CHAPTER 5
OBJECTIVE FUNCTION

The objective function, equation *objf* in Section 27 of Appendix VII, calculates the present value of all operating costs and all capital costs for new equipment over the planning horizon.

The objective function in the full model is broken down into 3 parts: I Fuel & Variable Operating Costs, II Cost of Unserved Energy and Unmet Reserves, III Capital Costs, including fixed operating costs.

In what follows, for purposes of exposition, each of the cost terms are first explained for a given year, not a given period. Since the model allows users to specify the number of years per period, an adjustment needs to be made to convert these yearly costs in to period costs. This adjustment along with the present value adjustment will be explained in the last section of the chapter.

5.1 Yearly Fuel and Variable Operating Costs

A) <u>Thermal Units</u>

All thermal units operating costs are calculated in the same way. In a given year the costs for old (*PG*), new turbines (*NT*), new combined cycle (*CC*), new small coal (*SC*), and new large coal (*LC*) are of the generic form;

$$\sum_{ts,td,th,z} \sum_{i} \overbrace{PG(ty,ts,td,th,z,i)}^{power\ generation} \left[\overbrace{HRO(z,i)}^{heat\ rate} \overbrace{fpO(z,i)}^{fuel\ cost} \overbrace{fpescO(z,i)^{n(ty)-1}}^{fuel\ escalation} + \overbrace{OMO(z,i)}^{variable\ O\&M\ cost} \right]$$

one each for each of the unit types, with appropriate modifications in notation made for each: since generation is MWh, the costs are \$/MWh.

Power generation for the 4 technologies, *PGNT(ty,ts,td,th,z,ni)*, *PGNCC(ty,ts,td,th,z,ni)*, *PGNSC(ty,ts,td,th,z,ni)* and *PGNLC(ty,ts,td,th,z,ni)* are as entered in the supply/demand module.

HRO(z,i), the heat rates for the thermal plants (BTU x 10^6/MWh) are given in Tables *HRO(z,i)* (Section 11), *HRNT(z,ni)* (Section 11), *HRNCC(z,ni)* (Section 12), *HRNLC(z,ni)* (Section 12) and *HRNSC(z,ni)* (Section 13) in Appendix IV. Nominal values in the tables are taken from U.S. data, and can be altered by country *z* and site (*i,ni*) by users.

Fuel costs for old plants - Table *fpo(z,i)* (Section 7)- and new plants - Tables *fpNT(z,ni)* (Section 7), *fpNCC(z,ni)* (Section 8), *fpNSC(z,ni)* (Section 8) and *fpNLC(z,ni)* (Section 8) in cents per 10,000 BTU are given in Appendix IV. Normal values in the tables generally reflect costs provided by SAPP, but in instances where SAPP data are lacking, US data are used. These numbers can be changed in the tables by users to reflect SAPP members' changing price expectations.

The fuel escalation rates *fpescO(z,i)*, *fpescNT(z)*, *fpescNCC(z)*, *fpescNSC(z)* and *fpescNLC(z)* are tabled in Appendix IV, Sections 9 and 10. A nominal value of 1% a year growth is in all tables; users can enter their own estimates.

The tables for *O&M* costs in $/MWh for the various options, *OMO(z,i)* for old plants (Section 19) and *OMT(z,ni)*, *OMCC(z,ni)*, *OMSC(z,ni)* and *OMLC(z,ni)* for new, are found in Sections 17, 18 and 19 of Appendix IV; default values are based upon U.S. experience. Only variable *O&M* costs should be included; fixed *O&M* costs (those set at the time the plant expansion is decided upon and do not vary with output) are capitalized, and will be included in the capital cost of the plants.

The parameter *Mperiod(ty)* in Appendix VII, Section 1, converts yearly fuel escalation rates into period growth rates, since periods contain multiple years.

Finally, within a given year, the proper weights for the seasons, days, and hours need to be entered into the objective function to insure that the fuel costs represent all 8,760 hours per year. The scalars *Mseason*, *Mday(td)* and *Mtod(th)* (all in Section 1, Appendix I) provide the necessary scale up. For example, the full equation reflecting fuel and variable operating costs for combustion turbines (*NT*) in a given year would be;

$$\sum_{ts,td,th,z,ni} \left(Mseason(ts)\right)\left(Mday(td)\right)\left(Mtod(th)\right) PGNT(ty,ts,td,th,z,ni) * \left[HRNT(z,ni)\left(fpNT(z,ni)\right)\left(fpescNT(z)\right)^{n(ty-1)} + OMT(z,ni)\right]$$

Similar terms appear in the objective function for old plants and other new technologies.

B) Hydro Units

The only operating costs are the cost of water *wcost(z,ty)* (found in Section 1, Appendix V), now set at $1.50/MWh, which can be altered by changing scalar *wcost* in the appendix, and variable cost for old *VarOMoh(z,ih)* (Section 9, Appendix V) and new *VarOMnh(z,nh)* (Section 9, Appendix V) hydro plants. (Fixed *O&M* costs for new plants are annualized, and will be included in the capital cost of the plants.) Hence, the operating costs for new and old hydros in year *ty* are simply;

$$\sum_{ts,td,th,z,ih,nh} H(ty,ts,td,th,z,ih)(Mseason(ts))(Mday(td))(Mtod(th))\left[wcost(z,ty)+VarOMoh(z,ih)\right]$$
$$+Hnew(ty,ts,td,th,z,nh)(Mseason(ts))(Mday(td))(Mtod(th))\left[wcost(z,ty)+VarOMnh(z,nh)\right]$$

Variable costs of new and old pumped storage in the model are limited to the variable *O&M* costs of operation e.g.; *VarOMph(z,phn)* (found in Section 9 of Appendix V), times the sum of old and new power generation, *PGPSO(ty,ts,td,th,z) + PGPSN(ty,ts,td,th,z,phn)*. (No water costs are charged for the use of pumped storage.)

$$\sum_{ts,td,th,z,phn} \left[PGPSO(ty,ts,td,th,z)+PGPSN(ty,ts,td,th,z,phn)\right] \quad VarOMph(z,phn)$$

5.2 Costs of Unserved Energy, Dumped Energy, and Unmet Reserve Requirements

Unserved energy cost is the product of parameter *UEcost* (value in Appendix II, Section 1) times the variable *UE(ty,ts,td,th,z)*. *UEcost* has a nominal value of $140/MWh, (Section 1, Appendix II) users can specify their own values. Unmet reserve cost is the product of the parameter *UMcost* (Appendix II, Section 1) times the variable *UM(z,ty)*. Dumped energy cost is the product of the variable *DumpEn(ty,ts,td,th,z)* times a scalar *DumpCost* (Appendix II, Section 1; nominal value is $.10/MW).

Thus, these costs for year *ty* are in equation form;

$$\sum_{ts,td,th,z} \left(Mseason(ts)\right)\left(Mday(td)\right)\left(Mtod(th)\right)$$
$$\left[UE(ty,ts,td,th,z)*UEcost + DumpEn(ty,ts,td,th,z)*DumpCost\right] + \sum_{z}\left(UMcost\right)\left(UM(z,ty)\right)$$

5.3 Yearly Capital Costs

Capital costs in year *ty* are broken down by equipment type:

- Section A: capital costs associated with expansion of existing thermal, hydro, and transmission facilities,
- Section C: capital costs associated with constructing and expanding new thermal sites,
- Section D: capital costs associated with constructing and expanding new hydro sites,
- Section E: capital costs associated with constructing and expanding new transmission lines,
- Section F: capital costs of expanding existing pumped storage sites,
- Section G: capital cost of constructing and expanding new pumped storage facilities.

For new plants, the fixed component of *O&M* cost, *FixOMCC(z,ni), FixOMLC(z,ni), FixOMT(z,ni)* and *FixOMSC(z,ni)* in $/MW/year should be annualized ($/MW/yr), and included as part of the capital costs of capacity. They are found in Section 19 of Appendix IV. Fixed *O&M* costs for old plants are considered sunk, as are old plant capital costs.

A) Existing Sites/Lines

First the generic annualized cost of expanding existing facilities (which must be charged to the objective function each year subsequent to the expansion date) is;

$$\sum_{z,i} \overbrace{PGOexp(tyb,z,i)PGOexpstep(z,i)Oexpcost(z,i)}^{\text{total investment at "i" in "tyb"}}\, crfi(z,i)$$

PGOexp(tyb,z,i) PGOexpstep(z,i) – the former a variable, the latter a parameter found in Section 4, Appendix IV – is the MW amount of expansion that takes place in period *tyb*, regardless of the choice of expansion modeling - fixed increment, or continuous. Multiplying the MW expansion by *Oexpcost(z,i)* (Section 2, Appendix IV), the cost/MW of expansion yields the total capital investment made in year *tyb* at site *i*. Multiplying this total investment by the capital recovery factor *crfi(z,i)*, (tabled in Appendix IV, Section 16), converts the total investment into the amount to be recovered annually until the end of the horizon, starting in year *tyb*.

Thus, in year *ty*, the annual charges in that year should be the sum of all annual charges arising as a result of investments made up to and including, year *ty*, e.g.

$$\sum_{z,i} \sum_{tyb=1}^{ty} PGOexp(tyb,z,i) PGOexpstep(z,i) Oexpcost(z,i)\, crfi(z,i)$$

In similar fashion, old hydro capacity expansion capital costs in year *ty* are:

$$HOcapcost(ty) = \sum_{z,ih} \sum_{tye=1}^{ty} HOVexp(tye,z,ih) HOexpstep(z,ih) HOVcost(z,ih) crfih(z,ih)$$

(The three parameters are found in Sections 3, 5 and 7 respectively in Appendix V.)
The expression for capital costs for existing transmission line expansion in year *ty* are;

$$PFOcapcost(ty) = \sum_{z,zp} \sum_{tye=1}^{ty} PFOVexp(tye,z,zp) PFOVcost(z,zp)(.5) crf(z,zp)$$

(The two parameters are found in Sections 1 and 2 in Appendix III.)

Note that since new capacity added in the (*z,zp*) direction also expands capacity in the (*zp,z*) direction, the capital costs are split in half - hence the (.5) in the expression. Note also no expansion step is needed, since transmission expansion is always continuous.

The equations, in GAMS format, for old sites/lines are as follows, as equations *CONCOST1* – old thermal plants - (Appendix VII, Section 17); *CapcostHO* – old hydro plants - (Appendix VII, Section 10); and *CapcostPFO* – old transmission lines - (Appendix VII, Section 12). (Note these are present valued, which is discussed below.)

B) New Sites/Lines

The difference between existing and new site development is that initial construction site preparation and initial capacity installation must be completed before any site expansion takes place. There are two differences between new and old site construction cost terms in the objective function.

- The cost of the initial site preparation.
- The inclusion of fixed *O&M* costs.

The generic equation for capital expenses in year *ty* for a given technology at site *ni* in country *z* is;

$$\sum_{z,ni} \sum_{tya=1}^{ty} \left[NFcost(z,ni) Y(tya,z,ni) + PGNexp(tya,z,ni) Nexpstep(z,ni) Nexpcost(z,ni) \right] (crfn(z,ni))$$
$$+ \sum_{z,ni} \sum_{tya=1}^{ty} \left[PGNinit(z,ni) Y(tya,z,ni) + PGNexp(tya,z,ni) Nexpstep(z,ni) \right] \left[FIXOM(z,ni) \right]$$

The first double summation in the capital cost expression for year *ty* is the levelized annual cost of all site developments up to year *ty*; the second double summation is the annualized cost of fixed *O&M* associated with the new construction up to year *ty*.

Within the first double summation, the first term in the bracket is *NFcost(z,ni)*, a parameter giving the fixed cost of the initial plant at site *ni*, *Y(tya,z,ni)* is the binary decision variable which is 1 if a new plant is built at site *ni* in *tya*, 0 otherwise. *PGNexp(tya,z,ni)* is a continuous or integer decision variable which gives the amount of site expansion which takes place in year *tya*; *Nexpstep(z,ni)* is a fixed MW value. *Nexpcost(z,ni)*, a parameter, giving the expansion cost/unit for each technology where expansion is allowed; *crfn(z,ni)* a parameter giving the capital recovery factor appropriate for the location of the site and the type of equipment.

To understand the logic of the first term of the equation, the capital cost term in year *ty* should include the annualized capital expense charges for all projects initiated up to and including year *ty*. Hence, the cost in *ty* is the sum of the annualized cost of projects initiated in year 1, year 2, and so forth up to and including year *ty*. The annualized cost of projects started in year 1 is:

$$[NFcost(z,ni)Y(1,z,ni)+PGNexp(1,z,ni)PGNexpstep(z,ni)Nexpcost(z,ni)]\,[crfn(z,ni)],$$

in year 2 *[NFcost(z,ni)Y(2,z,ni)...]*, etc. Using *tya* as the alias for year *ty*, the total annualized costs in year *ty* can be written;

$$\sum_{tya=1}^{ty}\left[NFcost(z,ni)Y(tya,z,ni)+PGNexp(tya,z,ni)PGNexpstep(z,ni)(Nexpcost(z,ni))\right]\left[crfn(z,ni)\right]$$

Turning to the second double summation, the first term in the bracket gives the MW added by the initial investment, the second MW subsequently added. Multiplying the sum of these by *FIXOM(z,ni)*, the fixed *O&M* cost/MW/year, gives the cost of fixed *O&M* in year *tya*. Summing these from the start to year *ty* gives the value of fixed *O&M* expenses in year *ty* for a given technology at site *ni* in country *z*.

C) <u>New Thermal Sites</u>

These equations for the four new thermal options - the two which allow expansion only after the initial fixed construction expenditure - combined cycle (*CC*) and large coal (*LC*), and the two which do not require the initial fixed cost expenditure - small coal (*SC*) and combustion turbine (*T*) - are given in Equation *CONCOST2* in GAMS format, Appendix VII, Section 17, and are similar in form to the previous equations involving a double sum over the periods up to and including *ty*, and the sum over all new units.

The GAMS equation first lists the expansion costs of *NT*, *SC*, *CC* and *LC*, and then the initial construction costs for *CC* and *LC*.

The parameters for the initial fixed costs of *CC* and *LC* - Tables *FGCC(z,ni)* and *FGLC(z,ni)* - the expansion step costs for *NT*, *SC*, *CC* and *LC* - Tables *NTexpcost(z,ni)*, *NSCexpcost(z,ni)*, *NCCexpcost(z,ni)*, *NLCexpcost(z,ni)* are given in Sections 1, 2, 3, and 4 respectively in Appendix IV. The capital recovery factors *crfni(z,ni)* is in Section 17, while the fixed *O&M* cost per MW per year, tables *FIXOMT*, *FIXOMCC*, *FIXOMSC*, *FIXOMLC*, for new thermal plants, are given in Section 19 of Appendix IV.

D) <u>New Hydro Sites</u>

The value of the capital costs in year *ty* for new hydro plants installed up to and including year *ty* is similar in form to the generic equation previously given, involving the double sum over all elapsed *ty* and projects.

The parameters are given in Appendix V in the following sections for the new hydro sites (the initial fixed costs) *HNFcost(z,nh)* – Section 1; the fixed *O&M FIXOMNH* – Section 9; the expansion costs per MW, *HNVcost(z,nh)* – Section 2; the expansion step size, *HNexpstep(z,nh)* – Section 3; and the capital recovery factors *crfnh(z,nh)* – Section 6. Recall that the initial fixed costs include the site preparation, dam construction, and installation of the initial generating capacity; expansion costs are for adding generating units to the existing dam, not for expansion of the dam's capacity.

E) <u>New Transmission Lines</u>

The capital costs charged in year *ty* for transmission construction projects completed up to and including year *ty* follows the form of the generic equations.

The parameters *PFNFc(z,zp)* - the initial fixed cost of a new line, *PFNVc(z,zp)* – the cost/MW of additional capacity, and *crf(z,zp)* for new transmission lines are given in Appendix III, Sections 4, 5 and 2. (No *expstep* is needed for transmission, since it is always continuous.)

F) <u>Old Pump Storage</u>

Letting *PSOexpcost(i)* and *crfpso(i)* be the expansion cost/MW and the capital recovery factor for pumped storage, the SAPP wide value of the capital cost of existing pumped storage capacity expansion in year *ty*, *PSOcapcost(ty)* is;

$$PSOcap\cos t(ty) = \sum_{z} \sum_{\tau=1}^{ty} PSOexp(\tau,z)PSOexpstep(z)PSOexpcost(z)crfpso(z)$$

The current model does not allow expansion, hence *PSOcapcost(ty) = 0*; no tables are found in the appendices.

G) <u>New Pumped Storage</u>

In the same manner, letting *Yph(ty,z,phn)* be a binary variable indicating initial construction at site *phn* in *z*, *PHNFcost(z,phn)* (Section 9, Appendix V) the fixed cost of such development, *PSNexpcost(z,phn)* the cost/MW of capacity expansion after initial development at site *phn* and *crfphn(z,phn)* (Section 9, Appendix V) the capital recovery factor for new pumped storage, we have; the capital charges associated with construction of new pumped storage in year *ty*;

$$\sum_{phn}\sum_{z}\sum_{\tau=1}^{ty}\left[PHNFcost(z,phn)Yph(\tau,z,phn)+PSNexp(\tau,z,phn)PSNexpstep(z,phn)PSNexpcost(z,phn\right]\left[crfphn(z,phn)\right]$$

plus the fixed *O&M* cost component. The current model does not allow expansion at new sites; hence, only the first term in the bracket is non-zero.

5.4 Present Valuing and Weighting these Expenditures

So far, the equation for all eight technologies give the capital and operating costs in period *ty* for each of the technologies.

What remains is to convert these streams of annual costs into a single present value, properly weighted by the number of years per period. This can be accomplished by summing the expressions for capital and operating costs in year *ty* over all *ty*, properly discounted by the discount rate (*disc*) (found in Section 1 of Appendix II), and multiplying the sum by the number of years per period – e.g.;

$$\begin{aligned}Present\ value\ of\ all\ costs &= \sum_{ty=1}^{Y} Mperiod(ty)\left[\frac{PGOcapcost(ty)+...+PSNcapcost(ty)}{(1+disc)^{n(ty)}}\right]\\ &+\sum_{ty=1}^{Y} Mperiod(ty)\left[\frac{All\ fuel\ and\ operating\ costs\ in\ (ty)}{(1+disc)^{n(ty)}}\right]\\ &+\sum_{ty=1}^{Y} Mperiod(ty)\left[\frac{All\ costs\ of\ unserved\ energy, dumped\ energy, and\ unmet\ reserve\ requirements}{(1+disc)^{n(ty)}}\right]\end{aligned}$$

This is what appears in the objective function, Appendix VII, Section 27.