Estimating Customer Impact of Volt-Watt

Using Only Smart Meter Voltage Data

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Background and Objective

• **Challenge**
  
  — Hawaii has more distributed PV than any other U.S. state, as proportion of load
  
  — DERs play a major part in the plan for 100% renewables by 2045
  
  — Current levels of PV result in steady-state over-voltage issues
  
  — Near-term solution: autonomous inverter-based voltage regulation
Autonomous inverter-based voltage response

- Volt-var and volt-watt control
  - Volt-var control (now required for all new DERs) helps reduce high voltages, but is not 100% effective
  - Volt-watt control serves as a protection against occasional voltages outside ANSI C84.1 ranges (1.05-1.06 pu)
Volt-watt control

- Volt-watt control is recommended as a backstop to occasional high voltages outside ANSI ranges*
  - Because problem voltages often can’t be predicted in advance, system-wide activation of volt-watt control is required to obtain the benefit
- Various past NREL studies have found impact of volt-watt control on PV energy production is typically near zero
  - Confirmed through detailed computer simulations (right) as well as field data
- In rare cases with voltage persistently or frequently above 1.06 pu, volt-watt control can result in curtailment
  - In such cases, the utility has a pre-existing obligation to fix the voltage issue. That fix will also bring any volt-watt curtailment near zero.
- The DER business process improvement (BPI) is designed to identify problem locations (when possible, before DER is installed)
  - This will streamline DER interconnections by avoiding the need for detailed secondary modeling/studies
  - System-wide activation of volt-watt allows utility to relax interconnection screens/studies

*See 2018 NREL Technical Report and Oct 31, 2018, presentation to AITWG for addition details relevant to this slide
Mitigation methods for persistently high meter voltages

- **Conventional**
  - Replace or add distribution transformer
  - Replace or add secondary conductors
  - Reconfigure primary or LTC settings

- **Non-wires alternatives**
  - Distributed static var compensators (e.g. Varentec)
  - Add energy storage
  - (Future:) Advanced load control solutions
  - (Future:) Coordinated DER controls
  - Inverter-based solutions (increased grid support) from customer in question and/or neighbors – likely compensated
Autonomous inverter-based solutions for persistently high voltages

- Replace neighbors’ legacy inverters?
- Add active power controls or storage to legacy systems?
- Use more aggressive volt-var curve?
- Use volt-watt and compensate customer for lost production
  - Key: need reliable estimate of lost production without additional sensors
- Could also combine multiple of these methods.
Estimating PV curtailment

• **Estimating PV curtailment due to volt-watt control without adding any additional sensors**
  • Past NREL-HECO [work](#) has estimated curtailment using irradiance sensors with good accuracy, but this is costly and invasive
  • It is likely also possible to estimate curtailment based on inverter data, but this is less accurate, and inverter data is not always available, especially to the utility

• **Goal: estimate curtailment based on AMI (smart meter) voltage data only**
  • AMI data is available for all new DER customers as part of the “BPI” (business process improvement)
Some California stakeholders have proposed using NREL’s PVWatts tool

- PVWatts is great for forward-looking predictions, but:
  - In the rare very high-voltage cases of interest, curtailment is expected to be a few percent of monthly production – within the margin of error of PVWatts
  - PVWatts uses TMY (typical meteorological year) weather data, not actual weather
  - Geographical granularity is too low to accurately estimate site-specific PV curtailment of a few percent
  - Any shading or other site-specific losses would be misinterpreted as curtailment

- When voltage is above 1.06 pu, assume PV could have been at full output, and calculate curtailment from volt-watt curve
  - Subsequent slides describe and evaluate this method
Estimating curtailment from AMI voltage

- When the voltage is \( V_A \), the maximum possible curtailed power due to volt-watt is \( P_A \)
- This assumes the inverter \textit{could have been} at maximum power whenever voltage was above 1.06 pu

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Volt-Watt Curve

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 pu</td>
<td>0</td>
</tr>
<tr>
<td>1.06 pu</td>
<td>( P_A )</td>
</tr>
<tr>
<td>1.1 pu</td>
<td>0</td>
</tr>
</tbody>
</table>
```

“Method 1”
Estimating curtailment from AMI voltage

“Method 1”

• Expressing it in math:

\[ E_{\text{curtailed}} = P_{PV} \cdot t_{AMI} \cdot \sum_{v_{AMI}} \max \left( \frac{v_{AMI} - 1.06}{1.1 - 1.06}, 0 \right) \]

• \( E_{\text{curtailed}} \) is the maximum possible curtailment due to volt-watt, in kWh, over the time period of interest
• \( P_{PV} \) is the rated AC power of the PV system, in kW
• \( t_{AMI} \) is the period of the AMI measurements, in hours (so for 15-minute readings, \( t_{AMI} \) is 0.25)
• \( v_{AMI} \) is the set of AMI voltage readings for the time period between 9am and 3pm, in per unit (pu)
A stakeholder proposed a simpler method that assumes curtailment equal to the inverter rating \((P_{\text{rated}})\) whenever the voltage is above 1.06 pu.
A simpler method?

• Expressing it in math:

\[ E_{\text{curtailed}} = \sum_{v_{AMI}} \begin{cases} P_{PV} \cdot t_{AMI}, & v_{AMI} > 1.06 \\ 0, & v_{AMI} \leq 1.06 \end{cases} \]
Evaluating the methods

• To evaluate accuracy, the two methods were applied to computer simulation (VROS) data and to field data
  • Method 1
  • Method 2
  • Both methods evaluate volt-watt effects only (not volt-var)
• The PVWatts-based method was not evaluated
  • Proposal did not contain sufficient detail to determine how it was intended to be implemented
Evaluating the methods – VROS simulation data

• 2017/2018 VROS study simulated a very high penetration Oahu feeder (M34) in a future, even higher penetration state
  • 6.5 MVA peak load, 2.8 MVA min load
  • 10.9 MW total PV
    • 1.6 MW legacy PV, 5.2 MW FIT, 4.1 MW smart PV
• VROS quantified curtailment for all customers over time
• VROS data from a high-voltage week in June selected for evaluation of curtailment estimation methods
  • Used “all export” case for worst-case voltages (as opposed to CSS case)
Evaluating the methods – VROS simulation data

- Results align reasonably well, especially for the most-curtailed customers
- VROS captures all curtailment, not just V-W, so curtailment is more common and percentages are higher
- Method 1 overestimates V-W curtailment, but does not capture volt-var curtailment; these effects counterbalance, resulting in pretty good estimate for customers in V-W region

*Note y-axis scales are similar but not identical*
• Method 2 vastly overestimates curtailment

*Note y-axis scales differ by an order of magnitude
Evaluating the methods – field data

• High-voltage location from advanced inverter pilot: “Location 3”
• Analyzed normal period and 15-day period of unusually high voltage

August – October 2018

[Graph showing voltage and power fluctuations with marked periods]
Evaluating the methods – field data: Location 3

Typical period

Unusual high voltage period

Non-blue dots indicate elevated DC voltage, typically due to curtailment (for this inverter type)

Some volt-var curtailment

Volt-watt curtailment
Evaluating the methods – finding curtailment in field data

Location 3

Typical period
Evaluating the methods – finding curtailment in field data

Location 3

High voltage period

Irradiance (W/m²)

Power (W)

Actual

Identified as curtailed

Estimated
Evaluating the methods – quantifying curtailment – **Location 3**

<table>
<thead>
<tr>
<th></th>
<th>Measured production (kWh)</th>
<th>Estimated possible production (kWh)*</th>
<th>Actual curtailment (kWh)*</th>
<th>Method 1 - Estimated VW curtailment (kWh)</th>
<th>Method 2 - Estimated VW curtailment (kWh)</th>
<th>Actual curtailment (% of expected energy)*</th>
<th>Method 1 - Estimated VW curtailment (% of expected energy)</th>
<th>Method 2 - Estimated VW curtailment (% of expected energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical period</strong></td>
<td>425.2</td>
<td>426.5</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
<td>0.30%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>High V period</strong></td>
<td>385.0</td>
<td>431.7</td>
<td>46.7</td>
<td>62.1</td>
<td>271.7</td>
<td>10.81%</td>
<td>14.39%</td>
<td>62.93%</td>
</tr>
</tbody>
</table>

*As estimated from irradiance curve fit to inverter data

- Method 1 comes out surprisingly close; slightly high
- Method 2 is not close (6x too high)
- Reminder: Actual curtailment includes volt-var *and* volt-watt curtailment
- Side note: *annual* curtailment assuming one high-voltage period such as this per year would be about 1.1%
Evaluating the methods – quantifying curtailment – **Cluster 1**

- Method 1 comes out surprisingly close; slightly high
- Method 2 is not close (20x too high)
- Reminder: Actual curtailment includes volt-var *and* volt-watt curtailment
- This location was analyzed in some detail in Oct 31, 2018, AITWG presentation and 2018 IEEE PVSC paper. Curtailment analysis method updated to align with that used for Location 3.

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</tr>
</thead>
<tbody>
<tr>
<td><strong>Typical period</strong></td>
<td>197.0</td>
<td>197.0</td>
<td>0.01</td>
<td>0.0</td>
<td>0</td>
<td>0.01%</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>High V period</strong></td>
<td>106.8</td>
<td>107.9</td>
<td>1.0</td>
<td>2.8</td>
<td>24.5</td>
<td>0.95%</td>
<td>2.57%</td>
<td>22.71%</td>
</tr>
</tbody>
</table>

*As estimated from irradiance curve fit to inverter data*
Evaluating the methods – quantifying curtailment – Location 4

- Highest voltage location from initial pilot
- Significant behind-the-meter voltage rise and high meter voltage
- July 2017: 51% of 9am-3pm inverter voltage readings were > 1.06 (top right)
- Installed irradiance sensor in Summer 2018 to estimate curtailment, but...
- After Sept 2017, inverter voltages rarely > 1.06 (July 2018, bottom right)
- Volt-watt curtailment is zero or near zero every month since irradiance sensor installed*

*Unable to quantify exactly due to poor regression fit between inverter power and irradiance measurements.

Based on applying Method 1 to inverter voltage readings, worst-case curtailment is 0.4%.
Conclusions

- A simple method of estimating lost production due to volt-watt control comes out surprisingly close to reality
  - Uses only AMI voltage data (no additional sensors or communications, no need for inverter data)
  - Validated against detailed computer simulation for hundreds of customers, and against field data with irradiance sensing and inverter data
  - Could be used to estimate curtailment for compensation purposes as a simple non-wires solution for high voltage due to PV
Thank you!

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Extra slides
Curtailment is near zero if voltages are inside ANSI C84.1

- Current HECO technical sub-screens identify potential high-curtailment customers that can be monitored while secondary upgrades are underway.
- HECO is working on a business process initiative (BPI) to streamline DER interconnections and ensure customers are not experiencing high-voltage conditions.
- BPI will leverage the finding that curtailment is near zero in cases where voltage is inside ANSI C84.1.
Summary of conclusions  
(VROS and AI pilot)

• **Intent of volt/Watt is not to mitigate persistently high voltages, but rather to protect against occasional temporary high voltage conditions outside of tariff rules**
  – Because events that occasionally result in high-voltage conditions in the field are very difficult to predict in advance, volt/Watt is only effective as a protection function if enabled system-wide
  – Vast majority of the time, voltages are in normal operating ranges and volt/Watt is not active

• **Simulations and field tests show non-negligible curtailment from volt/VAR and volt/Watt occurs only when voltages are persistently outside of tariff**
  – The utility has an existing obligation to fix out-of-tariff voltages; that fix will also correct any curtailment issue
  – Active monitoring of customer meter voltages both before and after PV installation will ensure such cases are caught and proactively mitigated (BPI initiative)

• **Combined system-wide activation of volt/VAR and volt/Watt control can enable very high levels of PV generation while helping ensure voltages remain within the allowed safe ranges, without significant impact on PV energy production**
Field pilot: Cluster 1 (on M34 feeder)

Higher voltages due to temporary primary configuration

Curtailment during high voltage period: 1.6%

Curtailment during typical period: 0.04%
• Key take-aways from previous slide
  – Despite relatively high voltage (peaking around 1.04-1.05 daily), annual curtailment impact is negligible (<<1% of annual energy production)
  – Temporary higher voltage condition illustrates intended purpose of volt/Watt: backstop against temporary high voltage conditions outside ANSI range
Field pilot: Highest voltage location

- Inverter daytime voltage persistently high
- Irradiance sensor recently installed at this location.
- Curtailment may be non-negligible
- Customer was scheduled for a secondary circuit upgrade prior to pilot. Upgrade will bring voltage down and mitigate curtailment.
Field pilot: Example of mitigation

- Cluster 1 secondary upgrade completed July 12, 2018
- Voltage now peaks below 1.02 pu
- Was upgrade necessary?

- AMI voltage significantly lower due to strengthened secondary
- Transformer voltage unchanged
Field pilot: Expected vs measured voltages

- Measured max voltages consistently lower than expected from detailed screen.
- Distribution planners do not have information needed to accurately predict customer voltages; must make assumptions.
- Leads to more systems than necessary being identified as problems.
- Is there a better way?
Operationalizing pilot methods

- Key missing information: customer voltage data
- Solution (business process improvement): install AMI upon receipt of interconnection application
- Identify potential problems early
- Can problems be identified before DER is installed?
BPI: Predicting voltage issues before DER is installed

- Analyze AMI data to estimate relationship between power and voltage
- Extrapolate to negative power (PV export) to predict voltage rise
- Flag problem locations for mitigation
- Simple example shown here; reality is more complex
- HECO working with NREL to develop analytics for early identification of problem locations
Cheat sheet – advanced inverters

Hawaiian Electric’s approved volt-var curve

Possible operating points:
- Active power priority
- Reactive power priority
- Constant PF (PF priority)

Hawaiian Electric’s approved optional volt-watt curve

Active power limit, per unit of inverter rating

Reactive power limit, per unit of inverter rating
Key findings from report

• It is difficult for anyone (utility, customers, PV installers) to accurately predict in advance whether a given location will experience high voltage issues (and resulting PV energy curtailment) before PV has been installed
  – Absence of smart meters in most Hawaii locations and the lack of customer inverter data available to utility planners makes this task even harder

• Weekly curtailment of energy production is negligible as long as typical peak voltages are inside the ranges specified in American National Standards Institute (ANSI) Standard C84.1
  – For any location where curtailment would be a problem, voltage is high enough that it would likely require mitigation even if curtailment were not a concern

• HECO has embarked on a new business process improvement to streamline the interconnection of DER systems by integrating new methods, including early deployment of smart meters, to proactively identify and address problem locations