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Renewable Integration Model Presentation

California Long-Term Procurement Plan Workshop

Energy Division
California Public Utilities Commission (CPUC)

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Presented by:
Judy Chang
Philip Hanser

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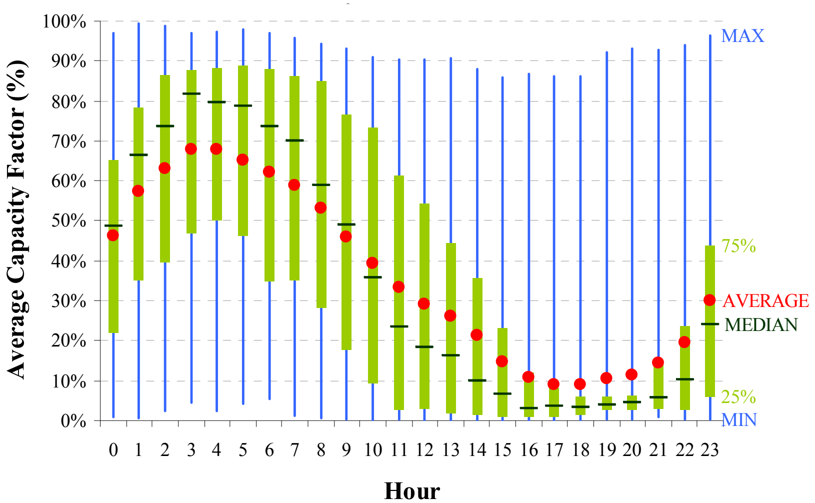
Renewable Generation Characteristics

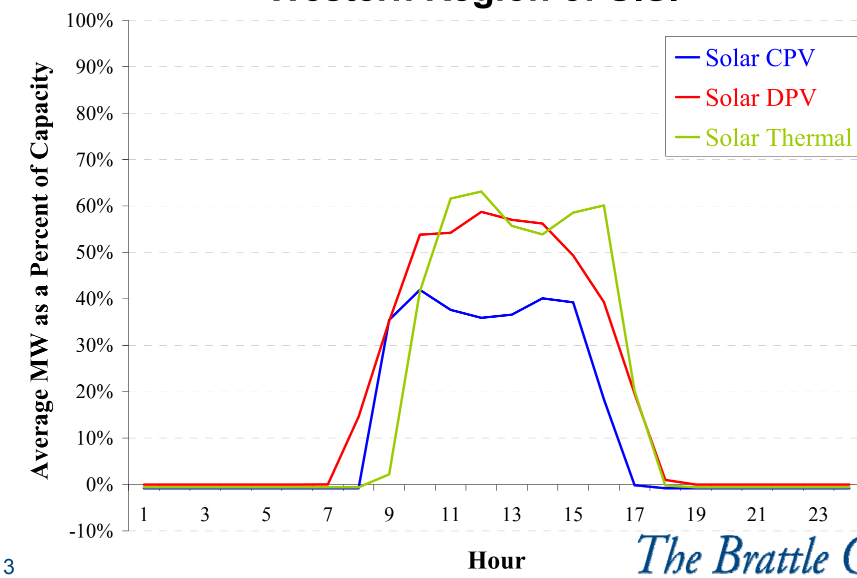
- Renewable energy provides significant environmental benefits
- Incorporating them into existing system consists of new challenges
- Some renewable resources have variable output; wind and solar with the following characteristics:
  - **<u>Variability</u>:** the magnitude of power output from one moment to the next can change dramatically
  - **<u>Unpredictability</u>:** sudden changes in generation output not well-forecasted

Sample Wind Profile for July Western Region of U.S.



Source: Calculated based on hourly wind generation data from TEPPC.

Sample Solar Profile for January Western Region of U.S.



Motivation and Goals of the Renewable Integration Model (RIM)

PG&E's Goal: Analyze and estimate resource requirements and costs associated with integrating various levels of variable generation resources

Various other wind integration analyses revealed that:

- Statistical processing to parameterize intra-hour volatilities is needed
  - Lack of granular historical data requires using assumptions to forecast future renewable energy production patterns
  - These intra-hour volatility assumptions drive results
- Many rely on production cost modeling to simulate full systems
  - Production cost simulations are not designed for intra-hour analyses
  - Difficult to determine if models represent actual operations and the use of reserves
- Most analyses ignore potential incremental capital costs associated with incremental resource additions

A simple, transparent and flexible model is needed

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Important Considerations for Model Design

The Renewable Integration Model (RIM) focuses on the central issues:

- Evaluate incremental service requirements
- Estimate magnitude of resources to provide those services
- Estimate variable and fixed costs

RIM is designed to achieve above goals with functional features below:

- Simple but careful
  - Uses simplifying assumptions to represent complex issues
  - Focus and care is placed on using all available information to best simulate reality
  - Runs quickly
- Transparent
  - Accepts user input assumptions
  - Uses fully transparent calculations
- Flexible
  - Can provide results across many scenarios and resource portfolios
  - User defines the analytical period and the system conditions
  - Can be updated as system and forecast capabilities change
  - Portable – based on Excel spreadsheets

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RIM Overall Structure

Data Input	Calculations	Output
Installed variable generation	Estimate incremental operational requirements	Flexible requirements (regulation, load-following, day-ahead commitment)
Detailed load & generation profiles	Estimate system's reliability requirements	New capacity required to integrate variable generation
Forecast errors for load & generation	Quantify resource requirements	Mix of resources based cost assumptions
Costs of conventional generation	Estimate fixed and variable costs of integration	Fixed and variable costs of integration

RIM Key Assumptions

Like all models, input assumptions drive model results.

RIM has relatively few parameters:

- **Load**
  - Parameters that describe load forecast errors and load variability (can be derived from historical data)
  - Load growth
  - Alternatively, a future year load profile can be used
- **Wind and solar**
  - Parameters that describe forecast errors and output variability (can be derived from historical data)
  - Correlation coefficients for generation output across sites
- **Resource costs and characteristics**
  - Capital costs
  - Heat rates
  - Fuel costs
  - Emissions costs

All default parameters can be updated and changed by users

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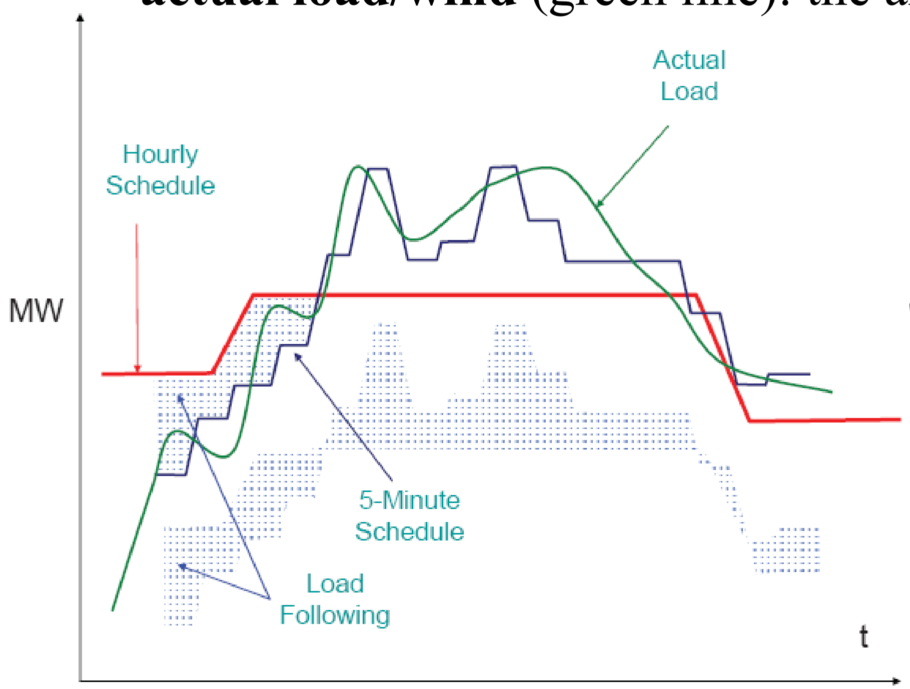
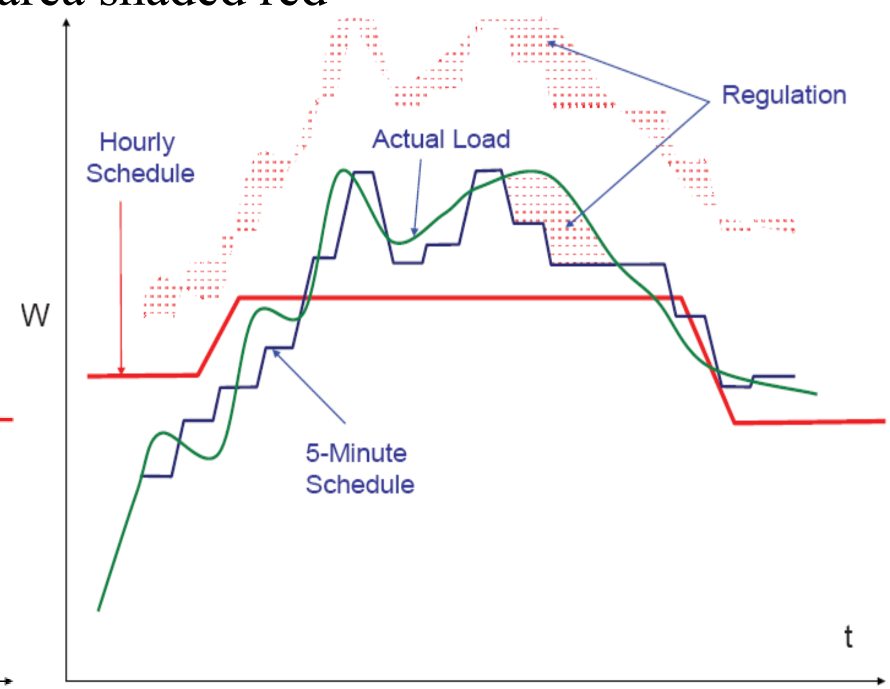
RIM uses CAISO's definition regulation and load following

The CAISO differentiates the two services by the scheduling process and the timing of the forecast

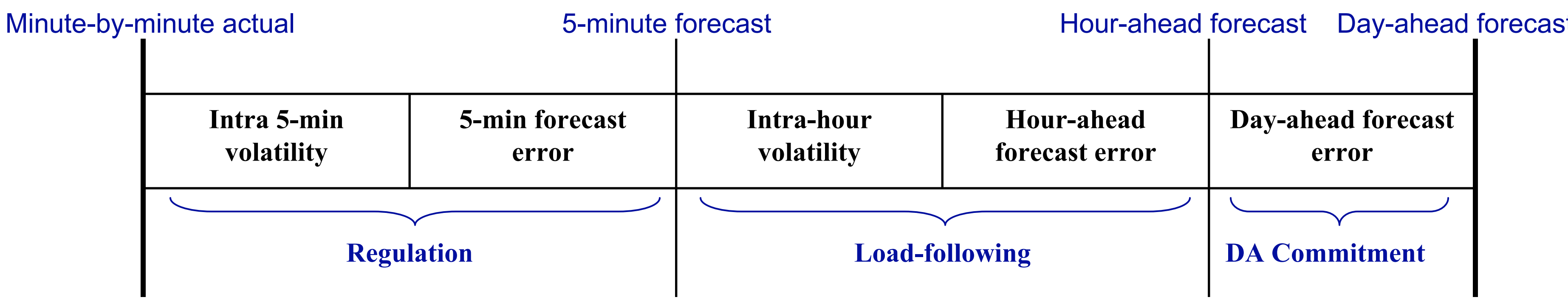
- Load following = difference between the **hourly schedule** (shown as red line) and the **5-minute schedule** (blue line) of generation to meet forecast load: the area shaded light blue
- Regulation = difference between the **5-minute schedule** (blue line) and the **actual load/wind** (green line): the area shaded red





Source: CAISO Integration of Renewable Resource, November 2007

Types of Services Needed to Compensate for Variability and Unpredictability



Regulation

- RIM uses parameters that describe deviations from relevant scheduling
- Two primary parameters: intra 5-min volatility and average 5-minute forecast error (next slide explains)

Load following

- RIM uses parameter that describe deviations between the 5-minute and the hour-ahead schedules
- Two primary parameters: intra-hour volatility and average hour-ahead forecast error

Day-ahead commitment

- Deviation between day-ahead and hour-ahead schedule

The model uses all 5 statistical parameters shown in diagram

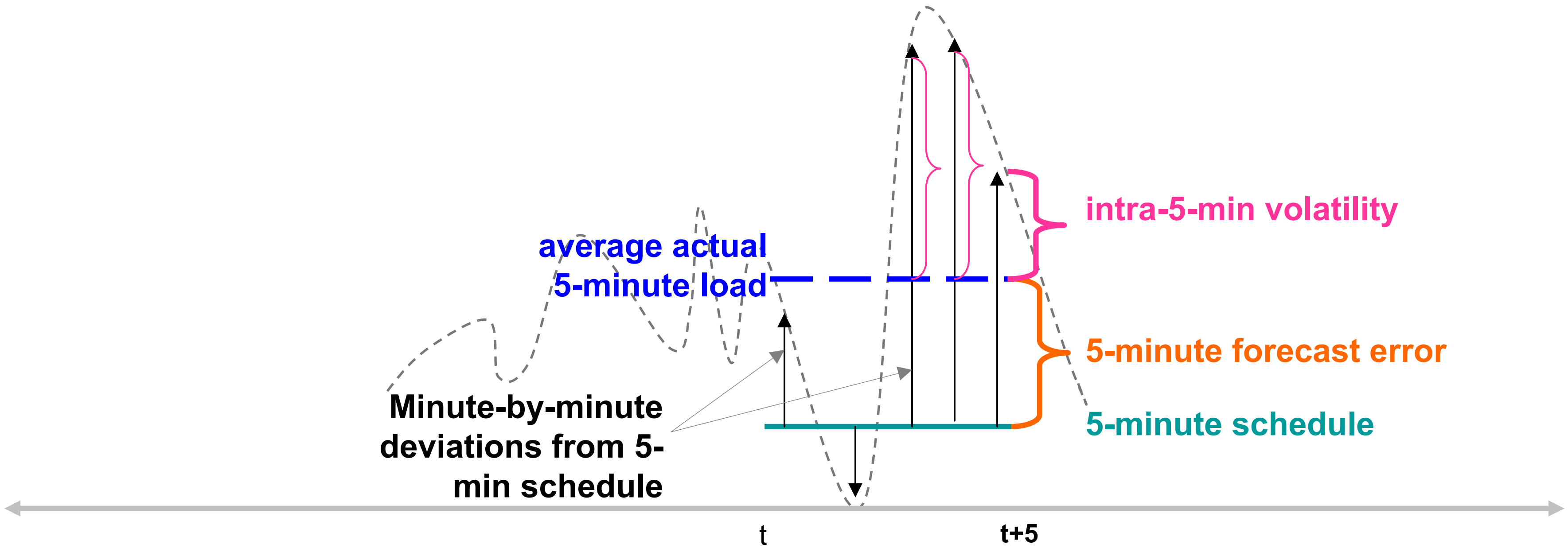
RIM uses statistical relationships of schedules and actuals to estimate services requirements

Regulation requirement for each 5 minute interval is estimated with two components of variance of load and generation:

1. *5-minute forecast error,* PLUS
2. *intra-5-minute volatility*

Analogous estimation methodology is applied to load-following

Day-ahead commitment need uses forecast error only



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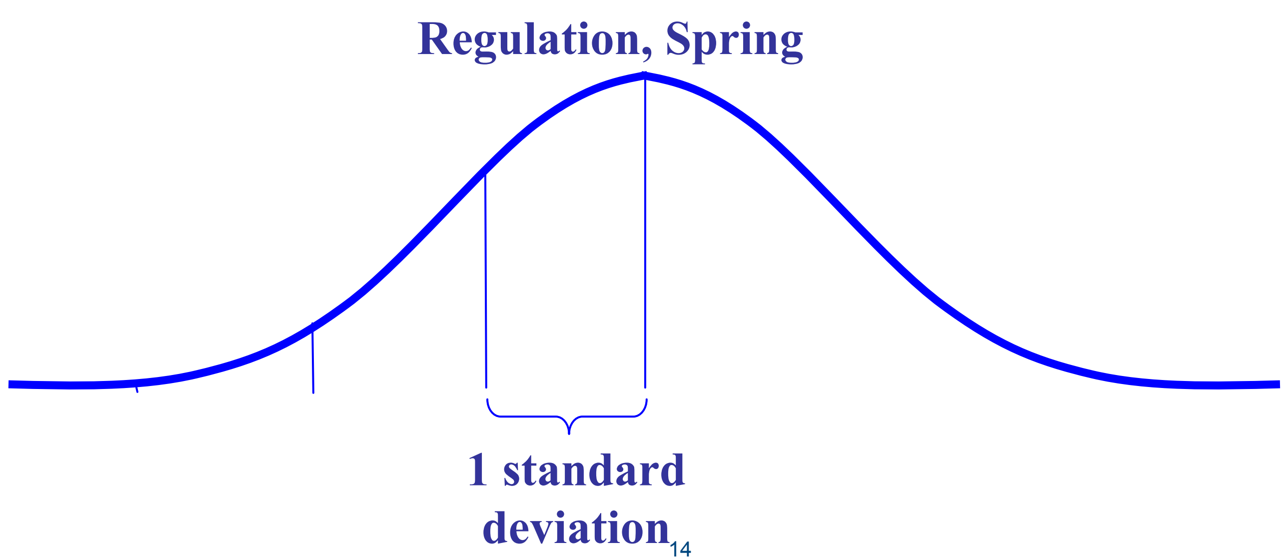
RIM summarizes regulation, load-following and day-ahead commitment needs by season

- RIM uses the standard deviations to estimate the services needs
  - User can input the magnitude and the number of standard deviation used to determine the needs
- RIM takes into account the correlation between sites and forecast errors
  - All of which are parameterized and user-driven
- RIM reports the operational requirements for regulation, load following and day-ahead commitment for each season



Derivation of Resources Required for Integration

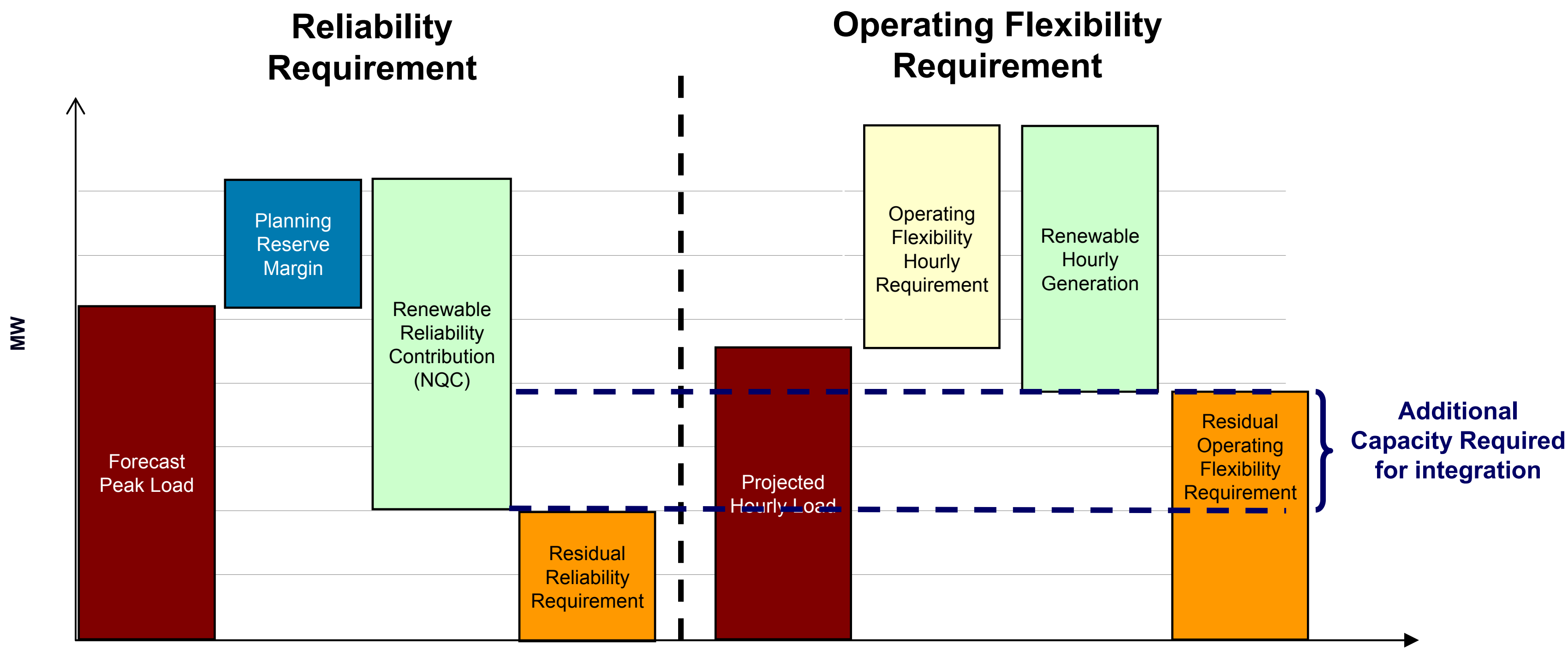
Assumptions:

- New or existing generating capacities can be used to provide the operational requirements of the system

Steps Taken:

- Estimate the magnitude of resources needed to meet the operational flexibility requirement after renewable resources are added to the system
- Estimate the resources needed to meet the reliability requirement of the system
  - Load plus planning reserves
- Compare the two and determine if additional resources will be needed above the planning reserve requirements

Steps in Estimating Resource Requirements



Forecast Peak Load
\+ Planning Reserve Margin
– Reliability Contribution of Renewables (NQC)

Reliability Requirement

Hourly Load
\+ Hourly Operating Flexibility Services
– Hourly renewable generation

Operating Flexibility Requirement

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Estimation of Fixed Costs

RIM uses 3 categories of inputs assumptions to derive the fixed cost of integration

- Fixed and variable costs of resources used for integration (*e.g.* CCs, CTs, storage, other technologies)
- The planning reserve requirement
- *Composite* load duration curve (*e.g.* load net of renewable generation, *plus* hourly operational requirements for integration).

Estimation of Variable Costs

RIM uses simplifying assumptions about operations to estimate variable costs:

- ♦ The cost of potential daily startups from resources to provide the needed services
- ♦ The cost of potential out-of-merit dispatch during ramp up and down time
  - Simulated with efficiency differential between in-merit and out-of-merit resources
  - This approach assumes the system potentially will need incremental resources to meet faster ramping during ramp up and down hours
- ♦ For meeting regulation needs, RIM can incorporate an efficiency penalty for all hours a resource must operate at a less than fully efficient set point

Observations from Other Recent Integration Analyses

Compared to production cost simulations, RIM's variable cost estimation uses consistent methodology

- Regulation and load following are translated into regulation and other reserves such that certain resources are "held aside" to react if necessary
- When certain resources are held aside, the next resource must be used – either by demanding certain resources to be "on reserve", or putting the in-merit resource on reserve and move up the dispatch curve to serve energy
- Some out-of-merit dispatch occurs – RIM simulate with using efficiency "penalty" between in-merit resource and the "next one up" on the dispatch ladder
- This is consistent with system operations
- All production efficiency assumptions can be adjusted by users

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Primary Strengths of RIM

- Full transparency
- User control over key assumptions
- Clear & flexible cost methodologies
- Ease of updating parameters as better information is available
- Ease of adaptation to forecast improvements
- Accommodates up to four renewable generation categories
- Facilitates policy discussions
- Based on CAISO-equivalent service definitions

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RIM Applications

RIM can be utilized to:

- Quantify incremental effects of changes in generation portfolio
- Estimate potential cost savings associated improved generation forecast and/or operational processes
- Evaluate the potential effects of resource diversity among renewable generators
- Compare resource requirements and integration cost estimates across a *range* of potential renewable portfolio selections with fast model execution of scenario outcomes
- Evaluate the benefits/costs of alternative renewable portfolios prior to contracting

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Questions and Answers

Appendix

Quantifying Regulation

To estimate the seasonal regulation need, we assume that it can be decomposed into 2 principal components:

- Intra-5-minute volatility (the difference between the actual 5-minute average and the actual 1-minute load/output)
- 5-minute forecast error (the difference between the actual 5-minute average and the 5-minute forecast (schedule))

In addition, RIM incorporates potential correlations between:

- The intra-5-minute load volatility and the 5-minute load forecast error
- The intra-5-minute renewables volatility and the 5-minute wind forecast error
- The 5-minute forecast error for load and the 5-minute forecast error for renewables

Quantifying Regulation

$$Regulation_{\text{every 1 min}} = Load^{actual}_{1min} - Load^{5min forecast} + Wind^{5min forecast} - Wind^{actual}_{1min}$$

(assume *Wind* stands for IR in general)

starting point for formulation

$$= L^a_1 - (L^a_5 - \varepsilon_{5L}) + (W^a_5 - \varepsilon_{5W}) - W^a_1$$

define the difference between the 1-minute actual and the 5 min actual (which is really the average of *five* 1-minute observations) as:

actual 5-min avg. load

actual 1-min load

$$\delta^{1m5m}_L = L^a_1 - L^a_5$$

intra-5-minute volatility for load

$$\delta^{1m5m}_W = W^a_1 - W^a_5$$

intra-5-minute volatility for wind

As a result:

$$Regulation = \delta^{1m5m}_L + \varepsilon_{5L} - \delta^{1m5m}_W - \varepsilon_{5W}$$

5-minute forecast error for load

5-minute forecast error for wind

Quantifying Regulation

$$Var(Regulation) = Var(\delta_L^{1m5m} + \varepsilon_{5L} - \delta_W^{1m5m} - \varepsilon_{5W})$$

Assuming relevant correlations exists for only a few parameters, the above will simplify to:

$$\begin{aligned} Var(Regulation) &= Var(\delta_L^{1m5m}) + Var(\varepsilon_{5L}) + Var(\delta_W^{1m5m}) + Var(\varepsilon_{5W}) \\ &+ 2Cov(\delta_L^{1m5m}, \varepsilon_{5L}) + 2Cov(\delta_W^{1m5m}, \varepsilon_{5W}) - 2Cov(\varepsilon_{5L}, \varepsilon_{5W}) \end{aligned}$$

intra-5-minute volatility for load

5-minute forecast error for load

intra-5-minute volatility for wind

5-minute forecast error for wind

$$\begin{aligned} Var(Regulation) &= Var(\delta_L^{1m5m}) + Var(\varepsilon_{5L}) + Var(\delta_W^{1m5m}) + Var(\varepsilon_{5W}) + \\ &+ 2\rho_{\delta_L^{1m5m}, \varepsilon_{5L}} \sqrt{Var(\delta_L^{1m5m}) Var(\varepsilon_{5L})} + \\ &+ 2\rho_{\delta_W^{1m5m}, \varepsilon_{5W}} \sqrt{Var(\delta_W^{1m5m}) Var(\varepsilon_{5W})} - \\ &- 2\rho_{\varepsilon_{5L}, \varepsilon_{5W}} \sqrt{Var(\varepsilon_{5L}) Var(\varepsilon_{5W})} \end{aligned}$$

CORRELATION (intra-5-minute volatility for load,5-min load forecast error)

CORRELATION (intra-5-minute volatility for wind,5-min wind forecast error)

CORRELATION (5-min load forecast error, 5-min wind forecast error)

Quantifying Load Following Need

To estimate the seasonal load following need we assume that it can be decomposed into 3 principal components:

- Intra-hour volatility (the difference between the actual 5-minute average and the actual hourly average of load/output)
- 5-minute forecast error (the difference between the actual 5-minute average and the 5-minute forecast (schedule))
- Hour-ahead forecast error (the difference between the actual hourly average and the hour-ahead forecast (schedule))

In addition, the total variance of the load following need is also assumed to depend on the annual correlations between:

- The intra-hour volatility for load and the hour-ahead forecast error for load;
- The intra-hour volatility for renewables and the hour-ahead forecast error for renewables;
- The hour-ahead forecast error for load and the hour-ahead forecast error for renewables;
- The 5-minute forecast error for load and the 5-minute forecast error for renewables.

Quantifying Load Following Need

$$LF_{\text{every 5 min}} = Load^{5min\,forecast} - Load^{HA\ forecast} + Wind^{HA\ forecast} - Wind^{5min\,forecast}$$

starting point for formulation

actual 60-min avg. load

actual 5-min avg. load

$$\delta_L^{5m60m} = L_5^a - L_{60}^a$$

intra-hour volatility for load

$$\delta_W^{5m60m} = W_5^a - W_{60}^a$$

intra-hour volatility for wind

Rearranging, we get:

5-minute forecast error for load

hour-ahead forecast error for wind

$$LF = L_5^a - L_{60}^a + \varepsilon_{60L} - \varepsilon_{5L} - (W_5^a - W_{60}^a) + \varepsilon_{5W} - \varepsilon_{60W}$$

hour-ahead forecast error for load

5-minute forecast error for wind

Which simplifies to:

$$LF = \delta_L^{5m60m} + \varepsilon_{60L} - \varepsilon_{5L} - \delta_W^{5m60m} + \varepsilon_{5W} - \varepsilon_{60W}$$

Quantifying Load Following Need

$$Var(LF) = Var(\delta_L^{5m60m} + \varepsilon_{60L} - \varepsilon_{5L} - \delta_W^{5m60m} + \varepsilon_{5W} - \varepsilon_{60W})$$

Therefore, the variance of Load Following service is:

Intra-hour volatility for wind

Intra-hour volatility for load

5-minute (5) and hour-ahead (60) forecast error for load

5-minute (5) and hour-ahead (60) forecast error for wind

$$Var(LF) = Var(\delta_L^{5m60m}) + Var(\varepsilon_{60L}) + Var(\varepsilon_{5L}) +$$

$$+ Var(\delta_W^{5m60m}) + Var(\varepsilon_{60W}) + Var(\varepsilon_{5W}) +$$

CORRELATION (intra-hour volatility for load, hour-ahead load forecast error)

$$+ 2\rho_{\delta_L^{5m60m}, \varepsilon_{60L}} \sqrt{Var(\delta_L^{5m60m}) Var(\varepsilon_{60L})} +$$

CORRELATION (intra-hour volatility for wind, hour-ahead wind forecast error)

$$+ 2\rho_{\delta_W^{5m60m}, \varepsilon_{60W}} \sqrt{Var(\delta_W^{5m60m}) Var(\varepsilon_{60W})} -$$

CORRELATION (5-min load forecast error, 5-min wind forecast error)

$$- 2\rho_{\varepsilon_{5L}, \varepsilon_{5W}} \sqrt{Var(\varepsilon_{5L}) Var(\varepsilon_{5W})} -$$

CORRELATION (hour-ahead load forecast error, hour-ahead wind forecast error)

$$- 2\rho_{\varepsilon_{60L}, \varepsilon_{60W}} \sqrt{Var(\varepsilon_{60L}) Var(\varepsilon_{60W})}$$

Quantifying Day-Ahead Forecast and Dispatch Errors (DAFD)

The day-ahead commitment need is expressed as the difference between the hour-ahead forecast and the day-ahead forecast

The overall variance of the day-ahead commitment need is also assumed to depend on the correlations between:

- The day-ahead forecast error for load and the hour-ahead forecast error for load;
- The day-ahead forecast error for wind and the hour-ahead forecast error for renewables;
- The hour-ahead forecast error for load and the hour-ahead forecast error for renewables.

Quantifying Day-Ahead Forecast and Dispatch Errors (DAFD)

$$DAFD = Load^{HA\ forecast} - Load^{DA\ forecast} + Wind^{DA\ forecast} - Wind^{HA\ forecast}$$

starting point for formulation

5-minute (5) and hour-ahead (60) forecast error for load

hour-ahead (60) and day-ahead (D) forecast error for wind

$$\begin{aligned} Var(DAFD) &= Var(\varepsilon_{DL} - \varepsilon_{60L} + \varepsilon_{60W} - \varepsilon_{DW}) \\ &= Var(\varepsilon_{DL}) + Var(\varepsilon_{60L}) + Var(\varepsilon_{60W}) + Var(\varepsilon_{DW}) - \\ &- 2\rho_{\varepsilon_{60L},\varepsilon_{DL}}\sqrt{Var(\varepsilon_{60L})Var(\varepsilon_{DL})} - \\ &- 2\rho_{\varepsilon_{60W},\varepsilon_{DW}}\sqrt{Var(\varepsilon_{60W})Var(\varepsilon_{DW})} - \\ &- 2\rho_{\varepsilon_{60L},\varepsilon_{60W}}\sqrt{Var(\varepsilon_{60L})Var(\varepsilon_{60W})} \end{aligned}$$

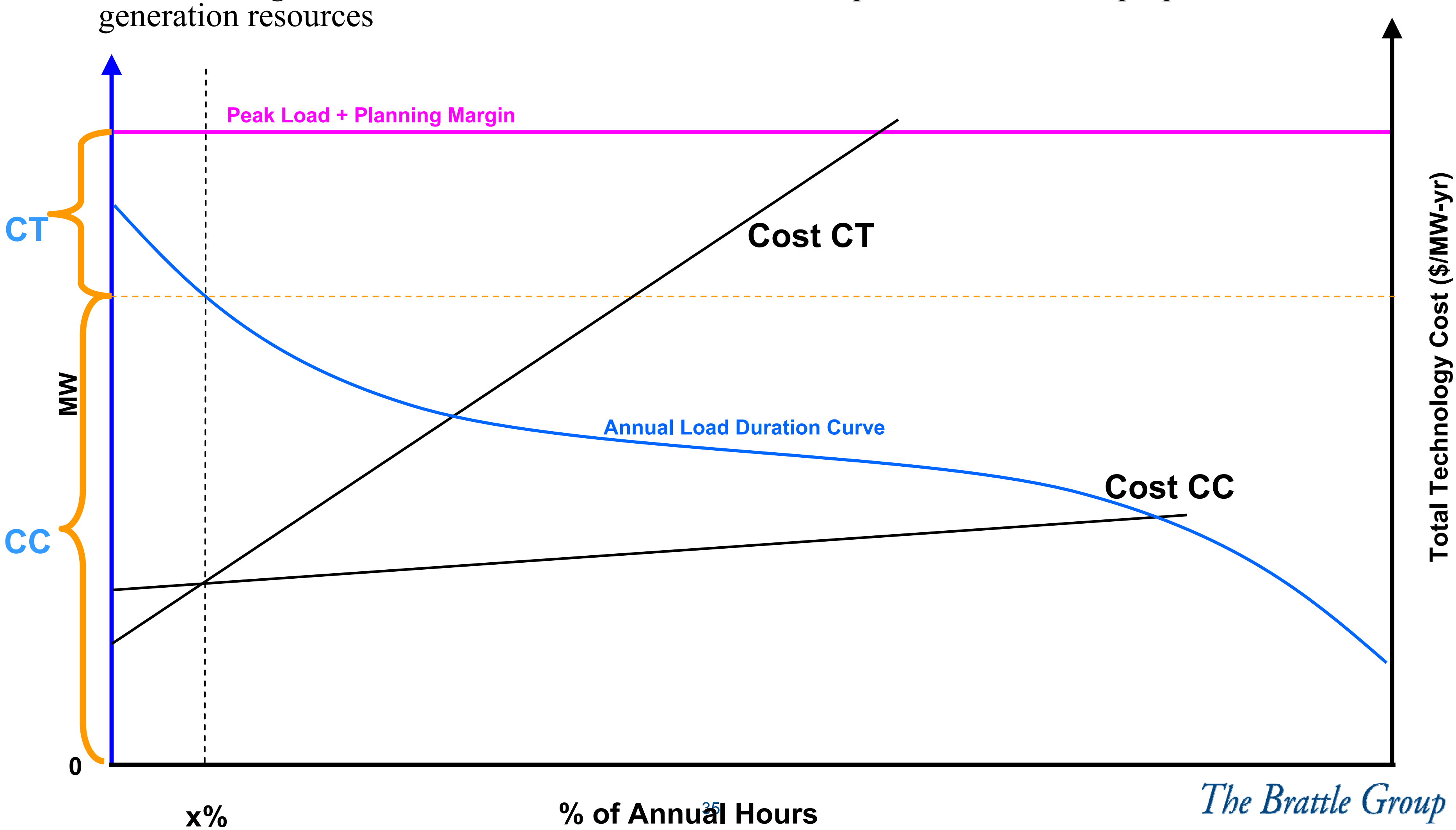
CORRELATION (hour-ahead load forecast error, day-ahead load forecast error)

CORRELATION (hour-ahead wind forecast error, day-ahead wind forecast error)

CORRELATION (hour-ahead load forecast error, hour-ahead wind forecast error)

Screening Curve to Derive Capacity Needs

- A *screening curve* approach divides the resources needed between specified resource types (currently specified as CCs and CTs)
- The *screening curve* uses fixed and variable costs assumptions to derive the proportions of generation resources



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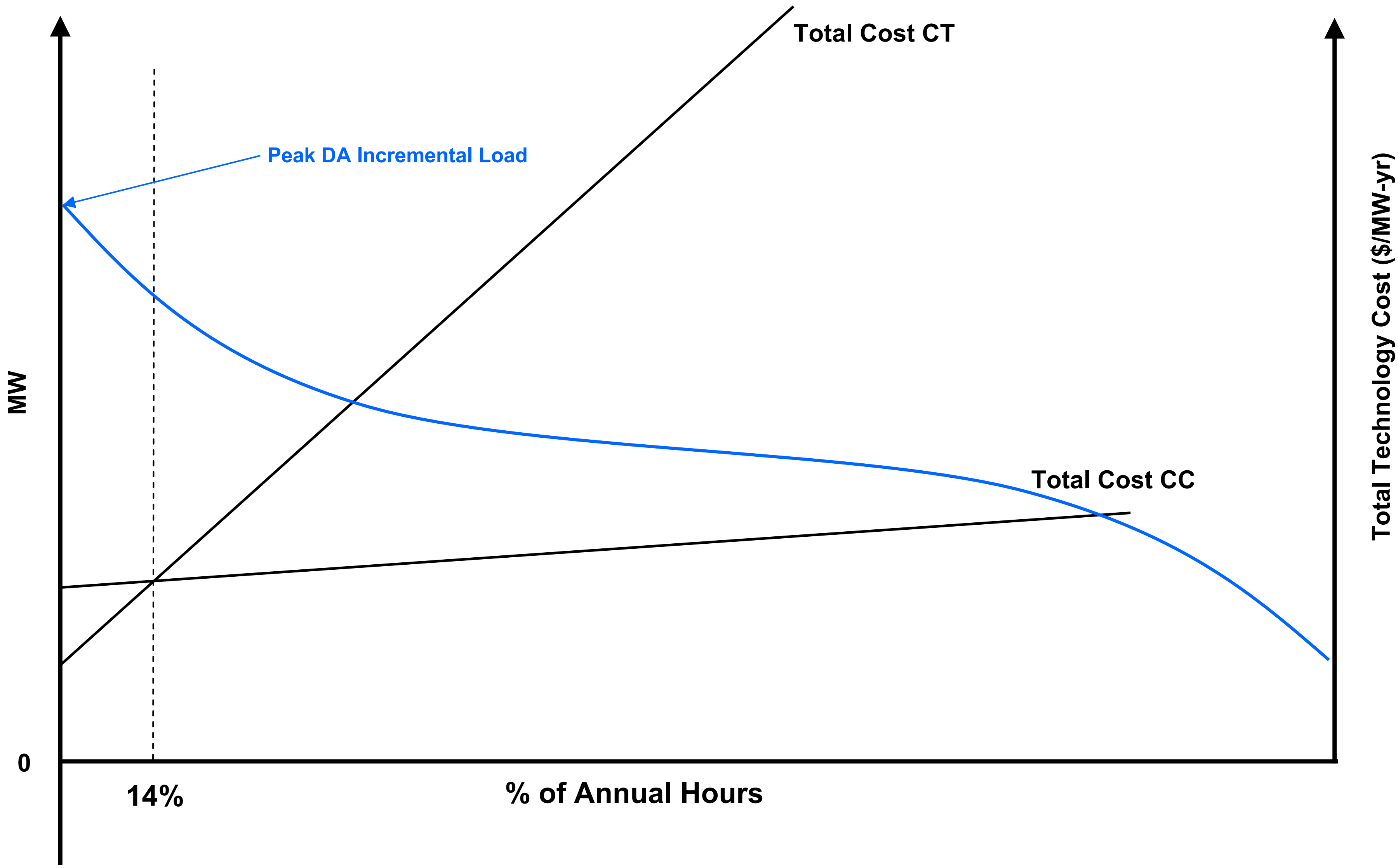
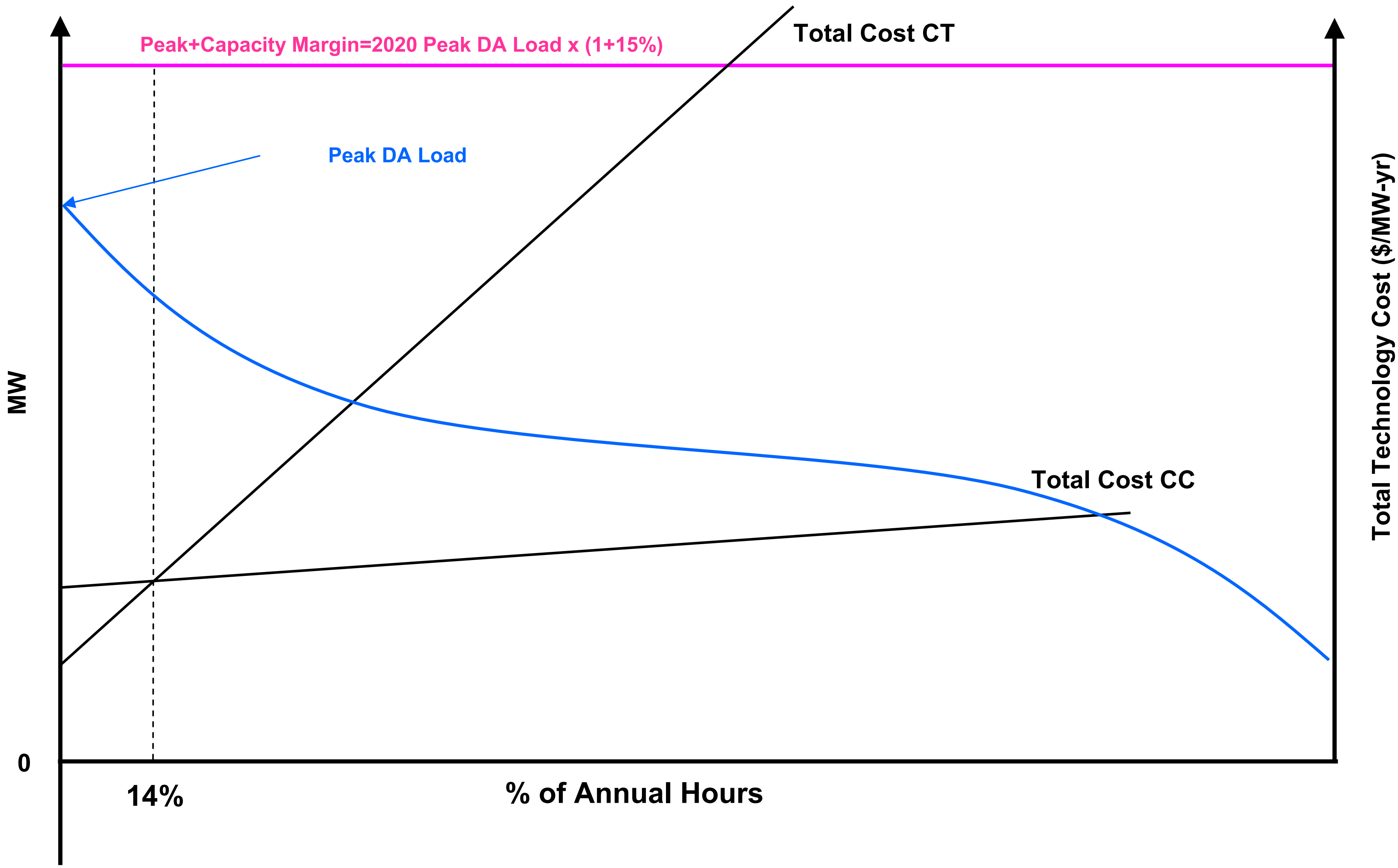
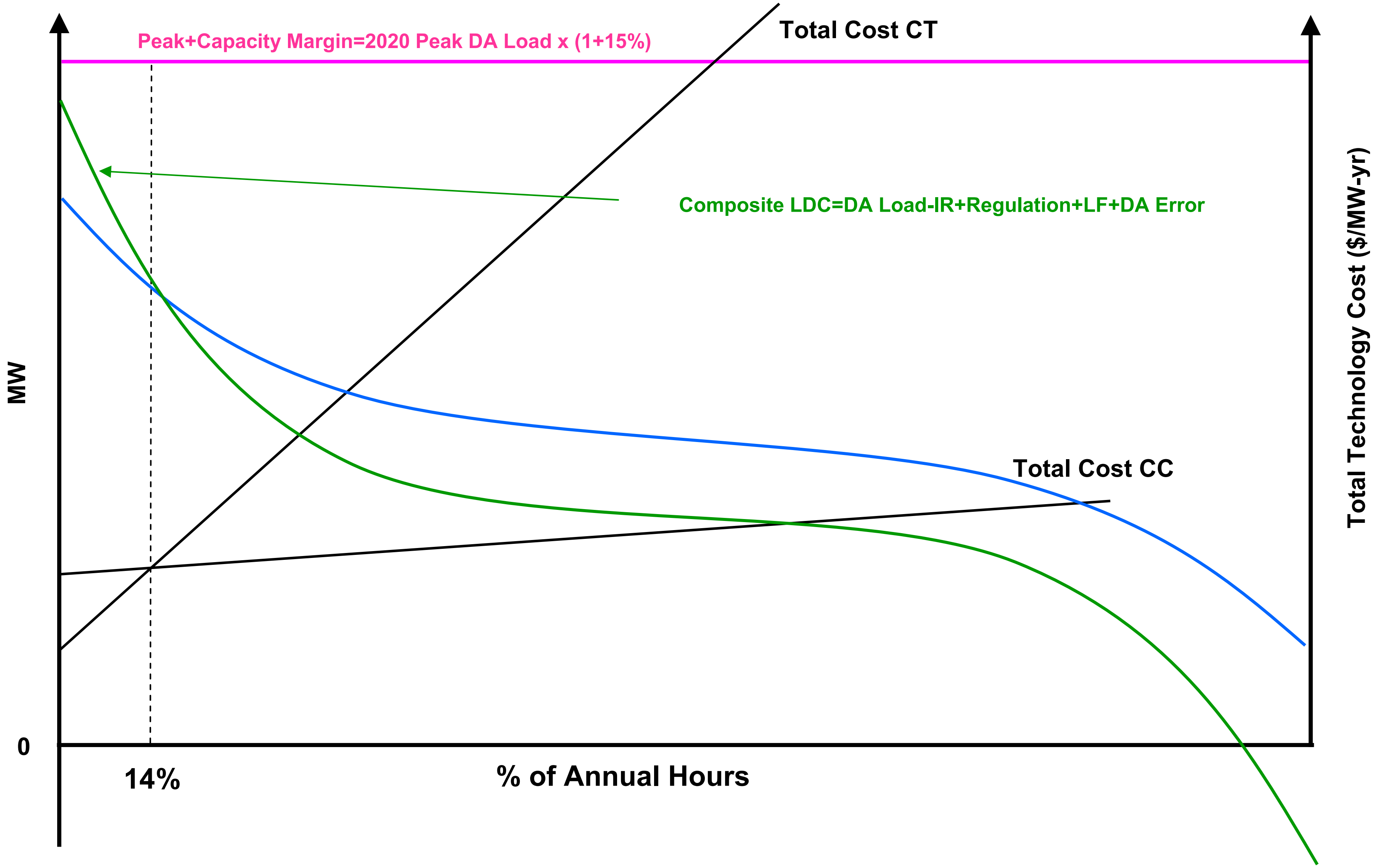
Example of Using Screening Curve Analysis Step 1



Screening Curve Analysis Step 2



Screening Curve Analysis Step 3



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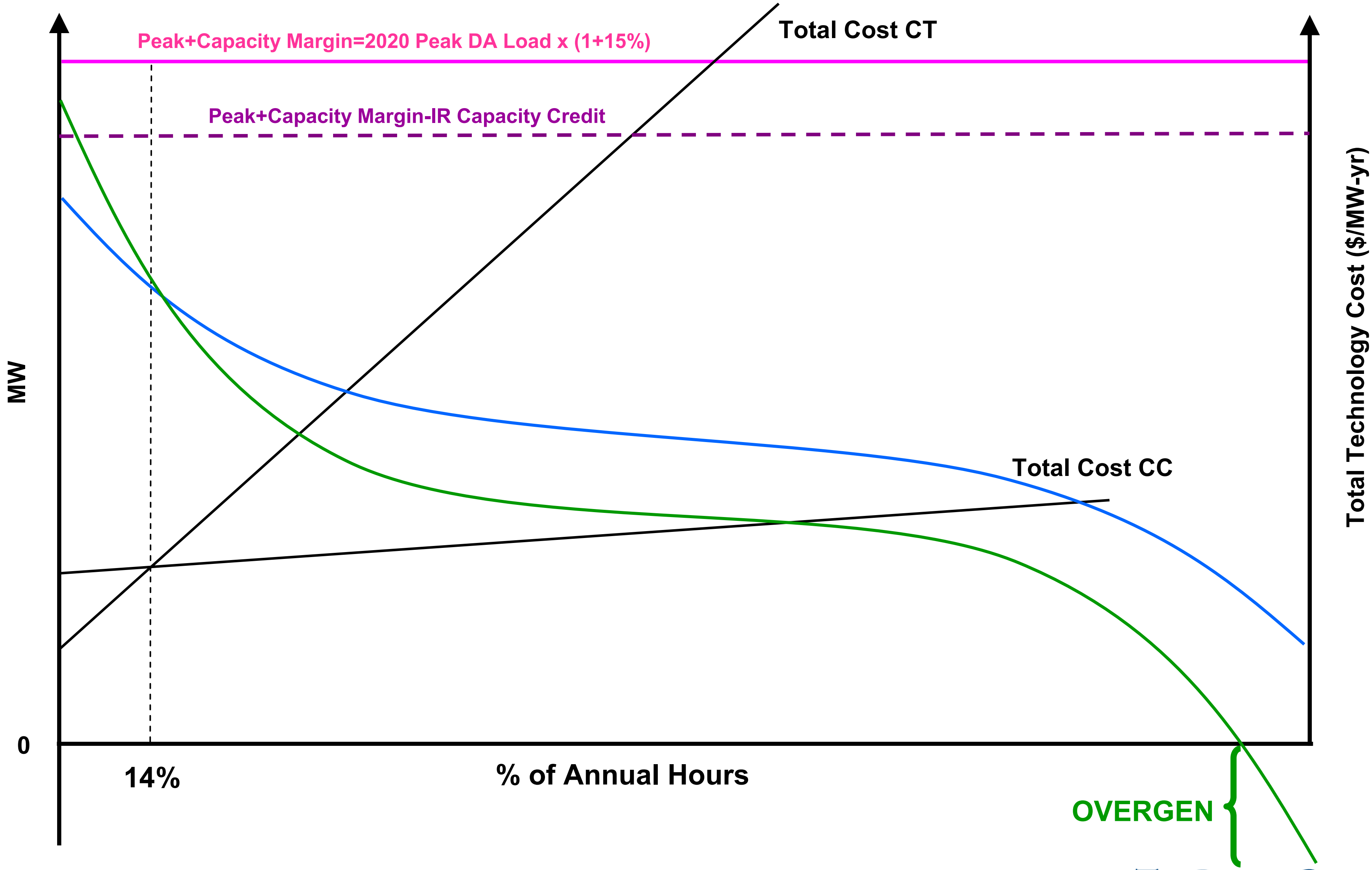
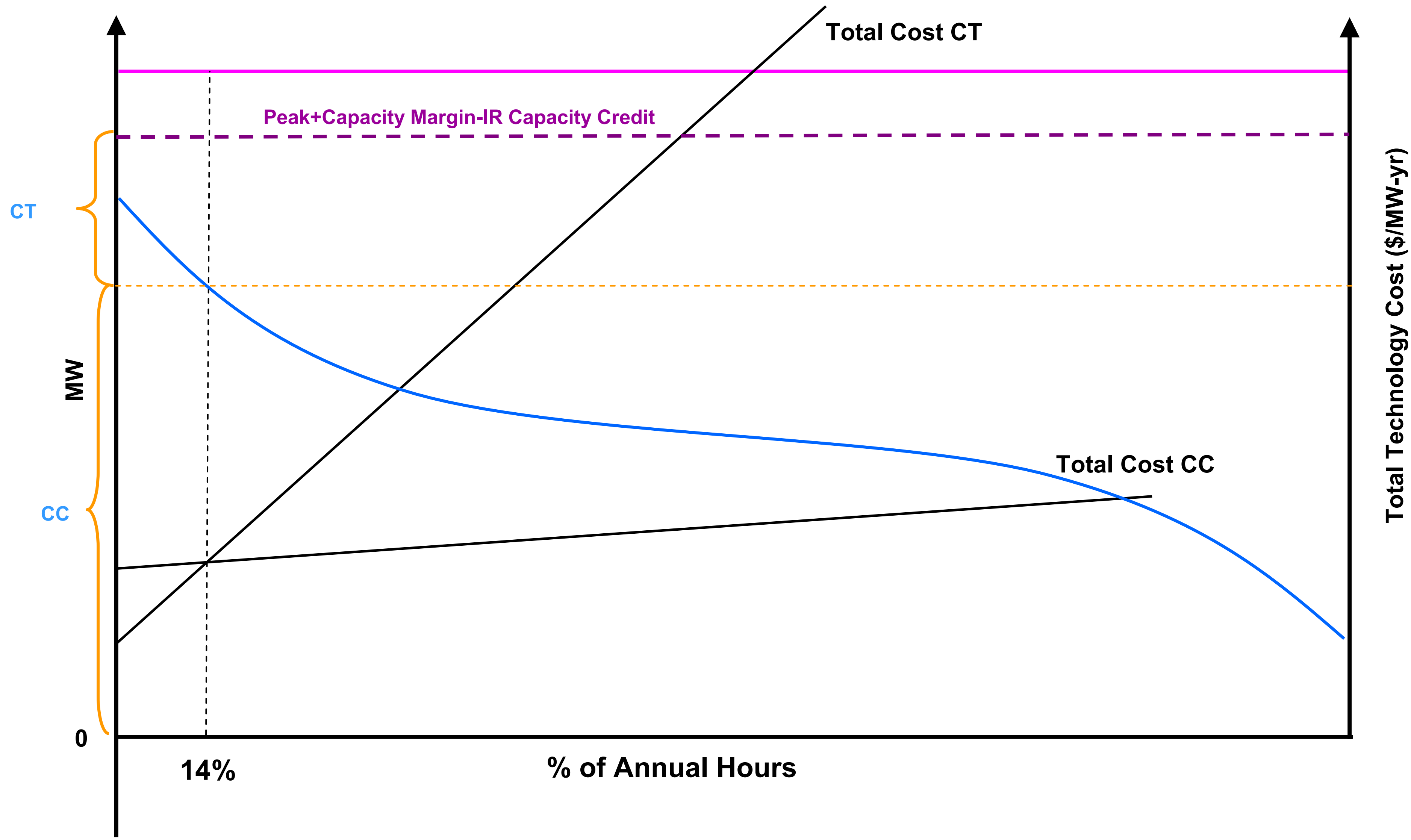
Screening Curve Analysis Step 4



Screening Curve Analysis Step 5



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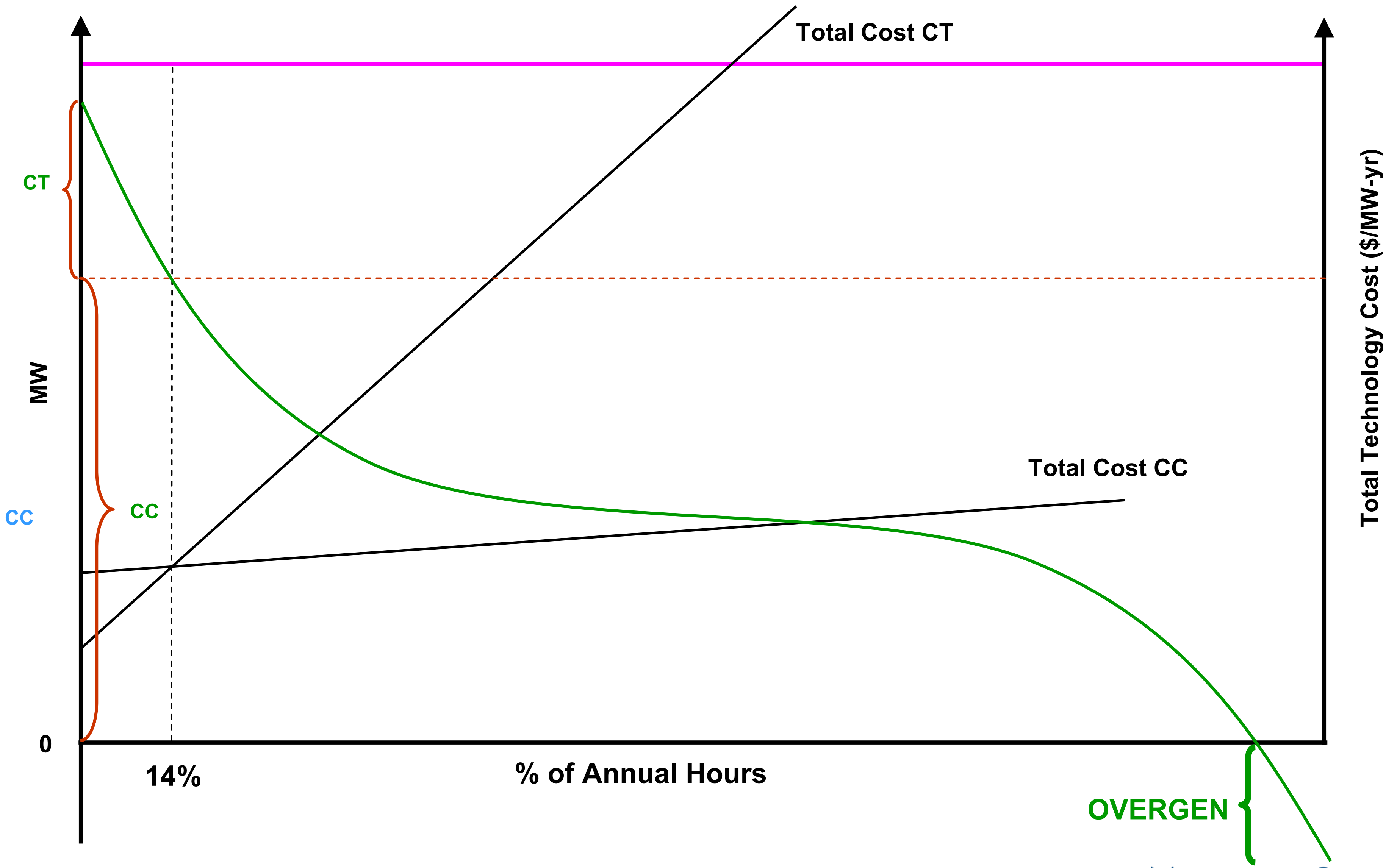
Screening Curve Analysis Step 6



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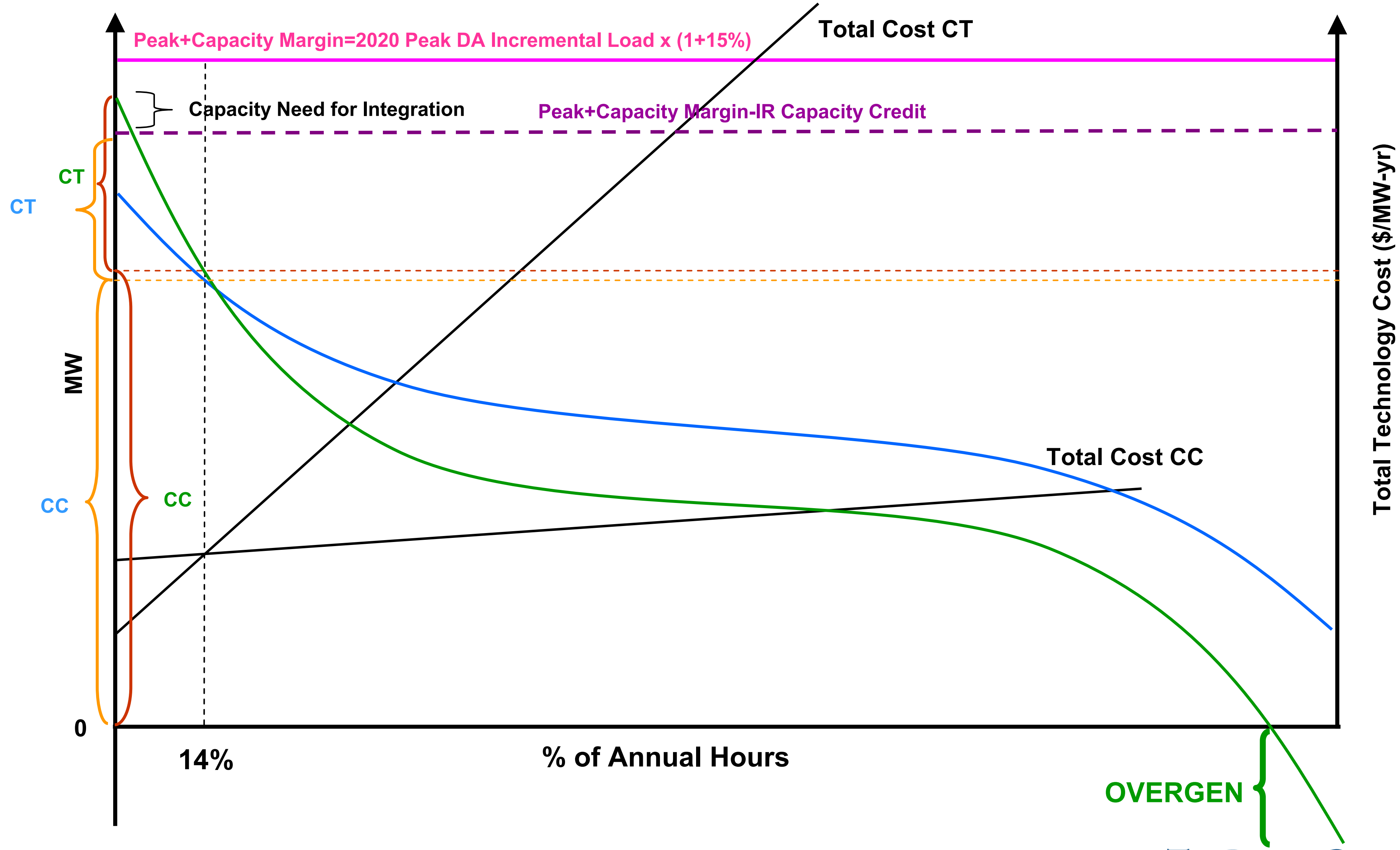
Screening Curve Analysis Step 7



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Calculating Variable Costs

$$
\begin{aligned}
&\text{Annual Variable Cost(Regulation)} = \qquad (35)\\
&\quad [(\textstyle\sum \text{seasonal REG need 1 hour of the day}) \times \text{start-up cost in Btu/kW of capacity} \times\\
&\quad \times \text{Gas Cost} \times \text{number of start-ups per day}] +\\
&\quad +[(\textstyle\sum \text{morning peak hours} \times \text{hourly seasonal regulation need}) \times \text{Min Load Factor} \times\\
&\quad \times((\text{CT-CC}) \text{ HR differential}) \times \text{Gas Cost}] \times 2 +\\
&\quad +(\text{all hours of the year}) \times (\text{Inefficiency HR Penalty}) \times \text{Gas Cost}
\end{aligned}
$$

$$
\begin{aligned}
&\text{Annual Variable Cost(Load Following)} = \qquad (36)\\
&\quad [(\textstyle\sum \text{seasonal LF need 1 hour of the day}) \times \text{start-up cost in Btu/kW of capacity} \times\\
&\quad \times \text{Gas Cost} \times \text{number of start-ups per day}] +\\
&\quad +[(\textstyle\sum \text{morning peak hours} \times \text{hourly seasonal LF need}) \times \text{Min Load Factor} \times\\
&\quad \times((\text{CT-CC}) \text{ HR differential}) \times \text{Gas Cost}] \times 2
\end{aligned}
$$

$$
\begin{aligned}
&\text{Annual Variable Cost(DA Commitment)} = \qquad (37)\\
&\quad [(\textstyle\sum \text{seasonal DA need 1 hour of the day}) \times \text{start-up cost in Btu/kW of capacity} \times\\
&\quad \times \text{Gas Cost} \times \text{number of start-ups per day}] +\\
&\quad +[(\textstyle\sum \text{morning peak hours} \times \text{hourly seasonal DA Commitment need}) \times \text{Min Load Factor} \times\\
&\quad \times((\text{CT-CC}) \text{ HR differential}) \times \text{Gas Cost}] \times 2
\end{aligned}
$$