APPENDIX III AND IV

INDEX

APPENDIX III

MARKET OPERATION SIMULATION METHODOLOGY

1. SDDP MODEL

The operational simulation of the Colombia market was done using the economical hydrothermal generation dispatch model called SDDP. This computational tool allows calculate a future generation dispatch, energy prices, fuel consumption, etc., of the Colombian system.

The SDDP models calculate the optimal hydrothermal dispatch using a technique called "stochastic *dual* dynamic programming". This technique is based on the use of a piecewise linear function to approximate the future cost function and on the use of sampling techniques to represent the "tree" of hydrological scenarios. This allows the calculation of the optimal stochastic operation policy for multiple reservoir systems. The model calculate also several economic indices such as bus marginal costs, network congestion revenues, water values, etc.

2. SIMULATION OBJETIVES

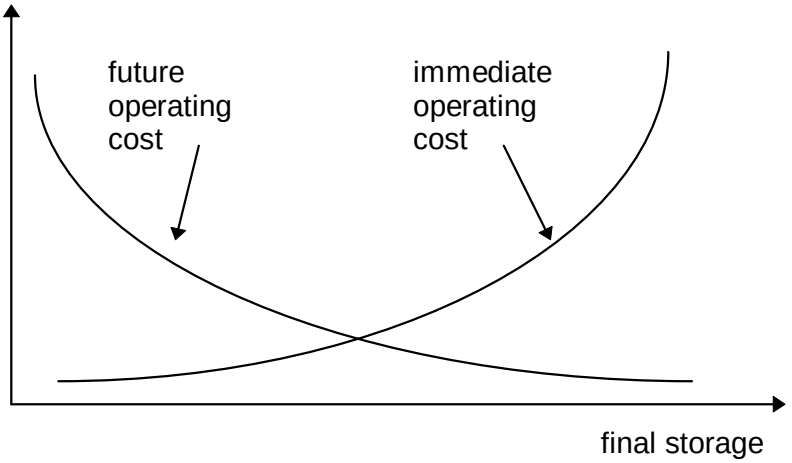
The basic objective of operations simulation is to ensure an *economic* and *reliable* supply of predicted load along the planning period. The economy objective is to minimize fuel costs in thermal plants (coal, oil, natural gas, etc.). The reliability objective is to avoid supply interruptions, including those due to failures in generating units or in the transmission system, and rationing due to the depletion of hydro energy stocks in system reservoirs.

Systems with a substantial component of hydroelectric generation, like Colombia, can use the "free" stored hydro energy in the system reservoirs to meet demand, thus avoiding fuel expenses with the thermal units.

However, the availability of hydroelectric energy is limited by the storage capacity of the reservoirs. This introduces a relationship between the operative decision in a given stage and the future consequences of this decision. In other words, if the stored hydroelectric energy is used today, and a drought occurs, it may be necessary to use expensive thermal generation in the future, or even interrupt the energy supply. If, on the other hand, reservoir levels are kept high through a more intensive use of thermal generation, and high inflows occur in the future, there may be a spillage in the system, which represents a waste of energy and, in consequence, an increase in operation cost.

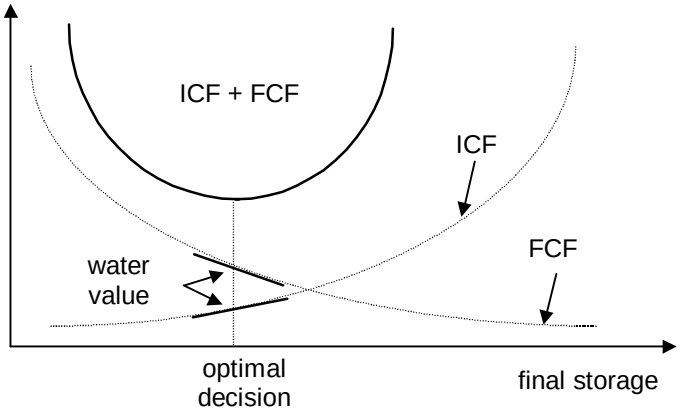
The optimal solution to the hydrothermal scheduling problem is to establish a *balance* between the *immediate* benefit from using the water now (IOC) and the *future* benefit from storing it (FOC).

- IOC: related to thermal generation costs in stage *t*
- FOC: associated with the *expected* thermal generation expenses from *t*+1 to the end of the planning period



In the optimum the total cost (IOC+FOC) is minimum. The model to calculate the water value uses these criteria. Hydro plants compete with thermal unit's trough this value. If the water value is less than the variable production cost of thermal power plant then its dispatched firs the hydro power plant.

- **Optimal use of water:** minimize sum of immediate and future costs
- **Water values:** derivatives of ICF and FCF with respect to storage are equal and opposite.



3. SDDP FEATURES

The SDDP model has the following features:

- Hydro: perform water balance for cascade, spillage, filtration, variable head, evaporation etc.; stochastic inflow modeling with time and spatial dependence
- Thermal: multiple fuels, non-linear heat rates, start-up costs etc.
- Network: power flow model with quadratic losses, circuit flow constraints, DC links etc.
- **THERMAL SCHEDULING**
  - Decoupled in time

- Generating units have a direct operating cost
- Plant operation does not affect generation capacity or availability of other plants

♦ **HYDRO SYSTEM OPERATION:**

- Coupled in time, that is, a decision today affects operating costs in the future
- Hydro plants have an indirect *opportunity* cost, associated to savings in displaced thermal generation now or in the future.

♦ **OBJECTIVE FUNCTION**

- $ZT = \text{Min } \Sigma\ c(j)*gt(j) + \text{water value}$
- List of merit dispatch
  - Thermal: Variable Production Cost
  - Hydro: Water value

♦ **CONSTRAINTS:**

- Water balance
- Limits on storage and outflow
- Limits on thermal generation
- Load supply equation

APPENDIX IV
MONTHLY ENERGY PRICES

Average STMC in the Colombian WEM [US$/MWh]						
Monthly	Case # 1	Case # 2	Case # 3	Case # 4	Case # 5	Case # 6
Ene-03	1.96	1.96	2.17	3.06	3.48	3.16
Feb-03	2.26	1.98	2.15	3.42	3.41	3.52
Mar-03	2.89	2.97	3.11	4.15	4.84	4.61
Abr-03	3.55	3.78	3.95	5.62	5.57	5.35
May-03	3.70	3.76	4.01	5.71	6.23	5.83
Jun-03	4.03	4.14	4.39	6.61	7.34	6.75
Jul-03	6.17	6.12	6.84	8.86	9.45	9.03
Ago-03	6.83	7.09	7.69	9.27	9.80	9.54
Sep-03	8.29	8.44	8.95	9.93	10.17	9.92
Oct-03	9.53	9.44	10.05	11.02	10.86	10.58
Nov-03	11.81	12.13	12.13	13.22	12.65	13.61
Dic-03	25.00	19.95	18.86	20.26	21.09	20.22
Ene-04	24.51	24.53	24.42	25.22	25.24	25.01
Feb-04	25.96	25.79	26.50	26.39	26.14	27.30
Mar-04	26.49	46.53	40.92	28.16	27.25	40.04
Abr-04	11.83	18.24	16.24	25.65	25.43	25.58
May-04	11.54	11.45	11.40	18.59	12.08	12.06
Jun-04	11.37	11.23	11.21	12.07	12.01	12.09
Jul-04	10.19	10.04	10.04	10.99	10.84	10.95
Ago-04	10.49	10.20	10.26	11.27	11.12	11.15
Sep-04	10.74	10.53	10.55	11.53	11.34	11.44
Oct-04	12.34	12.09	12.46	13.90	14.49	13.01
Nov-04	17.10	16.78	16.80	21.16	20.10	17.83
Dic-04	24.45	24.18	24.41	26.78	25.41	24.76
Ene-05	26.16	26.20	26.50	30.27	29.85	28.28
Feb-05	12.91	13.37	13.65	21.17	18.12	14.14
Mar-05	26.33	34.98	26.53	43.53	28.92	34.74
Abr-05	26.37	27.57	27.78	41.70	35.92	27.66
May-05	18.39	18.67	18.35	26.96	26.19	19.90
Jun-05	25.17	25.44	25.00	26.83	26.37	26.40
Jul-05	11.11	11.28	10.90	12.94	12.45	12.49
Ago-05	11.60	11.69	11.44	13.65	13.01	12.91
Sep-05	11.80	12.12	12.14	14.22	13.40	13.30
Oct-05	25.47	24.65	32.88	33.07	27.29	26.32
Nov-05	27.41	28.62	29.26	42.89	30.90	20.33
Dic-05	26.60	27.06	27.27	36.70	32.36	28.29

Average STMC in the Colombian WEM [US$/MWh]						
Monthly	Case # 1	Case # 2	Case # 3	Case # 4	Case # 5	Case # 6
Ene-06	26.33	26.78	26.16	35.64	29.78	27.96
Feb-06	26.37	26.61	27.83	42.54	29.21	28.46
Mar-06	36.15	29.80	42.46	57.31	38.56	36.72
Abr-06	23.12	22.93	22.78	31.75	32.28	22.75
May-06	12.65	12.85	12.52	14.73	14.22	14.06
Jun-06	12.41	12.46	12.26	14.74	14.30	13.70
Jul-06	11.88	11.88	11.71	14.05	13.81	13.41
Ago-06	12.21	12.03	12.04	14.75	14.65	13.63
Sep-06	12.81	12.38	12.42	15.88	16.17	14.14
Oct-06	17.66	17.97	17.18	25.19	29.33	19.64
Nov-06	19.85	18.53	20.19	32.56	33.38	22.36
Dic-06	25.88	25.95	26.95	37.91	37.84	29.83
Ene-07	28.03	27.42	27.87	33.27	31.88	28.75
Feb-07	14.69	26.90	19.14	27.86	30.48	19.18
Mar-07	27.12	28.06	28.71	32.71	30.65	32.38
Abr-07	27.60	32.41	33.26	46.71	39.58	32.47
May-07	13.41	13.21	13.43	16.44	17.52	16.00
Jun-07	13.56	13.69	13.72	17.17	17.15	16.12
Jul-07	12.54	12.48	12.50	15.70	15.64	15.06
Ago-07	13.06	13.52	13.49	17.49	16.98	15.59
Sep-07	14.30	14.82	15.43	20.76	19.49	16.59
Oct-07	15.00	15.69	15.96	22.41	20.76	17.49
Nov-07	21.06	21.48	22.04	36.89	29.75	22.28
Dic-07	27.49	29.39	29.27	37.15	35.35	28.48
Ene-08	28.76	29.09	28.30	35.97	33.73	31.12
Feb-08	16.08	17.05	16.18	27.09	24.71	25.06
Mar-08	44.15	31.09	36.45	51.73	39.07	45.68
Abr-08	31.51	32.67	32.75	32.69	31.70	32.01
May-08	15.34	15.37	14.35	17.87	16.66	16.50
Jun-08	14.70	15.05	14.49	17.13	17.07	16.15
Jul-08	14.23	14.84	13.81	16.83	16.77	16.11
Ago-08	15.00	16.00	14.49	17.76	17.10	16.40
Sep-08	17.38	19.67	16.12	19.42	18.54	16.64
Oct-08	29.67	31.37	23.05	29.05	25.98	18.87
Nov-08	33.32	34.82	23.98	28.74	27.02	18.71
Dic-08	30.52	30.92	26.63	28.93	29.46	23.83

Average STMC in the Colombian WEM [US$/MWh]						
Monthly	Case # 1	Case # 2	Case # 3	Case # 4	Case # 5	Case # 6
Ene-09	34.65	32.37	30.03	32.43	31.66	30.56
Feb-09	27.95	28.32	15.96	31.88	24.66	24.82
Mar-09	33.60	30.70	30.40	31.74	33.05	31.15
Abr-09	40.40	37.99	30.77	32.04	33.68	31.08
May-09	23.18	22.73	15.43	24.60	18.60	17.17
Jun-09	15.29	15.17	14.82	17.87	17.61	16.89
Jul-09	14.28	14.22	13.92	16.95	16.72	16.41
Ago-09	15.03	14.77	14.25	17.42	17.04	16.57
Sep-09	15.67	15.15	14.73	17.73	17.42	16.85
Oct-09	27.33	20.82	18.98	25.00	22.23	18.88
Nov-09	40.90	29.04	24.45	31.80	30.75	24.18
Dic-09	44.48	39.84	33.77	43.09	39.88	32.21
Ene-10	48.43	36.57	34.28	45.10	36.99	35.04
Feb-10	42.20	34.09	29.20	46.77	35.78	22.32
Mar-10	40.47	37.43	36.51	40.35	35.40	29.39
Abr-10	38.53	30.17	16.99	19.97	25.49	19.24
May-10	23.10	16.82	15.65	18.18	17.71	17.59
Jun-10	15.99	15.94	15.68	17.76	17.70	17.59
Jul-10	15.05	15.16	14.78	16.71	16.65	16.61
Ago-10	15.53	15.49	15.16	16.90	16.67	16.61
Sep-10	16.08	16.03	15.57	17.42	16.82	16.82
Oct-10	21.71	22.03	21.02	22.13	20.07	18.40
Nov-10	31.46	32.01	28.81	28.30	26.06	21.33
Dic-10	32.26	32.04	31.00	26.32	24.97	22.87
Ene-11	35.25	36.95	32.94	34.66	33.26	31.22
Feb-11	30.99	28.02	32.37	33.81	26.54	31.31
Mar-11	43.27	37.71	34.87	34.82	33.17	32.11
Abr-11	32.71	25.60	18.35	20.05	19.35	18.59
May-11	17.52	17.27	17.00	18.11	17.62	17.47
Jun-11	17.97	17.35	17.05	18.00	17.72	17.20
Jul-11	18.12	16.92	16.57	17.63	17.44	16.87
Ago-11	18.65	17.25	16.85	17.92	17.61	16.98
Sep-11	19.91	18.05	17.00	20.32	18.79	17.22
Oct-11	26.70	23.50	20.64	28.48	25.24	19.43
Nov-11	35.54	28.07	22.92	35.37	30.66	21.41
Dic-11	36.76	31.44	30.40	39.70	32.94	27.33
Ene-12	31.46	30.80	29.73	33.03	32.33	20.81
Feb-12	19.17	18.05	17.52	20.72	26.59	20.17
Mar-12	30.44	30.73	30.27	28.64	34.40	25.04
Abr-12	29.75	17.60	17.26	45.25	27.08	18.71
May-12	24.92	18.01	17.41	31.31	32.69	18.44
Jun-12	18.66	18.28	17.64	25.17	18.45	18.12
Jul-12	18.49	17.77	16.85	18.92	18.29	17.82
Ago-12	18.25	17.41	16.86	18.51	18.25	17.82
Sep-12	20.53	19.21	18.27	20.20	19.86	18.68
Oct-12	31.12	26.60	22.70	28.93	26.01	22.90
Nov-12	37.87	33.47	27.66	32.22	30.17	24.88
Dic-12	47.26	42.16	37.57	42.53	41.34	32.35