELpp,v,t,r} - \sum_{ELf} ELupspincap_{ELpspin,v,ELl,ELf,t,r}\right] - \sum_{ELf} ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r} \geq 0$$

For nuclear, the above constraint is enforced as an equality to reflect the difficulty in ramping:

$$\sum_{v} ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELcapfactor_{ELpnuc}\big(ELexistcp_{ELpnuc,v,t,r} + ELbld_{ELpnuc,v,t,r}\big) - \sum_{ELf}\sum_{v} ELop_{ELpnuc,v,ELl,ELs,ELday,ELf,t,r} = 0$$

This constraint sums up the costs of ramping up and down:
Note: We have two different summations of $ELop_{ELpd,v,ELl,ELs,ELday,ELf,r}$ for when it is the first load segment and when it is not.

$ELrampcst_{ELpd}$ are the ramping costs for each thermal power plant; Van den Bergh and Delarue (2015) have reported the currently-used figures.

$$-ELrampcst_{ELpd} \textstyle\sum_{v,Elf} \left(\frac{ELop_{ELpd,v,ELl,ELs,ELday,ELf,r}}{ELlchours_{ELl}} - \frac{ELop_{ELpd,v,ELl-1,ELs,ELday,ELf,r}}{ELlchours_{ELl-1}}\right) + ELrampupcst_{ELpd,ELl,ELs,ELday,r} - ELrampdncst_{ELpd,ELl,ELs,ELday,r} = 0$$

Measures the generation by PV plants:

$ELdiffGWsol_{ELl,ELs,r}$ is the power generation, in GW, 50 GW of solar PV would generate throughout the day, during the season and in each region. $ELsoloplevel_{ELppv,v,t,r}$ is then the variable that interpolates (it ranges from 0 to 1) based on how much capacity is installed.

$$\begin{aligned}\left(ELdiffGWsol_{ELl,ELs,r}ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELsoloplevel_{ELppv,v,t,r}\right)\\ - ELsolop_{ELppv,v,ELl,ELs,ELday,t,r} \geq 0\end{aligned}$$

Ensures PV plants do not operate beyond capacity:

$ELsolcap$ is a regional 50-GW capacity upper bound placed on PV capacity. The PV degradation factor in a long-term steady state model is defined below the constraint; it is the effective degradation rate over the life of the plant. The equation is conditioned to only be active when there is more than one element in the set `trun`.

$$ELrenexistcp_{ELppv,v,t,r} + ELrenbld_{ELppv,v,t,r} - ELsoloplevel_{ELppv,v,t,r}ELsolcap \geq 0$$

$$\frac{1}{Lifetime}\left[\frac{(1 - PVdegrade)^{Lifetime} - 1}{\ln(1 - PVdegrade)}\right]$$

Ensures PV operation level remains within the PV capacity cap:

$$-\sum_{ELppv}\sum_{v} ELsoloplevel_{ELppv,v,t,r} \geq -1$$

Measures the generation by wind plants:

$ELdiffGWwind_{ELl,ELs,r}$ is the power generation, in GW, 50 GW of onshore wind turbines would generate throughout the day, during the season and in each region. $ELwindoplevel_{ELpw,v,t,r}$ is then the variable that interpolates (it ranges from 0 to 1) based on how much capacity is installed.

$$\begin{aligned}ELdiffGWwind_{ELl,ELs,r}ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELwindoplevel_{ELpw,v,t,r}\\ - ELwindop_{ELpw,v,ELl,ELs,ELday,t,r} \geq 0\end{aligned}$$

Ensures wind plants do not operate beyond capacity:
$ELwindcap$ is a regional 50-GW capacity upper bound placed on onshore wind turbine capacity.

$$ELrenexistcp_{ELpw,v,t,r} + ELrenbld_{ELpw,v,t,r} - ELwindoplevel_{ELpw,v,t,r}ELwindcap \geq 0$$

Ensures wind operation level remains within the wind capacity cap:

$$-\sum_{ELpw}\sum_{v} ELwindoplevel_{ELpw,v,t,r} \geq -1$$

Measures the level of up spinning reserve capacity:
$ELsolspin$ and $ELwindspin$ are the fractions of solar PV and wind generation to have as up-spinning reserves. This capacity is specified as gas turbines consuming natural gas or diesel.

$$\begin{aligned}-ELsolspin\sum_{ELppv}\sum_{v} ELdiffGWsol_{ELl,ELs,r}ELsoloplevel_{ELppv,v,t,r}\\ - ELwindspin\sum_{ELpw}\sum_{v} ELdiffGWwind_{ELl,ELs,r}ELwindoplevel_{ELpw,v,t,r}\\ + \sum_{ELf}\sum_{v} ELupspincap_{ELpspin,v,ELl,ELs,ELday,ELf,t,r} \geq 0\end{aligned}$$

Measures amount of solar energy transferred from CSP field:
$ELCSPtransloss$ is the heat loss during the transfer of the fluid from the solar collection field to the steam generator or storage. $ELdirectirradiance_{ELl,ELs,r}$ is the solar direct irradiance on the aperture plane of the collectors; it is distinguished by time of day, season and region.

$$\begin{aligned}(1 - ELCSPtransloss)ELlchours_{ELl}ELdaysinseason_{ELs,ELday}ELdirectirradiance_{ELl,ELs,r}ELCSPlandarea_{t,r}\\ - ELheatstorin_{ELl,ELs,ELday,t,r} - ELheatinstant_{ELl,ELs,ELday,t,r} \geq 0\end{aligned}$$

Energy balance for CSP thermal storage device (all load segments except for the last):
$ELstorehrloss$ is the hourly loss of stored heat in the molten salt unit. Since we have load segments, the amount of heat that is not lost is raised to the number of hours in each load segment. $ELstorecycloss$ is the heat loss incurred by going through the storage unit.

$$
\begin{aligned}
&(1 - ELstorehrloss)^{ELlchours_{ELl}} ELheatstorage_{ELl,ELs,ELday,t,r} \\
&\qquad + (1 - ELstorecycloss) ELheatstorin_{ELl,ELs,ELday,t,r} - ELheatstorout_{ELl,ELs,ELday,t,r} \\
&\qquad - ELheatstorage_{ELl+1,ELs,ELday,t,r} = 0
\end{aligned}
$$

Energy balance for CSP thermal storage device (last load segment only):

$$
\begin{aligned}
&(1 - ELstorehrloss)^{ELlchours_{ELl}} ELheatstorage_{ELl,ELs,ELday,t,r} \\
&\qquad + (1 - ELstorecycloss) ELheatstorin_{ELl,ELs,ELday,t,r} - ELheatstorout_{ELl,ELs,ELday,t,r} \\
&\qquad - ELheatstorage_{L1,ELs,ELday,t,r} = 0
\end{aligned}
$$

Measures electricity generation by CSP plants:
$ELCSPthermaleff$ is the net (first law) thermal efficiency of the CSP plant; this value is taken as 38 percent by default, but could be changed.

$$
\begin{aligned}
&ELCSPthermaleff\left(ELheatstorout_{ELl,ELs,ELday,t,r} + ELheatinstant_{ELl,ELs,ELday,t,r}\right) \\
&\qquad - \sum_{v} ELsolop_{ELpcsp,v,ELl,ELs,ELday,t,r} \geq 0
\end{aligned}
$$

Measures aperture area of parabolic trough collectors:
$ELaperturearea$ is how much land area the collectors consume per unit of capacity.

$$
-ELCSPlandarea_{t,r} + ELaperturearea \sum_{v} \left(ELrenexistcp_{ELpcsp,v,t,r} + ELrenbld_{ELpcsp,v,t,r}\right) \geq 0
$$

Ensures generation by CSP remains within capacity:

$$
\begin{aligned}
&ELlchours_{ELl} ELdaysinseason_{ELs,ELday}\left(ELrenexistcp_{ELpcsp,v,t,r} + ELrenbld_{ELpcsp,v,t,r}\right) \\
&\qquad - ELsolop_{ELpcsp,v,ELl,ELs,ELday,t,r} \geq 0
\end{aligned}
$$

Limits the level of thermal storage for CSP to pre-defined amount:
$CSPstoragehours$ is the number of hours the CSP plant runs at full capacity using stored heat.

$$ELheatstorage_{ELl,ELs,ELday,t,r} + \left(\frac{CSPstoragehours}{ELCSPthermaleff}\right) ELdaysinseason_{ELs,ELday} \sum_{v} \left(ELrenexistcp_{ELpcsp,v,t,r} + ELrenbld_{ELpcsp,v,t,r}\right) \geq 0$$

The following three constraints allow for specifying lower bounds for the operation and/or construction of alternative power generation technologies:
If the user wishes, $ELrenprodlow_{ELpsw,t} > 0$ would specify a lower bound on generation by renewable technologies. $ELnucprodlow_{ELpnuc,t} > 0$ would have the same effect on nuclear generation. $ELbldlow_{t} > 0$ would specify that the sector has to build a certain capacity of combined nuclear and renewable plants, if a prospective policy sets a target that includes both.

$$\sum_{ELl} \sum_{ELs} \sum_{ELday} \sum_{r} \left(ELwindop_{ELpw,v,ELl,ELs,ELday,t,r} + ELsolop_{ELps,v,ELl,ELs,ELday,t,r}\right) \geq ELrenprodlow_{ELpsw,t}$$

$$\sum_{ELl} \sum_{ELs} \sum_{ELday} \sum_{r} ELop_{ELpnuc,v,ELl,ELs,ELday,ELf,t,r} \geq ELnucprodlow_{ELpnuc,t}$$

$$\sum_{v} \sum_{r} \left[\sum_{ELpnuc} ELbld_{ELpnuc,v,t,r} + \sum_{ELpsw} ELrenbld_{ELpsw,v,t,r}\right] \geq ELbldlow_{t}$$

Supply constraint:

Note: $WAELsupply_{ELl,ELs,ELday,t,r}$ and $WAELconsump_{ELl,ELs,ELday,t,r}$ are variables that are defined in the water desalination section.

$$\sum_{ELpd}\sum_{v}\sum_{ELf} ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r} + \sum_{ELps}\sum_{v} ELsolop_{ELps,v,ELl,ELs,ELday,t,r} + \sum_{ELpw}\sum_{v} ELwindop_{ELpw,v,ELl,ELs,ELday,t,r} + WAELsupply_{ELl,ELs,ELday,t,r} - WAELconsump_{ELl,ELs,ELday,t,r} - \sum_{rr} ELtrans_{ELl,ELs,ELday,t,r,rr} \geq 0$$

Satisfying demand (endogenous and exogenous demands):

$ELtransyield_{r,rr}$ specifies how much electricity is lost during intra-region and interregional transmission and distribution. $PCELconsump_{ELl,ELs,ELday,t,rr}$, $CMELconsump_{ELl,ELs,ELday,t,rr}$ and $RFELconsump_{ELl,ELs,ELday,t,rr}$ are the electricity consumed from the grid by the petrochemicals, cement and refining sectors, respectively; they are variables and are defined in their respective sections. $ELlcgw_{ELl,ELs,ELday,rr}$ are the exogenous loads (not in KEM-SA) that model has to additionally satisfy.

$$\sum_{r}\left(ELtransyield_{r,rr} ELtrans_{ELl,ELs,ELday,t,r,rr}\right) - PCELconsump_{ELl,ELs,ELday,t,rr} - CMELconsump_{ELl,ELs,ELday,t,rr} - RFELconsump_{ELl,ELs,ELday,t,rr} \geq ELlchours_{ELl} ELdaysinseason_{ELs,ELday} ELlcgw_{ELl,ELs,ELday,rr} ELdemgro_{t,rr}$$

Enforces planning reserve margin requirement:

$CSPreservecontr$ is set to zero by default, i.e., CSP is not contributing to the reserve margin. If the technology is deemed reliable enough to partially or fully contribute the reserve margin, its value may be set accordingly. $ELreserve$ is how much over the peak load the reserve margin has to be. In the default setup, the value is 1.1, or 10 percent above the peak load.

$ELcgwmax_{r}$ is the absolute hourly peak load throughout the year by region. $ELdemgro_{t,r}$ is the specified electricity demand growth over time by region.

$$
\begin{aligned}
&\sum_{ELpd}\sum_{v} ELexistcp_{ELpd,v,t,r} \\
&\qquad + \sum_{ELpd}\sum_{v}\left(\sum_{ELpp} ELcapadd_{Elpp,ELpd}\, ELbld_{ELpp,v,t,r}\right) + WAELrsrvcontr_{t,r} \\
&\qquad + CSPreservecontr \sum_{ELpcsp}\sum_{v}\left(ELrenexistcp_{ELpcsp,v,t,r} + ELrenbld_{ELpcsp,v,t,r}\right) \\
&\qquad \geq ELreserve\big(ELcgwmax_r ELdemgro_{t,r} + WAELpwrdemand_{t,r} \\
&\qquad + PCELpwrdemand_{t,r} + CMELpwrdemand_{t,r}\big)
\end{aligned}
$$

Capacity balance for transmission:

$$ELtransexistcp_{t,r,rr} + ELtransbld_{t,r,rr} - ELtransexistcp_{t+1,r,rr} \geq 0$$

Ensures electricity transmission does not exceed capacity:

$$
\begin{aligned}
&\left(ELtransexistcp_{t,r,rr} + ELtransbld_{t,r,rr}\right) ELlchours_{ELl} ELdaysinseason_{ELs,ELday} \\
&\qquad - ELtrans_{ELl,ELs,ELday,t,r,rr} \geq 0
\end{aligned}
$$

Below are the dual problem's constraints. They are shown for the power sector for illustration purposes.

Dual constraint associated with total equipment purchase cost:

$ELdiscfact_t$ are the discount factors over time; the default discount rate for this sector is 6 percent.

$$ELdiscfact_t \geq -DELpurchbal_t$$

Dual constraint associated with total construction cost:

$$ELdiscfact_t \geq -DELcnstrctbal_t$$

Dual constraint associated with total non-fuel operation cost:

$$ELdiscfact_t \geq -DELopmaintbal_t$$

Dual constraint associated with fuel consumption:
Note: $fuelsubsidy_t$ is fixed to zero unless scenario uses it.

$$if \begin{cases} prices\ are\ deregulated, & \begin{bmatrix} Dfdem_{ELfup,t,r}ELdiscfact_t(1-fuelsubsidy_t) \\ +DRFdem_{ELfref,t,r}ELdiscfact_t(1-fuelsubsidy_t) \end{bmatrix} \\ prices\ are\ administered, & \begin{bmatrix} ELAPf_{ELf,t,r}ELdiscfact_t \end{bmatrix} \end{cases}$$
$$\geq \quad DELfcons_{ELpd,ELf,t,r} - DELfavail_{ELf,t,r} + DELfavailcr_{ELf,t,r}$$

Dual constraint associated with conventional dispatchable plant build activity:
Note: $DELbldreq_t$ only appears for nuclear plants

$$\begin{aligned}
&0 \\
&\geq DELpurchbal_t ELpurcst_{Elpd,t,r}\left(1-\gamma_{capital\ credit}\right) + DELcnstrctbal_t ELconstcst_{ELpd,t}\left(1-\gamma_{capital\ credit}\right) \\
&+ \sum_{ELpp}\left(DELopmaintbal_t ELcapadd_{ELpd,ELpp} ELfixedOMcst_{ELpp,t}\right) \\
&+ \sum_{ELpp}\left(DELcapbal_{ELpp,v,t,r} ELcapadd_{ELpd,ELpp}\right) - DELgtconvlim_{ELpd,v,t,r} \\
&+ \sum_{ELpp}\sum_{ELl}\sum_{ELs}\sum_{ELday} ELcapfactor_{ELpp} ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELcaplim_{ELpp,v,ELl,ELs,ELday,t,r} ELcapadd_{ELpd,ELpp} \\
&+ DELrsrvreq_{t,r}\sum_{ELpp} ELcapadd_{ELpd,ELpp} \\
&+ \sum_{ELl}\sum_{ELs}\sum_{ELday} ELcapfactor_{ELpnuc} ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELnucconstraint_{ELpnuc,ELl,ELs,ELday,t,r} \\
&+ DELbldreq_t
\end{aligned}$$

Dual constraint associated with conversion of single-cycle GT to CCGT activity:

$$0 \geq DELgtconvlim_{ELpgttocc,vo,t,r} - DELgtconvlim_{ELpgttocc,vo,t-1,r}$$

Dual constraint associated with transmission activity:

$$\begin{aligned}
0 \geq\ & DELopmaintbal_t ELtransomcst_{r,rr} - DELsup_{ELl,ELs,ELday,t,r} \\
& + DELdem_{ELl,ELs,ELday,t,rr} ELtransyield_{r,rr} - DELtranscaplim_{ELl,ELs,ELday,t,r,rr}
\end{aligned}$$

Dual constraint associated with transmission build activity:

$$0 \geq DELpurchbal_t ELtranspurcst_{t,r,rr} + DELcnstrctbal_t ELtransconstcst_{t,r,rr} + DELtranscapbal_{t,r,rr} + \sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELtranscaplim_{ELl,ELs,ELday,t,r,rr}\right)$$

Dual constraint associated with transmission existing capacity variable:

$$0 \geq DELtranscapbal_{t,r,rr} - DELtranscapbal_{t-1,r,rr} + \sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELtranscaplim_{ELl,ELs,ELday,t,r,rr}\right)$$

Dual constraint associated with conventional dispatchable plant operation activity:
Note: $DELnucconstraint_{ELpnuc,ELl,ELs,ELday,t,r}$ and $DELnucprodreq_{ELpd,v,t}$ are for nuclear plants only. The ramping terms are written for the first load segment and other load segments separately, to ensure continuity.

$$\begin{aligned} 0 \geq\ & DELopmaintbal_t ELomcst_{Elpd,v,r} - DELnucconstraint_{ELpd,ELl,ELs,ELday,t,r} \\ & - DELcaplim_{ELpd,v,ELl,ELs,ELday,t,r} + DELsup_{ELl,ELs,ELday,t,r} \\ & - DELfcons_{ELpd,ELf,t,r} ELfuelburn_{Elpd,v,ELf,r} + DELnucprodreq_{ELpd,v,t} \\ & - ELrampcst_{ELpd}\left(\frac{DELrampbal_{ELpd,ELl,ELs,ELday,t,r}}{ELlchours_{ELl}} \right. \\ & \left. - \frac{DELrampbal_{ELpd,ELl+1,ELs,ELday,t,r}}{ELlchours_{ELl}}\right) \end{aligned}$$

Dual constraint associated with conventional dispatchable plant existing capacity variable:

$$0$$
$$\geq DELopmaintbal_t ELfixedOMcst_{ELpd,t} + DELcapbal_{ELpd,v,t,r} - DELcapbal_{ELpd,v,t-1,r}$$
$$+ \sum_{ELl} \sum_{ELs} \sum_{ELday} \left(DELcaplim_{ELpd,v,ELl,ELs,ELday,t,r} ELlchours_{ELl} ELdaysinseason_{ELs,ELday} ELcapfactor_{ELpd} \right)$$
$$+ \sum_{ELl} \sum_{ELs} \sum_{ELday} \left(DELnucconstraint_{ELpnuc,ELl,ELs,ELday,t,r} ELlchours_{ELl} ELdaysinseason_{ELs,ELday} \right.$$
$$\left. \cdot ELcapfactor_{ELpnuc} \right) + DELrsrvreq_{t,r}$$

Dual constraint associated with renewables build activity:
Note: PVdegrade only applies to PV plants.

$$0$$
$$\geq DELpurchbal_t ELpurcst_{ELpsw,t,r} \left(1 - \gamma_{capital\ credit}\right)$$
$$+ DELcnstrctbal_t ELconstcst_{ELpsw,t,r} \left(1 - \gamma_{capital\ credit}\right)$$
$$+ DELopmaintbal_t ELfixedOMcst_{ELpsw,t} + DELrencapbal_{ELpsw,v,t,r}(1 - PVdegrade)$$
$$+ DELsolcaplim_{ELpsw,v,t,r} + DELwindcaplim_{ELpsw,v,t,r} + DELCSPlanduselim_{t,r} ELaperturearea$$
$$+ \sum_{ELl} \sum_{ELs} \sum_{ELday} \left(ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELCSPcaplim_{ELpcsp,v,ELl,ELs,ELday,t,r} \right)$$
$$+ DELbldreq_t$$
$$+ \left(\frac{CSPstoragehours}{ELCSPthermaleff} \right) \sum_{ELl} \sum_{ELs} \sum_{ELday} \left(ELdaysinseason_{ELs,ELday} DELstorlim_{ELpcsp,ELl,ELs,ELday,t,r} \right)$$
$$+ DELrsrvreq_{t,r} CSPreservecontr$$

Dual constraint associated with solar operation activity:

$$\begin{aligned} 0 \geq\ & DELopmaintbal_t ELomcst_{Elps,v,r} + DELsup_{ELl,ELs,ELday,t,r} - DELsolutil_{ELppv,ELl,ELs,ELday,v,t,r} \\ & - DELCSPutil_{ELl,ELs,ELday,t,r} - DELCSPcaplim_{ELpcsp,v,ELl,ELs,ELday,t,r} \\ & + DELrenprodreq_{ELps,v,t} \end{aligned}$$

Dual constraint associated with renewable existing capacity variable:
Note: PVdegrade only applies to PV plants.

$$\begin{aligned}
0 &\geq DELrencapbal_{ELpsw,v,t,r}(1 - PVdegrade) - DELrencapbal_{ELpsw,v,t-1,r} \\
&+ DELopmaintbal_{t} ELfixedOMcst_{ELpsw,t} + DELsolcaplim_{ELps,v,t,r} + DELwindcaplim_{ELps,v,t,r} \\
&+ DELCSPlanduselim_{t,r} ELaperturearea \\
&+ \sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELlchours_{ELl} ELdaysinseason_{ELs,ELday} DELCSPcaplim_{ELpcsp,v,ELl,ELs,ELday,t,r}\right) \\
&+ \left(\frac{CSPstoragehours}{ELCSPthermaleff}\right)\sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELdaysinseason_{ELs,ELday} DELstorlim_{ELpcsp,ELl,ELs,ELday,t,r}\right) \\
&+ DELrsrvreq_{t,r} CSPreservecontr
\end{aligned}$$

Dual constraint associated with solar operating level within capacity cap:

$$\begin{aligned}
0 &\geq -DELsolcaplim_{ELppv,v,t,r} ELsolcap \\
&+ \sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELdiffGWsol_{ELl,ELs,r} ELlchours_{ELl} ELdaysinseason_{ELs,ELday}\right. \\
&\left.\cdot DELsolutil_{ELppv,ELl,ELs,ELday,v,t,r}\right) - DELsolcapsum_{t,r} \\
&- ELsolspin \sum_{ELl}\sum_{ELs}\sum_{ELday}\sum_{ELpspin}\left(ELdiffGWsol_{ELl,ELs,r} DELupspinres_{ELpspin,ELl,ELs,ELday,t,r}\right)
\end{aligned}$$

Dual constraint associated with wind operation activity:

$$\begin{aligned}
0 \geq\ & DELopmaintbal_{t} ELomcst_{Elpw,v,r} + DELsup_{ELl,ELs,ELday,t,r} - DELwindutil_{ELpw,ELl,ELs,ELday,v,t,r} \\
&+ DELrenprodreq_{ELpw,v,t}
\end{aligned}$$

Dual constraint associated with wind operating level within capacity cap:

$$0 \geq -DELwindcaplim_{ELpw,v,t,r}ELwindcap - DELwindcapsum_{t,r} + \sum_{ELl}\sum_{ELs}\sum_{ELday}\left(ELdiffGWwind_{ELl,ELs,r}ELlchours_{ELl}ELdaysinseason_{ELs,ELday} \cdot DELwindutil_{ELpw,ELl,ELs,ELday,v,t,r}\right) - ELwindspin\sum_{ELl}\sum_{ELs}\sum_{ELday}\sum_{ELpspin}\left(ELdiffGWwind_{ELl,ELs,r}DELupspinres_{ELpspin,ELl,ELs,ELday,t,r}\right)$$

Dual constraint associated with up spinning reserve capacity activity:

$$0 \geq DELupspinres_{ELpspin,ELl,ELs,ELday,t,r} - ELlchours_{ELl}ELdaysinseason_{ELs,ELday}DELcaplim_{ELpspin,v,ELl,ELs,ELday,t,r} - ELfuelburn_{ELpspin,v,ELfspin,r}ELlchours_{ELl}ELdaysinseason_{ELs,ELday}DELfcons_{ELpspin,ELfspin,t,r} \cdot ELUSRfuelfrac$$

Dual constraint associated with CSP collection area:

$$0 \geq \sum_{ELl}\sum_{ELs}\sum_{ELday}\left[(1 - CSPtransloss)ELdirectirradiance_{ELl,ELs,r}DELsolenergybal_{ELl,ELs,ELday,t,r} \times ELlchours_{ELl}ELdaysinseason_{ELs,ELday}\right] - DELCSPlanduselim_{t,r}$$

Dual constraint associated with amount of heat transferred to CSP storage:

$$0 \geq -DELsolenergybal_{ELl,ELs,ELday,t,r} + if\begin{cases} ELl < last\ load\ segment, & (1 - ELstorecycloss)DELstorenergybal_{ELl,ELs,Elday,t,r} \\ ELl = last\ load\ segment, & (1 - ELstorecycloss)DELstorenergyballast_{ELl,ELs,Elday,t,r} \end{cases}$$

Dual constraint associated with amount of heat drawn from CSP storage:

$$0 \geq DELCSPutil_{ELl,ELs,ELday,t,r} ELCSPthermaleff - if \begin{cases} ELl < last\ load\ segment, & DELstorenergybal_{ELl,ELs,Elday,t,r} \\ ELl = last\ load\ segment, & DELstorenergyballast_{ELl,ELs,Elday,t,r} \end{cases}$$

Dual constraint associated with stored heat for CSP:
Note: $DELstorenergyballast_{L1,ELs,Elday,t,r}$ only appears when ELl is the last load segment.

$$0 \geq if \begin{cases} ELl < last\ load\ segment, (1 - ELstorehrloss)^{ELlchours_{ELl}} DELstorenergybal_{ELl,ELs,Elday,t,r} \\ ELl = last\ load\ segment, (1 - ELstorehrloss)^{ELlchours_{ELl}} DELstorenergyballast_{ELl,ELs,Elday,t,r} \end{cases}$$
$$- DELstorenergybal_{ELl-1,ELs,Elday,t,r} - DELstorenergyballast_{L1,ELs,Elday,t,r}$$
$$- DELstorlim_{ELpcsp,ELl,ELs,ELday,t,r} + DELopmaintbal_t ELstoromcst_r$$

Dual constraint associated with the amount of heat used instantaneously in CSP plants:

$$0 \geq -DELsolenergybal_{ELl,ELs,ELday,t,r} + DELCSPutil_{ELl,ELs,ELday,t,r} ELCSPthermaleff$$

Dual constraints associated with the up and down ramping of dispatchable plants:

$$0 \geq DELrampbal_{ELpd,ELl,ELs,ELday,t,r} + DELopmaintbal_t$$

$$0 \geq -DELrampbal_{ELpd,ELl,ELs,ELday,t,r} + DELopmaintbal_t$$

<u>Residential demand</u>

When not operating the bottom-up residential electricity use model shown in Figure 1, a simplified representation of residential electricity demand may be alternatively estimated using KEM-SA. The file called **ResidentialELdem.gms** is located within the electric power sub-model.

Current metering does not allow the tracking of power use by consumer type for each hour of the day beyond the industrial sector. We, therefore, estimate the residential fraction of total demand in each region and season and apply that fraction to all hours in each day. The fractions are derived by incorporating the seasonal shares estimated for each region by the sole distributer of electricity in the country, the Saudi Electricity Company.

Since electricity prices are flat during the day and have changed very little over the last couple of decades, estimating hourly elasticities for Saudi Arabia is not possible. To address this problem, we have developed a set of representative hourly elasticities based on those of other countries and KAPSARC's estimate of historical annual residential price elasticity in Saudi Arabia. Thus, any analysis using this section is only a first cut at measuring the effect of price changes on households and the energy sector.

The file **Elast_LS.xlsx** inputs the estimated hourly own- and cross-price elasticities for residential customers. It is read by how much the demand rows' load segments changes as price is changed in the column's load segments. With demand for electricity represented by hourly load curves, it would be interesting to observe how demand responds throughout the day to changing prices.

Household electricity demand equations are used to characterize their demand as a function of price:
Note: The coefficients, $ELREchange_{ELl,ELll,ELs,ELday,t,r}$, are based on the price elasticities defined above.

$$ELRElcgw_{ELl,ELs,ELday,t,r} ELlchours_{ELl} ELdaysinseason_{ELs,ELday} 10^6 =$$
$$ELREconstant_{ELl,ELs,ELday,t,r} + \sum_{ELll} ELREchange_{ELl,ELll,ELs,ELday,t,r} \cdot$$
$$\begin{cases} if\ electricity\ price\ is\ administered,\ ELelecAPHH_{ELll,ELs,ELday,t,r} \\ if\ electricity\ price\ is\ the\ marginal\ cost\ of\ delivery,\ DELdem_{ELll,ELs,ELday,t,r} \\ if\ electricity\ price\ is\ the\ average\ cost\ of\ delivery,\ ELavgcost_{ELll,ELs,ELday,t,r} \end{cases}$$

Where,

- $ELelecAPHH_{ELll,ELs,ELday,t,r}$ are the administered price(s) of electricity,
- $ELavgcost_{ELll,ELs,ELday,t,r}$ are the average costs of electricity generation and delivery by in each season and region, and
- $DELdem_{ELll,ELs,ELday,t,r}$ are the marginal costs by time- and type-of-day in each season and region of delivering electricity.

<u>The petrochemicals sector</u>

The petrochemicals sub-model is defined in **petchemsubmodel.gms**. It maximizes its profit and represents the processes listed in Table 2. The petrochemicals sub-model accounts for 24 products spanning basic and intermediate chemicals, polymers, fertilizers and specialty chemicals. Selection of these products is based on the annual reports of the Saudi Basic Industries Corporation (SABIC), which owns or is part owner of a majority of all petrochemical production in Saudi Arabia. The output capacities by product are obtained from Stratner (2015).

The model, like the other sectors, has investment and operation activities that capture the different technology choices for producing bulk chemicals. The investment and operational costs are derived from Alfares et al. (2007) and Stratner (2015). Since this is an export sector, the model is highly sensitive to price differences between feedstock costs and world market prices.

Production of petrochemicals require intricate mass balances. A feedstock, like ethane or naphtha, is initially cracked to yield several products at different mass shares. The modeled units of a process are unit of input per unit of main product. The other produced materials are named as by-products and are accounted for in the mass balance relationships. The resulting product, for example ethylene, may either be sold as is or further processed to produce other chemicals downstream. The product of that process faces the same decision tree. They mass yields of each process are calibrated from Sumitomo Chemical (2006), the Kirk-Othmer Encyclopedia of Chemical Technology (2006), Aitani (2006) and Al-Manssoor (2008).

The operation is solved for a whole year. Thus, the electricity loads that are output are assumed to be constant all-year-round. We thought about indexing the operation variables by time of day, type of day and season, but two main issues stopped this:

- We would not be able to reliably calibrate seasonal demands of products in each region in the model.
- The number of variables and equations in the model would grow to a point where analyses could not be done within a reasonable timeframe.

Input(s)	Process path	Output
Ethane	Steam cracking	Ethylene, Propylene and Butadiene
Naphtha	Steam cracking	Ethylene, Propylene and Butadiene
Propane	Steam cracking	Ethylene, Propylene and Butadiene
Propane	Dehydrogenation	Propylene
Ethylene	Reactor-fractionation-evaporator-distiller	Ethylene Glycol
Ethylene	Polymerization (low-pressure)	HDPE
Ethylene	Polymerization (high-pressure)	LDPE
Ethylene	Polymerization (low-pressure)	LLDPE
Ethylene	Chlorination-oxidation-pyrolysis	VCM
Ethylene	Alkylation-dehydrogenation (liquid-phase)	Styrene and Toluene
Ethylene	Alkylation-dehydrogenation (gas-phase)	Styrene and Toluene
VCM and toluene	Suspension polymerization	PVC
VCM	Bulk polymerization	PVC
Styrene	Reactor-centrifuge-blending (Lummus Crest)	Polystyrene
Propylene	Union Carbide/Shell process	Polypropylene
Propylene	Himont Inc. spheripol process	Polypropylene
Methane	Reformer-reactor (ICI LCA process)	Ammonia
Methane	Desulfurization-reactor-xxchanger	Methanol
Methanol	Reactors-distillation-extractor (BP process)	MTBE
Propylene	Hydroformylation-condensation-hydrogenation	2-EH
Ammonia	Reactor-crystallization-prilling	Urea
Ethylene	Catalytic reaction with acetic acid & palladium	Vinyl Acetate
Propylene	Chlorohydrin process	Propylene Oxide
Propylene	Epoxidation with Ethylbenzene Hydroperoxide	Propylene Oxide and Styrene
Propylene Oxide	Hydration	Propylene Glycol
Methane	Kellogg Process	Ammonia
Methanol	Oxidation and catalysis using Fe-Mo oxide catalyst	Formaldehyde
Urea and formaldehyde	Alkaline methylolation and acid condensation	Urea-Formaldehyde Resin
Ammonia	DAP plant with granulation units	Diammonium phosphate (DAP)

Table 2 – Production process paths in the petrochemical sub-model

Description of sets and variables:

```
Sets
PCim(allmaterials) all petrochemical feedstock and products /ethylene,
methanol, mtbe methyl tert-butyl ether, styrene, propylene, ethylene-glycol,
vcm vinyl chloride monomer, ldpe low-density polyethylene, lldpe linear low-
density polyethylene, hdpe high-density polyethylene, pp polypropylene, pvc
polyvinyl chloride, polystyrene, ammonia, urea, 2EH 2-ethylhexanol,
vinacetate vinyl acetate, propoxide propylene oxide, prop-glycol propylene
glycol, toluene, formal formaldehyde, DAP diammonium phosphate, urea-formald
urea-formaldehyde, butadiene, ethane, methane, propane, naphtha/

PCMTBE(allmaterials) only MTBE /mtbe/

* i (im) and m (im) declares that i and m a subset of (im)
PCi(PCim) petrochemical products /ethylene, methanol, mtbe, styrene,
propylene, ethylene-glycol, vcm, ldpe, lldpe, hdpe, pp, pvc, polystyrene,
ammonia,urea,2EH,vinacetate,propoxide,prop-glycol,toluene,formald,
urea-formald,butadiene,DAP/

PCm(f) feedstock /ethane,methane,propane,naphtha/
PCmCH4(PCm) natural gas only /methane/
PCmnoCH4(PCm) all fuels without methane /ethane,propane,naphtha/
PCmgas(PCm) ethane and methane /methane,ethane/
PCmngas(PCm) fuels not methane or ethane /propane,naphtha/

PCmref(PCm) refined inputs /naphtha/
PCmup(PCm) inputs from upstream /ethane,methane,propane/

PCmsub(PCm) subsidized feedstock (used for a policy) /methane,ethane/
PCmnsub(PCm) not subsidized feedstock (used for a policy) /propane,naphtha/
PCfsub(fup) subsidized feedstock (used for a policy /methane,ethane/
PCfnsub(fup) not subsidized feedstock (used for a policy) /propane/

PCp petrochemical processes in KEM-SA /p1eth, p1naph, p2ethylene,
p2propyleneprop, p3*p7, p8ldpe, p8pp_liq, p8pp_gas, p9*p25/
;

A description of the processes/plants:

p1eth           Steam cracking of ethane
p1naph          Steam cracking of naphtha
p2ethylene      Steam cracking of propane
p2propyleneprop Catalytic dehyrogenation of propane
p3              Reactor-fractionation-evaporator-distiller (ethylene to EG)
p4              Polymerization1 (ethylene to HDPE.. low-pressure process)
p5              Suspension Polymerization (VCM to PVC)
p6              Bulk Polymerization (VCM to PVC)
p7              Suspension Lummus Crest Process(styrene to PS)
p8ldpe          Polymerization (ethylene to LDPE.. high-pressure process)
p8pp_liq        Union Carbide process in liquid phase (PP from propylene)
p8pp_gas        Union Carbide process in gas phase (PP from propylene)
p9              Reformer-Reactor_ICI LCA process (methane to ammonia)
p10             Chlorination/Oxychlorination/Oxidation/Pyrolysis (ethylene to
```

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                VCM)
p11             Reactor-Crystalization-Prilling (ammonia to urea)
p12             BP_process_Reactor (methanol to MTBE)
p13             Alkylation of benzene with ethylene/Dehydogenation-liquid
                process (ethylene to styrene)
p14             Alkylation of benzene with ethylene/Dehydogenation-vapor
                process (ethylene to styrene)
p15             Desulfurization-reactor-exchanger (methane to methanol)
p16             Copolymerization (ethylene to LLDPE.. low-pressure process)
p17             Hydroformylation-condensation-hydrogenation (propylene to 2-
                EH)
p18             Catalytic reaction with acetic acid and palladium (and
                oxygen) (ethylene to vinyl acetate)
p19             Chlorohydrin process (propylene to propylene oxide)
p20             Epoxidation with ethylbenzene hydroperoxide and catalysis
                (propylene to propylene oxide, styrene is a byproduct after
                dehydration of one of the main products) (ARCO method)
p21             Hydration (propylene oxide to propylene glycol)
p22             Kellogg Process (methane to ammonia)
p23             Oxidation & catalysis using iron-molybdenum catalyst
                (methanol to formaldehyde)
p24             Alkaline methylolation and acid condensation (urea and
                formaldehyde to urea-formaldehyde resin)
p25             DAP plant with granulation units

alias(PCp,PCpp);

Positive Variables
PCImports(trun) Equipment capital costs in millions of USD (usually imported)
PCConstruct(trun) Construction capital costs in millions of USD
PCOpandmaint(trun) Non-feedstock operating costs in millions of USD
PCELconsump(ELl,ELs,ELday,trun,r) Quantifies electricity use per region in
                                  TWh
PCbld(PCp,trun,r) Built capacity of process PCp in millions of metric  tonnes
PCexistcp(PCp,trun,r) Existing capacity of process PCp in millions of metric
                       tonnes
PCop(PCp,trun,r) Quantities produced using PCp in millions of metric  tonnes
PCtrans(PCim,trun,r,rr) Supply of product "i" from one region to another in
                        millions of metric  tonnes
PCfconsump(f,trun,r) Quantifies regional use of feedstock m in the units of m
PCexports(PCi,trun,r) Quantity of exported petrochemicals by region in
                      millions of metric  tonnes
PCRevenues(trun) Revenues gathered from exporting petrochemical products in
                 millions of USD
PCELpwrdemand(trun,r) Electric power used by the petrochemicals industry in
                      GW
```

Here we show the primal linear program we used to formulate the MCP.

Objective function minimizes negative profit:
Note: $fuelsubsidy_t$ is fixed to zero except for the constrained-price-adjustment scenario. $PCdiscfact_t$ are the discount factors over time; the default discount rate for this sector is 8 percent. $PCfconv_{PCmup}$ are conversion factors to go from MMBTU to tonnes. If fuel prices are regulated, $PCfeedcst_{PCm,t}$ is a parameter used to set the price. The variable $Dfdem_{PCmup,t,r}$ are the marginal costs of delivering the inputs by the upstream sector. Likewise, $DRFdem_{PCmref,t,r}$ are the marginal costs of delivering inputs by the refining sector. $PCELprice_{ELl,ELs,Elday}$ are the administered prices of electricity charged to the petrochemicals sector. $DELdem_{ELl,ELs,Elday,t,r}$ are the marginal costs of delivering electricity by time of day in dollars per MWh.

$$
\min \left[\sum_t (PCImports_t + PCConstruct_t + PCOpandmaint_t) PCdiscfact_t \right.
$$

$$
+ if \begin{cases} \text{feedstock prices are deregulated,} \\ \displaystyle\sum_{PCm} \sum_t \sum_r \left(PCfconsump_{PCm,t,r} \begin{pmatrix} Dfdem_{PCmup,t,r}(1 - fuelsubsidy_t) PCfconv_{PCmup} \\ + DRFdem_{PCmref,t,r} \end{pmatrix} \right) \\ \text{feedstock prices are administered,} \\ \displaystyle\sum_{PCm} \sum_t \sum_r (PCfconsump_{PCm,t,r} PCfeedcst_{PCm,t} PCdiscfact_t) \end{cases}
$$

$$
+ if \begin{cases} \text{electricity prices are deregulated,} \\ \displaystyle\sum_{ELl} \sum_t \sum_r \sum_{ELs} \sum_{ELday} (PCELconsump_{ELl,ELs,ELday,t,r} DELdem_{ELl,ELs,Elday,t,r}) \\ \text{electricity prices are administered,} \\ \displaystyle\sum_{ELl} \sum_t \sum_r \sum_{ELs} \sum_{ELday} (PCELconsump_{ELl,ELs,ELday,t,r} PCELprice_{ELl,ELs,Elday} PCdiscfact_t) \end{cases}
$$

$$
\left. - \sum_t (PCrevenues_t PCdiscfact_t) \right]
$$

In the objective function, only revenues sourced from exports are included. Domestic revenues do not change between scenarios, because the sector is forced to meet domestic demand without changing product prices between the scenarios and therefore it would only be a constant.

Note: The petrochemicals sector includes a budget constraint that is not enforced in the model and is therefore not shown here.

Accumulates all equipment capital costs:
$PCpurcst_{PCp,t,r}$ are the portion of the capital costs attributed to purchasing the equipment for each process.

$$\sum_{PCp}\sum_{r} PCpurcst_{PCp,t,r} PCbld_{PCp,t,r} = PCImports_t$$

Accumulates all construction capital costs:
$PCconstcst_{PCp,t,r}$ are the portion of the capital costs attributed to purchasing land and construction of each process.

$$\sum_{PCp}\sum_{r} PCconstcst_{PCp,t,r} PCbld_{PCp,t,r} = PCConstruct_t$$

Accumulates non-feedstock operations and maintenance costs:
$PComcst_{PCp,r}$ are the O&M costs for each process. $PCtranscst_{r,rr}$ are the transportation costs within the same regions or between regions.

$$\sum_{PCp}\sum_{r}\left(PComcst_{PCp,r} PCop_{PCp,t,r}\right) + \sum_{PCi}\sum_{r}\sum_{rr}\left(PCtranscst_{r,rr} PCtrans_{PCi,t,r,rr}\right) = PCOpandmaint_t$$

Accumulates all export revenues:
$PCintlprice_{PCi,t}$ are the export prices of petrochemical products; they are taken from the trade statistics of the recently-renamed Central Department of Statistics and Information (CDSI).

$$\sum_{PCi}\sum_{r} PCintlprice_{PCi,t} PCexports_{PCi,t,r} = PCrevenues_t$$

Enforces feedstock availability, if supply is limited:
$PCfeedsup_{PCm,t,r}$ are the supply limits of feedstock. Similar to the power utilities, natural gas and ethane supply is constrained to the petrochemical sector.

$$-PCfconsump_{PCm,t,r} \geq -PCfeedsup_{PCm,t,r}$$

Capacity balance for petrochemicals processes:

$$PCexistcp_{PCp,t,r} + PCbld_{PCp,t,r} - PCexistcp_{PCp,t+1,r} \geq 0$$

Ensures production level does not exceed capacity:
$PCcapfactor_{PCpp,PCp}$ are the petrochemical plants' capacity factors. By default, they are specified as 0.96 to account for maintenance downtime during the year.

$$-PCop_{PCp,t,r} + \sum_{PCpp} \left[\left(PCexistcp_{PCp,t,r} + PCbld_{PCp,t,r} \right) PCcapfactor_{PCpp,PCp} \right] \geq 0$$

The following two constraints represent mass balance and supply:
Note: Natural gas is used as both a fuel and feedstock material for fertilizers.

$PCfuelburn_{PCm,PCp}$ are the amounts of fuel required to produce a ton of main product.

$$-\sum_{PCp} \left(PCfeedstockin_{PCm,PCp} PCop_{PCp,t,r} \right) - \sum_{PCp} \left(PCfuelburn_{PCm,PCp} PCop_{PCp,t,r} \right) + PCfconsump_{PCm,t,r} \geq 0$$

Supply of petrochemical products:
$PCprocessuse_{PCi,PCp}$ specify the processes that are used to make products. $PCfeedstockin_{PCi,PCp}$ are the feedstock that is used in each process in units of mass of input per unit of main product produced. $PCbyproduct_{PCi,PCp}$ are the by-products that are used in subsequent processes.

$$\sum_{PCp}\left(PCprocessuse_{PCi,PCp}PCop_{PCp,t,r}\right) - \sum_{PCp}\left(PCfeedstockin_{PCi,PCp}PCop_{PCp,t,r}\right) + \sum_{PCp}\left(PCbyproduct_{PCi,PCp}PCop_{PCp,t,r}\right) - PCexports_{PCi,t,r} - \sum_{rr} PCtrans_{PCi,t,r,rr} \geq 0$$

Satisfies demand (endogenous and exogenous):
Note: MTBE can be transferred to the refining sector for gasoline blends.

$PCdemval_{PCi,t,rr}$ are the exogenous demands for petrochemical products; it is currently defined by the values obtained from the Gulf Petrochemicals and Chemicals Association.

Similar to the electricity sector, this constraint has a dual variable associated with it, $DPCdem_{PCi,t,rr}$ in the model. This variable is the marginal cost of delivering the products to each demand region. It may be used as the price in a fully deregulated setting.

$$-RFPCconsump_{PCi,t,rr} + \sum_{r} PCtrans_{PCi,t,r,rr} \geq PCdemval_{PCi,t,rr}$$

Aggregates regional exports to the national level:

$$PCnatexports_{PCi,t} - \sum_{r} PCexports_{PCi,t,r} \geq 0$$

Measures total electricity requirement (as base load):
$PCELin_{PCp}$ are the amounts of electricity required in each process to produce one main product. $ELlchrsfraction_{ELl}ELnormdays_{ELs,ELday}$ are the fraction of hours in each load segment by season and type of day.

$$PCELconsump_{ELl,ELs,ELday,t,r} - ELlchrsfraction_{ELl}ELnormdays_{ELs,ELday}\sum_{PCp}\left(PCELin_{PCp}PCop_{PCp,t,r}\right) \geq 0$$

Calculates power demand from the electricity requirement:

$$PCELpwrdemand_{t,r} - \frac{8760}{1000}\sum_{ELl}\sum_{ELs}\sum_{ELday} PCELconsump_{ELl,ELs,ELday,t,r} = 0$$

The refining sector

The refining sub-model maximizes the refining sector's profit while meeting domestic demand; it is defined in the file **refiningsubmodel.gms**. As shown in Figure 6 below, it can choose the slate of crude oil inputs to produce what is desired locally and for export. The units, processes and product flows considered in the model are presented by the figure.

The sub-model aggregates each refinery's capacities into one refinery per region. KAPSARC has utilized the capacity data published in the IHS Midstream Database to calibrate existing and planned unit capacities. The public version of KEM-SA does not show this proprietary data.

Mass input-output relationships for each process unit characterizes the flows of products through the refining structure; it is a simplified version of a corporate refinery model. Mass yields of the various processes are calibrated in KEM-SA using Ceric (2001), Favennec (2001) and Gary and Handwerk (2005). Crude oil prices charged to the refineries are set at the marginal cost of delivery in the upstream sector, as Saudi Aramco is the owner of or a major stakeholder in all domestic refineries.

The model contains activities for building each unit and the ability to operate the units at different severities. Six primary inputs can be processed: Arabian Super Light, Arabian Extra Light, Arabian Light, Arabian Medium, Arabian Heavy and gas condensate. The outputs include nine petroleum products: two grades of gasoline, diesel, liquefied petroleum gas (LPG), jet fuel, heavy fuel oil (HFO), naphtha, petroleum coke and asphalt.

Properties of blended products are specified according to Saudi Arabian Oil Co. requirements. The properties considered for each finished product in the model are shown in Table 3; upper and lower bounds are and may be imposed on any of them. In the case of HFO, viscosity blending is non-linear and thus it is linearized by taking an index for the blending.

The model also allows for flexibility in the use of electricity during operation, as power can either be generated on-site or bought from the grid. Data on existing generation capacity in the refining sector are derived from ECRA's National Electricity Registry, found on its website. Similar to the petrochemicals sub-model, the operation and thus the electricity use, is for the entire year because of calibration issues and model tractability. The electricity use is, therefore the base load demand.

Gasoline	Research octane number
	Reid vapor pressure
	Mass density
	Sulfur mass content
	MTBE volume content
HFO	Mass density
	Sulfur mass content
	Viscosity blending index
Naphtha	Reid vapor pressure
	Mass density
	Sulfur content
Diesel	Cetane index
	Mass density
	Sulfur content

Table 3 – Properties for which limits are set in the current version KEM-SA

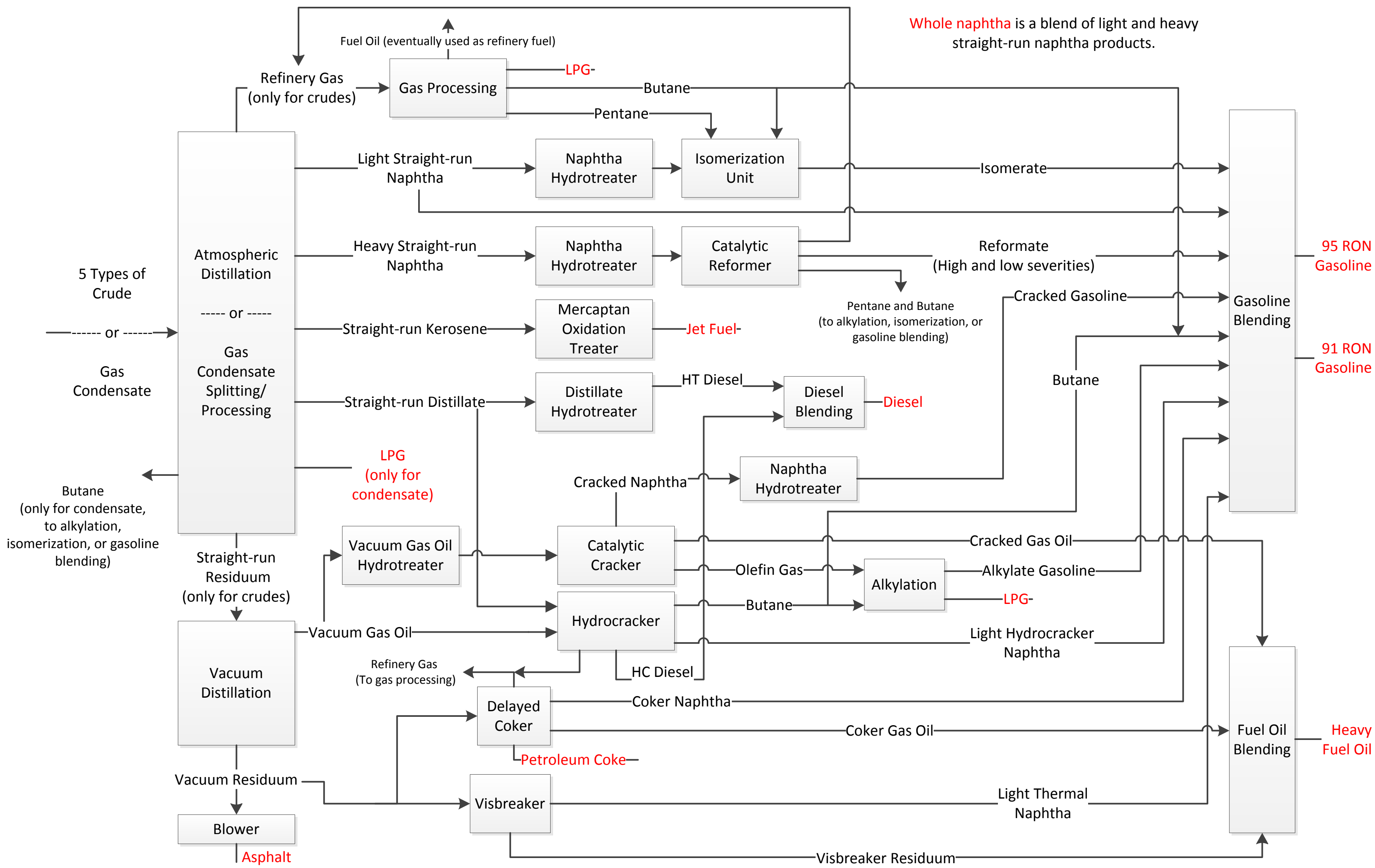

Figure 6 – Refinery scheme used in KEM-SA

```
Sets
RFf(f) all refining fuels
                     /Gcond        Gas condensate
                      Arabsuper    Arabian super light crude
                      Arabextra    Arabian extra light crude
                      Arablight    Arabian light crude
                      Arabmed      Arabian medium crude
                      Arabheavy    Arabian heavy crude
                      hsr-naphtha  Heavy straight-run naphtha
                      lsr-naphtha  Light straight-run naphtha
                      hh-naphtha   Hydrotreated heavy SR-naphtha
                      hl-naphtha   Hydrotreated light SR-naphtha
                      sr-resid     Straight-run residuum
                      sr-keros     Straight-run kerosene or jet fuel
                      sr-distill   Straight-run distillate
                      cc-gasoline  CC gasoline
                      cc-naphtha   Catalytic cracked naphtha
                      lhc-naphtha  Light hydrocracker naphtha
                      lt-naphtha   Light thermal naphtha
                      a-gasoline   Alkylate gasoline
                      v-gas-oil    Vacuum gas oils
                      hv-gas-oil   Hydrotreated vacuum gas oil
                      v-resid      Vacuum residuum
                      cc-gas-oil   FCC gas oil
                      c-gas-oil    Coker gas oil
                      c-naphtha    Coker naphtha
                      ref-gas      Refinery gas
                      fuel-gas     Fuel gas
                      isomerate    Isomerate
                      h-reformate  High severity reformate
                      l-reformate  Low severity reformate
                      ht-diesel    Hydrotreater diesel
                      hc-diesel    Hydrocracker diesel
                      MTBE         Methyl Tert-Butyl Ether
                      95motorgas   RON 95 motor gasoline
                      91motorgas   RON 91 motor gasoline
                      LPG          LPG
                      vis-resid    vis breaker residue
                      olefingas    Olefin gas
                      petcoke      Petroleum coke
                      HFO          Heavy Fuel Oil
                      Diesel       Diesel (based on Aramco's A-870 Diesel)
                      Butane       Butane (separate from butane as 'LPG')
                      Pentane      Pentane
                      Naphtha      Naphtha
                      Jet-fuel     Kerosene or jet fuel
                      Asphalt      Asphalt (also known as bitumen)/
*Asphalt is not used as a fuel, but it is included as a final product.

RFcf(RFf) final products
/95motorgas,91motorgas,HFO,Diesel,LPG,Naphtha,Jet-fuel,Asphalt,Petcoke/

RFcr(RFf)  crude oil grades
/Gcond,Arabsuper,Arabextra,Arablight,Arabmed,Arabheavy/

RFci(RFf) intermediate products /hsr-naphtha,lsr-naphtha,sr-resid,sr-keros,h-
reformate,v-gas-oil,cc-gasoline,c-gas-oil,butane,pentane,a-
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gasoline,isomerate,sr-distill,c-naphtha,cc-gas-oil,ref-gas,v-
resid,petcoke,olefingas,lt-naphtha,cc-naphtha,hh-naphtha,hl-naphtha,lhc-
naphtha,vis-resid,hv-gas-oil,fuel-gas,l-reformate,ht-diesel,hc-diesel,MTBE/

RFMTBE(RFf) MTBE only /MTBE/
RFdie(RFcf) diesel only /diesel/
RFHFO(RFcf) HFO only /HFO/

RFp   refining processes    /a-dist       Atmospheric distillation of crudes
                             refgasp      Processing refinery gas
                             v-dist       Vacuum distillation of sr-residuum
                             n-reform     Naphtha reforming
                             hc-gas-oil   Hydrocracking gas oils
                             cc-gas-oil   Catalytic cracking of gas oils
                             n-hydro      Hydrotreating naphtha
                             d-hydro      Hydrotreating diesel-gasoil
                             vg-hydro     Hydrotreating vacuum gas oil
                             gc-splitp    Gas condensate fractionation
                             r-coke       Coking vacuum residuum
                             jf-merox     Merox treatment of jet fuel
                             lpg-merox    Merox treatment of LPG
                             Alkylation   Alkylation of butane to a-gasoline
                             Isomerp      Isomerization of hydrotreated naphtha
                             visbreakp    Visbreaking
                             Blowing      Asphalt Blowing
                             g95-blend    Gasoline 95 blending
                             g91-blend    Gasoline 95 blending
                             fo-blend     Fuel oil blending
                             d-blend      Diesel blending
                             n-mix        Producing a generic naphtha/

RFu   refining units        /a-still      Atmospheric distiller
                             refgasu      Refinery gas processing unit
                             v-still      Vacuum distiller
                             c-reformer   Catalytic reformer
                             c-crack      Catalytic cracker
                             h-crack      Hydrocracker
                             n-hydrou     Naphtha Hydrotreater
                             d-hydrou     Distillate hydrotreater
                             vg-hydrou    vacuum gasoil hydrotreating unit
                             coker        Delayed coker
                             meroxu       Mercaptan oxidation treater
                             Alkylu       Alkylation unit
                             Isomeru      Isomerization unit
                             Visbreaku    Visbreaking unit
                             Blower       Asphalt blower unit
                             gc-splitu    Gas condensate splitter
                             Blendu       Blending unit/

* Severities are low and high, but could add more levels in the future.
RFs Process severity           /l low,h high/

RFqlim  upper and lower limits for quality specification
/max maximum, min minimum/

prop  final product properties
```

```
/RON       Research octane number
 RVP       Reid vapor pressure (bar)
 VBI       Kinematic viscosity blending index at 100C
 Density   Density (Mg per m^3) at 15C
 Sulfur    Sulfur content (10^3 ppmw)
 CI        Cetane index (for diesel)
 MTBEvol   Fraction of MTBE by volume/

;
alias(RFf,RFff);

Variables
Blendamount91(RFci,trun,r)  amount of intermediates used to produce 91-octane
                            gasoline in millions of metric  tonnes
BlendamountHFO(RFci,trun,r) amount of intermediates used to produce HFO in
                            millions of metric  tonnes
BlendamountNaphtha(RFci,trun,r) amount of intermediates used for whole
                                naphtha in millions of metric  tonnes
BlendamountDiesel(RFci,trun,r) amount of intermediate used to produce Diesel
                               in millions of metric  tonnes

Positive variables
RFop(RFs,RFf,RFp,trun,r)  regional operation level of feedstock in each
                          process and severity in millions of metric  tonnes
RFbld(RFu,trun,r) built regional refining units in trun in millions of metric
                  tonnes
RFExistcp(RFu,trun,r) existing regional refining units in trun in millions of
                      metric  tonnes
RFOpandmaint(trun) O&M costs in trun in millions of USD
RFConstruct(trun) construction capital costs in trun in millions of USD
RFImports(trun) equipment purchased costs in trun in millions of USD
RFtrans(f,trun,r,rr) finished products transported from region r to
                     region rr in millions of metric  tonnes
RFcrconsump(f,trun,r) quantities processed of the different grades
                      crude oil each year in millions of metric
tonnes
RFprodimports(RFcf,trun,r) amounts of refined products imported each
                           year in millions of metric  tonnes
RFRevenues(trun) Revenues gathered from exporting finished refined oil
                 products in millions of USD
RFExports(RFcf,trun,r) Quantity of exported refined products by region in
                       millions of metric  tonnes
RFnatExports(RFcf,trun) Quantity of exported refined products nationally in
                        millions of metric  tonnes
RFELexistcp(trun,r) existing regional on-site electricity generation
                    capacities in trun in GW
RFELbld(trun,r) built regional on-site electricity generation
                capacities in trun in GW
RFELop(ELl,ELs,ELday,trun,r) operation of on-site electricity capacity
                             in each load segment in TWh
RFtotELconsump(ELl,ELs,ELday,trun,r) regional quantity of on-site
                                     generated and purchased
```

```
                                             electricity from grid in each
                                             load segment in trun in TWh
RFELconsump(ELl,ELs,ELday,trun,r)  electricity purchased from the grid
                                   (from power sub-model) in each load
                                   segment in trun in TWh
RFPCconsump(allmaterials,trun,r)  use of petrochemical products in
                                  refining in millions of metric  tonnes
```

Objective function minimizes negative profit:

$RFdiscfact_t$ are the discount factors over time; the default discount rate for this sector is 8 percent. $RFfconv_{RFcr}$ are conversion factors from barrels to tonnes; the refining sub-model is built on mass balance relationships. If the transfer prices are regulated, $RFELprice_{ELl,ELs,Elday}$ and $RFPCprice_{RFci,t,r}$ are the prices of electricity and MTBE, respectively. If they are deregulated, the model uses their respective marginal costs of delivery, $DELdem_{ELl,ELs,Elday,t,r}$ and $DPCdem_{MTBE,t,r}$.

$$\min \left[\sum_t (RFImports_t + RFConstruct_t + RFOpandmaint_t) RFdiscfact_t \right.$$

$$+ \sum_{RFcr} \sum_t \sum_r \left(RFcrconsump_{RFcr,t,r} Dfdem_{RFcr,t,r} RFfconv_{RFcr} \right)$$

$$+ if \begin{cases} \text{electricity prices are deregulated,} \\ \sum_{ELl} \sum_t \sum_r \sum_{ELs} \sum_{ELday} \left(RFELconsump_{ELl,ELs,ELday,t,r} DELdem_{ELl,ELs,Elday,t,r} \right) \\ \text{electricity prices are administered,} \\ \sum_{ELl} \sum_t \sum_r \sum_{ELs} \sum_{ELday} \left(RFELconsump_{ELl,ELs,ELday,t,r} RFELprice_{ELl,ELs,Elday} RFdiscfact_t \right) \end{cases}$$

$$+ if \begin{cases} \text{MTBE prices are deregulated,} \\ \sum_{RFci} \sum_t \sum_r \left(RFPCconsump_{RFci,t,r} DPCdem_{RFci,t,r} \right) \\ \text{MTBE prices are administered,} \\ \sum_{RFci} \sum_t \sum_r \left(RFPCconsump_{RFci,t,r} RFPCprice_{RFci,t,r} RFdiscfact \right) \end{cases}$$

$$\left. - \sum_t (RFrevenues_t RFdiscfact_t) \right]$$

Accumulates all equipment capital and product import costs:
$RFpurcst_{RFu,t,r}$ are the portion of the capital costs attributed to purchasing the equipment for each refining unit. $RFELpurcst_t$ accounts for the investment cost attributed to power generation equipment. $RFImportprice_{RFcf,t,r}$ are the import prices for finished refined products; currently calibrated using the trade statistics of the CDSI.

$$\sum_{RFu}\sum_{r}\left(RFpurcst_{RFu,t}RFbld_{RFu,t,r}\right)+\sum_{r}\left(RFELpurcst_t RFELbld_{t,r}\right) + \sum_{RFcf}\sum_{r} RFImportprice_{RFcf,t,r}RFprodimports_{RFcf,t,r} = RFImports_t$$

Accumulates all construction capital costs:
$RFconstcst_{RFu,t,r}$ are the portion of the capital costs attributed to land and construction. $RFELconstcst_t$ accounts for the investment cost attributed to land and construction.

$$\sum_{RFu}\sum_{r}\left(RFconstcst_{RFu,t}RFbld_{RFu,t,r}\right)+\sum_{r}\left(RFELconstcst_t RFELbld_{t,r}\right) = RFConstruct_t$$

Accumulates non-feedstock operations and maintenance costs:
$RFomcst_{RFs,RFp,t}$ are the O&M costs for each process and severity. $RFELomcst_t$ is the O&M cost for electricity generation; all plants operating or would be operated are assumed to be gas turbines. $RFtranscst_{r,rr}$ are the transportation costs within the same regions or between regions.

$$\sum_{RFs}\sum_{r}\sum_{RFp}\sum_{RFf}\left(RFomcst_{RFs,RFp,t}RFop_{RFs,RFf,RFp,t,r}\right) + \sum_{r}\sum_{ELl}\left(RFELomcst_t RFELop_{ELl,t,r}\right) + \sum_{RFcf}\sum_{r}\sum_{rr}\left(RFtranscst_{r,rr}RFtrans_{RFcf,t,r,rr}\right) = RFOpandmaint_t$$

Accumulates all export revenues:
$RFintlprice_{RFcf,t}$ are the export prices of refined oil products; they are taken from the trade statistics of the CDSI.

$$\sum_{RFcf}\sum_{r}\left(RFintlprice_{RFcf,t}RFexports_{RFcf,t,r}\right) = RFrevenues_t$$

Balances mass flows between processing units:
Note: $RFPCconsump_{RFci,t,r}$ only shows up for MTBE used in gasoline blending.

$RFyield_{RFs,RFf,RFci,RFp}$ are the mass relationships between units, distinguished by different severities where appropriate.

$$\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFci,RFp}RFop_{RFs,RFf,RFp,t,r}\right) + RFPCconsump_{RFci,t,r} - \sum_{RFs}\sum_{RFp}RFop_{RFs,RFci,RFp,t,r} \geq 0$$

Sums consumption of feedstock input to refineries:

$$RFcrconsump_{RFcr,t,r} - \sum_{RFs}\sum_{RFp}RFop_{RFs,RFcr,RFp,t,r} \geq 0$$

Enforces feedstock availability, if supply is limited:
Currently, there are no constraints on the supply of all crude oil grades.

$$-RFcrconsump_{RFcr,t,r} \geq -RFcrudesupply_{RFcr,t,r}$$

Capacity balance for refining units:

$$RFexistcp_{RFu,t,r} + RFbld_{RFu,t,r} - RFexistcp_{RFu,t+1,r} \geq 0$$

Ensures production level does not exceed capacity:
$RFcapfactor_{RFu,RFp}$ defines the capacity factors for each unit; the current setup takes a 90 percent utilization rate.

$$RFexistcp_{RFu,t,r} + RFbld_{RFu,t,r} - \sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFcapfactor_{RFu,RFp}RFop_{RFs,RFf,RFp,t,r}\right) \geq 0$$

Supply constraint:

$$\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFcf,RFp}RFop_{RFs,RFf,RFp,t,r}\right) - RFexports_{RFcf,t,r} - \sum_{rr} RFtrans_{RFcf,t,r,rr} \geq 0$$

Satisfying demand (endogenous and exogenous demands):

$RFdemval_{RFcf,t,rr}$ represent demands that external to KEM-SA. The equation also accounts of endogenous demands from the petrochemicals, electricity, water desalination and cement sectors.

Similar to the electricity sector, this constraint has a dual variable associated with it, $DRFdem_{RFcf,t,rr}$ in the model. This variable is the marginal cost of delivering the refined oil products to each demand region. It may be used as the price in a fully deregulated setting.

$$-PCfconsump_{RFcf,t,rr} - ELfconsump_{RFcf,t,rr} - WAfconsump_{RFcf,t,rr} - CMfconsump_{RFcf,t,rr} + RFprodimports_{RFcf,t,rr} + \sum_{r} RFtrans_{RFcf,t,r,rr} \geq RFdemval_{RFcf,t,rr}$$

Aggregates regional exports to the national level:

$$RFnatexports_{RFcf,t} - \sum_{r} RFexports_{RFcf,t,r} = 0$$

$Qspecification_{RFqlim,RFcf,prop}$ are the minimum and maximum constraints for blended fuel properties, whereas $Qattributes_{RFf,prop}$ are the properties of the blend inputs. $RFconv_{RFf,prop}$, different from $RFfconv_{RFcr}$, is in the two constraints below because some property constraints are blended on volumetric basis and some are blended on based on mass.

Ensures upper limit of blend properties is satisfied:

$$Qspecification_{max,RFcf,prop}\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFcf,RFp}RFconv_{RFf,prop}RFop_{RFs,RFf,RFp,t,r}\right) - \sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFcf,RFp}RFconv_{RFf,prop}RFop_{RFs,RFf,RFp,t,r}Qattributes_{RFf,prop}\right) \geq 0$$

Ensures lower limit of blend properties is satisfied:

$$-Qspecification_{min,RFcf,prop}\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFcf,RFp}RFconv_{RFf,prop}RFop_{RFs,RFf,RFp,t,r}\right)$$
$$+\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFyield_{RFs,RFf,RFcf,RFp}RFconv_{RFf,prop}RFop_{RFs,RFf,RFp,t,r}Qattributes_{RFf,prop}\right)\geq 0$$

Capacity balance for on-site power generation (assumed to all be GT):

$$RFELexistcp_{t,r}+RFELbld_{t,r}-RFELexistcp_{t+1,r}\geq 0$$

Ensures on-site electricity generation does not exceed capacity:

$$\left(RFELexistcp_{t,r}+RFELbld_{t,r}\right)ELlchours_{ELl}ELdaysinseason_{ELs,ELday}-RFELop_{ELl,ELs,ELday,t,r}\geq 0$$

Measures total electricity requirement (as base load):

The product $RFELlchrsfraction_{ELl}ELnormdays_{ELs,ELday}$ stipulates that the consumption is distributed evenly across the year. $RFELin_{RFs,RFp}$ are the amounts of electricity required in each process and severity to process one unit of input material.

$$-RFELlchrsfraction_{ELl}ELnormdays_{ELs,ELday}\sum_{RFs}\sum_{RFf}\sum_{RFp}\left(RFELin_{RFs,RFp}RFop_{RFs,RFf,RFp,t,r}\right)$$
$$+RFtotELconsump_{ELl,ELs,ELday,t,r}\geq 0$$

Ensures electricity requirement is satisfied by either on-site generation or the grid:

$$RFELop_{ELl,ELs,ELday,t,r}+RFELconsump_{ELl,ELs,ELday,t,r}-RFtotELconsump_{ELl,ELs,ELday,t,r}=0$$

The water desalination sector

Defined in the file **watersubmodel.gms**, the water desalination sector minimizes the total variable and annualized capital costs of supplying desalinated water to consumers connected to regional water networks. Off-network water generators may be included; however, estimates for off-grid water demand needed are difficult to obtain. For this reason, off-network water supplies are not explicitly modeled. As most of the desalinated water is produced through cogeneration, the water sector also minimizes total cost of supplying power generation capacity and electric energy to the power sector model. Water demand is represented as a flat demand curve, assuming that sufficient water storage is readily available.

Desalination technologies are broken down into three categories; standalone thermal desalination, Reverse Osmosis (RO), and thermal cogeneration. Standalone thermal plants include Multiple-effect distillation (MED) and multi-stage flash distillation (MSF). Standard reverse osmosis technologies are represented in three different configuration; Salt Water RO (SWRO) and Brackish Water RO (BWRO) operating off a conventional electric power source, and Hybrid SWRO (SWROhyb) with power and water supplied by a cogeneration plant. The purpose of a Hybrid SWOR plants is combining product water from the two desalination cycles, increasing the minimum concentration of impurities in the SWRO product water, and total energy use.

Cogeneration plant types include Steam Turbine Cogeneration operating MSF units (STCo) and Combined Cylce Gas Turbine Cogeneration plants operating either MED (CCCoMED) or MSF (CCCoMSF) units. These cogeneration plants supply steam to the desalination cycle using a Back pressure steam Turbine Generator (BTG) with a fixed Power to Water Ratio (PWR). These plants supply baseload power running at full capacity.

Other cogeneration plants have variable PWR's (STCoV, CCCoVMED, CCCoVMSF). These plants use Extraction Steam Turbines (EST) to vary the amount of energy extracted from a steam turbine for desalination. Gas Turbines congeneration plants (GTCO) are configured with a Heat Recovery Steam Generator (HRSG).

Plants that can vary their PWR may store water off peak and generate excess power during peak demand period when the price communicated by the power sector model is sufficiently high. The MCP model has been configured such that the price of electricity paid to cogeneration plants by the power sector are administered. This reflects current policies with electricity prices fixed below the marginal value. This feature of the water model can be used to assess price coordination between the power and desalination sectors that can impact overall system operation and costs.

Sets and variables description:

```
Sets

WAp  desalination plant types in KEM-SA
       /MED,MSF,BWRO,SWRO,StCo,GTCo,CCCoMED,CCCoMSFStCoV,CCCoVMED,CCCoVMSF/

WApV(WAp) variable PWR cogen plants /StCoV,GTCoV,CCCoVMED,CCCoVMSF/

WApF(WAp) standalone and fixed PWR cogen
/MED, MSF, BWRO ,SWRO, StCo,GTCo,CCCoMED,CCCoMSF/

WAps(WApF) standalone plants /MED,SWRO,BWRO/

WAf(f) fuels for water plants /Arablight,HFO,diesel,methane/

opm   cogen operation modes (m0 = no water, m1 = cogen) /m0,m1/


Positive variables

WAbld(WAp,v,trun,r) building water plants in MMm3 per day (for standalone) or
                    TW (for cogen)
WAexistcp(WAp,v,trun,r) existing capacity in MMm3 per day and GW
WAop(WApF,v,WAf,trun,r) operation (standalone) MMm3 and fixed cogen in TWh
WAVop(WApV,v,ELl,ELs,ELday,WAf,opm,trun,r) operation variable cogen in TWh
WAtrans(ELl,ELs,trun,r,rr) water transportation in MMm3
WAtransexistcp(trun,r,rr) exisiting waater transporation capacity in MMm3
WAtransbld(trun,r,rr) building new transport capacity  in MMm3
WAImports(trun) equipment purchased costs in millions of USD
WAConstruct(trun) construction capital costs in millions of USD
WAOpandmaint(trun) O&M costs in millions of USD
WAELsupply(ELl,ELs,ELday,trun,r) electricity supply for power sub-model in
                                 TWh
WAELconsump(ELl,ELs,ELday,trun,r) electricity consumption in TWh
WAELconsumphyb(ELl,ELs,ELday,trun,r) electricity consumption by hybrid RO in
                                     TWh
WAelconsumpsol(WApsingle,ELl,ELs,ELday,trun,r)
WAELpwrdemand(trun,r) power demand  from water producers in GW
WAELrsrvcontr(trun,r) cogen elec contribution to ELp reserve in GW
WAfconsump(f,trun,r) fuel consumption by water plants in MMBTU BBL Tonne
WAfconsumpcr(f,trun,r) fuel consumption by water plants in MMBTU BBL Tonne
WAstoexistcp(trun,r) existing water storage capacity in billion m3
WAstobld(trun,r) building water storage capacity in billion m3
WAstoop(ELl,ELs,trun,rr) water storage in billion m3 in each load segment
WAgr(WAf,trun,r) supply of ground water in Billion cubic meters
WAgrexistcp(trun,r) existing ground water capacity in billion m3
```

Accumulate all equipment capital costs:

Note: $\gamma_{capital\ credit}$ is set to zero except for investment credit scenarios.

$WApurcst_{ELp,t}$, $WAstopurcst_{ELp,t}$ and $WAtranspurcst_{t,r,rr}$ are the portion of the capital costs attributed to purchasing equipment for production, storage and transportation, respectively. The same equation exists for calculating the construction costs, $WAConstruct$, using construction cost parameters $WAconstcst_{WAp,t}$, $WAstoconstcst_{rr,t}$ and $WAtransconstcst_{t,r,rr}$.

$$\sum_{WAp}\sum_{v}\sum_{r}\left\{\left[WApurcst_{WAp,t}\left(1-\gamma_{capital\ credit_{WAp}}\right)\right]WAbld_{WAp,v,t,r}\right\} + \sum_{rr}\left\{\left[WAstopurcst_{t,rr}\right]WAstobld_{t,rr}\right\} + \sum_{r}\sum_{rr}\left[WAtranspurcst_{t,r,rr}WAtransbld_{t,r,rr}\right] = WAImports_{t}$$

Accumulates all non-fuel variable and fixed operations and maintenance costs:

$WAomcst_{WAp,v,r}$ and $WAfixedOMcst_{WAp,t}$ are the variable and fixed operation and maintenance (O&M) costs for the various desalination plants. $WAyield_{WApF,v,r}$ are the yields of total water produced per unit of electricity generated for plants with cogeneration. $WAVyield_{WApV,v,opm,r}$ are the yields for variable PWR cogeneration plants; $WAELomcst_{WAp,v,r}$ are the variable operation and maintenance (O&M) costs for the power generation units. $WAstoomcst_{r}$ and $WAtransomcst_{r,rr}$ are the O&M costs of water storage and transportation, respectively.

$$\sum_{WApF}\sum_{v}\sum_{r}\sum_{WAf}\left(WAELomcst_{WApF,v,r}+WAomcst_{WApF,r}WAyield_{WApF,v,r}\right)\cdot WAop_{WApF,v,WAf,t,r} + \sum_{WApV}\sum_{v}\sum_{r}\sum_{WAf}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left(WAELomcst_{WApV,v,r} + WAomcst_{WApF,r}WAyield_{WApV,v,opm,r}\right)\cdot WAVop_{WApV,v,ELl,ELs,ELday,WAf,opm,t,r} + \sum_{ELl}\sum_{ELs}\sum_{ELday}\sum_{r}WAstoomcst_{r}WAstoop_{ELl,ELs,ELday,t,r} + \sum_{r}\sum_{rr}\sum_{ELl}\sum_{ELs}\sum_{ELday}\left[WAtransomcst_{r,rr}WAtrans_{ELl,ELs,ELday,t,r,rr}\right]$$

Capacity balance for dispatchable technologies:

Note: $WAaddition_{WAp,v,t+1,r}$ and $WAretirement_{WAp,v,t+1,r}$ are parameters to add plants already under construction and set rules for retirement, respectively. Additions and retirements are assumed to take place at the end of time period, t.

$$WAexistcp_{WAp,v,t,r} + WAaddition_{WAp,v,t+1,r} - WAretirement_{WAp,v,t+1,r} + WAbld_{WAp,v,t,r} - WAexistcp_{WAp,v,t+1,r} \geq 0$$

Capacity limit for standalone and fixed PWR cogeneration plants.

$WAFoptime_{WApF}$ represents the total amount of time in hours for power-water co-generators and days for standalone water plants, excluding scheduled maintenance time.

$$WAFoptime_{WApF}\left[WAexistcp_{WApF,v,t,r} + WAbld_{WApF,v,t,r}\right] - \sum_{WAf} WAop_{WApF,v,WAf,t,r} \geq 0$$

Capacity limit for variable PWR cogeneration plants.

Same as above but for variable PWR plants. $WAFoptime_{WApF}$ represents the total number of hours available to a given power and water co-generator in each demand period from the powers sector, excluding scheduled maintenance time. $WAVpwrincr_{WApV,v,opm}$ represents increase in the power output of the cogeneration plant when water output is switched off.

$$WAVoptime_{WApV,ELl,ELs,ELday}\left[WAexistcp_{WApV,v,t,r} + WAbld_{WApV,v,t,r}\right] - \sum_{WAf}\sum_{opm} WAVop_{WApV,v,ELl,ELs,ELday,WAf,opm,t,r}/WAVpwrincr_{WApV,v,opm} \geq 0$$

Capacity balance for water storage:

$$WAstoexistcp_{t,r} + WAstobld_{t,r} - WAstoexistcp_{t+1,r} \geq 0$$

Capacity limit for water storage:

$ELdaysinseason_{ELs,ELday}$ used to approximate an upper bound on the total amount of water storage available in a given season. It is assumed that the available water storage capacity is used on a daily cycle, not for inter-seasonal storage.

$$\left(WAstoexistcp_{t,r} + WAstobld_{t,r}\right)\sum_{ELday}\left(ELdaysinseason_{ELs,ELday}\right) - WAstoop_{ELl,ELs,t,rr} \geq 0$$

Water supply balance equation:

Water supply equation setting the upper bound on the amount of water available for transportation within and between regions. $ELnormhours_{ELl,ELs,ELday}$ is the normalized number of hours in each load segment from the power model. The type of day in a given season (week and weekend) are not considered in the transportation and storage of desalinated water.

$$\sum_{WApF}\sum_{v}\sum_{WAf} WAop_{WApF,v,WAf,t,r} WAyield_{WApF,v,r} \sum_{ELday} ELnormhours_{ELl,ELs,ELday} + \sum_{WApV}\sum_{v}\sum_{WAf}\sum_{ELday} WAVop_{WApV,v,ELl,ELs,ELday,WAf,opm,t,r} WAVyield_{WApV,v,opm,r} - \sum_{rr} WAtrans_{ELl,ELs,t,r,rr} \geq 0$$

Water demand balance equation:

Water demand equation balancing the total quantity of water transported into a region and the storage balance with the exogenous demand, $WAdemval_{t,r}$; the water demand is normalized throughout the year. $WAtransyield_{r,rr}$ represents the transportation losses between region *r* and *rr*. The last two terms represent the water storage balance as the difference between storage in the current and previous demand segments.

Similar to the electricity sector, this constraint has a dual variable associated with it, $DWAdem_{ELl,ELs,ELday,t,rr}$ in the model. This variable is the marginal cost of delivery to each demand region. It may be used as the price in a fully deregulated setting.

$$\sum_{r} WAtrans_{ELl,ELs,t,r,rr} WAtransyield_{r,rr} - WAstoop_{ELl,ELs,t,rr} + WAstoop_{ELl-1,ELs,t,rr} \geq WAdemval_{t,r} ELnormdays_{ELs,ELday} ELlcnorm_{ELl}$$

Capacity balance for water transport:

$$WAtransexistcp_{t,r,rr} + WAtransbld_{t,r,rr} - WAtransexistcp_{t+1,r,rr} \geq 0$$

Capacity limit for water transport:

$$\left(WAtransexistcp_{t,r,rr} + WAtransbld_{t,r,rr}\right)\sum_{ELday} ELdaysinseason_{ELs,ELday} - WAtrans_{ELl,ELs,t,r,rr} \geq 0$$

Auxiliary variable for total electricity requirement (as base load):

$$WAELconsump_{ELl,Els,ELday,t,r} - ELlnormhours_{ELl.ELs,ELday}\sum_{WAps}\left(WAop_{WAps,v,WAf,t,r}WAelrate_{WApsat,v}\right) = 0$$

Calculates power demand from the electricity requirement:

$$WAELpwrdemand_{t,r} - \sum_{ELl,ELs,ELday}\left(\frac{WAELconsump_{ELl,ELs,ELday,r}}{ELlchours_{ELl}ELdaysinseason_{ELs,ELday}}\right) \geq 0$$

Enforces fuel availability, if supply is limited:

$WAfconsumpmax_{ELf,t,r}$ are the supply limits for fuels use by the water sector, when prices do not equal marginal values, and fuel supplies are limited.

$$WAfconsump_{ELf,t,r} \leq WAfconsumpmax_{WAf,t,r}$$

Accumulates fuel consumption:

$WAfuelburn_{WAp,v,ELf,r}$ are the heat rates of the power plants in fuel units per GWh of electricity generated for cogeneration plants and billion cubic meters for standalone water plants.

$$WAfconsump_{WAf,t,r} - \sum_{WApF}\sum_{v}\sum_{r}\sum_{WAf} WAfuelburn_{WApF,v,WAf,r} \cdot WAop_{WApF,v,WAf,t,r} + \sum_{WApV}\sum_{v}\sum_{r}\sum_{WAf}\sum_{ELl}\sum_{ELs}\sum_{ELday}\sum_{opm}\left[WAfuelburn_{WApV,v,WAf,r} \cdot WAVop_{WApV,v,ELl,ELs,ELday,WAf,opm,t,r}\right] \geq 0$$

The upstream sector

The upstream sub-model is defined in **fuelsubmodel.gms**. The oil and gas production of the Kingdom is taken exogenously from Saudi Aramco. The oil and gas upstream sector is, therefore, represented with available fuel supplies and a pipeline structure that minimizes the cost of meeting regional demands for gas and crude oil through pipelines. It is written as a profit maximization sub-model because it can export various crude oil grades at world market prices; we may also allow the model to consider any saved quantities of oil resulting from assessing a policy to be valued less the world market prices.

```
Sets
fup(f) upstream fuels /crude all crude oil grades, Arabsuper Arabian super
light, Arabextra Arabian extra light, Arablight Arabian light crude, Arabmed
Arabian medium crude, Arabheavy Arabian heavy crude, methane natural gas,
ethane, NGL natural gas liquids (excluding ethane), propane, Gcond gas
condensate, u-235 uranium fuel, dummyf dummy fuel (only used in the water
desalination sub-model), Coal steam coal imported from South Africa/

natgas(fup) natural gas, NGLs and gas condensate /methane, ethane, NGL,
propane, Gcond/

crude(fup) crude grades /Arabsuper, Arabextra, Arablight, Arabmed, Arabheavy/


Positive variables

ftrans(f,trun,r,rr) transported quantities of fuels from region r to region
                    rr in units of the fuels; crude oils and gas condensate
                    in million barrels and natural gas (and gas products) in
                    trillion BTU
ftransexistcp(fup,trun,r,rr) existing pipeline capacities between regions in
                             units of fuels
ftransbld(fup,trun,r,rr) built pipeline capacities between regions in units
                         of fuels
fImports(trun) equipment purchased costs in trun in millions of USD
fConstruct(trun) construction capital costs in trun in millions of USD
fOpandmaint(trun) O&M costs in trun in millions of USD
fueluse(fup,ss,trun,r) quantity of fuel used regionally in the units of the
                       fuel
fExports(fup,trun,r) quantity of exported fuels from each region in the units
                     of the fuel
fnatexports(fup,trun) quantity of exported fuels nationally in the units
                      of the fuel
fRevenues(trun) revenues gathered from exporting upstream products in
                millions of USD
```

Objective function minimizes negative profit:
$fdiscfact_t$ are the discount factors over time; the default discount rate for this sector is 6 percent. $fuelcst_{fup}$ are the production costs of upstream fuels, or as in the case of coal imported from South Africa, it is the import cost.

$$\min\left[\sum_t (fImports_t + fConstruct_t + fOpandmaint_t)fdiscfact_t + \sum_{fup}\sum_t\sum_r \left(fueluse_{fup,t,r}fuelcst_{fup}fdiscfact_t\right) - \sum_t (fRevenues_t fdiscfact_t)\right]$$

Accumulates all equipment capital and product import costs:
$ftranspurcst_{fup,t,r,rr}$ are the portion of the transportation (pipeline) capital costs attributed to purchasing the equipment for each fuel between regions.

$$\sum_{fup}\sum_r\sum_{rr}\left(ftranspurcst_{fup,t,r,rr}ftransbld_{fup,t,r,rr}\right) = fImports_t$$

Accumulates all construction capital costs:
$ftransconstcst_{fup,t,r,rr}$ are the portion of the transportation (pipeline) capital costs attributed to purchasing the land and construction for each fuel between regions.

$$\sum_{fup}\sum_r\sum_{rr}\left(ftransconstcst_{fup,t,r,rr}ftransbld_{fup,t,r,rr}\right) = fConstruct_t$$

Accumulates non-feedstock operations and maintenance costs:
$fomcst_{fup,r,rr}$ are the pipelines' O&M costs to transport the fuel between regions.

$$\sum_{fup}\sum_r\sum_{rr}\left(ftransomcst_{fup,r,rr}RFtrans_{fup,t,r,rr}\right) = fOpandmaint_t$$

Accumulates all export revenues:
$fintlprice_{fup,t}$ are the upstream fuels' world market prices; they are obtained historically from the CDSI.

$$\sum_{fup}\sum_r\left(fintlprice_{fup,t}fexports_{fup,t,r}\right) = fRevenues_t$$

Aggregates regional exports to the national level:

$$fnatexports_{fup,t} - \sum_{r} fexports_{fup,t,r} = 0$$

Capacity balance for pipelines:

$$ftransexistcp_{fup,t,r,rr} + ftransbld_{fup,t,r,rr} - ftransexistcp_{fup,t+1,r,rr} \geq 0$$

Ensures transportation level does not exceed capacity:

$$ftransexistcp_{fup,t,r,rr} + ftransbld_{fup,t,r,rr} - ftrans_{fup,t,r,rr} \geq 0$$

Supply constraint:
Note: Production is used as upper bounds for $fueluse_{fup,t,r}$.

$$fueluse_{fup,t,r} - fexports_{fup,t,r} - \sum_{rr} ftrans_{fup,t,r,rr} \geq 0$$

Satisfying demand (endogenous and exogenous demands):
$OTHERfconsump_{fup,t,rr}$ represents exogenous demands by sectors not represented in KEM.

Similar to the electricity sector, this constraint has a dual variable associated with it, $Dfdem_{fup,t,rr}$ in the model. This variable is the marginal cost of delivering the fuels to each demand region. It may be used as the price in a fully deregulated setting.

$$\begin{aligned} -PCfconsump_{fup,t,rr}fPCconv_{fup} - ELfconsump_{fup,t,rr} - WAfconsump_{fup,t,rr} \\ - CMfconsump_{fup,t,rr} - RFcrconsump_{fup,t,rr}fRFconv_{fup} \\ - OTHERfconsump_{fup,t,rr} + \sum_{r} \left(ftransyield_{fup,r,rr} ftrans_{fup,t,r,rr} \right) \geq 0 \end{aligned}$$

The cement sector

The cement sub-model, defined in **cementsubmodel.gms**, accounts for the production of three types of cement; Portland Type I, Portland Type V and Pozzolan. The cement sector, which behaves as a profit-maximizing agent, is designed to meet domestic demand but may also export finished product. Furthermore, the sub-model has the ability to import either clinker or finished cement. In the current version of KEM, the fuels that could be used for pyroprocessing and on-site power generation are HFO, Arabian Heavy crude oil, natural gas and diesel. The electricity consumed for operation can be generated on-site or purchased from the power grid. We estimate that electricity demand of the cement industry is base load. Based on a set of capital, non-fuel operation and maintenance, and fuel costs, the sub-model solves for build and operation decision variables to maximize its profit.

The modeling approach consists of applying strict mass balance relationships between the production units. The modeled steady flows of production are stylized in Figure 7 below.

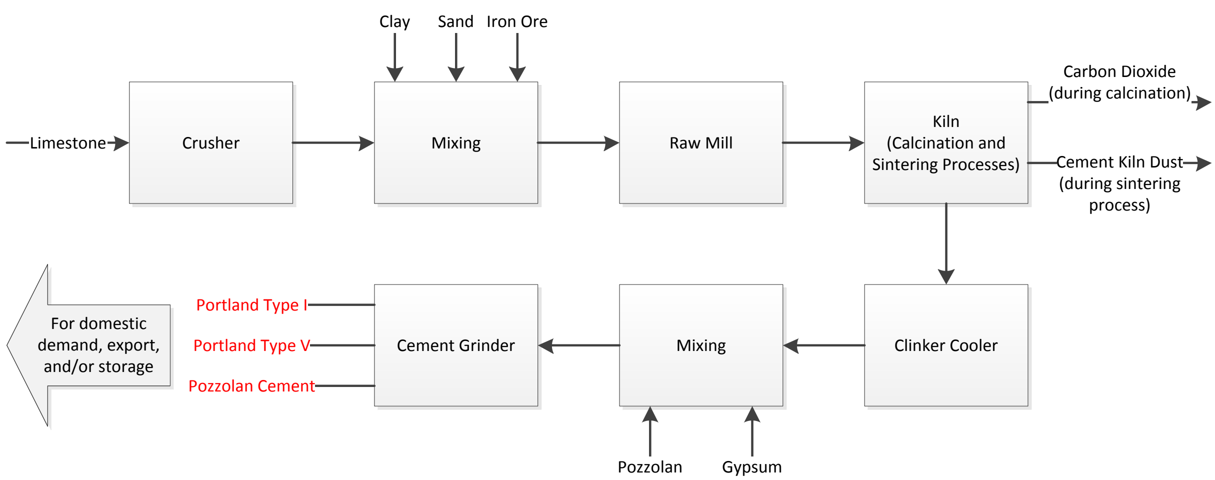


Figure 7 – Cement production path (source: Matar et al., 2014)

Approximated as pure calcite, limestone is typically quarried in close proximity to the production line and is the primary raw material. After being crushed, it is mixed with clay, sand and iron ore and sent through the mill. The resulting raw mix passes through the pyroprocessing stage, where the calcination and sintering reactions take place to produce clinker. Only dry processes are considered in this version of KEM and therefore the technologies represented are long dry kilns, kilns with preheating and kilns with both preheating and precalcination. Each technology has a corresponding specific fuel consumption value per unit of output. The model also has the ability to upgrade existing long dry kilns to the more efficient technologies. The modeled stoichiometric pyroprocessing reactions are described below.

$$Calcination\text{: } CaCO_3 \rightarrow CO_2 + CaO$$

$$Sintering\text{: } CaO + a(SiO_2) + b(Al_2O_3) + c(Fe_2O_3) \rightarrow d(C_3S) + e(C_2S) + f(C_3A) + g(C_4AF)$$

The preceding coefficients are the number of moles to achieve a chemical balance. These molar coefficients are calculated by the model based on the required mass composition of clinker for each type of cement; the clinker mass content is specified according to the standard ASTM C-150. As shown by the chemical reactions, calcite is first dissociated to carbon dioxide and calcium oxide. The calcium oxide and the remainder of the raw mix are then reacted at a higher temperature to produce clinker. Achieving the required reaction conditions is the main driver of energy consumption during cement production. Based on van Oss (2005), the modeled cement kiln dust (CKD) output is estimated to be 17 percent by mass of total kiln output. After being cooled, the clinker is mixed with gypsum and/or pozzolan (differing mixing requirements based on cement type), and the mixture passes through the grinder to produce final cement.

Sets and variable descriptions:

```
Sets CMm all cement production materials
                              /CaCO3   Calcium Carbonate (approx. for limestone)
                               CaCO3c Crushed CaCO3
                               CaCO3SAFm Raw mix
                               Sand    Sand
                               Clay    Clay
                               Irono   Iron Ore
                               Gypsum Gypsum
                               Pozzn   Pozzolan
                               PortI   Portland Cement Type I
                               PortV   Portland Cement Type V
                               PozzC   Pozzolan Cement
                               PortIp Prelim. Portland Cement Type I
                               PortVp Prelim. Portland Cement Type V
                               PozzCp Prelim. Pozzolan Cement
                               ClinkIh High temp Clinker for Portland I
                               ClinkVh High temp Clinker for Portland V
                               ClinkPh High temp Clinker for Pozzolan Cement
                               ClinkI Clinker for Portland I
                               ClinkV Clinker for Portland V
                               ClinkP Clinker for Pozzolan Cement
                               CKD     Cement kiln dust (particulate emission)
                               CaCO3SAF Mixer 1 output
                               CSAF    Clinker reactants
                               Ca      Calcium
                               O       Oxygen
                               Si      Silicon
                               Al      Aluminum
                               Fe      Iron
                               CO2     Carbon Dioxide
                               CaO     Calcium Oxide
                               SiO2    Silicon Oxide
                               Al2O3   Aluminum Oxide
                               Fe2O3   Iron Oxide
                               C3S     Tricalcium Silicate
```

```
                          C2S    Dicalcium Silicate
                          C3A    Tricalcium Aluminate
                          C4AF   Tetracalcium aluminoferrite/

     CMcr(CMm) input materials /CaCO3,Sand,Clay,Irono,Gypsum,Pozzn/

     CMci(CMm) intermediate materials
/ClinkI,ClinkV,ClinkP,ClinkIh,ClinkVh,ClinkPh,

CaO,SiO2,Al2O3,Fe2O3,C3S,C2S,C3A,C4AF,PortIp,

PortVp,PozzCp,CaCO3c,CaCO3SAFm,CaCO3SAF,CSAF/
     CMcii(CMm) without molecules or atoms
/ClinkI,ClinkV,ClinkP,ClinkIh,ClinkVh,ClinkPh,

PortIp,PortVp,PozzCp,CaCO3c,CaCO3SAFm,CaCO3SAF,CSAF/
     CMclinker(CMci) clinker types only /ClinkIh,ClinkVh,ClinkPh/
     CMcl(CMci) clinker reactants and products
/CaO,SiO2,Al2O3,Fe2O3,C3S,C2S,C3A,C4AF/
     CMclr(CMcl) clinker reactants /CaO,SiO2,Al2O3,Fe2O3/
     CMclp(CMcl) clinker products /C3S,C2S,C3A,C4AF/
     CMlime(CMcl) lime only/CaO/

     CMcsaf(CMm) CSAF only/CSAF/

     CMcf(CMm) final products /PortI,PortV,PozzC,CO2,CKD/
     CMcements(CMcf) cements only /PortI,PortV,PozzC/

     CMma(CMm) atomic particles /Ca,O,Si,Al,Fe/

     CMf fuels used in cement production /Methane,Arabheavy,HFO,Diesel/
     CMfup(CMf) upstream fuels /Methane,Arabheavy/
     CMfref(CMf) refined fuels /HFO,Diesel/

     CMu production units /crusher,kiln long dry kiln,
                          phkiln 4-stage preheater kiln,
                          phpckiln 4-stage preheater kiln with
precalcination,
                          kilntophkiln converted kiln to phkiln,
                          kilntophpckiln converted kiln to phpckiln,
                          cooler,grinder,mixer,rawmill/
     CMuk(CMu) kilns only /kiln,phkiln,phpckiln,kilntophkiln,kilntophpckiln/
     CMukcon(CMu) conversion activity units /kilntophkiln,kilntophpckiln/

     CMp processes
/crushing,milling,mixing1,mixing2I,mixing2V,mixing2P,calcining1,        sinte
ringI,sinteringV,sinteringP,sinteringphI,sinteringphV,sinteringphP,
sinteringphpcI,sinteringphpcV,sinteringphpcP,cooling,grinding,
calciningph,calciningphpc/

     CMpk(CMp) sintering processes
/sinteringI,sinteringV,sinteringP,sinteringphI,         sinteringphV,sinterin
gphP,sinteringphpcI,sinteringphpcV,sinteringphpcP/
```

```
     CMpkiln(CMp) operating dry kiln /sinteringI,sinteringV,sinteringP/
     CMpkilnph(CMp) operating dry kiln with preheat
/sinteringphI,sinteringphV,sinteringphP/
     CMpkilnphpc(CMp) operating dry kiln with preheat and precalcination
/sinteringphpcI,sinteringphpcV,sinteringphpcP/

     CMprop properties /masscon content as mass fraction/
     CMqlim property and mixing limits /max,min/
;
alias(CMm,CMmm),(CMp,CMpp),(CMu,CMuu),(CMuk,CMukk);


Positive variables
CMmol(CMcl,CMci,trun,r) number of moles of kiln reactants and products in
                        thousand kmol
CMmass(CMcl,CMm,trun,r) mass of kiln products in millions of metric  tonnes
CMop(CMm,CMp,CMf,trun,r) amount of mass input in process CMp in millions of
                         metric  tonnes
CMexistcp(CMu,trun,r) existing regional capacities of the production units in
                      trun in millions of input metric  tonnes
CMbld(CMu,trun,r) built regional capacities of the production units in trun
                  in millions of input metric  tonnes
CMtrans(CMcf,trun,r,rr) cement product transported from supply region r to
                        demand region rr in millions of metric  tonnes
CMOpandmaint(trun) O&M costs in trun in millions of USD
CMprodimports(CMcf,trun,rr) imported cement products
CMImports(trun) equipment purchased costs in trun in millions of USD
CMConstruct(trun) construction capital costs in trun in millions of USD
CMcrconsump(CMcr,trun,r) regional consumption of raw materials (like
                         limestone, etc.) in millions of metric  tonnes
CMfconsump(f,trun,r) regional consumption of fuels in millions of barrels in
                     the case  of crude oil, trillions of BTU for natural gas
                     and millions of metric  tonnes for refined oil products
CMexports(CMcf,trun,r) regional export quantities of cement products in trun
                       in millions of metric  tonnes
CMnatexports(Cmcf,trun) national export quantities of cement products in trun
                        in millions of metric  tonnes
CMRevenues(trun) revenues gathered from exporting cement in millions of USD
CMtotELconsump(ELl,ELs,ELday,trun,r) total regional electricity consumption
                                     by time-of-year in TWh
CMELconsump(ELl,ELs,ELday,trun,r) electricity purchased regionally from the
                                  grid (from power sub-model) by time-of-year
                                  in TWh
CMELop(CMf,ELl,ELs,ELday,trun,r) regional on-site electricity generation by
                                 time-of-year in TWh
CMELbld(trun,r) built regional on-site electricity capacity in trun in GW
CMELexistcp(trun,r) existing regional on-site electricity capacity in trun in
                    GW
CMclinkimport(CMcii,trun,r) regional imports of clinker in trun in millions
                            of metric  tonnes
CMkupgrade(CMukcon,trun,r) upgradable existing long dry kiln capacity to more
```

```
                               efficient kilns in millions of metric  tonnes
CMkupgradetot(trun,r) sum of all upgradable technologies to relate to kiln
                      capacity in millions of metric  tonnes
CMstorexistcp(trun,r) existing regional storage capacity in trun in millions
                      of metric  tonnes
CMstorbld(trun,r) built regional storage capacity in trun in millions
                  of metric  tonnes
CMstorage(CMcf,trun,r) stored quantities of cement products by year and
                       region in millions of metric  tonnes
CMstoragein(CMcf,trun,r) input amount of cement to storage by region and year
                         in millions of metric  tonnes
CMstorageout(CMcf,trun,r,rr) amount of cement taken out of storage by region
                             and year in millions of metric  tonnes
```

Objective function minimizes negative profit:

Note: $fuelsubsidy_t$ is fixed to zero except for the Constrained-price-adjustment scenario

$CMdiscfact_t$ are the discount factors over time; the default discount rate for this sector is 6 percent. $CMAPf_{CMf,t}$ are the administered fuel prices, if one wishes to run the scenario. If the user further wishes to have a regulated power price, $CMELprice_{ELl,ELs,Elday}$ is the exogenously-administered price of electricity offered to the cement sector.

$$
\min \left[\sum_t (CMImports_t + CMConstruct_t + CMOpandmaint_t) CMdiscfact_t \right.
$$

$$
+ if \begin{cases} \text{fuel prices are deregulated,} \\ \sum_{CMf}\sum_{t}\sum_{r}\left(CMfconsump_{CMf,t,r}\left(Dfdem_{CMfup,t,r}(1 - fuelsubsidy_t) + DRFdem_{CMfref,t,r}\right)\right) \\ \text{fuel prices are administered,} \\ \sum_{CMf}\sum_{t}\sum_{r}\left(CMfconsump_{CMf,t,r} CMAPf_{CMf,t} CMdiscfact_t\right) \end{cases}
$$

$$
+ if \begin{cases} \text{electricity prices are deregulated,} \\ \sum_{ELl}\sum_{t}\sum_{r}\sum_{ELs}\sum_{ELday}\left(CMELconsump_{ELl,ELs,ELday,t,r} DELdem_{ELl,ELs,Elday,t,r}\right) \\ \text{electricity prices are administered,} \\ \sum_{ELl}\sum_{t}\sum_{r}\sum_{ELs}\sum_{ELday}\left(CMELconsump_{ELl,ELs,ELday,t,r} CMELprice_{ELl,ELs,Elday} CMdiscfact_t\right) \end{cases}
$$

$$
\left. - \sum_t (CMrevenues_t CMdiscfact_t) \right]
$$

Accumulates all equipment capital and product imports costs:
$CMpurcst_{CMu,t,r}$ and $CMstorpurcst_t$ are the portion of the capital costs attributed to purchasing the equipment, the producing or storage units. $CMELpurcst_t$ accounts for the investment cost attributed to power generation equipment; the technology used for on-site power generation is taken as gas turbines. $CMimportprice_{CMcf,t,r}$ are the import prices for finished cement products, and $CMclinkprice_{CMcii,t,r}$ are the import prices for cement clinker.

$$\begin{aligned}\sum_{CMu}\sum_{r}\left(CMpurcst_{CMu,t}CMbld_{CMu,t,r}\right) + \sum_{r}\left(CMELpurcst_t CMELbld_{t,r}\right) \\ + \sum_{r}\left(CMstorpurcst_t CMstorbld_{t,r}\right) \\ + \sum_{CMcf}\sum_{r}\left(CMimportprice_{CMcf,t,r}CMprodimports_{CMcf,t,r}\right) \\ + \sum_{CMcii}\sum_{r}\left(CMclinkprice_{CMcii,t,r}CMclinkimport_{CMcii,t,r}\right) = CMImports_t\end{aligned}$$

Accumulates all construction capital costs:
$CMconstcst_{CMu,t,r}$ and $CMstorconstcst_t$ are the portion of the capital costs for producing and storage units attributed to land and construction. $CMELconstcst_t$ accounts for the investment cost attributed to land and construction.

$$\begin{aligned}\sum_{CMu}\sum_{r}\left(CMconstcst_{CMu,t}CMbld_{CMu,t,r}\right) + \sum_{r}\left(CMELconstcst_t CMELbld_{t,r}\right) \\ + \sum_{r}\left(CMstorconstcst_t CMstorbld_{t,r}\right) = CMConstruct_t\end{aligned}$$

Accumulates non-fuel operations and maintenance costs:
$CMomcst_{CMp,t}$ are the O&M costs for each process. $CMmassout_{CMm,CMmm,CMp}$ relates the masses of the input and output materials for specific processes. $CMtranscst_{r,rr}$ and $CMstorageout_{CMcf,t,r,rr}$ are the transportation costs within the same regions or between regions; the latter cost stipulates the cement is taken from storage, whereas $CMtranscst_{r,rr}$ is moving manufactured cement. $CMELomcst_t$ is the O&M cost for electricity generation. $CMstoromcst_t$ is the operating cost of keeping finished cement in storage.

$CMfeedcst_{CMcr,t,r}$ are the costs of the non-fuel raw materials used in cement production, like limestone and iron ore.

$$\sum_{CMm}\sum_{CMmm}\sum_{CMp}\sum_{CMf}\sum_{r}\left(CMomcst_{CMp,r}CMmassout_{CMm,CMmm,CMp}CMop_{CMm,CMp,CMf,t,r}\right)$$
$$+\sum_{CMcf}\sum_{r}\sum_{rr}\left[\left(CMtrans_{CMcf,t,r,rr}+CMstorageout_{CMcf,t,r,rr}\right)CMtranscst_{r,rr}\right]$$
$$+\sum_{ELl}\sum_{CMf}\sum_{r}\left(CMELomcst_{t}CMELop_{CMf,ELl,t,r}\right)$$
$$+\sum_{CMcr}\sum_{r}\left(CMcrconsump_{CMcr,t,r}CMfeedcst_{CMcr,t,r}\right)$$
$$+\sum_{CMcf}\sum_{r}\left(CMstoromcst_{t}CMstorage_{CMcf,t,r}\right)=CMOpandmaint_{t}$$

Accumulates all export revenues:
$CMintlprice_{CMcf,t}$ are the export prices of the various cement types; they are taken from the trade statistics of the CDSI.

$$\sum_{CMcf}\sum_{r}\left(CMintlprice_{CMcf,t}CMexports_{CMcf,t,r}\right)=CMrevenues_{t}$$

Sums consumption of raw materials (e.g., limestone, iron ore, gypsum) input to cement plants:
$CMprocessuse_{CMcr,CMp}$ is a control table that is unity if an input is used in a process.

$$CMcrconsump_{CMcr,t,r}-\sum_{CMp}\sum_{CMf}\left(CMprocessuse_{CMcr,CMp}CMop_{CMcr,CMp,CMf,t,r}\right)\geq 0$$

Enforces raw materials availability, if supply is limited:
No supply limit is presently enforced, so $CMfeedsuplim_{CMcr,t,r}$ is set to infinity.

$$-CMcrconsump_{CMcr,t,r}\geq -CMfeedsuplim_{CMcr,t,r}$$

Capacity balance for production units:
$CMcapadd_{CMuu,CMu}$ provides the ability to upgrade existing long-dry kilns to more efficient kilns. If a long-dry kiln is upgraded, the table subtracts the upgraded capacity from the long-dry kiln category and adds it to the more efficient kiln technology.

$$CMexistcp_{CMu,t,r}+\sum_{CMuu}\left(CMcapadd_{CMuu,CMu}CMbld_{CMuu,t,r}\right)-CMexistcp_{CMu,t+1,r}\geq 0$$

Ensures production level does not exceed capacity:
$CMcapfactor_{CMu,CMp}$ are the utilization rates by unit.

$$CMexistcp_{CMu,t,r} + \sum_{CMuu} \left(CMcapadd_{CMuu,CMu} CMbld_{CMuu,t,r}\right) - \sum_{CMm} \sum_{CMp} \sum_{CMf} \left(CMcapfactor_{CMu,CMp} CMprocessuse_{CMm,CMp} CMop_{CMm,CMp,CMf,t,r}\right) \geq 0$$

Accounting for convertible long dry kiln capacities over time:

$$-CMkuprgrade_{CMukcon,t+1,r} - CMbld_{CMukcon,t,r} + CMkuprgrade_{CMukcon,t,r} \geq 0$$

Capacity balance for storage facilities:

$$CMstorexistcp_{t,r} + CMstorbld_{t,r} - CMstorexistcp_{t+1,r} \geq 0$$

Ensures storage level does not exceed capacity:

$$CMstorexistcp_{t,r} + CMstorbld_{t,r} - \sum_{CMcf} CMstorage_{CMcf,t,r} \geq 0$$

Mass balances between production units:
Note: $\mathrm{CMclinkimport}_{\mathrm{CMcii,t,r}}$ is only for when CMcii is clinker.

$$\sum_{CMm} \sum_{CMp} \sum_{CMf} \left(CMprocessuse_{CMm,CMp} CMmassout_{CMm,CMcii,CMp} CMop_{CMm,CMp,CMf,t,r}\right) + CMclinkimport_{CMcii,t,r} - \sum_{CMp} \sum_{CMf} \left(CMprocessuse_{CMcii,CMp} CMop_{CMcii,CMp,CMf,t,r}\right) = 0$$

$CMmixingspec_{CMqlim,CMm,CMci,CMprop}$ are the minimum and maximum mass content constraints for the mixing operations during cement production. There are two instances of mixing, as shown in Figure 7 above, whose mass content limits depend on the finished type of cement required.

Satisfies upper bound specifications for mass content during mixing processes:

$$CMmixingspec_{max,CMm,CMci,CMprop} \sum_{CMmm} \sum_{CMp} \sum_{CMf} \sum_{t} \left(CMprocessuse_{CMmm,CMp} CMmassout_{CMmm,CMci,CMp} \cdot CMop_{Cmm,CMp,CMf,t,r} \right) - \sum_{CMp} \sum_{CMf} \sum_{t} \left(CMprocessuse_{CMm,CMp} CMmassout_{CMm,CMci,CMp} CMop_{Cm,CMp,CMf,t,r} \right) \geq 0$$

Satisfies lower bound specifications for mass content during mixing processes:

$$-CMmixingspec_{min,CMm,CMci,CMprop} \sum_{CMmm} \sum_{CMp} \sum_{CMf} \sum_{t} \left(CMprocessuse_{CMmm,CMp} CMmassout_{CMmm,CMci,CMp} \cdot CMop_{Cmm,CMp,CMf,t,r} \right) + \sum_{CMp} \sum_{CMf} \sum_{t} \left(CMprocessuse_{CMm,CMp} CMmassout_{CMm,CMci,CMp} CMop_{Cm,CMp,CMf,t,r} \right) \geq 0$$

After converting the kiln input from mass to moles, a mass balance is carried out for the clinker reaction reactants and products:

The clinker mass balances are performed by stoichiometrically balancing the mass on the reactant and product side. To do this, $atomsub_{CMclr,CMma}$ defines the number of atoms in the reactants and products.

$$\sum_{CMclr} \left(atomsub_{CMclr,CMma} CMmol_{CMclr,CMclinker,t,r} \right) - \sum_{CMclp} \left(atomsub_{CMclp,CMma} CMmol_{CMclp,CMclinker,t,r} \right) = 0$$

After converting all the individual molecular products of the clinker into mass units, the following two constraints ensure the upper and lower bounds of the products' mass composition is satisfied, for each type of clinker:

$CMclinkspec_{CMqlim,CMclinker,CMclp,CMprop}$ are the maximum and minimum specifications for mass content of individual chemical compounds in clinker.

$$CMclinkspec_{max,CMclinker,CMclp,CMprop} \sum_{CMclp} \left(CMmass_{CMclp,Cmclinker,t,r} \right) - CMmass_{CMclp,Cmclinker,t,r} \geq 0$$

$$
-CMclinkspec_{min,CMclinker,CMclp,CMprop} \sum_{CMclp} \left(CMmass_{CMclp,Cmclinker,t,r}\right) + CMmass_{CMclp,Cmclinker,t,r} \geq 0
$$

To relate the clinker reactions' mass output to the overall mass balance relationship:

$$
\sum_{CMclp} \left(CMmass_{CMclp,Cmclinker,t,r}\right) - \sum_{CMf} \sum_{CMp} \sum_{CMcsaf} \left(CMprocessuse_{CMcsaf,CMp} CMmassout_{CMcsaf,CMclinker,CMp} CMop_{CMcsaf,CMp,CMf,t,r}\right) = 0
$$

Mass balance for storage of finished cement products:

$$
CMstorage_{CMcf,t,r} + CMstoragein_{CMcf,t,r} - CMstorage_{CMcf,t+1,r} - \sum_{rr} CMstorageout_{CMcf,t,r,rr} \geq 0
$$

Supply constraint:

$$
\sum_{CMp} \sum_{CMci} \sum_{Cmf} \left(CMprocessuse_{CMci,CMp} CMmassout_{CMci,CMcf,CMp} CMop_{CMci,CMp,CMf,t,r}\right) - CMexports_{CMcf,t,r} - CMstoragein_{CMcf,t,r} - \sum_{rr} CMtrans_{CMcf,t,r,rr} \geq 0
$$

Satisfying demand (exogenous demands):

$CMdemval_{CMcf,t,rr}$ represents exogenous demands. KEM-SA does not contain endogenous demands for cement by the various sectors.

Similar to the electricity sector, this constraint has a dual variable associated with it, $DCMdem_{CMcf,t,rr}$ in the model. This variable is the marginal cost of delivering the products to each demand region. It may be used as the price in a fully deregulated setting.

$$
CMprodimports_{CMcf,t,rr} + \sum_{r} CMtrans_{CMcf,t,r,rr} + \sum_{r} CMstorageout_{CMcf,t,r,rr} \geq CMdemval_{CMcf,t,rr}
$$

Aggregates regional exports to the national level:

$$CMnatexports_{CMcf,t} - \sum_{r} CMexports_{CMcf,t,r} = 0$$

Accumulates fuel consumption in kilns and for on-site electricity generation:

$CMfuelburn_{CMf,CMp,r}$ and $CMelecfuelburn_{CMf}$are the fuel burn rates in units for fuel per unit of output. The former is for the pyrprocessing stage, and the latter is for on-site power generation.

$$\begin{aligned}
&CMfconsump_{CMf,t,r} \\
&- \sum_{CMmm} \sum_{CMp} \sum_{CMcsaf} \left(CMfuelburn_{CMf,CMp,r} CMprocessuse_{CMcsaf,CMp} CMmassout_{CMcsaf,CMmm,CMp} CMop_{CMcsaf,CMp,CMf,t,r} \right) \\
&- \sum_{ELl} \sum_{ELs} \sum_{ELday} \left(CMelecfuelburn_{CMf} CMELop_{CMf,ELl,ELs,ELday,t,r} \right) \geq 0
\end{aligned}$$

Enforces fuel availability, if supply is limited:

A fuel supply constraint that mainly deals with natural gas quotas offered to the cement companies in a regulated fuel price scenario.

$$-CMfconsump_{CMf,t,r} \geq -CMfconsumpmax_{CMf,t,r}$$

Capacity balance for on-site power generation (assumed to all be GT):

$$CMELexistcp_{t,r} + CMELbld_{t,r} - CMELexistcp_{t+1,r} \geq 0$$

Ensures on-site electricity generation does not exceed capacity:

$$\begin{gathered}
\left(CMELexistcp_{t,r} + CMELbld_{t,r} \right) ELlchours_{ELl} ELnormdays_{ELs,ELday} \\
- \sum_{CMf} CMELop_{CMf,ELl,ELs,ELday,t,r} \geq 0
\end{gathered}$$

Measures total electricity requirement (as base load):

$CMELin_{CMp}$ are the amounts of electricity used by each process. Cement production is annual, due to the same reasons given in the petrochemicals section. As such we distribute electricity consumption evenly across all day types, seasons and times of day.

$$-CMELlchrsfraction_{ELl}ELnormdays_{ELs,ELday} \cdot \sum_{CMm}\sum_{CMci}\sum_{CMp}\sum_{CMf}\left(CMELin_{CMp}CMprocessuse_{CMm,CMp}CMmassout_{CMm,CMci,CMp}CMop_{CMm,CMp,CMf,t,r}\right) + CMtotELconsump_{ELl,ELs,ELday,t,r} \geq 0$$

Ensures electricity requirement is satisfied by either on-site generation or the grid:

$$-CMtotELconsump_{ELl,ELs,ELday,t,r} + CMELconsump_{ELl,ELs,ELday,t,r} + \sum_{CMf} CMELop_{CMf,ELl,ELs,ELday,t,r} = 0$$

Pollution emissions

We account for the emissions of certain pollutants in all of the sectors characterized by KEM-SA; they are carbon dioxide, NO_x and SO_x. The sets, data, variables and equations are defined below. The model file is called **emissions.gms**. Although the objective of this sub-model is to minimize emissions costs, the price of emissions is set to zero by default. So by default, the objective function is always zero and therefore it is not truly being minimized; the resulting operation of the sectors in KEM-SA is not influenced.

```
Sets EMcp pollutants considered by the model /CO2,NOx,SOx/
     CO2(EMcp) CO2 only /CO2/

     Sect sectors /PC,RF,EL,WA,CM/
```

The sets below are used to condition the constraints to only consider certain terms for each sector:

```
     ELsect(sect) electric power sector only
     CMsect(sect) cement production sector only
     WAsect(sect) water desalination sector only
     PCsect(sect) petrochemicals production sector only
     RFsect(sect) oil refining sector only
```

```
Positive variables
EMcost(sect,EMcp,trun) cost of emissions to the various sectors in KEM-SA (if
                       an emissions price is known or assumed) in millions of
                       USD
EMquant(sect,EMcp,trun) quantity of emitted pollutants by each sector in trun
                        in millions of metric  tonnes
EMallquant(EMcp,trun) quantity of emitted pollutants by all sectors in KEM-SA
                      in trun in millions of metric  tonnes
```

The objective function is to minimize total emissions cost to the economy:

$$min \sum_{sect,EMcp,t} EMcost_{sect,EMcp,t}$$

Allows to place a price on the quantity of pollution by the sectors:

$EMprice_{sect,EMcp,t}$ are exogenously specified prices for CO_2, NO_X and SO_X. They can vary by sector and over time. The price is set to 0 when modeling carbon trading.

$$EMcost_{sect,EMcp,t} - EMquant_{sect,EMcp,t} EMprice_{sect,EMcp,t} = 0$$

Sums up the quantities of emissions by sector:
Note: This constraint allows the modeler to place an upper limit on the quantity of emissions for carbon trading.

$$EMallquant_{EMcp,t} - \sum_{sect} EMquant_{sect,EMcp,t} \geq 0$$

Aggregates the quantity of emissions by each sector:
$EMfactors_{sect,f,EMcp}$ are the emissions factors in units of metric tonnes of polluatants per metric ton or GWh or m^3 produced. They are currently defined for most sectors for CO_2 only. Some petrochemical processes consume, as reactants, CO_2 emitted by previous processes. $EMPCrecovery_{EMcp,PCp,PCpp}$ is therefore included to account for the re-use of CO_2.

When the constraint is binding, its dual variable is the marginal cost of emitting pollutants for each sector.

$$\begin{aligned}
&EMquant_{sect,EMcp,t} - \sum_{ELpd,ELl,ELs,ELday,ELf,v,r} EMfactors_{sect,ELf,EMcp} ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r} \\
&- \sum_{CMf,r} EMfactors_{sect,CMf,EMcp}\, CMfconsump_{CMf,t,r} \\
&- \sum_{CMp,CMci,CMf,r} CMprocessuse_{CMci,CMp} CMmassout_{CMci,CO2,CMp} CMop_{CMci,CMp,CMf,t,r} \\
&- \sum_{WAf,r} EMfactors_{sect,WAf,EMcp}\, WAfconsump_{WAf,t,r} \\
&- \sum_{RFf,r} EMfactors_{sect,RFf,EMcp} \left(\sum_{RFs,RFp,RFff} RFyield_{RFs,RFf,RFff,RFp} RFop_{RFs,RFf,RFp,t,r} \right) \\
&- \sum_{PCpp,PCM,PCp,r} EMPCrecovery_{EMcp,PCp,PCpp} EMfactors_{sect,PCm,EMcp} \\
&\cdot PCfconv_{PCm}\, PCfuelburn_{PCm,PCpp} PCop_{Rfs,RFf,RFp,t,r} \geq 0
\end{aligned}$$

Displaying results

The integrated files of KEM-SA contain close to 53,000 variables for a single year; the number of variables scale linearly with the number of years the user wishes to cover. Those variable solutions may not be directly useful for the user to produce desired results. For instance, the model has heat rates for power plants as the parameter $ELfuelburn_{ELpd,v,ELf,r}$, but the user may be interested in the generating plants' net thermal efficiency by season or for the whole year. While the model solves for electricity production, $ELop_{ELpd,v,ELl,ELs,ELday,ELf,t,r}$, and displays it in the resulting solution file, we have to perform ex-post calculations to derive those values of interest.

Therefore, we have a folder called RW (report writer) that comprises all the display variables and parameters that are derived from the model's solution. In addition to files that define parameters that span all or several of the sectors (e.g., **expost_param.gms** and **expost_calc.gms**), there are files specific to each sub-model's results. Those files are called **displayCM.gms**, **displayRF.gms**, **RW_CMcalc.gms**, **RWELcalc.gms**, **RW_fupcalc.gms**, **RW_PCcalc.gms**, **RW_RFcalc.gms** and **RW_WAcalc.gms**.

In the previous example of presenting the results of thermal efficiency, the expost calculation is performed in the file **RW_ELcalc.gms**, as shown in Figure 8 below. The parameter name is first defined, then the calculation is written as shown in the figure and finally display commands are included after the calculation step.

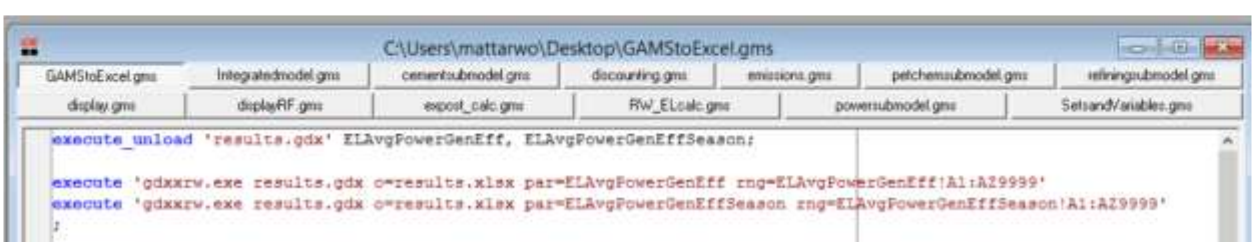

```
*293.07 kWh per million BTU.
ELAvgPowerGenEff(trun)=sum((ELpd,ELl,ELs,ELday,v,ELf,r)$(ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r)>0),
     1/(ELfuelburn(ELpd,v,ELf,r)*Fuelencon1(ELf)*293.07e-3)*ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r))
                         /sum((ELpd,ELl,ELs,ELday,v,ELf,r)$(ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r)>0),
     ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r));

ELAvgPowerGenEffSeason(ELs,trun)=sum((ELpd,ELl,ELday,v,ELf,r)$(ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r)>0),
     1/(ELfuelburn(ELpd,v,ELf,r)*Fuelencon1(ELf)*293.07e-3)*ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r))
                         /sum((ELpd,ELl,ELday,v,ELf,r)$(ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r)>0),
     ELop.l(ELpd,v,ELl,ELs,ELday,ELf,trun,r));

Display ELAvgPowerGenEff, ELAvgPowerGenEffSeason;
```

Figure 8 – An example of using model variables to derive and display results of interest

Display commands display parameters and variables in the solution file after KEM-SA is run. However, large displayed data sets are difficult to manipulate in the GAMS solution file. The user can export the data sets to a spreadsheet for convenience, as shown in Figure 9 below. The desired parameters (and variables) are saved to a GAMS GDX file using the first line in the figure. The executable gdxxrw.exe is subsequently called to output the GDX contents to Excel, with ranges optionally specified, as shown.




```
execute_unload 'results.gdx' ELAvgPowerGenEff, ELAvgPowerGenEffSeason;

execute 'gdxxrw.exe results.gdx o=results.xlsx par=ELAvgPowerGenEff rng=ELAvgPowerGenEff!A1:AZ9999'
execute 'gdxxrw.exe results.gdx o=results.xlsx par=ELAvgPowerGenEffSeason rng=ELAvgPowerGenEffSeason!A1:AZ9999'
;
```

Figure 9 – Exporting the desired parameters (and/or variables) to Excel

Any result the user wishes to obtain from the main variables can be performed in the files as shown. For more information, the user can refer to the GAMS documentation published by McCarl et al. (2016).

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