Intercomparison between Switch 2.0 and GE MAPS for simulation of high-renewable power systems in Hawaii

SUPPLEMENTARY INFORMATION

Matthias Fripp[1,*]

[1] University of Hawaii, Department of Electrical Engineering, Honolulu, Hawaii 96822, USA
* mfripp@hawaii.edu

Supplementary tables

Table S1. Renewable and transmission capacity in study scenarios 2–18 (MW)

Scenario	Oahu Wind	Oahu Central PV	Oahu Dist. PV	Maui Wind	Maui Central PV	Maui Dist. PV	Gen-Tie Wind	Grid-Tie Cable
2	100	11	220	72	0	40	0	0
3	100	200	260	72	0	40	0	0
4	200	200	260	72	0	40	0	0
5	300	200	260	72	0	40	0	0
6	100	300	360	72	0	40	0	0
7	200	300	360	72	0	40	0	0
8	200	400	460	72	0	40	0	0
9	200	300	560	72	0	40	0	0
10	100	200	260	72	0	78	200	0
11	100	200	260	272	0	78	0	200
12	100	200	260	272	100	78	200	200
13	100	300	360	72	0	78	200	0
14	100	300	360	272	0	78	0	200
15	100	300	360	272	100	78	200	200
16	200	400	460	72	0	78	200	0
17	200	400	460	272	0	78	0	200
18	200	400	460	272	100	78	200	200

Table S2. Commitment order for Oahu and Maui power plants used in Switch for intermodel comparison

Order	Unit	Order	Unit
1	H-Power (firm RE)	22	Maalaea 11 (cycling)
2	Honua (firm RE)	23	Maalaea 12 (cycling)
3	AES (baseload)	24	Maalaea 13 (cycling)
4	Kalaeloa 1 (baseload)	25	Maalaea 8 (cycling)
5	Kahe 5 (baseload)	26	Maalaea 9 (cycling)
6	Kahe 3 (baseload)	27	Maalaea 4 (peaking)
7	Kahe 4 (baseload)	28	Maalaea 6 (peaking)
8	Kahe 2 (baseload)	29	Maalaea 1 (peaking)
9	Kahe 6 (baseload)	30	Maalaea 2 (peaking)
10	Kahe 1 (baseload)	31	Maalaea 3 (peaking)
11	Waiau 7 (baseload)	32	Maalaea X1 (peaking)
12	Waiau 8 (baseload)	33	Maalaea X2 (peaking)
13	Maalaea CC1415 (baseload)	34	Maalaea 5 (cycling)
14	Maalaea CC1516 (baseload)	35	Maalaea 7 (cycling)
15	Maalaea CC1718 (cycled baseload)	36	New ICE 1 (peaking)
16	Maalaea CC1819 (cycled baseload)	37	New ICE 2 (peaking)
17	Kalaeloa 2 (cycled baseload)	38	Airport DSG (peaking)
18	Kalaeloa 3 (on if Kal 1 & 2 are)	39	CIP CT (peaking)
19	Waiau 5 (cycling)	40	Waiau 9 (peaking)
20	Waiau 6 (cycling)	41	Waiau 10 (peaking)
21	Maalaea 10 (cycling)	42	Schofield (peaking)

Non-standard operating schedules for some power plants

The main text notes that some power plants did not follow the general pattern used for baseload, firm renewable ("firm RE"), cycling, and peaking in the Switch and MAPS modeling. Here we detail the rules we used for those plants in the Switch modeling.

Combined-Cycle Power Plants

Although the Kalaeloa plant on Oahu and the Maalaea combined cycle plants on Maui were all identified as "baseload" plants in the RPS Study [1], we determined by inspection of the RPS Study results that MAPS was able to turn some of their units on and off like cycling plants. In the Switch modeling, we allowed these units to be committed as needed based on the day-ahead forecast (like cycling plants) but treated them as baseload generators in all other respects (i.e., allocating up and down reserve targets and reporting production).

Oahu Firm RE Plants

The RPS Study did not report how the firm renewable energy plants on Oahu (H-Power and Honua) were scheduled. However, GE reported separately [2] that they modeled H-Power and Honua as following a fixed schedule at maximum output other than during outages. They also provided details on the hourly production from Oahu plants in scenarios 2 and 16 [3], from which we inferred the dates of full and partial outages for H-Power (Honua had no outages).

Kalaeloa Combined Cycle Plant

GE reported separately [2] that "There is a cogen requirement that forces Kalaeloa to operate in either single train (KAL1) or dual train (KAL2) as must-run (unless both units are on forced outage). There is also a scheduled weekly maintenance cycle for each GT [gas turbine] that takes Kal1 out of service on Friday evening into Saturday morning, and Kal2 out of service from Saturday evening to Sunday morning." The Hawaii Solar Integration Study [4] identified these wash times as 9 pm Friday or Saturday to 9 am Saturday or Sunday. The clock used in Switch starts 1 hour earlier than MAPS (first hour of the day is 0 in Switch, 1 in MAPS), so this corresponds to the 8 pm hour through the 8 am hour, inclusive in Switch. Inspection of Figures 8 and 9 of the RPS Study [5] also indicated that MAPS was able to decommit the second Kalaeloa unit when not needed.

Consequently, in the Switch modeling, we configured Kalaeloa 1 to be committed at all times except from the 8 pm hour on Friday through the 9 am hour Saturday, and configured Kalaeloa 2 to be committed at all times when Kalaeloa 1 was out of service, unless Kalaeloa 2 was also scheduled to be out of service. We also scheduled Kalaeloa 2 to be out of service from 8:00 pm Saturday through 8:59 am Sunday. At all other times, there were no restrictions on whether Kalaeloa 2 was committed or not (i.e., we treated it like a cycling unit).

By inspection of Figures 8 and 9 of the RPS Study [5], we determined that Kalaeloa produced at least 75 MW at all times (even though each unit's minimum load was 65 MW). We assumed this reflected the cogen requirement, so we configured Switch to dispatch at least 75 MW from the Kalaeloa plant whenever it was not on maintenance outage.

Maui Peaking and Cycling Units

A 2008 validation report for the Maui version of MAPS, "Maui Electrical System Simulation Model Validation" indicated that Maalaea units 4–9 (a mix of cycling and peaking generators) were not available from 10 pm to 7 am [6]. This restriction was not mentioned in the RPS Study report, but we configured Switch to enforce this constraint.

Maui Combined Cycle Units

The Maui validation report for MAPS said that the Maalaea CC1 plant (consisting of M14, M15 and M16) operated in dual-train combined-cycle mode (using all three units) at all times, and that Maalaea CC2 (M17, M18, M19) operated in dual-train mode from 6 am to 10 pm and single-train mode (turning off M17 or M19) from 10 pm to 6 am [6]. The RPS Study report said that scenarios 2–18 included "cycling of Maalaea CC" as a departure from current practice [5]. It was unclear from these sources what commitment restrictions were placed on the Maalaea combined cycle units (M14–M19) in MAPS. We configured Switch to commit Maalaea CC1 (M14–16) at all times and allow unrestricted cycling of Maalaea CC2 (M17–19).

Allocating up reserve targets to individual plants

Once the reserve targets are set for each power system, commitment and dispatch of individual power plants must be scheduled to ensure that enough reserves are available at all times. Individual plants can provide spinning up reserves when they are operating (committed), but not producing their maximum output, so that production can be raised on short notice. This "headroom" is each plant's contribution to the system reserve target. A key job of system operating models is to decide how much reserves will be provided from each plant in order to meet the target, i.e., allocating the overall target among individual plants.

It is not clear from the RPS Study report which power plants were designated to provide up reserves. The report says, "All of the HECO baseload units are modeled to provide a portion of the [up] contingency reserves" [5]. Table 7 of the RPS Study [5] indicates that the HECO baseload units consist only of Kahe 1–6 and Waiau 7–8. However, for the Switch modeling work, we assumed several additional plants were able to provide up-reserves. These were AES and Kalaeloa (third-party baseload plants) and Waiau 5–6 (HECO-owned cycling plants). We assumed AES and Kalaeloa were included because provision of up-reserves from Kalaeloa was discussed on pp. 45-46 of the study [5], and because they were designated as able to provide down-reserves [7]. We assumed the cycling plants were able to provide up-reserves based on inspection of Figures 8 & 9 of the RPS Study [5].

We also assumed that all plants designated as Baseload or Cycling in Table 7 of the RPS Study [5] provided up reserves on Maui. This was nearly the same as indicated in an earlier validation report for MAPS [6], which said that Maalaea 4–13 and Maalaea CC1 and CC2 (units 14–19) could provide up reserves; the only difference is that we excluded Maalaea units 4 and 6, which were listed as Peaking units in Table 7 of the RPS Study [5]. We excluded these units for two reasons: (a) GE reported separately that "peaking plants were assumed to provide supplemental replacement reserves only" (i.e., bulk power to free up other plants, but not spinning reserves) [8]; and (b) all peaking units (including these) were listed in Table 7 as having minimum loads of 0 MW; consequently, if they were allowed to provide up reserves, they could be "committed" at a 0 MW load and provide up reserves at no cost, which would be unrealistic.

Allocating Down Reserve Targets to Individual Plants

Division between renewable and thermal plants

The RPS Study also stated that the Oahu down reserve target was served partly by utility-scale wind and solar plants, and partly by conventional thermal plants, using the following formula [5]:

$$\text{Ratio of Down Reserves from W\&S} = \frac{\text{Wind \& Solar Capacity}}{\text{Wind \& Solar Capacity} + \text{Thermal Capacity}}$$

GE reported separately that the formula is recalculated hourly, and is based on the committed capacity of thermal plants and nameplate rating of utility-scale wind and solar plants [7]; we used that approach for Switch.

We assumed the formula only included the thermal plants that could provide down-reserves (discussed in the next subsection).

The Hawaii Solar Integration Study reported an additional assumption that "the solar and wind plants can contribute to down-reserves only when their output is above 20% of their rated capacity" [4]. GE reported separately that the same assumption was used in the RPS Study, and that it was applied per-plant [7]; we used the same approach for Switch.

This gives the following formulas for the active renewable and thermal capacity in hour h:

$$\begin{aligned}[\text{Wind \& Solar Capacity}]_h &= \sum_{p \in R_h} [\text{Nameplate Rating}]_p \\ [\text{Thermal Capacity}]_h &= \sum_{p \in T_h} [\text{Nameplate Rating}]_p\end{aligned}$$

where,

$$\begin{aligned}R_h &= \left\{ p \in [\text{Wind \& Solar Plants}]\text{: } \frac{[\text{Available Power}]_{p,h}}{[\text{Nameplate Rating}]_p} \geq 0.2 \right\} \\ T_h &= \left\{ p \in [\text{Thermal Plants}]\text{: committed}\left(p,h\right) = \text{True} \right\}.\end{aligned}$$

Then we used the following, more-specific equations to set the shares of the down-reserve target to be served by utility-scale renewable and thermal plants during each hour h:

$$\begin{aligned}[\text{Ratio of Down Reserves from W\&S}]_h &= \frac{[\text{Wind \& Solar Capacity}]_h}{[\text{Wind \& Solar Capacity}]_h + [\text{Thermal Capacity}]_h} \\ [\text{Ratio of Down Reserves from Thermal}]_h &= 1 - [\text{Ratio of Down Reserves from W\&S}]_h.\end{aligned}$$

We then allocated the thermal portion of down-reserves among the individual thermal plants using a process discussed in the next subsection. For the wind and solar plants, we assumed that the 20% rule combined with their low operating cost would ensure that they always produced enough power to satisfy their portion of the down reserve target. Consequently, we did not directly enforce the wind and solar portion of the down-reserve target.

Allocation among thermal plants

For Oahu, the RPS Study states that "All of the baseload HECO units and utility-scale wind and solar generating were modeled to provide down reserves" [5] GE reported separately [1, 7] that they assumed that AES and Kalaeloa provided down reserves in addition to all the HECO power plants identified as "Baseload" in Table 7 of the RPS Study [5]. We followed this approach with Switch.

GE reported separately that "the [down] reserve requirement is set for the thermal units, and then there is a tiered price approach to allocate it evenly" [7]. It appears that a supply-curve approach was used to allocate down reserve targets to individual plants, instead of optimizing that decision during the economic dispatch stage. We were not able to obtain or infer the details of this tiered approach, so we configured Switch to allocate down-reserves in direct proportion to each plant's committed capacity.

Generator Unit Commitment Process

Overview

Switch is normally configured to make commitment decisions automatically, in a way that minimizes operating cost while respecting reserve requirements and plant operating rules. However, for the intermodel comparison, we configured Switch to commit plants according to the priority lists discussed in the "Commitment Priority" subsection below, in order to more closely match HECO operations simulated in MAPS.

Although selecting plants from a queue to meet the energy and reserve targets appears simple at first, it is actually fairly complicated. As the decisionmaker steps through the commitment queue, the main challenge is determining whether the plants that have already been committed can be dispatched in such a way that they simultaneously meet the requirements for energy, up reserves and down reserves, and minimum up-time and down-time constraints. If not, additional capacity must be committed.

GE used an iterative process to commit plants to meet the power system's energy and reserve targets, and all power plants were committed based on day-ahead conditions, and then commitment for peaking plants was readjusted based on real-time conditions [1, 7, 8].

We configured Switch with a custom commitment algorithm that followed these broad guidelines. Specifically, our algorithm does the following, once for day-ahead commitment, and then again for real-time commitment:

1. Commit units from the appropriate queue until enough capacity is scheduled to meet the total demand for power plus up reserves. This calculation is done on a balancing-area-wide basis (individual islands if there was no grid tie, otherwise both islands together).

2. Commit additional up-reserve-eligible units if needed, until the system has enough up reserve capacity to meet the up-reserve requirement. Up reserve capacity was defined as the maximum production possible with currently committed up-reserve-eligible units, minus the minimum load and down-reserve targets for those units (i.e., the maximum up and down range for all units currently online). GE reported separately that they used the same method [9].

In this algorithm, Steps 1 and 2 work together to ensure that the system has enough energy and up reserves at all times, while taking account of down reserve targets that may impinge on up reserve capacity. Step 1 ensures that the system has enough capacity committed to meet the total requirement for energy and up reserves. Step 2 ensures that the plants that have been committed have enough maneuvering room to provide the required up-reserves. Together, these ensure that the system can be dispatched to provide enough power each hour, and also has a band of dedicated up reserves on top of that that is large enough to satisfy the reserve target.

Note that we do not know whether MAPS's commitment process was similar to this. For example, we do not know whether MAPS performed its commitment on a multi-island basis or per-island, or the details of how MAPS ensured that the power system could simultaneously meet power and up- and down-reserve requirements.

The following subsection describes these in more detail. The code and data to perform these steps are also available from [10].

Commitment Priority

Oahu Power Plants

We prioritized commitment of the Oahu power plants as follows:

1. Firm RE plants and baseload plants except Kalaeloa 2 and 3 (i.e., H-Power, Honua, Kahe 1–6, Waiau 7–8, Kalaeloa 1) were committed at all times they were available.
2. Cycling plants, were committed in order by full-load operating cost (Kalaeloa 2 & 3, then Waiau 5, then Waiau 6).
3. Peaking and biodiesel plants in order by full-load heat rate, but with Schofield moved to end of queue based on information from GE [11].

Maui Power Plants

The Maui validation report states that “The general commitment order was obtained from MECO as: K3, K4, M14/15/16 [CC1], M17/18 [CC2], K1, K2, M10, M19, M11, M12, M13, M8, M9, M4, M6, M1-3, X1, X2, M5, M7” [6]. We assumed that MAPS followed this sequence for the RPS Study, but with two new internal combustion engines added to the end of the list, and we used the same sequence for Switch.

Grid-Tie Scenarios

In grid tie scenarios, the model must prioritize between plants on both Maui and Oahu. We assumed that the two islands’ plants were prioritized as follows:

1. All firm RE and baseload plants except Kalaeloa 2 & 3 (always committed)
2. Oahu cycling plants and Kalaeloa 2 & 3
3. Maui Maalaea 10 through Maalaea 7 from the list in the “Maui Power Plants” subsection above (mixed cycling and peaking). We placed these later in the ordering than Oahu cycling plants because MAPS used them much less intensively than the Oahu cycling plants in the grid-tie scenarios (11–12, 14–15, 17–18) (see Table 9 of the RPS Study [5]).
4. Oahu peaking plants

The two-island commitment order we used in Switch is shown in Table S2. For scenarios without a grid tie, we used the same order, but considered only the plants on each island.

Commitment Algorithm

The unit commitment algorithm used in Switch for the intermodel comparison consisted of a main workflow and several supporting subroutines. These are each described below. The main process was run once during model initialization to select a commitment schedule for all units during all timesteps. Then, during the main optimization phase, unit commitment was constrained to match this schedule.

Note that normally Switch would optimize unit commitment directly; these scheduling rules were added to Switch to mimic HECO and MECO’s queue-based approach, as modeled in MAPS.

Main commitment process

1. Commit all plants that have a must-run requirement.
2. Perform day-ahead unit commitment for each balancing area. This performs the “commit plants” subroutine (discussed below) for all thermal plants, using the day-ahead renewable energy forecast. This produces a commitment plan for all plants for the next day. The commitment plan for cycling and baseload plants is locked in at this point, but commitment for peaking generators will be adjusted later.
3. Perform real-time unit commitment:
    a. “Commit” all wind and solar facilities. This adds their real-time output to the subsequent unit commitment calculations.

b. Reduce commitment for all peaking plants to the minimum allowed level (generally zero). This prepares them for recommitment based on real-time conditions. (Peaking plants are listed in Table S2 of this report and Table 7 of the RPS Study [5].

c. Perform real-time unit commitment. This performs the "commit plants" subroutine (discussed below) for only peaking thermal plants, using the real-time renewable energy production. This chooses the right commitment level for peaking plants based on real-time conditions.

"Commit plants" subroutine

This subroutine contains most of the logic for unit commitment. It is called for a particular balancing area (one island if there is no grid-tie cable, otherwise both islands together). It can optionally be instructed to use a day-ahead forecast of renewable power production. It completes the following steps:

```
# choose commitment queue (ordered list of generating units whose commitment should be
# adjusted upward if needed):
if day-ahead:
    commitment queue is all plants in current balancing area, sorted as shown in Table S2
else:
    commitment queue is all peaking plants in current balancing area, sorted as shown in Table S2
# meet energy and reserve requirements for whole balancing area:
Perform "allocate down reserves" subroutine (below).
For each unit in the commitment queue:
    If this unit requires special commitment:
        Do special commitment and return to top of the loop.
    For each timestep:
        If the total capacity currently committed for this timestep (including, optionally, the day-ahead renewable forecast) is insufficient to meet the energy and up reserve target:
            Commit the current unit.
        Otherwise, if the current generating unit is eligible to provide up reserves and the system currently has insufficient up reserve capacity (see "Overview" subsection above):
            Commit the current unit.
    Perform "fix commit schedule" subroutine for current generating unit. This commits the plant if necessary in any timestep to ensure that the minimum up- or down-time rules are never violated.
    If the current generating unit provides down reserves:
        Perform the "allocate down reserves" routine to update all down reserve targets.
```

"Allocate down reserves" subroutine

This subroutine selects a down-reserve target for each down-reserve-eligible thermal generating unit. This is done primarily by choosing a "down reserve fraction," which is the percentage of each unit's rated capacity to allocate for down reserves. The same down reserve fraction is applied to all eligible plants. The down reserve quota for each unit is set equal to the lesser of [down reserve fraction times committed capacity] or [committed capacity minus minimum load]. The down reserve fraction is raised until enough down reserves are available (or until the supply from committed plants is exhausted; this typically only happens in the early stages of unit commitment, before all plants are committed).

"Fix commit schedule" subroutine

This subroutine steps through all timesteps and commits the plant if necessary to ensure that the minimum up- or down-time rules are never violated. It attempts to fix violations of the minimum up-time rule by extending the commitment schedule later, but if that is not possible, it extends the schedule earlier instead. It fixes violations of the minimum-down-time rule by extending up-time through the brief down-time window (rather than extending down-time). It is possible that MAPS uses a much different approach to address these issues.

“Perform special commitment” subroutine

This routine provides specialized commitment for individual generating units that follow unusual rules. In our final configuration, this only applied to the Kalaeloa duct burner (Kalaeloa 3). This routine committed Kalaeloa 3 if and only if Kalaeloa 1 and 2 were already currently committed for the same timestep (see “Kalaeloa Combined Cycle Plant” section above).

Notes

The Maui commitment queue mixes cycling and peaking units (see “Maui Power Plants” subsection above). That is not a problem for this commitment algorithm. This algorithm makes a day-ahead commitment plan following the units’ ordering in the commitment queue (e.g., it may decide not to commit a cycling plant if higher-priority peaking plants provide sufficient capacity). This plan is binding for the cycling plants, but the commitment of the peaking plants is then readjusted based on real-time conditions.

When using this algorithm, Switch did not commit additional units specifically to meet the down reserve requirement; we assumed that by the end of the normal commitment process, enough down-reserve-eligible units were always committed to meet the down reserve target (10% of load, prorated between renewable and thermal capacity; see “Allocating Down Reserve Targets to Individual Plants” section above).

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