CHAPTER 4
RELIABILITY CONSTRAINTS

The reliability constraints insure that a proper reserve margin is maintained between domestic and imported installed MW capacity and peak period MW demand in every period *PeakD(z)*dgr(z,ty)*.

Reliability requirements enter the model in two ways:

<u>Requirement #1:</u>

Each country must maintain a SAPP specified reserve margin for each of the major sources of supply - thermal plants, including pumped storage, (Parameter *RESTHM* in Appendix VI, Section 12 - default value 19%) and hydro plants (Parameter *RESHYD* - 10% default value in Appendix VI, Section 13). Since the model, as in the real world, allows trade in reserves (imports held by others and exports held for others) to enter into the equation, imports must be added (*Fmax(ty,zp,z)*, imports of reserves) and exports subtracted (*Fmax(ty,z,zp)* exports of reserves) from the supply side of the reserve equation. Alternatively, exports of reserves can be added and imports subtracted from domestic peak demand to create the peak responsibility of a region. Imports of reserves need to be adjusted downward by the line loss between *z* and *zp*; no adjustment for forced outage is necessary, according to SAPP definitions of reserve requirements.

As in the case of the demand equation, a country can choose not to meet the reserve constraint by choosing a positive value for unsatisfied reserve requirements – variable *UM(z,ty)*, at a cost/MW set by the user parameter *UMcost* found in Section 1 of Appendix II. (The nominal value is set at $1000/KW in the model.) This cost should reflect SAPP penalty costs to be imposed on SAPP members when these agreed upon reserve requirements are violated for a given year.

$$\left[\begin{array}{l} \dfrac{Available\ Installed\ Thermal\ Capacity}{1+RESTHM\left(z\right)}+\dfrac{Available\ Installed\ Hydro\ Capacity}{1+RESHYD\left(z\right)} \\ \quad +\text{ Reserves held by others to back up firm imports to } z\left(1\text{ - }lineloss\right)+UM\left(z,ty\right)\geq \\ \quad\quad \text{Reserves held by } z \text{ to back up firm exports to others} \\ \quad\quad\quad +\left[PeakD\left(z\right)*dgr\left(z,ty\right)-LM\left(z,th\right)\right]\left[DLC\left(z\right)\right] \end{array}\right]$$

Note that the choice of *RESTHM* and *RESHYD* are behavioral choices; values can be entered to reflect each SAPP member's attitudes.

The full equation is as follows (the expressions for installed capacity in year *ty* were explained in Chapter 3):

$$\text{existing thermal capacity}\left\{\dfrac{\left[\begin{array}{l} PGOinit(\cdot)(1-DecayPGO)^{n(ty)} \\ \quad +PGO\exp step(\cdot)\sum_{\tau=1}^{ty}PGO\exp(\tau,z,i)(1-DecayPGO)^{n(ty-\tau)} \\ + \\ NT\exp step(\cdot)\sum_{\tau=1}^{ty}PGNT\exp(\tau,z,i)(1-DecayNT)^{n(ty-\tau)} \\ \quad +NSC\exp step(\cdot)\sum_{\tau=1}^{ty}PGNSC\exp(\tau,z,ni)(1-DecayNSC)^{n(ty-\tau)} \\ + \\ PGNCCinit(\cdot)\sum_{\tau=1}^{ty}YCC(\tau,z,ni)(1-DecayNCC)^{n(ty-\tau)} \\ \quad +NCC\exp step(\cdot)\sum_{\tau=1}^{ty}PGNCC\exp(\tau,z,ni)(1-DecayNCC)^{n(ty-\tau)} \\ + \\ PGNLCinit(\cdot)\sum_{\tau=1}^{ty}YLC(\tau,z,ni)(1-DecayNLC)^{n(ty-\tau)} \\ \quad +NLC\exp step(\cdot)\sum_{ty=1}^{ty}PGNLC\exp(\tau,z,ni)(1-DecayNLC)^{n(ty-\tau)} \end{array}\right]}{1+RESTHM(z)}\right.$$

existing hydro capacity

$$+\left\{\frac{\left[\begin{aligned}&+\ HOinit(\cdot)(1-DecayHO)^{n(ty)}+HOV\exp step(\cdot)\sum_{\tau=1}^{ty}HOV\exp(\tau,z,ih)(1-DecayHO)^{n(ty-\tau)}\\&+\ HNinit(\cdot)\sum_{\tau=1}^{ty}Yh(\tau,z,nh)(1-DecayHN)^{n(ty-\tau)}\\&\qquad+HN\exp step(\cdot)\sum_{\tau=1}^{ty}HNV\exp(\tau,z,nh)(1-DecayHN)^{n(ty-\tau)}\\&+\ PGPSOinit(z)(1\text{-}DecayPHO)^{n(ty)}\\&\qquad+\sum_{phn}\sum_{\tau=1}^{ty}\left[PHNinit(z,phn)Yph(\tau,z,phn)\right](1-DecayPHN)^{n(ty-\tau)}\end{aligned}\right]}{1+RESHYD(z)}\right.$$

reserves held in ty by country zp for country z , adjusted for loss

$$+\sum_{zp}\left(F\max(ty,zp,z)\right)(1-PFOloss(zp,z))$$

unsatisfied reserve requirements

$$+\ UM\left(z,ty\right)\geq$$

peak demand in year ty plus reserves in ty held by country z for use by country zp

$$+\left[PeakD\left(z\right)dgr\left(z,ty\right)\text{-}\ LM\left(z,th\right)\right]DLC\left(z\right)+\left[\sum_{zp}Fmax\left(ty,z,zp\right)\right]$$

This reserve margin constraint, as stated in GAMS notation, is equation *ResvREG2* and is shown in Appendix VII, Section 14.

4.1 The Autonomy Constraints

In addition to system reliability considerations, non-technical, political, and economic factors may require that domestic capacity be maintained at some prescribed fraction of domestic peak demand, regardless of the economic advantages of importing cheap power or reserve capacity. This will be the function of the country autonomy constraint, which reflects the level of self-sufficiency each country wishes to maintain, by specifying a country autonomy factor, $\overline{AF\left(z,ty\right)}\geq\ 0$ (found in Section 1 of Appendix VI), which reflects each country's desire to be completely self-sufficient ($\overline{AF}=\ 1$), willing to depend completely on firm imports during peak, if it is economic to do so ($\overline{AF} = 0$), or something in between, $\left(0 < \overline{AF(z,ty)} < 1\right)$.

Available Installed Thermal plus hydro capacity in period *ty*, adjusted for forced outage:

$$\geq \overline{AF(z)}\left[\overline{D(peak,y,z)} - \overline{DSM(peak,y,z)}\right]\left[\overline{DLC(z)}\right] \quad \forall \; y,z,peak$$

These equations are found in Appendix VII, Section 16 for:

- all but RSA, DRC, and MOZ; Equation *ResvREG4*
- RSA; *ResvREG4 a, b, c*
- MOZ; *ResvREG4 d, e, f*
- DRC

A single autonomy constraint for RSA, DRC, and MOZ, which covers both nodes in the three countries requires an autonomy equation of a different form for these two countries.

In addition to each country requiring that domestic production capacity always be large enough to satisfy a given fraction of domestic peak demand, a country might also require that a certain fraction of demand in all periods be met by domestic production. This is a far more costly (to SAPP) constraint, because it prevents any trade (beyond that allowed by the constraint) taking place in all time slices. This constraint, when added, would enter the demand/supply constraint by requiring that x% of domestic production over a year be met by domestic generation - e.g.,

$$\sum_i PG(ty,ts,td,th,z,i) + \sum_{ni} PGN(ty,ts,td,th,z,ni)$$
$$+ \sum_{ih} H(ty,ts,td,th,z,ih) + \sum_{nh} Hnew(ty,ts,td,th,z,nh) \geq Enaf(z,ty)\,Demand$$

where *Enaf(z,ty)* is the fraction of demand in country *z* during year *ty*, which must be met by domestic production (Table *Enaf(z,ty)* Section 1, Appendix VI). These equations are found in Appendix VII, Section 26 and are called "Equation Energy AF", a, b, c (RSA), d, e, f (MOZ).

4.2 The Treatment of Capacity and Energy Trading and Firm and Non-Firm Power in the Model

In an ideal world with no limits on computer memory and running time, models such as ours would distinguish in the optimization between two types of power – Firm power, as defined in section 2.17 Article 1 of SAPP's ABOM, and economy energy, as defined in section 2.11 of the same document.

To conserve on memory and running time Purdue's model does not distinguish between the two power flows during the optimization, but does allow users to distinguish between them after the optimization.

A) <u>Splitting up power flows into firm and non-firm components</u>

The characteristic of firm power flow is that the exporting country must have on hand, either in the form of its own generating capacity, or capacity available from other countries, sufficient capacity to always provide such power to the importing country.

In our model, this capacity commitment is the variable *Fmax(ty,z,zp)*, representing country *z*'s "leasing" of capacity in *ty* to country *zp*.

Once *Fmax(ty,z,zp)* is known, along with the flow variables *PF(ty,ts,td,th,z,zp)* and *PFnew(ty,ts,td,th,z,zp)*, the following rules can be used to split up the flows between *z* and *zp* into firm and economy trade;

<u>Case A power flows exceed *Fmax*</u>

If $PF\left(ty,ts,td,th,z,zp\right)+PFnew\left(ty,ts,td,th,z,zp\right)>\ Fmax\left(ty,z,zp\right)$;

$$\begin{cases}\text{Firm } = Fmax\left(ty,z,zp\right) \\ \text{economy} = PF\left(ty,ts,td,th,z,zp\right)+PFnew\left(ty,ts,td,th,z,zp\right)-Fmax\left(ty,z,zp\right)\end{cases}$$

Case B Power flows less than or equal to *Fmax*

$$\text{If } PF(ty,ts,td,th,z,zp) + PFnew(ty,ts,td,th,z,zp) \leq Fmax(ty,z,zp), \text{ then;}$$

$$\begin{cases} \text{Firm} = PF(ty,ts,td,th,z,zp) + PFnew(ty,ts,td,th,z,zp) \\ \text{Economy} = 0 \end{cases}$$

Thus, all power flows are firm, unless power flows exceed the capacity commitment represented by *Fmax(ty,z,zp)*; only the excess (if any) of power flows over *Fmax(ty,z,zp)* should be considered economy sales, since such sales are not backed up by any committed capacity in the exporting country (e.g., "non-capacity, non-firm transactions" – SAPP ABOM, service schedule "e").

B) Treatment in the Transmission Capacity Constraint

The flow variables for old and new lines - *PF(ty,ts,td,th,z,zp)* and *PFnew(ty,ts,td,th,z,zp)* - power flows from country *z* to country *zp* in a given time slice – give the total flow between two countries consisting of the sum of all firm and non-firm power trades. Thus, the transmission capacity flow constraints for old lines involve only *PF(ty,ts,td,th,z,zp)* and the current capacity of the old lines connecting *z* to *zp* – e.g., for old lines (ignoring decay and forced outages):

$$PF(ty,ts,td,th,z,zp) \leq PFinit(z,zp) + \sum_{tye=1}^{ty} PFOVexp(tye,z,zp)$$

a similar equation holds for new lines.

In addition, since firm power trade can be much less than its maximum *Fmax*, a constraint requiring that there be sufficient transmission capacity at all times to handle the maximum promised import/export of reserves must be added; e.g. the sum of current new and old transmission capacity, derated by decay and forced outage, must be greater then or equal to *Fmax(ty,z,zp)*:

$$Fmax(ty,z,zp) \le PFinit(z,zp) + \sum_{tye=1}^{ty} PFOVexp(tye,z,zp) + PFnew(z,zp) + \sum_{tye=1}^{ty} PFNVexp(tye,z,zp)$$

This equation (Equation *FmaxTcapAj*) is found in Appendix VII, Section 13.

C) Treatment in the Load Balance Constraints

The hourly load balances which require that supplies must equal demands, involve only domestic generation, power imports, power exports, and demand. Ignoring both unserved and dumped energy the load balance equation for the time slice *(ty,ts,td,th)* is simply:

$$\begin{pmatrix} \text{Sum of all Domestic Generation} \\ \text{in } (ty,ts,td,th) \end{pmatrix} + \sum_{zp} PF(ty,ts,td,th,zp,z)(1 - lineloss) = \text{Demand in } (ty,ts,td,th,z,zp) + \sum_{zp} PF(ty,ts,td,th,z,zp)$$

No distinction is made between firm and non-firm power in meeting demand, nor should there be; both can interchangeably satisfy the load balance equation.

D) Treatment in the Reliability Constraints

According to section 2.33 and Appendix I of the SAPP ABOM, the reserve capacity obligation of each country can be expressed as:

$$\frac{Thermal\ Capacity}{1.19} + \frac{Hydro\ Capacity}{1.10} \ge Peak\ Demand - Firm\ Power\ Purchases + Firm\ Power\ Sales$$

Since firm power purchases/sales are not variables in the model, we use capacity purchases/sales (*Fmax(ty,z,zp)*) in the equation, the purchases suitably adjusted for line loss:

$$\frac{Thermal\ Capacity\ in\ ty}{1.19}+\frac{Hydro\ Capacity\ in\ ty}{1.10}+\sum_{zp} Fmax(ty,zp,z)(1-lineloss)$$
$$\geq Peak\ Demand(ty,z)+\sum_{zp} Fmax(ty,z,zp)$$

To summarize:

- Power flows between countries can after the fact be broken down into firm and non-firm power;
- Both the transmission and load balance constraints consider the total flows of firm and non-firm power;
- A separate constraint must be added to insure that, at all times, sufficient transmission capacity is available to handle reserve power flows between countries.