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GENESYS Redevelopment Requirements Specifications

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1 Introduction

The GENESYS model was developed to test the adequacy of the regional power supply, given that future conditions, such as load and generation, are uncertain. GENESYS is also the primary analytical tool the Council uses for understanding the impacts of changes in the hydroelectric system’s operation on the regional power system.

1.1 Purpose

The GENESYS redevelopment project is intended to enhance the analytical capabilities for both adequacy assessment and hydro-based analysis and to structure the code base to simplify future development and maintenance. This document comprehensively describes what a redeveloped GENESYS will encompass, including the functionality contained in the current code base.

1.2 Intended Audience

This document provides a sufficient level of detail to describe the scope of the redevelopment process that is targeted for the members of the Council’s advisory committees and other interested stakeholders. It is also intended to lay out requirements for future developers who will be implementing the requirements in this document.

1.3 Scope

GENESYS will simulate the coordinated operation of dispatchable resources. The simulations will cover a wide spectrum of uncertainty in: load (due to temperature and economic conditions), natural stream flows, thermal availability, energy efficiency and demand response achievement and variable energy resource output (wind and solar). Outputs will provide data that allows calculation of adequacy measures and basic statistics on operations and the marginal prices implied by the operations.

2 Overall Description

GENESYS, **GEN**eration **E**valuation **SYS**tem, is a constrained economic dispatch model that uses Monte Carlo sampling to simulate uncertainty in short-term load forecasts, streamflows, wind, solar and forced outages of thermal generation plants. The current version of the model performs a detailed constrained dispatch of the regulated hydroelectric power projects in the watershed of the Columbia River Basin and of Pacific Northwest regional thermal plants alongside an extra-regional import market, on a 14 period per year basis, on a user defined window (2 to 7 days) basis, and on an hourly basis.

2.1 History

In 1999, the deterministic load-resource balance in the region, as assessed by the Bonneville Power Administration, was nearly 4,000 aMW deficit. GENESYS was developed as a dispatch model to evaluate adequacy in a single year by dispatching resources within user defined nodes within and outside of the region. A distinguishing characteristic of GENESYS from predecessor production cost models was the ability to utilize stochastic and deterministic input variables and perform a hydro and thermal generation dispatch. Unlike predecessor models GENESYS was not designed to test long-term load uncertainty and utilize system expansion logic. In the Council’s modeling portfolio, GENESYS is used to provide adequacy thresholds, in the form of adequacy reserve margins, to the Regional Portfolio Model (RPM) which considers long-term load uncertainty and performs regional power system expansion studies.

2.2 Functions

GENESYS will be able to simulate the operation of the region’s power system on an hourly basis, including the simulation of individual hydroelectric facilities, while meeting system requirements for energy, capacity and ancillary services. It will also adhere to all non-power constraints for all resources, in particular, hydroelectric operations mandated in the Council’s Fish and Wildlife Program and by the Biological Opinion. It will appropriately dispatch non-hydro resources based on dispatch price parameters and determine when economics would dictate that stored water should be used to dispatch hydroelectric resources in coordination with these resources.

It will also be able to identify when it is not possible to meet load while satisfying all constraints and determine/illustrate the underlying cause. It will be able to track metrics or functions of the underlying dispatch and produce summary results in a simple format that can either be read directly or easily imported into other programs such as Excel and/or a database.

2.3 Description of Anticipated Users

Users are anticipated to be Council staff, BPA staff, other utility IRP planners or specialized regional stakeholders with a desire to participate in regional or utility specific adequacy assessments.

2.4 Design and Implementation Constraints

GENESYS will need to be capable of using distributed computing, but the install should be kept simple enough that it does not cause issues for utility users. Depending on the approach to redevelopment, it may need to have access to a database server.

While the program should be adaptive by changing inputs, there will also be the capability to alter source code as needed. Thus, the source code will need to be in a managed repository, e.g. GitHub, with the exception of BPA's HYDSIM module.

2.5 Documentation Approach

Documentation should be developed concurrently with the model and should be posted to the Council's website and updated and maintained in that location.

2.6 Assumptions and Dependencies

GENESYS will depend on HYDSIM or a similar hydro regulation model for monthly regulation of natural flows. That is, the model will simulate operations that are consistent with the results from the HYDSIM model that estimate required flows to meet non-power constraints. It will likely also require a mathematical programming solver, e.g. Gurobi, Xpress/Mosel, CPLEX, etc. for the hourly dispatch.

3 External Interface Requirements

3.1 User Interfaces

The user interface should accommodate changing input assumptions or any switches to turn on or off model logic. While it would be possible for the interface to be quite basic, it would be preferred that there be a clean and simple GUI for initiating GENESYS runs and to manage both input and output data. Larger changes may be better accomplished with database editors or other tools.

3.2 Hardware Interfaces

The program should be capable of interfacing with cluster computing either through the Message Passing Interface (MPI) standard or another technology. Expandability to AWS (Amazon Web Service) or a similar service would be ideal.

3.3 Software Interfaces

There should not be a need for direct interface with other software, but the inputs to GENESYS should be coordinated with the inputs for HYDSIM, RPM and AURORA. Further, GENESYS should create outputs that are better coordinated with the needs of other programs or post-processing applications.

3.4 Communication Protocols and Interfaces

The main communication protocol will be the requirements for distributed computing. This will likely be some sort of MPI interface.

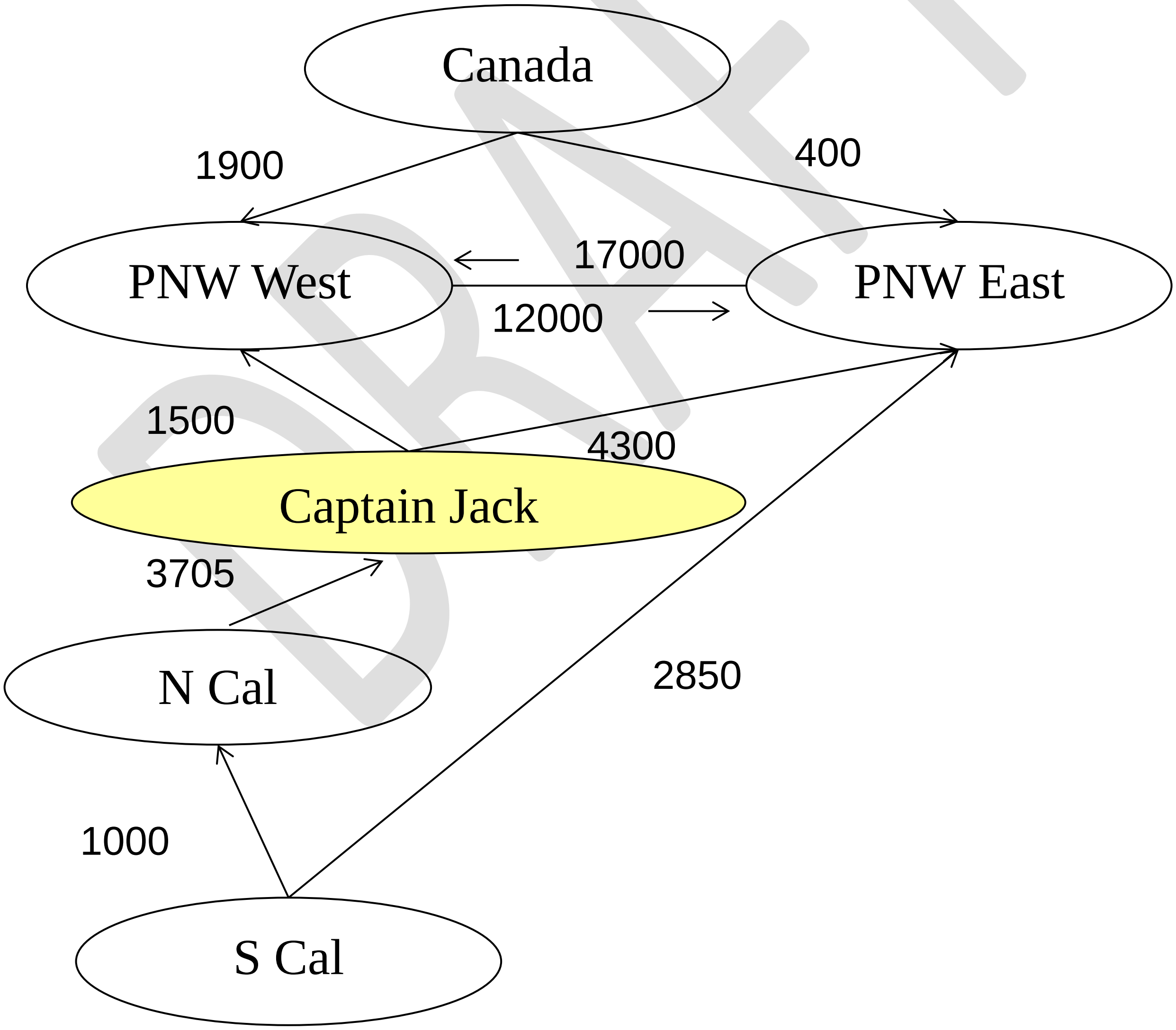
4 Model Features

4.1 Logic Requirements

4.1.1 Zones

GENESYS currently models several nodes within the region and can be run with different nodal configurations that are defined by data inputs. Figure 1 is the current configuration the Council models (with transmission flow constraints between nodes). BPA runs the model in a different configuration.

Figure 1 – Current GENESYS Transmission Topology



The revised model will be similar to the current model but should be more user friendly that allows the user to easily define geographic zones within the region, the resources and loads within those zones, the resources dedicated to specific zones, and the transmission capability between the zones. The model output will be the hourly generation of each resource and the reserves held within each zone and the transfers between zones.

4.1.2 Outside the Region Markets

Purchases and sales outside the region will be modeled on an hourly basis, including appropriate uncertainty in purchase and intertie availability. The prices of purchases from outside the region may be a user input with an appropriate uncertainty associated with it.

4.1.3 Monthly Hydro Regulator

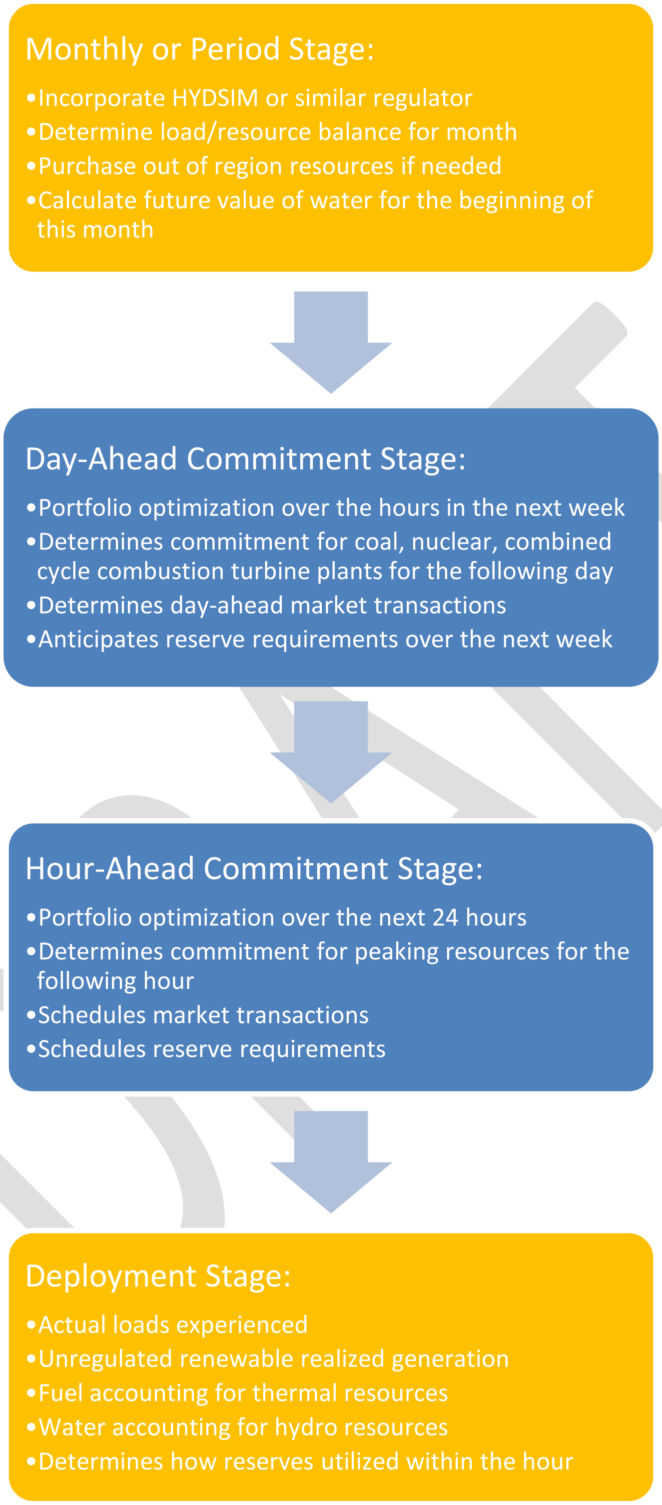
The model will use a monthly hydro regulator (such as BPA's HYDSIM) to define monthly/period hydro generation availability for each simulation, to ensure meeting monthly hydro targets, and to track individual hydro plant elevations and flows on a monthly/period basis. The hydro regulator will also be used within the model to define the Treaty Storage Regulation and, thus, the Canadian project operation for a particular water condition (or simulation).

4.1.4 Multi-Time Stages

The model will perform a multi-stage decision making process, similar to what the existing GENESYS does; the stages being a month or period, day-ahead, hour-ahead, and a "Deployment". The month stage will be an average energy dispatch for the month. The day-ahead commitment stage will commit units for the next day and optimize the forecasted hourly operation over a week. It will be performed every 24 hours on a "rolling" basis. The hour-ahead commitment stage will optimize the hourly forecasted operation over a day and will be performed every hour. The Deployment stage will determine the actual operation in an hour.

Figure 2 is a graphic showing the time stages. The stages in blue are anticipated to be optimizations. For a mathematical description of equations, see the Appendix III.

Figure 2 - Multi-Stage Resource Commitment



Monthly or Period Stage:

- Incorporate HYDSIM or similar regulator
- Determine load/resource balance for month
- Purchase out of region resources if needed
- Calculate future value of water for the beginning of this month

Day-Ahead Commitment Stage:

- Portfolio optimization over the hours in the next week
- Determines commitment for coal, nuclear, combined cycle combustion turbine plants for the following day
- Determines day-ahead market transactions
- Anticipates reserve requirements over the next week

Hour-Ahead Commitment Stage:

- Portfolio optimization over the next 24 hours
- Determines commitment for peaking resources for the following hour
- Schedules market transactions
- Schedules reserve requirements

Deployment Stage:

- Actual loads experienced
- Unregulated renewable realized generation
- Fuel accounting for thermal resources
- Water accounting for hydro resources
- Determines how reserves utilized within the hour

4.1.5 Monthly Stage

The model logic for the revised GENESYS will be similar to the current GENESYS for the monthly stage. A hydro year is split up into 14 periods which are, for the most part, monthly, with April and August split into the first and last halves of the month[1]. The 14 period hydro regulator model used to determine available hydro in GENESYS currently is HYDSIM, developed and maintained by BPA. Reservoir and flow characteristics are modeled such as beginning and ending contents, minimum and maximum flows, minimum and maximum storage, and spills at each hydro project for each of the 14 periods. Each period, the amount of hydro energy available to each regional zone for the month is calculated, given the starting contents of the reservoirs of that month. The total available hydro energy is separated into what will be referred to as "blocks" of hydro energy by zone. The hydro blocks are the amount of energy available if the system was drafted down to a given point. To determine the boundaries of the hydro blocks, the hydro regulator is run four times at the beginning of the month: to URC (Upper Rule Curve[2]), to VECC (Variable Energy Content Curve[3]), to draft point 6 (Proportional Draft Point), and to draft point 8 (Empty[4]).

> *Hydro block 1* is the amount of energy that must be generated to get to URC plus the energy generated by the hydro independents.
>
> *Hydro block 2* is the amount of energy between URC and VECC.
>
> *Hydro block 3* is the amount of energy between VECC and draft point 6.
>
> *Hydro block 4* is the amount of energy between draft point 6 and CRC, Critical Rule Curve[5].
>
> *Hydro block 5* is the amount of energy between hydro block 4 and draft point 8, limited by the user input for "borrowed hydro" of a 1000 MW-periods. Draft point 8 is the total energy when drafting from starting content to as close to empty as constraints allow.

The hydro blocks are divided between the zones in the PNW region according to the total amount of hydro energy output from the hydro projects specified for each zone.

Currently in GENESYS the shadow prices of the hydro blocks, which determines the order that they are dispatched in relation to the thermal resources, are user inputs, but an algorithm to determine the future

---

[1] This is due to distinctive runoff and operation characteristics between the first and second halves of April and August.

[2] *Upper Rule Curve* is also known as the flood control rule curve. Calculated by the Army Corp of Engineers, it "defines the drawdown required to assure adequate space is available in a reservoir to regulate predicted runoff for the year without causing flooding downstream.", per "Modeling the System" pamphlet.

[3] *Variable Energy Content Curve* guides non-firm generation energy generation, and is usually the lowest of the four rule curves in winter and early spring and is based on the predicted runoff during the year. Functionally this is a reservoir energy content curve. Drafting a reservoir no further than this point ensures a high probability of refilling by the end of spring runoff season. VECC is made up of Made up of the Assured Refill (ARC), Variable Refill (VRC), and Limiting Rule (LRC) Curves from BPA

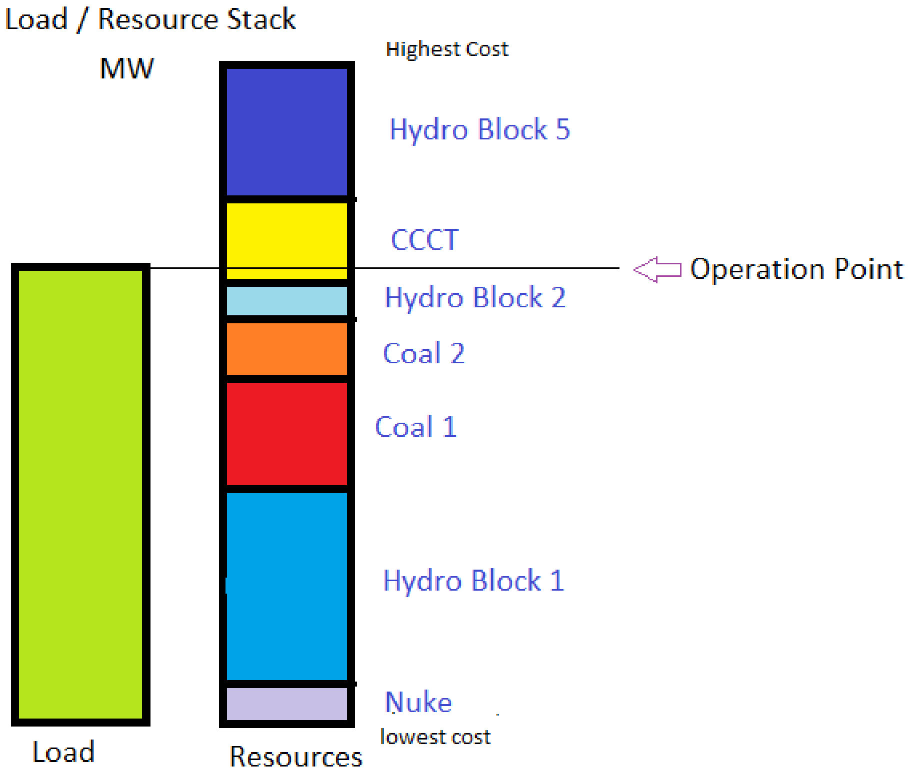
[4] Because of constraints other than the rule curves, GENESYS never gets to empty.

[5] *Critical Rule Curve* "defines the reservoir elevations that meet firm energy hydro requirements under the most adverse streamflows on record", per "Modeling the System" pamphlet.

value of water based on the fact that the system refills by July 30th (or other potential elevation or storage targets), should also be used[6]. This would be calculated given the system storage target and a distribution of inflow uncertainty in the preceding period. It can be worked forward in time from any system content to the system storage target to find the expected cost. This expected cost is calculated incorporating inflow uncertainty, meeting the load during the period, and ending up at full (the storage target). This would give a value for any system content at the beginning of July to meet the load and end full. Now a backwards time step can be used, minimizing costs given the uncertainty of inflows to meet the previous period load. This process continues until we get to the time step of interest. For example, we can calculate a future value of water at the beginning of January given that we need to fill by the end of July. The future value would be by hydro blocks of energy in the system and would be in $/MW-mo.

GENESYS currently does a monthly/period economic average energy dispatch by node[7] using an algorithm that mimics what is shown in Figure 3. After dispatching resources within each node for the node's load, it finds "opportunities" in each of the nodes for displacement of resources or the meeting of load that was not served by the node's own resources. It then goes through the resources not yet dispatched by economic order and determines, given economics and transmission constraints, whether that resource supplies any of the "opportunities". This results is an economic dispatch of the Region's resources, given transmission constraints between the nodes.

Figure 3 – Load/Resource Stack in GENESYS Period Dispatch



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[6] See Discussion of Future Value in Day-Ahead Commitment Stage.

[7] Note that in the revised version of GENESYS, "nodes" are now referred to as "zones."

Currently GENESYS, after going through the month dispatch, week dispatch, day dispatch, and hour dispatch for the entire month, calculates the total amount of hydro energy dispatched in the month and the hydro regulator is run again to determine the ending contents of the reservoirs for that month, which become the starting contents for the next month. The revised GENESYS would not need to calculate an end of month reservoir elevation, since they will be determined in the Deployment stage.

4.1.6 Day-Ahead Commitment Stage

GENESYS will optimize the forecasted use of hydro and thermal resources over the next week by hour in order to minimize costs. In addition it will commit coal, nuclear and CCCT for the next day. It will revisit this forecast/commitment decision every day on a rolling basis. Individual resources will be modeled including all the regional hydro resources and how they interact with each other, thermal resources, variable energy resources (like solar and wind), energy limited resources (like demand response and storage), and must-take resources (like long-term contracts). The requirements that will be modeled include:

1. Base Load[8]
2. Regulation up
3. Imbalance up
4. Regulation down
5. Imbalance down
6. Spinning reserve
7. Non-spinning reserve

The model will be formulated to explicitly model the “holding” of reserves by specific plants and the determination of whether those reserves are used will be made in the Deployment stage. The summation of all “held” capacity amounts for a particular requirement must meet the total system requirement. The optimization will be over the total region[9].

4.1.6.1 Objective Function

The objective function will be to minimize cost. This will include the variable O&M costs, wear and tear costs, and startup costs of resources. It will also include a penalty for forced spill at hydro projects and a subtraction for the future value of resources. The future value of water may be determined by reservoir or it may be determined as a system wide value. Figure 4 is a graphical representation of the tradeoff between immediate thermal costs and storing water versus drafting hydro and running thermal in the future.

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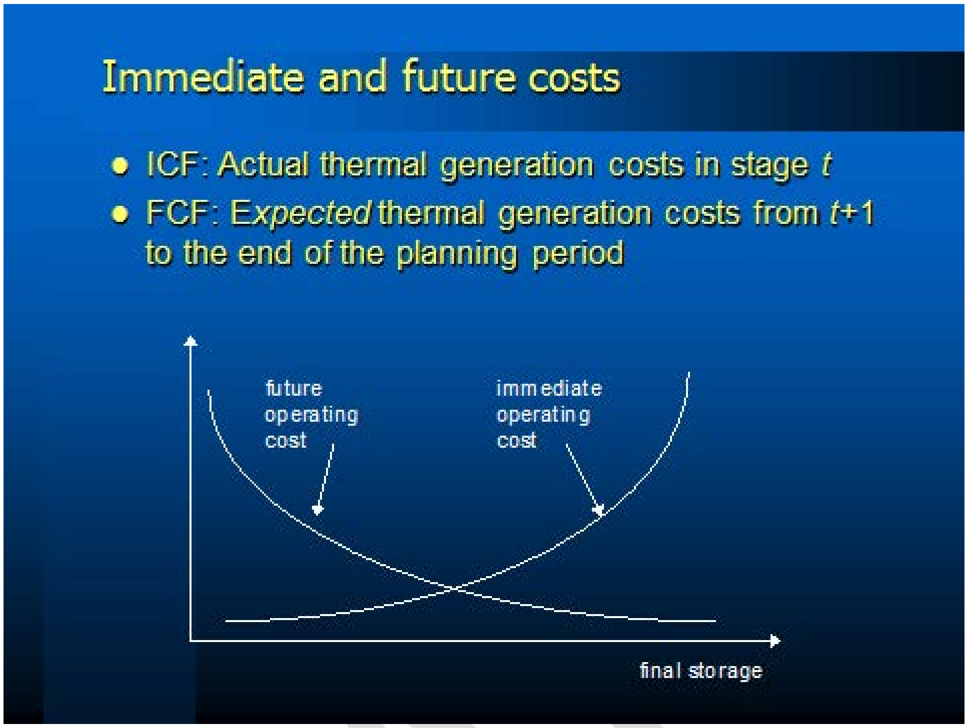
[8] The base load plus regulation down and imbalance down requirements equals the scheduled load.

[9] Recall that the region consists of all the loads and resources within each zone of the region and transmission constraints between the zones.

Figure 4 – Immediate versus future cost graph



Immediate and future costs

- ICF: Actual thermal generation costs in stage *t*
- FCF: *Expected* thermal generation costs from *t*+1 to the end of the planning period

4.1.6.2 *Thermal Resources*

Thermal resources will be limited in the optimization by their ramping capability, minimum operating level, and maximum capacity. If a coal plant or combined cycle combustion turbine is forecasted to be needed in the next day, or a natural gas peaking plant, in the next hour, they are deemed to be committed. If they are committed in an hour they are constrained by their minimum generation amount and the minimum and maximum amount of fuel usage accounted for in the fuel schedule. Also, a plant's minimum up and down times will constrain whether a plant is running or not.

4.1.6.3 *Hydro Resources*

Hydro resources will be constrained by their maximum capacity and by their minimum generation amounts. The scheduled outflows plus spill will be constrained by the minimum and maximum outflows at a project. The total spill at a project will be constrained by the minimum spill at that project and the spill requirement at certain projects will be a percent of total outflows. Reservoir volumes will be equal to the reservoir volume in the last hour plus the outflows from upstream projects due in this hour plus side flows minus outflows at this project. They will be constrained by the minimum and maximum reservoir volumes[10].

The computation of generation from a hydro project is a non-linear function of the forebay elevation, tailwater elevation and turbine flow. Conversion factors (H/K) of hydro projects vary with the forebay elevations and the tailwater elevations. The proposal is to pick a conversion factor that is reasonable for the first optimization and then use the actual forebay and tailwater at a project from the last optimization to

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[10] Storage targets can be modeled as a range of possible values that narrows as it approaches the target date.

determine the H/K for the next optimization. We believe the H/K's will converge to about the correct level fairly quickly. See Appendix II for a broader discussion of H/K.

4.1.6.4 Variable Energy Resources

The maximum amount of capacity "held" on a particular variable energy resource must be less than or equal to its energy forecast.

4.1.6.5 Energy Limited Resources

The maximum amount of capacity "held" on a particular energy limited resource must be less than or equal to its maximum capability. If the resource is committed, the amount "held" must be at least the minimum amount of the energy limited resource.

4.1.6.6 Must-Take Resources

Must-take resources can only meet the "base load" requirement and are equal to their forecast.

4.1.7 Hour Ahead Stage

GENESYS will optimize the forecasted use of hydro and thermal resources, including reserves, over the next day by hour in order to minimize costs. It will do this hourly on a rolling basis. The commitment of short term plants such as gas-fired turbines will be re-examined. The constraints will essentially be the same as for the Day-Ahead stage, but over a different time period. The loads and variable energy resource forecasts will be revised.

4.1.8 Deployment Stage

This stage models an after the hour "true up" to resolve the difference in actual versus forecasted load, wind and solar generation, and how that effects the actual generation and the reserves used. Actual utilization of all resources will be determined, thermal plants will be stochastically forced out, and fuel accounting calculated.

4.1.9 Slice

The model will be able to mimic slice contracts and accounting between BPA and other utilities within the region.

4.2 Input Requirements

4.2.1 Load

- Parameters to simulate "Actual" hourly loads
- Parameters to simulate forecasted hourly loads on a monthly, day-ahead, and hour-ahead time frame

4.2.2 Hydro

- Upper rule curve limits, flood control elevation targets (storage targets) as a function of anticipated side-flows and/or a range of acceptable elevations as a function of time and reservoir

- Refill requirements by reservoir
- Drafting rights limitations (elevations) by reservoir
- Limit on ability to exceed drafting rights for short periods of time by reservoir
- Reserve provision capability
- Parameters to simulate “Actual” Hydro side flows by water condition and period
- Parameters to simulate day-ahead and hour-ahead forecast side flows by hour
- Runoff forecast by water condition
- Plant parameters including, but not limited to:
    - Number of Units
    - Minimum and Maximum Generation by Unit
    - Ramp Limits
    - Tables of Storage vs Elevation, discharge vs. tailwater, and head vs. H/K
    - Lag Time to next plant and/or functional description of when lagged water arrives into the downstream plants pool
    - Full Gate Flows
    - Size of reservoirs
    - H/K conversion factors for outflows to generation
- Non-power constraints:
    - Elevation constraints
    - Bypass Spill constraints
    - Flow constraints
    - Rate of change limits on fore-bay and tail-water

4.2.3 Thermal

- Forced outage rates, mean time to failure and mean time to repair
- Fuel constraints, e.g. natural gas supply or contract constraints (pipeline drafting/packing, storage, nomination timeline)
- Minimum up and down time for plants
- Ramp rates
- Reserve provision capability
- Heat rates and efficiency curve assumptions
- Variable O&M and Wear and Tear costs
- Maximum and minimum plant capacities (and any other operating states)
- Emissions tracking parameters (CO_2 emissions)

4.2.4 Other Resources

- Demand Response/DSG/Emergency Resource dispatch price, capacity and availability
- Parameters to simulate “Actual” wind and solar hourly generation
- Parameters to simulate day-ahead and hour-ahead forecast wind and solar generation
- Parameters to simulate “Actual” hourly conservation
- Parameters to simulate day-ahead and hour-ahead forecast conservation

- Reserve provision capability
- External market supply, demand and pricing forecast by period.
- External market supply, demand and pricing forecast for day-ahead and hour-ahead stages by hour
- Simulated “Actual” external market supply, demand and pricing
- Generic storage and energy limited capacity resources, including:
    - Notification for dispatch (day-ahead notification for some demand response),
    - Ramp rates
    - Energy Limit
    - Capacity Limit
    - Losses
    - Efficiency parameter needed

4.2.5 Transmission

- Available Transfer Capability between zones (transmission access and limitations)
- Parameters to model intertie availability uncertainty
- Dynamic transfer constraints
- Losses
- Other pertinent line parameters

4.2.6 Reserve Requirements

- Requirements for Regulation up and down, hourly and dynamically calculated based on load and generation forecasts
- Requirements for Load Following/Imbalance up and down, hourly and dynamically calculated based on load and generation forecasts
- Requirements for Contingency Reserves, hourly and dynamically calculated based on load and generation forecasts

4.3 Output Requirements

See Appendix I for a complete listing of current GENESYS outputs, which outputs are proposed to be kept, and what changes may be made.

4.3.1 Resource Adequacy Parameters

The resource adequacy parameters calculated will include but not be limited to traditional metrics like LOLP (peak and energy), EUE, LOLE and CVAR (peak and energy), on an annual and monthly (periodic) basis, with all values subject to user-controlled degrees of thresholding and filtering. Event-based parameters will include but not be limited to event curtailment magnitude and duration, peak and energy curtailments, average loads during event, temperatures scenario, thermal forced outage rate and wind/ solar/ thermal/ hydro generation.

4.3.2 Hourly Resource Generation Information

The outputs will include the ability to produce hourly generation information for a selected resource as well as being able to produce hourly generation information for a bundle of resources of a similar type or of a particular owner.

4.3.3 Hydro Information

The outputs will include monthly (periodic) hydro regulator output information by period and project as well as hourly hydro information. Values included but are not limited to natural streamflows, outflows, minimum flows, all of the spill components, draft amount, ending storage/elevation, rule curve storage/elevation, target storage/elevation, power factor and average generation

5 Other Nonfunctional Requirements

5.1 Performance requirements

GENESYS should be able to produce a full scenario run in 12 hours or less. A “full” scenario at the very least would be a study that simulates the operation over every combination of wind and temperature years, currently 6,160 games. In the future a full scenario will likely mean running with random combinations of all uncertain variables, which would require many more simulations, perhaps as many as 10,000 or more.

5.2 Project documentation

Project documentation should be incorporated into the source code repository and include both functional specifications and technical discussions for the model.

5.3 User documentation

User documentation should be included in the software install as either HTML help or as a Word Document.

6 Appendix I – The Outputs

Listed below is a catalog of a common output file types that can be selected for GENESYS

6.1 GENESYS Text files (.out files)

Borhydsum.out (need similar, but revised for new functionality)

- Monthly summary of hydro, other resources, unserved load, forced outages, and load by day
- Includes information on hydro (including borrowed hydro) dispatched in window and day dispatches

Contractdbg.out (need similar, but revised for new functionality)

- Summary of contract inputs by contract by hour for Weekday, Saturday, and Sunday
- Used for debug

DispatchResources.out (need similar, but revised for new functionality)

- MW dispatched by hour for all games for a resource specified in Studydef

EndCont.out (need exactly for debugging)

- Ending contents of each reservoir at the end of each game
- Used to reproduce the results of an individual game

FILEREC.out (need similar, but revised for new functionality)

- Report of file paths of the files used to run GENESYS.
- Does not include files to run HYDSIM, which are shown in MDFILEREC.out

Flex.out (obsolete by new functionality)

- Maximum borrowed hydro in MWh used during a month and the amount still in the system at the end of the month

FOR.out (need similar for debugging, want realized forced outage rate for individual plants)

- Total forced outages in MW and the percent forced out for every hour of every game

Gameseed.out (need similar)

- Random seeds used for every game, IF switch is activated in *StudyDef.dat*.
- Could be random seed same for all games, different for any game, or random seed taken from clock.

HourlyLoadDebug.out (need similar info somewhere)

- Loads, wind, and solar by hour, used for debug purposes

HydCapac.out (need similar, but revised for new functionality)

- Window hydro availability
- Sustained peak limits used each day
- Hourly hydro shaping information
- Used for debug purposes

Message.out (need similar and expanded error trapping, but revised for new functionality)

- GENESYS error and warning log.

MonthyHyd.out (need similar info)

- Size of hydro blocks in MW and total hydro generation for each month for the first ten games

NodePath.out (need similar, but revised for new functionality)

- All possible permutations of transaction paths between nodes. Note that a transaction can move between several nodes before getting to final destination.
- Includes wheeling cost (in $ per MWh), losses, shadow price, node names.
- Includes resources by home node and destination nodes.

OPRFileRec.out (need similar info)

- Report of the files used to run HYDSIM in an OPR run when running with the TSR

Overgen.out (need similar, but revised for new functionality)

- Amount of overgeneration spill in MW
- Must run thermal not used in MW
- Load reduction resources not used in MW

PurMW.out (need similar, but revised for new functionality)

- Purchase ahead resources purchased
- Purchases by day, window, and month each shown by hour

RelibRec.out (need similar, but revised for new functionality)

- Hourly output by game that returns megawatts curtailed, reserve violation flag, load, reserve requirement, additional reserves, thermal generation, contract purchases, hydro generation, wind generation, megawatts forced out, percentage of thermal resources forced out, wind capacity factor, and slice account (which is zero unless running a BPA version).

ResOut.out (need similar, but revised for new functionality)

- Hourly dispatch for specified resources, for the game specified in Studydef.
- Resources included in file are specified in GenRes

SegOp.out (need similar, but revised for new functionality)

- Hourly generation by resource for the game specified in Studydef
- Includes reserve violations, unserved load, overgeneration, and transmission flows

Slicesystem.out (need similar, but revised for new functionality)

- Similar information as System.out, but also includes slice generation
- Output for BPA version

SliceSegOp.out (need similar, but revised for new functionality)

- Similar information as SegOp, but also includes slice generation
- Output for BPA version

SOS1.out (need all the same metrics and expanded functionality as described in specs)

- State of the System output
- Average dispatch over all games and all hours, by period of resource types.
- Raw LOLP (prior to emergency resource dispatch), probability of using borrowed hydro, maximum borrowed hydro used in a game (GWh).

SOS2.out (need all the same metrics and expanded functionality as described in specs)

- State of the System output
- Dispatch level percentiles over all games by resource type, unserved load and market.

SOS3.out (need all the same metrics and expanded functionality as described in specs)

- State of the System output
- Hourly duration curves by period by selected resource type and for unserved load.

SustPkLimHits.out (obsolete)

- Gives the game, year, month, and day a sustained peaking limit was hit, what the limit is, and the hourly shape of the hydro before and after adjusting for the limit.

System.out (need all the same metrics and expanded functionality as described in specs)

- Specified single game summary (default is game 1).
- Supply demand summary, supply availability and dispatch, node-to-node, contracts, transmission loading across all nodes by period.

Therm.out (need all the same metrics and expanded functionality as described in specs)

- Total gas, coal, nuclear, other thermal, and IPP running by hour for the game specified in Studydef

Transact.out (need similar, but revised for new functionality)

- Dispatch information for month, window, day and hour dispatches for the game and months specified in Studydef

- Supply stack, initial pass dispatch, opportunity transactions available, final dispatch, and period summary

Tranflow.out (need similar, but revised for new functionality)

- Mean, minimum, and maximum transmission flow between nodes by period for a game
- Note: there seems to be a bug in this output with respect to the game number

TSRFileRec.out (need similar)

- Report of the files used to run HYDSIM in a TSR run

UnservedReason.out (need similar, but revised for new functionality)

- Summary of generation dispatched in those hours that have load curtailment.
- Note: there seems to be a bug in this output with respect to the games output

WeatherYr.out (need exactly this functionality)

- Selection for the water, temperature and the wind year plus the wind set (out of the 20 different correlated wind capacity factors for that temperature year)

6.2 GENESYS Text files (.vbi files)

- Made obsolete by new functionality, except must have info from SegTrak.vbi

These text files often summarize the above text output files in a format created for the graphics package in an old user interface.

DayUSDDurat.vbi

- Duration curve data for daily unserved demand by node.

Exceed.vbi

- Unserved demand by percentile

GamePV.vbi

- Present values for each game.

MeanDemand.vbi

- Mean period nodal demand

MeanMonthlySourceAvail.vbi

- Mean period resource availability across all games

MeanMonthlySourceCapacity.vbi

- Mean period resource capacity across all games

MeanMonthlySourceFixOp.vbi

- Mean period fixed operating costs by resource across all games (in millions $)

MeanMonthlySourceFuelUse.vbi

- Mean period source fuel use by resource across all games (in trillions of Btu)

MeanMonthlySourceOutput.vbi

- Mean period output by resource for all games (in aMW)

MeanMonthlySourceVarOp.vbi

- Mean period variable operating costs by resource (in millions of dollars)

Multidam.vbi

- Subset of the BPAREGU.OUT results.
- 6160 by 14 periods of minimum flows, forced spill, bypass spill, generation, ending content, ending elevation, flood control and PDP.

NetDemandDurat.vbi

- Duration curve for period demand

PNW Balance.vbi

- Average load resource balance by period by game

Pods.vbi

- Probability of designated shortage values

SegTrak.vbi

- For a specified game, gives hourly load, curtailment, long-term purchases, hydro generation, wind generation, contract imports/exports, reserve requirements, hydro reserves, thermal reserves, reserve violation.

SegTrans.vbi

- Hourly transmission flows by node for a specified game.

SegUnservedDurat.vbi

- Hourly unserved demand data (MW) by year for a specified game.

SourceAvailDurat.vbi

- Sorting hourly availability for resources specified in GenRes by period

SourceOutput.vbi

- Sorted hourly generation for resources specified in GenRes by period

Srcecost.vbi

- Mean variable and fixed operating costs, and capital costs by resource.

TranFlow.vbi

- Mean transmission flow by period for each transmission source/destination pair.

TransDuratMo.vbi

- Sorted hourly transmission observations by period for four transmission segments

6.3 HYDSIM Text Files (.out and .log files)

BPAREGU.out (need exactly the same information)

- End of period results by plant.
- Outflow, bypass spill, force spill (spill because flow above turbine limits), overgeneration, other spill (sluiceway, leakage, locks), incremental H over K (H over K for that plant and everything downstream), average MW, draft (in ksfd), end storage (in ksfd), ending elevation (in feet above sea level), rule curves (flood control, ECC, AER in ksfd), constraint violations in order of violation (farthest right violation is first constraint violated, farthest left is the last constraint encountered, which controlled plant operation).
- Asterisk by plant name means generation not counted in the total to meet load.
- Period energy that one can get to draft to each hydro block.
- System generation summary including hydro independents, pumping (currently always zero, built into loads), One Dam model stats like content of the entire system in energy (MW-periods).

DEBUG.out (need exactly the same information)

- Error trapping for HYDSIM.

MDFileREC.out (need exactly the same information)

- Report of file paths of the files used to run HYDSIM.
- WaterYearOverride80.dat file path is overwritten by FILEREC.OUT

OvergenSpill.log (need exactly the same information)

Logs when certain constraints were relaxed in order to allocate the overgeneration spill in HYDSIM.

6.4 Post Processor Text Files (.out files)

Plant by Plant Generation.out (Need similar, but expanded for new functionality)

- Output of a post-processing program, READBPAREGU program.Builds summary matrices of output or input by plant.

7 Appendix II – H/K Discussion

Modeling of H/K in a Hydro-Thermal Scheduling Model

The reformulated GENESYS will solve a large number of Mixed Integer Linear Programming (MILP) problems. Modern MILP algorithms can solve many non-linear problems, especially those that can be formulated in terms of integer/binary variables. They cannot solve, in particular, problems with quadratic terms. The generation of a hydro plant= (H/K)*(turbine flow), is such a term.[11] Most modern hydro scheduling algorithms either assume that the H/K is well enough known that it can be reasonably modeled as a constant over short periods or the algorithm is iterated on the H/K’s until reasonable convergence is attained.

The reformulated GENESYS will likely model 39 plants with hourly detail. Can a “reasonable HK” be found for a set 39 plants for a week (168hours), that is, a set of 6552 numbers? This question is addressed in a multitude of computerized hydro scheduling programs and even more publications in the technical literature on hydro scheduling. The answer is: it all depends. It depends on the characteristics of the system you are modeling.

The Pacific Northwest hydro system has a variety of system characteristics that dramatically influence HK. Consider the following table:

Sample change in H/K within 24 hours

Plant\HK parameters	HIGH	LOW	Range	Δ4B[12]	ΔTW[13]
GCL	25.17	23.75	6%	3”	17’
LIB	19.6	19.1	2.6%	5”	7.2’
BON	5.06	4.81	5.2%	1’	9.5’
CHJ	13.09	12.45	5.1%	9’	6.6’
LWG	7.09	6.78	4.6%	6’	1.2’

---

[11] HK is often defined by a piecewise linear table of mw/kcfs as a function of head in feet where head is defined by forebay elevation in feet minus tailwater elevation in feet.

[12] range of forebay in feet (‘) or inches (“)

[13] range of tailwater in feet (‘) or inches (“)

For a large reservoir the fluctuations in HK values on a daily basis are generally driven by tailwater changes. PNW examples are Grand Coulee and Libby with forebay changes in inches and tailwater changes in 10's of feet over a day. For intermediate and small reservoirs/ponds the fluctuations in HK are still often driven by tailwater changes. However for these types of plants the forebay changes would be in feet while the tailwater changes can be in 10s of feet on a daily basis. There are of course exceptions; plants where fluctuation in HK is driven more by change in forebay than by change in tailwater. The PNW plants on the lower Snake are examples. Consider the behavior of Lower Granite (LWG) shown above.

Developers of hydro scheduling algorithms often assume the current elevation of a reservoir is a good aid in quickly and reasonably approximating H/K over multiple days. For intermediate/small plants they often use an average forebay elevation for the same purpose but over all time.

The initial H/K guesses will almost never be the H/K's of the operation they imply. Improving the H/K's is the crux of most iterative procedures. Below is a very simple iterative algorithm to improve the H/K's:

step 1 – make an initial guess at the H/Ks for all the plants

step 2 – solve the least cost hydro operation problem

step 3 – find the H/Ks implied by the discharge, turbine flow and forebay elevations in step 2

step 4 – determine if the H/Ks are "close enough"

step 5 – if "not close enough" then use these new H/Ks go to step 2

step 6 – if "close enough" then output the results

There is no "proof" of the convergence of this process. There is the fact that the problem is solved in real-life operations (through the combination of AGC, generator set points, plant operators etc.) which turn a computer estimates into a real solution. Getting close to the actual H/K is still required in GENESYS and there are many ways to change/improve the above iterative algorithm, such as more intelligent initial guesses, more sophisticated H/K improvement algorithms, the use of non-linear optimization methods and many others.

In GENESYS, the H/K values can be guessed at for initial hours of an optimization stage, and then updated based on actual hydro used in the deployment stage. Thus, the iterative process can be captured implicitly within the flow of the model.

8 Appendix III - The Equations

Unit Commitment Model

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9 Multi-Stage Unit Commitment Discussion

The basics of this stage of a multiple stage unit commitment model are that the percentage of system requirements can be assigned by the model to minimize cost and commit units for the following stage.

Figure 1 summarizes model flow within the context of the future value of hydro. The model flow is similar to the current GENESYS process where a simple resource stack is used to determine initial hydro allocation into price blocks to establish the periodic targets where there are less robust forward markets. The window period then uses resource stacking like the period target stage to estimate hydro generation and commit long lead time start-up resources like coal and nuclear plants.

Then, in the day-ahead and hour-ahead unit commitment stages the assigned volume and initial price of hydro in each window (a one week period) established by the price blocks are the initial starting points for the hydro pricing in the day–ahead period. Since the problem is bounded by the volume of hydro available in the commitment time period (with the exception of the situation where hydro from a future period is needed for reliability, not all hydro is needed in a current period, or hydro volumes need to be decreased due to a previous period need), most of these stages will have a straight-forward solution.

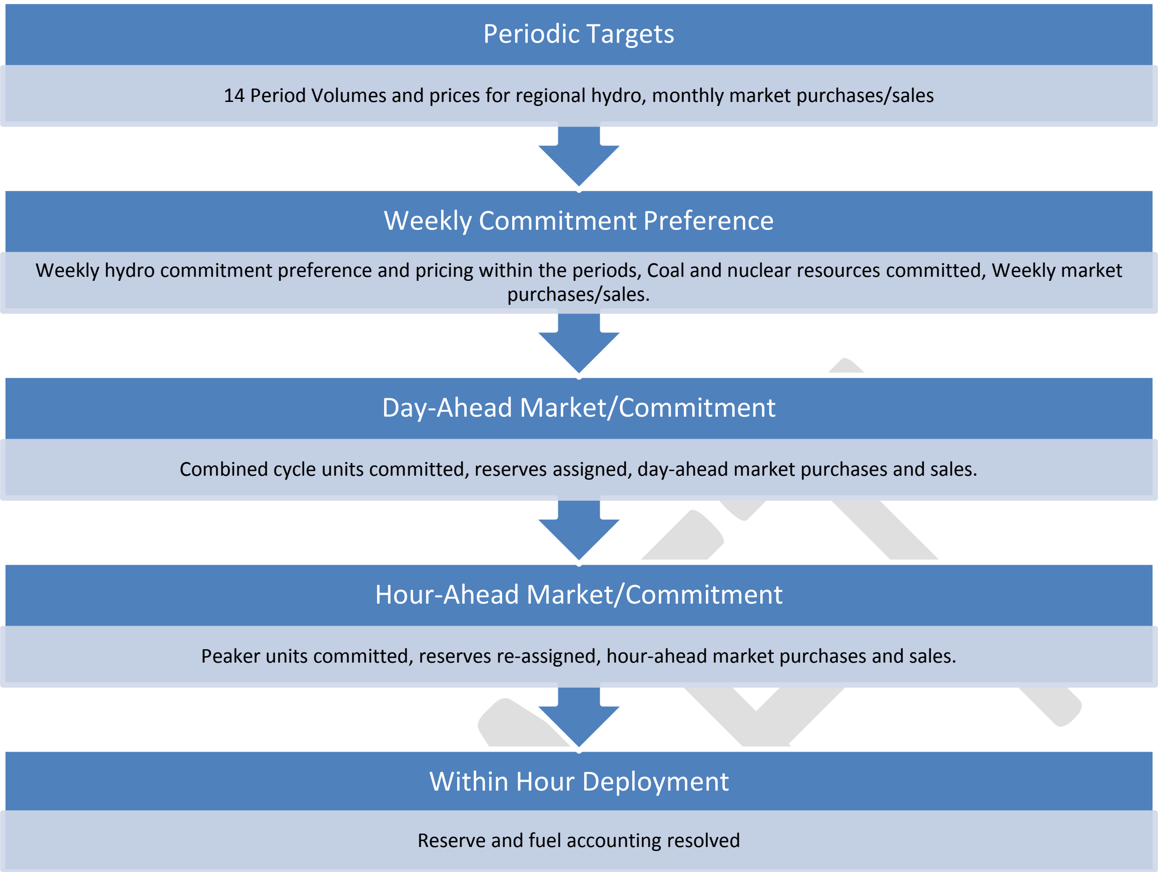

Figure 1: GENESYS Model Stages in terms of Hydro Future Value

The unit commitment model described below assumes that there is either an implicit valuing of hydro in a rolling time frame (per a market price), or there is an explicit price for hydro fuel passed from the resource stacking steps (period and window). Then, once the coal and nuclear thermal commitment has been established in the window stage, within the day-ahead and hour ahead commitment stages, explicit external fundamental market electricity prices from wholesale electricity market pricing model (like AuroraXMP) can be used to implicitly value hydro.

Technically, all resources require some level of implicit future valuation to determine best resource assignment, but for resources without fuel storage capability the future value would arguably not change decision making for the plant. However, when there might be an arbitrage to be predicted in the future and the fuel can be stored or energy limited resource commitment can be shifted, future valuation is important in correctly committing the unit.

9.1 System Requirements

Note that the usage of *x* as a general descriptor of system requirements rather than a treatment of load and ancillary services is specifically to accomplish a few different objectives:

(1) The only actual system requirement being addressed explicitly is load, and differentials from scheduled or forecasted load over different timeframes.

(2) Defining system requirements this way allows for assignment of different attributes to specific power plants or markets (combination of unspecified power plants with attributed characteristics that more simply represent the underlying plants)
(3) Defining it this way allows for model extensibility should that be needed, while still creating a specific enough model structure that can be interpreted simply.

The way *x* is used basically splits the model into loads that can be addressed pre-commitment/schedule stage and post commitment/schedule stage. This delineation is what allows us to simplify the operating time frame (intra-hour power system granularity) into an hourly adequacy planning model, but still address the generator range and fueling requirements to meet the differentials of intra-schedule system requirements from scheduled system requirements.

10 Chronological Variable Requirements

Chronological variable requirements in the model will prevent some parallel processing within a particular simulation. Some of the main anticipated chronological variable information are as follows:

1. Reservoir elevations from hour to hour
2. Market purchases and sales from a previous unit-commitment/resource-stacking stage
3. Energy limited resource limits that extend beyond commitment evaluation window.
4. Previous stage plant commitment.

11 *Parameter Definitions*

Assume all parameters are greater than or equal to 0 unless otherwise noted.

11.1.1 General

T: The duration of the period over which the optimization takes place. This will likely be some reasonable subset of the entire year to fit within the staged approach to the model and yet still incorporate some of the fuel accounting issues associated with cascading hydro systems with storage, like say two weeks for the day-ahead and hour-ahead commitment stages.

Table 1 – Commitment Time Frames

Stage	T (in hours)	Description
Day-Ahead Commitment	168 (or 24 + 2*6)	Rolling week look-ahead
Hour-Ahead Commitment	24	Rolling day look-ahead
Within-Hour Deployment	1	Resolve uncertainty for the hour

Target: A time (likely date, day or hour) that represents when a hard target elevation or volume must be met on the hydro system.

Therm: The number of specified thermal resources in the regional portfolio.

Hydro: The number of specified hydro resources in the regional portfolio.

VER: The number of specified Variable Energy Resources like wind and solar in the regional portfolio.

Must-Take: The number of specified must-take resources like energy efficiency, independent run-of-river hydro, and long term contracts in the regional portfolio.

EnergyLim: The number of specified energy limited resources like demand response, utility-scale storage and distributed standby generation.

Market:The number of markets accessible to the regional portfolio.

ResOfLastResort:

The number of resources of last resort for each system requirement. This resource is only available to meet system requirements in the Within-Hour stage. The number of MW assigned to this unit are indicative of a shortfall in the regional portfolio.

Δ_{DA}: This is a proxy for a general uncertainty parameter to indicate that there will be forecast error in this term for the day-ahead unit commitment stage.

Δ_{HA}: This is a proxy for a general uncertainty parameter to indicate that there will be forecast error in this term for the day-ahead unit commitment stage.

Φ: This is a proxy for a general uncertainty parameter to indicate that there will be uncertainty in market price due to bid/ask spread, etc.

11.2 Indexes

x: System requirements including the following:

8. Scheduled/Observed Firm Load for hour
9. Regulation up
10. Imbalance up
11. Regulation down
12. Imbalance down
13. Spinning reserve
14. Non-spinning reserve

k: A discrete index representing a particular resource accessible to the regional portfolio. Could be a market (external/internal subset of resources) or a specified regional resource.

m: A discrete index of months/periods important for delineating the effect of seasonality on particular plant/market parameters.

i: Granularity of the model stage, hourly.

f: Fuel type such as hydro, wind, solar, coal, gas, etc.

a: The index a is associated with a particular spill regime. Since this may be in the form of a date range or particular hours in a day depending on the plant, the notation is left general.

11.2.1 Indexed Parameters

X^k: Describes a subset of system attributes that can be bought or sold together in a market resource k.

DWN^k: The set of all downstream plants of k.

$\Omega^k(m)$: The number of hours in a particular period of time m, over which an energy limited resource k can dispatch.

Max^k_m: Maximum generation in megawatts for resource k in month m. This could also be maximum liquidity in the case of market resources, and may need to be of hourly granularity i.

Min^k_m: Minimum generation in megawatts for resource k in month m.

M^k: Set of months m for energy limited resource k is available for use.

S^k: Set of plants immediately upstream of plant k.

$P_{\delta SpillMax}$: *Penalty assigned to slack variable* $\delta SpillMax$ in price format (dollars per kcfs).

$P_{\delta SpillMin}$: *Penalty assigned to slack variable* $\delta SpillMin$ in price format (dollars per kcfs).

$WT^k(x)$: *Price in \$ per MW of wear and tear costs associated with moving a plant through its range or demand charge on the market to meet some system requirement x.*

$VOM^k(i)$: *Variable operations and maintenance costs for resource k in hour i.*

$F^k_m(i,)$: Fuel conversion curve in month m for resource k for translating energy (MWh) to fuel f (MMBtu or hydro volume) in hour i.

For thermal resources, this will be a piecewise linear representation of a polynomial or a constant function. For energy limited resources, market resources and variable energy resources, this will be constant function initially.

<u>A note about “H over K”</u>

For a hydropower resource k, this might be a function of the tailwater and forebay height differential. For those resources the estimates will improve per the forecast period and flow information. The goal is to get this close enough to not massively overestimate or underestimate flows required to produce at a particular generation level.

The proposed method of determining this value in an hour i is to use a lookup from a set of forebay and tailwater tables that list observed level changes per flow through the dam *(from generation or spill). From here there will be some uncertainty about hourly flow levels to provide the target generation. Normally this would be an iterative process where one would guess at the flow required at a particular dam to generate a certain amount of power, but due to changing forebay and tailwater levels the guess at how much flow is needed to produce a certain amount of power out of the system will likely be wrong. One then, iterates using a method that tends toward convergence on flows required to produce energy from the system.*

Since this is a multi-stage model, knowing exactly how much flow is required to generate a certain amount from the hydro system is not required in the first part of the day-ahead commitment stage. The idea being that we assume the system can provide the power for commitment in the day-ahead commitment stage in the first hour, then observe the flows required to generate that power, and update the H/K guess for the second hour and so forth.

Then, by the time we get to the end of the day-ahead stage, we will have a better idea of what flows will be associated with the desired system generation. Furthermore, additional error will be reduced when in the hour-ahead commitment stage, so by the time we get to within-hour actual flows and generation, the uncertainty will be in the noise.

$FuelSched^k(i)$:

Let *FuelSched* be the period over which a fuel schedule for a committed resource *k* in hour *i* must utilized, within a tolerance. For example, for a gas resource this might be a daily nomination schedule, but for a cascading hydro resource this may be a volumetric representation of a particular target elevation established by a previous model stage.

$SpillSched^k(a)$:

Let *SpillSched(a)* be the period over which a spill schedule *a* must be met by resource *k* within a tolerance (see definitions of the spill slack variables). This allows for multiple spill schedules for a particular resource.

$Draft_m$: The amount over a daily gas nomination in a given month *m* that can be withdrawn from a pipeline. Note that this may be the same as *UnscheduledPipelineMax*.

$Pack_m$: The amount under a daily gas nomination in a given month *m* that can be packed from a pipeline. Note that this is not likely the same as *UnscheduledPipelineMin* which is likely 0.

$SchedFuelMax^k(i)$:

Maximum fuel usage per schedule over number of hours *FuelSched*^{k}*(i)* or hour *i*, coming into hourly commitment stage. For gas, this will be the daily fuel allotted (per daily nomination schedule from the day-ahead schedule of energy for the model) and this would be the equivalent of the scheduled gas plus the drafting limit. In the case of a combined cycle gas unit this would look like

Equation 1 - Scheduled Fuel Max Definition for Gas Resources

$$
\begin{aligned}
SchedFuelMax^k\left(FuelSched^k\right) &= \left(\mathrm{F^k}_{\mathrm{m}}(\mathrm{i}) * \mathrm{EnergyMax^k}_{\mathrm{DA}}\left(\mathrm{GRA^k}(\mathrm{x},\mathrm{i})\right) + Draft_m\right) * \ \mathrm{Committed^k}(\mathrm{i},\mathrm{DA}) \\
&+ UnscheduledPipelineMax * (1 - \ \mathrm{Committed^k}(\mathrm{i},\mathrm{DA}))
\end{aligned}
$$

SchedFuelMin^k*(i)*:

Minimum fuel usage per schedule over number of hours *FuelSched*^{k}*(i)*, or hour *i,* coming into hourly commitment stage. For gas, this will be the daily fuel allotted (per daily nomination schedule from the day-ahead schedule of energy for the model) and this would be the equivalent of the scheduled gas minus the packing limit. In the case of a combined cycle gas unit this would look like

Equation 2 - Scheduled Fuel Min Definition for Gas Resources

$$
\begin{aligned}
SchedFuelMin^k\left(FuelSched^k\right) &= \left(\mathrm{F^k}_{\mathrm{m}}(\mathrm{i}) * \mathrm{EnergyMin^k}_{\mathrm{DA}}\left(\mathrm{GRA^k}(\mathrm{x},\mathrm{i})\right) + Pack_m\right) * \ \mathrm{Committed^k}(\mathrm{i},\mathrm{DA}) \\
&+ UnscheduledPipelineMin * (1 - \ \mathrm{Committed^k}(\mathrm{i},\mathrm{DA}))
\end{aligned}
$$

SpillMax^k*(SpillSched*^{k}*(a))*:

Maximum spill allowed over the number of hours defined by *SpillSched*^{k}*(a)*, coming into the hourly commitment stage. For hydro, *SpillSched*^{k}*(a)* will be a variable per different non-power requirements.

SpillMin^k*(SpillSched*^{k}*(a))*:

Minimum spill required over a number of hours defined by *SpillSched*^{k}*(a)*, coming into hourly commitment stage. *SpillSched*^{k}*(a)* will be a variable per different non-power requirements.

ConBlkSize(X^k*)*:

The contract block size available for purchasing or selling in a market *k*.

$RangeLimit^k_m(x,i)$:

Maximum dynamic capability for attribute or multiple attributes, *x*, in month *m* and hour *i,* on resource *k*. This can be used to control the maximum amount of a particular set of attributes for transmission and/or generator constraints.

$SideFlows(k,i)$:

This parameter represents flows from streams/rivers/non-modeled hydro plants (in kcfs) into the reservoir directly behind plant *k* in hour *i*.

$MinUpTime^k_m$:

The minimum up time in period *m*, for committed resource *k*.

$MinDownTime^k_m$:

The minimum down time in period *m*, for committed resource *k*.

$ActualEnergy^k(i)$:

The actual generation limit of a wind or solar unit *k* in hour *i*.

$ActualFuel^k(i)$:

The actual fuel usage of a thermal plant unit *k* in hour *i*.

12 Decision Variable Definitions

$Perc^k(x,i)$:	*Percentage of system requirement x that is met in hour I, by generator k. Note that by definition,* $\mathrm{Perc}^{\mathrm{k}}(\mathrm{x},\mathrm{i}) \in [0,1]$.
$RunCount^k$:	*This variable keeps track of the consecutive hours for which a resource is committed.*
$EOM_m(i)$:	This variable is a counter to be used as a way of hours until the end of the month *m* in terms of hour *i*.

Equation 3 – End Of Month Counter Definition

$$\mathrm{EOM_m(i)} = \begin{cases} 31 * 24 - \mathrm{i}, & \text{for } \mathrm{m} = 1,3,4,6,10,11,12 \\ 30 * 24 - \mathrm{i}, & \text{for } \mathrm{m} = 2,7,8,9 \\ 28 * 24 - \mathrm{i}, & \text{for } \mathrm{m} = 5 \end{cases}$$

$P_f(i,)$:	*Price of f, which could be fuel for a generator or the market electricity price in hour i. For market resources, there will also be an uncertainty parameter* Φ to indicate uncertainty in prices.

For hydropower resources price will be explicitly passed from the previous stage (resource stacking stages), or implicitly valued by using a rolling time frame (constrained optimization unit commitment stages). If this variable looks like $P_f(i,\Phi)^*$ *then the fuel f in the subscript is referring to the market at which this resource will be evaluated. This is primarily used in Future Value functions for cascading hydro and demand response resources.*

$I^k(x)$: Indicator function for resource *k* that is 1 when the resource is capable of providing attribute *x* and 0 when it is incapable. Functionally, this is a switch that defines which resources can provide which attributes. For example, this vector of 1's and 0's would delineate if a resource could provide energy and hold imbalance reserves, but maybe cannot ramp fast enough to provide regulation and contingency reserves.

$J^k(m)$: Indicator function for resource *k* that indicates which set of months M^k the resource is available.

Equation 4 - Seasonal Indicator of Availability of Energy Limited Resource.

$$\mathrm{J}^k(m) = \begin{cases} 1, & m \epsilon M^k \\ 0, & m \epsilon \left(M^k\right)^C \end{cases}$$

$FOR^k(i)$: *This is a proxy for a forced outage parameter (or set of parameters) that will represent* forced outages on resource k, in hour *i,* in the within-hour deployment. When a unit is forced out in the within-hour deployment then this percentage will be unavailable until it is fixed. Each plant could have a slightly different forced outage calculation based on partial outages (individual turbine outages). Mean time to repair distributions are a way to calculate when an outage might occur and how long it might last. There could be a different distribution for each unit commitment forecast period to represent uncertainty on when a plant might come back after an outage.

$Maint^k(i)$: This represents a percentage of the plant that is unavailable due to scheduled maintenance.

$Avail^k(i)$: This represents the percentage of the plant available after forced and maintenance outages.

Equation 5 – Availability Multiplier Definition

The availability multiplier is a function of a stochastic forced outage and scheduled maintenance outage.

$$\mathrm{Avail^k(i)} = \left(1 - \mathrm{FOR^k(i)}\right) * \left(1 - \mathrm{Maint^k(i)}\right)$$

$ResVol^k(i)$: Reservoir (forebay) volume available to plant *k* in hour *i*.

$Req(x,i)$: *The amount of system requirement x (in MW), like load or reserves, to be met in hour i.*

$GRA^k(x,i)$: Generator range attribute (in MW of range) providing system requirement *x* with resource *k* and hour *i*. These attributes include contingency reserves (spinning and supplementary reserves) and operating reserves (imbalance reserves and regulation). There are currently assumed to be up to 7 different, separable range attributes that can be assigned a generator.

Equation 6 – Generator Range Attribute Definition

The amount of MW range assigned to a generator to meet system requirement *x* for resource *k* in hour *i* are determined by assigning a percentage of the total system requirement *x* to that generator.

$$\mathrm{GRA}^k\big(x,i\big) = I^k\big(x\big) * \mathrm{Avail}^k\big(i\big) * \mathrm{Perc}^k\big(x,i\big) * \mathrm{Req}(x,i)$$

$Committed^k(i,)$:

The resource k is committed (heuristic for fueling purposes and market obligation) in hour i. This will be calculated at the previous stage and passed to the next stage.

Equation 7 - Commitment index definition

A nuclear or coal resource k is committed in the weekly stage and must be run for at least that entire week when committed. Define market resource k as committed for notation convenience, since a weekly market purchase must be purchased on or off-peak power purchase/sale obligation for such periods in the week.

$$\mathrm{Committed}^k(i,\mathrm{WA}) = \begin{cases} 1, & \text{if } \mathrm{GRA}^k(x,i) > 0, \text{for } x \in \{1,2,3,4,5,6,7\} \\ 0, & \text{if } \mathrm{GRA}^k(x,i) = 0, \text{for } x \in \{1,2,3,4,5,6,7\} \end{cases}$$

Combined cycle gas resource k is committed in the day-ahead stage and must be run within the draft and pack limits, min up and min down times and fuel constraints for all days in which they are committed. Define market resource k as committed for notation convenience, since a daily market purchase must be purchased as an on or off-peak power purchase or sale obligation for a day. Some energy limited resources like demand response may also be necessary to commit day-ahead.

$$\mathrm{Committed}^k(i,\mathrm{DA}) = \begin{cases} 1, & \text{if } \mathrm{GRA}^k(x,i) > 0, \text{for } x \in \{1,2,3,4,5,6,7\} \\ 0, & \text{if } \mathrm{GRA}^k(x,i) = 0, \text{for } x \in \{1,2,3,4,5,6,7\} \end{cases}$$

Peaker gas resource k is committed in the hour-ahead stage and must be run within the draft and pack limits, min up and min down times and fuel constraints for all days in which *they are committed. Define market resource k as committed for notation convenience, since an hourly spot market purchase or sale is then an obligation for the hour. Note that peakers might be available for non-spinning reserve whether committed or not. Some energy limited resources like demand response may also be necessary to commit hour-ahead.*

$$\mathrm{Committed}^{k}(\mathrm{i},\mathrm{HA}) = \begin{cases} 1, & \text{if } \mathrm{GRA}^{k}(\mathrm{x},\mathrm{i}) > 0, \text{for } \mathrm{x} \in \{1,2,3,4,5,6\} \\ 0, & \text{if } \mathrm{GRA}^{k}(\mathrm{x},\mathrm{i}) = 0, \text{for } \mathrm{x} \in \{1,2,3,4,5,6\} \end{cases}$$

CommittedGRA^k(x,i,):

Generator range attribute *GRA^k(x,i)* defined as from a previous commitment stage WA (Week-Ahead), DA (Day-Ahead), or HA (Hour-Ahead). Some attributes will be fixed and must be accounted correctly. This will be calculated at the previous stage and passed to the next stage.

Market Purchases Example

If in the day-ahead commitment stage, the 25 MW on-peak purchase would be part of the market position of the portfolio during the hourly commitment stage. In the case of the market, the total transfer capability available to the hour ahead market would be 25 MW less.

Committed Unit Example

If in the weekly unit commitment stage, a 600 MW coal plant is committed. In the day-ahead and hour ahead unit commitment stages, the plant may be cycled within its range, but not turned off. In other words, at the very least, the minimum generation of the coal plant becomes part of the portfolio position in the day-ahead, hour-ahead and deployment stages, no matter how disadvantageous.

Emergency commitment in hour-ahead to make up for forced outages, check full system capability with committed units, if not met then full system check with all non-nuclear resources considered for emergency commitment. Respect startup time. This may work for gas plants within the draft and pack limits set by the fuel limitations.

Equation 8 - Committed Capacity from Previous Stage Definition

$$\mathrm{CommittedGRA}^{k}\left(\mathrm{x,\,i,\,WA}\right) = \mathrm{Committed}^{k}\left(\mathrm{i,\,WA}\right) * \mathrm{GRA}^{k}\left(\mathrm{x,\,i}\right)$$

$$\mathrm{CommittedGRA}^{k}\left(\mathrm{x,\,i,\,DA}\right) = \mathrm{Committed}^{k}\left(\mathrm{i,\,DA}\right) * \mathrm{GRA}^{k}\left(\mathrm{x,\,i}\right) + \mathrm{CommittedGRA}^{k}\left(\mathrm{x,\,i,\,WA}\right)$$

$$\begin{aligned}\mathrm{CommittedGRA}^{\mathrm{k}}(\mathrm{x, i, HA}) \\ &= \mathrm{Committed}^{\mathrm{k}}(\mathrm{i, HA}) * \mathrm{GRA}^{\mathrm{k}}(\mathrm{x, i}) + \mathrm{CommittedGRA}^{\mathrm{k}}(\mathrm{x, i, WA}) \\ &+ \mathrm{CommittedGRA}^{\mathrm{k}}(\mathrm{x, i, DA})\end{aligned}$$

__Energy Variables__

Since during the commitment stages, the energy associated with providing an intra-hour system requirement (2 through 7) is uncertain. For regulation and imbalance/load following a planner must allow for enough fuel to provide the service at any time during the hour, and also allow for the fact that the service may not be called upon within the hour. In the within hour deployment, a percentage of the energy planned for will actually be generated. This will be determined stochastically.

Equation 9 – Energy Scheduled/Generated Definitions

$\mathit{Energy}^{k}(\mathit{GRA}^{k}(x,))$:

*The energy produced in MWh that is associated with holding a range GRA (in MW) on a generator k associated with meeting system requirement x. This is probabilistic and only used in the **within-hour** deployment stage.*

$$\mathrm{Energy}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i})\right) = \begin{cases} \mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i}), \text{for } \mathrm{x} = 1 \\ \%(\mathrm{x}) * \mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i}), \quad for\ x \in \{2,3,4,5\} \\ \%(\mathrm{x}) * \mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i}) * (\text{indicator of FO}), \text{for } \mathrm{x} \in \{6,7\} \end{cases}$$

$\mathit{EnergyMax}^{k}_{DA}(\mathit{GRA}^{k}(x,i))$:

*The maximum energy in MWh that is associated with, scheduling **day-ahead**, a range GRA (in MW) on a generator k associated with meeting system requirement x. This is deterministic and only used to correctly account for the maximum fuel needed for a committed resource k.*

$$\mathrm{EnergyMax}^{\mathrm{k}}{}_{\mathrm{DA}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i})\right) = \mathrm{GRA}^{\mathrm{k}}(\mathrm{x,i}), \forall \mathrm{x}$$

$\mathit{EnergyMin}^{k}_{DA}(\mathit{GRA}^{k}(x,i))$:

*The minimum energy in MWh that is associated with, scheduling **day-ahead**, a range GRA (in MW) on a generator k associated with meeting system requirement x. This is deterministic and only used to correctly account for the minimum fuel needed for a committed resource k.*

$$\mathrm{EnergyMin^k}_{\mathrm{DA}}\left(\mathrm{GRA^k(x,i)}\right) = 0, \forall \mathrm{x} \in \{2,3,4,5,6,7\}$$

$$\mathrm{EnergyMin^k}_{\mathrm{HA}}\left(\mathrm{GRA^k(x,i)}\right) = \mathrm{GRA^k(x,i)}, \text{for } \mathrm{x} = 1$$

$EnergyMax^k{}_{HA}(GRA^k(x,i))$:

*The maximum energy in MWh that is associated with, scheduling **hour-ahead**, a range GRA (in MW) on a generator k associated with meeting system requirement x. This is deterministic and only used to correctly account for the maximum fuel needed for a committed resource k.*

$$\mathrm{EnergyMax^k}_{\mathrm{HA}}\left(\mathrm{GRA^k(x,i)}\right) = \mathrm{GRA^k(x,i)}, \forall \mathrm{x}$$

$EnergyMin^k{}_{HA}(GRA^k(x,i))$:

*The minimum energy in MWh that is associated with, scheduling **hour-ahead**, a range GRA (in MW) on a generator k associated with meeting system requirement x. This is deterministic and only used to correctly account for the minimum fuel needed for a committed resource k.*

$$\mathrm{EnergyMin^k}_{\mathrm{HA}}\left(\mathrm{GRA^k(x,i)}\right) = 0, \forall \mathrm{x} \in \{2,3,4,5,6,7\}$$

$$\mathrm{EnergyMin^k}_{\mathrm{HA}}\left(\mathrm{GRA^k(x,i)}\right) = \mathrm{GRA^k(x,i)}, \text{for } \mathrm{x} = 1$$

$TotalSpill^k(i)$: Total amount of spill from resource *k* in hour *i*.

Outf(k,i): This parameter represents actual or scheduled outflows (i.e. discharge in kcfs) of plant *k* in hour *i*.

Equation 10 – Outflows Definition

Outflows for plant *k* in hour *i* are calculated by converting the energy to flow and summing with spill.

$$Outf(k,i) = \sum_{\mathrm{x}=1}^{7} \mathrm{F^k}_{\mathrm{m}}(\mathrm{i}) * \mathrm{Energy^k}\left(\mathrm{GRA^k(x,i)}\right) + \mathrm{TotalSpill^k(i)}$$

$$Outf_{Max}(k,i) = \sum_{x=1}^{7} \mathrm{F^k}_{\mathrm{m}}(\mathrm{i}) * \mathrm{EnergyMax^k}\left(\mathrm{GRA^k}(\mathrm{x},\mathrm{i})\right) + \mathrm{TotalSpill^k}(\mathrm{i})$$

$$Outf_{Min}(k,i) = \sum_{x=1}^{7} \mathrm{F^k}_{\mathrm{m}}(\mathrm{i}) * \mathrm{EnergyMin^k}\left(\mathrm{GRA^k}(\mathrm{x},\mathrm{i})\right) + \mathrm{TotalSpill^k}(\mathrm{i})$$

$\omega^k(m,i)$: This is an hour counter (a cumulative sum of hours within a particular period) that keeping track of how many hours an energy limited resource *k* dispatches in a particular period *m*.

Equation 11 – Energy-Limited Resource Hour Counter Definition

If energy limited plant is dispatched/utilized there may be a limit to the number of total dispatches in a season, so a counter is needed.

$$\omega^k(m,i) = \begin{cases} \omega^k(m,i-1)+1, \mathrm{Energy^k}\left(\mathrm{GRA^k}\left(\mathrm{x},\omega^k(m,i-1)\right)\right) \neq 0, \forall i \\ \omega^k(m,i-1),\ \ \mathrm{Energy^k}\left(\mathrm{GRA^k}\left(\mathrm{x},\omega^k(m,i-1)\right)\right) = 0, \forall i \end{cases}$$

$PlantOn^k(i,)$: This is an indicator function that determines if the plant *k* is turned on in hour *i* for model stage Day-Ahead (*DA*) or Hour-Ahead (*HA*).

Equation 12 – Plant Online Definition

If the plant is on in a previous hour, it does not need to be charged startup costs.

$$PlantOn^k(i,) = \begin{cases} 1,\ \mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) > 0 \text{ and } \mathrm{x}\ \in \{1,2,3,4,5\} \\ 0,\ \mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) = 0 \text{ and } \mathrm{x}\ \in \{1,2,3,4,5\} \end{cases}$$

$OnlineHours^k(i)$:

This is a running tally of how long a plant has been generating in its current cycle.

$$OnlineHours^k(i+1) = PlantOn^k(i+1) * \left(PlantOn^k(i+1) + OnlineHours^k(i)\right), \forall i$$

$OfflineHours^k(i)$:

This is a running tally of how long a plant has not been generating in its current cycle.

$$\begin{aligned} OfflineHours^k(i+1) \\ &= \left(1 - PlantOn^k(i+1)\right) \\ &* \left(\left(1 - PlantOn^k(i+1)\right) + OfflineHours^k(i)\right), \forall i \end{aligned}$$

$StartupC^k_m$: Startup costs in month *m* for resource *k* in $ per start.

FV^k(T,):

The future value of any resource k (definitely applies to cascading hydro resources) past the optimization window of length T accounts for the value of generating in a period after T, if the decision to store the fuel is made within the optimization window of length T. For cascading hydro resources the value of downstream generation should be accounted for when choosing to generate using hydro stored behind a particular plant k.

For a hydro plant k, the future value might look like the following equation. In this case the expected fuel conversions (akin to H over K) might be persistence based, the market price might be from Aurora, the expected energy usage from previous stage.

Equation 13 – Future Value Function Definition for Hydro Resources

$$\mathrm{FV}^{\mathrm{k}}\left(\mathrm{T},\mathrm{DWN}^{\mathrm{k}},\phi\right)=\sum_{\mathrm{j=T+1}}^{\mathrm{Target}}\sum_{\mathrm{k\in DWN^k}}\sum_{\mathrm{x=1}}^{7}\left(\mathrm{Exp}\left[\mathrm{P_f}(\mathrm{i},\phi)^{*}\right]\right)*\mathrm{Exp}\left[\mathrm{F^k}_{\mathrm{m}}(\mathrm{j})\right]*\mathrm{Exp}\left[\left[\mathrm{Energy^k}_{\mathrm{DA}}\left(\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i})\right)\right]\right]$$

$$\mathrm{FV}^{\mathrm{k}}\left(\mathrm{T},\mathrm{DWN}^{\mathrm{k}},\phi\right)=\sum_{\mathrm{j=T+1}}^{\mathrm{Target}}\sum_{\mathrm{k\in DWN^k}}\sum_{\mathrm{x=1}}^{7}\left(\mathrm{Exp}\left[\mathrm{P_f}(\mathrm{i},\phi)^{*}\right]\right)*\mathrm{Exp}\left[\mathrm{F^k}_{\mathrm{m}}(\mathrm{j})\right]*\mathrm{Exp}\left[\left[\mathrm{Energy^k}_{\mathrm{HA}}\left(\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i})\right)\right]\right]$$

Equation 14 - Future Value Function Definition for Energy Limited Resources with Max Dispatch Hours

$$\begin{aligned}&\mathrm{FV}^{\mathrm{k}}\left(\mathrm{T},\omega^{k}(m,),\phi\right)\\&\quad=\sum_{\mathrm{j=T+1}}^{\mathrm{EOM_m}}\sum_{\mathrm{x=1}}^{7}\left(\mathrm{Exp}\left[\mathrm{P_f}(\mathrm{i},\phi)^{*}\right]-\mathrm{P_f}(\mathrm{i})\right)*\left(\Omega^{k}(m,\omega)-\omega^{k}(m,j)\right)\\&\quad*\mathrm{Exp}\left[\mathrm{Energy^k}_{\mathrm{DA}}\left(\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i})\right)\right]\end{aligned}$$

$$\begin{aligned}&\mathrm{FV}^{\mathrm{k}}\left(\mathrm{T},\omega^{k}(m,),\phi\right)\\&\quad=\sum_{\mathrm{j=T+1}}^{\mathrm{EOM_m}}\sum_{\mathrm{x=1}}^{7}\left(\mathrm{Exp}\left[\mathrm{P_f}(\mathrm{i},\phi)^{*}\right]-\mathrm{P_f}(\mathrm{i})\right)*\left(\Omega^{k}(m,\omega)-\omega^{k}(m,j)\right)\\&\quad*\mathrm{Exp}\left[\mathrm{Energy^k}_{\mathrm{HA}}\left(\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x},\mathrm{i})\right)\right]\end{aligned}$$

Cost^k(i,ϕ): Actual or projected cost to run generator, commit resource, or buy and sell from market *k* in hour *i*. This cost may depend on uncertainty in market price φ.

Equation 15 – Resource Cost Definitions

The projected resource cost for each resource k in each unit commitment stage is used by the objective function to minimize cost and determine an operating strategy, and market purchases and sales. However, with the exception of market purchases and sales, which accrues between stages, the actual resource cost cannot be evaluated in full until the within hour deployment.

The following is true for all k,

1. Cascading Hydro Resource *k*:

Note that due to the value of storage (i.e. future value of hydro) resources will be evaluated in the *FV^k(T,) function which net against costs in the objective function:*

a. Day-Ahead Commitment Stage:

$$
\begin{aligned}
Cost^{k}(\mathrm{i}) = \mathrm{VOM^{k}(i)} & \\
& * \sum_{\mathrm{x=1}}^{7}\left[\mathrm{EnergyMin^{k}}_{\mathrm{DA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right)\right. \\
& \left. + \left(\frac{\mathrm{EnergyMax^{k}}_{\mathrm{DA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right) - \mathrm{EnergyMin^{k}}_{\mathrm{DA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right)}{2}\right)\right] \\
& + \sum_{\mathrm{x=2}}^{7} \mathrm{WT^{k}(x)} * \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i}) + \mathrm{StartupC^{k}}_{\mathrm{m}} * (\mathrm{PlantOn^{k}(i)} \\
& - \mathrm{PlantOn^{k}(i-1)}) + \mathrm{P}_{\mathrm{\delta SpillMax}} * \mathrm{\delta SpillMax(k,i)} + \mathrm{P}_{\mathrm{\delta SpillMin}} \\
& * \mathrm{\delta SpillMin(k,i)}
\end{aligned}
$$

b. *Hour-Ahead Commitment Stage:*

$$
\begin{aligned}
Cost^{k}(\mathrm{i}) = \mathrm{VOM^{k}(i)} & \\
& * \sum_{\mathrm{x=1}}^{7}\left[\mathrm{EnergyMin^{k}}_{\mathrm{HA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right)\right. \\
& \left. + \left(\frac{\mathrm{EnergyMax^{k}}_{\mathrm{HA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right) - \mathrm{EnergyMin^{k}}_{\mathrm{HA}}\left(\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i})\right)}{2}\right)\right] \\
& + \sum_{\mathrm{x=2}}^{7} \mathrm{WT^{k}(x)} * \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x,i}) + \mathrm{StartupC^{k}}_{\mathrm{m}} * (\mathrm{PlantOn^{k}(i)} \\
& - \mathrm{PlantOn^{k}(i-1)}) + P_{\delta SpillMax} * \delta SpillMax(k,i) + P_{\delta SpillMin} \\
& * \delta SpillMin(k,i)
\end{aligned}
$$

2. *Market Resource k:*

$$Cost^{k}(\mathrm{i},\phi) = (\mathrm{P_f}(\mathrm{i},\phi)) * \sum_{\mathrm{x}=1}^{7} \mathrm{Energy}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{i})\right) + \sum_{\mathrm{x}=2}^{7} \mathrm{WT}^{\mathrm{k}}(\mathrm{x}) * \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i})$$

Note that in this case the wear and tear costs substitute for a demand charge on the market.

3. Thermal, Energy-Limited, Must Run and Variable Energy Resource *k*:

$$\begin{aligned} Cost^{k}(\mathrm{i}) = (\mathrm{P_f}(\mathrm{i},)) * \sum_{\mathrm{x}=1}^{7} \mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{i}) * \mathrm{Energy}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{i})\right) + \mathrm{VOM}^{\mathrm{k}}(\mathrm{i}) \\ * \sum_{\mathrm{x}=1}^{7} \mathrm{Energy}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i})\right) + \sum_{\mathrm{x}=2}^{7} \mathrm{WT}^{\mathrm{k}}(\mathrm{x}) * \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \\ + \mathrm{StartupC}^{\mathrm{k}}{}_{\mathrm{m}} * PlantOn^{k}(i) \end{aligned}$$

ForecastEnergy^{k}*(i, Δ)*:

The available energy in hour *i* for dispatch on a variable energy resource *k*. The forecast error or uncertainty term, *Δ,* defined for the day-ahead and hour-ahead unit commitment stages modifies the wind. In the within hour deployment stage of the model, the actual fuel for the unit (wind or sun) is available and known. This is defined to be an upper limit of generation for the wind or solar unit.

Equation 16 – Available Energy for Variable Energy Resource Definition

$$ForecastEnergy^{k}(i,\Delta) = \begin{cases} ActualEnergy^{k}(i) + \Delta^{k}{}_{DA}(i), & for\ the\ Day\ Ahead\ Commitment\ Stage \\ ActualEnergy^{k}(i) + \Delta^{k}{}_{HA}(i), & for\ the\ Hour\ Ahead\ Commitment\ Stage \\ ActualEnergy^{k}(i), & for\ the\ Within\ Hour\ True\ Up\ Stage \end{cases}$$

MaxAvailEnergy^{k}*(m,ω,i)*:

The maximum available energy in hour *i* during period *m* for dispatch on energy limited resource *k*.

FDD(ResVol(k,i)):

Forebay drawdown for a particular plant *k* in an hour *i* is a polynomial function (or piecewise linear function approximation) depending on the previous hour's reservoir volume. Currently, only known requirement for Grand Coulee forebay.

Equation 17 – Forebay Drawdown Function Definition

This is a forebay drawdown function controlling the rate of drawdown from hour to hour.

$$ResVol(k,i+1) = FDD(ResVol(k,i))$$

DisRate(Outf(k,i)):

Discharge rate for a particular plant *k* in an hour *I* is a polynomial function (or piecewise linear function approximation) depending on the previous hour's outflow. Currently, only known requirement for Bonneville tailwater.

Equation 18 – Tailwater Rate Of Change Function Definition

This is a tailwater rate of change function that controls discharge rate from hour to hour.

$$Outf(k,i+1) = DisRate(Outf(k,i))$$

$DisPerc_m(k)$: Percent of total discharge of the plant *k* in period *m* that is dedicated to spill.

ResVolMax(k,i):

Maximum allowed reservoir volume (in ksfd) for hydro resource *k* in hour *i*. This maximum limit will enforce target elevation/volume ranges within the day-ahead and hour-ahead unit commitment stages.

ResVolMin(k,i):

Minimum allowed reservoir volume (in ksfd) for hydro resource *k* in hour *i*. This maximum limit will enforce target elevation/volume ranges within the day-ahead and hour-ahead unit commitment stages.

12.1.1.1.1 Slack Variables

δDisMin(k,i):

Slack variable associated with minimum total outflow of the plant *k* in hour *i*.

δSpillMin(k,i):

Slack variable associated with minimum spill of the plant *k* in hour *i*. Since the minimum spill to satisfy BiOp are not guaranteed but desired, this allows the objective function to be penalized if not met.

δSpillMax(k,i):

Slack variable associated with maximum spill of the plant *k* in hour *i*. Since the maximum spill satisfying the BiOp are not guaranteed but desired, this allows the objective function to be penalized if not met.

13 Resource Constraints General

In addition, for the sake of ease assume the constraints below apply to all resources. Resources that have been committed in a previous stage will need to also satisfy the following criteria. This could be generalized with a commitment indicator function.

Equation 19 – General Committed Generator Minimum Generation Requirement

If a generator is committed and utilized before than the energy generated must be greater than the minimum generation of the unit. If the generator is committed for non-spinning reserve, the unit is not required to be at minimum generation.

$$\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x},\mathrm{i}\right) \geq Min^{k}{}_{m}, \forall i\ AND\ \exists\ CommittedGRA^{k}{}_{m}\left(x, i, \right) > 0\ for\ x \in \left\{1,2,3,4,5,6\right\}$$

Equation 20 - Minimum Up Time Constraint

$$PlantOn^{k}(i,) * MinUpTime^{k} \leq Max(PlantOn^{k}(i,), \dots, PlantOn^{k}\left(i + MinUpTime^{k},\right))$$

Equation 21 - Minimum Down Time Constraint

$$\left(1 - PlantOn^{k}(i,)\right) * MinDownTime^{k} \leq Max\left[\left(1 - PlantOn^{k}(i,)\right), \dots, \left(1 - PlantOn^{k}\left(i + MinDownTime^{k},\right)\right)\right] \forall i$$

14 Day-Ahead Commitment

In the day-ahead unit commitment stage, the minimization of cost achieves a unit commitment of combined cycle gas units, on and off-peak day-ahead market purchases and sales, and a forecast of hourly hydro flows for the next week.

14.1 Thermal Generator Constraints

14.1.1.1 Operating Range Constraints

These constraints refer to the machine capability of the thermal plants which can be fuel limited.

Equation 22 – Total Generator Range Attribute Max Limitation for Thermal Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq Max^{k}{}_{m}, \forall i$$

Equation 23 – Individual Thermal Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

14.1.1.2 Fuel Constraints

In the day-ahead stage, the fuel limitations are likely to only be based on the size of the pipeline to a plant or based on fuel ordered for previously committed plants.

Equation 24 – Maximum Daily Fuel Usage Limitation for Thermal Resources

When meeting system requirements, the generator must not use more fuel than was scheduled.

$$SchedFuelMax^{k}\left(FuelSched^{k}\right) \geq \sum_{j=1}^{i}\sum_{x=1}^{7}\left(\mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMax}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right)\right) + \sum_{r=1}^{j}\mathrm{ActualFuel}^{k}(r),$$

$$\forall i \leq FuelSched^{k}$$

Equation 25– Minimum Daily Fuel Usage Limitation

When meeting system requirements, the generator must not produce less fuel than was scheduled.

$$SchedFuelMin^{k}\left(FuelSched^{k}\right) \leq \sum_{j=1}^{i}\sum_{x=1}^{7}\left(\mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMin}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right)\right) + \sum_{r=1}^{j}\mathrm{ActualFuel}^{k}(r),$$

$$\forall i \ \leq FuelSched^{k}$$

14.1.1.2.1 Commitment Constraints

Equation 26 – Minimum Committed Thermal Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7}\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \geq Min^{k}{}_{m}, if \ \exists x \ such \ that \ CommittedGRA^{k}{}_{m}(x,i,) > 0, \forall i$$

Equation 27 – Uncommitted Thermal Generation Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{\mathrm{x}=1}^{7}\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) = 0, if \sum_{x=1}^{7} CommittedGRA^{k}{}_{m}(x,i,) = 0, \forall i$$

14.2 Cascading Hydro Generator Constraints

14.2.1 Generator Operating Range Constraints

These constraints refer to the machine capability of the hydropower plants which are fuel limited.

Equation 28 – Total Generator Range Attribute Max Limitation for Cascading Hydro Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{k}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq Max^{k}{}_{m}, \forall i$$

Equation 29 – Individual Cascading Hydro Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i)\ , \forall i$$

14.2.2 Fuel Constraints

- If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour.

Equation 30 - Maximum Daily Fuel Usage Limitation for Cascading Hydro Resources

In general, when meeting system requirements, the generator must not use more fuel than was scheduled. If hydropower plant drafts outside the maximum of the range that is calculated in previous stages to reach particular elevation/volume targets it will do it at a steep penalty that can be enforced by the slack variable.

$$SchedFuelMax^{k}(i) \geq \sum_{j=1}^{i}\sum_{\mathrm{x}=1}^{7}\left(\mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMax}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right)\right) + \mathrm{TotalSpill}^{\mathrm{k}}(\mathrm{j}) + \sum_{r=1}^{j}\mathrm{Outf}^{\mathrm{k}}(\mathrm{r}) - \delta SpillMax(k,i)\ ,$$

$$\forall i \leq FuelSched^{k}$$

Equation 31 – Minimum Daily Fuel Usage Limitation for Cascading Hydro Resources

In general, when meeting system requirements, the generator must not use less fuel than was scheduled. If hydropower plant drafts less than the minimum of the range that is calculated in previous stages to reach particular elevation/volume targets it will do it at a steep penalty that can be enforced by the slack variable.

$$SchedFuelMin^{k}(i) \leq \sum_{j=1}^{i}\sum_{x=1}^{7}\left(\mathrm{F^{k}}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMin^{k}}\left(\mathrm{GRA^{k}}(\mathrm{x},\mathrm{j})\right)\right) + \mathrm{TotalSpill^{k}}(\mathrm{j}) + \sum_{r=1}^{j}\mathrm{Outf^{k}}(\mathrm{r}) - \delta SpillMin(k,i), \quad \forall i \leq FuelSched^{k}$$

14.2.2.1.1 Total Discharge

Equation 32 – Maximum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be under the maximum allowed in the fish and wildlife constraints. If a plant spills more than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMax^{k}\left(SpillSched^{k}(a)\right) \geq \sum_{j=1}^{i}\mathrm{TotalSpill^{k}}(\mathrm{j}) - \delta SpillMax(k,i), \ \forall i \leq SpillSched^{k}(a)$$

Equation 33 – Minimum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be over the minimum allowed in the fish and wildlife constraints. If a plant spills less than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMin^{k}\left(SpillSched^{k}(a)\right) \leq \sum_{j=1}^{i}\mathrm{TotalSpill^{k}}(\mathrm{j}) - \delta SpillMin(k,i), \forall i \leq SpillSched^{k}(a)$$

Equation 34 – Total Spill Percent of Outflow Constraint

Total spill at a plant must be greater than or equal to a particular percentage of the total plant outflow.

$$TotalSpill^{k}(i) \geq \begin{cases} 0, if\ TotalSpill^{k}(i) > SpillMax^{k} \\ DisPerc_{m}(k) * \left(Outf(k,i)\right), if\ TotalSpill^{k}(i) \leq SpillMax^{k} \end{cases}$$

14.2.3 Commitment Constraints

Equation 35– Committed Cascading Hydro Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7}\mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \geq Min^{k}{}_{m}, if\ \exists\ CommittedGRA^{k}{}_{m}(x,i,) > 0, \forall i$$

Equation 36 – Uncommitted Cascading Hydro Generation Constraint

The generator may not account for meeting most system requirements if not committed.

$$\sum_{x=1}^{5} \mathrm{GRA}^{k}{}_{m}(x, i) = 0, if \sum_{x=1}^{5} CommittedGRA^{k}{}_{m}(x, i,) = 0, \forall i$$

14.2.4 Water Balance

14.2.4.1 Chronological Reservoir Volume

Equation 37 – Chronological Reservoir Volume Accounting

In a cascading hydropower system the change in storage in hour i at plant k is the difference between inflows and outflows. Inflows to plant k are: the sum of the outflows of plants immediately upstream of plant k accounting for the travel time between the upstream plants and plant k plus the natural incremental flow, the side flow into plant k. The outflows are the discharge of plant k. The division by 24 of the sum of the natural inflows along with the outflows from directly upstream plants outflows netted with the outflows of plant k in hour i is for unit conversion purposes (kcfs to ksfd).

$$ResVol(k, i) = ResVol(k, i-1) + \frac{\left(SideFlows(k, i) - \mathrm{Outf}^{k}(i-1) + \sum_{s}^{S(k)} \sum_{\alpha=1}^{A_{p,k}} Outf(s, i-\alpha)\right)}{24}, \forall i$$

14.2.4.2 Reservoir Constraints

These reservoir constraints should be active in the day-ahead and hour-ahead unit commitment. These will be important in enforcing elevation/storage constraints from the weekly stage within the optimization window.

Equation 38 – Maximum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be under the reservoir maximum. This should enforce a range a for particular reservoir elevation or volume targets.

$$ResVolMax(k, i) \geq ResVol(k, i) + \frac{\left(\delta SpillMax(k, i) + \sum_{j=1}^{i} \sum_{x=1}^{7} \left(\mathrm{F}^{k}{}_{m}(j) * \mathrm{EnergyMax}^{k}\left(\mathrm{GRA}^{k}(x, j)\right)\right) + \mathrm{TotalSpill}^{k}(j)\right)}{24}, \forall i$$

Equation 39 – Minimum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be over the reservoir minimum. This should enforce a range a for particular reservoir elevation or volume targets.

$$ResVolMin(k, i) \leq ResVol(k, i) + \frac{\left(\delta SpillMin(k, i) + \sum_{j=1}^{i} \sum_{x=1}^{7} \left(\mathrm{F}^{k}{}_{m}(j) * \mathrm{EnergyMin}^{k}\left(\mathrm{GRA}^{k}(x, j)\right)\right) + \mathrm{TotalSpill}^{k}(j)\right)}{24}, \forall i$$

14.3 Variable Energy Resource Constraints

For the purposes of the unit commitment, variable energy resources will be considered to be wind and solar. While independent run-of-river hydro is similar it will not have the capability to dispatch down, in other words it is a must-take resource.

14.3.1 Operating Range Constraints

Equation 40 – Total Generator Range Attribute Max Limitation for Variable Energy Resources

The generator cannot attribute more discretionary range than the forecasted available energy of the unit (which would be derived from the variable fuel forecast). This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{k}{}_{m}(x, i) \leq ForecastEnergy^{k}(i, \Delta_{DA}), \forall i$$

Equation 41 – Individual Generator Range Attribute Max Limitation for Variable Energy Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x, i) \leq RangeLimit^{k}{}_{m}(x, i), \forall i$$

14.4 Energy Limited Resource Constraints

Energy limited resources have limits on the number of hours or amount of energy available within a certain period of time. Demand response resources and dispatchable standby generation can provide capacity that can be used to reduce system requirements, but only for a limited number of hours in a particular time period. Storage resources have a maximum energy available to discharge before recharge.

14.4.1 Operating Range Constraints

These are not elegant definitions in terms of optimizations, but should be the correct constraints.

Equation 42 – Total Generator Range Attribute Max Limitation for Energy Limited Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{k}{}_{m}(x, i) \leq Max^{k}{}_{m}, \forall i$$

Equation 43 – Individual Generator Range Attribute Max Limitation for Energy Limited Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x, i) \leq RangeLimit^{k}{}_{m}(x, i), \forall i$$

14.4.2 Commitment Constraints

Equation 44 – Committed Energy Limited Resource Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right) \geq Min^{k}{}_{m}\,, if\ \exists\ CommittedGRA^{k}{}_{m}\left(x,i,\right) > 0, \forall i$$

Equation 45 – Uncommitted Energy Limited Resource Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right) = 0, if \sum_{x=1}^{7} CommittedGRA^{k}{}_{m}\left(x,i,\right) = 0, \forall i$$

14.5 Energy Limitations and Dispatch Constraints

If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour.

Let the following be an energy limit on the energy limited dispatch, if necessary. Note that for the storage resources and for demand response, the energy can be positive or negative depending on whether charging/recharging for storage or increasing/decreasing load for demand response.

Equation 46 – Maximum Available Energy Content Constraint

The total energy committed to dispatch by the energy limited resource must be less than the maximum available fuel/energy.

$$MaxAvailEnergy^{k}(m,\omega) \geq \left| \mathrm{J}^{k}(m) * \sum_{j=1}^{\omega}\sum_{\mathrm{x}=1}^{7} \mathrm{EnergyMax}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x,j})\right) \right|$$

Equation 47 – Planned Dispatch Hour Limitation for Energy Limited Resources

The total hours of dispatch/commitment of the energy limited resources and kept under the seasonal limit.

$$\Omega^{k}(m,\omega) \geq \omega^{k}(m,i), where\ i \leq T$$

14.6 Must Take Resource Constraints

For the purposes of the unit commitment, must take resources will be energy efficiency, long-term purchase or sale contracts (out of region) and independent run-of-river hydro generation. Must-take plants do not to be dispatched/committed and thus do not have operational constraints per se, but still reduce system need.

14.7 Market Constraints

Let *k* be defined as a market providing a subset of system requirements $x \in X^{k}$ and where $\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right)/\mathrm{ConBlkSize}\left(X^{k}\right)$ *is an element of the integers.*

Note that purchases and sales are a different market resource and will have opposite sign.

Equation 48 – Total Market Commitment Limitation After Day—Ahead Transactions

The net total market purchases and sales from the hour-ahead stage and previous stages must be under the total available market capacity.

$$Max^{k}{}_{m}(\mathrm{i}) \geq \left|\sum\nolimits_{\mathrm{x}\in X^{k}} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum\nolimits_{\mathrm{x}\in X^{k}} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right|, \forall i$$

where the total capacity available from market resource *k* is limited by $Max^{k}{}_{m}(\mathrm{i})$.

The transmission transfer constraints can be represented as with a generator.

Equation 49 – Transmission Limitation for Day-Ahead Transactions

For a particular hour, the total net purchases and sales must be within the transmission limit.

$$\left|\sum_{\mathrm{x}\in X^{k}} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{\mathrm{x}\in X^{k}} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right| \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

14.8 Portfolio Constraints

Load and operating reserve requirements must be met exactly, however it is sufficient for a system to carry at least enough contingency reserves.

14.8.1 Firm Load and Operating Reserve Requirements

Equation 50 – Load, Regulation, and Imbalance Requirements

Day-ahead load and operating reserve requirements forecast must be met exactly.

$$\begin{aligned} Req(x,i) = {} & \sum_{k=1}^{Therm} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=Therm+1}^{Hydro} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \\ & + \sum_{k=Hydro+1}^{VER} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=VER+1}^{EnergyLim} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=EnergyLim+1}^{MustTake} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \\ & + \sum_{k=MustTake+1}^{Market} \left[\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},\mathrm{WA})\right], \forall i \end{aligned}$$

$$where\ x = 1,2,3,4,5$$

14.8.2 Contingency Reserve Requirements

Equation 51 – Contingency Reserve Requirement

It is sufficient for a system to carry at least enough contingency reserves meet the requirement. In addition, a portion or all of the non-spinning reserve requirement can be satisfied by a spinning reserve, but not vice versa.

$$
\begin{aligned}
Req(x,i) \le{}& \sum_{k=1}^{Therm} \mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) + \sum_{k=Therm+1}^{Hydro} \mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) \\
&+ \sum_{k=Hydro+1}^{VER} \mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) + \sum_{k=VER+1}^{EnergyLim} \mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) + \sum_{k=EnergyLim+1}^{MustTake} \mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) \\
&+ \sum_{k=MustTake+1}^{Market} \left[\mathrm{GRA}^{k}{}_{m}(\mathrm{x,i}) + \mathrm{CommittedGRA}^{k}{}_{m}(\mathrm{x,i,WA})\right], \forall i
\end{aligned}
$$

$$where\ x = 6{,}7$$

Note that technically all available uncommitted space on qualifying generators in the system could be considered contingency reserve.

14.9 Objective Function for Day-Ahead Commitment

The objective function in the day-ahead stage will seek to minimize all the costs within a 168 hour window netted with the future value of resources outside that window.

Equation 52 - Objective Function Definition for Day-Ahead Commitment

Minimize system cost over a particular rolling window of length *T*.

$$
\begin{aligned}
&SystemCost(T) \\
&= \sum_{i=1}^{T} \left[\sum_{k=1}^{Therm} Cost^{k}(\mathrm{i}) + \sum_{k=Therm+1}^{Hydro} Cost^{k}(\mathrm{i}) + \sum_{k=Hydro+1}^{VER} Cost^{k}(\mathrm{i}) + \sum_{k=VER+1}^{EnergyLim} Cost^{k}(\mathrm{i}) \right. \\
&\quad \left. + \sum_{k=EnergyLim+1}^{MustTake} Cost^{k}(\mathrm{i}) + \sum_{k=MustTake+1}^{Market} Cost^{k}(\mathrm{i},\phi) \right] - FV(T,), \forall i
\end{aligned}
$$

The minimized cost will require a certain set of resources to be committed to achieve that particular cost. If this is the stage at which the resource evaluated must be committed for fueling/operational reasons, then that resource is considered to be committed in following stages.

15 Hour-Ahead Unit Commitment

In the hour-ahead unit commitment stage, the minimization of cost achieves a unit commitment of peaker thermal units, hourly market purchases and sales, and a forecast of hourly hydro flows for the next day.

15.1 Thermal Generator Constraints

15.1.1.1 Operating Range Constraints

These constraints refer to the machine capability of the thermal plants which can be fuel limited.

Equation 53 – Total Generator Range Attribute Max Limitation for Thermal Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq Max^{k}{}_{m}, \forall i$$

Equation 54 – Individual Thermal Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

15.1.1.2 Fuel Constraints

Equation 55 – Maximum Daily Fuel Usage Limitation for Thermal Resources

When meeting system requirements, the generator must not use more fuel than was scheduled. An example is a gas plant cannot consume more than the daily gas nomination plus the daily draft limit.

$$SchedFuelMax^{k}(i) \geq \sum_{j=1}^{i}\sum_{\mathrm{x}=1}^{7}\left(\mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMax}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right)\right) + \sum_{r=1}^{j} \mathrm{ActualFuel}^{k}(r)\,,$$

$$\forall i \leq FuelSched^{k}$$

Equation 56– Minimum Daily Fuel Usage Limitation

When meeting system requirements, the generator must not produce less fuel than was scheduled. An example is a gas plant cannot consume less than the daily gas nomination minus the daily pack limit.

$$SchedFuelMin^{k}\left(FuelSched^{k}(i)\right)$$

$$\leq \sum_{j=1}^{i}\sum_{\mathrm{x}=1}^{7}\left(\mathrm{F}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMin}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right)\right) + \sum_{r=1}^{j} \mathrm{ActualFuel}^{k}(r)\,,$$

$$\forall i \in FuelSched^{k}(i)$$

15.1.1.2.1 Commitment Constraints

Equation 57 – Minimum Committed Thermal Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \geq Min^{k}{}_{m}\,, if\ \exists\ CommittedGRA^{k}{}_{m}(x,i,) > 0, \forall i$$

Equation 58 – Uncommitted Thermal Generation Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) = 0, if \sum_{x=1}^{7} CommittedGRA^{k}{}_{m}(x,i,) \;= 0, \forall i$$

15.2 Cascading Hydro Generator Constraints

15.2.1 Generator Operating Range Constraints

These constraints refer to the machine capability of the hydropower plants which are fuel limited.

Equation 59 – Total Generator Range Attribute Max Limitation for Cascading Hydro Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq Max^{k}{}_{m}, \forall i$$

Equation 60 – Individual Cascading Hydro Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i)\;, \forall i$$

15.2.2 Fuel Constraints

- If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour.

15.2.3 Total Discharge

Equation 61 – Maximum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be under the maximum allowed in the fish and wildlife constraints. If a plant spills more than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMax^{k}\left(SpillSched^{k}(a)\right) \geq \sum_{j=1}^{i} \mathrm{TotalSpill}^{\mathrm{k}}(\mathrm{j}) - \delta SpillMax(k,i),\; \forall i \leq SpillSched^{k}(a)$$

Equation 62 – Minimum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be over the minimum allowed in the fish and wildlife constraints. If a plant spills less than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMin^{k}\left(SpillSched^{k}(a)\right) \leq \sum_{j=1}^{i} \mathrm{TotalSpill}^{\mathrm{k}}(\mathrm{j}) - \delta SpillMin(k,i), \forall i \leq SpillSched^{k}(a)$$

Equation 63 – Total Spill Percent of Outflow Constraint

Total spill at a plant must be greater than or equal to a particular percentage of the total plant outflow.

$$TotalSpill^{k}(i) \geq \begin{cases} 0, if\ TotalSpill^{k}(i) > SpillMax^{k} \\ DisPerc_{m}(k) * \left(Outf_{Max}(k,i)\right), if\ TotalSpill^{k}(i) \leq SpillMax^{k} \end{cases}$$

15.2.4 Commitment Constraints

Equation 64– Committed Cascading Hydro Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA^{k}}_{\mathrm{m}}\left(\mathrm{x,i}\right) \geq {Min^{k}}_{m}, if\ \exists\ {CommittedGRA^{k}}_{m}\left(x,i,\right) > 0, \forall i$$

Equation 65 – Uncommitted Cascading Hydro Generation Constraint

The generator may not account for meeting most system requirements if not committed.

$$\sum_{\mathrm{x}=1}^{5} \mathrm{GRA^{k}}_{\mathrm{m}}\left(\mathrm{x,i}\right) = 0, if \sum_{x=1}^{5} {CommittedGRA^{k}}_{m}\left(x,i,\right) = 0, \forall i$$

15.2.5 Water Balance

15.2.5.1 Chronological Reservoir Volume

Equation 66 – Chronological Reservoir Volume Accounting

In a cascading hydropower system the change in storage in hour i at plant k is the difference between inflows and outflows. Inflows to plant k are: the sum of the outflows of plants immediately upstream of plant k accounting for the travel time between the upstream plants and plant k plus the natural incremental flow, the side flow into plant k. The outflows are the discharge of plant k. The division by 24 of the sum of the natural inflows along with the outflows from directly upstream plants outflows netted with the outflows of plant k in hour i is for unit conversion purposes (kcfs to ksfd).

$$ResVol(k,i) = ResVol(k,i-1) + \frac{\left(SideFlows(k,i) - \mathrm{Outf^{k}(i-1)} + \sum_{s}^{\mathrm{S}(k)} \sum_{\alpha=1}^{A_{p,k}} Outf(s,i-\alpha)\right)}{24}, \forall i$$

15.2.5.2 Reservoir Constraints

These reservoir constraints should be active in the day-ahead and hour-ahead unit commitment.

Equation 67 – Maximum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be under the reservoir maximum. This should enforce a range a for particular reservoir elevation or volume targets.

$$\begin{aligned} &ResVolMax(k,i) \\ &\geq ResVol(k,i) \\ &+ \frac{\left(\delta SpillMax(k,i) + \sum_{j=1}^{i} \sum_{\mathrm{x}=1}^{7} \left(\mathrm{F^{k}}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMax^{k}}\left(\mathrm{GRA^{k}(x,j)}\right)\right) + \mathrm{TotalSpill^{k}(j)}\right)}{24}, \forall i \end{aligned}$$

Equation 68 – Minimum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be over the reservoir minimum. This should enforce a range a for particular reservoir elevation or volume targets.

$$ResVolMin(k,i) \le ResVol(k,i) + \frac{\left(\delta SpillMin(k,i) + \sum_{j=1}^{i}\sum_{\mathrm{x}=1}^{7}\left(\mathrm{F^k}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMin^k}\left(\mathrm{GRA^k}(\mathrm{x,j})\right)\right) + \mathrm{TotalSpill^k}(\mathrm{j})\right)}{24}, \forall i$$

15.3 Variable Energy Resource Constraints

For the purposes of the unit commitment, variable energy resources will be considered to be wind and solar. While independent run-of-river hydro is similar it will not have the capability to dispatch down, in other words it is a must-take resource.

15.3.1 Operating Range Constraints

Equation 69 – Total Generator Range Attribute Max Limitation for Variable Energy Resources

The generator cannot attribute more discretionary range than the forecasted available energy of the unit (which would be derived from the variable fuel forecast). This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x,i}) \le ForecastEnergy^k(i, \Delta_{HA}), \forall i$$

Equation 70 – Individual Generator Range Attribute Max Limitation for Variable Energy Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^k{}_m(x,i) \le RangeLimit^k{}_m(x,i), \forall i$$

15.4 Energy Limited Resource Constraints

Energy limited resources have limits on the number of hours or amount of energy available within a certain period of time. Demand response resources and dispatchable standby generation can provide capacity that can be used to reduce system requirements, but only for a limited number of hours in a particular time period. Storage resources have a maximum energy available to discharge before recharge.

15.4.1 Operating Range Constraints

Equation 71 – Total Generator Range Attribute Max Limitation for Energy Limited Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x}, \mathrm{i}\right) \leq Max^{k}{}_{m}, \forall i$$

Equation 72 – Individual Generator Range Attribute Max Limitation for Energy Limited Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x, i) \leq RangeLimit^{k}{}_{m}(x, i), \forall i$$

15.4.2 Commitment Constraints

Equation 73 – Committed Energy Limited Resource Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x}, \mathrm{i}\right) \geq Min^{k}{}_{m}, if \ \exists \ CommittedGRA^{k}{}_{m}\left(x, i,\right) > 0, \forall i$$

Equation 74 – Uncommitted Energy Limited Resource Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{x=1}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x}, \mathrm{i}\right) = 0, if \sum_{x=1}^{7} CommittedGRA^{k}{}_{m}\left(x, i,\right) = 0, \forall i$$

15.4.3 Energy Limitations and Dispatch Constraints

If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour. Let the below be an indicator function *$J^k(m)$*.

Equation 75 – Seasonal Indicator of Availability of Energy Limited Resource.

$$\mathrm{J}^{k}(m) = \begin{cases} 1, & m \in M^{k} \\ 0, & m \in \left(M^{k}\right)^{C} \end{cases}$$

Let the following be an energy limit on the energy limited dispatch, if necessary. Note that for the storage resources and for demand response, the energy can be positive or negative depending on whether charging/recharging for storage or increasing/decreasing load for demand response.

Equation 76 – Maximum Available Energy Content Constraint

The total energy committed to dispatch by the energy limited resource must be less than the maximum available fuel/energy.

$$MaxAvailEnergy^{k}(m,\omega) \geq \left| \mathrm{J}^{k}(m) * \sum_{j=1}^{\omega} \sum_{\mathrm{x}=1}^{7} \mathrm{EnergyMax}^{\mathrm{k}}\left(\mathrm{GRA}^{\mathrm{k}}(\mathrm{x},\mathrm{j})\right) \right|$$

Equation 77 – Planned Dispatch Hour Limitation for Energy Limited Resources

The total hours of dispatch/commitment of the energy limited resources and kept under the seasonal limit.

$$\Omega^{k}(m,\omega) \geq \omega^{k}(m,i), where\ i \leq T$$

15.5 Must Take Resource Constraints

For the purposes of the unit commitment, must take resources will be energy efficiency, long-term purchase or sale contracts (out of region) and independent run-of-river hydro generation. Must-take plants do not to be dispatched/committed and thus do not have operational constraints per se, but still reduce system need.

15.6 Market Constraints

Let *k* be defined as a market providing a subset of system requirements $x \in X^{k}$ and where $\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i})/\mathrm{ConBlkSize}(X^{k})$ *is an element of the integers.*

Note that purchases and sales are a different market resource and will have opposite sign.

Equation 78 – Total Market Commitment Limitation After Hour—Ahead Transactions

The net total market purchases and sales from the hour-ahead stage and previous stages must be under the total available market capacity.

$$Max^{k}{}_{m}(\mathrm{i}) \geq \left|\sum\nolimits_{\mathrm{x}\in X^{k}} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum\nolimits_{\mathrm{x}\in X^{k}} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right|, \forall i$$

where the total capacity available from market resource *k* is limited by $Max^{k}{}_{m}(\mathrm{i})$.

The transmission transfer constraints can be represented as with a generator.

Equation 79 – Transmission Limitation for Day-Ahead Transactions

For a particular hour, the total net purchases and sales must be within the transmission limit.

$$\left|\sum_{\mathrm{x}\in X^{k}} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{\mathrm{x}\in X^{k}} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right| \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

15.7 Portfolio Constraints

Load and operating reserve requirements must be met exactly, however it is sufficient for a system to carry at least enough contingency reserves.

15.8 Firm Load and Operating Reserve Requirements

Equation 80 – Load, Regulation, and Imbalance Requirements

Hour-Ahead load and operating reserve requirements forecast must be met exactly.

$$Req(x,i) = \sum_{k=1}^{Therm} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=Therm+1}^{Hydro} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=Hydro+1}^{VER} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=VER+1}^{EnergyLim} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=EnergyLim+1}^{MustTake} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=MustTake+1}^{Market} \left[\mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \mathrm{CommittedGRA^k}_\mathrm{m}(\mathrm{x,i,DA})\right], \forall i$$

$$where\ x = 1,2,3,4,5$$

15.9 Contingency Reserve Requirements

Equation 81 – Contingency Reserve Requirement

It is sufficient for a system to carry at least enough contingency reserves meet the requirement. In addition, a portion or all of the non-spinning reserve requirement can be satisfied by a spinning reserve, but not vice versa.

$$Req(x,i) \leq \sum_{k=1}^{Therm} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=Therm+1}^{Hydro} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=Hydro+1}^{VER} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=VER+1}^{EnergyLim} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=EnergyLim+1}^{MustTake} \mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \sum_{k=MustTake+1}^{Market} \left[\mathrm{GRA^k}_\mathrm{m}(\mathrm{x,i}) + \mathrm{CommittedGRA^k}_\mathrm{m}(\mathrm{x,i,DA})\right], \forall i$$

$$where\ x = 6,7$$

Note that technically all available uncommitted space on qualifying generators in the system could be considered contingency reserve.

15.10 Objective Function for Hour-Ahead Commitment Stage

Currently, GENESYS does a daily shaping of hydro energy in previous stages which could allow the explicit price of hydro to be passed from one timeframe to another. The objective function in the hour-ahead stage will seek to minimize all the costs within a 24 hour window netted with the future value of resources outside that window.

Equation 82 - Objective Function Definition for Hour-Ahead Commitment

$$SystemCost(T) = \sum_{i=1}^{T}\left[\sum_{k=1}^{Therm} Cost^{k}(\mathrm{i}) + \sum_{k=Therm+1}^{Hydro} Cost^{k}(\mathrm{i}) + \sum_{k=Hydro+1}^{VER} Cost^{k}(\mathrm{i}) + \sum_{k=VER+1}^{EnergyLim} Cost^{k}(\mathrm{i}) + \sum_{k=EnergyLim+1}^{MustTake} Cost^{k}(\mathrm{i}) + \sum_{k=MustTake+1}^{Market} Cost^{k}(\mathrm{i},\phi)\right] - FV(T,), \forall i$$

The minimized cost will require a certain set of resources to be committed to achieve that particular cost. If this is the stage at which the resource evaluated must be committed for fueling/operational reasons, then that resource is considered to be committed in following stages.

16 Within Hour Deployment

The within hour deployment is an accounting step (no optimization) that resolves the remaining sources of uncertainty, and passes the repercussions to the following period:

(1) Resources are dispatched according to week-ahead, day-ahead, and hour-ahead commitment guidelines.
(2) Uncertainty between scheduled and actual load, VER generation, and intra-hour reserve application is resolved, and fuel accounting, where necessary is adjusted.
(3) Resources (generation or transmission) that have a forced outage are forced out for some or all of the hour, and allocated contingency reserves are deployed. If more than the amount of contingency reserves assigned is needed to resolve the outage, than a simple resource stack is used to meet load and other system obligations.

16.1 Thermal Generator Constraints

16.1.1.1 Operating Range Constraints

These constraints refer to the machine capability of the thermal plants which can be fuel limited.

Equation 83 – Total Generator Range Attribute Max Limitation for Thermal Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq Max^{k}{}_{m}, \forall i$$

Equation 84 – Individual Thermal Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

16.1.1.2 Fuel Constraints

Equation 85 – Maximum Daily Fuel Usage Limitation for Thermal Resources

When meeting system requirements, the generator must not use more fuel than was scheduled. An example is a gas plant cannot consume more than the daily gas nomination plus the daily draft limit.

$$SchedFuelMax^k\left(FuelSched^k(i)\right) \geq \sum_{j=1}^{i}\sum_{x=1}^{7}\left(\mathrm{F^k}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMax^k}\left(\mathrm{GRA^k}(\mathrm{x,j})\right)\right) + \sum_{r=1}^{j}\mathrm{ActualFuel}^k(r)\,,$$

$$\forall i \leq FuelSched^k$$

Equation 86– Minimum Daily Fuel Usage Limitation

When meeting system requirements, the generator must not produce less fuel than was scheduled. An example is a gas plant cannot consume less than the daily gas nomination minus the daily pack limit.

$$SchedFuelMin^k\left(FuelSched^k(i)\right) \leq \sum_{j=1}^{i}\sum_{x=1}^{7}\left(\mathrm{F^k}_{\mathrm{m}}(\mathrm{j}) * \mathrm{EnergyMin^k}\left(\mathrm{GRA^k}(\mathrm{x,j})\right)\right) + \sum_{r=1}^{j}\mathrm{ActualFuel}^k(r)\,,$$

$$\forall i \ \in FuelSched^k(i)$$

16.1.1.2.1 Commitment Constraints

Equation 87 – Minimum Committed Thermal Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7}\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x,i}) \geq Min^k{}_m\,, if \ \exists\ CommittedGRA^k{}_m(x,i,) > 0, \forall i$$

Equation 88 – Uncommitted Thermal Generation Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{\mathrm{x}=1}^{7}\mathrm{GRA^k}_{\mathrm{m}}(\mathrm{x,i}) = 0, if \sum_{x=1}^{7} CommittedGRA^k{}_m(x,i,) \ = 0, \forall i$$

16.1.2 Cascading Hydro Generator Constraints

16.1.2.1 Generator Operating Range Constraints

These constraints refer to the machine capability of the hydropower plants which are fuel limited.

Equation 89 – Total Generator Range Attribute Max Limitation for Cascading Hydro Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{x=1}^{7} \mathrm{GRA}^{k}{}_{m}(x, i) \leq Max^{k}{}_{m}, \forall i$$

Equation 90 – Individual Cascading Hydro Generator Range Attribute Max Limitation

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x, i) \leq RangeLimit^{k}{}_{m}(x, i)\ , \forall i$$

16.1.2.2 Fuel Constraints

- If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour.

Equation 91 - Maximum Daily Fuel Usage Limitation for Cascading Hydro Resources

In general, when meeting system requirements, the generator must not use more fuel than was scheduled. If hydropower plant drafts outside the maximum of the range that is calculated in previous stages to reach particular elevation/volume targets it will do it at a steep penalty that can be enforced by the slack variable.

$$\begin{aligned} &SchedFuelMax^{k}(i) \\ &\quad \geq \sum_{j=1}^{i} \sum_{x=1}^{7} \left(\mathrm{F}^{k}{}_{m}(\mathrm{j}) * \mathrm{Energy}^{k}\left(\mathrm{GRA}^{k}(\mathrm{x}, \mathrm{j})\right)\right) + \mathrm{TotalSpill}^{k}(\mathrm{j}) + \sum_{r=1}^{j} \mathrm{Outf}^{k}(\mathrm{r}) \\ &\quad - \delta SpillMax(k, i)\ , \end{aligned}$$

$$\forall i \leq FuelSched^{k}$$

Equation 92 – Minimum Daily Fuel Usage Limitation for Cascading Hydro Resources

In general, when meeting system requirements, the generator must not use less fuel than was scheduled. If hydropower plant drafts less than the minimum of the range that is calculated in previous stages to reach particular elevation/volume targets it will do it at a steep penalty that can be enforced by the slack variable.

$$\begin{aligned} &SchedFuelMin^{k}(i) \\ &\quad \leq \sum_{j=1}^{i} \sum_{x=1}^{7} \left(\mathrm{F}^{k}{}_{m}(\mathrm{j}) * \mathrm{Energy}^{k}\left(\mathrm{GRA}^{k}(\mathrm{x}, \mathrm{j})\right)\right) + \mathrm{TotalSpill}^{k}(\mathrm{j}) + \sum_{r=1}^{j} \mathrm{Outf}^{k}(\mathrm{r}) \\ &\quad - \delta SpillMin(k, i), \end{aligned}$$

$$\forall i \ \leq FuelSched^{k}$$

16.1.2.2.1 Total Discharge

Equation 93 – Maximum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be under the maximum allowed in the fish and wildlife constraints. If a plant spills more than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMax^k\left(SpillSched^k(a)\right) \geq \sum_{j=1}^{i} \mathrm{TotalSpill}^{\mathrm{k}}(\mathrm{j}) - \delta SpillMax(k,i),\ \forall i \leq SpillSched^k(a)$$

Equation 94 – Minimum Spill Limitation

The total spill from a hydropower plant with particular spill schedules must be over the minimum allowed in the fish and wildlife constraints. If a plant spills less than the targeted spill it will do it at a steep penalty that can be enforced by the slack variable.

$$SpillMin^k\left(SpillSched^k(a)\right) \leq \sum_{j=1}^{i} \mathrm{TotalSpill}^{\mathrm{k}}(\mathrm{j}) - \delta SpillMin(k,i), \forall i \leq SpillSched^k(a)$$

Equation 95 – Total Spill Percent of Outflow Constraint

Total spill at a plant must be greater than or equal to a particular percentage of the total plant outflow.

$$TotalSpill^k(i) \geq \begin{cases} 0, if\ TotalSpill^k(i) > SpillMax^k \\ DisPerc_m(k) * \left(Outf(k,i)\right), if\ TotalSpill^k(i) \leq SpillMax^k \end{cases}$$

16.1.2.2.2 Commitment Constraints

Equation 96– Committed Cascading Hydro Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x}, \mathrm{i}) \geq Min^{k}{}_{m}, if\ \exists\ CommittedGRA^{k}{}_{m}(x, i,) > 0, \forall i$$

Equation 97 – Uncommitted Cascading Hydro Generation Constraint

The generator may not account for meeting most system requirements if not committed.

$$\sum_{\mathrm{x}=1}^{5} \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x}, \mathrm{i}) = 0, if \sum_{x=1}^{5} CommittedGRA^{k}{}_{m}(x, i,) = 0, \forall i$$

16.1.2.3 Water Balance

16.1.2.4 Chronological Reservoir Volume

Equation 98 – Chronological Reservoir Volume Accounting

In a cascading hydropower system the change in storage in hour i at plant k is the difference between inflows and outflows. Inflows to plant k are: the sum of the outflows of plants immediately upstream of plant k accounting for the travel time between the upstream plants and plant k plus the natural incremental flow, the side flow into plant k. The outflows are the discharge of

plant k. The division by 24 of the sum of the natural inflows along with the outflows from directly upstream plants outflows netted with the outflows of plant k in hour i is for unit conversion purposes (kcfs to ksfd).

$$ResVol(k,i) = ResVol(k,i-1) + \frac{\left(SideFlows(k,i) - \mathrm{Outf}^{\mathrm{k}}(\mathrm{i}-1) + \sum_{s}^{\mathrm{S}(k)} \sum_{\alpha=1}^{A_{p,k}} Outf(s,i-\alpha)\right)}{24}, \forall i$$

16.1.2.5 Reservoir Constraints

These reservoir constraints should be active in the day-ahead and hour-ahead unit commitment.

Equation 99 – Maximum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be under the reservoir maximum. This should enforce a range a for particular reservoir elevation or volume targets.

$$ResVolMax(k,i) \geq ResVol(k,i) + \frac{\left(\delta SpillMax(k,i) + \sum_{j=1}^{i} \sum_{\mathrm{x}=1}^{7} \left(\mathrm{F^{k}}_{\mathrm{m}}(\mathrm{j}) * \mathrm{Energy^{k}}\left(\mathrm{GRA^{k}}(\mathrm{x},\mathrm{j})\right)\right) + \mathrm{TotalSpill^{k}}(\mathrm{j})\right)}{24}, \forall i$$

Equation 100 – Minimum Reservoir Volume Constraint

The reservoir volume in any hour plus the net outflows must be over the reservoir minimum. This should enforce a range a for particular reservoir elevation or volume targets.

$$ResVolMin(k,i) \leq ResVol(k,i) + \frac{\left(\delta SpillMin(k,i) + \sum_{j=1}^{i} \sum_{\mathrm{x}=1}^{7} \left(\mathrm{F^{k}}_{\mathrm{m}}(\mathrm{j}) * \mathrm{Energy^{k}}\left(\mathrm{GRA^{k}}(\mathrm{x},\mathrm{j})\right)\right) + \mathrm{TotalSpill^{k}}(\mathrm{j})\right)}{24}, \forall i$$

16.2 Variable Energy Resource Constraints

For the purposes of the unit commitment, variable energy resources will be considered to be wind and solar. While independent run-of-river hydro is similar it will not have the capability to dispatch down, in other words it is a must-take resource.

16.2.1 Operating Range Constraints

Equation 101 – Total Generator Range Attribute Max Limitation for Variable Energy Resources

The generator cannot attribute more discretionary range than the forecasted available energy of the unit (which would be derived from the variable fuel forecast). This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x}=1}^{7} \mathrm{GRA^{k}}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \leq ForecastEnergy^{k}(i, \Delta_{HA}), \forall i$$

Equation 102 – Individual Generator Range Attribute Max Limitation for Variable Energy Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

16.3 Energy Limited Resource Constraints

Energy limited resources have limits on the number of hours or amount of energy available within a certain period of time. Demand response resources and dispatchable standby generation can provide capacity that can be used to reduce system requirements, but only for a limited number of hours in a particular time period. Storage resources have a maximum energy available to discharge before recharge.

16.3.1 Operating Range Constraints

Equation 103 – Total Generator Range Attribute Max Limitation for Energy Limited Resources

The generator cannot attribute more discretionary range than the capacity of the unit. This guarantees capacity is attributed correctly and not double counted.

$$\sum_{\mathrm{x=1}}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right) \leq Max^{k}{}_{m}, \forall i$$

Equation 104 – Individual Generator Range Attribute Max Limitation for Energy Limited Resources

This limits the amount of a particular system requirement that can be met by a particular resource. For example this could be a dynamic transfer constraint on a plant.

$$GRA^{k}{}_{m}(x,i) \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

16.3.2 Commitment Constraints

Equation 105 – Committed Energy Limited Resource Minimum Generation Constraint

The generator must produce at least its min generation if committed in the previous stage.

$$\sum_{\mathrm{x=1}}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right) \geq Min^{k}{}_{m}, if \ \exists \ CommittedGRA^{k}{}_{m}\left(x,i,\right) > 0, \forall i$$

Equation 106 – Uncommitted Energy Limited Resource Constraint

The generator may not account for meeting any system requirements if not committed.

$$\sum_{\mathrm{x=1}}^{7} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}\left(\mathrm{x,i}\right) = 0, if \sum_{x=1}^{7} CommittedGRA^{k}{}_{m}\left(x,i,\right) = 0, \forall i$$

16.4 Energy Limitations and Dispatch Constraints

If the hourly model is solving a week at a time, this constraint will probably have to be refreshed every hour. Let the below be an indicator function *$J^k(m)$*.

Equation 107 – Seasonal Indicator of Availability of Energy Limited Resource.

$$\mathrm{J}^k(m) = \begin{cases} 1, & m \epsilon M^k \\ 0, & m \epsilon \left(M^k\right)^C \end{cases}$$

Let the following be an energy limit on the energy limited dispatch, if necessary. Note that for the storage resources and for demand response, the energy can be positive or negative depending on whether charging/recharging for storage or increasing/decreasing load for demand response.

Equation 108 – Maximum Available Energy Content Constraint

The total energy committed to dispatch by the energy limited resource must be less than the maximum available fuel/energy.

$$MaxAvailEnergy^k(m,\omega) \geq \left| \mathrm{J}^k(m) * \sum_{j=1}^{\omega} \sum_{\mathrm{x}=1}^{7} \mathrm{EnergyMax}^k\left(\mathrm{GRA}^k(\mathrm{x},\mathrm{j})\right) \right|$$

Equation 109 – Planned Dispatch Hour Limitation for Energy Limited Resources

The total hours of dispatch/commitment of the energy limited resources and kept under the seasonal limit.

$$\Omega^k(m,\omega) \geq \omega^k(m,i), where\ i \leq T$$

16.5 Must Take Resource Constraints

For the purposes of the unit commitment, must take resources will be energy efficiency, long-term purchase or sale contracts (out of region) and independent run-of-river hydro generation. Must-take plants do not to be dispatched/committed and thus do not have operational constraints per se, but still reduce system need.

16.6 Market Constraints

Let *k* be defined as a market providing a subset of system requirements $x \in X^k$ and where $\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i})/\mathrm{ConBlkSize}(X^k)$ *is an element of the integers.*

Note that purchases and sales are a different market resource and will have opposite sign.

Equation 110 – Total Market Commitment Limitation After Hour—Ahead Transactions

The net total market purchases and sales from the hour-ahead stage and previous stages must be under the total available market capacity.

$$Max^{k}{}_{m}(\mathrm{i}) \geq \left|\sum\nolimits_{\mathrm{x}\in X^k} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum\nolimits_{\mathrm{x}\in X^k} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right|, \forall i$$

where the total capacity available from market resource *k* is limited by $Max^{k}{}_{m}(\mathrm{i})$.

The transmission transfer constraints can be represented as with a generator.

Equation 111 – Transmission Limitation for Day-Ahead Transactions

For a particular hour, the total net purchases and sales must be within the transmission limit.

$$\left|\sum_{\mathrm{x}\in X^k} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{\mathrm{x}\in X^k} \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},)\right| \leq RangeLimit^{k}{}_{m}(x,i), \forall i$$

16.7 System Requirements

By only requiring that non-contingency reserve system requirements must be met in the within-hour stage, if resources are forced out then the services they provided will be replaced by another resource in the portfolio. Use a resource stacking mechanism similar to the period and weekly stage to dispatch contingency reserves. The model can first look through all committed plants with available fuel, second all committed plants holding contingency reserve, and then through all non-committed plants with the capability to turn on with no notice.

If these plants are exhausted, then the model will dispatch a resource of last resort, which will be a proxy for a curtailment.

Equation 112 – System Requirements Definition

$$\begin{aligned}Req(x,i) = &\sum_{k=1}^{Therm} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=Therm+1}^{Hydro} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \\ &+ \sum_{k=Hydro+1}^{VER} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=VER+1}^{EnergyLim} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \sum_{k=EnergyLim+1}^{MustTake} \mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) \\ &+ \sum_{k=MustTake+1}^{Market} \left[\mathrm{GRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}) + \mathrm{CommittedGRA}^{\mathrm{k}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i},\mathrm{HA})\right] \\ &+ \mathrm{GRA}^{\mathrm{ResOfLastResort}}{}_{\mathrm{m}}(\mathrm{x},\mathrm{i}), \forall i\end{aligned}$$

$$where\ x = 1,2,3,4,5$$

16.8 Fuel Accounting

Equation 113 – Fuel Accounting for Resource k

$$\text{ActualFuel}^{k}(i) = \sum_{x=1}^{7} \left(F^{k}{}_{m}(i) * \text{Energy}^{k}\left(\text{GRA}^{k}(x,i)\right)\right)$$

$$\text{where k is a thermal resource}$$

Recall from the definitions above that

$$\text{Outf}^{k}(i) = \sum_{x=1}^{7} \left(F^{k}{}_{m}(i) * \text{Energy}^{k}\left(\text{GRA}^{k}(x,i)\right)\right) + \text{TotalSpill}^{k}(i),$$

$$\text{where k is a hydropower resource}$$

Note that the actual fuel usage is accounted for in subsequent day-ahead and hour-ahead optimization stages when knowing that information is important to evaluate whether constraints will be met in the future.

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