Distribution System State Estimation (DSSE) Performance Evaluation

SOUTHERN CALIFORNIA EDISON
An EDISON INTERNATIONAL® Company

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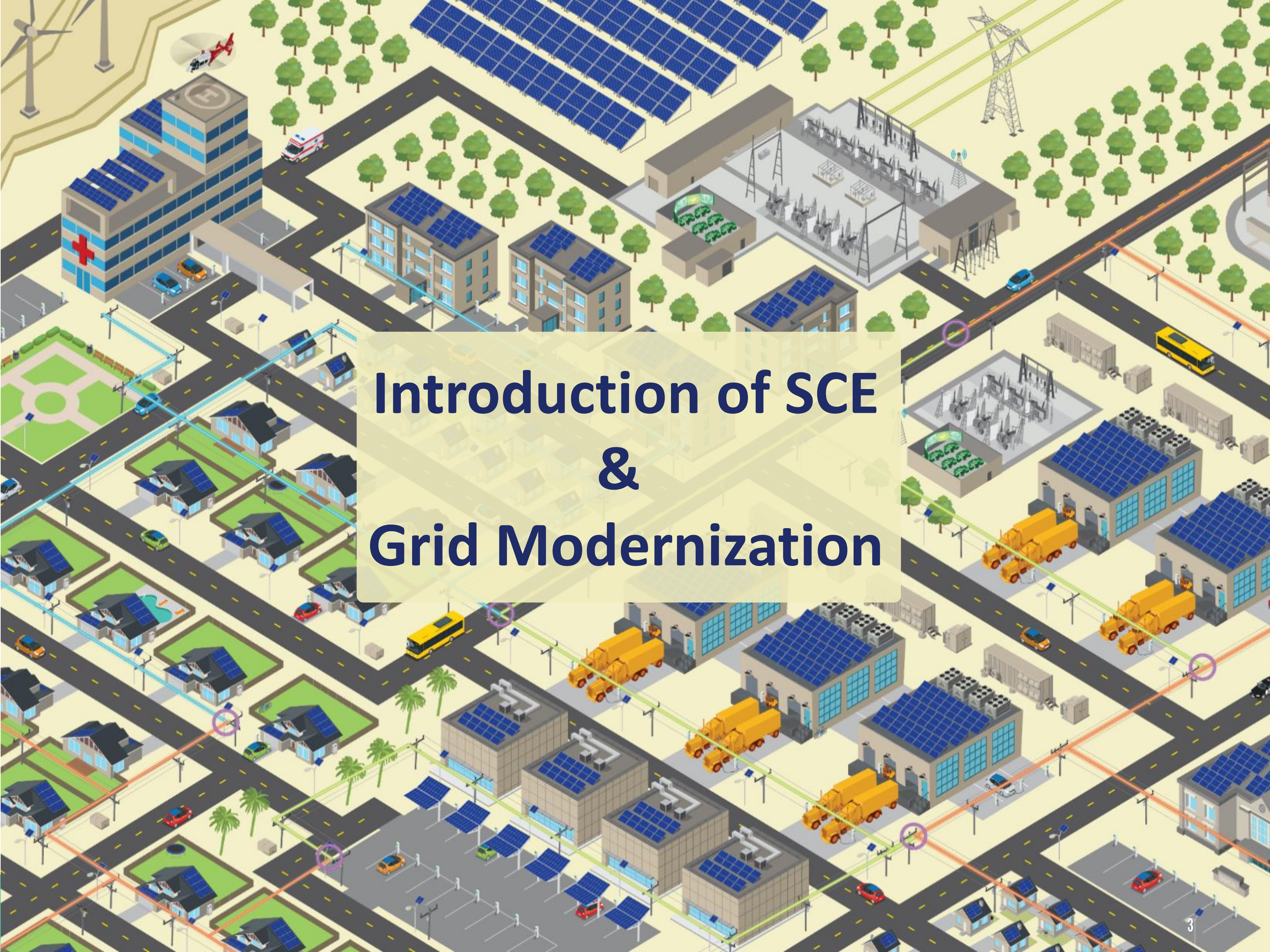
AGENDA

1. Introduction of SCE & Grid Modernization
2. DSSE Performance Evaluation
   a) Driver & Objectives
   b) Planning Mode – Overview
   c) Planning Mode – Concept
   d) Planning Mode – Implementation
   e) Planning Mode – Functions
   f) Planning Mode – Selected Results
   g) Operational Mode
3. Summary and Next Steps

Introduction of SCE & Grid Modernization

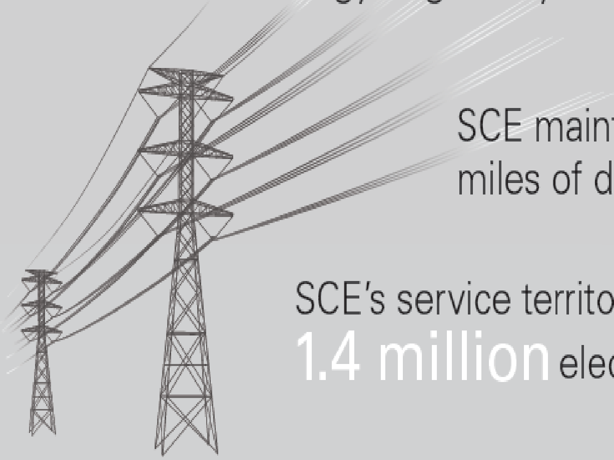


Southern California Edison (SCE)

SCE's service territory includes about 430 cities and communities with a total customer base of about 5 million residential and business accounts.

The company serves approximately 15 million people in a 50,000-square-mile service area within Central, Coastal and Southern California.

SCE is regulated by the California Public Utilities Commission and the Federal Energy Regulatory Commission.

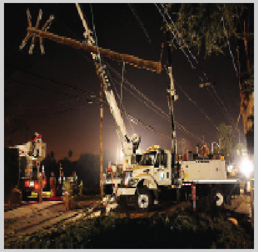


SCE maintains more than 105,773 miles of distribution lines.

SCE's service territory contains approximately 1.4 million electricity poles.

Based in Rosemead, Calif., the utility has been providing electric service in the region for more than 125 years.

During the past five years, SCE's energy efficiency programs have helped customers save enough energy to power 1 million homes for a year.



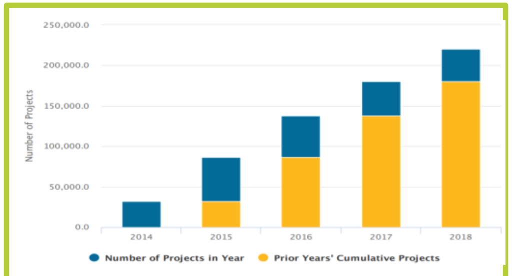
In order to continue powering California's growing population and economy, SCE plans to invest up to $14.7 billion over the next three years expanding and strengthening its electric system infrastructure.

Key Drivers for Modernizing Grid & DER Management Capabilities

State Energy & Environmental Policy

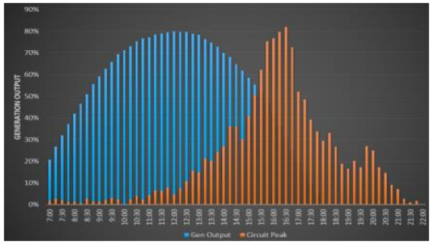
Customer Choice & Reliability

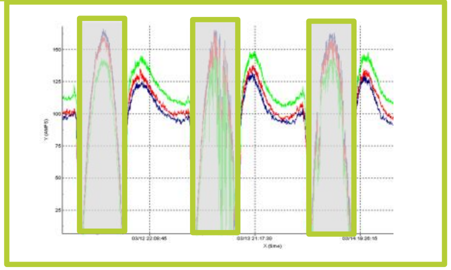
Increasingly Complex Grid



*Trend of NEM PV Projects in SCE's Territory

*Source: California Distributed Generation Static, available at: https://www.californiadgstats.ca.gov/charts/nem





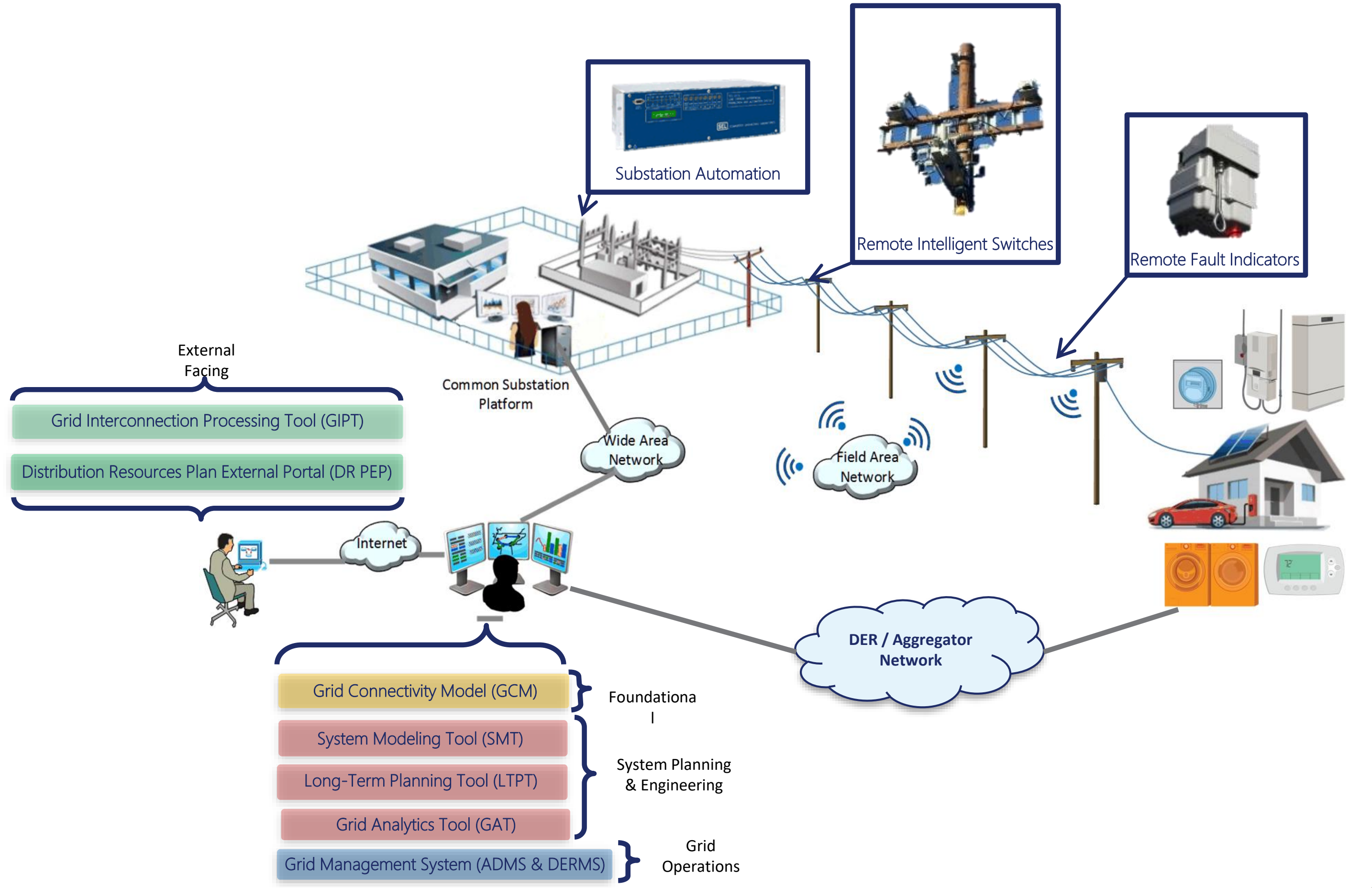
Distribution Grid 2-Way Power Flow

Non-coincident DER Offset

DER Masked Load

Leveraging DER's for Distribution Overloads

Grid Modernization System Overview



DSSE Performance Evaluation: Drivers & Objectives

STATE ESTIMATION (SE)

- SE is a Foundational Application that provides situational awareness and DER Visibility.
- Uses real-time measurements (e.g., current/power injection, voltage magnitude at bus, power flow through line segment) to calculate system state (i.e., voltage and angel at each bus).
- Distribution System State Estimation (DSSE) very different from SE for transmission systems.

Transmission vs. Distribution SE

Transmission SE

Much Data Available

- System usually observable.
- High data redundancy.
- Bad data detection possible.

High Quality Pseudo Data

- Useful if part of the system is unobservable.
- Often not needed (because of high data redundancy).

Routinely used application that provides robust bad data and topological error detection.

Distribution SE

Limited Data Available

- System not observable.
- No data redundancy.
- Bad data detection difficult.

Varying Pseudo Data Quality

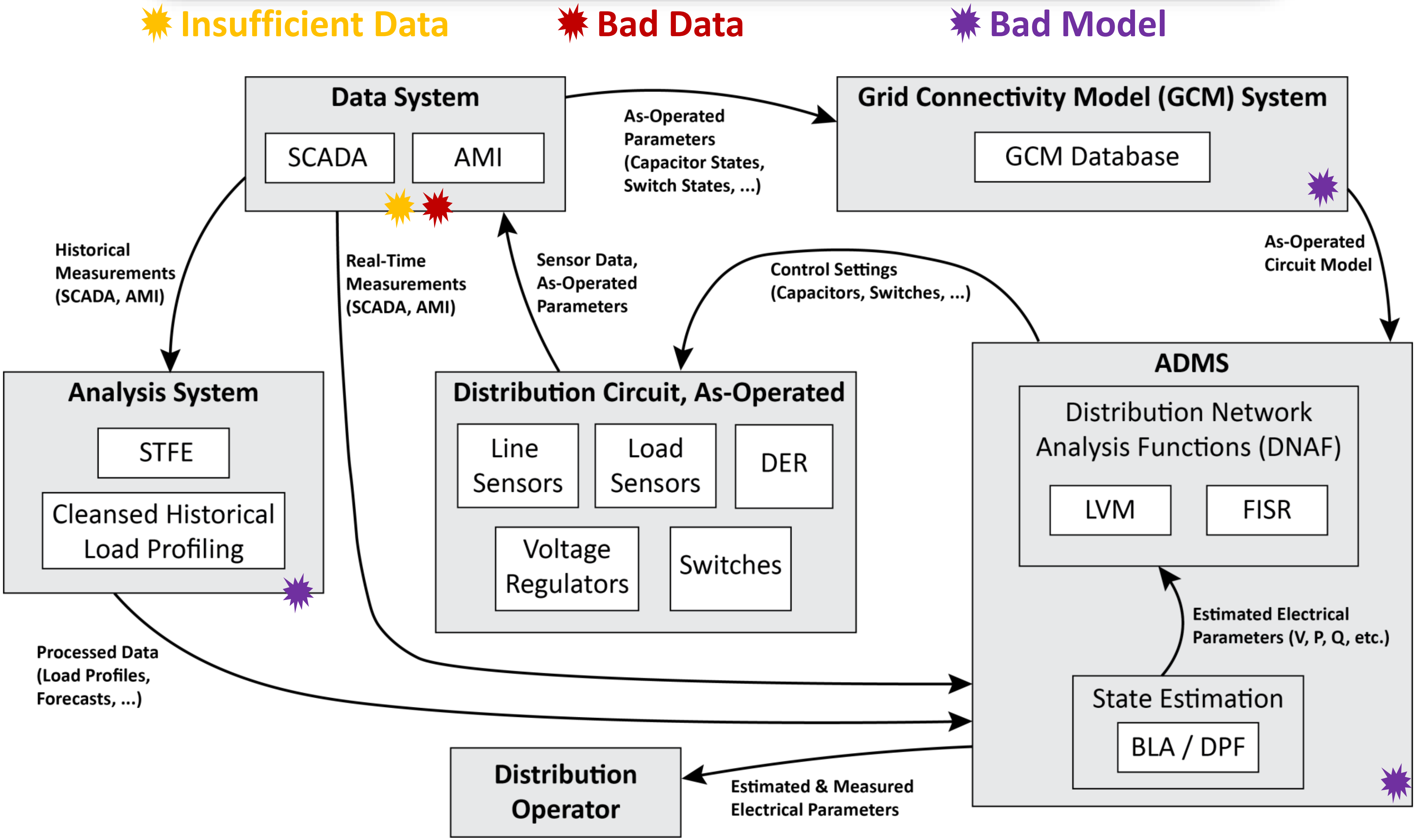
- Pseudo data needed to make system observable.
- Important to ensure high quality of pseudo data.

Additional circuit-level sensors and reliable short-term forecasting needed for successful deployment.

ADMS Deployment Challenges

- DSSE needs to provide results that are sufficiently accurate for the execution of Advanced Applications such as Volt-Var Optimization (VVO) and Fault Location, Isolation, and Service Restoration (FLISR).
- **Insufficient Data Problem:** Errors due to insufficient number of sensors resulting in the need to use less accurate pseudo-measurements.
  - Pseudo-measurements of load consumption.
  - Pseudo-measurements of DER generation.
- **Bad Data Problem:** Errors due to erroneously measured electrical parameters (voltages and flows) from AMI, SCADA or other sources.
  - Erroneous line / load sensor / substation data
  - Erroneous DER generation data
- **Bad Model Problem:** Errors due to erroneous models. A “model” can be a circuit model or any analytical method. Examples are
  - Circuit models with topological errors, erroneous line impedances, etc.
  - Errors in the DPE Methodology, such as discrepancies between ADMS DSSE results (i.e., BLA) and CYME DSSE results (i.e., Load Allocation)

ADMS Error Sources



DSSE Performance Evaluation (DPE)

Planning Objective Develop Hardware & Software Requirements to achieve DSSE accuracy needed to run all Advanced Applications optimally and violation-free.				Operational Objective Develop Operational Requirements to maintain adequate DSSE accuracy under all conditions while running Advanced Applications.	
Adding telemetry points to fix **Insufficient Data** problem – how many are needed and optimal locations?	How often should the DSSE be executed?	Optimal use of data from line sensors, Large Customer Metering, Short Term Forecasting & Residential AMI?	Are P & Q data needed or is measuring current magnitude enough?	What is the impact of ○ measurement errors (**Bad Data**)? ○ topological errors (**Bad Model**)? ○ DER and disrupting technologies such as Smart Inverters, storage, etc. (**Bad Data, Bad Model**)?	How can the operator tell if DSSE solution can be trusted?

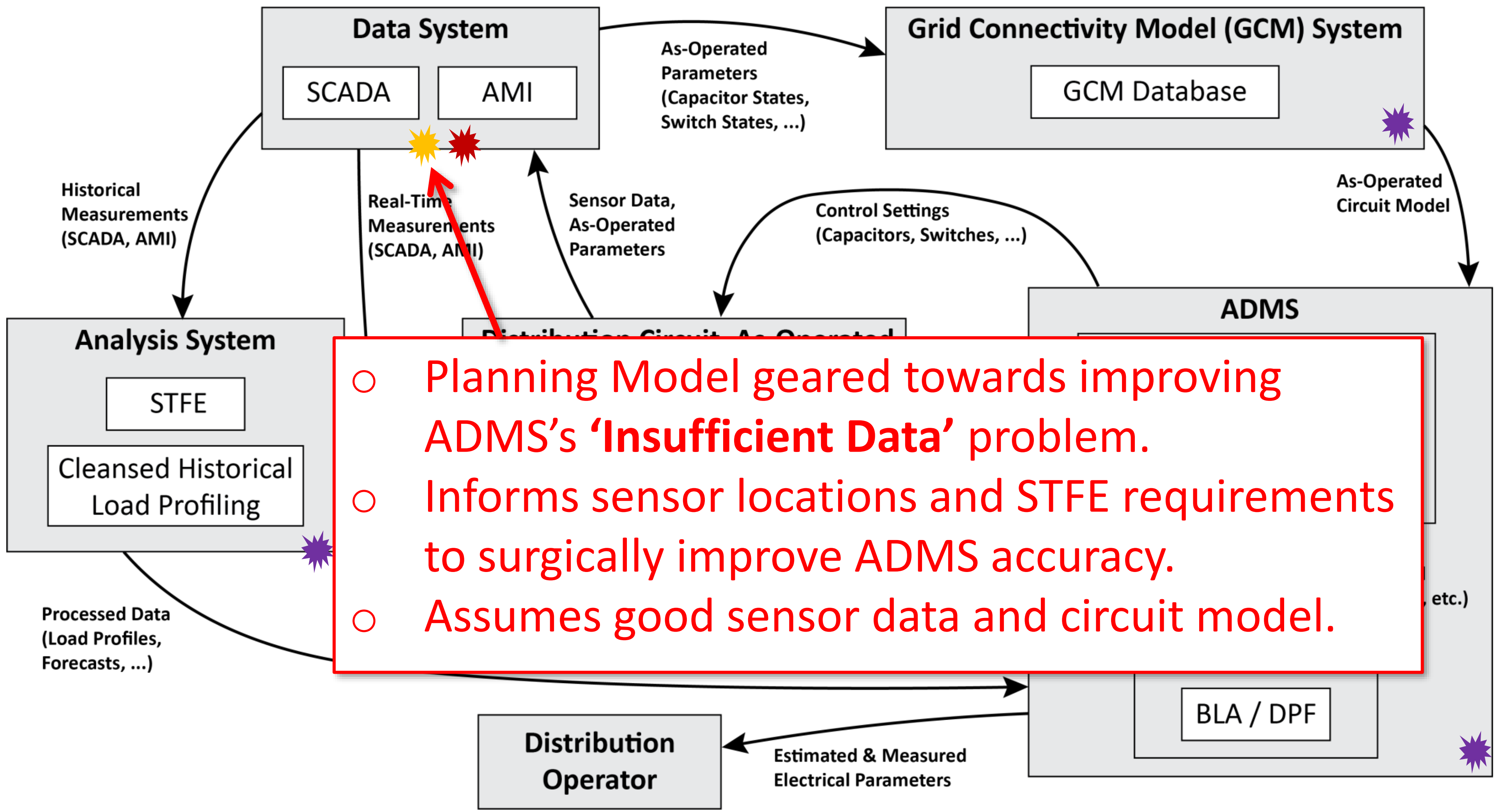
DSSE Performance Evaluation (DPE)

- Developed DPE Methodology to achieve planning and operational objectives.
- DPE Methodology & Tool are simulation based.
  - AMI / SCADA / PV Performance Data to create pseudo-measurements and mimic real-time data.
  - CYME circuit simulation to mimic real-world.
  - CYME circuit simulation to mimic ADMS behavior.
- Methodology agnostic to state estimation algorithm.
  - We use CYME's load allocation as this method is similar to the state estimation algorithm in our ADMS.
  - Other state estimation algorithms, such as CYME's DSSE module, can be used instead.

DSSE Performance Evaluation: Planning Mode - Overview

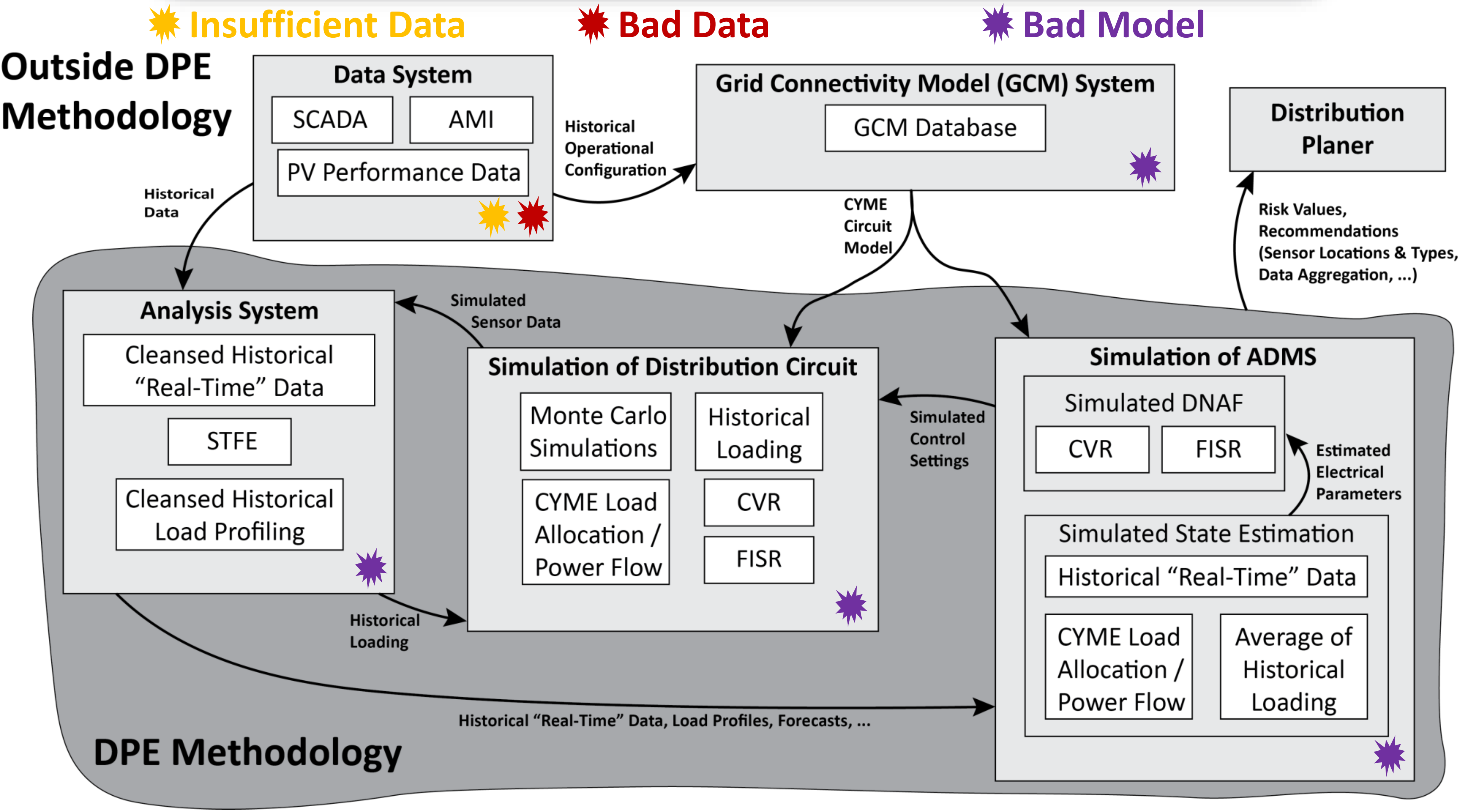
Objective of DPE Tool's Planning Mode

Insufficient Data   Bad Data   Bad Model



- Planning Model geared towards improving ADMS's **'Insufficient Data'** problem.
- Informs sensor locations and STFE requirements to surgically improve ADMS accuracy.
- Assumes good sensor data and circuit model.

DPE Tool – Overview of Planning Mode

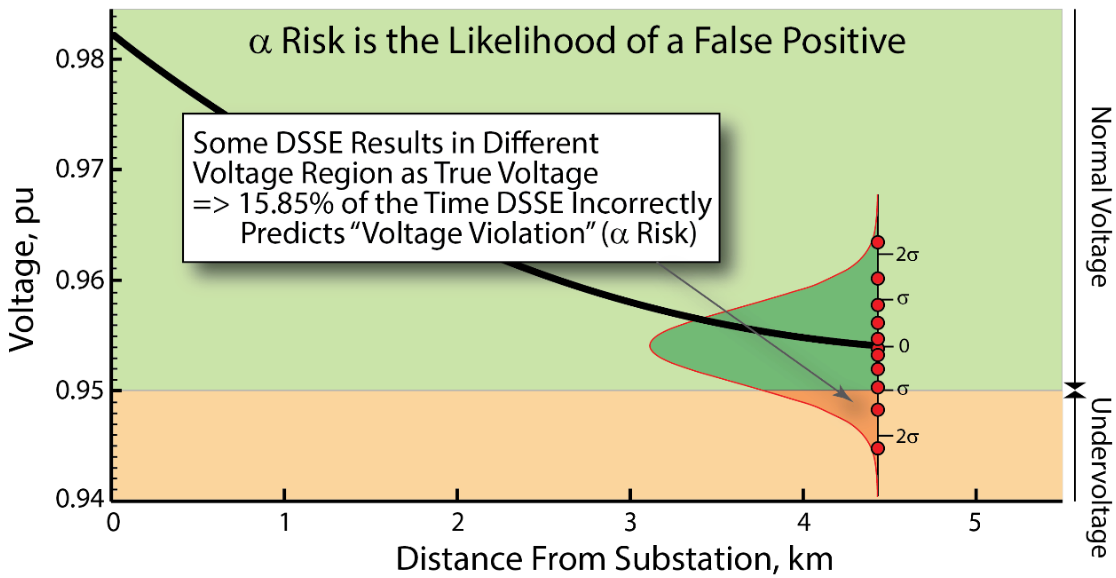


DSSE Performance Evaluation: Planning Mode - Concept

DPE: CONCEPT

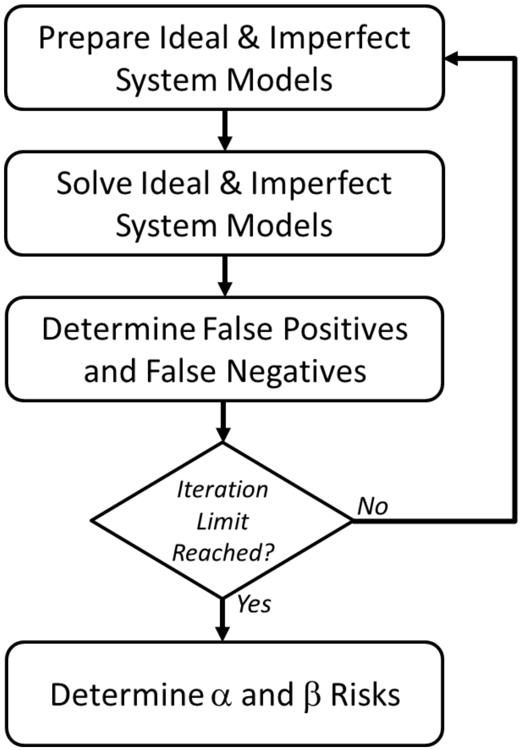
α Risk

Likelihood of DSSE reporting a violation when there is none.



Monte Carlo Analysis

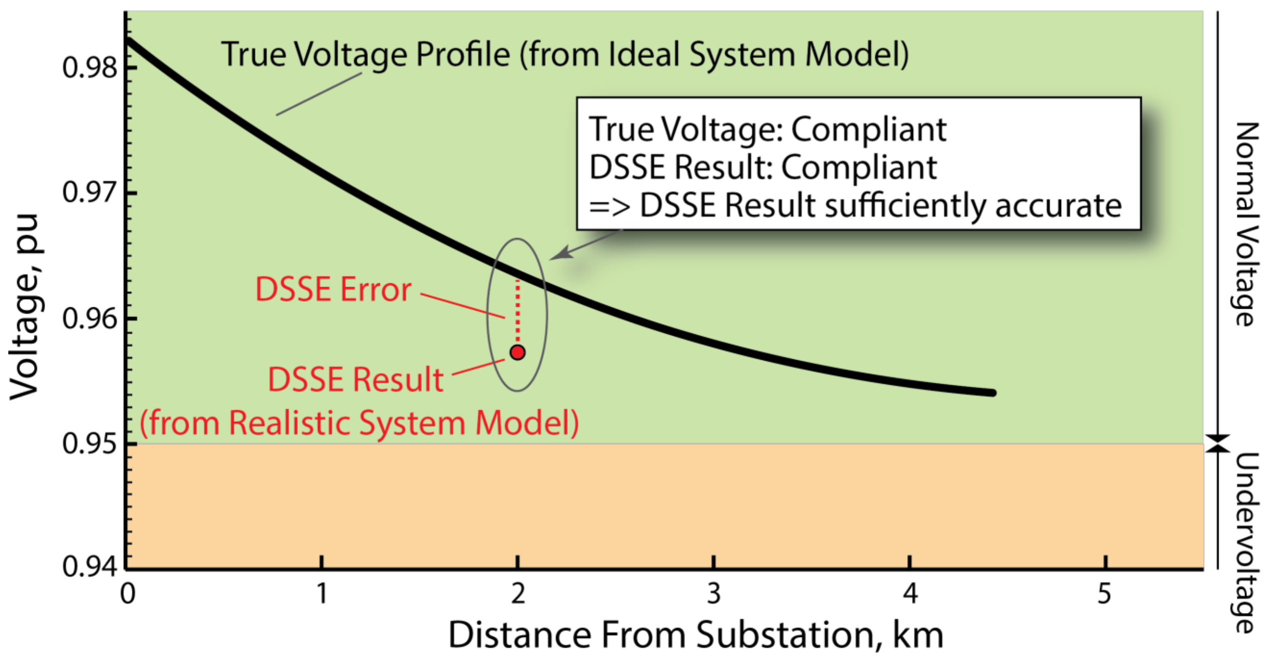
Determines α Risk by quantifying accuracies of DSSE estimates.



DPE: CONCEPT

Premise: DSSE results are sufficiently accurate if they correctly identify compliances and violations.

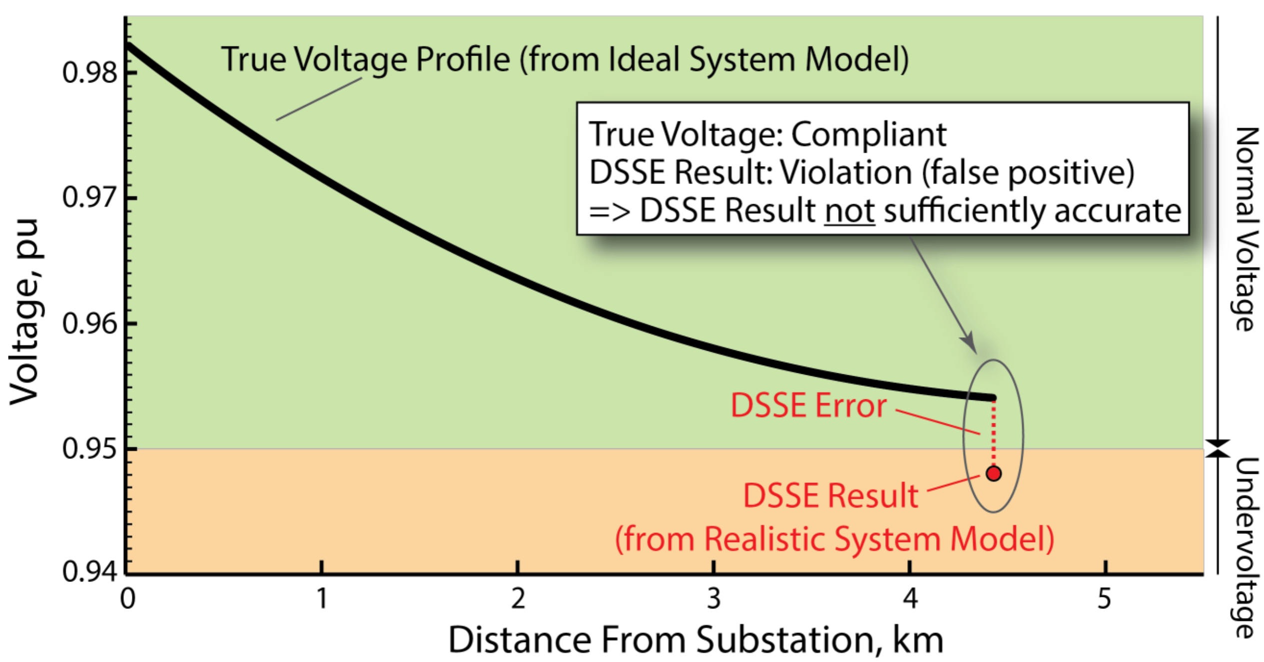
Example: DSSE <u>correctly</u> reports 'no undervoltage violation'.



DPE: Concept

Premise: DSSE results are sufficiently accurate if they correctly identify compliances and violations.

Example: DSSE <u>incorrectly</u> reports 'undervoltage violation'.



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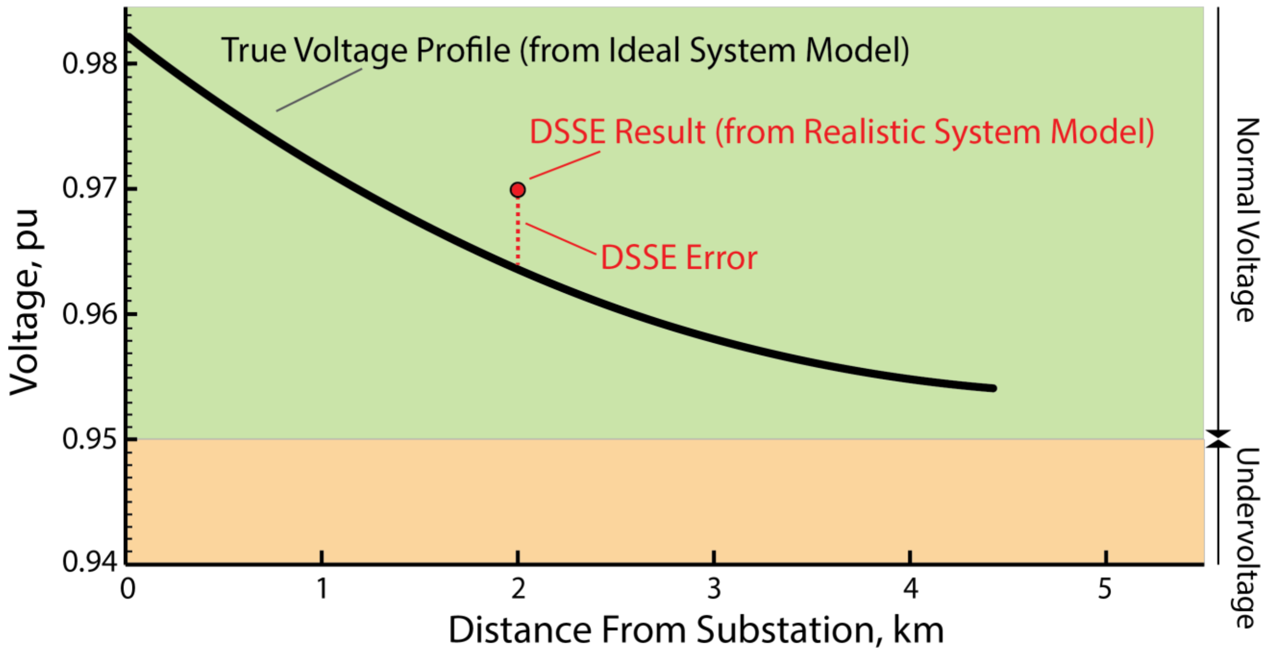
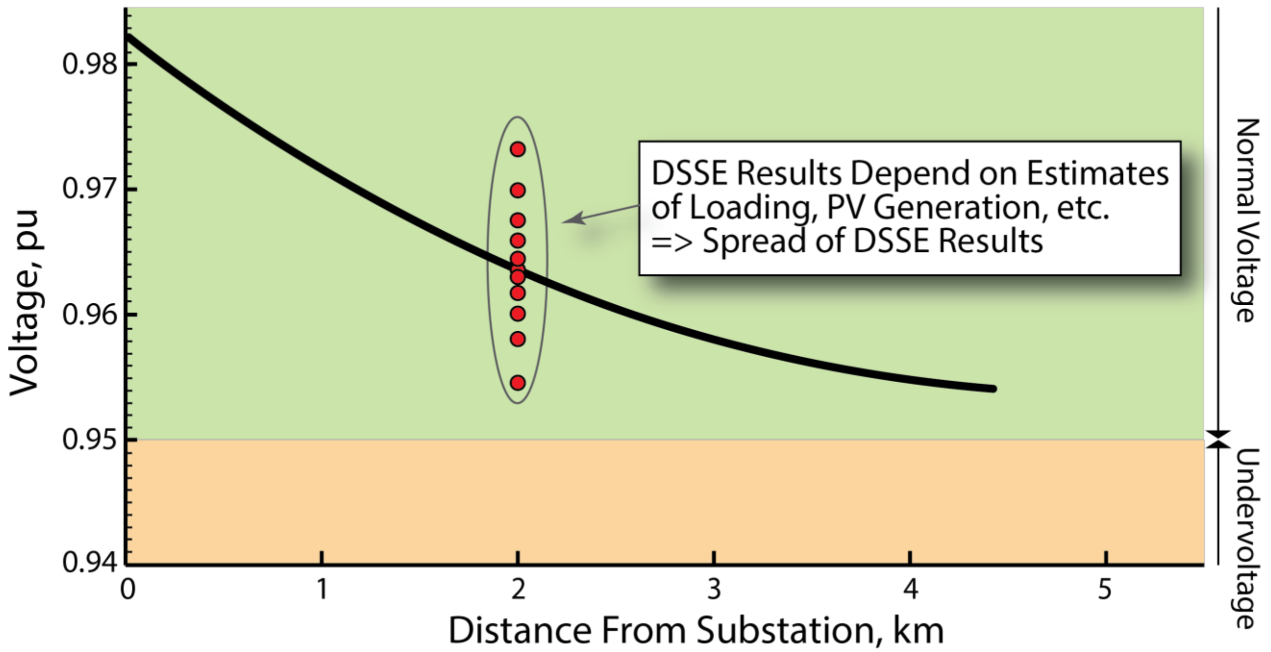
DPE: Concept

Running DSSE Once



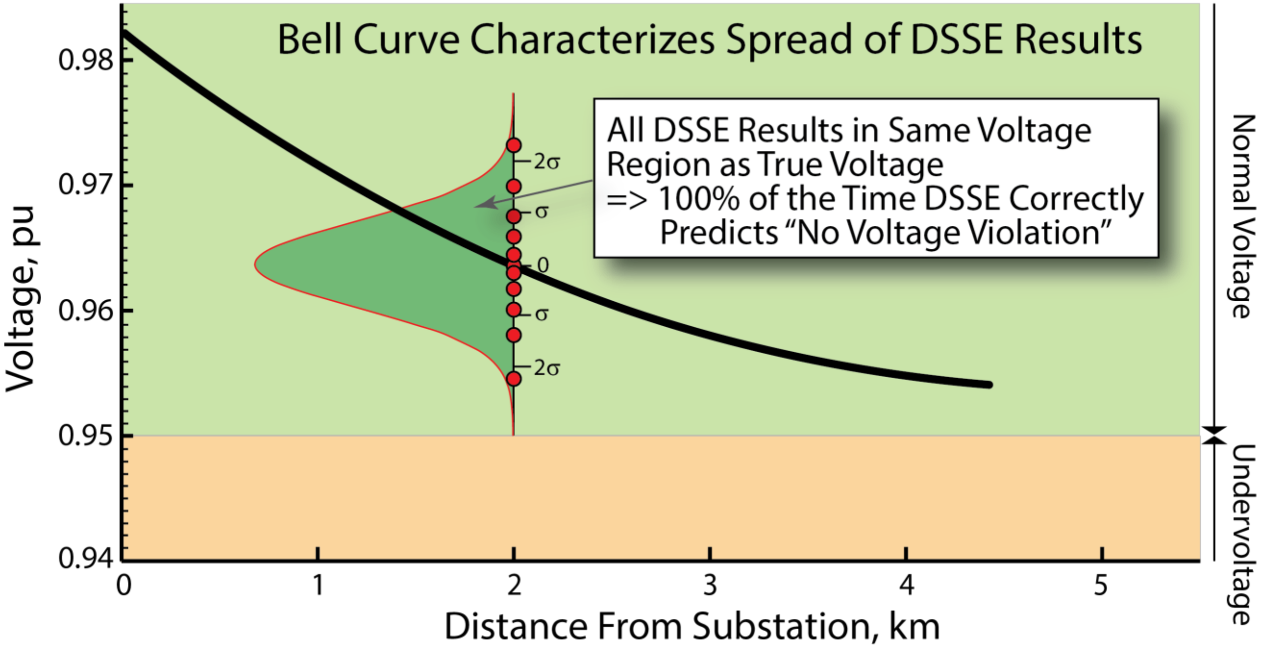
DPE: Concept

Running DSSE Multiple Times (Monte Carlo Analysis)



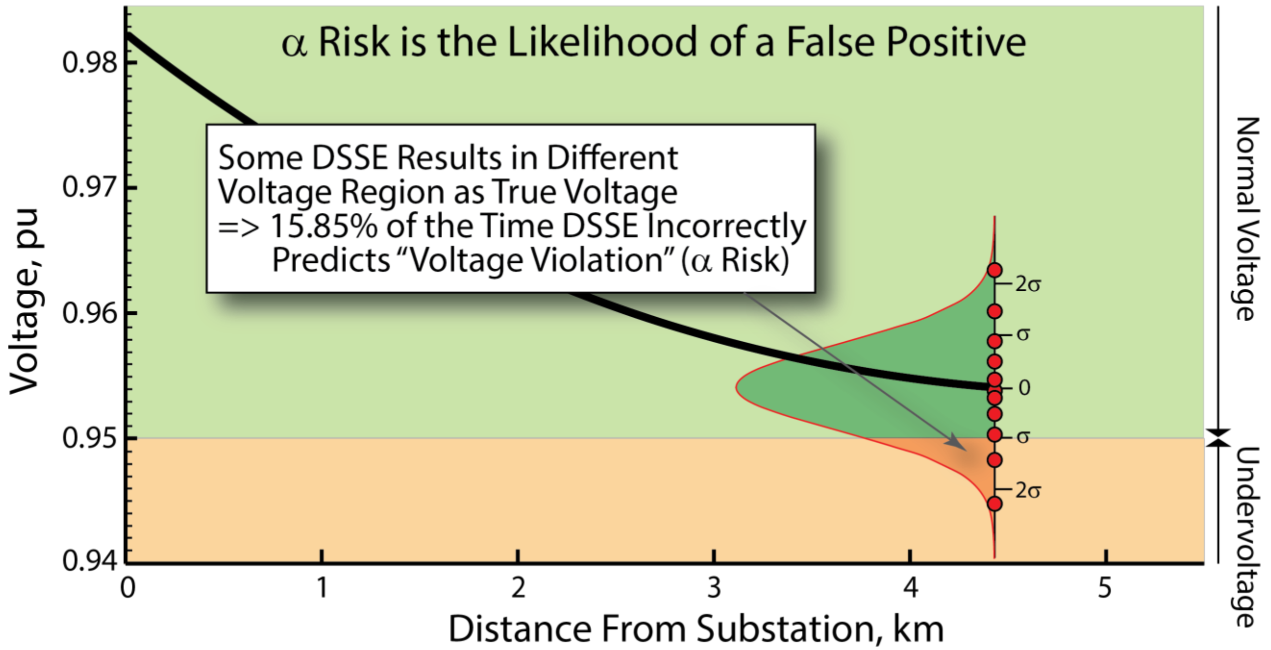
DPE: Concept

Two km from Substation, DSSE Result Always Sufficiently Accurate (for this circuit).



DPE: Concept

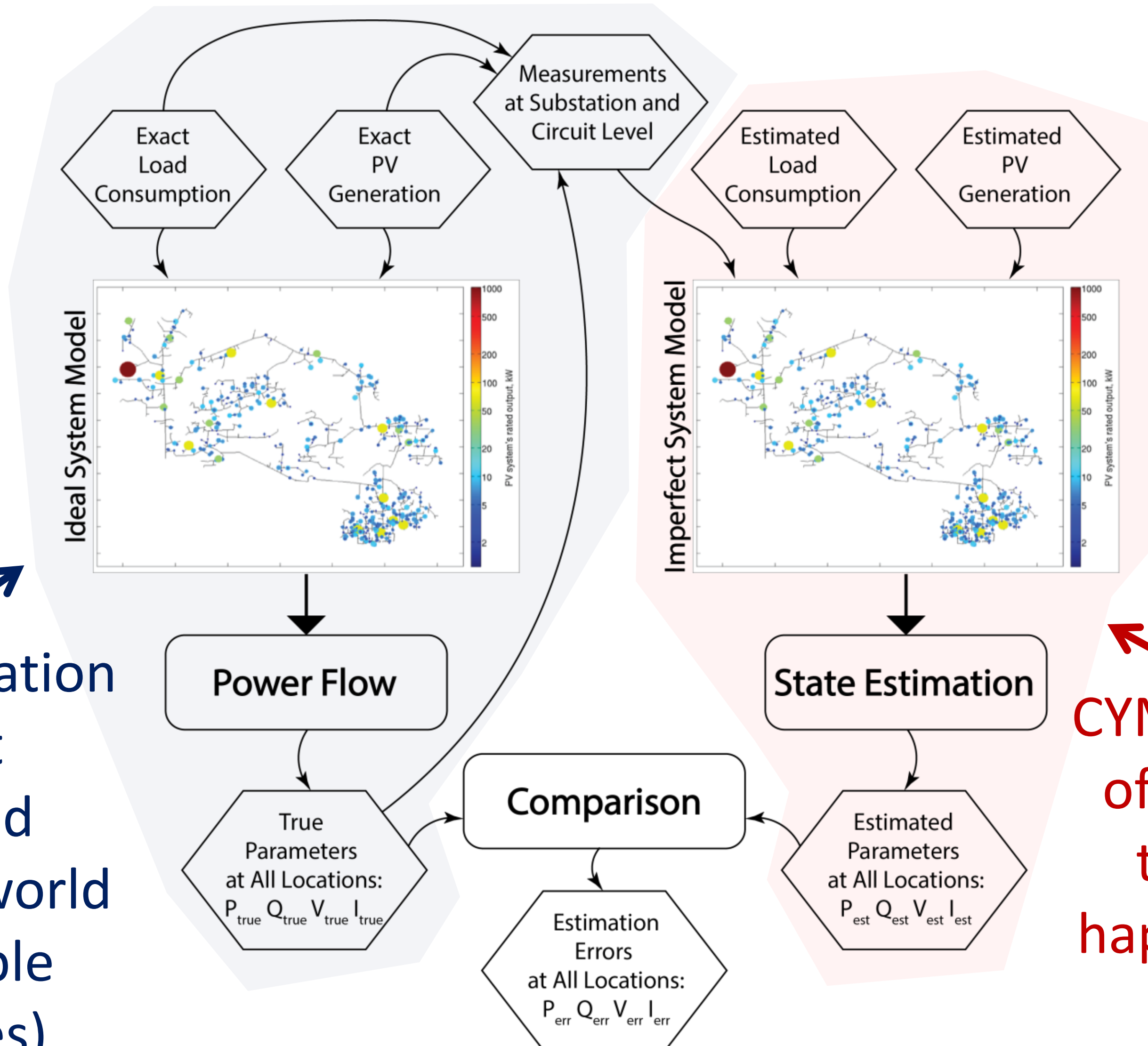
At End of Circuit, DSSE Result <u>Sometimes</u> (15.85% in this Example) Not Accurate Enough.



α Risk: The risk of the DSSE giving false positives with regards to identifying voltage and flow violations

DSSE Performance Evaluation: Planning Mode - Implementation

DPE: Implementation



CYME simulation of what happened In the real world (all possible True States).

CYME simulation of what ADMS thinks what happened in the real world.

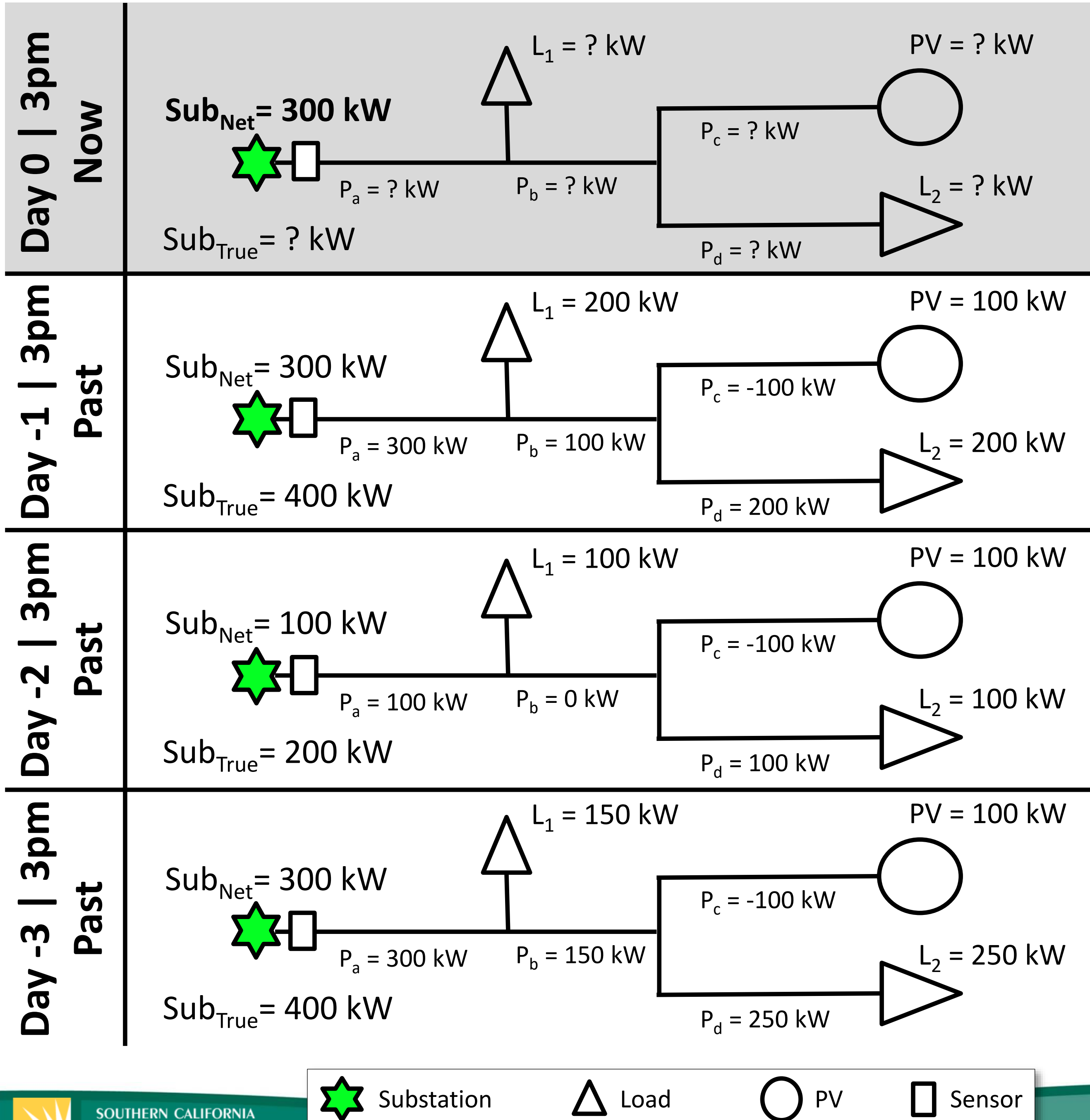
DPE: Implementation

- Collect historical data
  - P & Q measured at Substation (SCADA)
  - Circuit level data (AMI for load consumption and PV generation, PV performance data, capacitor bank status from SCADA).
- Use CYMDIST driven by Python scripting (CYMPY)
  - SCE's distribution circuits modeled in CYME (including loads, PVs, capacitors, switches, etc.)
  - Loading and PV generation assigned during each Monte Carlo simulation run.
- Use historical data and CYME to simulate
  - All possible True States
  - ADMS estimate of True States

CYME Simulation of True States

- CYME simulations of all loading scenarios that can happen based on historical data. These are our possible True States.
- Premise:
  What happened in the past can happen in the now.
- In other words
  - Use historical AMI data to capture loading scenarios that are possible during time of ADMS execution.
  - Realistically captures load variation and correlation between individual loads.

Data Availability (0.5 Scheme)

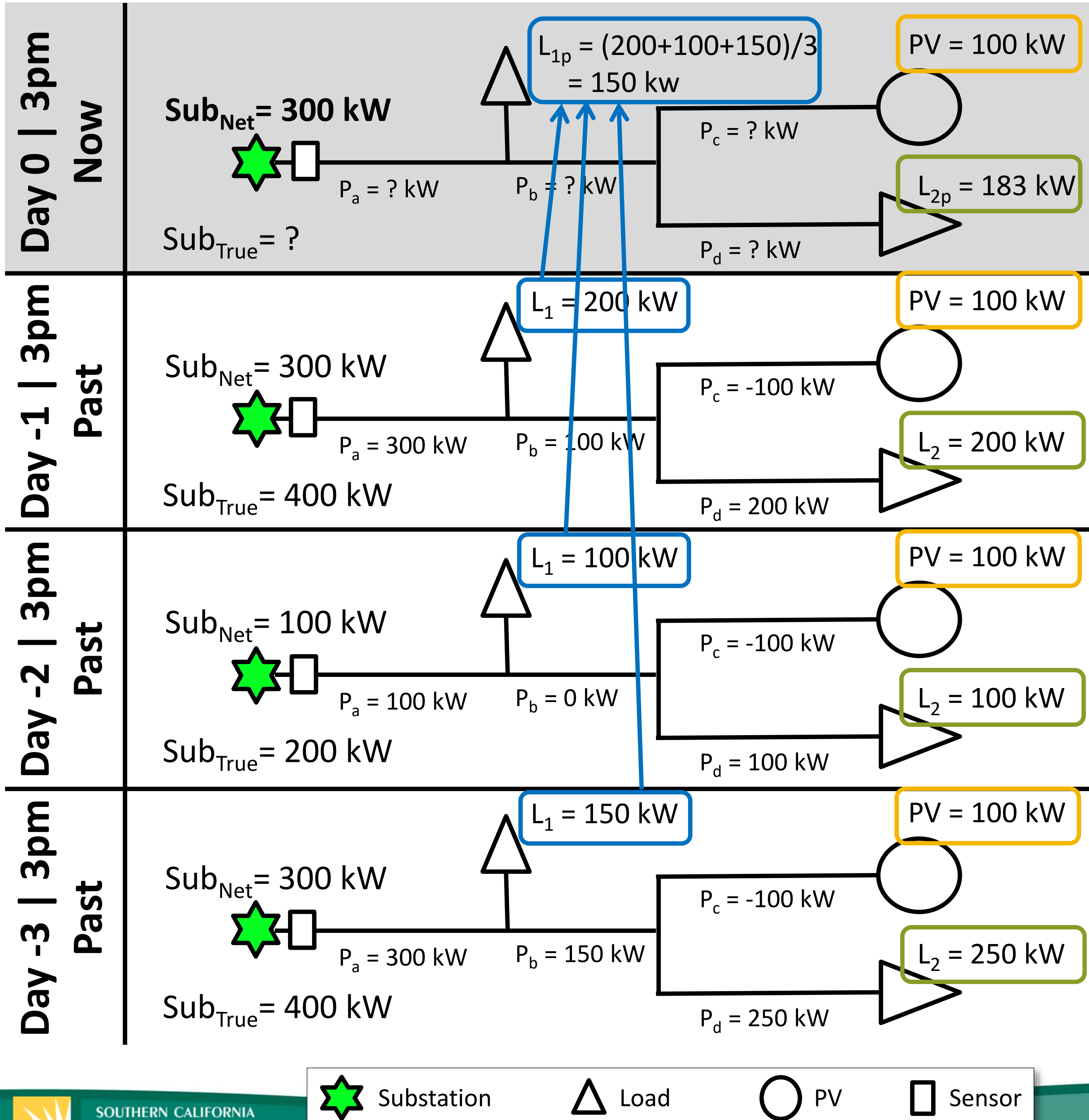


Real-Time Substation Data

Historical Substation & AMI Data (Possible True States)

CYME Simulation of ADMS Estimate

- Perform CYME simulation with all data available to the ADMS at time of state estimation execution.
- Real-Time Data
  - E.g., Substation Data, Large Loads and PVs (RTEMS), Bellwether Meters.
  - Plug in measurements into CYME model
- Pseudo Measurements
  - ADMS needs to "guess" parameters that are not available in real time. E.g., "best guess" for loading is to use average of historical AMI data (e.g., past 3 days) for loads w/o real-time data.
  - Plug in averages of historical data into CYME model.



Pseudo Measurements

Use Historical Data for Pseudo Measurements

$$L_{1p} = \frac{200 + 100 + 150}{3} kW = 150\ kW$$

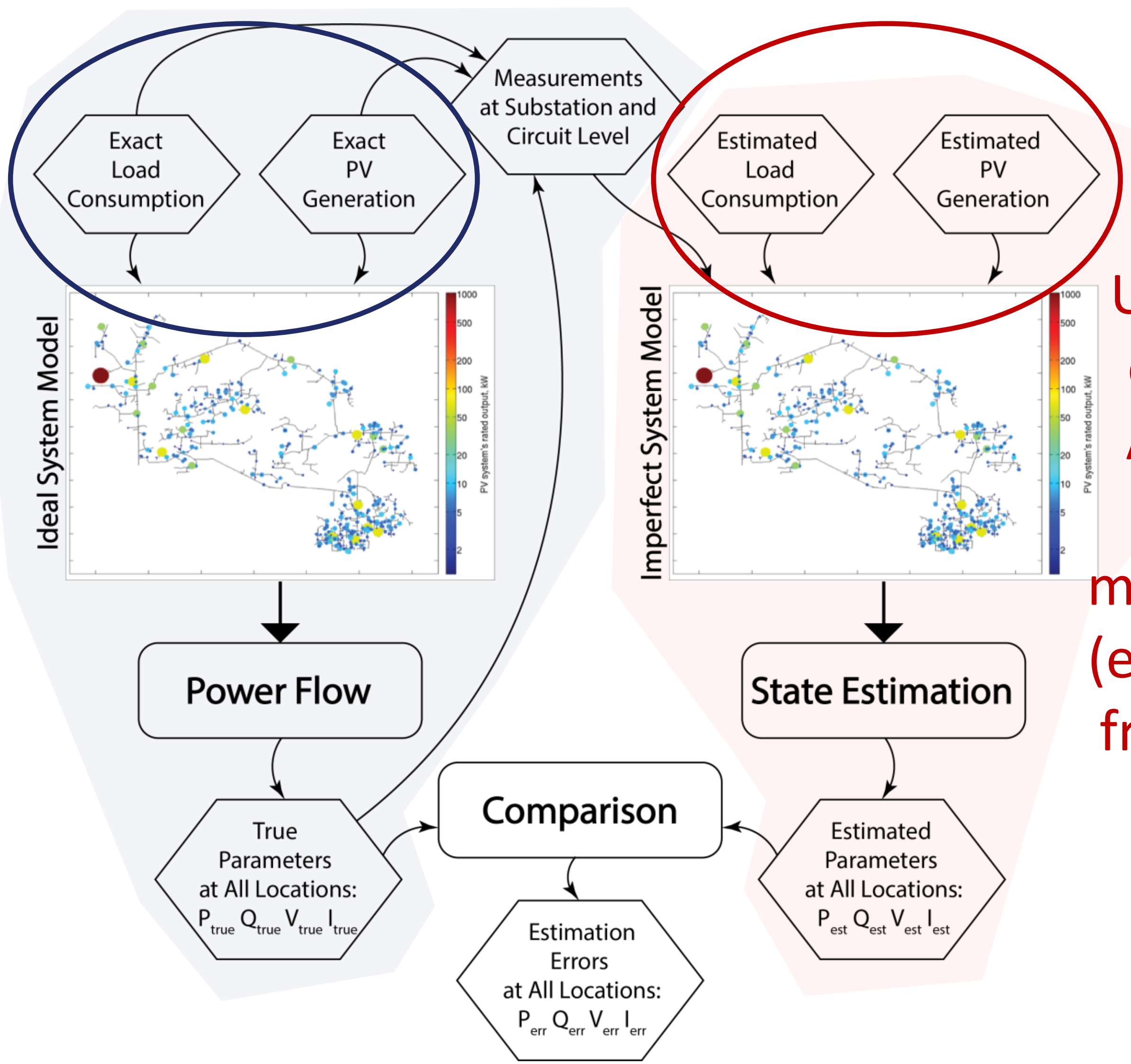
$$L_{2p} = \frac{200 + 100 + 250}{3} \text{kW} = 183\ kW$$

$$PV = \frac{100 + 100 + 100}{3} \text{kW} = 100\ kW$$

$$Sub_{True} = (300 + 100) kW = 400\ kW$$

AMI Data For Individual Loads

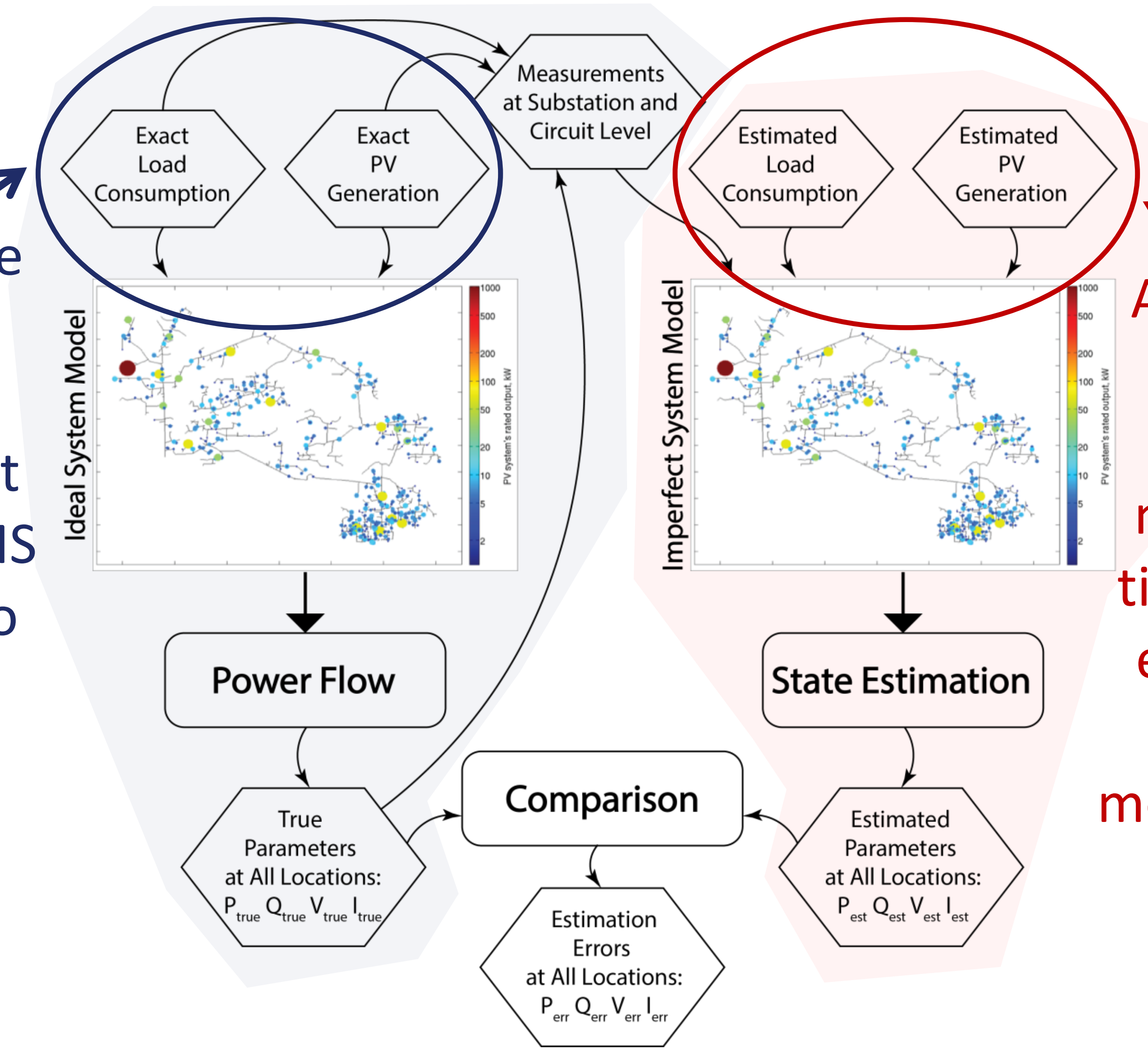
Use historical sets of AMI data from days with similar conditions.



Use averages of historical AMI data as pseudo measurements (e.g., AMI Data from previous 3 days).

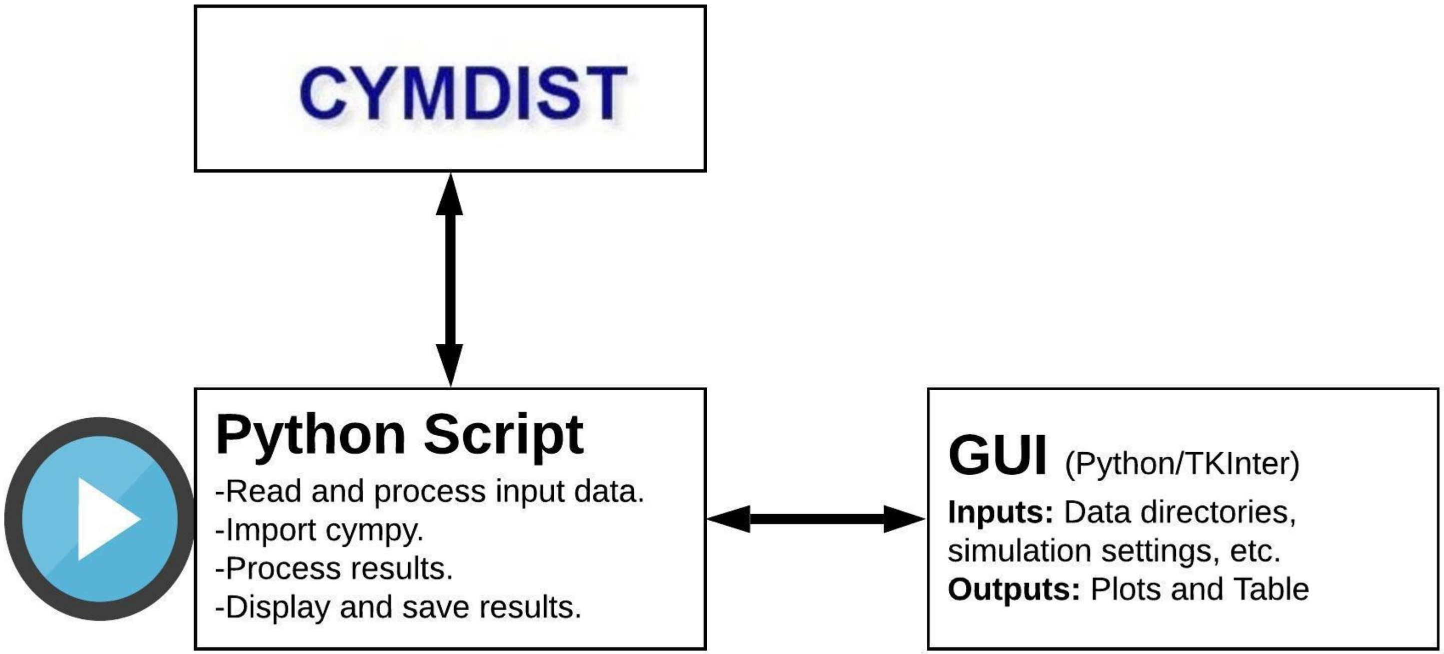
SUBSTATION DATA

Allocate true substation loading measured at time of ADMS execution to individual loads.



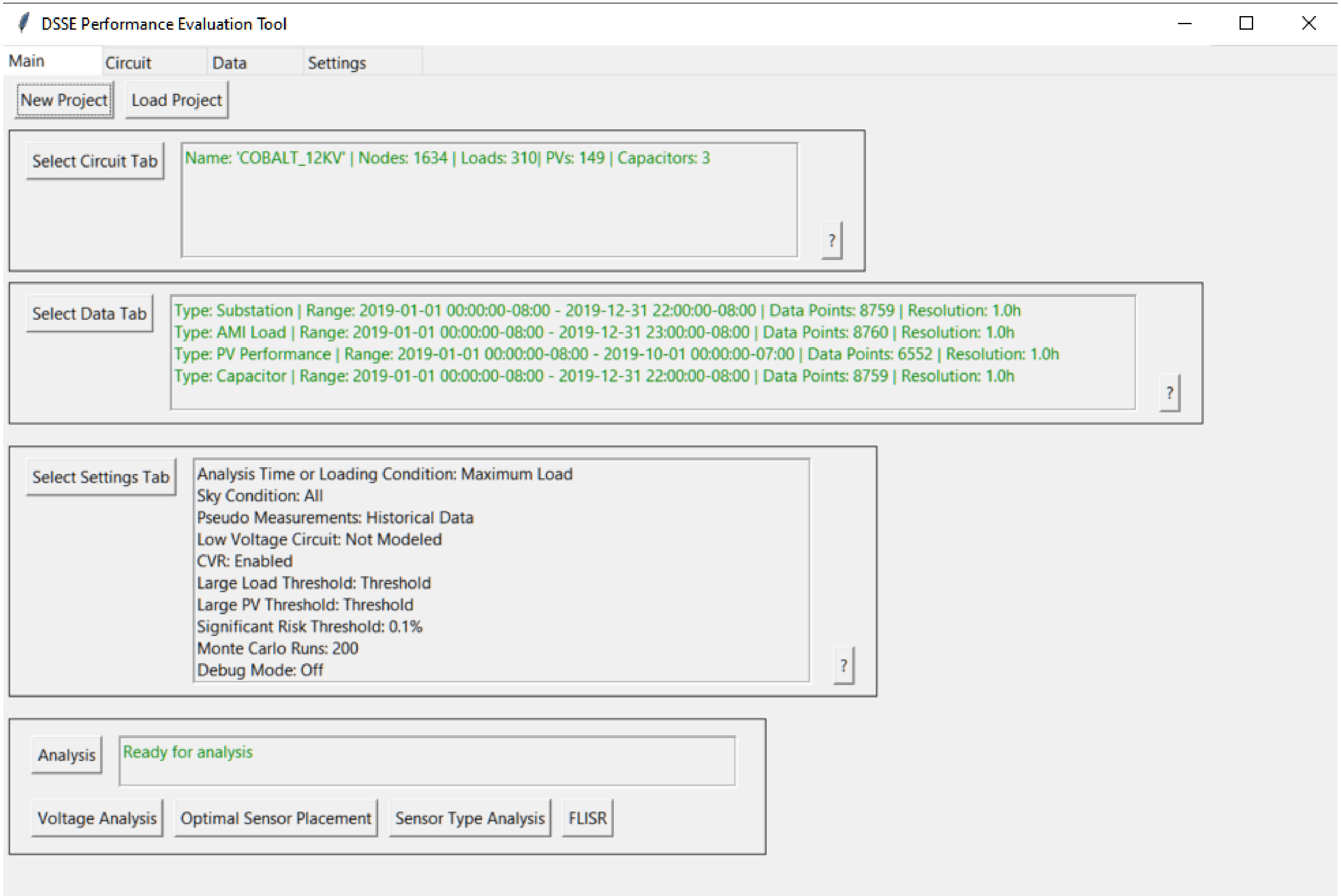
Allocate true substation loading measured at time of ADMS execution to pseudo measurements.

DPE Tool Automates Analysis



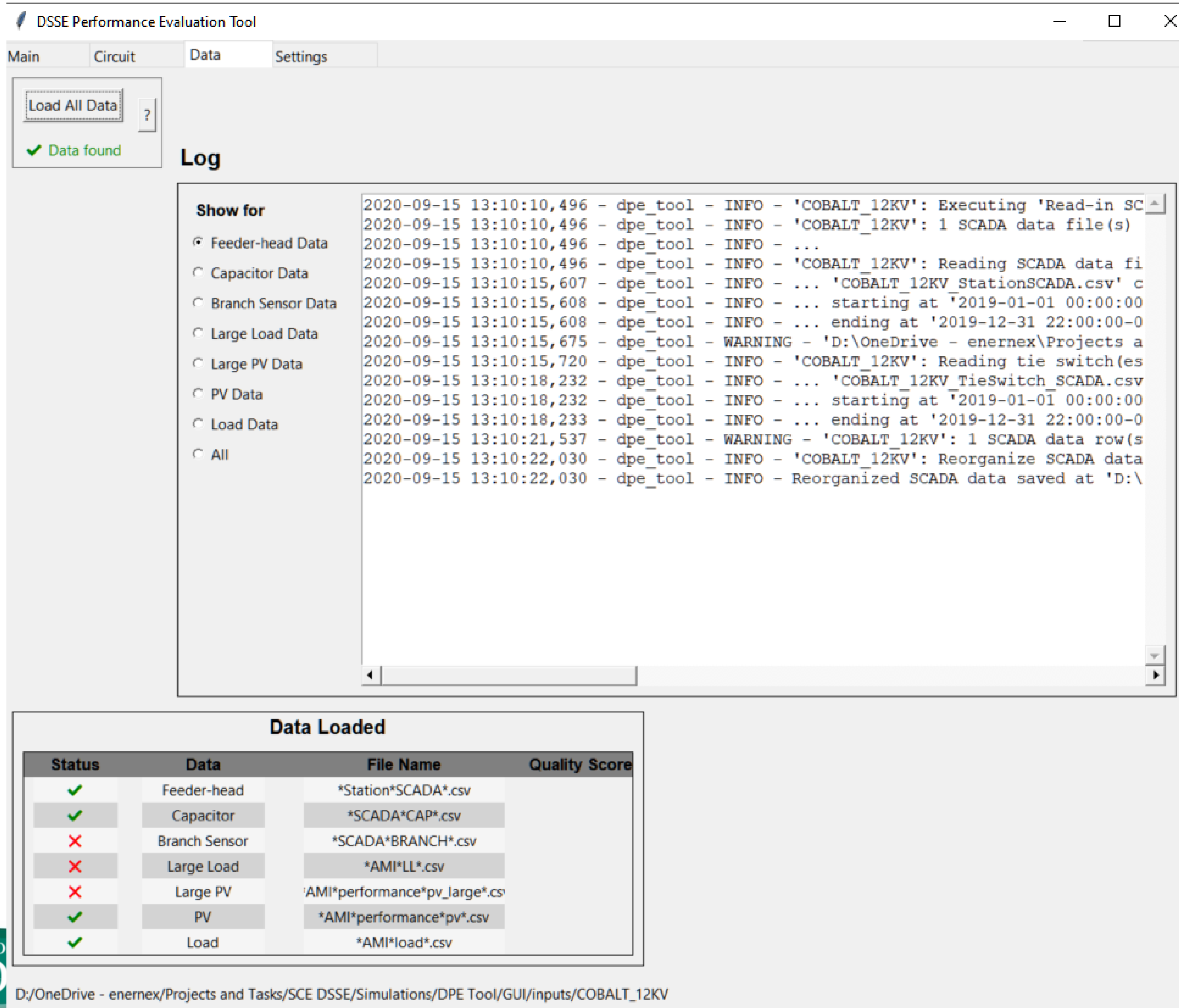
DPE Tool Automates Analysis

GUI-Main Form



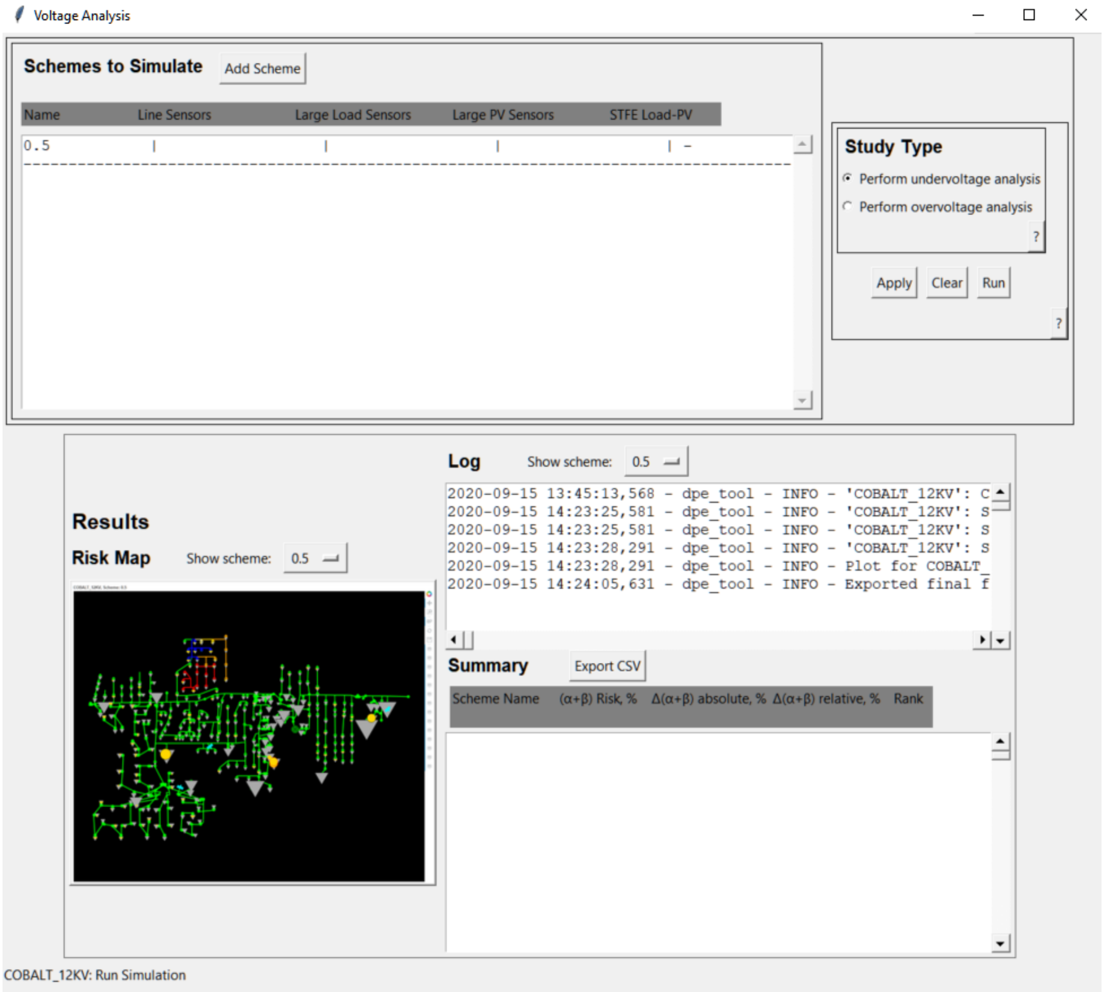
DPE Tool Automates Analysis

GUI-Data Form



DPE Tool Automates Analysis

GUI-Voltage Analysis Form



Execution Time: One scheme simulation takes 8-45 minutes, depending on the size of the network.

DSSE Performance Evaluation: Planning Mode - Functions

Planning Mode Functions

Estimation-Improving Measures	Quantifies DSSE performance improvements achieved by operational forecasting and adding circuit-level sensors that provide a full measurement set (i.e., P & Q).
Sensor Type Analysis	Compares the DSSE performance achieved by P & Q line sensors and line sensors that measure ‘current magnitude only’.
DSSE Execution Interval Analysis (Work In Progress)	Determines the maximum DSSE execution time interval that is needed to result in violation-free operation during normal operating conditions.
Optimal Sensor Placement Analysis	Identifies locations where placing a line sensor results in maximum DSSE performance improvement.
High PV Penetration	Perform analysis during clear-sky & cloudy-sky conditions when PV-caused voltage variability and DSSE estimation errors are largest.

DSSE Performance Evaluation: Planning Mode - Selected Results

Planning Mode Functions

Estimation-Improving Measures	Quantifies DSSE performance improvements achieved by operational forecasting and adding circuit-level sensors that provide a full measurement set (i.e., P & Q).
Sensor Type Analysis	Compares the DSSE performance achieved by P & Q line sensors and line sensors that measure 'current magnitude only'.
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Investigated Estimation-Improving Measures

Estimation accuracy improved by additional sensors and operational forecasting (STFE).

No Sensors on Circuit (Base Case)	• 0.5 Scheme: Substation Data Only
Automatic Switches w/ Sensors	• 1.5 / 2.5 / 3.5 Scheme: Substation Data + Data from One / Two / Three Circuit Locations • Switch placement driven by provided reliability improvement (for now).
Operational Forecasting	• STFE10: Short-Term Forecast Engine improves operational load forecast from +-30% to +-10% • STFE20: Short-Term Forecast Engine improves operational load forecast from +-30% to +-20%
HR Scheme	• Place sensors near high α risk areas.
LL Scheme	• Place sensors at large loads. This scheme simulates SCE's deployment of Real-Time Energy Meters (RTEMs), which monitor loads ≥200 kW capacity.
Combination Scheme	• 1.5+ Scheme: 1.5 Scheme + HR Scheme + LL Scheme

Alpha Risk Analysis for Undervoltage (VVO)

Quantified DSSE performance achieved by sensors and operational forecasting for seven circuits.

Low PV Penetration Circuits: C1–C6

High PV Penetration Circuit: C7

$\Delta_{min}<10^{-3}$pu		0.5	1.5	2.5	3.5	STFE10	STFE20	HR	LL	PV	1.5+
C1	Δα		9%	11%	11%	14%	9%	14%	7%	N/A	14%
	α	14%	5%	3%	3%	0%	5%	0%	7%		0%
C2	Δα		16%	16%	16%	15%	6%	4%	17%	N/A	18%
	α	18%	2%	2%	2%	3%	12%	14%	1%		0%
C3	Δα		0%	6%	7%	7%	4%	8%	11%	N/A	11%
	α	11%	11%	5%	4%	4%	7%	3%	0%		0%
C4	Δα		16%	N/A	N/A	11%	3%	9%	44%	N/A	44%
	α	44%	28%			33%	41%	35%	0%		0%
C5	Δα		7%	29%	N/A	17%	3%	12%	35%	N/A	37%
	α	37%	30%	8%		20%	34%	25%	2%		0%
C6	Δα		9%	9%	9%	20%	15%	22%	5%	N/A	24%
	α	24%	15%	15%	15%	4%	9%	2%	19%		0%
C7	Δα		2%	2%	N/A	10%	7%	4%	13%	0%	28%
	α	47%	45%	45%		37%	40%	43%	34%	47%	19%

α risk = 0%	0% < α risk ≤ 3%	3% < α risk ≤ 10%	α > 10%

Some Observations

- **Combination Scheme** needed to reduce α risk to near zero for all circuits.
- **Large Load Sensor Scheme** is most effective individual measure for reducing α risks on circuits with high portion of large loads (industrial/commercial).
- **Main Line Sensor Schemes** (1.5 / 2.5 / 3.5) improve α risk in most cases. Some ineffectiveness because α risk reduction is not a criterion for sensor placements (reliability is).
- **Short-Term Forecasting Engine** provides consistent reductions of α risks. Effectiveness highly dependent on forecast accuracy.
- **High Risk Sensor Scheme** can potentially provide high reduction of α risk, but has some implementation challenges.

Planning Mode Functions

Estimation-Improving Measures	Quantifies DSSE performance improvements achieved by operational forecasting and adding circuit-level sensors that provide a full measurement set (i.e., P & Q).
Sensor Type Analysis	Compares the DSSE performance achieved by P & Q line sensors and line sensors that measure 'current magnitude only'.
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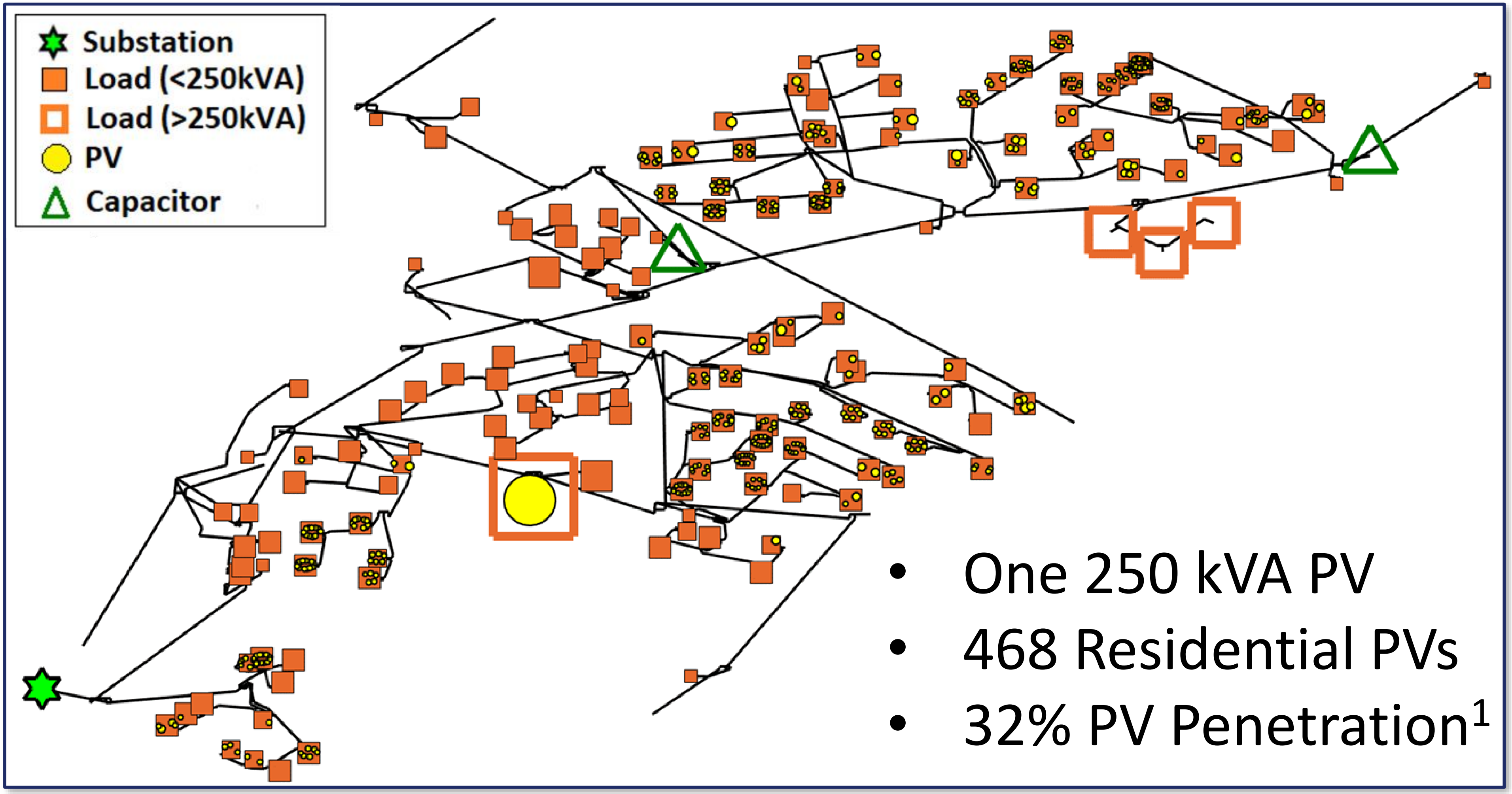
High PV Penetration	Perform analysis during clear-sky & cloudy-sky conditions when PV-caused voltage variability and DSSE estimation errors are largest.

High PV Penetration Circuit

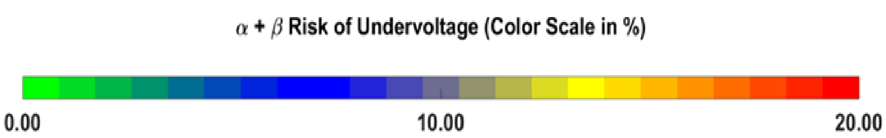


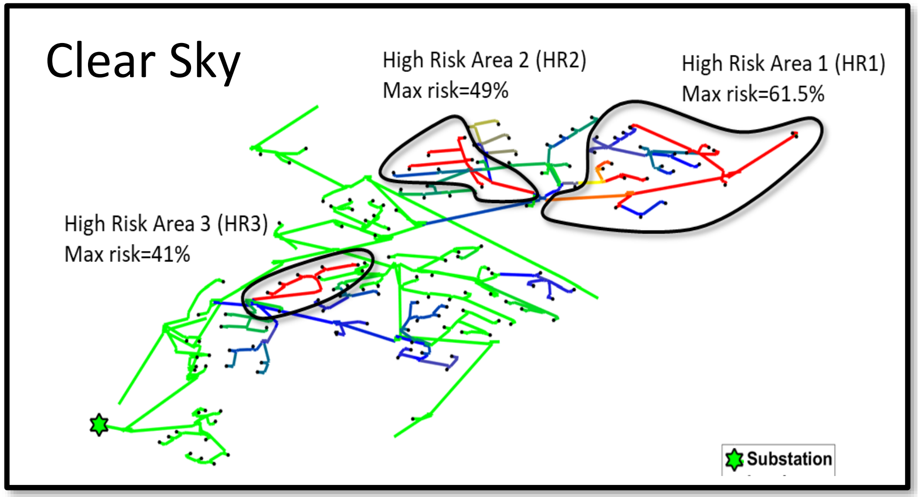
- One 250 kVA PV
- 468 Residential PVs
- 32% PV Penetration[1]

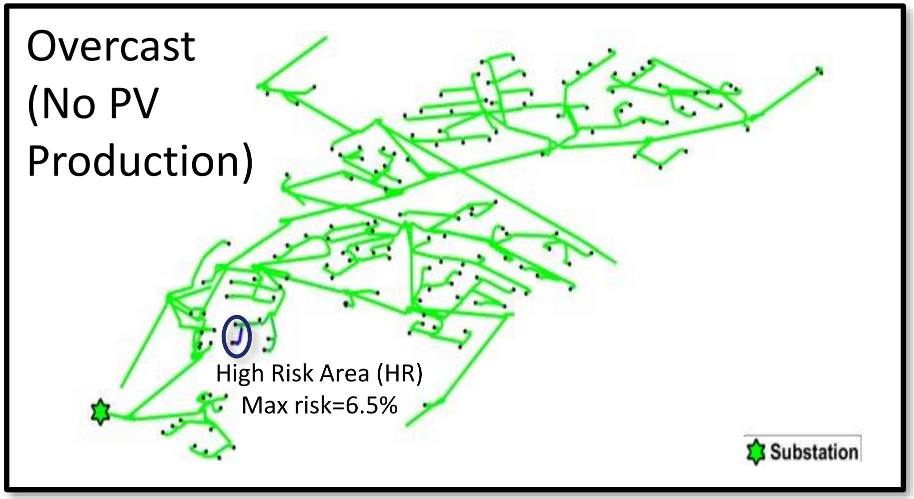
[1] PV Penetration calculated as the ratio between aggregate PV Capacity and aggregate load rating x 100.

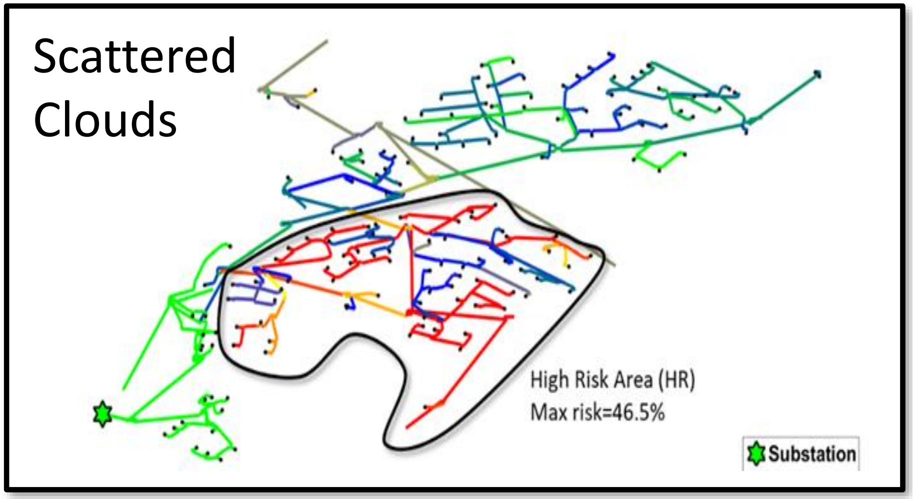
High PV Penetration Circuit

High Risk area locations and sensor placement requirements depend on sky condition.









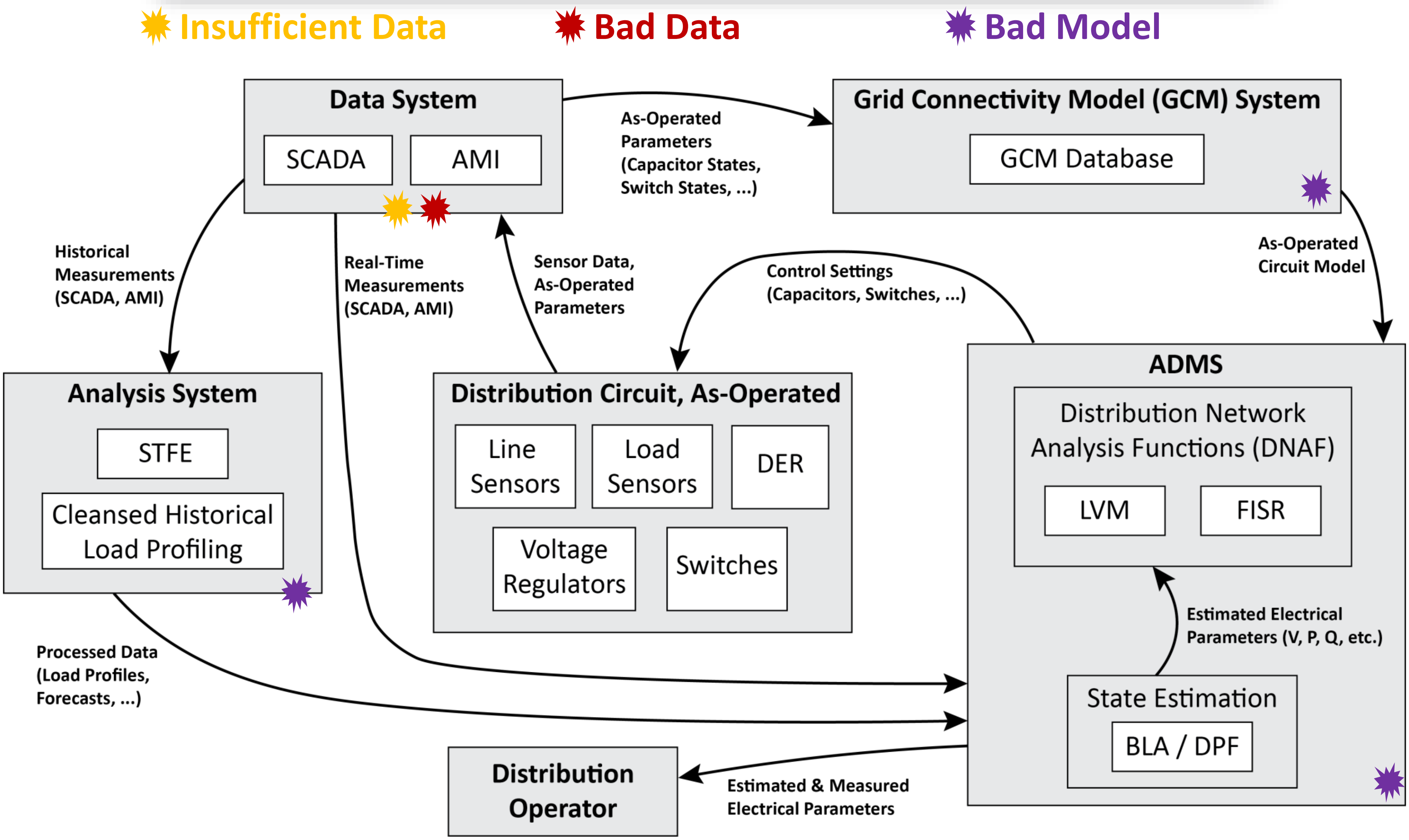
Ranking of Measures – Clear Sky

Short-Term Forecasting Engine most effective measure (also the case for cloudy sky conditions). Residential PV adds broad uncertainty.
=> Measures that broadly improve accuracy are most effective.

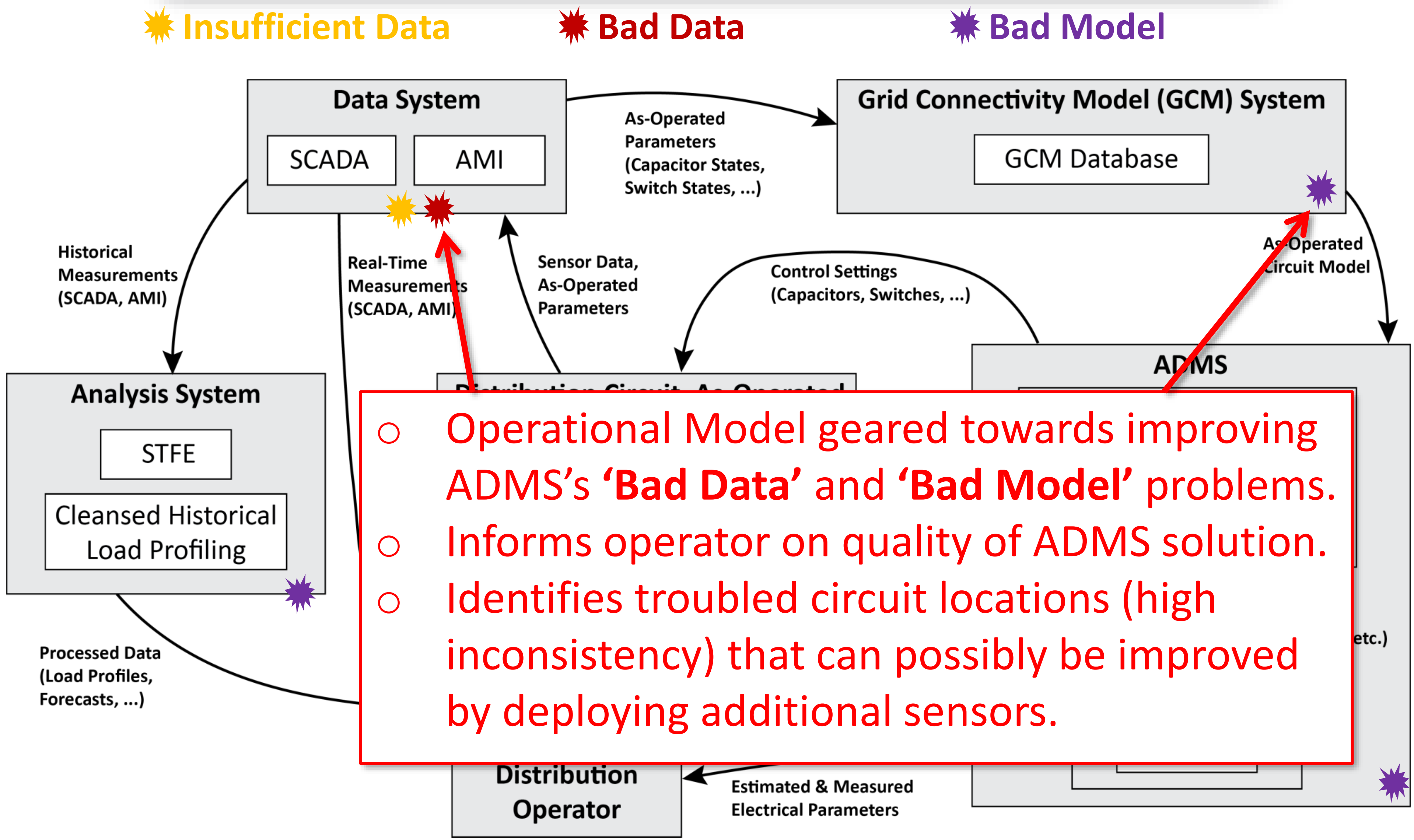
Rank 1 5.9% $\alpha+\beta$ Risk Reduction	•**STFE10** Short-Term Forecast Engine improves load and PV forecast to +-10%.
Rank 2 3.9% $\alpha+\beta$ Risk Reduction	•**STFE20** Short-Term Forecast Engine improves load and PV forecast to +-20%.
Rank 3 1.9% $\alpha+\beta$ Risk Reduction (1.9% per sensor)	• **HR Scheme with one additional sensor** Place a sensor near area with high risk.
Rank 4≈5 1.7% $\alpha+\beta$ Risk Reduction (0.003% per sensor)	•**PV Scheme** Place sensors at all PVs.
Rank 4≈5 1.7% $\alpha+\beta$ Risk Reduction (0.85% per sensor)	•**2.5 Scheme** Place two sensors on main line.
Rank 6 1.0% $\alpha+\beta$ Risk Reduction (1.0% per sensor)	•**1.5 Scheme** Place one sensor on main line.
Rank 7 0.1% $\alpha+\beta$ Risk Reduction (0.03% per sensor)	•**LL Scheme** Place sensors at large loads.
Rank 8 -0.5% $\alpha+\beta$ Risk Reduction (-0.5% per sensor)	•**LPV Scheme** Place sensors at Large PVs.

DSSE Performance Evaluation: Operational Mode

ADMS Error Sources

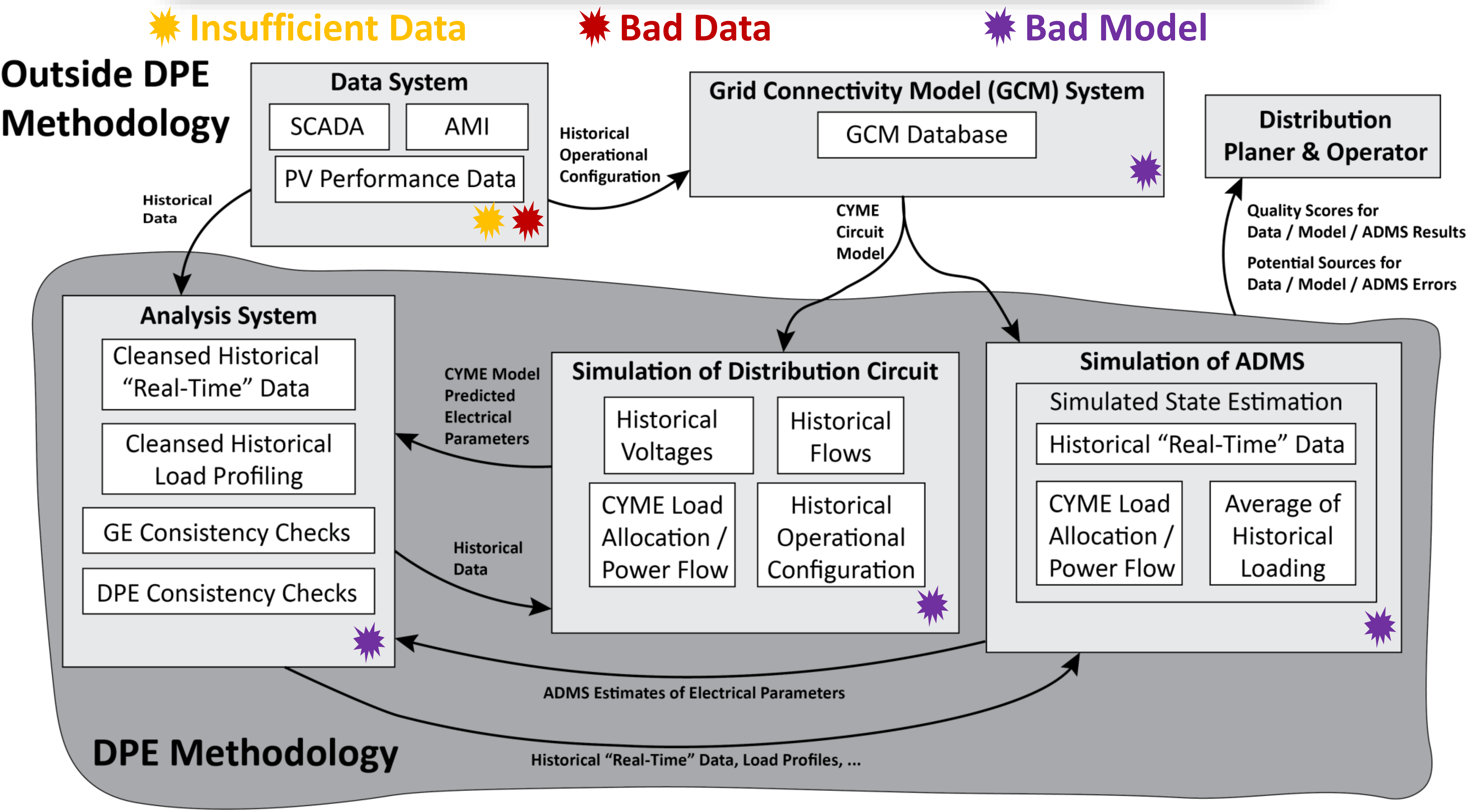


Objective of DPE Tool's Operational Mode



- Operational Model geared towards improving ADMS's **'Bad Data'** and **'Bad Model'** problems.
- Informs operator on quality of ADMS solution.
- Identifies troubled circuit locations (high inconsistency) that can possibly be improved by deploying additional sensors.

DPE Tool – Overview of Operational Mode



Benchmarking ADMS Performance

Circuit Simulations

Loading based on feeder-head P&Q data and either

- AMI data for time of analysis or
- Historical averages of loading (load profiles)

Field Data

- P&Q and voltage from automated switches
- Current from RFIs
- Voltages from AMIs and capacitors

Comparison

⇩

Quality of Circuit Model and Field Data

Benchmarking ADMS Performance

- Deterministic simulations.
- Use historical data as proxy for real-time data.
- Comparison of Model-Predicted Voltages and Flows with Field Data.
- Use some line sensors measurements in simulation to determine
  - impact on flow and voltage mismatches.
  - ability to pinpoint error sources.
- Informs (1) quality of ADMS results and (2) quality of DPE Tool's sensor deployment recommendations.
- Work in progress.

Summary & Next Steps

DSSE Performance Evaluation Methodology

- Planning mode:
  - suitable for evaluating **effectiveness of sensor deployment / operational forecasting scenarios** in supporting DSSE-driven Advanced Applications.
  - facilitates **integrated DA deployment strategy** for switch placement based on
    - reliability improvement (done today) +
    - situational awareness improvement (added value).
- Operational Mode: Provides operator information on the quality of the DSSE solution (work in progress).
- A few **general guidelines** extracted from analysis on a small number of circuits but **Circuit-by-circuit analysis** needed (especially <u>for high PV penetration circuits</u>) to fully inform sensor deployments and operational forecasting requirements.
  => Development of tool that automates analysis in progress!

Q & A

Thank you!

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Applications that rely on DSSE

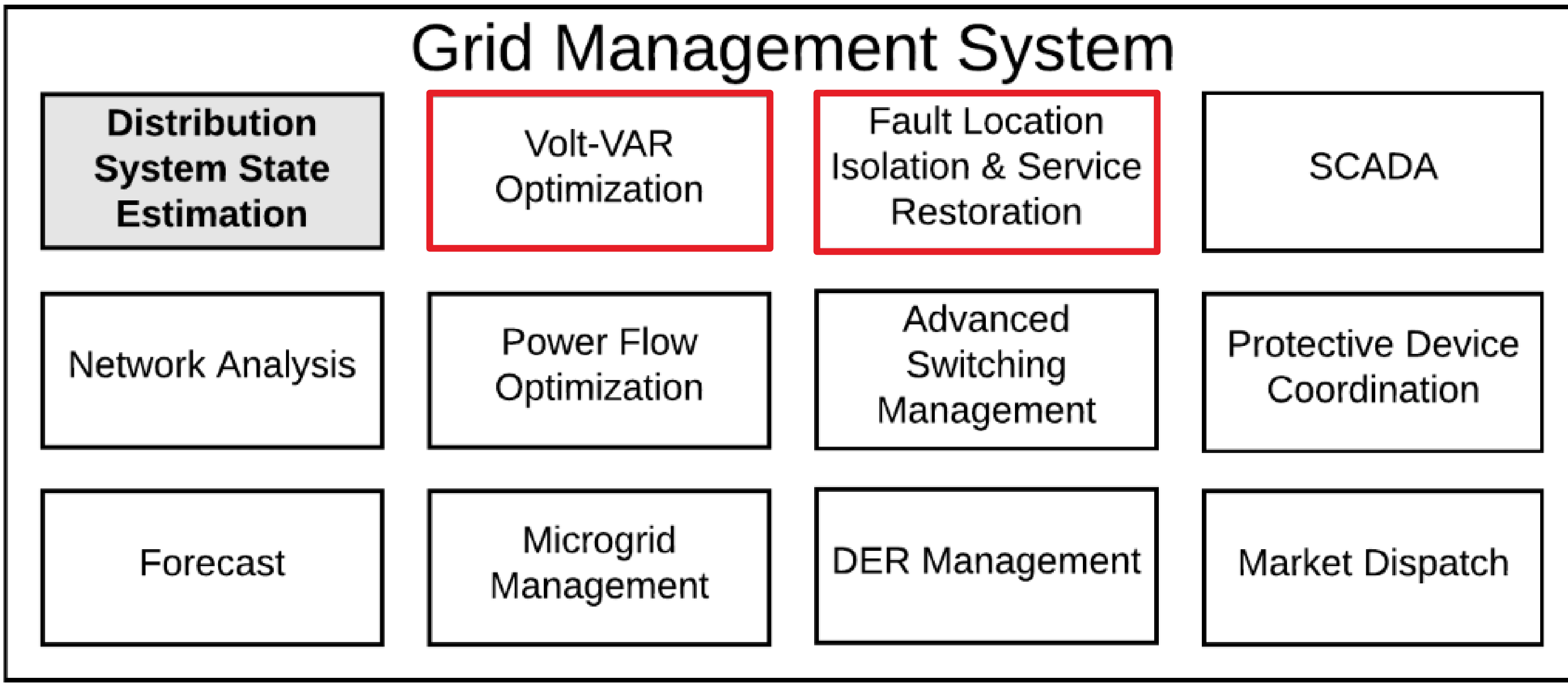
Basic and Advanced Applications

Basic Applications for DSSE

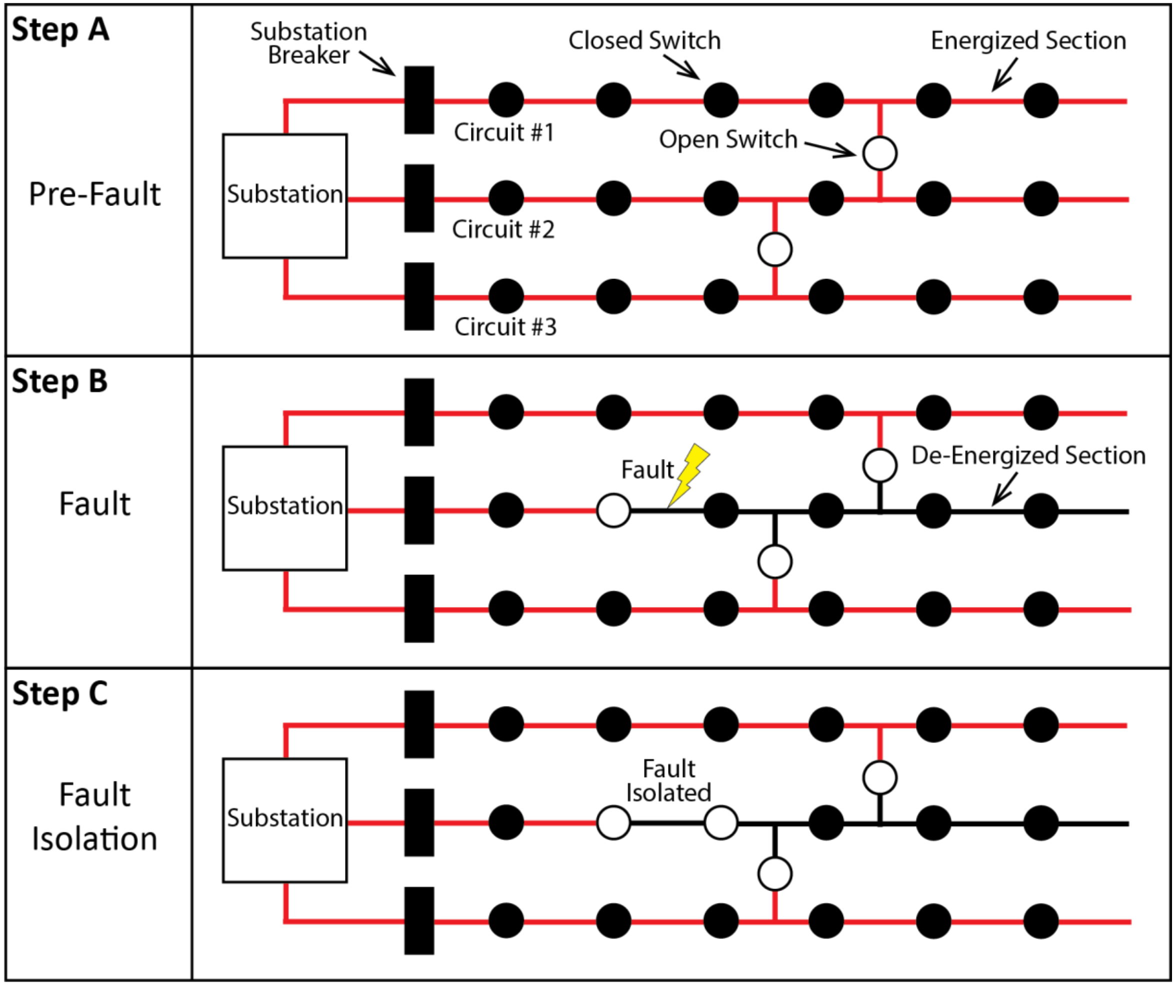
- Distribution System State Estimation (DSSE) is a Foundational Application that provides situational awareness and DER Visibility.
  - For instance, when a feeder is energized, inverter based generation will be offline for 5 minutes after re-energization. The operator needs visibility into inverter performance to avoid overloads, overvoltages, and undervoltages during switching.
- DSSE informs optimization and control decisions of Grid Management System (GMS) Advanced Applications.
  - For instance, DER can be dispatched to mitigate overloads instead of building new infrastructure (aka non-wire alternatives).

GMS Advanced Applications

- Focus of our DSSE work on ‘Volt-Var Optimization’ and ‘Fault Location, Isolation & Service Restoration’.
- Other Advanced Applications could be added later.



Fault Location & Isolation (DSSE Not Needed)

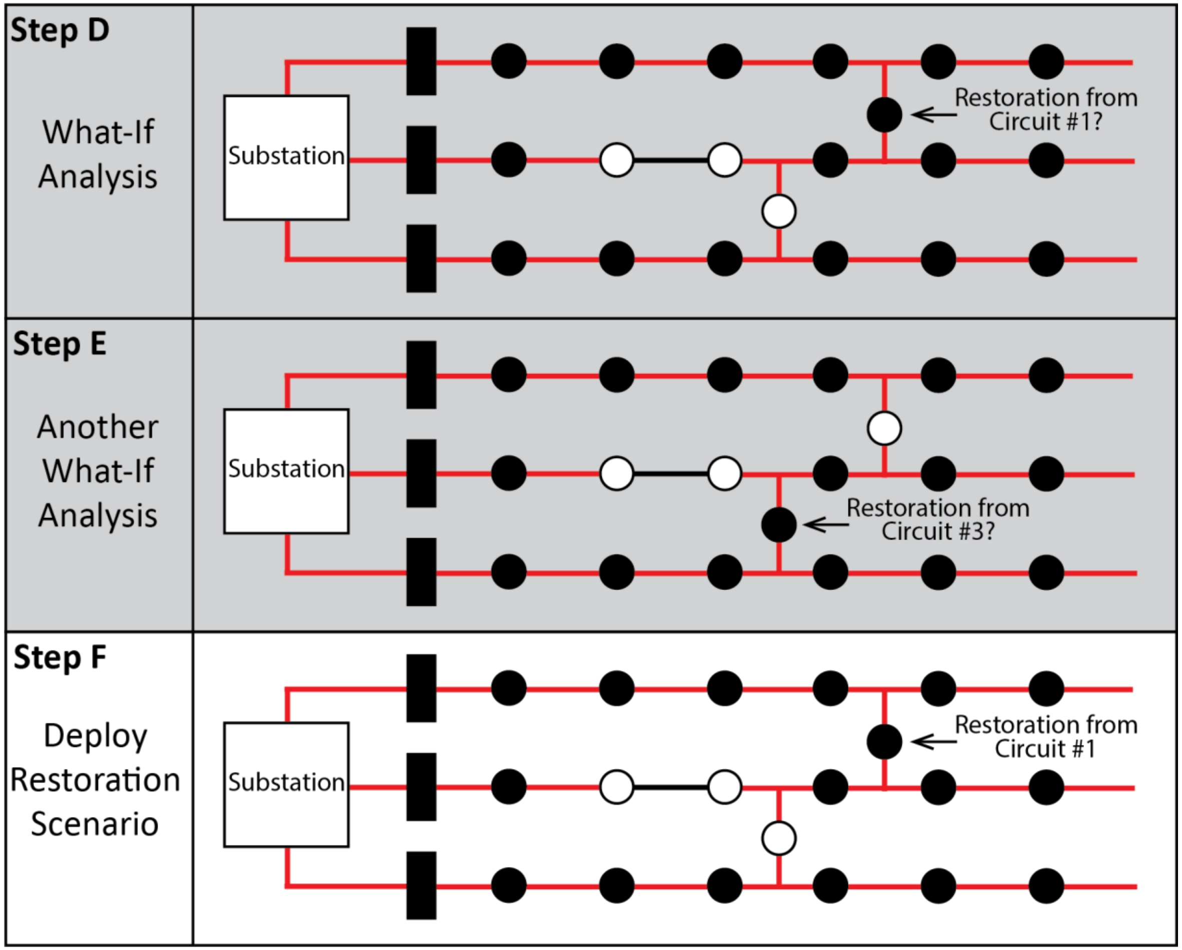


Step A: During the Pre-Fault stage, the Distribution Power Flow (DPF) application continuously calculates the states of the system and stores it in the Historian. The last calculation before the fault is the "last gasp" state.

Step B: A fault occurs on Circuit #2 and the system protection quickly trips the nearest upstream breaker resulting in de-energization of the faulted circuit section. The Fault Location application locates the fault using real-time SCADA.

Step C: The Fault Isolation application isolates the fault. The DPF calculates the state of the energized circuit based on real-time data and historic load data for that circuit.

GE's Service Restoration (DSSE Needed)



Steps D, E, & F: The Service Restoration (SR) application evaluates a number of 'what if' scenarios for service restoration. The evaluation comprises (1) determining a Switching Request that results in a circuit configuration that provides the optimal solution based on pre-specified optimization criteria and (2) ensuring that no violations occur during and after the execution of the Switching Request. Execution of the Protection Validation (PRV) application in study mode will ensure that the protective settings are valid for the new configuration. Execution of the Load Voltage Management (LVM) application in study mode to determine voltage control settings that avoid voltage problems.

Alpha Risk for Overloading – Guidelines

- For most scenarios, substation data is sufficient to inform service restoration.
- For some scenarios, the α risk is unacceptably high and can only be reduced to zero by reducing the transferred load.
- Telemetry provided by main line sensors can reduce the α risk to zero if the weak link is a line that is some distance from the substation.
- Telemetry provided by main line sensors does not reduce the α risk if the weak link is a line segment that originates from the substation.
- Real-time FLISR (Scenario B) is more successful in achieving zero α risks compared to FLISR that is based on a look-ahead analysis (Scenario A).

DSSE Evaluation Work

Methodology

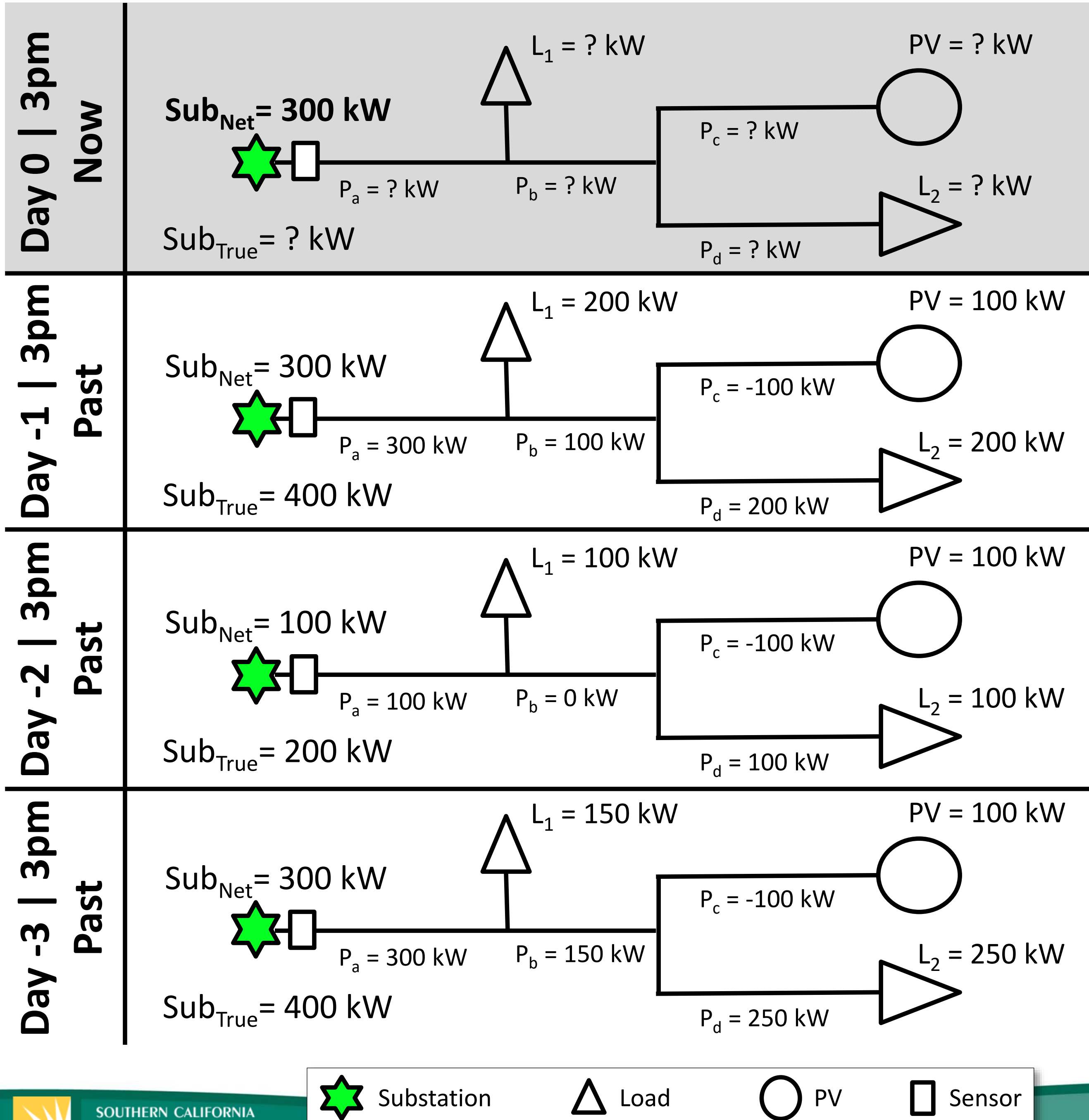
Simple Example

Example for simple circuit presented in next slides

- ADMS process to estimate loads
  - Used in the ADMS and replicated in our simulations.
  - Simple circuit with two loads and one PV. Ignore losses.
  - Clear-sky (i.e., predictable) PV generation.
  - 0.5 Scheme (substation data available in real-time).
  - Detailed cloudy-sky scenario in Phase III report.
- Possible true states of loads
  - Simple circuit with historical data from three days prior to ADMS execution (used as possible true states in stochastic analysis to evaluate ADMS estimates).
  - Filter out prior days with substation loading that is very different from the one at time of ADMS execution (addressing Josh's concern).

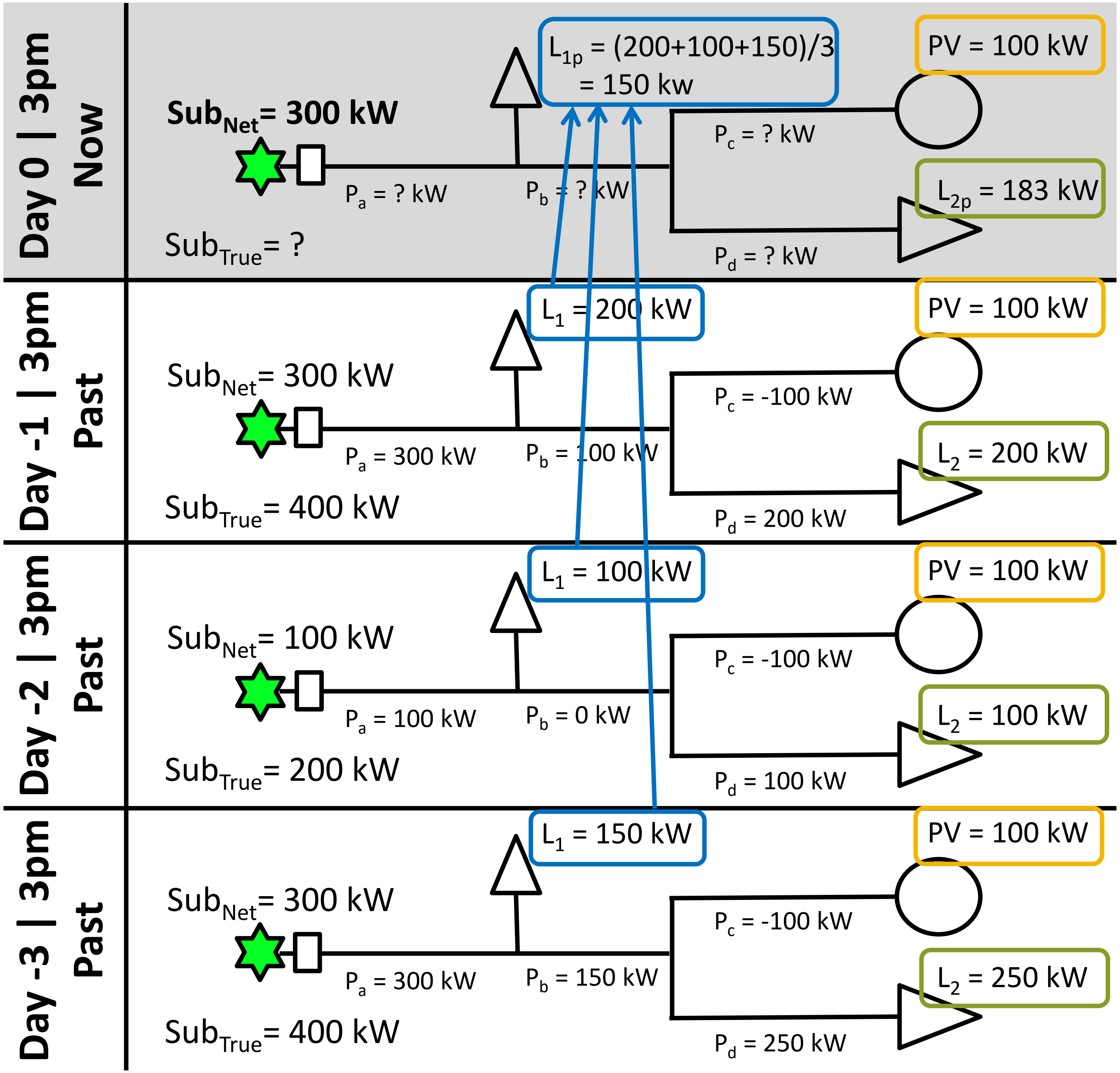
This is what the ADMS is doing…

Data Availability (0.5 Scheme)



Real-Time Substation Data

Historical Substation & AMI Data



Pseudo Measurements

Use Historical Data for Pseudo Measurements

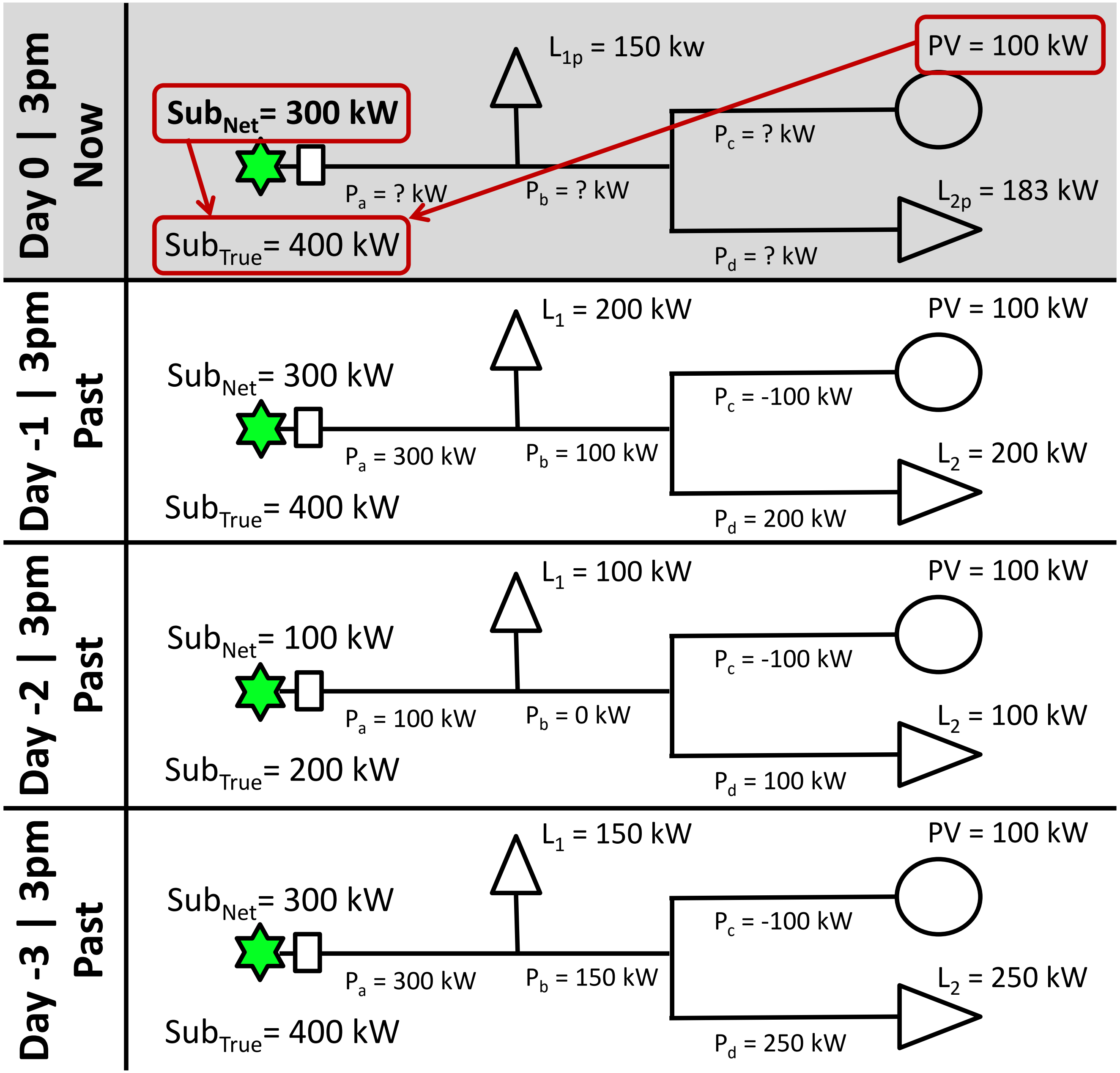
$$L_{1p} = \frac{200 + 100 + 150}{3} kW = 150\ kW$$

$$L_{2p} = \frac{200 + 100 + 250}{3} \text{kW} = 183\ kW$$

$$PV = \frac{100 + 100 + 100}{3} \text{kW} = 100\ kW$$

$$Sub_{True} = (300 + 100) kW = 400\ kW$$

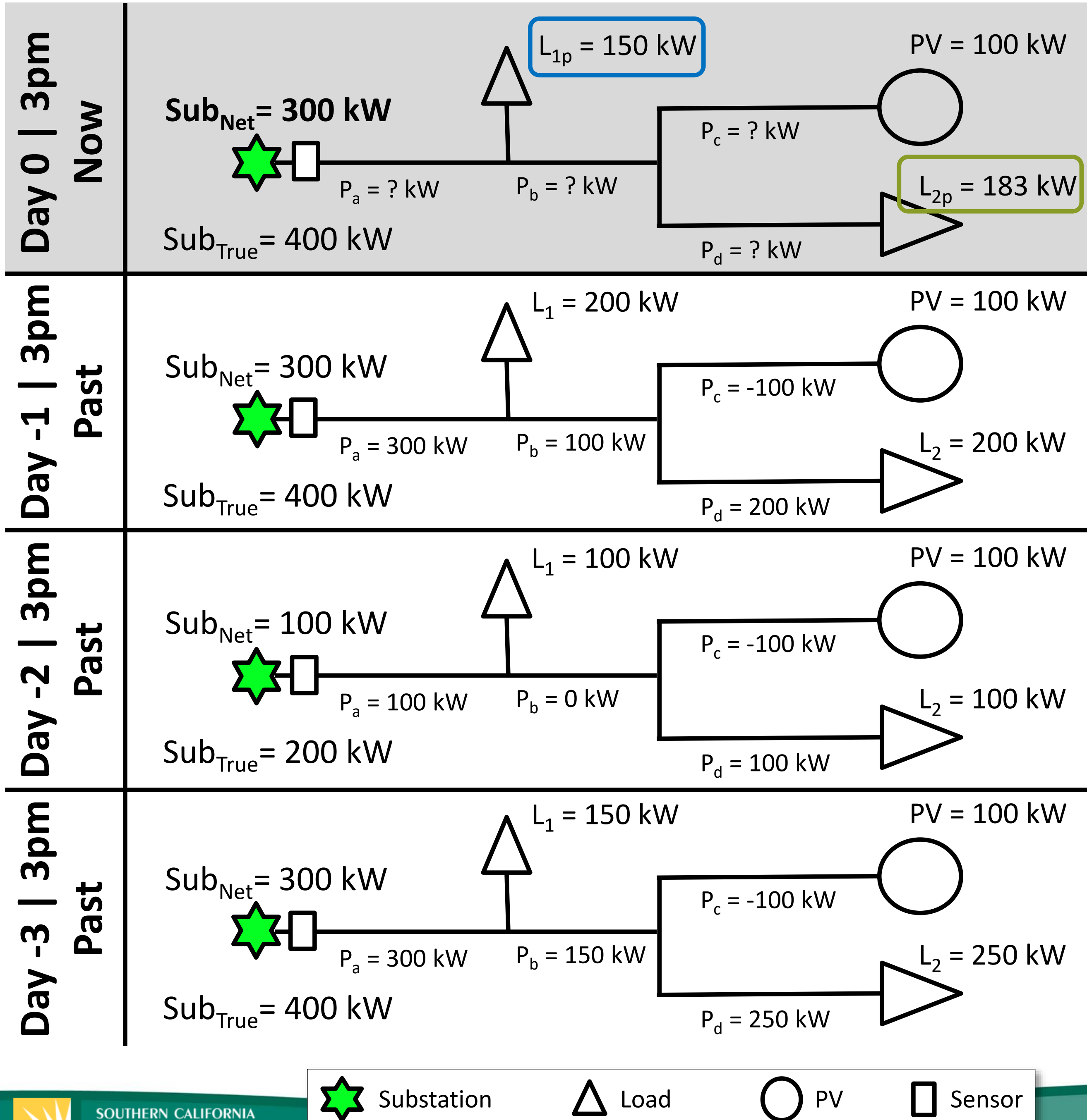
True Load



Use Real-Time Data and PV Pseudo Measurement to Calculate True Substation Load

$$Sub_{True} = (300 + 100)\ \mathrm{kW} = 400\ kW$$

Need for Load Allocation

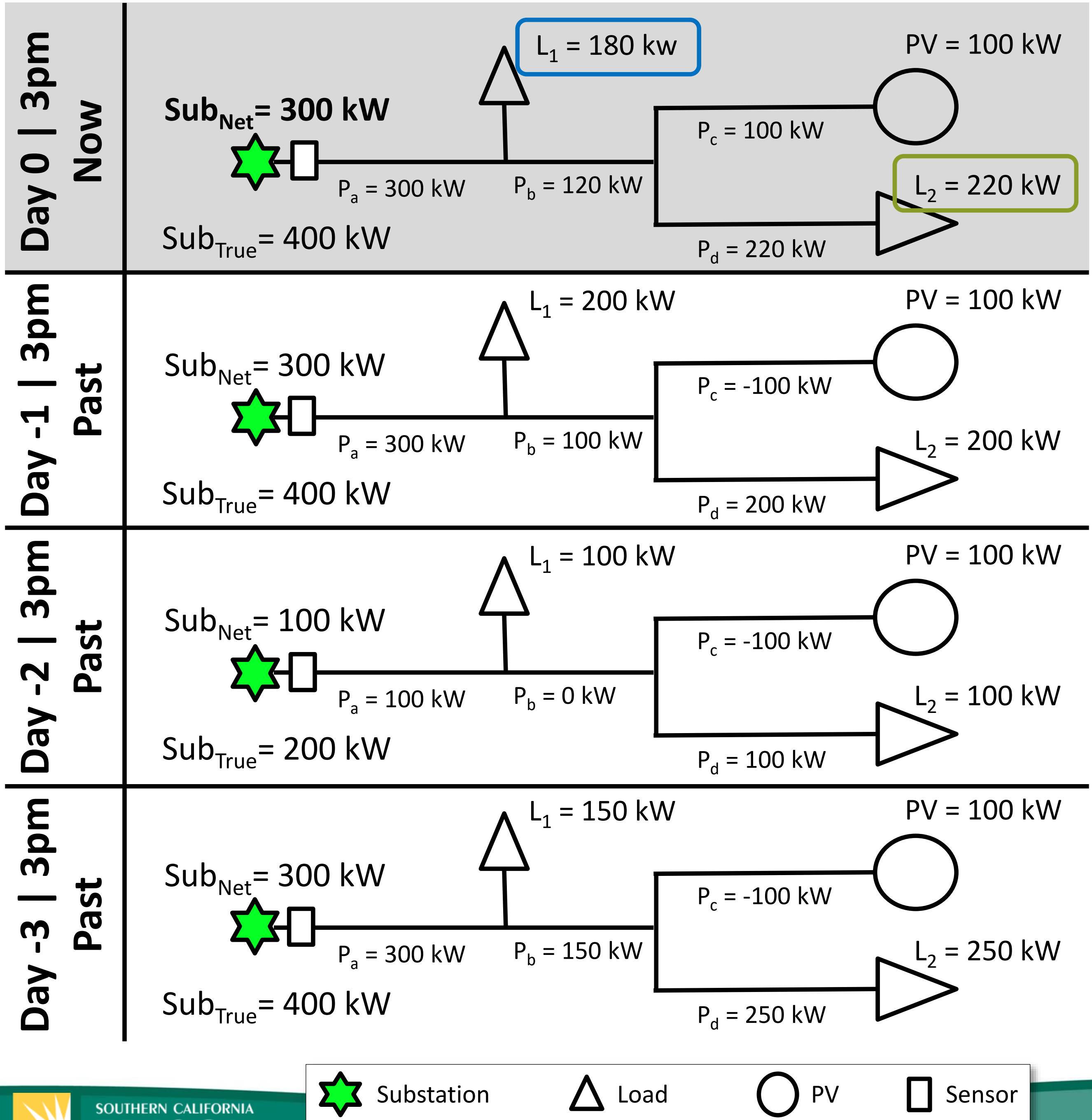


$$Sub_{True} = 400\ kW$$

$$L_{1p} + L_{2p} = (150 + 183)kW$$
$$= 333\ kW$$

Sub_{True} and $L_{1p} + L_{2p}$ do not match.

L_{1p} and L_{2p} need to be scaled to match substation loading (i.e., perform load allocation)



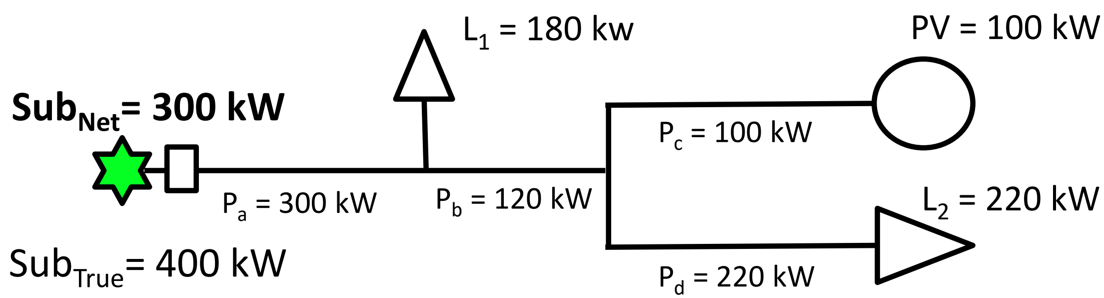
Allocate Load

Allocate True Substation Load to Individual Loads

$$L_1 = Sub_{True} \frac{L_{1p}}{L_{1p} + L_{2p}} kW$$
$$= 400 \frac{150}{150 + 183} kW$$
$$= 180\ kW$$

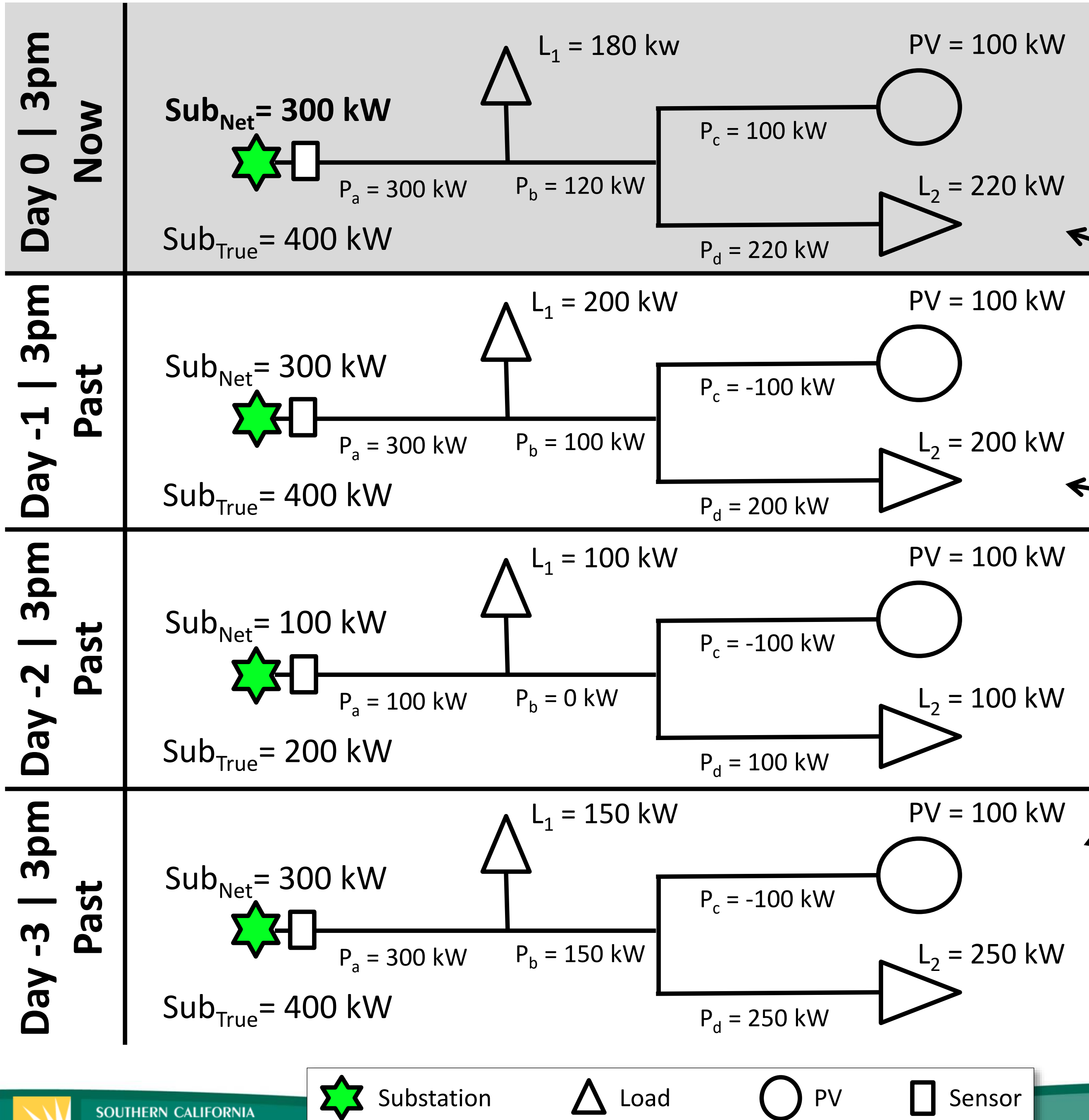
$$L_2 = Sub_{True} \frac{L_{2p}}{L_{1p} + L_{2p}} kW$$
$$= 400 \frac{183}{150 + 183} kW$$
$$= 220\ kW$$

Question: How can we quantify the accuracy of this ADMS result?



Answer: Need to compare to possible true states…

Possible True States

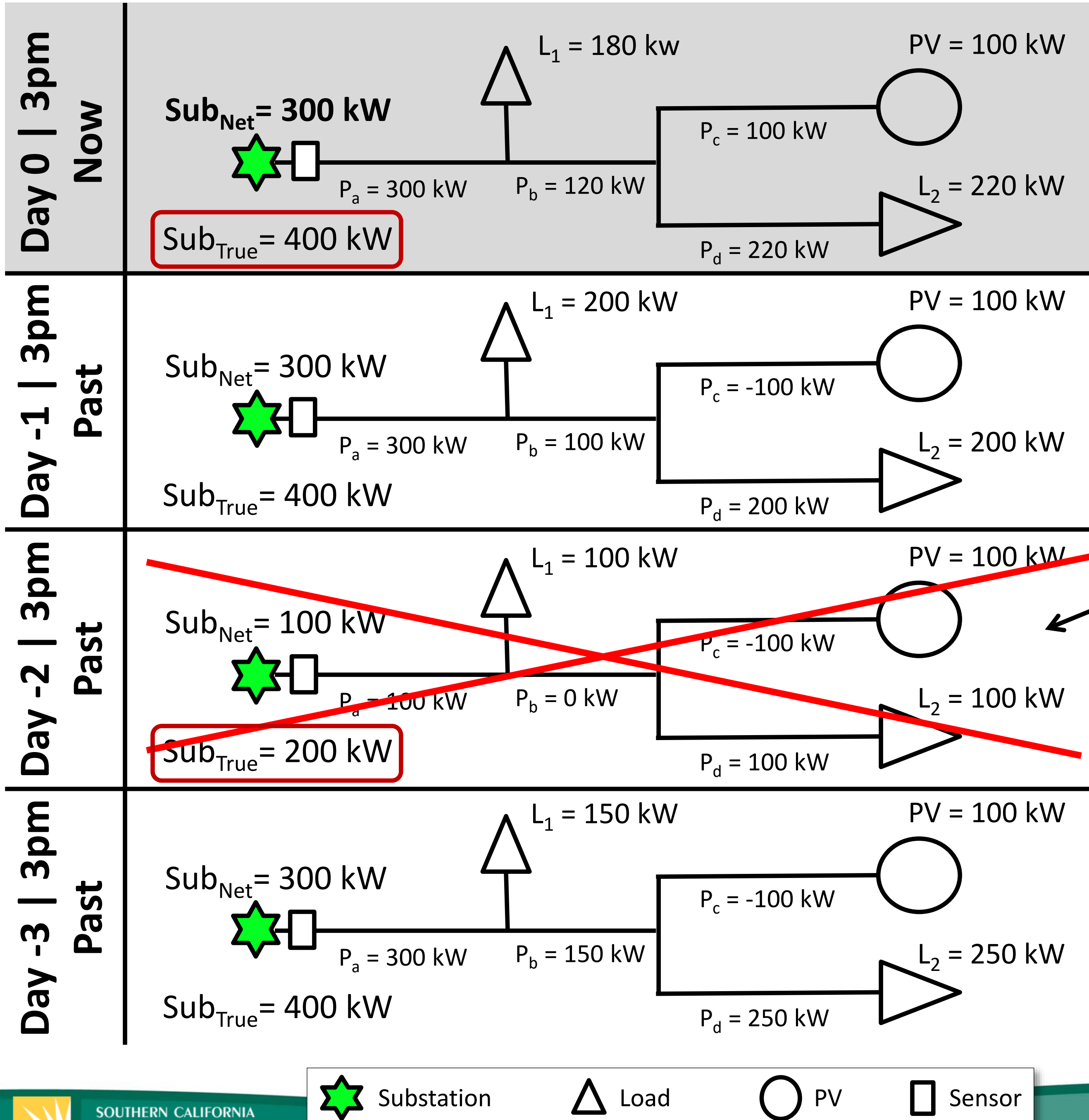


This is ADMS's "best guess" of the loading but…

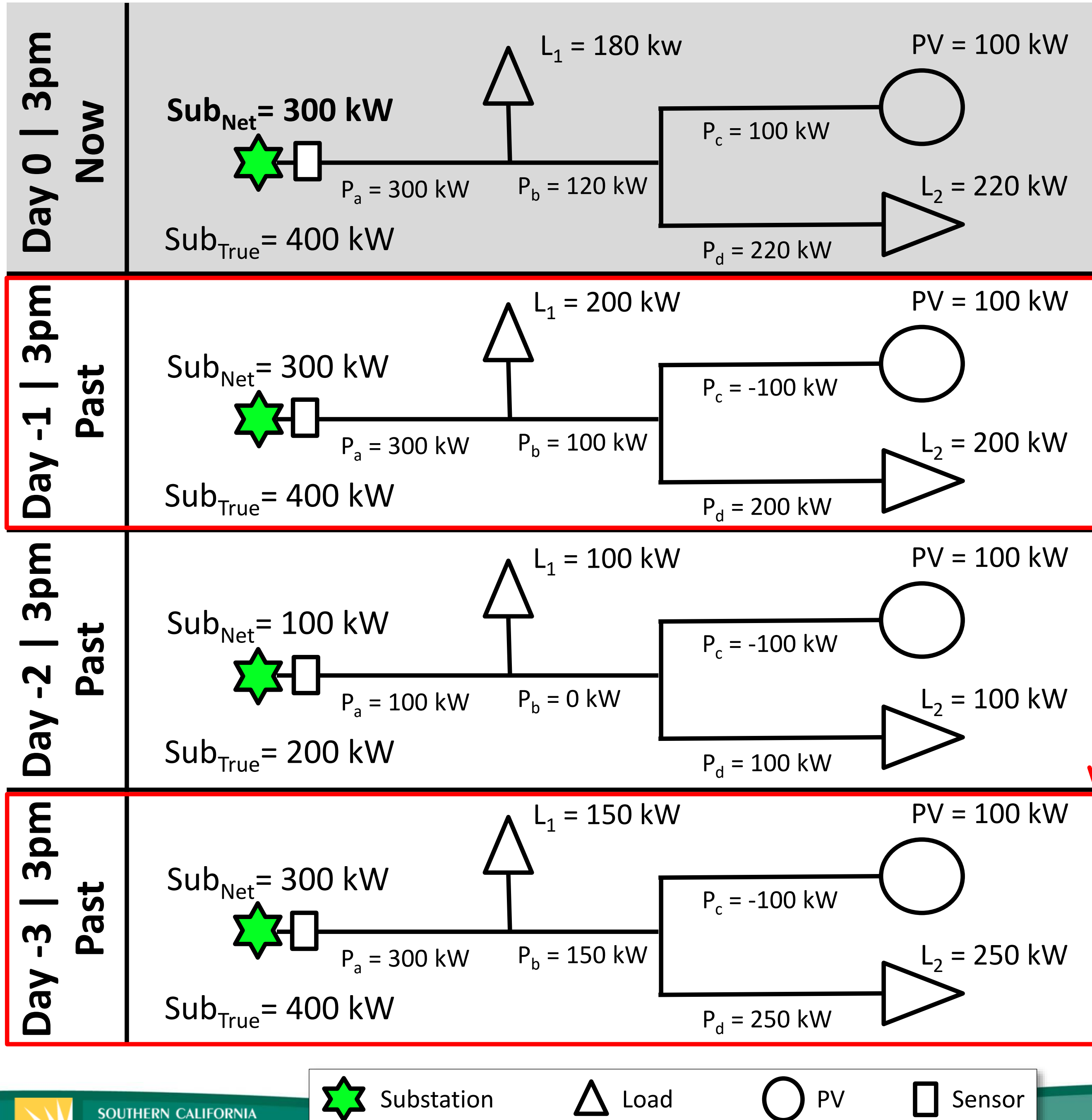
… loading at time of the ADMS execution could also be this…

… or this.

Not a Possible True States



Exclude this loading scenario because substation data is much lower than it is at the time of ADMS execution.



Possible True States

Use these loading scenarios as possible true states for quantifying accuracy of ADMS estimate.

Stochastic analysis realistically captures load variation (provided sufficient historical AMI data available)