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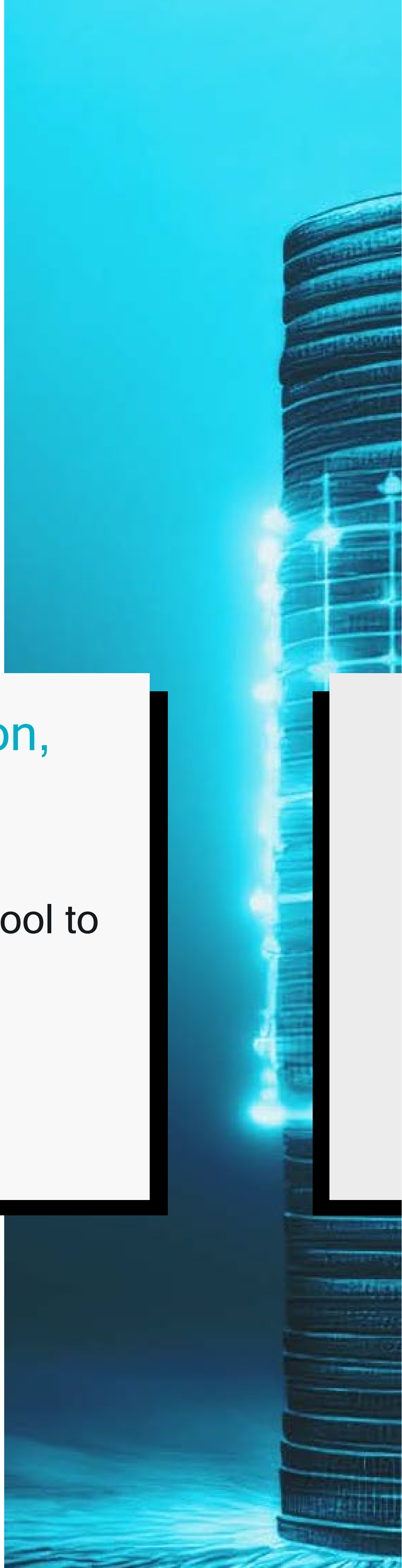
Grid Research, Innovation, and Transformation

Security Constrained Unit Commitment (SCUC)-Based Tool to Manage the Grid with Large Penetration of Energy Storage Resources

August 2025



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Executive Summary

The future resource mix trend shows increasing installed MW capacity of Intermittent Renewable Resources (IRRs) - (Wind and Solar) as well as increased installation of limited duration Energy Storage Resources (ESRs). Coupled with this is the growth in demand (load). Thus, in the future, with decreased thermal generation, the grid will be more reliant on storage to meet demand as well as balance (provide "slack" to) the intermittency of renewable generation.

Currently, the grid operator relies on Reliability Unit Commitment (RUC) that ensures that there is sufficient MW capacity on the supply side to meet the following objectives:

a. Meet forecasted Demand assuming forecasted IRR production and planned capacity of other types of Resources (thermal, battery energy storage);
b. Manage transmission congestion, and;
c. Satisfy the Ancillary Service (AS) needs to meet to the intra-day uncertainty of forecast errors (load and renewable) and forced outages of resources.

With thermal generation retiring and the challenging business case for installing new thermal generation, the grid is increasingly relying on ESRs to meet the intra-day uncertainty of forecast errors and forced outages of resources.

Currently in the ERCOT region, the average ESR duration is 1.5 hours. Recently some longer duration (2-hour and 4-hour) installations have come into commercial operations . From a ESR developer's perspective, the business case for capital investment for longer duration ESRs in the ERCOT region, are dependent on:

a. Ancillary Service requirement: Currently, most of the ESR's revenue is from the AS market but is gradually shifting to include revenue from energy price arbitrage as the AS market becomes saturated by ESRs. The duration requirement of an AS product will influence the capital investment for a longer duration ESR.

b. Energy Price arbitrage: With increased provision of the AS needs by ESRs, the AS market will (if not already) saturate leading to lower AS prices (Market Clearing Price for Capacity MCPCs). Energy arbitrage will be another source of revenue. The annual energy price duration curve informs the ESR developer of the duration that an ESR needs to have to capture any price differential (duration of high prices to discharge relative to the duration of low prices to charge). The energy price duration curve does not currently send a sufficient signal for the capital investment in duration exceeding 2 – 4 hours.
c. Capacity Construct: Capacity constructs such as Capacity Markets or Resource Adequacy (RA) mandate where ESR duration leads to its capacity contribution (e.g., effective load carrying capability metric) can provide a revenue stream that can justify the capital investment in longer duration ESRs. Other ISO's that have either a Capacity Market or a Resource Adequacy mandate have much longer duration ESRs than ERCOT as longer duration storage would contribute more to the RA requirement and thus earn greater revenue. For example, CAISO with a Resource Adequacy mandate, have most of the ESRs in their footprint with a duration of 4 hours. ERCOT does not have a Capacity construct.

The limited duration of ESRs (even with 4-hour duration) makes the job of ensuring sufficient energy (MWh) apart from sufficient MW capacity challenging for the grid operators, as real-time conditions (forced outages) may discharge ESRs earlier than expected leading to ESRs having insufficient energy to meet grid conditions at later time periods. For example, if a unit trips at 2:00 pm and batteries are deployed to make up for that energy, ERCOT may not have enough energy to meet peak demand later during the evening net load ramp.

In addition, during a multi-day event of high net load (high loads and low IRR output), it is challenging with existing operational strategies and short duration ESRs to ensure that the ESRs have sufficient stored energy that minimizes the probability of firm load shed.

To address these issues, ERCOT is implementing the Real-Time Co-optimization + Battery (RTC+B) project that is planned to go-live by the end of 2025. In this project there are explicit consideration for ESR stored energy (State-Of-Charge – SOC) in the Real-Time Market (RTM) as well as the Reliability Unit Commitment (RUC) process. The RTC+B RTM is a single interval market, i.e., The RTC+B RTM will dispatch for the prompt interval (5 minutes) and has no look ahead capability. CAISO has a multi-interval RTM market that has look ahead capability for a few hours. , CAISO experience has been that this look ahead capability, though useful, is not sufficiently long enough. CAISO has attempted to increase the look ahead capability of its multi-interval RTM but has hit performance bottlenecks as well as pricing and settlement concerns (dispatch instructions can be out of synch with the submitted market offers). From a reliability perspective, ERCOT operations would require a multi-interval RTM with a look ahead study horizon of approximately 8 hours. This is technically challenging at this time due to the computational performance requirement of clearing the multi-interval RTM quickly (as CAISO has experienced). Over the years, the ERCOT IMM has recommended moving to a multi-interval RTM in their State of the Market reports. This has not gained traction in the stakeholder community, primarily due to the issue of Resource dispatch instructions that could be out of synch with the submitted Bids/Offers leading to the issue of dealing with Make-Whole Payments (MWP).

ERCOT has taken a different route to address the longer look ahead capability required through the RTC-RUC process to ensure that there is sufficient ESR SOC (energy) over its study horizon. The RTC-RUC process self-schedules ESRs to the submitted Hour-Beginning Planned SOC (HBSOC) in their Current Operating Plan (COP) for each hour in the RUC study horizon. RTC-RUC utilizes ERCOT Operator entered Deployment Factors to simulate depletion of SOC from one interval to the next. Thus RTC-RUC will only dispatch for energy and award AS to an ESR, for a given hour, in a manner that considers deployment factors and the calculated SOC at the end of the given hour matches the COP HBSOC of the ESR for the next hour.

Even with the enhancements being made to the RTC-RUC, there remain some gaps. Current, as well as RTC versions of RUC model the energy costs (energy dispatch costs) above their Low Sustainable Limit (LSL) as almost zero. Only StartUp and Minimum Energy costs at LSL are realistic. This is to minimize the commitment instructions (out of the market) from RUC and thus minimize the impacts to Real-Time price formation. This approach of modeling energy costs in RUC is inappropriate for ESRs (especially limited duration ESRs) as their value is in their stored energy. This is the reason that for RTC-RUC, there is an enhancement to the RUC process to self-schedule ESRs to their submitted Current Operating Plan

(COP) values of SOC for each hour and RTC-RUC self-schedule ESRs to follow as close as possible the trajectory of individual ESR SOC to their respective COP values of SOC. This has the drawback that the results of RTC-RUC depend on good SOC data being submitted in the ESR COP for each hour.

As a further evolution/enhancement to the RTC-RUC tool/process, this paper describes an advanced SCUC multi-interval engine (RUC is also a SCUC multi-interval engine) that can allow the user flexibility in how the tool is used (e.g. changing inputs). The main salient features of this new SCUC tool are:

a. Modify the SOC accounting process (constraints in the new SCUC optimization engine) so as to make the new SCUC tool less dependent on the accuracy of the submitted COP data for ESR SOC.
b. Use the latest submitted market offers for Resources: This will provide a more accurate energy cost to the new SCUC tool that is essential in determining the expected energy dispatch of ESRs
c. "ISO-managed SOC" mode: This feature produces an "ideal/desired" energy dispatch for ESRs irrespective of their submitted market offers. This is to simulate a scenario where ERCOT determines the best way to utilize the stored energy in ESRs to minimize/eliminate firm load shed.
d. Ability to run "What-if-scenarios": This feature allows the ERCOT operator to simulate potential scenarios like sudden loss of a Generation Resource on a previous study to determine whether the previous commitment and dispatch pattern will be able to handle the "What-if-scenario" condition.

The additional outputs of this new tool on top of existing outputs from RTC-RUC are:

a. "Ideal/Desired" SOC trajectory across the hours of the study to be compared with the market submitted ESR SOC values in their respective COPs

The expected value addition of this new SCUC tool is a better situational awareness to ERCOT operators to identify critical periods where the system may go short on energy sufficiency. For example:

a. This will be useful on a daily basis to identify the net load ramp periods where there may be energy insufficiency.
b. A multi-day study with this new SCUC tool can be used to study upcoming weather fronts and identify periods that are best for the ESRs to discharge and charge so as to minimize/eliminate any firm load shed.

The focus of this paper is to describe a new SCUC tool that can identify periods of risk in terms of energy insufficiency. It does not go into any details on what to do with the results. That is future work.

1. Purpose

This paper describes features of a new study tool/process based on a Security Constrained Unit Commitment (SCUC) engine to manage a grid with increased penetration of Energy Storage Resources (ESRs).

This new SCUC based tool/process has many similar features of ERCOT's RTC-RUC tool. Here we describe only the features that differ from the standard features of RTC-RUC.

This SCUC based tool/process will optimize over a user defined multi-interval time period that can span multiple days (from remaining hours of the current day like HRUC to multiple days (up to 7 days like WRUC).

This new SCUC tool is expected to have a much slower performance than RTC-RUC and thus not expected to meet the RUC process timelines. The new SCUC tool is currently not proposed to replace RTC-RUC. It is proposed as an additional tool to be initially run on demand as needed by the user.

For RUC study horizons that span a whole day or multiple days, the new SCUC will evaluate the need to commit long lead time thermal Resources. For the shorter look ahead perspective (remaining hours of the day), the new SCUC study will evaluate the need to preserve SOC (if there are no thermal units with short enough lead time to commit).

The objective of RUC is to commit sufficient resources to meet the forecasted conditions. There are two main adjustments to this tool, both focused on ESRs:

1. Ensure that a realistic energy and AS profile for ESRs are assumed for the RUC process so that sufficient thermal resource commitments can be made if energy is not available during certain time periods within the RUC study horizon.

2. Ensure that, if necessary, energy from ESRs is held back so that sufficient energy may be available for critical time periods within the RUC study horizon.

In the new SCUC, the initial value of the ESR SOC is the COP value of HBSOC for the first hour in the SCUC study horizon. For the rest of the hours within the SCUC study horizon, the SCUC engine will determine energy and AS awards such that the calculated ESR SOC at the end of each hour respects each hour's minSOC and maxSOC limits, i.e., SCUC will not respect the COP value of HBSOC for each hour.

Use Cases are presented with potential ERCOT Operator actions based on the results of the studies. Note that any ERCOT Operator action using this tool will require NPRR(s) that are approved through the ERCOT Stakeholder Process.

2. Input Data Pre-Processing

2.1 Input Data Pre-Processing

ERCOT generates multiple IRR forecasts (currently 4 for solar and 4 for wind) using different forecasting models. ERCOT also generates multiple load forecasts using different models.

The ERCOT operations risk assessment tool will analyze the various IRR forecasts and load forecasts and select the IRR forecast and Load forecast to be used by ERCOT operations based on risk factors (high net load, high net load ramp), historical accuracy of a given forecast model for a given time period, etc. Below are some of the possible outcomes:

a. Combination of IRR and Load forecast that has highest net load ramp.
b. Combination of IRR and Load forecast that has highest net load.

For IRRs, ERCOT sets the individual IRR HSL in the COP using the ERCOT IRR forecast with a 50% chance of exceedance. The QSE operating the IRR can reduce the HSL in COP from the HSL value set by ERCOT.

RTC-RUC uses the input IRR (via IRR COP HSL) and selected load forecast. The new SCUC will use these same forecast inputs.

2.2 Missing Three Part offer (TPO), Bid/Offer, Bid-To-Buy or AS Offer data

For the new SCUC study horizon, if Resource TPO, Bid/Offer or AS Offer data is missing, there needs to be a way of automatically "filling in the blanks" to span the entire SCUC study horizon. One option is:

a. Missing GR TPO:If the GR is not on Outage (GR does not have an outage submitted in the ERCOT Outage Scheduler) - Set GR TPO to 150% of the Resource Category/Verifiable Costs for Startup and Minimum Energy Costs and 100% for the incremental energy costs.
b. Missing ESR TPO:If the ESR is not on Outage (ESR does not have an outage submitted in the ERCOT Outage Scheduler) - Set ESR Bid/Offer to the last valid submission of the Bid/Offer (or the last valid values for

the same hour on previous days?).

c. Missing CLR Bid-To-Buy: If the CLR is not on Outage - Set CLR Bid-To-Buy to the last valid submission of the Bid-To-Buy (or the last valid values for the same hour on previous days?).

d. Missing AS Offer data: Set the AS offer to be 0$/MW/h for all qualified AS MW.

2.3 ESR Input Data Sanity Checks and Massaging

COP data and calculated SOC of ESR for a given interval (hour Ending) is graphically presented below. The COP data of HSL, LSL, MinSOC, and MaxSOC for a particular interval (hour ending) is valid from the start to end of the whole interval. For first interval (first hour of study), the SOC is initialized to the Hour Beginning Planned SOC from the first hour of the

COP. i.e. the SOC variable depicted in later sections corresponds to the time-point at the start of the interval. For future intervals, the SOC variable at the start of that interval is a calculated value.

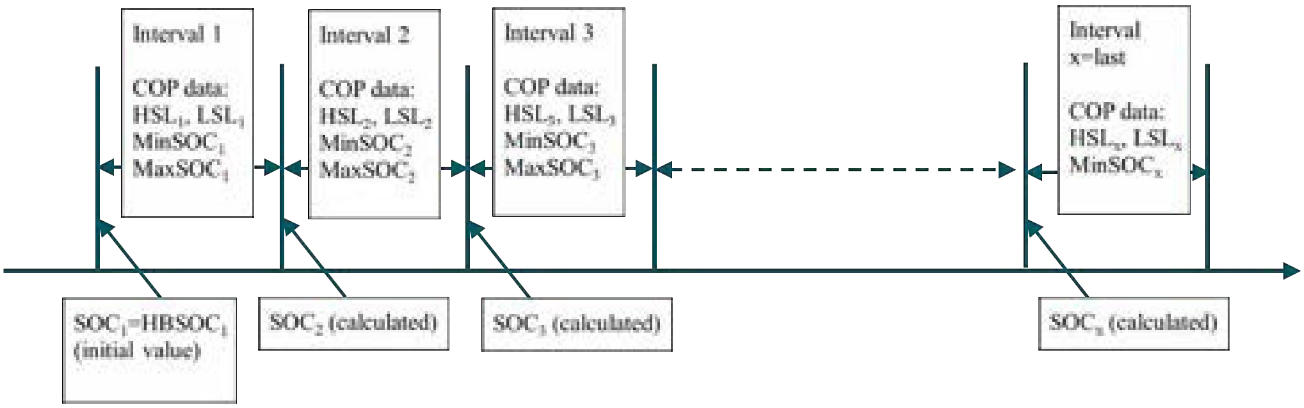

Figure 1. Graphical illustration of SOC calculation.

a. For RUC Study hours (h=1,2,3,4,…last hour) and for each ESR$_i$:

   i. If

   $$\left(COPHSL_{i,h} < 0 \;\&\&\; \left(COPHourBeginningPlannedSOC_{i,h_{i,h}} - COPHSL_{i,h} \times \Delta t^{ruc}_{ene}\right) > COPMaxSOC_{i,h}\right)$$

   then

   A. Log message:

   “Inconsistent COP data for hour ending h, Resource Name = ESR_XXX, HSL= xxx, MaxSOC=yyy, HBSOC= zzz. HSL is negative and the forced charging at a minimum of HSL will violate MaxSOC for the hour h. DSI setting HSL=0”

   B. Set $HSL_{i,h} = 0$ for this Resource for hour ending h

b. If

$$\left(COPLSL_{i,h} > 0 \;\&\&\; \left(COPHourBeginningPlannedSOC_{i,h_{i,h}} - COPLSL_{i,h} \times \Delta t^{ruc}_{ene}\right) < COPMinSOC_{i,h}\right)$$

then

A. Log message:

“Inconsistent COP data for hour ending h, Resource Name = ESR_XXX, LSL= xxx, MinSOC=yyy, HBSOC= zzz. LSL is positive and the forced discharging at a minimum of LSL will violate MinSOC for the hour h. DSI setting LSL=0”

B. Set $LSL_{i,h} = 0$ for this Resource for hour ending h

> Note: For the next validation check below, The COP values for HSL and LSL will be used unless they are overridden by these adjusted values.

c. RTC RUC preprocessing shall process the COP data (MinSOC, MaxSOC) and flag any ESR identified by hour(s) where two consecutive hours (MinSOC,MaxSOC) are such that they lead to infeasibility.

   i. For RUC study hours (h=2,3,4, … last hour) - serial processing (daisy chain):

      If $(COPMinSOC_{i,h} > COPMaxSOC_{i,h-1})$ then

      $$COPMinSOC_{i,h} = COPMaxSOC_{i,h-1} - ThresholdMWh$$

      A. Log message:

         “Inconsistent COP data for hour ending h, Resource Name = ESR_XXX, hour= uuu, COPMinSOC=vvv, next hour=www, COPMaxSOC=xxx, next hour COPMaxSOC changed = yyy”

         If $(COPMaxSOC_{i,h} < COPMinSOC_{i,h-1})$ then

         $$COPMaxSOC_{i,h} = COPMinSOC_{i,h-1} + ThresholdMWh$$

      B. Log message:

         “Inconsistent COP data for hour ending h, Resource Name = ESR_XXX, hour= uuu, COPMinSOC=vvv, next hour=www, COPMaxSOC=xxx, next hour COPMaxSOC changed = yyy”

3. Features of New SCUC

This section describes features of the new SCUC that are different than RTC-RUC. Unless otherwise specified, this new SCUC tool will have the same features as that of RTC-RUC (e.g. determining initial ON/OFF hours, Hot/Intermediate/Cold startup times, ignore Resource ramps, etc.)

3.1 New SCUC Objective Function

The objective function of SCUC is to maximize social welfare to meet grid demand, manage congestion and procure AS (as per the respective AS Demand Curves). This objective is the same as the objective function of RTC-RUC except for, depending on the options chosen, some category of resource costs included in the objective function.

3.1.1 Production costs

An ancillary output will be production costs. The new SCUC tool should output production costs based on Resource type/category, penalty violation costs by category, etc. One approach is having the objective function for the incremental costs be modeled from LSL to HSL so that the extraction of production costs can be directly obtained from the objective function of the optimization. If this is cumbersome with proxy extensions of the incremental energy costs, then a post processing can be used to recalculate the production cost component from incremental energy costs.

3.2 Energy Storage Resource (ESR) Modeling

There are two considerations for ESR modeling in this new SCUC:

a. How the SOC is managed, and
b. How the submitted ESR bid/offer are used

3.2.1 ESR SOC Constraint Modeling change from RTC-RUC

In RTC-RUC, ESR's are self-dispatched to their submitted COP values of HBSOC. RTC-RUC will award an ESR, energy and AS, using deployment factors such that the end of hour calculated SOC matches the next hours COP HBSOC. The reason for this approach in RTC-RUC is because this approach decouples inter hour SOC dependency and has less impact on RTC-RUC execution performance to meet operational timelines for the RUC process, also the use of Mitigated Offer Caps (MOC)with scaling as the incremental energy costs for Generation Resources (GRs) distorts the cost of energy and can lead to a misrepresentation of the energy costs which are crucial for the proper accounting of ESR State-Of-Charge (SOC).

For the new SCUC, the approach taken is to let the optimization engine determine the remaining SOC at the end of the hour (based on SCUC awards for energy and AS and using deployment factors) and use this value of SOC for the starting point for the next interval. This leads to a coupling between hours (inter hour SOC coupling constraints). Using this approach has a detrimental impact on SCUC computational performance but allows for a system wide optimization to determine the best way to utilize the stored energy (SOC) in the ESR. The approach proposed for the new SCUC is summarized below:

a. SCUC will initialize the first hour of study SOC as the value of HBSOC from COP for that first hour.
b. Preprocessing of data to ensure feasibility (before the optimization starts). The details are provided in the section 3.

Using deployment factors and SCUC awards for energy and AS, will calculate the SOC at the end of each hour that will be used as the starting SOC for the next hour in the study. Also, this calculated SOC at the end of each hour will satisfy the MinSOC and MaxSOC for the current hour as well as the MinSOC and MaxSOC for the next hour.

3.2.2 ESR SOC accounting related parameters:

- Δt_{ene}^{scuc} : Time duration required to sustain MW energy dispatch (analogous to Real-Time Base Point) – Default value 60 minutes
- Δt_{Reg}^{scuc} : Time duration required to sustain MW Regulation Up/Down dispatch (analogous to Real-Time Regulation Up/Down MW award) – Default value 60 minutes
- Δt_{RPF}^{scuc} : Time duration required to sustain MW RRS-PFR dispatch (analogous to Real-Time RRS-PFR MW award) – Default value 60 minutes
- Δt_{RFF}^{scuc} : Time duration required to sustain MW RRS-FFR dispatch (analogous to Real-Time RRS-FFR MW award) – Default value 60 minutes
- Δt_{ecr}^{scuc} : Time duration required to sustain MW ECRS dispatch (analogous to Real-Time ECRS MW award) – Default value 60 minutes
- Δt_{nsp}^{scuc} : Time duration required to sustain MW Non-Spin dispatch (analogous to Real-Time Non-Spin MW award) – Default value 60 minutes
- κ_h^{RegUp} : Deployment Factor for Regulation Up in hour h
- κ_h^{RegDn} : Deployment Factor for Regulation Down in hour h
- κ_h^{RPF} : Deployment Factor for RRS-PFR in hour h
- κ_h^{RFF} : Deployment Factor for RRS-FFR in hour h
- κ_h^{ecr} : Deployment Factor for ECRS in hour h
- κ_h^{nsp} : Deployment Factor for Non-Spin in hour h

3.2.3 Initial value of ESR SOC for the first hour (h=1) of SCUC study

For 1st hour of SCUC Study (h=1), the Initial Value of SOC is set to be the ESR COP value of HBSOC for the first hour (h=1).

$$SOC_{esr,1} = HBSOC_{esr,h=1}$$

The subscript h in the term $SOC_{esr,h}$ indicates the value of SOC at the END of interval h.

3.2.4 ESR SOC Constraints

Simultaneous upward and downward AS deployment scenario is not considered for either charging or discharging scenarios as the above constraints are more conservative and will ensure that the COP minimum and maximum operating SOC values are not violated with simultaneous upward and downward AS deployment. Note that in these equations, the variable SOC_x is the SOC at the start of the interval x.

For hour h of SCUC Study:

a. If $MW_{i,h}^{EnergyBidOfferAward} \geq 0$ then (ESR has discharge energy dispatch)

Ensure that, with a discharging energy dispatch, if all upward AS (RegUp, RRS-PFR, RRS-FFR, ECRS, NonSpin) are fully deployed (duration requirements for energy and AS), that there is sufficient SOC so that the ESR is not discharged below its COP minimum operating SOC value for the hour h:

$$SOC_{esr,h}$$
$$-MW_{esr,h}^{EnergyBidOfferAward} \times >\Delta\ t_{ene}^{scuc}$$
$$-MW_{esr,h}^{RegUpAward} \times >\Delta\ t_{Reg}^{scuc}$$
$$-MW_{esr,h}^{RRSPFAward} \times >\Delta\ t_{RPF}^{scuc}$$
$$-MW_{esr,h}^{RRSFFAward} \times >\Delta\ t_{RFF}^{scuc}$$
$$-MW_{esr,h}^{ECRSSAward} \times >\Delta\ t_{ecr}^{scuc}$$
$$-MW_{esr,h}^{NSPINAward} \times \Delta t_{nsp}^{scuc}$$
$$\geq MinSOC_{esr,h}$$

Ensure that, with a discharging energy dispatch, if downward AS (RegDown) is fully deployed (duration requirements for energy and AS), that the ESR's calculated SOC is not above its COP maximum operating SOC value for the hour h:

$$MaxSOC_{esr,h} \geq SOC_{esr,h}$$
$$-MW_{esr,h}^{EnergyBidOfferAward} \times \Delta t_{ene}^{scuc}$$
$$-MW_{esr,h}^{ECRSSAward} \times >\Delta\ t_{ecr}^{scuc}$$

The starting SOC for the next interval (hour h+1) is calculated using Deployment Factors for energy and AS. This calculated value of SOC for the start of the next interval must be within the min and max SOC limits for the next interval (h+1):

$$
\begin{aligned}
SOC_{esr,h+1} = SOC_{esr,h} \\
& -MW_{esr,h}^{EnergyBidOfferAward} \times \Delta t_{ene}^{ruc} \\
& -\kappa_h^{RegUp} MW_{esr,h}^{RegUpAward} \times \Delta t_{Reg}^{ruc} \\
& +\eta_{rt} \kappa_h^{RegDn} MW_{i,h}^{RegDnAward} \times \Delta t_{Reg}^{ruc} \\
& -\kappa_h^{RPF} MW_{esr,h}^{RRSPFAward} \times \Delta t_{RPF}^{ruc} \\
& -\kappa_h^{RFF} MW_{esr,h}^{RRSFFAward} \times \Delta t_{RFF}^{ruc} \\
& -\kappa_h^{ecr} MW_{esr,h}^{ECRSSAward} \times \Delta t_{ecr}^{ruc} \\
& -\kappa_h^{nsp} MW_{esr,h}^{NSPINAward} \times \Delta t_{nsp}^{ruc}
\end{aligned}
$$

$$SOC_{esr,h+1} \leq MaxSOC_{esr,h+1}$$

$$SOC_{esr,h+1} \geq MinSOC_{esr,h+1}$$

These last two constraints show that the calculated value of SOC_{h+1} at the end of a given interval h must be within the min and max SOC limits of the next interval (h+1).

The change in SOC during an interval is based on how much SOC was depleted due to discharging energy dispatch and likely RegUp deployment and boosted by likely RegDown deployment (taking into account regulation deployment factors). κ_h^{RegUp} and κ_h^{RegDn} are the Regulation Up and Regulation Down deployment factors respectively (value between 0 and 1 for the interval/hour h). In addition, RRS-PFR, RRS-FFR, ECRS and NSPIN deployment factors are considered. κ_h^{RPF}, κ_h^{RFF}, κ_h^{ecr} and κ_h^{nsp} are the RRS-PFR, RRS-FFR, ECRS and NSPIN deployment factors respectively (value between 0 and 1 for the interval/hour h).

b. If $MW_{i,h}^{EnergyBidOfferAward} < 0$ then (ESR has a charge energy dispatch)

Ensure that, with a charging energy dispatch, if all upward AS (RegUp, RRS-PFR, RRS-FFR, ECRS, NonSpin) are fully deployed (duration requirements for energy and AS), that there is sufficient SOC so that the ESR is not discharged below its COP minimum operating SOC value for the hour h:

i. $SOC_{esr,h}$

1. $-\eta_{rt} MW_{esr,h}^{EnergyBidOfferAward} \times \Delta t_{ene}^{ruc}$
2. $-MW_{esr,h}^{RegUpAward} \times \Delta t_{Reg}^{ruc}$
3. $-MW_{esr,h}^{RRSPFAward} \times \Delta t_{RPF}^{ruc}$
4. $-MW_{esr,h}^{RRSFFAward} \times \Delta t_{RFF}^{ruc}$
5. $-MW_{esr,h}^{ECRSSAward} \times \Delta t_{ecr}^{ruc}$
6. $-MW_{esr,h}^{NSPINAward} \times \Delta t_{nsp}^{ruc}$

ii. $\geq MinSOC_{esr,h}$

Ensure that, with a charging energy dispatch, if downward AS (RegDown) is fully deployed (factoring safety margin, duration requirements for energy and AS), that the ESR's calculated SOC is not above its COP maximum operating SOC value for the hour h:

$$
\begin{aligned}
MaxSOC_{esr,h} \geq\ & SOC_{esr,h} \\
& -\eta_{rt} MW_{esr,h}^{EnergyBidOfferAward} \times \Delta t_{ene}^{ruc} \\
& +\eta_{rt} MW_{esr,h}^{RegDnAward} \times \Delta t_{Reg}^{ruc}
\end{aligned}
$$

The starting SOC for the next interval (hour h+1) is calculated using Deployment Factors for energy and AS. This calculated value of SOC for the start of the next interval must be within the min and max SOC limits for the next interval (h+1):

$$
\begin{aligned}
SOC_{esr,h+1} =\ & SOC_{esr,h} \\
& -\eta_{rt} MW_{esr,h}^{EnergyBidOfferAward} \times \Delta t_{ene}^{ruc} \\
& -\kappa_h^{RegUp} MW_{esr,h}^{RegUpAward} \times \Delta t_{Reg}^{ruc} \\
& +\eta_{rt} \kappa_h^{RegDn} MW_{i,h}^{RegDnAward} \times \Delta t_{Reg}^{ruc} \\
& -\kappa_h^{RPF} MW_{esr,h}^{RRSPFAward} \times \Delta t_{RPF}^{ruc} \\
& -\kappa_h^{RFF} MW_{esr,h}^{RRSFFAward} \times \Delta t_{RFF}^{ruc} \\
& -\kappa_h^{ecr} MW_{esr,h}^{ECRSSAward} \times \Delta t_{ecr}^{ruc} \\
& -\kappa_h^{nsp} MW_{esr,h}^{NSPINAward} \times \Delta t_{nsp}^{ruc}
\end{aligned}
$$

$$SOC_{esr,h+1} \leq MaxSOC_{esr,h+1}$$

$$SOC_{esr,h+1} \geq MinSOC_{esr,h+1}$$

These last two constraints show that the calculated value of SOC_{h+1} at the end of a given interval h must be within the min and max SOC limits of the next interval (h+1).

The change in SOC during an interval is based on how much SOC was depleted due to discharging energy dispatch and likely RegUp deployment and boosted by likely RegDown deployment (taking into account regulation deployment factors). κ_h^{RegUp} and κ_h^{RegDn} are the Regulation Up and Regulation Down deployment factors respectively (value between 0 and 1 for the interval/hour h). In addition, RRS-PFR, RRS-FFR, ECRS and NSPIN deployment factors are considered. κ_h^{RPF}, κ_h^{RFF}, κ_h^{ecr} and κ_h^{nsp} are the RRS-PFR, RRS-FFR, ECRS and NSPIN deployment factors respectively (value between 0 and 1 for the interval/hour h).

3.2.5 ESR Energy Bid/Offer and AS Offer

RTC-RUC does not include ESR Energy Bid/Offer costs into the objective function as they are self-scheduled to their hourly HBSOC.

For the new SCUC the following options are proposed:

a. Option 1 (Default): ESRs are modeled using the concept of "ISO-managed SOC". In this concept, ERCOT's objective is to meet the reliability needs of the grid without consideration of the costs in the submitted ESR energy bid/offer, nor will the objective function consider the costs of the submitted ESR AS Offers. i.e. ESR energy Bid/Offer and ESR AS Offer costs are not included in the new SCUC objective function. i.e. this is equivalent to the ESR energy bid/offer and ESR AS offers being 0$/MWh or 0$/MW/h respectively.
b. Option 2: ESR energy Bid/Offer and AS Offer costs are included in the new SCUC Objective function. If energy Bid/Offer and/or AS Offer are not submitted then use 0$/MWh for the energy bid/offer and 0$/MW/h for all qualified AS. It should be noted that in the new optimization that links SOC across time as variables, the offers and bids of the ESR may not mean the same thing as they do without that functionality.

3.3 Generation Resource (GR) Modeling

Most of the RTC-RUC features are incorporated into the new SCUC. Additional features for the new SCUC are described below.

3.3.1 MinUp constraint for GR

RTC-RUC process will only commit a Resource if it can be shut down at the end of the RTC-RUC study horizon. An option will be available, where the new SCUC can model the MinUp constratint to be open at the end of the SCUC study horizon. For example, the new SCUC tool can commit a Resource for the last interval in the SCUC study horizon even if the MinUp time is greater than one interval duration. This may be needed at times - mainly for multi-day weather events allows the new SCUC tool to commit very long MinUp time Resources where the MinUp time Resources may exceed the SCUC study horizon.

3.3.2 Combined Cycle “Up” transition

RTC-RUC does not have the ability to change the combined cycle configuration to a higher (more MW capacity) configuration if the combined cycle has submitted a COP specifying one on-line configuration (RTC-RUC does not change the on-line self-committed configuration). The new SCUC tool will have the capability of moving a self-committed combined cycle configuration to a higher MW capacity configuration if required while satisfying all temporal constraints.

3.3.3 GR TPO (Startup, MinEnergy and Energy Offer Curve (EOC)) and AS Offers

RTC-RUC has various options for modeling a GRs EOC. In all these options the costs are included in the RTC-RUC objective function. The options for the new SCUC provided below have all option costs included in the objective function.

For the new SCUC tool the following options are provided:

a. **Option 1 (Default)**: The submitted GR TPO and AS Offer costs are used/included in the new SCUC Objective function. If the GR TPO and/or AS Offer are not submitted then use the 150% of Generic Costs/Verifiable costs by Resource Type for Startup and Minimum energy costs and 100% of the generic/verifiable incremental costs for energy and 0$/MW/h for AS offers.
b. **Option 2**: The GR MOC for the incremental energy costs and 150% of the Resource Category specific/Verifiable Startup and Minimum Energy Costs is used/included in the new SCUC Objective function. AS Offers are all considered to be offered for the qualified AS MW at 0$/MW/h. For Startup and Minimum.
c. **Option 3**: 150% of the Resource Category specific/Verifiable Startup and Minimum Energy Costs and 100% of the generic/verifiable incremental costs for energy is used/included in the new SCUC Objective function. AS Offers are all considered to be offered for the qualified AS MW at 0$/MW/h.

3.4 Controllable Load Resource (CLR) Modeling

RTC-RUC treats CLRs as firm load for energy and is thus not dispatched for energy. The new SCUC will have the following options: (this is for a post NPRR 1188 – nodal dispatch of CLRs)

a. **Option 1 (Default):** The submitted CLR Bid-To-Buy and AS Offers are used/included in the objective function. If a CLR Bid-To-Buy and/or AS Offer is not submitted, then the CLR is treated as firm load and is not considered dispatchable for energy as well as not eligible for any AS award.
b. **Option 2:** Treat CLR as firm load (same as RTC-RUC) for energy but AS Offers are used/included in the objective function. If AS offer not submitted, then the CLR is treated as firm load and is not considered dispatchable for energy as well as not eligible for any AS award.

With Option 1, the new SCUC will have a modified power balance constraint and will dispatch CLRs like GR and ESRs to meet demand and AS requirements while managing congestion

3.5 Non-Controllable Load Resource (NCLR) Modeling

RTC-RUC treats NCLRs as firm load and is thus not dispatched for energy. RTC-RUC will optimize any submitted AS Offers for a NCLR and thus are eligible for AS awards. There are restrictions on the combination of different AS type awards enforced through binary constraints.

For the new SCUC tool, more discussion is needed to determine :

a. Setting up a proxy Load Zone bid-to-buy for NCLRs to allow the new SCUC to dispatch NCLRs for energy.
b. For energy dispatch, binary variables are needed to properly model the “blocky” dispatch of NCLRs.
c. There will be a need to model temporal constraints (return to service time).
d. In addition, potential system wide constraints (PRC below a threshold) to trigger curtailment of NCLRs – simulation of Operator action.

Dispatching NCLRs for energy can be modeled by pseudo Generators at the Load Zone (using Load Zone Shift factors) to represent the curtailed amount of NCLR load.

3.6 Price Responsive Demand Response Modeling

RTC-RUC treats load as firm load and is thus not dispatched for energy. To simulate Price Responsive Demand, pseudo-Generators at the Load Zone (using Load Zone Shift factors) is used to represent the curtailed amount of Price Responsive Demand.

The user can setup at an individual Load Zone level a bid to buy curve (price and MW points) to represent different levels of price points where different levels of Price Responsive Demand will curtail. An option is provided to either enable or disable Price Responsive Demand in a study.

3.7 Incremental Energy and AS Cost Curve Extension

Based on the options for each category of Resource, if the incremental energy cost curve does not cover the submitted COP LSL to HSL range, then the following options are available to the user:

a. **Option 1**: Implement the logic for extending energy and AS cost curve as specified for RTC-RUC in the protocols. For AS, it means ensuring that the AS Offer is linked for all qualified AS types/sub-types.
b. **Option 2**: Implement the logic for extending energy and AS cost curve used in the Real-Time Market. For AS, it means ensuring that the AS Offer is linked for all qualified AS types/sub-types.
c. An issue with implementing the Real-Time logic for energy costs is that if the cost curve does not cover the LSL to HSL (LPC to MPC for CLRs) is that the Real-Time logic is to setup the proxy extension uses large negative cost (-250$/MWh) and high prices (RTSWCAP – 0.01 $/MWh). This leads to a large negative component in the objective function that obfuscates the production cost.
a. **Option 3**: Simple extensions of the incremental energy cost curve is used:
   1. For GR/ESR:
      i. extend the lowest price closest to LSL down to Min(LSL,0) MW.
      ii. extend the highest price closest to HSL up to Max (HSL,99999) MW.
   2. For CLR:
      i. extend the lowest price point closest to MPC up to MPC or 9999 MW.
      ii. extend the highest price closest to LPC down to LSL or 0 MW.

3.8 PowerFlow and Contingency Analysis

RTC-RUC uses a form of DC powerflow and DC contingency Analysis. For the new SCUC, the use of AC Powerflow and AC Contingency Analysis is proposed.

The AC powerflow and AC Contingency Analysis will switch to a DC powerflow and DC Contingency Analysis if the AC powerflow and contingency analysis does not converge. This allows the new SCUC to model reactive/voltage limits. This will align the results of the powerflow and contingency analysis with the EMS network analysis functions like STNET/RTNET.

a. Ability to output PSS/E format files (bus branch or node breaker model) with the solved commitment/dispatch for any interval in the SCUC study horizon.
b. RAS modeling should be the same as what is used in EMS Contingency Analysis

3.8.1 Transmission Loss Modeling

All the standard implementation of SCUC with AC powerflow/contingency analysis model losses using the incremental loss model. This results in the energy prices (LMP) output from the SCUC process having a loss component. The ERCOT RTM does not model incremental losses.

More discussion is needed to determine whether the new SCUC will use the incremental loss model or to be more aligned with the ERCOT RTM (average loss model). With the average loss model approach, transmission losses computed by the AC powerflow will need to be accounted for in the optimization engine so that the new SCUC process does not have convergence issues.

3.9 Calculate prices

Resource LMPs, Resource Node LMPs, HUB LMPs and Load Zone LMPs are calculated for each hour.

3.10 “What-If” Scenario Modeling

a. “What-if” scenario SCUC study horizon is within the “Base run” SCUC study horizon. For example, if the “Base run” SCUC study horizon is run at 9am for a study horizon for the remaining hours of the day (HE11-HE24), then any “What-if” scenario SCUC study horizon is within HE11-HE24.

b. "What-if" scenarios can be predefined and run sequentially after the "Base run" or can be setup on the fly to allow user to examine the "Base run" results and then develop "What-if" scenarios.

A particular "What-If" scenario could be any combination of the items below:

1. Change the AS deployment factors (different than what was used in the "Base run")
2. Change the IRR forecast and/or load forecast (different than what was used in the "Base run"): This may be more complex to implement as it requires changing the HSL of the IRRs for the changed IRR forecast and will require redistribution of the load forecast to the individual loads
3. Change COP status for individual Resources: For example, if the "Base run" study was from HE11-HE24 and the "What-if" scenario is from "HE15-HE24, change a large GR COP status from ON to OUT to simulate a forced outage from HE 15-HE24
4. Run only the dispatch optimization – i.e. use the commitment from the "Base run" and do not allow the "What-if" SCUC commit additional GR.
5. Others? Expand "What-If" Scenario builder capabilities

3.11 SCUC Outputs/Results

The new SCUC outputs are the same as RTC-RUC with the addition of:

a. Output on an individual ESR level, the calculated SOC at the end of each hour of the SCUC study horizon.

3.12 SCUC Output/Results Analysis

Apart from the same analysis done for the results of RTC-RUC, some additional analysis will be to:

a. Compare the calculated SOC at the end of each hour of the SCUC study period and compare it to the submitted COP value of HBSOC. This comparison is to show what the SCUC tool requires the SOC to be at versus what the QSEs are submitting to ERCOT in their ESR COPs on where they expect the ESR SOC level to be at.

b. Compare the calculated net load (using SCUC dispatch of IRR) against the input net load (using IRR forecasts). This will capture the impact of IRR curtailment.

c. Compare for overlapping study periods the results of the "Base run" to each of the "What-if" scenarios. Some of the items to compare could be:

   1. System wide SOC
   2. Thermal Unit Commitment
   3. Congestion pattern
   4. Others?

d. In Real-Time monitor system wide totals SOC and compare to the SCUC results of calculated SOC to get a situational awareness of how the current SOC levels are deviating from the expected value of SOC from the SCUC study.

4. Use Cases

The key difference between RTC-RUC and the new SCUC is in the way ESRs are modeled. In the new SCUC, the initial value of the ESR SOC is the COP value of HBSOC for the first hour in the SCUC study horizon. For the rest of the hours within the SCUC study horizon, the SCUC engine will determine energy and AS awards such that the calculated ESR SOC at the end of each hour respects each hours minSOC and maxSOC limits, i.e, SCUC will not respect the COP value of HBSOC for each hour.

4.1 Use Case 1

Analyzing evening net load ramp due to solar ramp down and evaluate the need to commit a long lead time thermal unit.

a. Run SCUC @10am (with one of the options) for remaining hours of day with all AS deployment factors set to zero. This is the "Base Case" and gives the "ideal" system wide SOC trajectory over the study period, if the forecasts are accurate. "Base Case" SCUC results do not recommend committing a long lead time thermal unit.
b. Run a "What-If" scenario with a study period from 10am to the end of the day (same study period as the "Base Case"). In this scenario, change the COP status of an on-line unit from "ON" to "OUT" in COP for hours 4pm-end of day.
    1. Long lead time thermal unit commitment is recommended for commitment by the "What-If" scenario run of SCUC.
    2. Operator assesses the risk involved and approves commitment of this long lead time thermal unit.

4.2 Use Case 2

Analyzing evening net load ramp due to solar ramp down and evaluate the need to issue SOC Verbal Dispatch Instruction (VDI) to set of ESRs (CAISO "Exceptional Dispatch of ESRs" with associated Make-Whole Payments).

a. Run SCUC @10am (with one of the options) for remaining hours of day with all AS deployment factors set to zero. This is the "Base Case" and gives the "ideal" system wide SOC trajectory over the study period, if the forecasts are accurate. "Base Case" SCUC results show that there are no long lead time thermal units to commit if there is a forced outage or forecast error (load forecast or IRR forecast).

b. Run a "What-If" scenario with a study period from 2pm to the end of the day. In this scenario, increase the load forecast during the solar ramp down period.
    1. "What-If" run of SCUC shows a higher value of SCUC calculated SOC is required just before the solar ramp period to meet the system demand.
    2. Operator compares this higher SOC level from the "What-If" scenario to the COP values of HBSOC for the solar ramp down period.
    3. Operator issues a SOC VDI (CAISO exceptional dispatch) @10am for a set of ESRs to each have an SOC @7pm that corresponds to the 7pm calculated ESR level SOC from the "What-If" scenario.
    4. The ESRs given a SOC VDI are eligible for Make-Whole Payment for the period 10am-7pm.

4.3 Use Case 3

Analyzing evening net load ramp due to solar ramp down.

a. Run SCUC @10am (with one of the options) for remaining hours of day and set AS deployment factors to high value for the time period spanning 1 hour before the start of the solar ramp down till 2 hours after the end of the solar ramp down period. The results will show if there is sufficient SOC available to meet the solar ramp down period.
b. Compare the calculated individual ESR SOC from SCUC to the individual COP values for HBSOC.
    1. Operator issues a SOC VDI (CAISO exceptional dispatch) @10am for a set of ESRs to each have an SOC @7pm that corresponds to the 7pm calculated ESR level SOC from the "Base Case".
    2. The ESRs given a SOC VDI are eligible for Make-Whole Payment for the period 10am-7pm

4.4 Use Case 4

Analyzing a forecasted Multi-Day Weather event

a. a. Run SCUC with a study period spanning the multi-day weather event and set AS deployment factors to high value for the time period spanning high net loads. The results will show if there is sufficient SOC available to meet the high net load periods. Also of interest is the time periods SCUC charges the ESRs.

b. Compare the calculated individual ESR SOC from SCUC to the individual COP values for HBSOC.

   1. Operator issues a SOC VDI (CAISO exceptional dispatch) to charge ESRs for time periods that does not increase any firm load shed in order to meet the periods of high net load during the multi-day weather period.
   2. The ESRs given a SOC VDI are eligible for Make-Whole Payment .

5. Conclusions and Future Considerations

The paper presents an advanced SCUC multi-interval engine that offers users flexibility in its application. Key features include modifying the SOC accounting process to reduce dependence on the accuracy of submitted COP data for ESR SOC, using the latest market offers for resources to provide more accurate energy cost estimations, and an "ISO-managed SOC" mode to simulate optimal energy dispatch for ESRs, regardless of their market offers, to minimize or eliminate firm load shedding. Potential future considerations include:

a. Probabilistic unit commitment: Further research is required to enable probabilistic unit commitment approach to be used in the operational time frame. The modeling of ESR SOC in probabilistic unit commitment is an issue that needs to be addressed.

b. Including PUN models in SCUC: Currently RTC-RUC models the Private-Use-Network as a net injection or withdrawal. This causes a disconnect from the EMS STNET/RTNET network models making it a cumbersome process if a RTC-RUC or SCUC output is fed as input to a STNET case for detailed AC analysis.

ercot

Taylor
2705 West Lake Drive
Taylor, TX 76574
T 512.248.3000
F 512.248.3095

Austin
8000 Metropolis Dr Building E
Austin, TX 78744
T 512.225.7000
F 512.225.7020

www.ercot.com