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

- **Overall Project Objective:**
  - Develop a production costing tool that includes intermittent sources of electricity.
- **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 formed.

Relevance to DOE's R&D program

- **What is the overall value of this work to DOE's R&D program?:**
  - Help transform the nation's energy infrastructure with more and more renewable integration
  - Improve the reliability, resilience, physical security and planning automation of energy infrastructure
  - Facilitate grid modernization to stress its importance to jobs, economic growth, and U.S. manufacturing competitiveness
- **What aspects should be modified going forward to ensure greater alignment with DOE's R&D objectives?**
  - Enable more diverse changing power generation mix
  - Plan renewable generators to replace aging infrastructure (thermal plants) in a more cost-effective way, subtle modeling of cash flow
  - Adapt to large-scale implementation in reasonable time

Motivation, Outcome and Impact

- **Motivation:**
  - 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

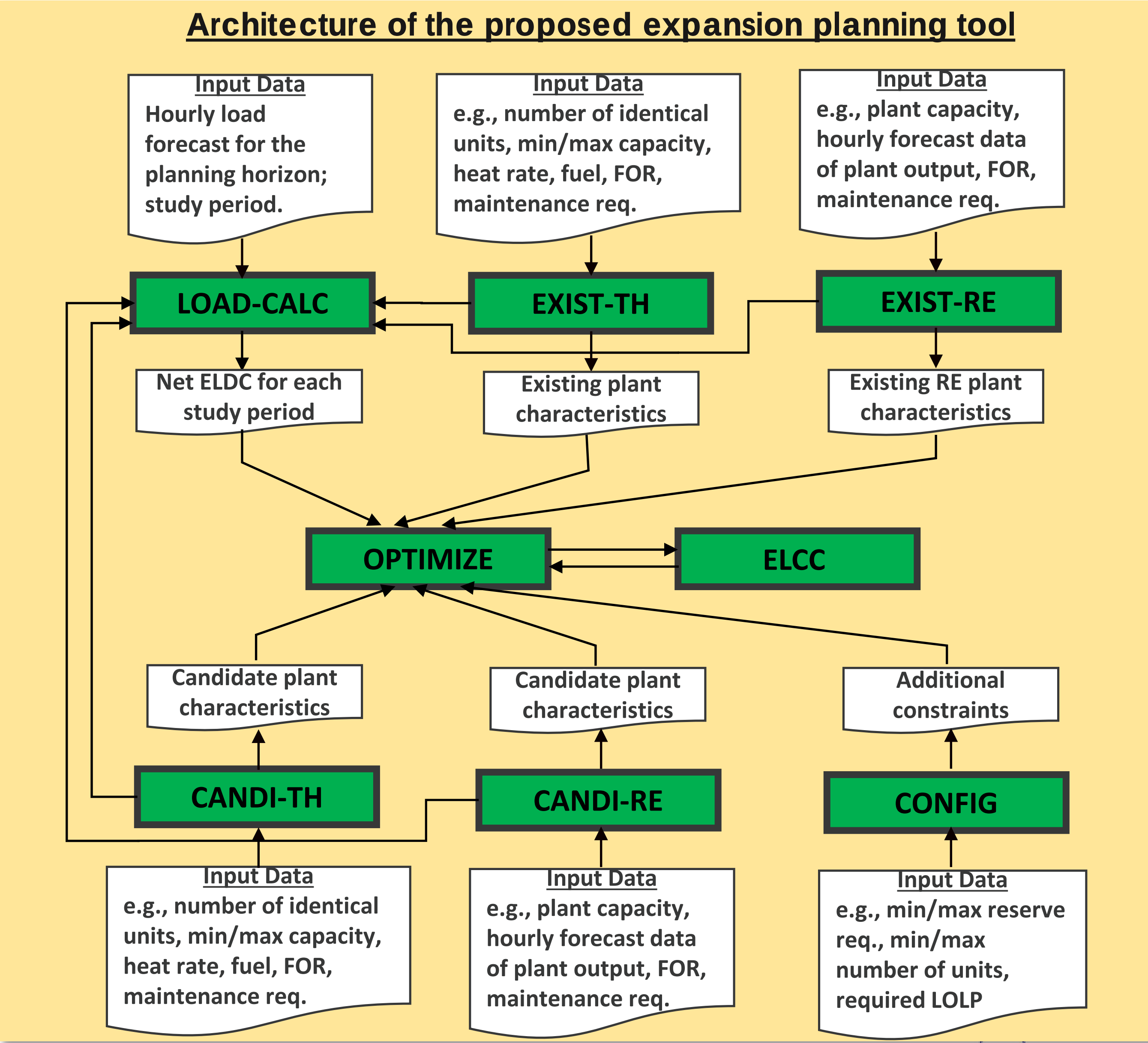
- **The work is divided into three phases:**
  - **Phase I.** Developed the proposed expansion planning tool, which comprises the following modules (similar to WASP):
    - LOAD-CALC: Load input module
    - EXIST-TH: Existing thermal plant input module
    - EXIST-RE: Existing renewable plant input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

Architecture of the Proposed Tool

Modules:

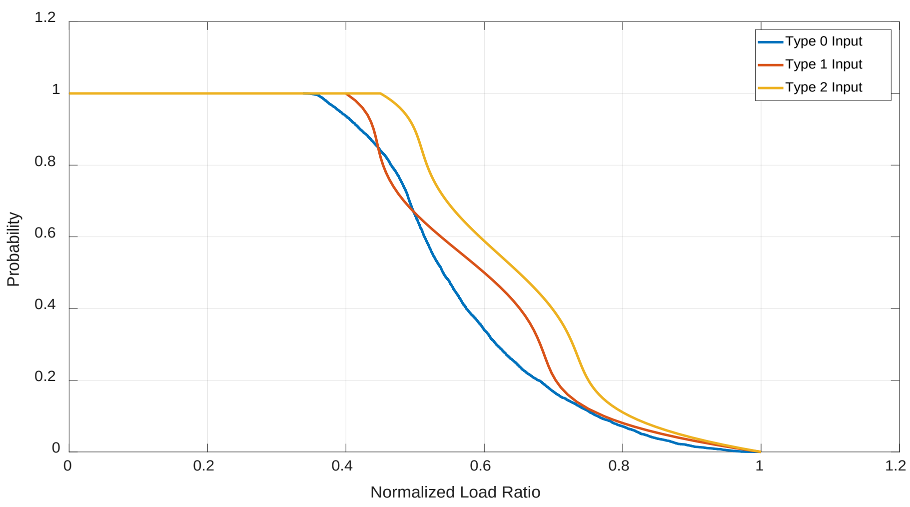
- LOAD-CALC*
- EXIST-TH
- EXIST-RE**
- CANDI-TH
- CANDI-RE**
- CONFIG*
- OPTIMIZE*
- ELCC*

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

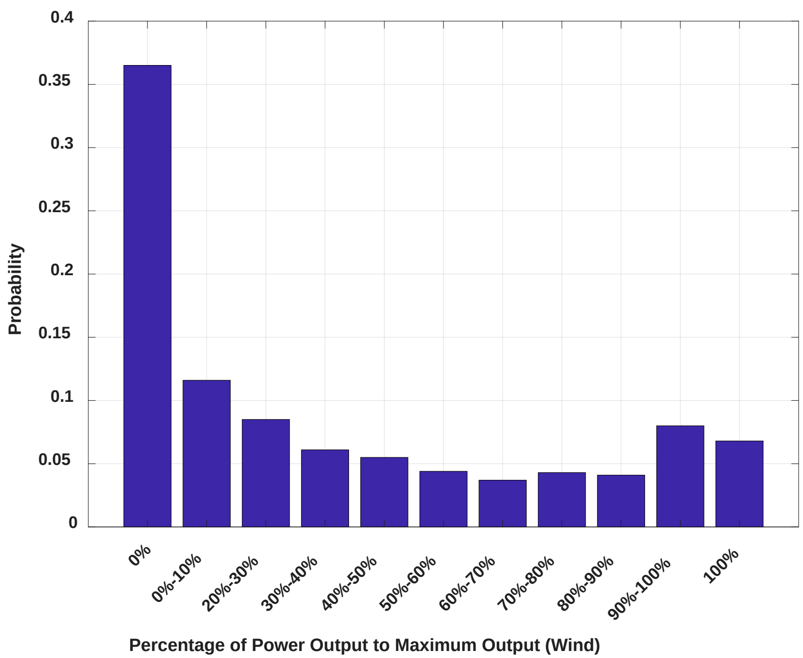
EXIST-RE and CANDI-RE Modules

- **Similarity to WASP:**
  - These two modules are important additions to WASP, as WASP cannot talk into account renewables.
  - EXIST-RE and EXIST-TH can be further combined as a generalized module EXIST-GEN
  - CANDI-RE and CANDI-TH can be further combined as a generalized module CANDI-GEN

- **EXIST-RE and CANDI-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

Probabilistic Representation of Renewables: Wind

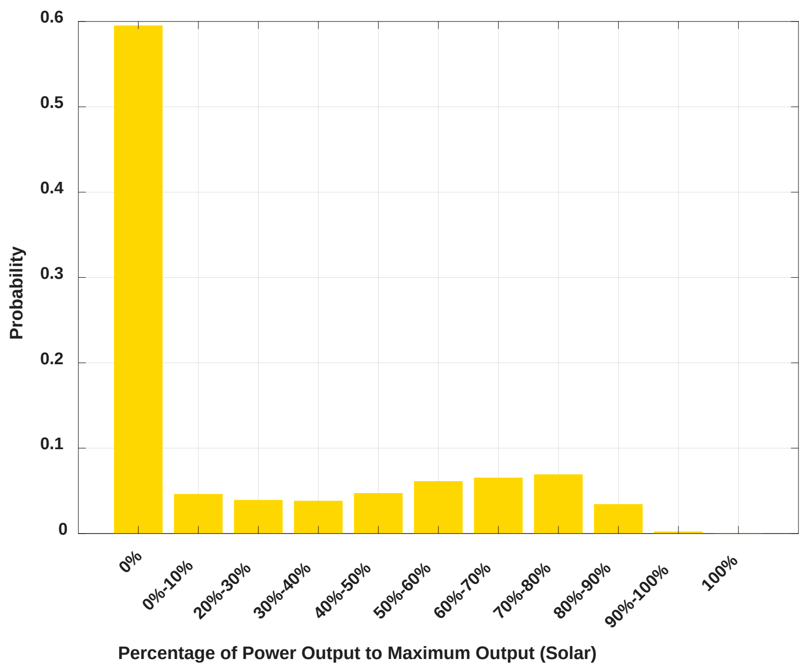
- **A multi-state model is used to represent wind generation probabilistically.**
  - Probability of wind power generation at different levels (state) can be estimated using Weibull distribution.



Probability distribution of wind power output

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.

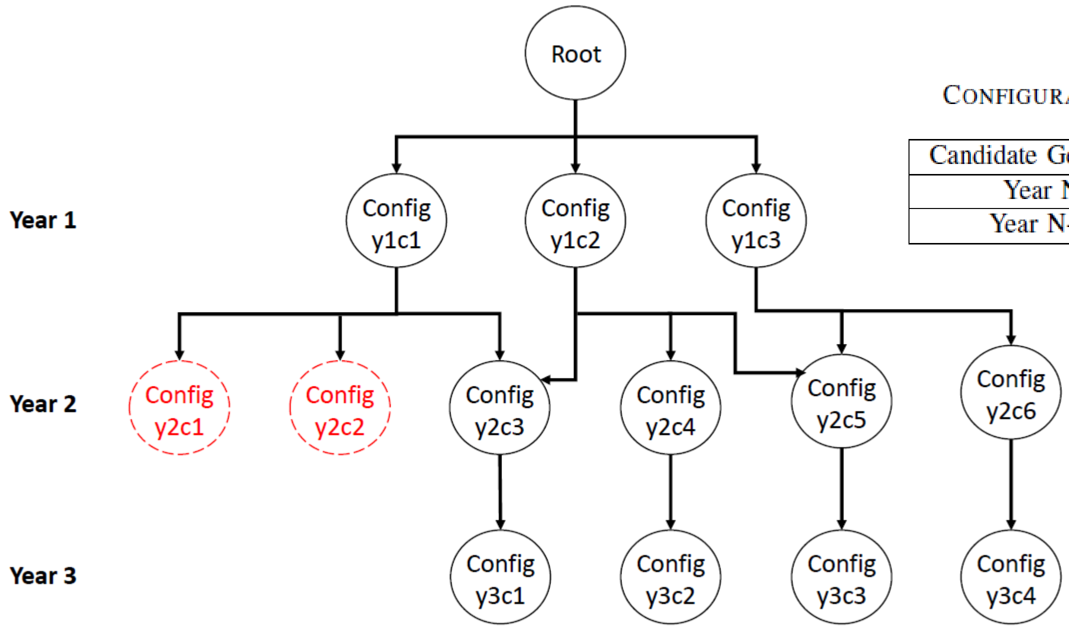
$$\Pr(p \approx k \cdot \Delta P) = \frac{Number\ of\ data\ points\ with\ power\ between\ (k \cdot \Delta P)\ and\ (k \cdot \Delta P + \Delta P)}{Number\ of\ all\ data\ points} \quad k \in [0, N-1]$$

$P_{\max}$: Maximum solar output

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

CONFIG Module

- **CONFIG Module**
  - The CONFIG module is used to generate all valid configurations over the planning years. For a specific year, a configuration shows the cumulative number of installed candidate plants of each kind in this year since the start.

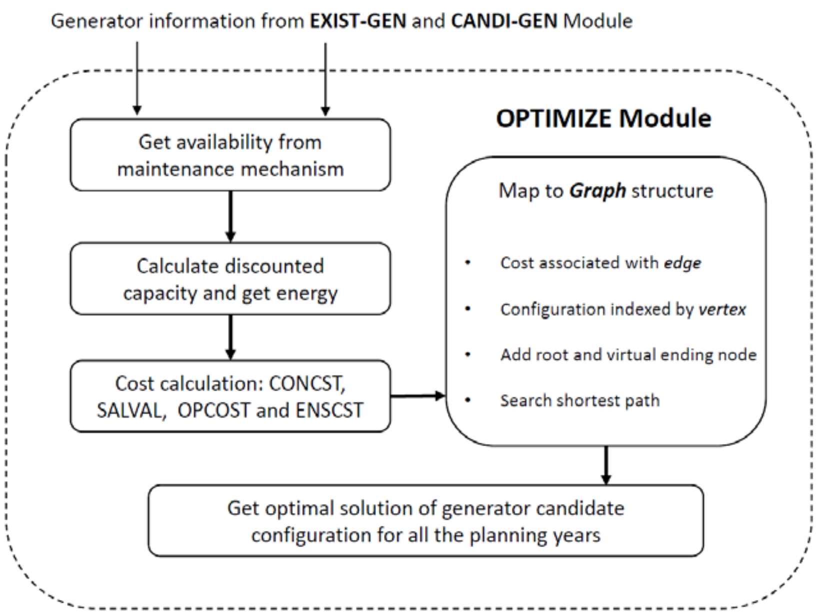


CONFIGURATION EXAMPLE FOR A SPECIFIC YEAR

Candidate Generator	G1	G2	G3	G4	G5
Year N	4	5	3	2	2
Year N+1	4	5	4	3	2

OPTIMIZE Module

- **OPTIMIZE Module**
  - OPTIMIZE is optimization module that combines probabilistic and optimization techniques to determine the optimal system expansion policy based on inputs defined in other modules.
  - The optimization is based on various cost calculation and graph structure search.



ELCC Module

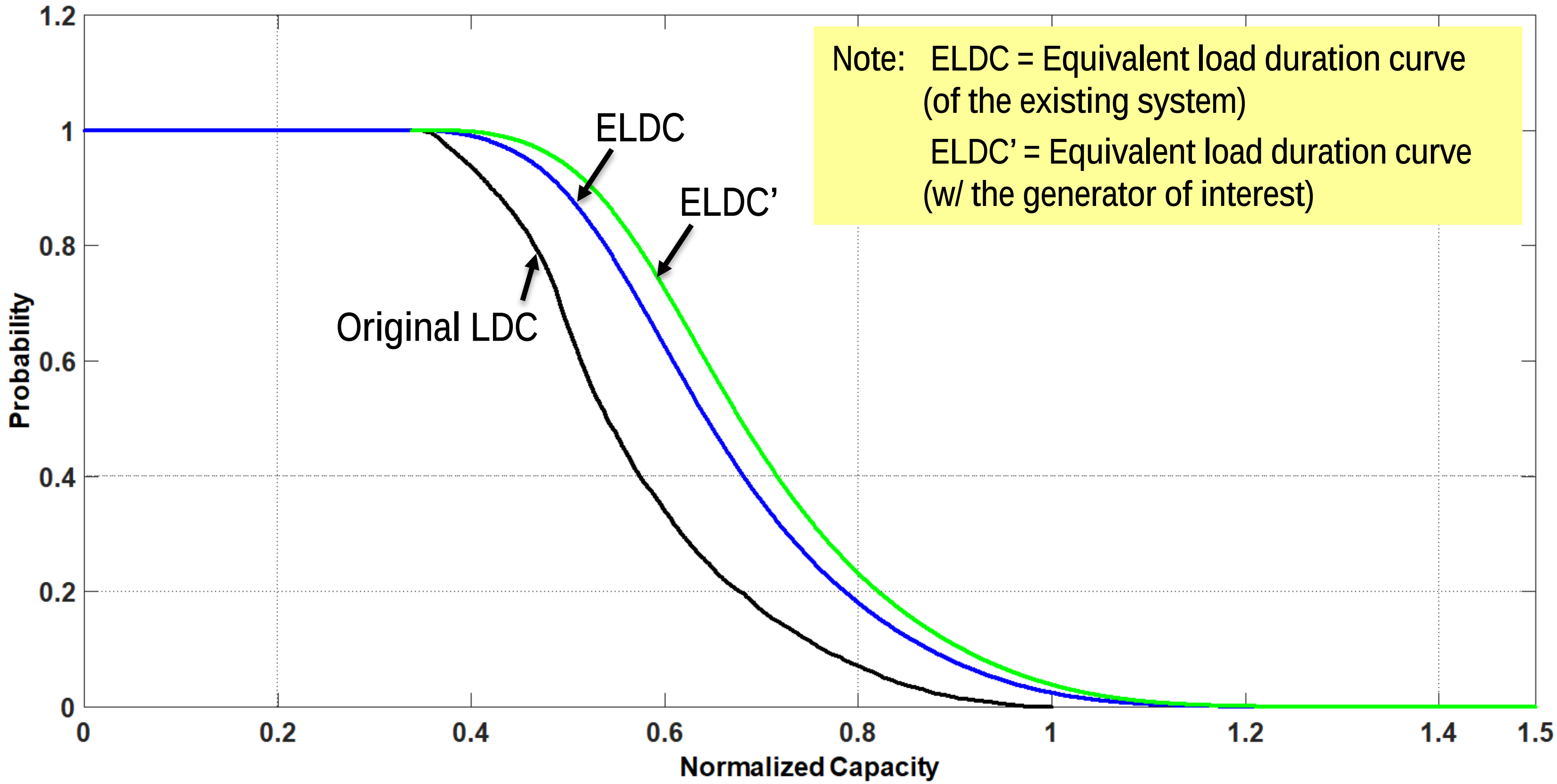
- **ELCC Module**
  - This module calculates equivalent load carrying capacity (ELCC) of each power plant. ELCC measures the contribution of an individual generator to system capacity with and without the generator of interest.
  - To calculate ELCC, Equivalent Load Duration Curve (ELDC) and the desired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

Equivalent Load Duration Curve (ELDC)

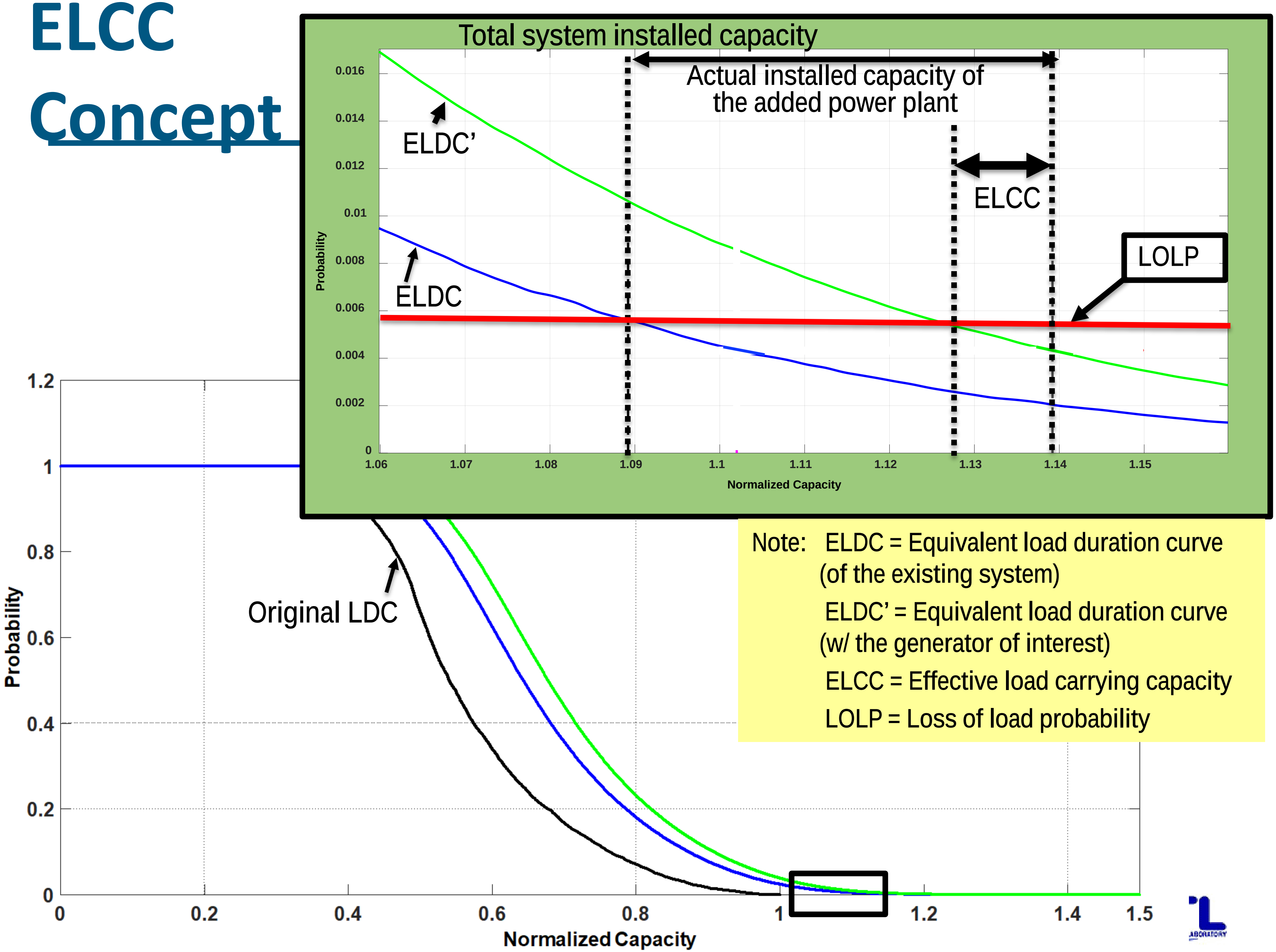
ELDC for thermal plants: $f^{i}(x) = p \cdot f^{i-1}(x) + q \cdot f^{i-1}(x - P)$

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 = Effective load carrying capacity

LOLP = Loss of load probability

Tool Validation

- **The newest version of WASP-IV package is used to validate our proposed tool dealing with conventional power plants expansion.**
  - Existing and candidate thermal plants are shown in the table below
  - Consider 20 study years from 1998 to 2017

Name of plants	FLG1	FLG2	FCOA	FOIL	FGT	F-CC	V-CC	VLG1	VLG2	VCOA	NUCL
No. of units	4	9	1	7	4	1	-	-	-	-	-
Base capacity (MW)	150	150	400	80	50	87	300	150	150	400	300
Max capacity (MW)	270	276	580	145	50	174	600	280	280	580	600
Forced outage rate (%)	10.0	8.9	8.0	7.3	6.0	15.0	10.0	10.0	10.0	8.0	10.0
Maintenance days	56	56	48	42	42	28	28	56	56	48	42
Fixed O&M cost ($/kW-month)	4.06	1.91	2.92	4.57	8.35	2.10	2.10	2.70	2.70	2.92	2.50
Variable O&M cost ($/MWh)	4.90	2.00	5.00	1.60	1.60	5.00	4.00	6.00	6.00	5.00	0.50
Fuel cost (cent/million kcals)	600	495	800	833	420	1266	1200	710	1100	800	194

Results

The optimal solution of the expansion plans are exactly the same over all the 20 study years for our proposed tool (MATPLAN) and WASP.

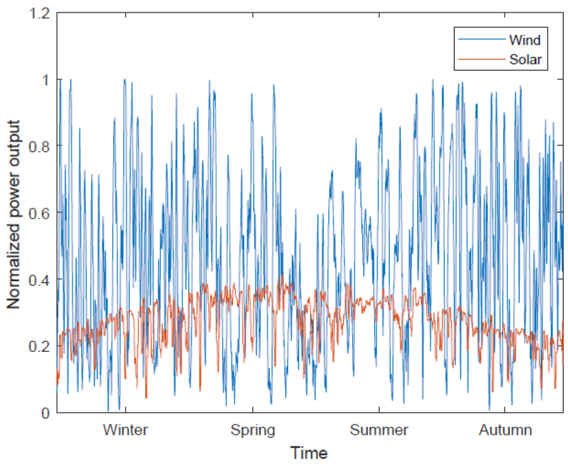
Result from proposed tool

Result from WASP

	MATPLAN						WASP					
Year	V-CC	VLG1	VLG2	VCOA	NUCL	LOLP (%)	V-CC	VLG1	VLG2	VCOA	NUCL	LOLP (%)
1998	0	0	0	0	0	15.717	0	0	0	0	0	14.924
1999	0	0	0	0	0	10.700	0	0	0	0	0	10.485
2000	0	0	0	0	0	14.055	0	0	0	0	0	12.899
2001	2	0	0	0	0	3.599	2	0	0	0	0	3.349
2002	2	0	0	1	0	2.766	2	0	0	1	0	2.595
2003	3	0	0	1	0	3.062	3	0	0	1	0	2.905
2004	4	1	0	2	0	0.397	4	1	0	2	0	0.537
2005	4	3	0	2	0	0.332	4	3	0	2	0	0.459
2006	4	3	0	3	1	0.116	4	3	0	3	1	0.212
2007	4	3	0	3	1	0.427	4	3	0	3	1	0.555
2008	4	3	0	4	1	0.384	4	3	0	4	1	0.510
2009	4	3	1	5	1	0.407	4	3	1	5	1	0.525
2010	4	3	1	6	1	0.407	4	3	1	6	1	0.517
2011	4	3	2	6	2	0.234	4	3	2	6	2	0.337
2012	4	3	2	7	2	0.353	4	3	2	7	2	0.458
2013	4	3	3	8	2	0.323	4	3	3	8	2	0.421
2014	4	4	4	9	2	0.380	4	4	4	9	2	0.472
2015	4	4	5	9	3	0.277	4	4	5	9	3	0.369
2016	4	4	5	10	3	0.359	4	4	5	10	3	0.449
2017	4	5	5	10	4	0.296	4	5	5	10	4	0.384

Case Study

- **We study the proposed tool for generation expansion planning with consideration for renewable energy, including wind and solar power.**
  - The study years are for future from 2019 to 2038
  - Eight time periods are considered in order to serve renewable energy
  - The annual wind/solar production data is obtained from the U.S. National Renewable Energy Laboratory (NREL)



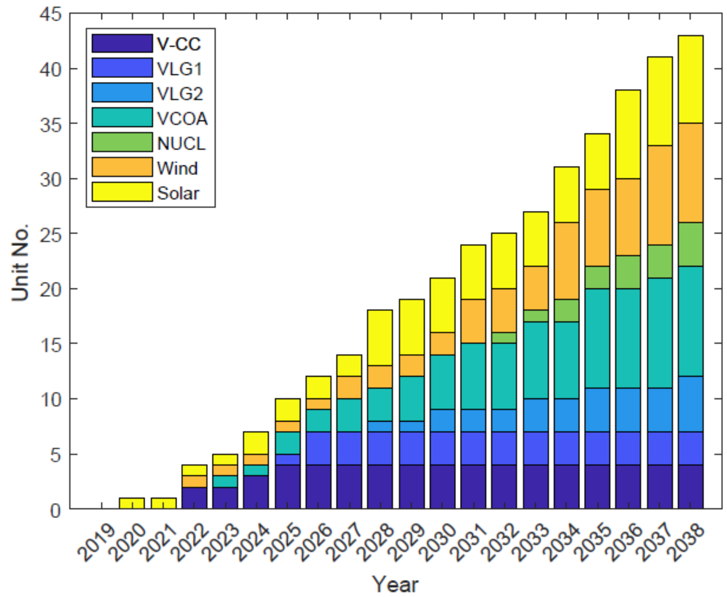
Example of normalized power output with moving average of 24-hour time

TIME PERIODS DIVISION FOR RENEWABLE ENERGY

Index No.	Time period
Period 1	07:00 - 18:00 in days 1 - 91
Period 2	06:00 - 19:00 in days 92 - 183
Period 3	07:00 - 20:00 in days 184 - 274
Period 4	08:00 - 17:00 in days 275 - 365
Period 5	18:00 - 07:00 in days 1 - 91
Period 6	19:00 - 06:00 in days 92 - 183
Period 7	20:00 - 07:00 in days 184 - 274
Period 8	17:00 - 08:00 in days 275 - 365

Results

Optimal expansion plan considering renewable energy



ELCC FOR CANDIDATE GENERATORS IN DIFFERENT PERIODS OF YEAR 2038

ELCC	V-CC		VLG1		VLG2		VCOA		NUCL		Wind		Solar	
	MW	%	MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Period 1	448.3	74.7	216.9	77.5	216.9	77.5	451.3	77.8	448.3	74.7	10.2	34.0	21.3	42.6
Period 2	432.3	72.1	209.3	74.8	209.3	74.8	435.6	75.1	432.3	72.1	8.9	29.6	20.0	40.0
Period 3	465.9	77.7	225.6	80.6	225.6	80.6	468.5	80.8	465.9	77.7	11.6	38.7	23.2	46.4
Period 4	503.9	84.0	243.7	87.1	243.9	87.1	505.7	87.2	503.9	84.0	15.0	50.1	25.7	51.5
Period 5	449.4	74.8	218.0	77.7	218.0	77.6	451.9	77.8	449.4	74.7	10.2	34.0	0	0
Period 6	433.1	72.2	209.1	74.7	209.1	74.7	436.3	75.2	433.1	72.2	8.9	29.6	0	0
Period 7	466.1	77.7	227.6	81.6	225.6	80.6	468.5	80.8	465.9	77.7	11.6	38.7	0	0
Period 8	504.0	84.0	244.2	87.1	243.9	87.1	506.7	87.3	504.9	84.1	15.0	50.1	0	0

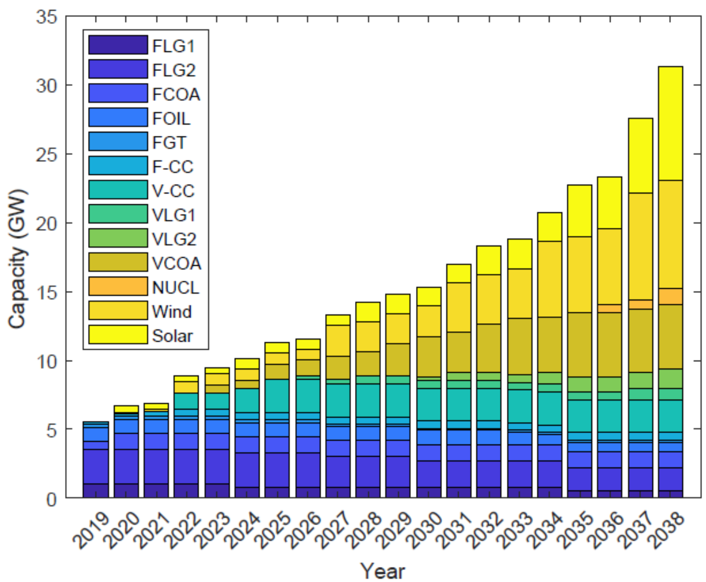
Results

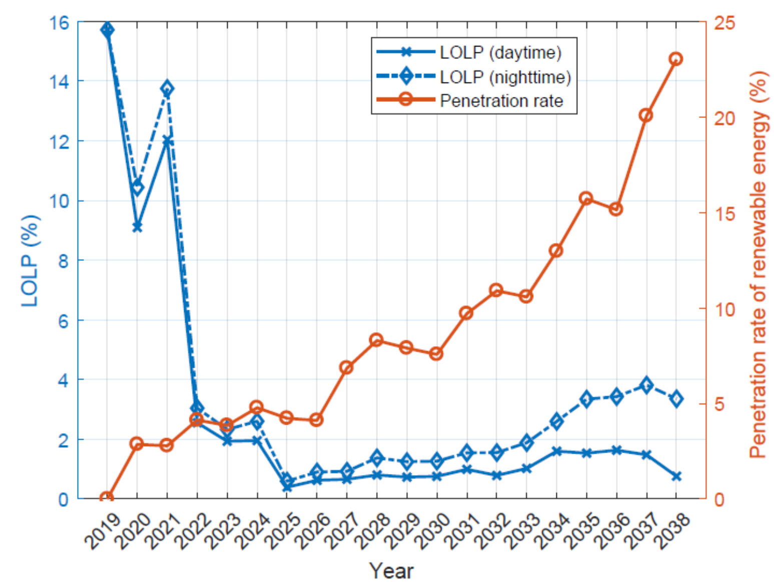
- The renewable energy generator is incorporated into the expansion plan at very beginning year due to its economic advantage of low maintenance cost, less capital investment and none fuel cost;

- The renewable energy generators usually have much less ELCC value in percentage compared with conventional generators due to the intermittent feature of their energy resources, especially for solar power of none capacity credit in nighttime.

Case Study (high penetration)

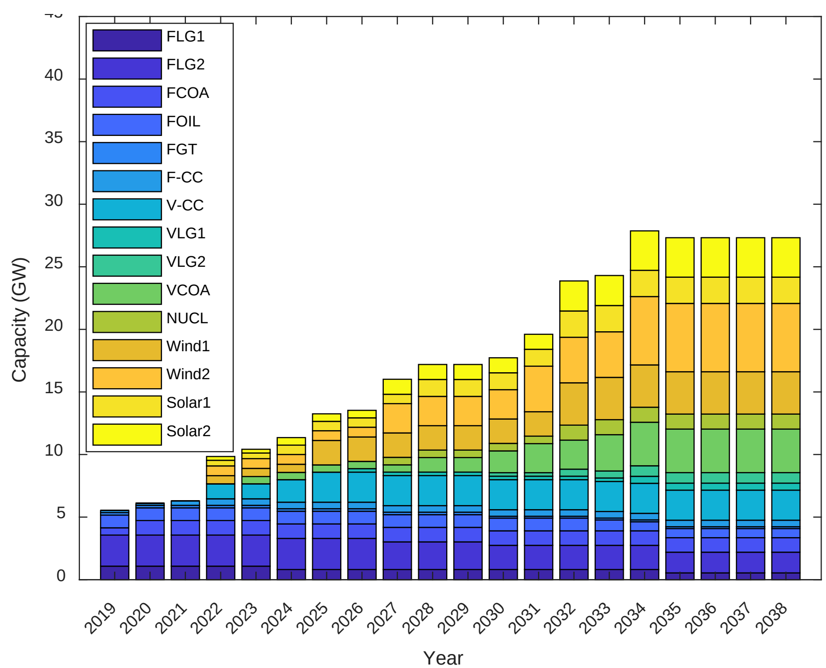
- **We study the high penetration scenario of renewables, which target roughly 30-50% penetration rate till the final study year 2038.**
  - The study years are for future from 2019 to 2038
  - LOLP should be kept at the same level or less by calibrating the reasonable capacity contribution of renewable energy generators

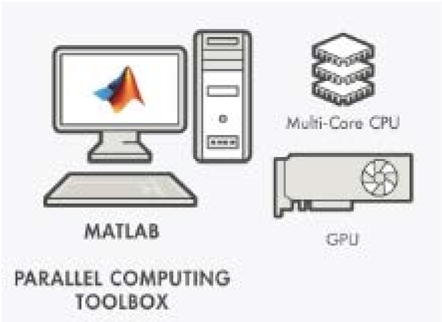




Case Study (multiple locations)

- **We study the high penetration scenario of renewables, consider multiple locations of renewable energy resources and use parallel computing implementation.**
  - 1205 candidate configurations in total (*including wind1, wind2, solar1, solar2)
  - 4 working cores in parallel pool to reduce time from 150 min to 49min





Summary: Accomplishment To-Date (Looking back)

- **FY18 Accomplishments**
  - Completed the development of all the eight modules in the proposed expansion planning tool
    - LOAD-CALC : prepares system load data
    - EXIST-TH : describes attributes of existing thermal generators
    - CANDI-TH : describes attributes of candidate thermal generators
    - EXIST-RE : describes attributes of existing renewable power plants
    - CANDI-RE : describes attributes of candidate renewable power plants
    - CONFIG: calculates all the valid configurations for expansion plan
    - OPTIMIZE: calculates the optimal solution of expansion plan
    - ELCC : calculates equivalent load carrying capacity of renewables (started)
  - Derived probabilistic models to represent renewable energy generation

Summary (cont.'): Accomplishment To-Date (Looking back)

- **FY19 Accomplishments**
  - Validated the proposed tool with WASP software package
  - Implemented some study cases for evaluation, with using parallel computing
  - Released the current source code under open-source license for public access
  - Summarized the major findings in one journal and one conference paper

Challenges

- The probabilistic analysis requires extra computation time. This computation efficiency can be improved by preprocessing the renewable data points (i.e., normalization) and choosing a reasonable number N (e.g., 10-15) for representing the multi-states to trade off computational complexity and accuracy.

- The optimization process depends on the frequent calculation of energy dispatch and LOLP, which requires the most computation time. The implementation is under re-testing on large machines and the algorithm is being readied for parallel computing.

Planned Activities and Schedules (Looking forward)

- **FY19 Planned Work**
  - **Phase III:** Complete the case study
    .... **September 2019**
  - **Miscellaneous:**
  - Improve the accuracy of LOLP calculation
  - Re-factor some parts of the code to reduce computation time
  - Final documentation of all the developed modules

.... **June - September 2019**

Publication and Deliverable

- **Publication**
  - X. Zhang, M. Pipattanasomporn and S. Rahman, “A Comprehensive Analysis of Renewable Energy Representations in Power System Generation Expansion Planning,”In Proc. ICUE 2018 on Green Energy for Sustainable Development, Phuket, Thailand, October 24-26, 2018.
  - T. Chen, I. Rahman, Z. Jing, M. Pipattanasomporn, and S. Rahman, "MATPLAN: A Probability-based Planning Tool for Cost-effective Integration of Renewable Energy into the Electricity Grid", to be submitted.
- **Deliverable**
  - Open source software MATPLAN with documentation in process, (https://github.com/jfct001/renewable_planning)

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 2019
Cost to Date: DOE: $262,523 VT: $58,725

Budget History			
Budget Year 1&2 Sept 2017 – Mar 2019 (past)		Future (planned)	
DOE	Cost-share	DOE	Cost-share
$262,523	$58,725	$97,168	$31,398

THANKS!

Q&A