DOE/OE Transmission Reliability Program

A Probability-based Model for Cost-effective Integration of Renewables into the Electricity Grid

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Project Objective and Milestones

- **Project Objective:**
  - Develop a production costing tool that considers the variable nature of renewable energy sources.

- **Key Milestones:**
  - Phase I: Expansion planning tool development (Sept 2018)
  - Phase II: Tool validation (Mar 2019)
  - Phase III: Case study (Sept 2019)

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Period of Performance:
September 6, 2017 – September 5, 2019

Location: Arlington, VA
Congressional District: VA-008

Federal Share (80%):	**$359,691**
Cost Share (20%):	**$90,123**
Total Project:	**$449,814**

Advisory committee is being formed.

Motivation, Outcome and Impact

- **Motivation:**
  - Existing power system planning tool is available (WASP), but not capable of integrating renewables.
  - Power system planning tool to be developed to perform production costing analysis using probabilistic data for renewable energy sources under high penetration scenarios.
- **Project Outcome:**
  - An open source production costing tool that takes into account the variable nature of renewable energy sources and treat them as generation candidates in a power system expansion plan. Specific outcomes are:
    - The source code and Wiki in a public repository, like Github or SourceForge
    - A report covering the validation and computation efficiency of the proposed tool
- **Project Impact:**
  - Facilitates cost-effective integration of renewables into the power grid

Approach

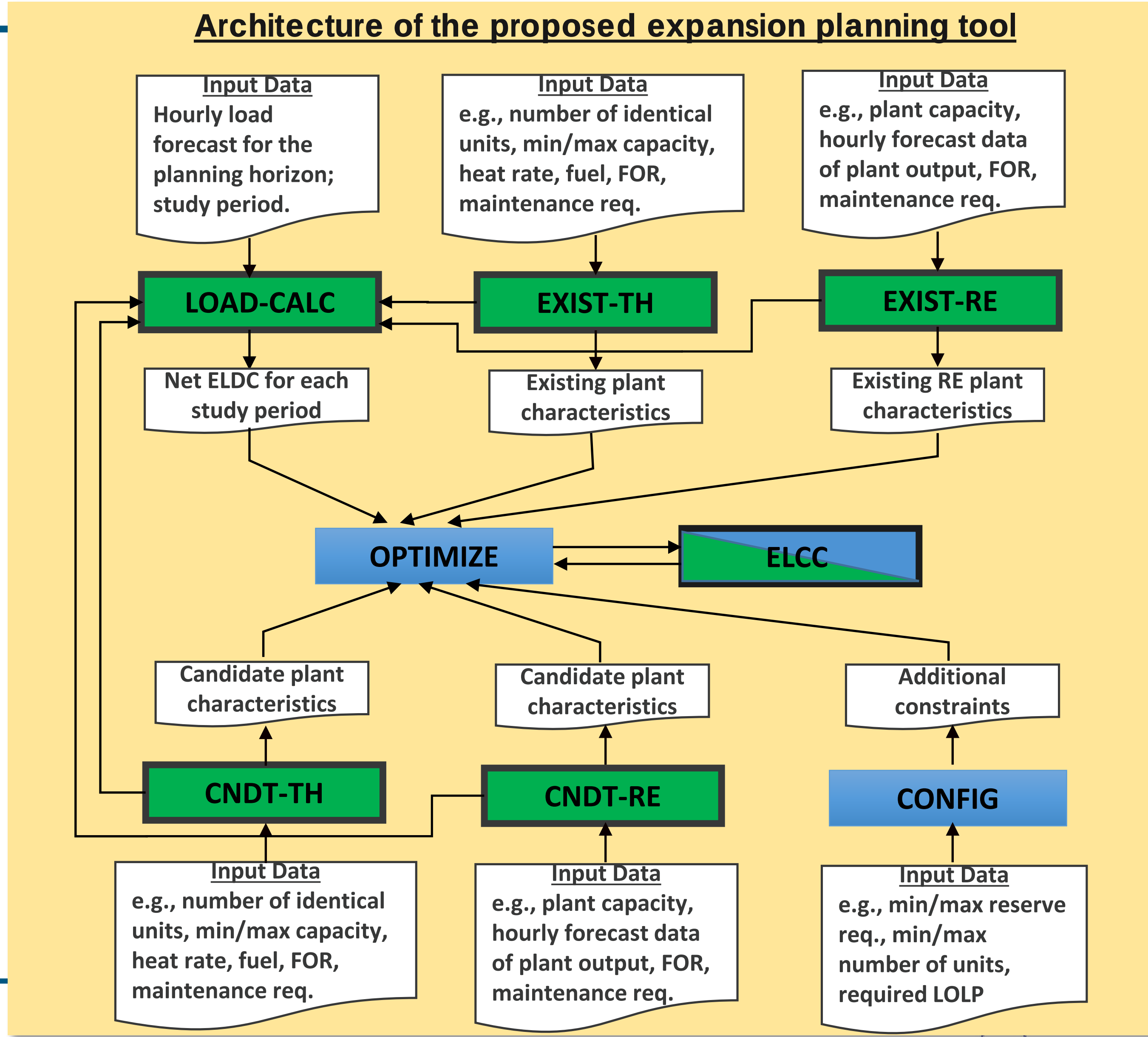
- **The work is divided into three phases:**
  - **Phase I.** Developed the proposed expansion planning tool, which comprises the following modules (similar to WASP):
    - LOAD-CALC: Load input module
    - EXIST-TH: Existing thermal plant input module
    - EXIST-RE: Existing renewable plant input module
    - CNDT-TH: Candidate thermal plant input module
    - CNDT-RE: Candidate renewable plant input module
    - CONFIG: Expansion configuration module
    - OPTIMIZE: Optimization module
    - ELCC: Equivalent Load Carrying Capacity calculation module
  - **Phase II.** Validate the proposed tool
  - **Phase III.** Run a case study based on a real-world data

Accomplishments To-date

Modules:

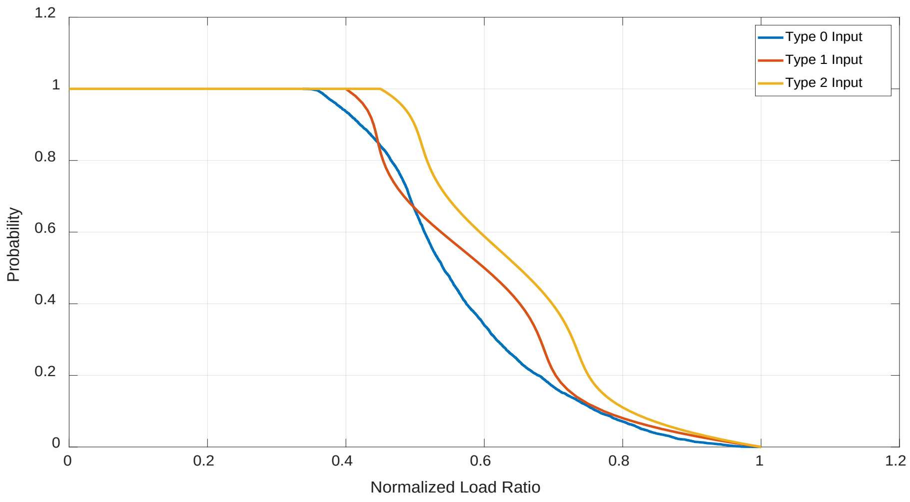
- LOAD-CALC*
- EXIST-TH
- EXIST-RE**
- CNDT-TH
- CNDT-RE**
- CONFIG*
- OPTIMIZE*
- ELCC*

Green = developed
Blue = started
Gray = to be developed
* = extended
** = new



LOAD-CALC Module

- **Similarity to WASP:**
  - The entire software architecture is designed to be similar to WASP.
  - The LOAD-CALC module corresponds to the 'LOADSY' module in WASP.
- **LOAD-CALC module:**
  - Prepares system load data in the form of load duration curve (LDC)
  - Designed to accept three types of input formats.



- **Input format:**
  - **Type 0:** Original hourly load profile (Hourly load data in a year) NEW
  - **Type 1:** LDC represented in points *
  - **Type 2:** LDC represented by 5-order polynomial coefficients *

* WASP supported inputs

EXIST-TH and CNDT-TH Modules

- **Similarity to WASP:**
  - The EXIST-TH module corresponds to the 'FIXSYS' module in WASP.
  - The CNDT-TH module corresponds to the 'VARSYS' module in WASP.

- **EXIST-TH and CNDT-TH:**
  - EXIST-TH prepares parameters that describe attributes of existing thermal generators in the system.
  - CNDT-TH describes candidate thermal generators.

Example Code Snippet of EXIST-TH

```
"generator": {
    "0": {
    "code": "FLG1",
    "unit_number": [4],
    "para": [150, 270, 1, 3300, 2850, 10, 10, 56, 280, 600, 0, 4.06, 4.9, 1800, 2.5, 1.0],
    "existing_plan":{
        "number": [-1, -1],
        "year": [2023, 2024]
        }
    },
```

Generator type code

Number of a specific generator type

Addition (1) or retirement (-1)

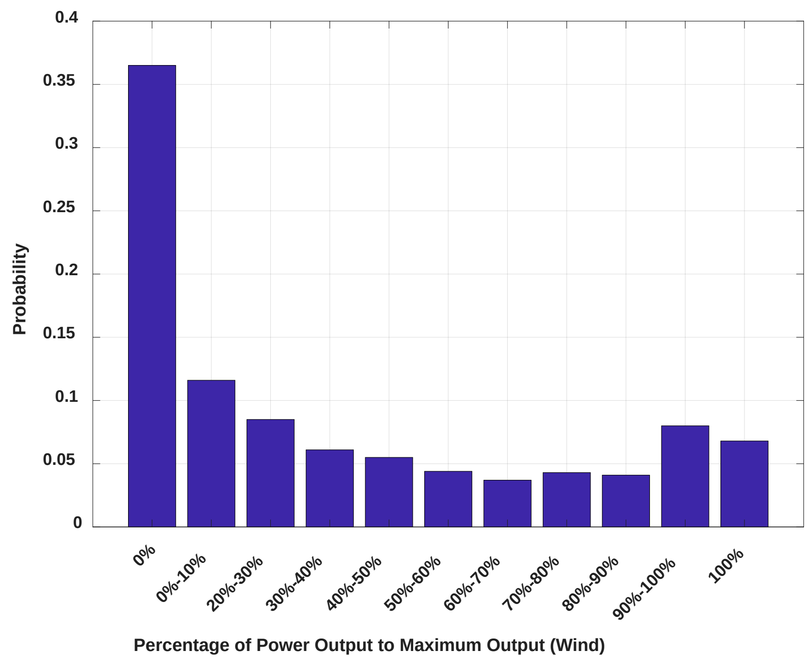
Year of addition or retirement

Generator attributes

Variables	Example values
Minimal operating power of a unit (MW)	150
Maximal generating power of a unit (MW)	270
Fuel Type	1
Heat rate at minimal operating level (kcal/kWh)	3300
Average incremental heat rate (kcal/kWh)	2850
Spinning reserve (% of unit capacity)	10
Forced outage rate (%)	10
Scheduled maintenance days of a year	56
Maintenance class size (MW)	280
Domestic fuel cost ($/million kcals)	600
Foreign fuel cost ($/million kcals)	0
Fixed O&M costs (in $/kW Month)	4.06
Variable O&M costs (in $/MWh)	4.90
Heat value of the fuel used (kcal/kg)	1800
Pollutant I emission (% wt. of fuel)	2.5
Pollutant II emission (% wt. of fuel)	1.0

Probabilistic Representation of Renewables: Wind

- **A multi-state model is used to represent wind generation probabilistically.**
  - Probability of wind power generation at different levels (state) can be estimated using Weibull distribution.



Probability distribution of wind power output

Weibull to Estimate Probability Distribution of Wind Power Output

$$\Pr(p=0)=\Pr(V<V_{cut-in}\ or\ V>V_{cut-out}))=F_w(V_{cut-in})+1-F_w(V_{cut-out})=e^{-(\frac{V_{cut-out}}{\sigma})^{\xi}}+1-e^{-(\frac{V_{cut-in}}{\sigma})^{\xi}}$$

$$\Pr(p=P_{\max})=\Pr(V\in(V_{\min},V_{cut-out}))=F_w(V_{cut-out})-F_w(V_{\min})=e^{-(\frac{V_{\min}}{\sigma})^{\xi}}-e^{-(\frac{V_{cut-out}}{\sigma})^{\xi}}$$

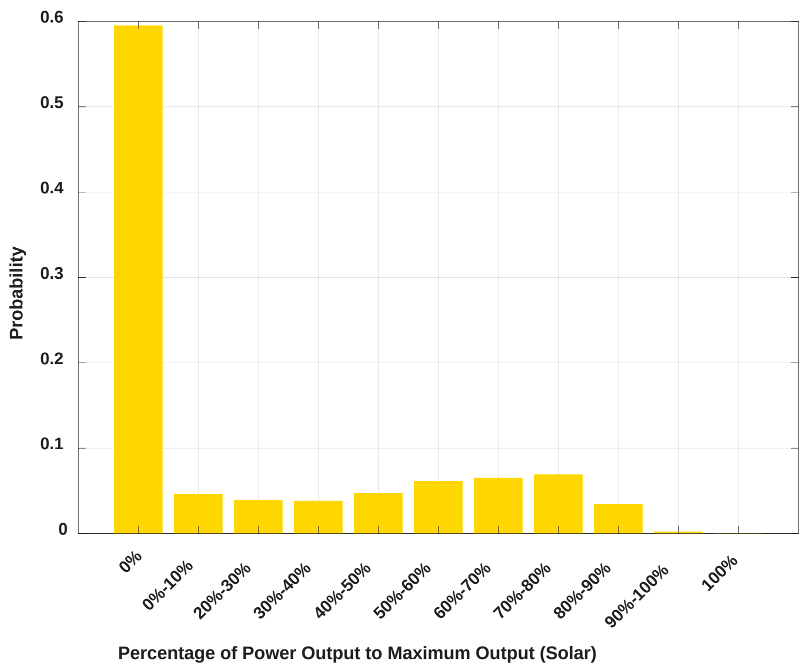
$$\Pr(p\approx k\cdot\Delta P)=e^{-(\frac{g(k\cdot\Delta P)}{\sigma})^{\xi}}-e^{-(\frac{g(k\cdot\Delta P+\Delta P)}{\sigma})^{\xi}}\qquad k\in[1,N-1]$$

Where:

$F_w(x)=1-e^{-(\frac{x}{\sigma})^{\xi}}$	: Cumulative distribution function of wind speed Weibull distribution
$P_{\max}$	: Maximum wind output
$V=g(p)$	: Function mapping power to wind speed
$V_{cut-in},V_{\min},V_{cut-out}$	: Cut-in, rated and cut-out speed for wind turbine
N	: Number of states, $P_{\max}=N\cdot\Delta P$

Probabilistic Representation of Renewables: Solar

- **A multi-state model is used to represent solar PV generation probabilistically.**
  - Probability of solar power generation at different levels (state) can also be calculated.



Probability distribution of solar power output

Calculating Probability Distribution of Solar Power Output

Since there is no widely accepted probability distribution representing solar PV output, its probability is calculated using the forecasted solar generation profile.

$$\Pr(p \approx k \cdot \Delta P) = \frac{Number\ of\ data\ points\ with\ power\ between\ (k \cdot \Delta P)\ and\ (k \cdot \Delta P + \Delta P)}{Number\ of\ all\ data\ points} \quad k \in [0, N-1]$$

$P_{\max}$: Maximum solar output

N : Number of states, $P_{\max} = N \cdot \Delta P$

EXIST-RE and CNDT-RE Modules

- **Similarity to WASP:**
  - These two modules are important additions to WASP, as WASP cannot talk into account renewables.

- **EXIST-RE and CNDT-RE:**
  - EXIST-RE and CNDT-RE take user defined inputs to describe existing and candidate renewable power plants.
  - A user can use as the input: (a) time-series renewable output data; or (b) probability distribution parameters

Example Code Snippets

Code snippet characterizing wind plants, specifying required input parameters:

```
"wind": {
    "0": {
    "code": "WIND2",
    "capacity": [250],
    "speed": [3.5, 12.5, 30
    "state_number": [10]
    "feature":{
        "type": [1],
        "ksigma": [1.87393780943606 7.38164769483493]
        }],
    "existing_plan": {
        "number": [50],
        "year": [2030]
        }
    }
}
```

- Generator code
- Unit capacity (MW)
- Cut-in, rated and cut-out wind speeds (m/s)
- State number for probability calculation
- **Shape (Ksi, ξ) and Scale factor (Sigma, σ) representing Weibull distribution of wind power plant output**
- Number of units added/retired
- Year of addition or retirement

Code snippet characterizing solar plants, specifying required input parameters:

```
"solar": {
    "0": {
    "code": "SOLAR1",
    "capacity": [500],
    "state_number": [10],
    "feature":{
        "type": [0],
        "path": "projects/project_1/user_input/data/solar_example1_5min.csv"
        }],
    "existing_plan": {
        "number": [1],
        "year": [2025]
        }
    }
}
```

- Generator code
- Unit capacity (MW)
- State number for probability calculation
- **Time-series output data from a solar plant**
- Number of units added/retired
- Year of addition or retirement

Work has Started on ELCC Module

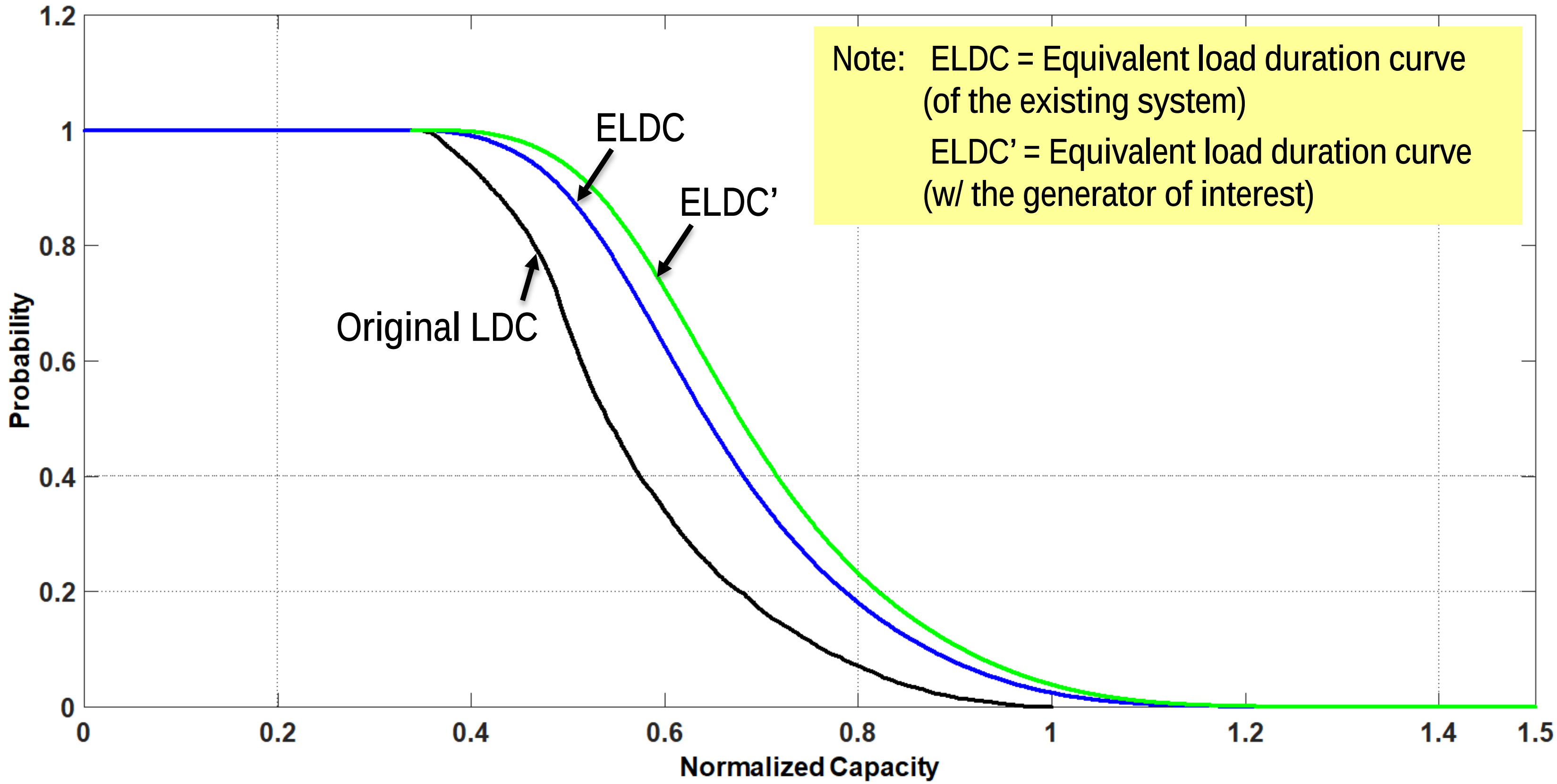
- **ELCC Module**
  - This module calculates equivalent load carrying capacity (ELCC) of each power plant. ELCC measures the contribution of an individual generator to system capacity with and without the generator of interest.
  - To calculate ELCC, Equivalent Load Duration Curve (ELDC) and the desired Loss of Load Probability (LOLP) must be known.

Equivalent Load Duration Curve (ELDC)

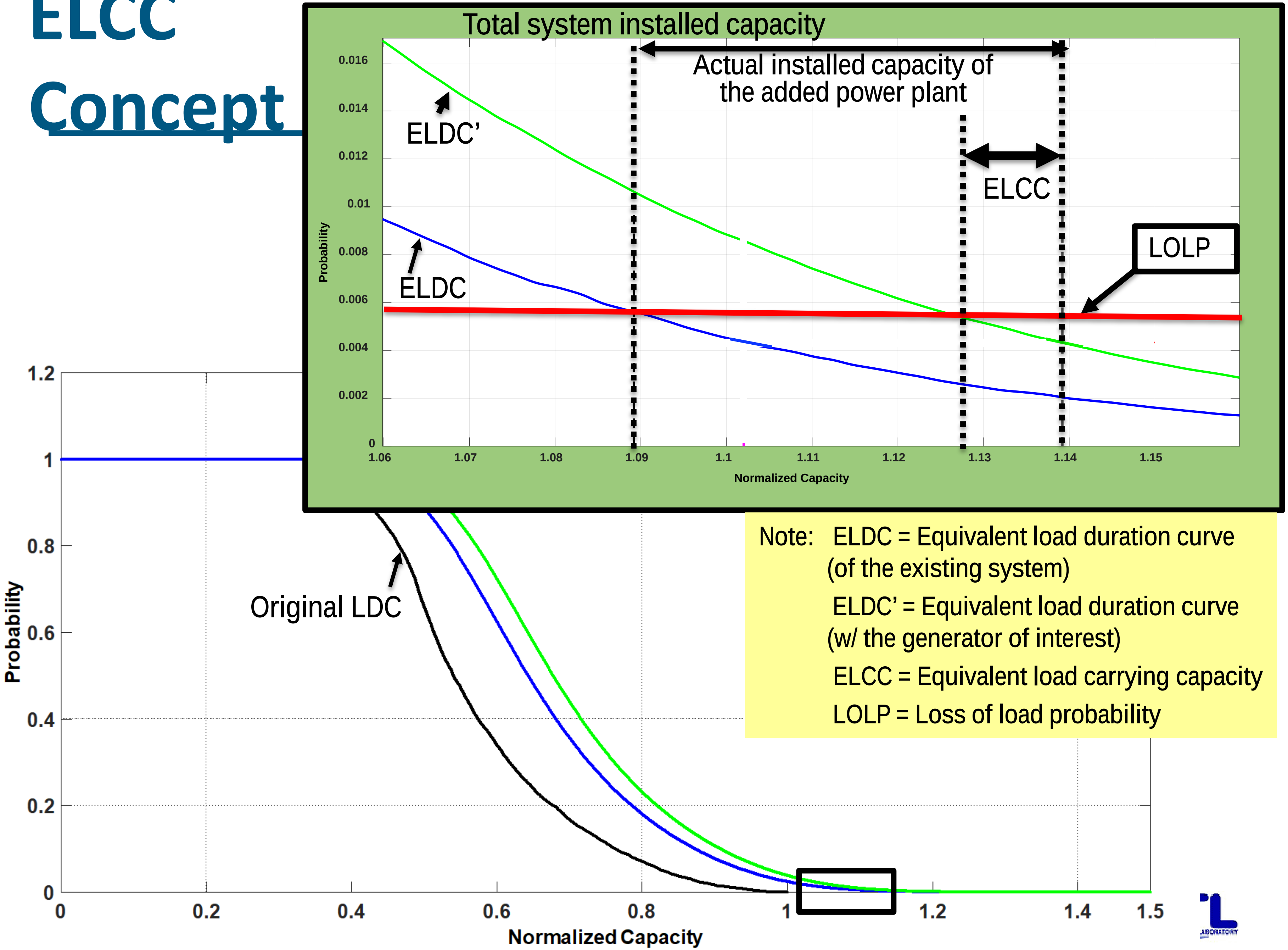
ELDC for thermal plants: $f^{i}(x) = p \cdot f^{i-1}(x) + q \cdot f^{i-1}(x - P)$

ELDC for renewables, using multi-state generator model:

$$f^{i}(x) = \sum_{k=0}^{N} \Pr(p \approx k \cdot \Delta p) \cdot f^{i-1}(x - (P_{\max} - k \cdot \Delta p))$$



ELCC Concept



Note: ELDC = Equivalent load duration curve (of the existing system)

ELDC' = Equivalent load duration curve (w/ the generator of interest)

ELCC = Equivalent load carrying capacity

LOLP = Loss of load probability

Case Study

- **Comparing the multi-state generator model with the negative load approach for calculating reliability indices:**
  - System load is 5000 MW
  - Thermal plants are shown in the table below
  - Either wind or solar power are added in the system with 500 MW generating capacity

Information of six thermal power plants considered in this case study.

Name of Plants	FLG1	FLG2	FCOA	FOIL	FGT	F-CC
No. of Units	4	9	1	7	4	1
Max Power (MW)	270	276	580	145	50	174
Force Out Rate	10%	8.9%	8.0%	7.3%	6%	15%

Results

Reliability indices calculated using negative load and multi-state generator approaches (wind):

	LOLP (%)	EENS (MWh)
Negative Load Approach	0.35162	7031.66
Multi-state Generator	0.36208	7297.83

Multi-state generator model can produce result similar to the negative load approach

Reliability indices calculated using negative load and multi-state generator approaches (solar):

	LOLP (%)	EENS (MWh)
Negative Load Approach	0.40031	8156.01
Multi-state Generator	0.43230	8809.09

Summary: Accomplishment To-Date

- **FY18 Accomplishments**
  - Completed the development of five out of eight modules in the proposed expansion planning tool
    - LOAD-CALC : prepares system load data
    - EXIST-TH : describes attributes of existing thermal generators
    - CNDT-TH : describes attributes of candidate thermal generators
    - EXIST-RE : describes attributes of existing renewable power plants
    - CNDT-RE : describes attributes of candidate renewable power plants
    - ELCC : calculates equivalent load carrying capacity of renewables (started)
  - Derived probabilistic models to represent renewable energy generation

Challenge and Publication

- **Challenge**
  - The probabilistic analysis may require extra computation time. This computation efficiency will be determined, and corrective measures will be taken, if needed.

- **Publication**
  - Xiangyu Zhang, Manisa Pipattanasomporn and Saifur Rahman, "A comprehensive analysis of renewable energy representations in power system generation expansion planning", to be submitted to a conference (TBD).

Planned Activities and Schedules

- **FY18 Planned Work**
  - **Phase I:** Complete the development of the expansion planning tool .... **September 2018**

- **FY19 Planned Work**
  - **Phase II:** Complete the tool validation .... **March 2019**
  - **Phase III:** Complete the case study .... **September 2019**

Tool Validation

- **Validate with WASP**
  - The case with thermal power plants (no renewables).
- **Validate using negative load approach**
  - The case with renewables will be validated with the negative load approach.
- **Validation criteria:**
  - Optimal expansion planning option
  - Optimal loss of load probability

BACK UP SLIDES

Project Budget

Project Period: **September 2017 – September 2019**
Project Budget: DOE: $359,691 VT: $90,123

Current Reporting Period: September 2017 – March 2018
Cost to Date: DOE: $93,976 VT: $18,299

Budget History			
Budget Year 1 Sept 2017 – Mar 2018 (past)		Future (planned)	
DOE	Cost-share	DOE	Cost-share
$93,976	$18,299	$265,715	$71,824