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A Transparent Framework for Evaluating the Effects of DGPV on Distribution System Costs

Kelsey A. W. Horowitz, Fei Ding, Barry Mather, Bryan Palmintier, and Paul Denholm

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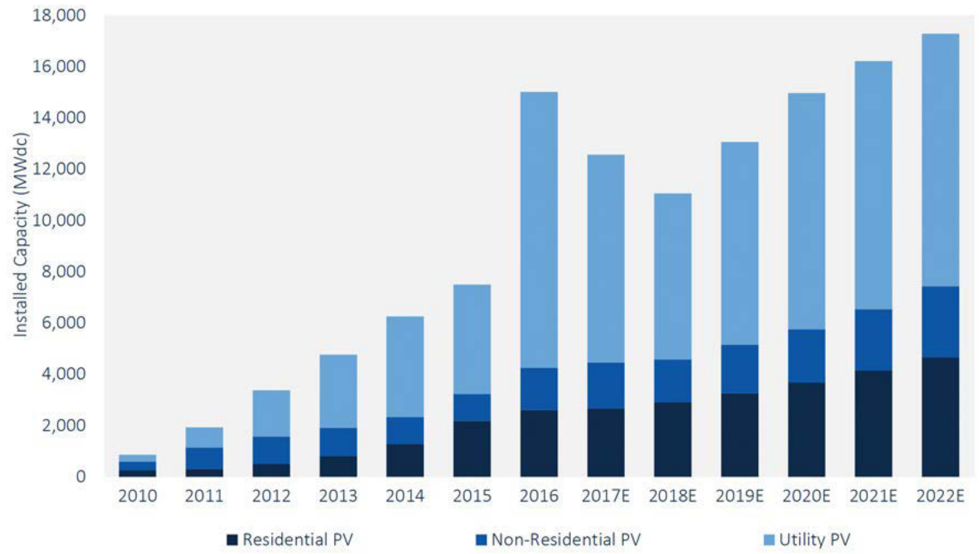
Introduction

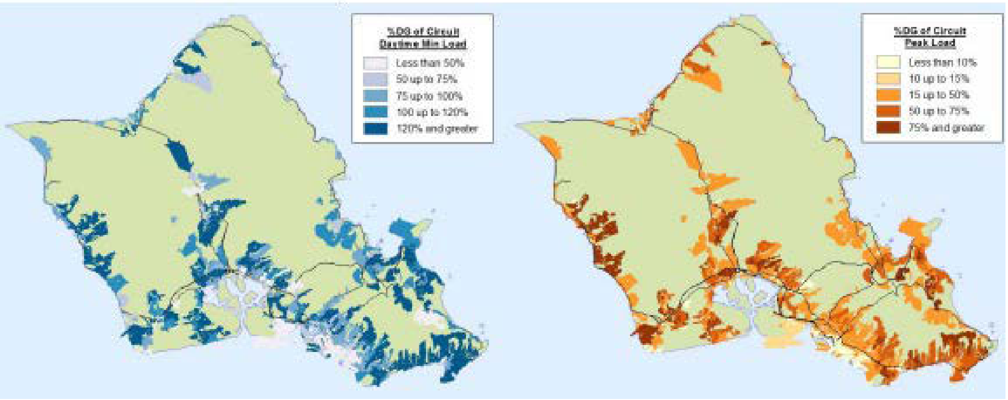
Motivation

- Increasing penetrations of distributed PV
  - How much does it cost to integrate DGPV?
  - How does DGPV benefit the grid?
- Need to develop forward-looking analysis approaches



GTM/SEIA

Locational value map for Oahu



Hawaiian Electric

Motivation

- Debate over net metering, tariff design, electricity charges for solar/other DER customers is fueled by:
  - Uncertainty of effects and costs of DGPV at high penetrations
  - Lack of an agreed upon framework for cost-benefit analysis

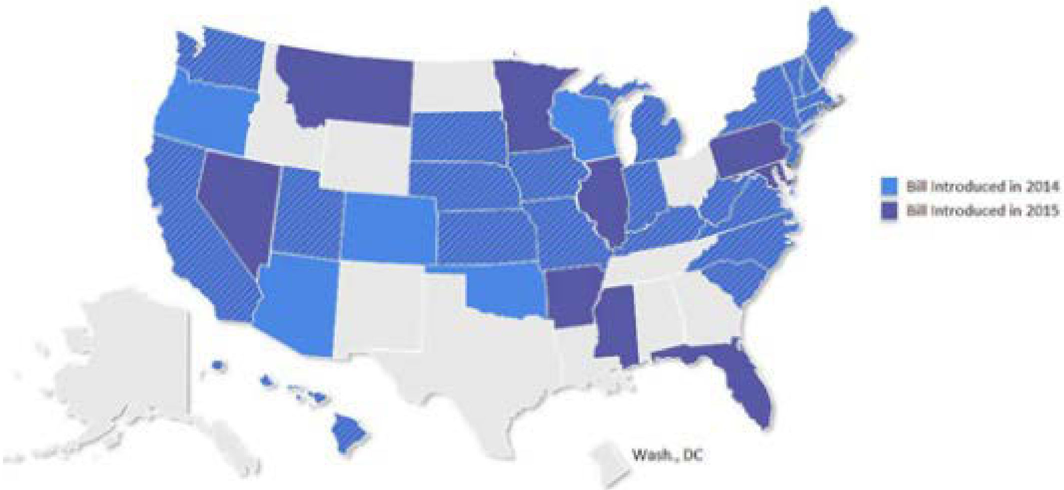


Figure 1. States where at least one NEM-related bill was introduced in 2014 and 2015

Source: Haynes 2015

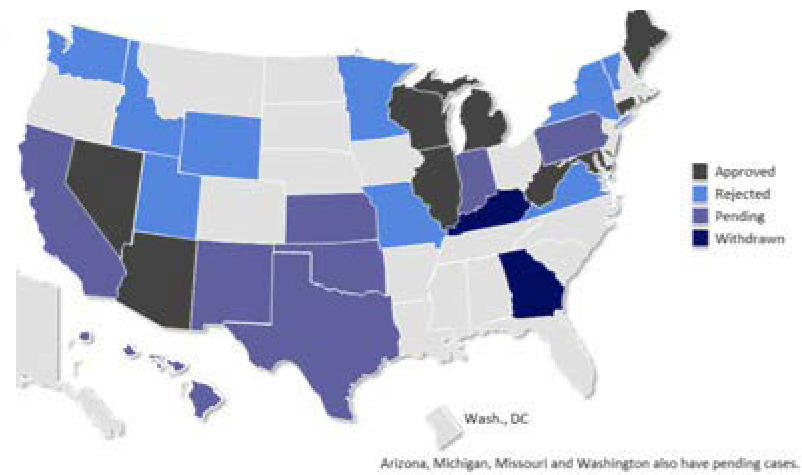
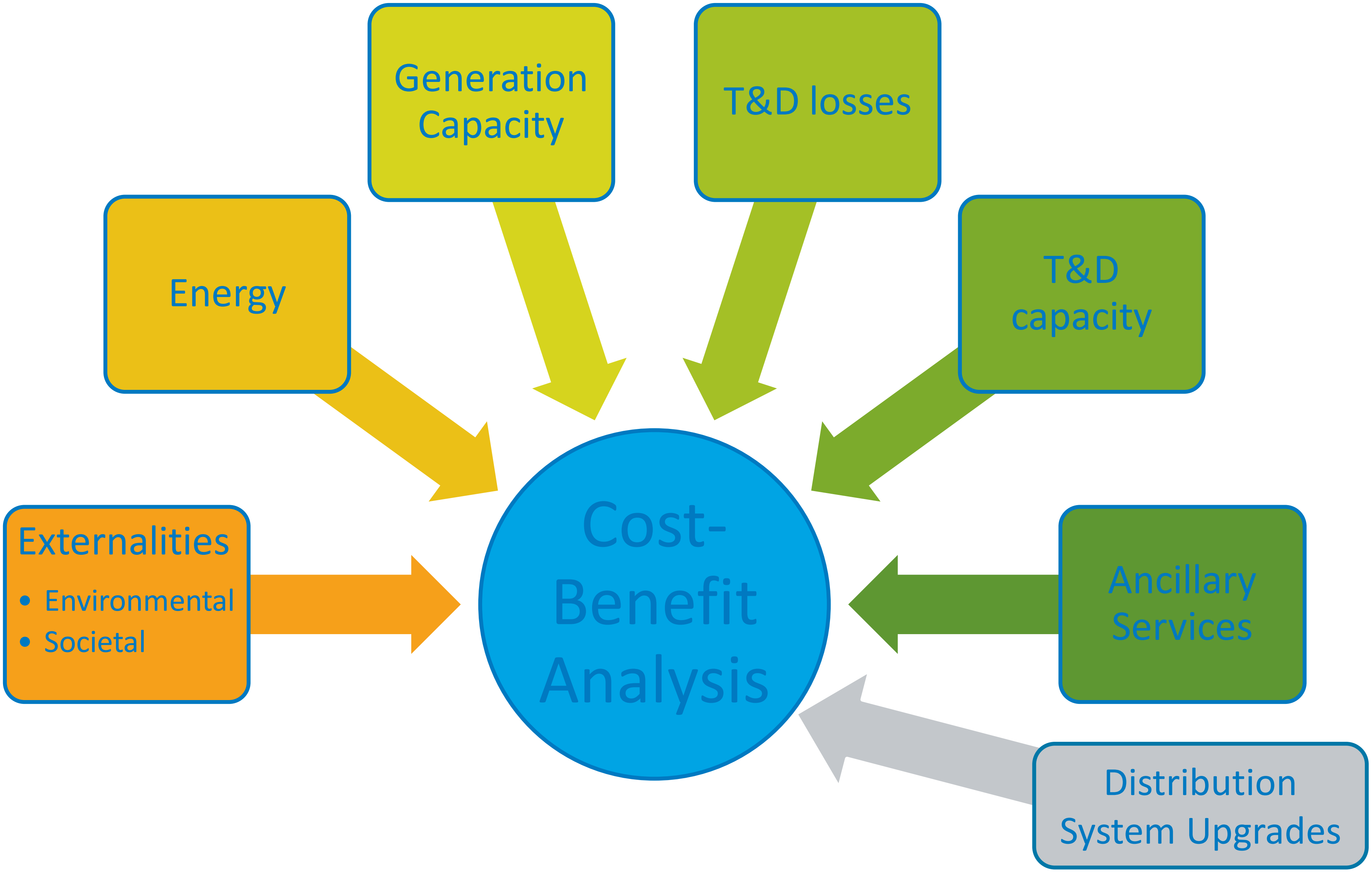


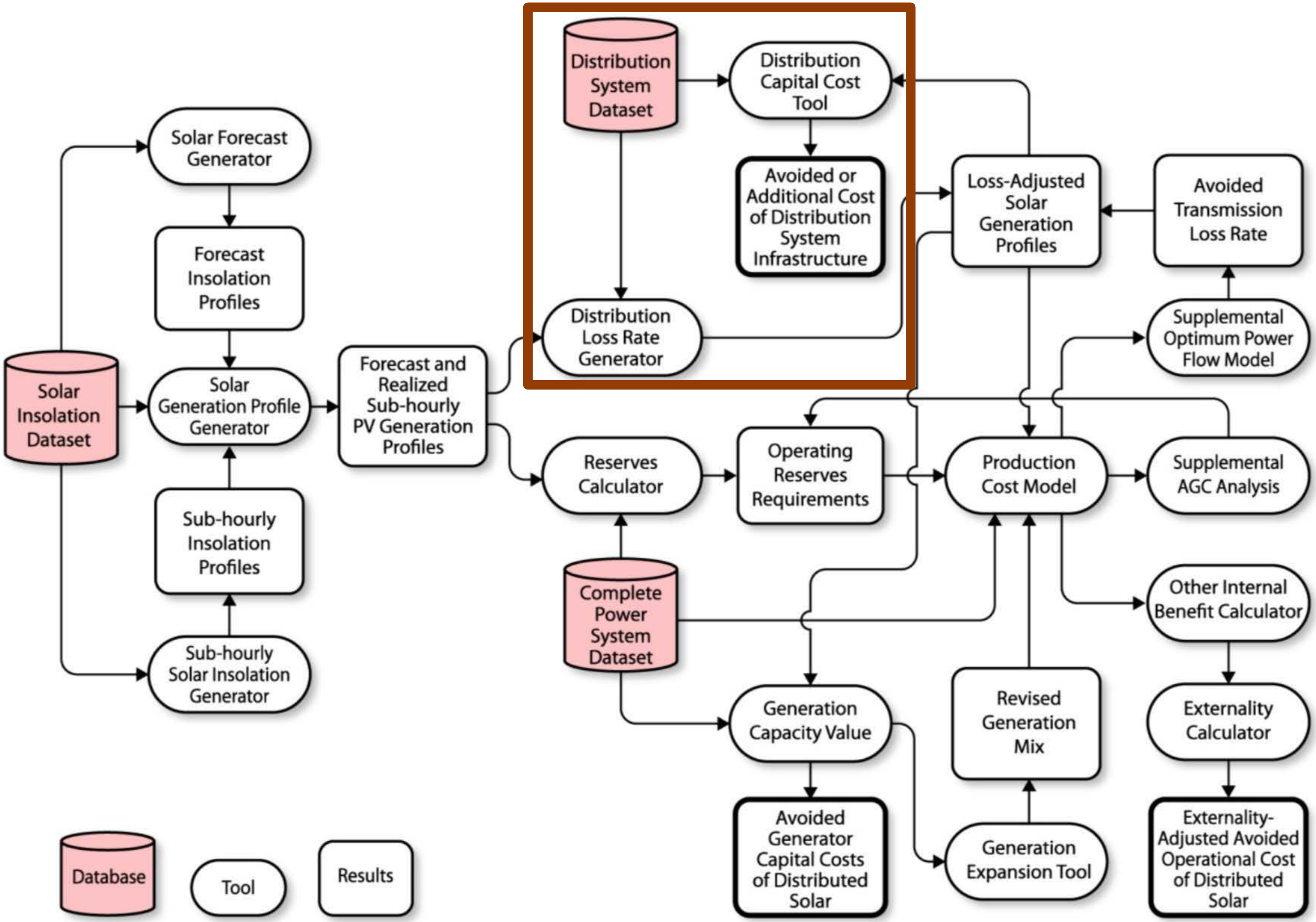
Figure 2. States in which utilities have proposed a change in rate structures since 2013 that would reduce compensation for DG

Sources: Hand 2015; Walton 2015; Roberts 2015; Inskeep et al. 2015; EQ Research 2015

Context for Distribution System Costs

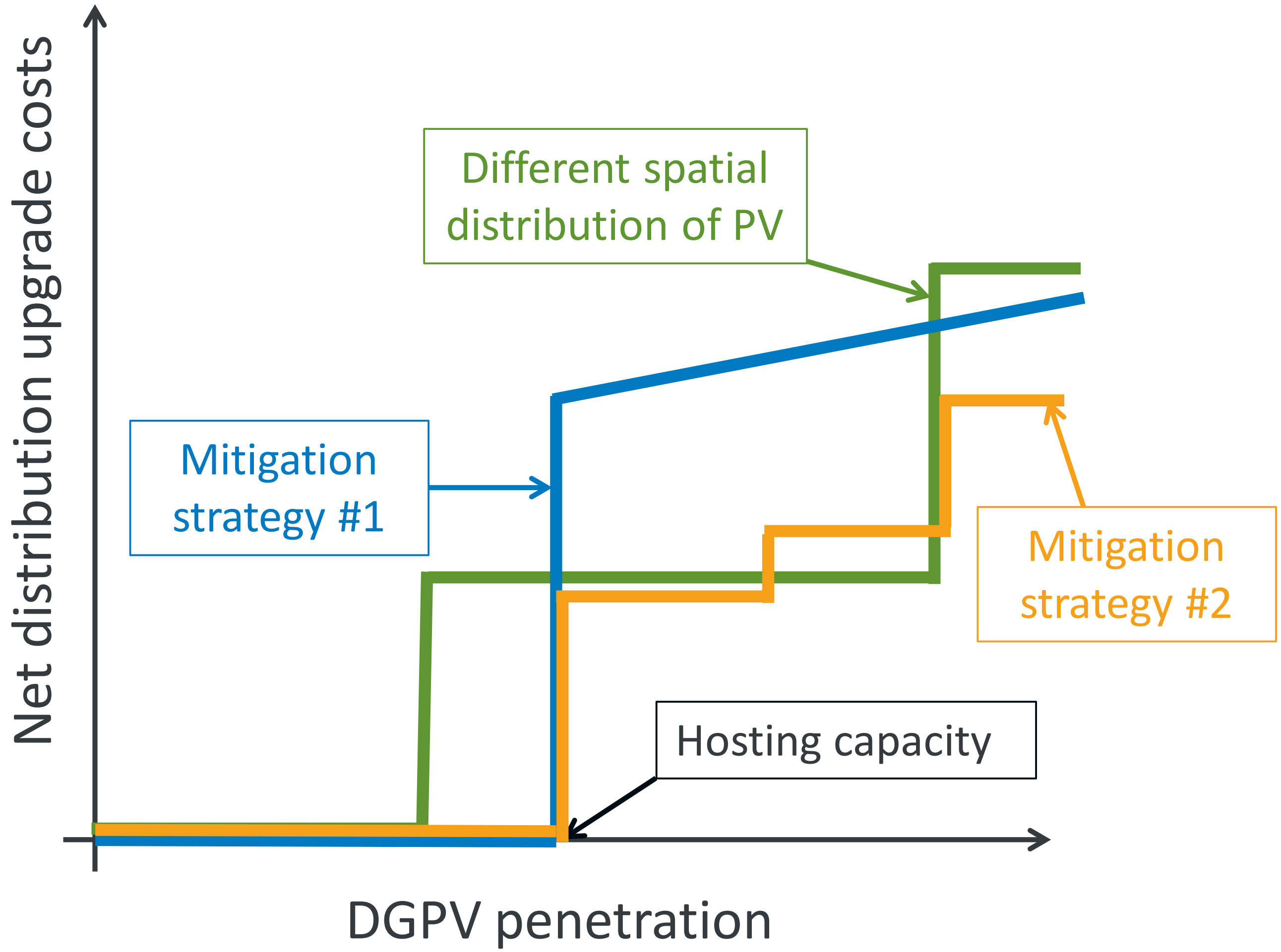


Context for Distribution System Costs

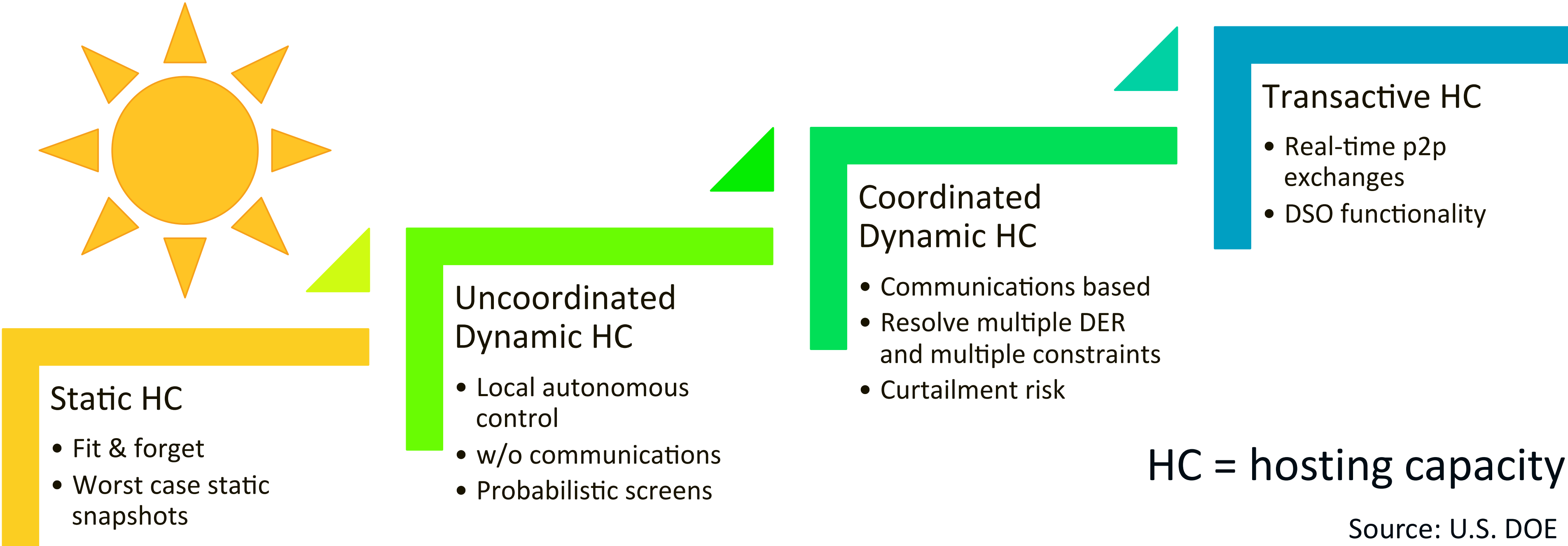


Defining Distribution Grid Integration Costs

Costs on a specific feeder or distribution system

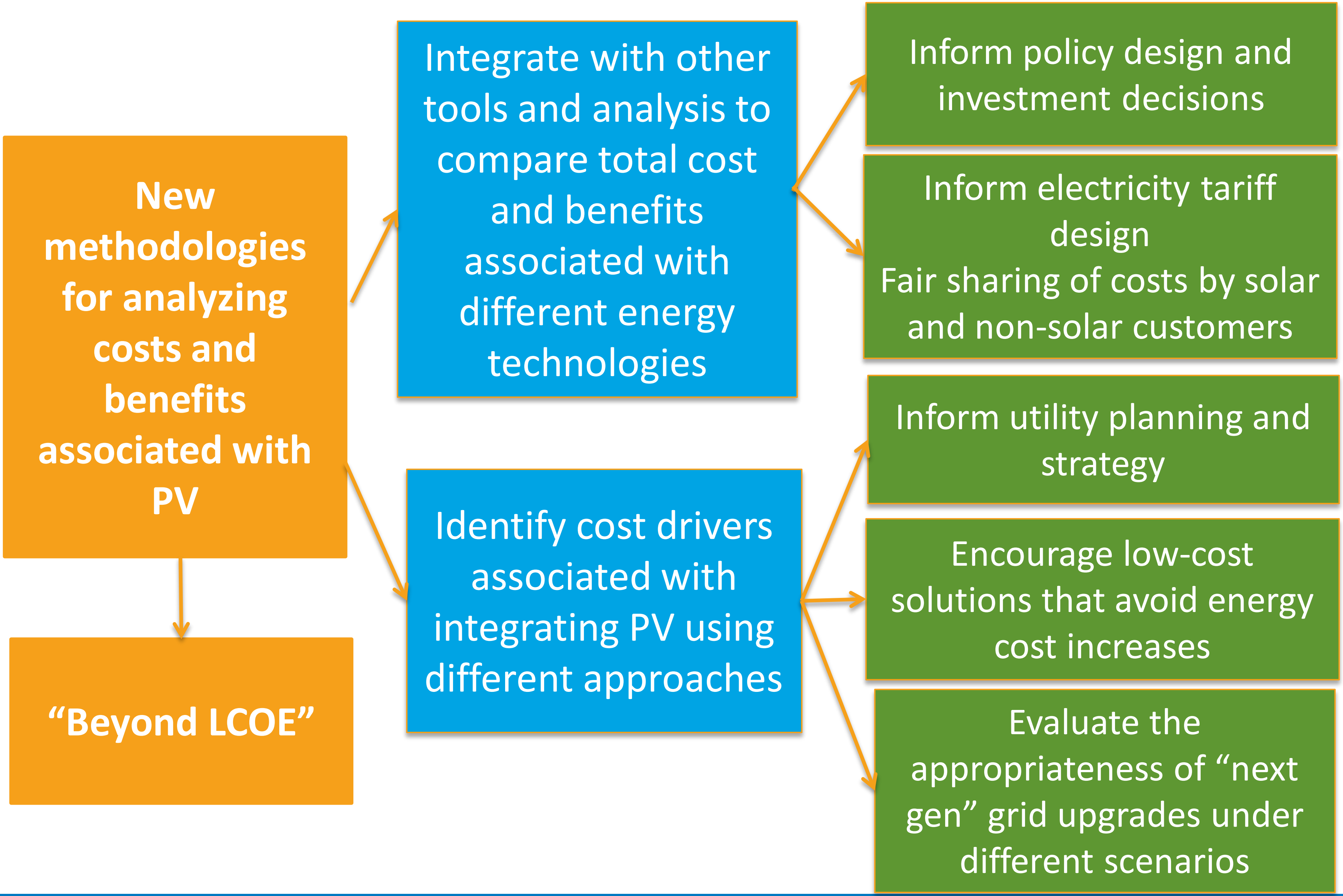


Different Paradigms of Analysis



- Most prior analysis has been performed using the static (conservative) definition of hosting capacity
- Dynamic and transactive regimes are based on dynamic, real-time operating constraints
- Each of these paradigms is associated with different set of upgrades to mitigate any impacts of DGPV on the system, and different costs
- Regulatory and/or market changes are required to fully implement coordinated dynamic and transactive HC approaches

Vision for Use of this Approach



Overview of the Understanding of Distribution System Integration Costs

- Quantitative cost analyses
- Hosting capacity studies
- Published frameworks and methodologies

Prior Quantitative Cost Studies: Geographic Focus

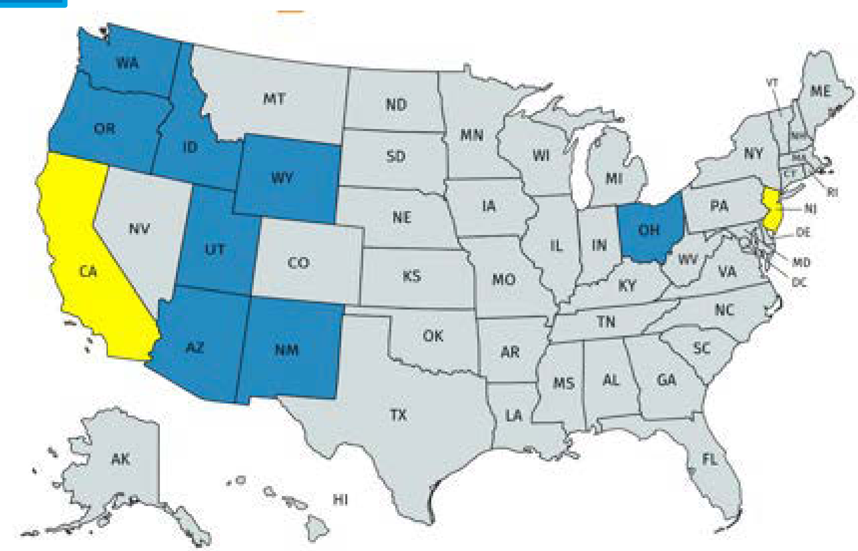
Studies have focused on U.S. and Europe

Number of udies

- 4
- 2
- 1
- 1 + SGIP
- SGIP only

5
total studies on European grids

3
total studies on U.S. grids



1 additional study on prototype networks modeled after U.S. and European-style grids → **9 total studies analyzed**

Penetration levels ranged from 0-600% of peak load, with most concentration at lower penetration levels

Summary of Results from Prior Analyses

- Difficult to compare results between studies
  - Different definitions of penetration level, and insufficient data to convert between different definitions
  - Different cost metrics
    - $/kW versus $/kWh
    - Discounted versus undiscounted costs
  - Included different costs
    - Assumed different mitigation strategies
    - Some included network loss costs, while others included only upgrade costs
  - Variability in methodology and assumptions

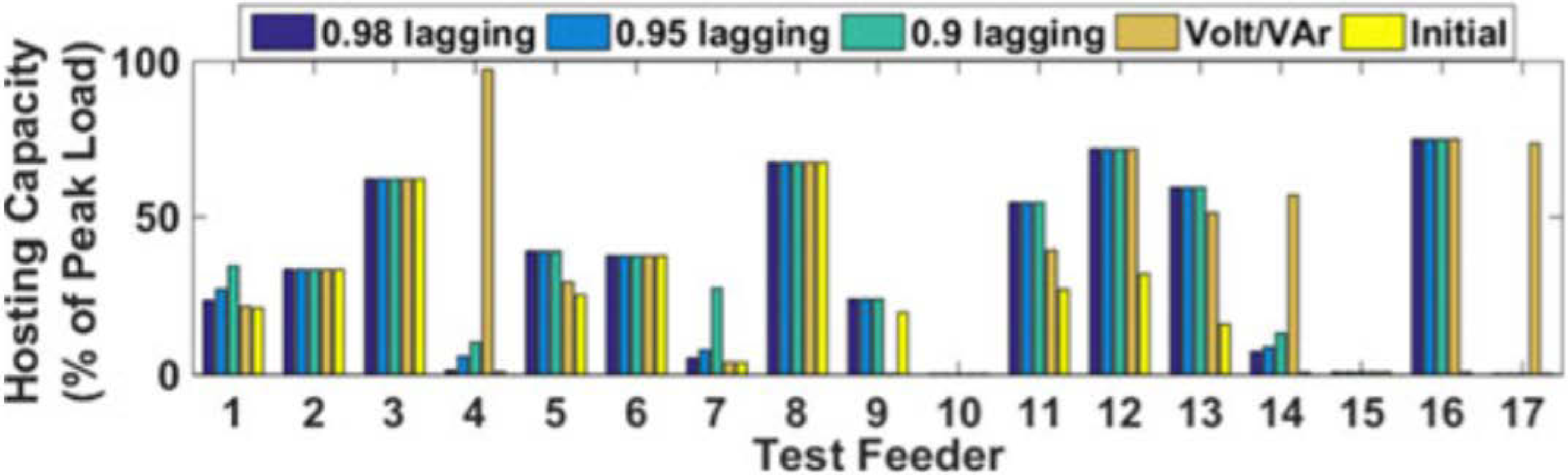
Summary of Results from Prior Analyses

- Net costs can be negative or positive, depending on the system or scenario
- Net costs are highly dependent on:
  - The specific feeder characteristics
  - Spatial distribution of PV on the feeder
  - Penetration level
  - Selection of mitigation strategies and their control settings
  - What costs are included
- Ranged from negative values around 15-20% of local LCOE, to positive values of roughly a third of typical installed system cost
  - Many cases incurred only small positive or negative costs
  - Based mostly on traditional and conservative mitigation strategies
    - Some limited use of alternative inverter set point changes
- High costs do not necessarily correspond to high penetration levels, and vice versa

Insights from Hosting Capacity Analysis

- Studies also consistently find significant variation in hosting capacity (and thus costs) depending on:
  - The feeder characteristics
  - Spatial distribution of DGPV
  - PV inverter set points
  - Controls on the other grid devices

Example Hosting Capacity Study Result



Needs for Future Analysis

- Methods exist for existing 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
    - Need more publicly available 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

A Proposed Approach

Distribution System Integration Cost

<u>Distribution System Integration Cost</u>		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

Calculation Approach

1. Power flow simulations on the feeder (with static or dynamic constraints) at a given level of DER penetrations

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

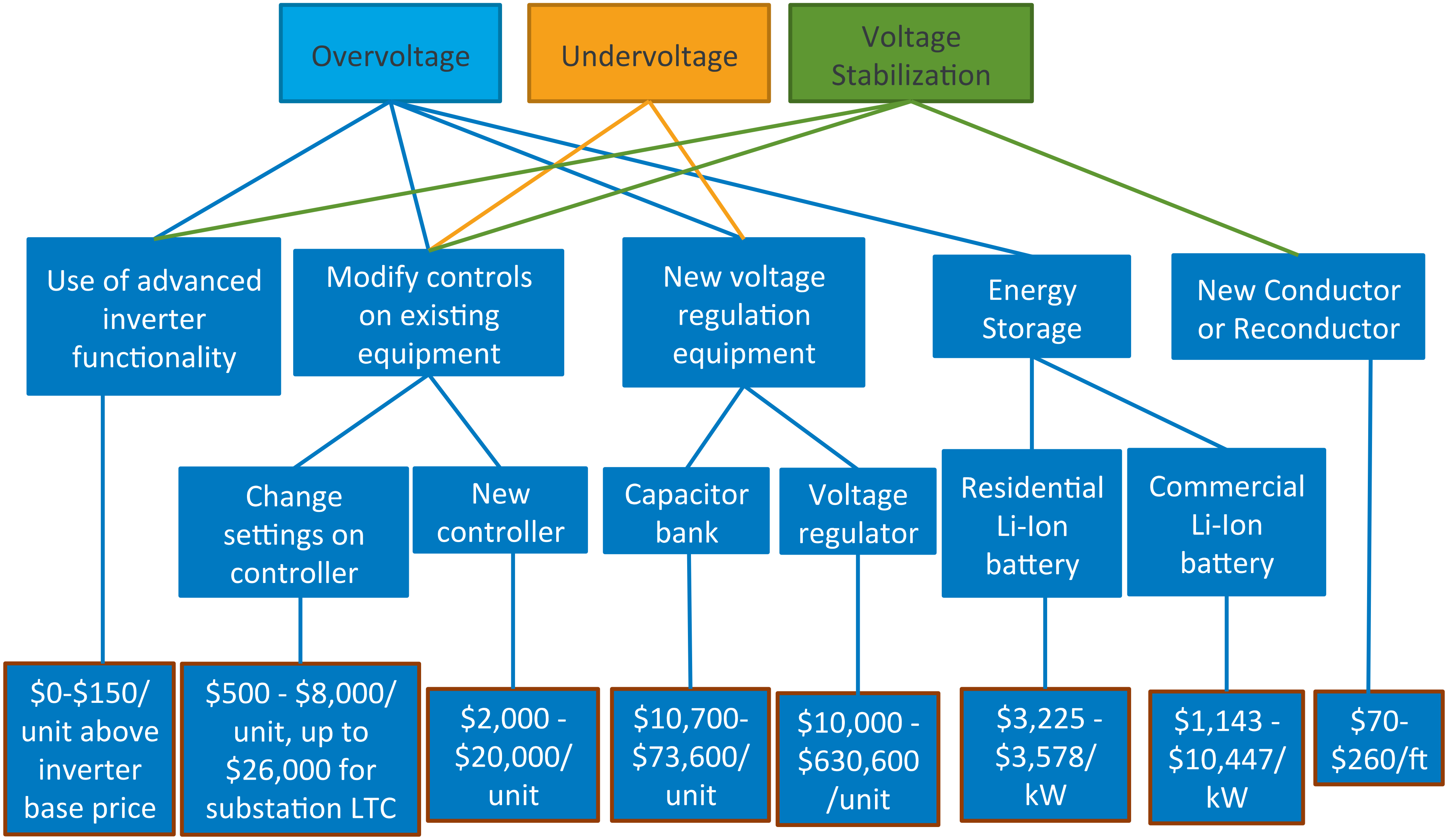
3. Map violations to a set of mitigation strategy options

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 end of the analysis period

Example of Mapping Violations to Unit Costs



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."

Summary & Conclusions

- There is no single cost to integrate distributed PV onto distribution systems
  - As penetration levels increase, require more sophisticated analysis approaches that consider advanced communications and controls options
  - Challenges still exist around using these approaches to inform policy, given significant dependence on specific scenarios (feeder, spatial PV distribution, etc.)
- Understanding of real cost variations in cost and cost drivers has been limited by a lack of transparency, accepted methodology and terminology in the literature
  - Building off prior work, we proposed such an approach
- Underlying datasets are key to expanding analysis and allowing for comparison between studies
  - Some are becoming publicly available

Thank you!

Kelsey.Horowitz@nrel.gov

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Supplementary Slides

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 power flows in scenarios with and without DER 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

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 up 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

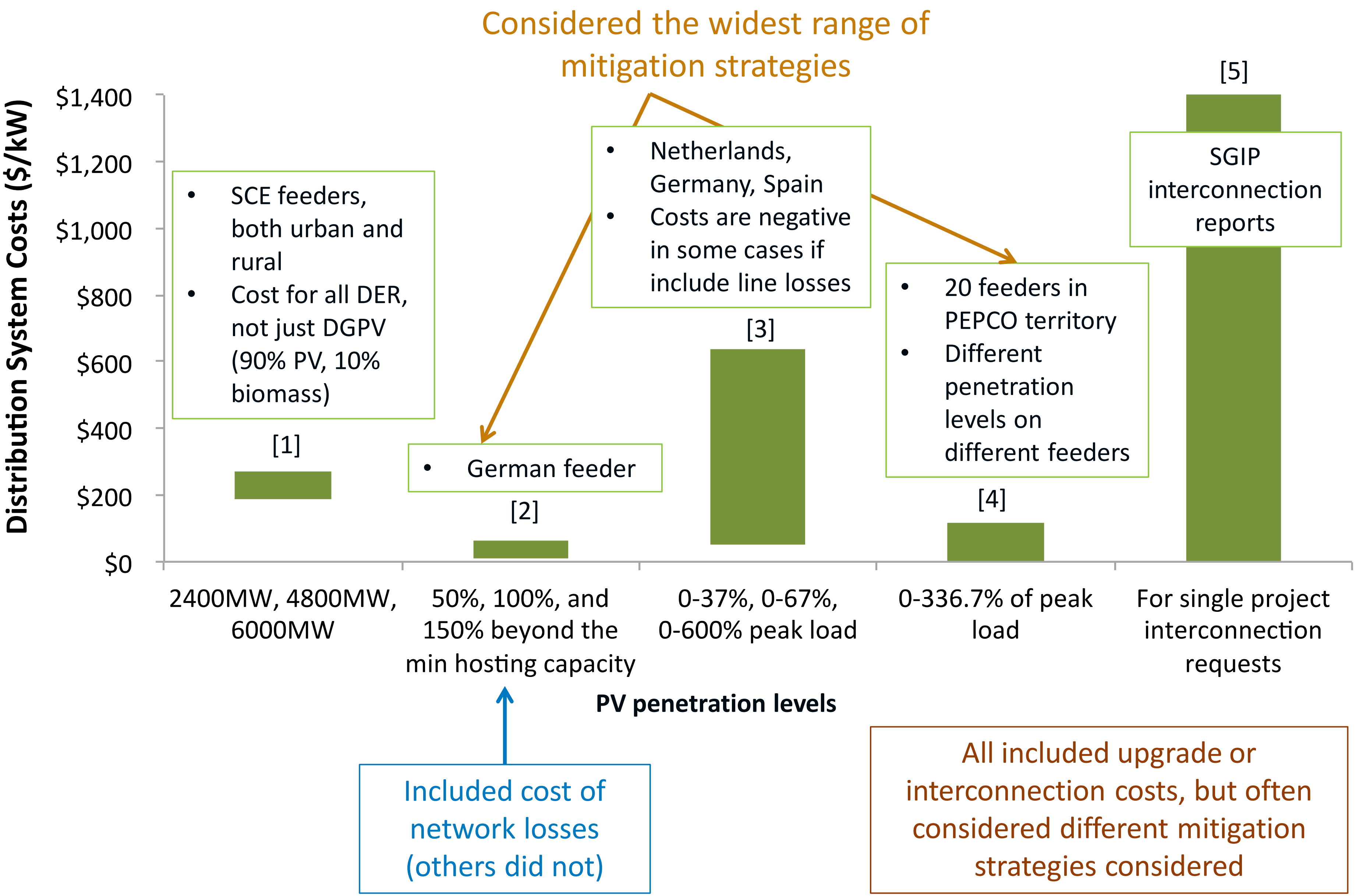
Distribution System Integration Cost

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

Where:

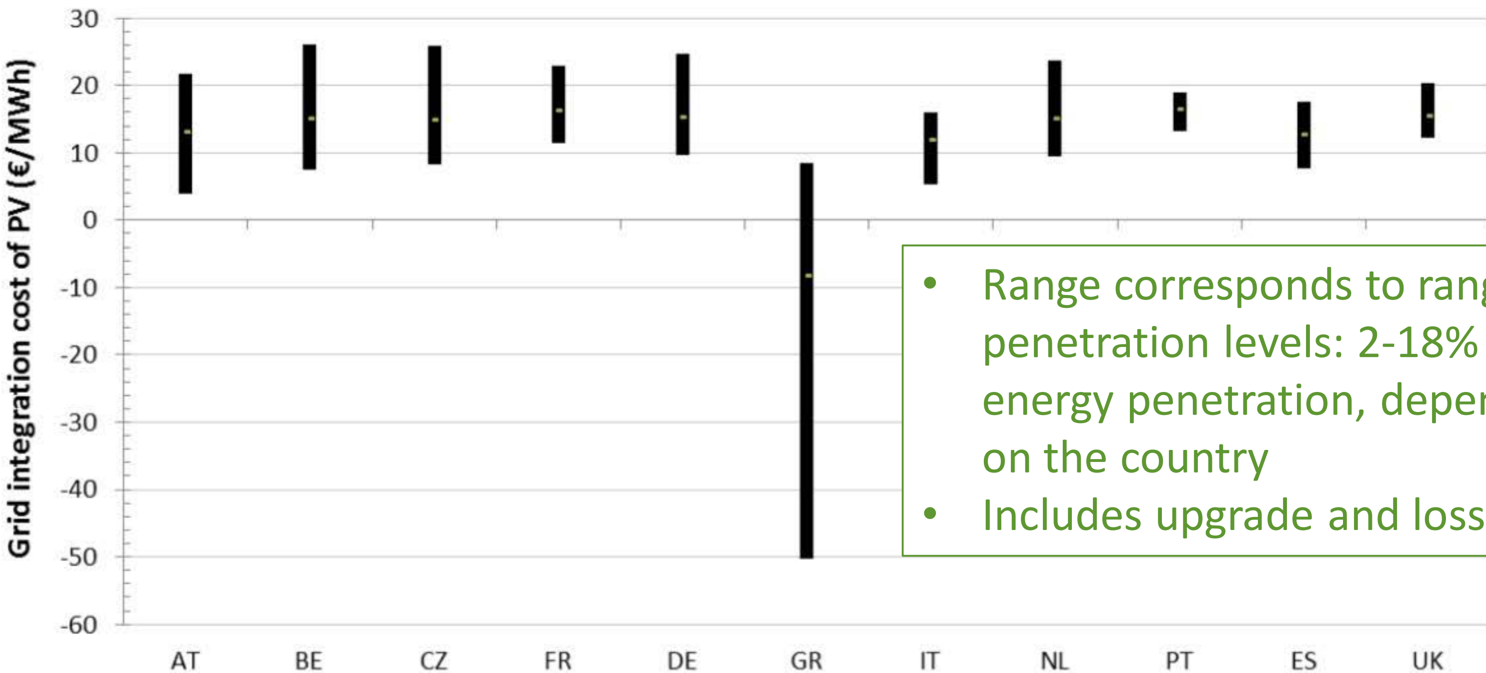
- $ONC_{DU,PV}(p,n)$ is the total overnight capital cost of all distribution system upgrades in year *n* with the presence of DPV at penetration *p*, in $.
- $O\&M_{DU,PV}(p,n)$ is the total operations and maintenance (O&M) cost associated with distribution system equipment upgrades that are required 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*

Overview of Prior Analysis



Overview of Prior Analysis

- Results of additional study of 11 countries in Europe find distribution grid integration costs correspond to roughly 15-20% of local LCOE
  - Not included on prior plot because of inability to convert to equivalent cost units
  - Cost for distribution upgrade costs alone ranged from -2.7 ¢/kWh to 1 ¢/kWh
  - Shape of the costs versus penetration level varied significantly depending on the system



- Range corresponds to range of penetration levels: 2-18% energy penetration, depending on the country
- Includes upgrade and loss costs