NATIONAL RENEWABLE ENERGY LABORATORY

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Overview of NREL Distribution Grid Integration Cost Projects

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Summary of Current Activities

DOE SETO Distribution Grid Integration Costs

- 2016
  - Meta-analysis of literature
  - Development of unit cost database
  - Development of general analysis framework and terminology
- 2017
  - Application of database and framework to real feeders with diverse characteristics in the static HC regime
- 2018
  - Application of database and framework to real feeders with diverse characteristics in the dynamic HC regimes
  - Algorithms for finding lowest cost solutions
  - Integration with other tools

ARPA-E Grid DATA

- Launched 2016: Smart DS program
  - Synthetic distribution sets for evaluation, cost data, scenario data

NREL LDRD

- 2016 –2017: Distribution System Planning for uncertain DER futures using Adaptive Dynamic Programming (ADP)
  - Being integrated with cost-benefit analysis work

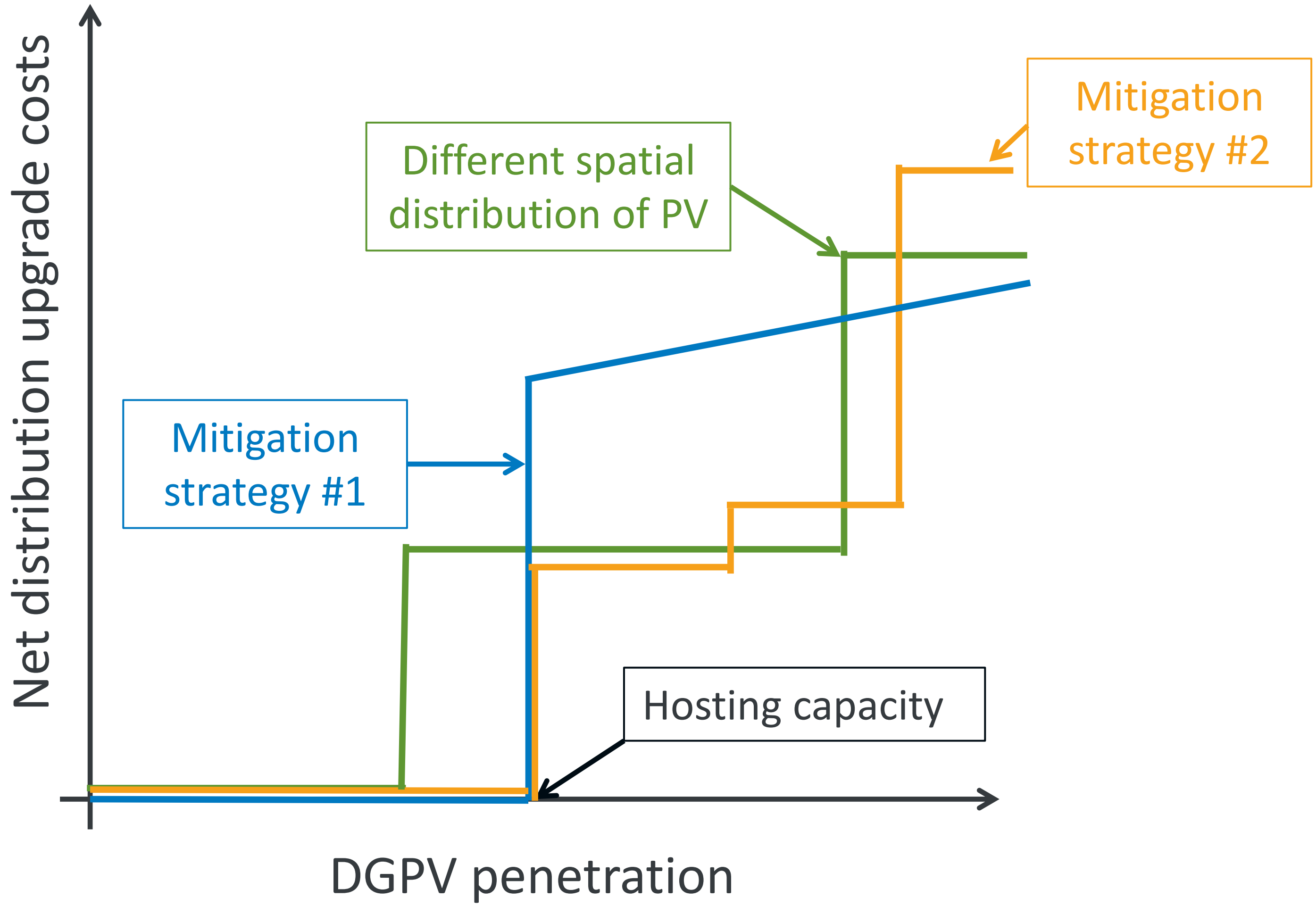
✧ Lots of other ongoing related work on:
- Interconnection soft costs
- Hosting capacity analysis
- Evaluation of different strategies for integrating DGPV and other DER
- Co-managing energy efficiency, demand response, storage, DGPV

Defining Distribution Grid Integration Costs

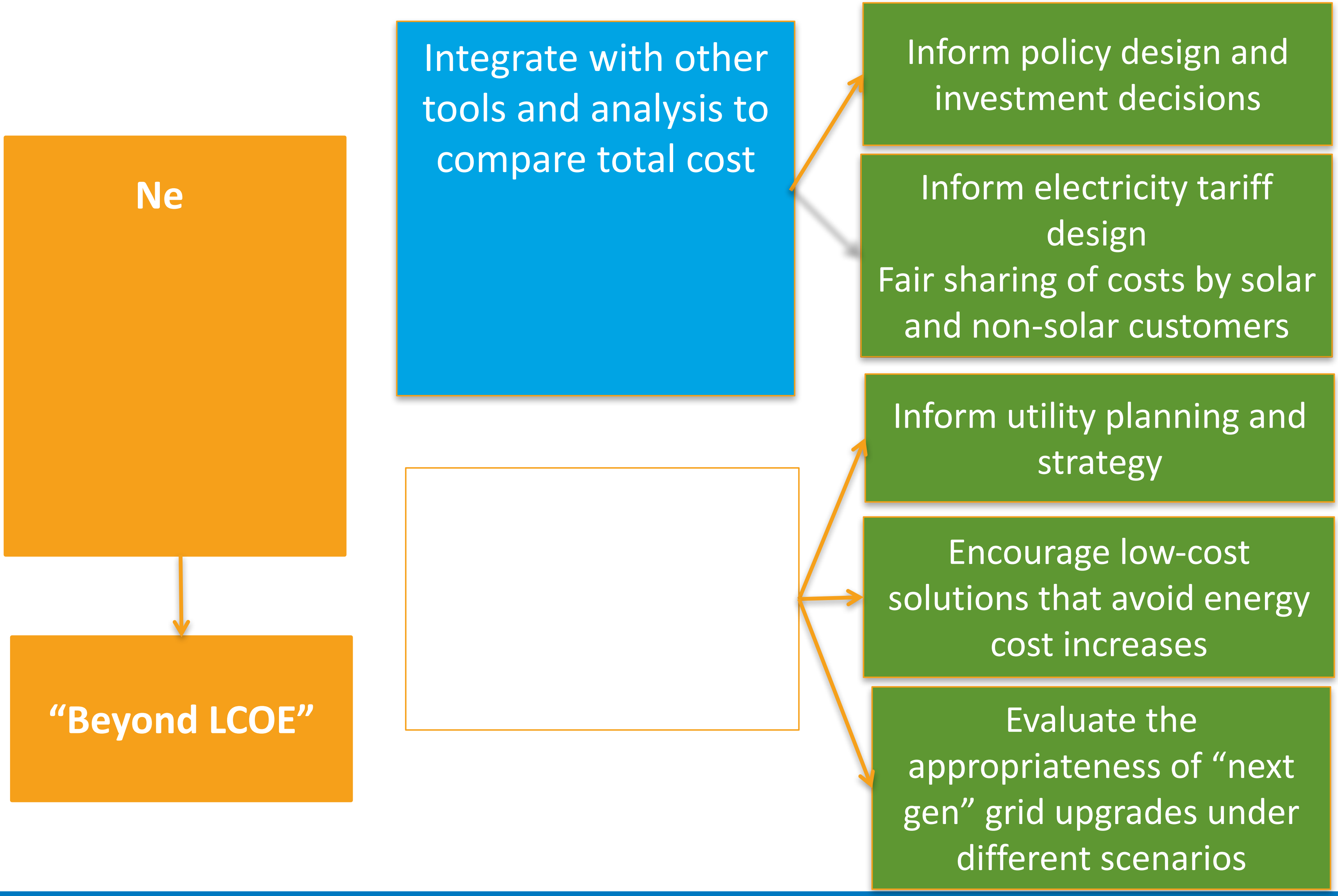
- Many times in practice these costs fall under interconnection costs for individual large DGPV systems
  - Soft costs for interconnection studies/reviews
  - Hardware costs for any upgrades required to maintain grid operating conditions
- Some utilities are thinking of larger distribution system overhauls required for grid integration
  - But motivations for upgrades extend beyond DGPV
- Literature on changes in distribution line loss, distribution line capacity costs, and upgrade costs at different penetration levels

Defining Distribution Grid Integration Costs

Costs on a specific feeder or distribution system



Vision for Use of this Approach



Needs for Future Analysis

- Methods exist for estimating the cost of specific mitigation strategies at different levels in the static hosting capacity regime, but:
  - There is no accepted comprehensive approach for estimating costs
  - Prior work has inconsistency in terminology
  - Often little transparency into methods and assumptions, in particular input cost data
- Future work is required to better understand distribution system costs and benefits in scenarios with flexibility, advanced communications and controls
  - These have been identified as potentially low cost options in prior work, but have not been well studied
  - Especially relevant at high penetration levels

Distribution System Integration Cost

Distribution System Integration Cost		Distribution upgrade cost		Interconnection cost		Distribution line loss cost
C_{DS}	=	C_{DU}	+	C_{IC}	+	C_{DL}

- Is a NET cost, referenced to a case with no DGPV
- Includes capital costs and O&M costs, discounted and summed over a specified analysis period
- Can be computed on a $/kW (capacity) or $/kWh (energy) basis
  - We suggest specific formulas for these for clarify and consistency in our paper/framework
- For both large and small DGPV systems

Interconnection Costs

$$C_{IC}(p) = \sum_{n=0}^{N} \sum_{i(p)} \frac{ONC_{IC,i}}{(1+d)^n}$$

where:

- n is the year index
- N is the planning horizon or planning period, in years
- d is the discount rate
- $ONC_{IC,i}$ is the total overnight capital cost of interconnection associated with generator i

Distribution Line Loss Costs

- Net cost associated with line losses in the distribution system
- Depends on assumptions about (or status of) bulk power system
- Calculate losses using time-series simulations in scenarios with and without DGPV present at each penetration level

$$C_{DL}(p) = c_{Loss} \cdot \left(\sum_{n=0}^{N} \frac{P_{PV}(p) - P_{ref}}{(1+d)^n} \right) \cdot \Delta t$$

where:

- c_{Loss} is the cost of loss compensation, in $/kWh
- $P_{PV}(p)$ are the total power losses within the distribution grid with DER at penetration *p*, in kW
- P_{ref} are the total power losses within the distribution grid in a reference case without DPV, in kW
- Δt is the time step of the time series power flow simulation

Distribution System Integration Cost

$$C_{DU}(p) = \sum_{n=0}^{N} \frac{ONC_{DU,PV}(p,n) + O\&M_{DU,PV}(p,n) - ONC_{DU,ref}(n) - O\&M_{DU,ref}(n)}{(1+d)^n}$$

Where:

- $ONC_{DU,PV}(p,n)$ is the total overnight capital cost of all distribution system upgrades in year *n* with the presence of DPV at penetration *p*, in $.
- $O\&M_{DU,PV}(p,n)$ is the total operations and maintenance (O&M) cost associated with distribution system equipment upgrades that are required with the DER at penetration *p*, plus any changes in O&M costs of existing equipment due to the presence of the DER
- $ONC_{DU,ref}(n)$ is the total overnight capital cost of any distribution system upgrades that would be required in a reference case without PV in year *n*
- $O\&M_{DU,ref}(n)$ consists of any O&M costs that would be incurred in a reference case without PV in year *n*

Specific Formulas and Metrics

Capacity-Based

$$\hat{C}_{DS,a} = \frac{\sum_p C_{DS}(p)}{\sum_{i(p_{max})} P_i}$$

P_i = rated DC power output (under STC) of DER generator *i* at the maximum penetration level, p_{max}

- Useful, e.g., for comparing total costs associated with DER across studies

Energy-Based

Marginal levelized cost at penetration *p*:

$$LCDS_m(p) = \frac{C_{DS}(p)}{\sum_{n=0}^{N} \sum_{i(p)} \frac{E_{n,i}}{(1+d)^n}}$$

Average, levelized cost for all DGPV u to the maximum penetration level:

$$LCDS_a = \frac{\sum_p C_{DS}(p)}{\sum_{n=0}^{N} \sum_{i(p_{max})} \frac{E_{n,i}}{(1+d)^n}}$$

$E_{n,i}$ = estimated energy production of DER *i* in year *n*

- Useful for comparing to to LCOE values, across analyses of DER costs

Calculation Approach

1. Power flow simulations on the feeder at a given level of DGPV penetrations

2. Identify any violations in distribution system operating conditions (e.g. voltage, thermal, protection coordination, etc.)

3. Map violations to a set of mitigation strategies

4. Obtain unit cost data for all components/modifications needed for mitigating violations and for other expected upgrades

5. Calculate the total cost associated with all required upgrades

Increase penetration of DGPV, and repeat until the maximum penetration level of interest

Unit Cost Inputs

- This approach requires a lot of data
- NREL and others are working to address this gap
  - Unit cost guides from CA utilities are now available online
  - More extensive NREL unit cost database will also be publicly released
  - Collecting some additional data for ARPA-E Grid Data project

"So things are good, stuff is OK, and I reiterate my request for more specific data."

NREL Unit Cost Database

Cost_database_for_release_June_2017.xlsx

Communications Component Costs

component	cost_type	cost_low	cost_mid*	cost_high	cost_unit	sources	date	*if no range given, put the single data value in the mid bucket
network inteface cards for meters/AMI	hardware	28		50	USD/unit	anonymized	2016	
communication bridges for capacitor bank controllers, feeder switches, and reclosers	hardware	600		1000	USD/unit	anonymized	2016	
gateways for field devices (equipped with ethernet, cellular, some with wi-fi)	hardware	100		598	USD/unit	anonymized	2017	
line sensors - for voltage, current, or both voltage and current	hardware	600	1600	2000	USD/unit (per phase)	anonymized	2016	
communication network infrastructure/backbone	capital costs, total	4		8	USD/customer	anonymized	2016	
network management control software package	software		4		USD/endpoint	anonymized	2016	
indoor wireless mesh routers and bridges	hardware	1000		1300	USD/unit	anonymized	2016	
outdoor mesh network router	hardware	4000		6000	USD/unit	anonymized	2016	
fault circuit indicators	hardware	350		1000	USD/unit	anonymized	2016	
Ethernet switch	hardware	800		2500	USD/unit	anonymized	2016	
Feeder RTU	hardware	1000		3500	USD/unit	anonymized	2016	
Substation RTU	hardware	3500		150000	USD/unit	anonymized	2016	
Dedicated RTU	total installed		120000		USD/unit	PG&E Unit Cost Guide	9/21/16	
Centralized RTU	total installed		6100		USD/unit	SCE Unit Cost Guide	9/21/16	
Dedicated RTU	total installed		140000		USD/unit	SCE Unit Cost Guide	9/21/16	
phasor measurement units	total installed		125000		USD/unit	EPRI Estimating the Costs and Benefits of the Smart Grid report	3/1/11	

Conductor | Service and Metering | Remove or Relocate | O&M | Misc. Overhead | Storage | **Communication and Sensing** | D-SVC, D-STATCOM, Power Regs | AMI | SCADA, DMS, DERMS, DR

Notes from Applying this Methodology: Static HC Case

- Use of even simple smart inverter functions can provide a low-cost way to mitigate voltage effects
  - In reality, effectiveness/cost depends on existing PV on the system
- Revising the set points of existing voltage regulators can help overcome overvoltage
  - Average cost to change a regulator's settings was $3,771
- Challenges with static HC approach
  - Impossible to estimate the increase in O&M costs associated with increased regulator movement without time series simulation
  - Costing out ways to mitigating potential flicker without dynamic approaches
  - Adding new voltage regulators and evaluating the impact
    - Voltage regulators are frozen
    - How to bound where the regulators could be located based on other constraints – more data?

Challenges and Needs from the Community

- Needs
  - Greater transparency
  - Common vocabulary
  - Finding mutually acceptable technical and commercial frameworks for looking beyond static hosting capacity and cost analysis
  - Regulatory and policy changes that incentivize the pursuit of low costs solutions
  - More data
    - E.g. O&M cost data
- Big Challenges
  - Trying to understand costs in a static hosting capacity regime
  - Attributing costs to DGPV versus other factors, especially in dynamic hosting capacity regimes
    - E.g. with communication system upgrades
    - Interaction among multiple DERs
  - Figuring out how to use this analysis for fair and equitable policy and rate design, cost allocation among generators and customers

Thank you!

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