NATIONAL RENEWABLE ENERGY LABORATORY

DC-connected Solar Plus Storage Modeling for Behind-the-Meter Systems in SAM

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NREL/PR-6A20-71779

2018 WPEC-7 and 45th IEEE PVSC

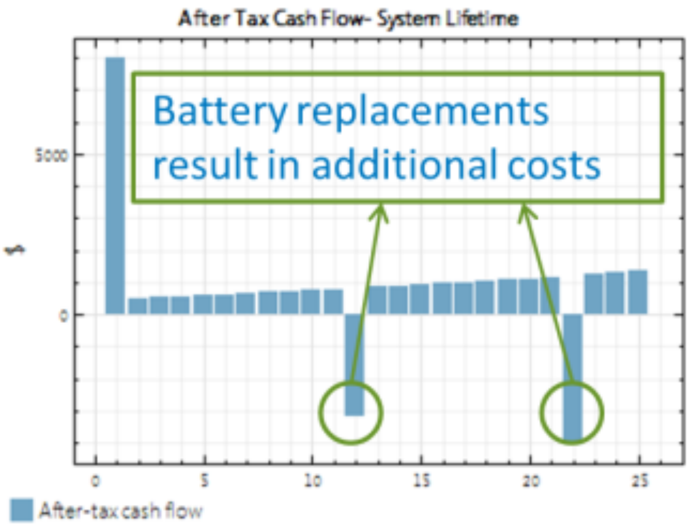
June 15, 2018

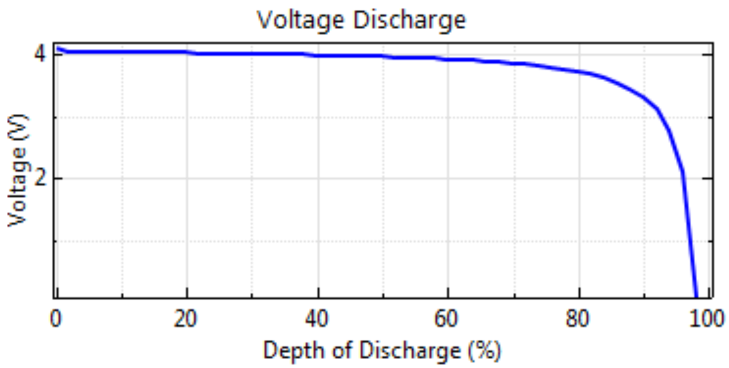
Overview

- High penetration of PV and changes to Net Energy Metering (NEM) policies have created incentives to self-consume PV power produced on site in some areas.
- Multiple PV plus storage system topologies have emerged, offering different benefits and modeling challenges
- A DC-coupled PV plus storage model was developed in NREL's System Advisor Model (SAM).
    - Compared to existing SAM AC-coupled battery model
- Hawaii case study presented

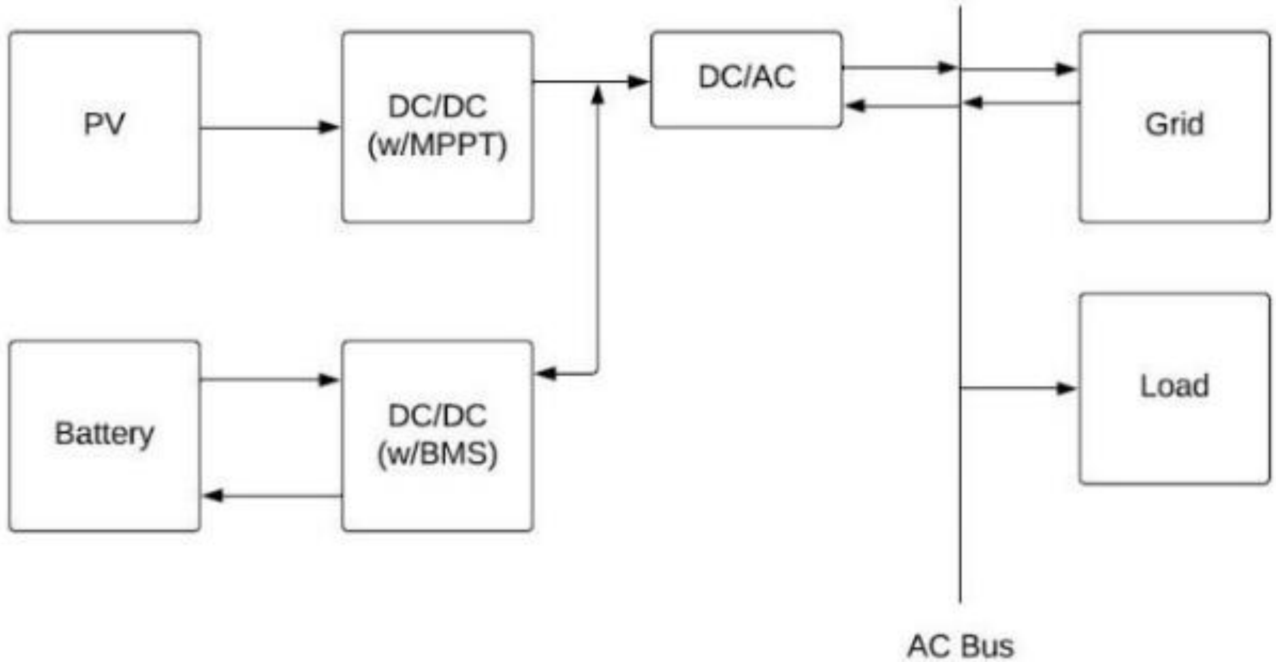
SAM Battery Model Overview

- Techno-economic model for residential, commercial, third-party ownership, and large PPA systems
  - Lead acid, lithium ion, and flow battery chemistries
  - System lifetime analysis including battery replacement costs
  - Detailed models for terminal voltage, capacity, temperature
  - Multiple dispatch controllers available

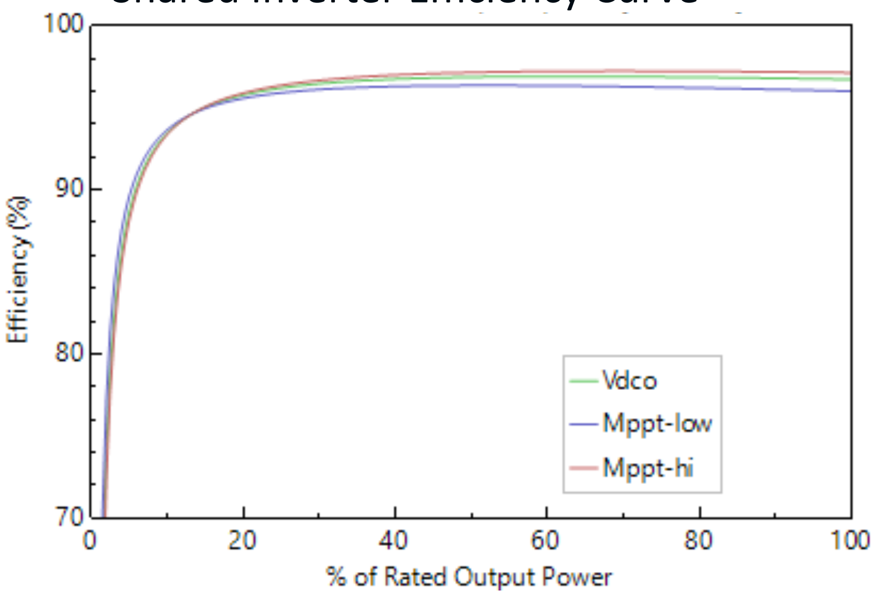




DC-Coupled System Configuration

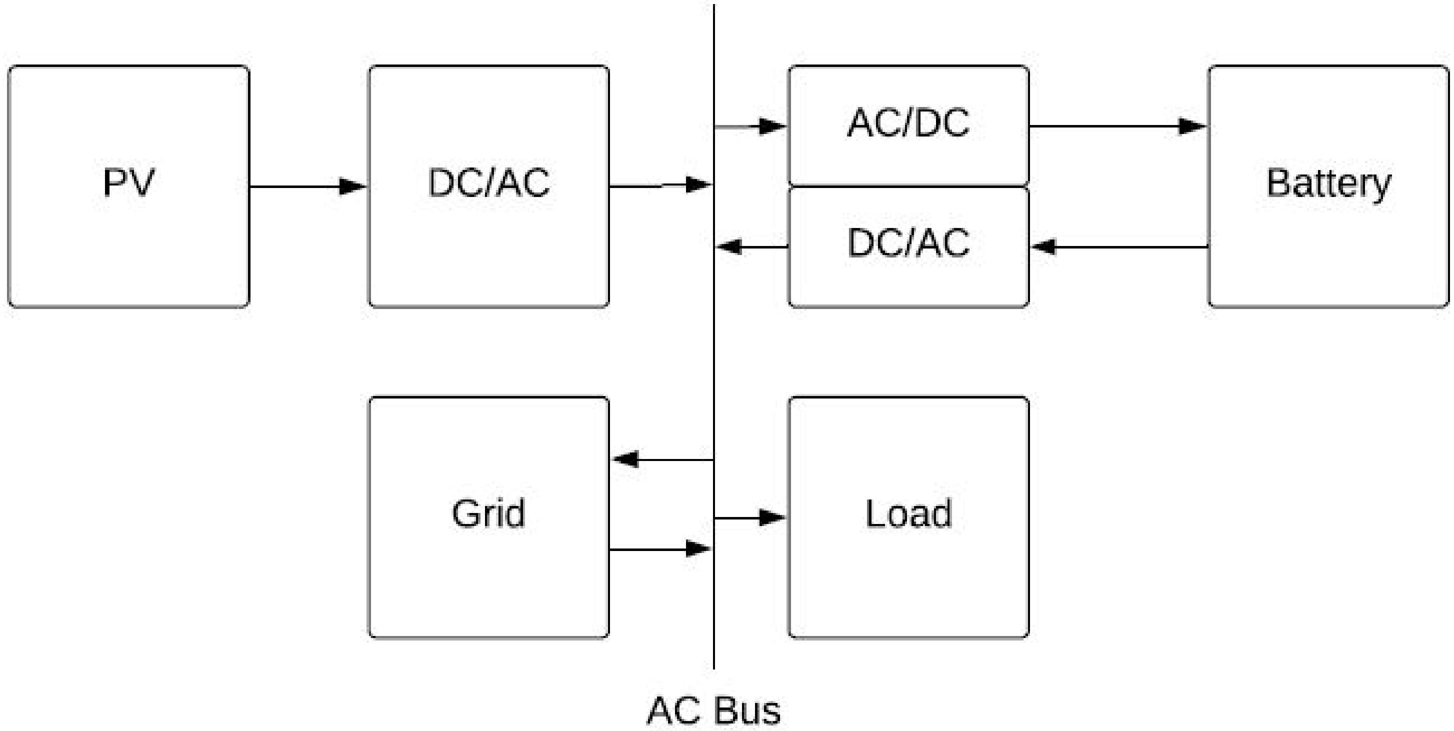


Shared Inverter Efficiency Curve



- DC-Coupled battery shares the hybrid inverter
- PV power can charge the battery without going through the inverter
- Potential cost savings due to shared inverter

AC-Coupled System Configuration



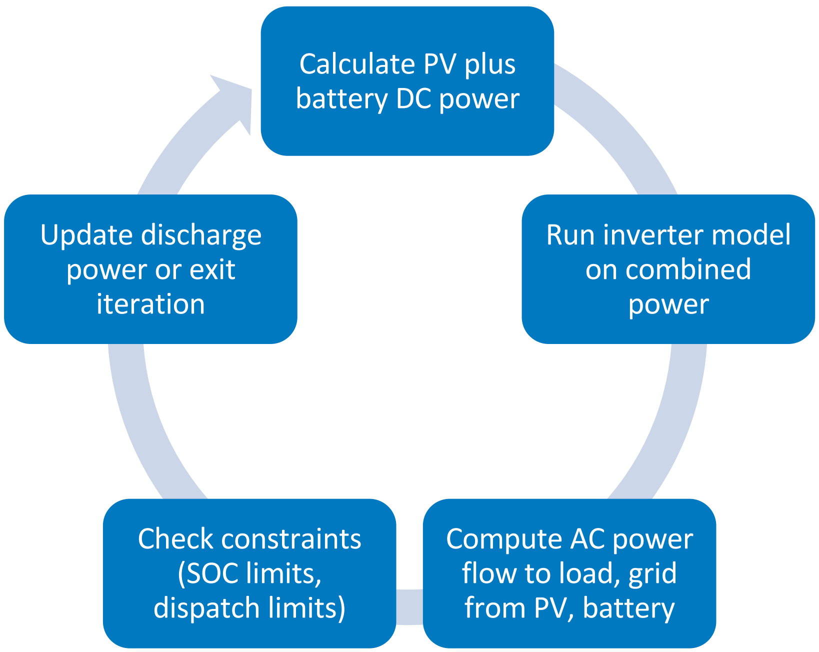
- Battery charges and discharges through dedicated power electronics, modeled as single-point efficiencies.
- PV power must go going through the inverter before charging battery
- Calculating AC power flow components relatively simple
- Potentially simpler to design and install

Modeling PV plus DC-coupled battery

Initialize battery power based on dispatch preferences, PV production, Electric load

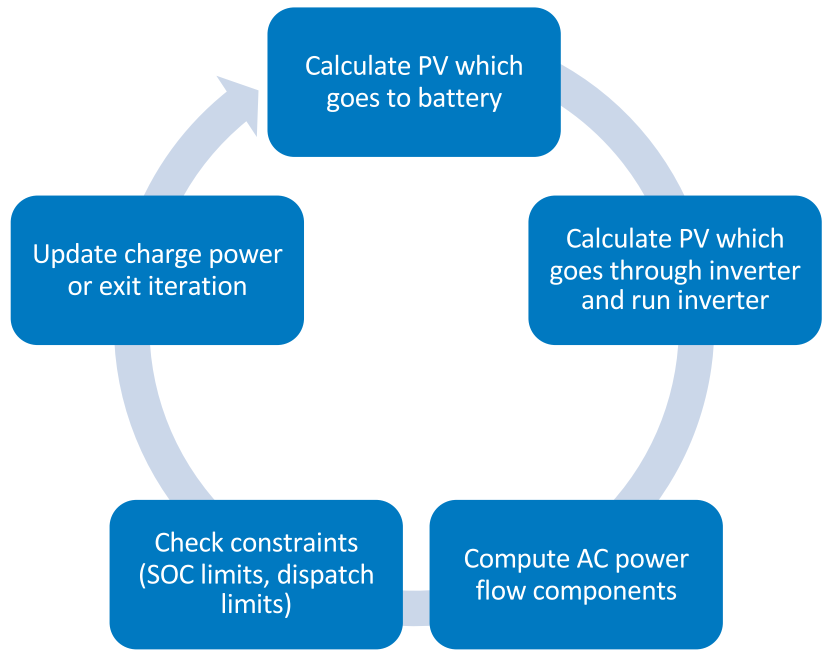
Battery discharging

Enter dispatch iteration



Battery charging

Enter dispatch iteration



For all equations, see paper.
Open source code available at https://github.com/NREL/ssc

Hawaii Case Study:

Evaluate the most cost effective system configuration out of following options: no PV, PV only, PV plus DC-coupled battery, PV plus AC-coupled battery

System Assumptions

- Residence in Honolulu
- Peak annual load 3.4 kW
- Proposed
  - 4.7 kW PV array (2 strings of 7 modules)
  - DC/AC ratio 1.23 (3.8 kWac inverter)
  - 5 kW / 24 kWh Lithium-ion battery system
- Self-consume all PV to qualify for HECO Customer Self Supply (CSS), otherwise must qualify for Customer Grid Service (CGS).
- No charging of battery from the grid is allowed

Cost, and Electric Rate Assumptions

- PV system costs: $2.92/Wdc [1]
- Storage costs: $2000/kW [2]
- Financial assumptions taken as SAM defaults, except for Hawaii specific taxes and incentives.
- HECO Schedule R Residential Service rates from OpenEI [3]
  - $0.257/kWh Tier 1
  - $0.268/kWh Tier 2
  - $0.287/kWh Tier 3

HECO Customer Renewable Programs

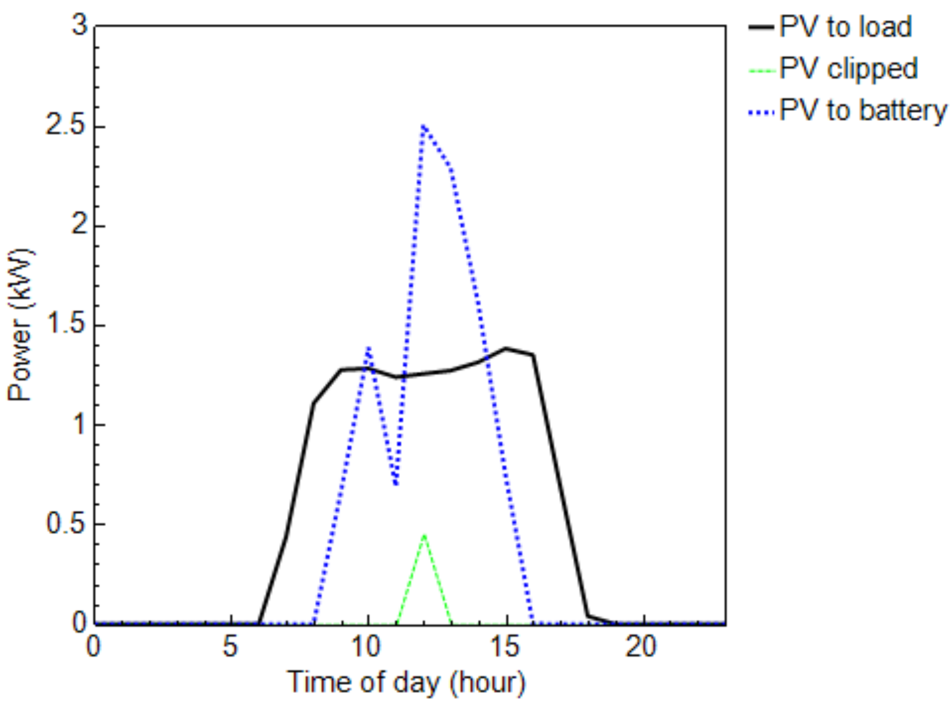
Program	Grid Export Rate*	Battery Storage Typical?	Grid Export Window
Customer Grid-Supply Plus	10 cents/kWh	No	Daylight
Smart Export	15 cents/kWh	Yes	4 p.m. to 9 a.m.
Customer Self-Supply	N/A	No, but usually installed	N/A
Customer Grid-Supply**	15 cents/kWh	No	Daylight

***Customer Grid-Supply remains open until installed capacity is reached. New applications are placed into queue for processing if and when space in the program becomes available. There is no guarantee that space will become available. New applications may be submitted via mail and are not supported in the Customer Interconnection Tool.*

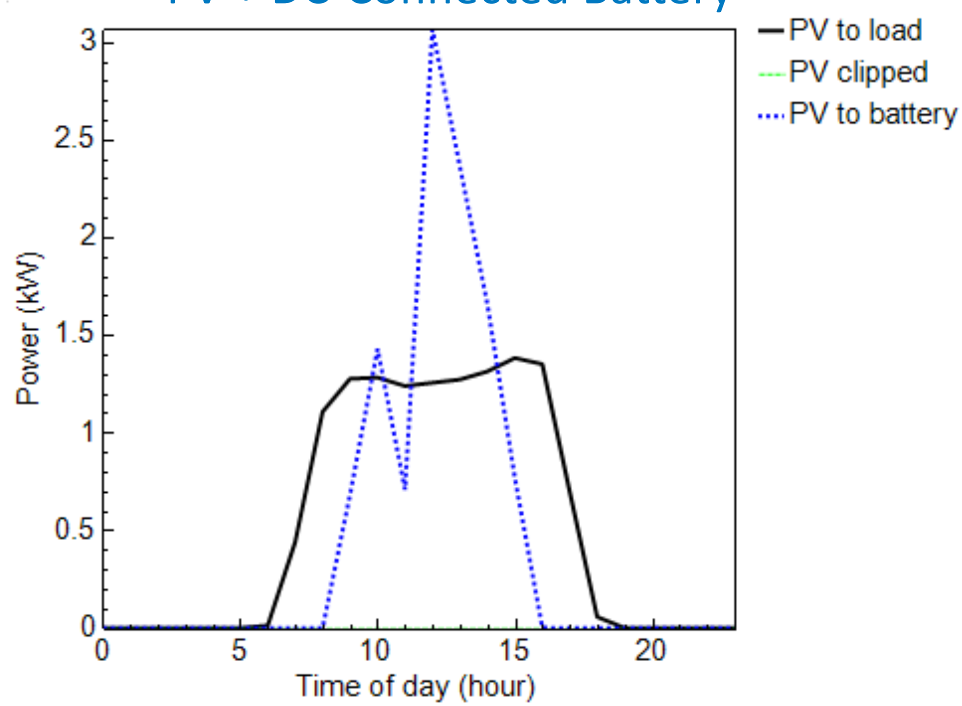
https://www.hawaiianelectric.com/clean-energy-hawaii/producing-clean-energy/customer-renewable-programs

Example daily operation

PV + AC-Connected Battery



PV + DC-Connected Battery



- When the PV DC power output exceeds the inverter DC power input, excess power is clipped
- In an AC connected system, even if PV power is dumped to the battery, it doesn't reduce clipping, since PV power must still pass through the inverter before going to the battery
- In a DC connected system, PV power can be dumped to the battery before passing through the inverter

Results comparison

CASE STUDY RESULTS: 1.23 DC/AC RATIO

Variable	No PV	PV Only	PV plus DC battery	PV plus AC battery
Year 1 Utility Bill	$3,973	$1,926	$1,985	$1,984
Year 1 Energy Clipped	0 kWh	5.66 kWh	0 kWh	5.66 kWh
Year 1 Battery Energy Charged	0 kWh	0 kWh	2,256 kWh	2,179 kWh
Year 1 Battery Energy Discharged	0 kWh	0 kWh	2,027 kWh	1,969 kWh
Net Present Value	$0	$19,948	$12,186	$12,402

- Installing no system is the worst option
- Installing PV only is the best option, if the customer can qualify for the limited Customer Grid Supply option.
- Installing a DC-connected battery mitigates all PV clipping, but provides approximately the same return as an AC-connected battery in this case.

Sensitivity: Boost DC to AC ratio

CASE STUDY RESULTS: 1.85 DC/AC RATIO

Variable	No PV	PV Only	PV plus DC battery	PV plus AC battery
Year 1 Utility Bill	$3,973	$1,240	$1,045	$1,345
Year 1 Energy Clipped	0 kWh	1220 kWh	4.21 kWh	1220 kWh
Year 1 Battery Energy Charged	0 kWh	0 kWh	5,435 kWh	4,152 kWh
Year 1 Battery Energy Discharged	0 kWh	0 kWh	4,886 kWh	3,756 kWh
Net Present Value	$0	$24,315	$16,247	$14,384

- Added string of seven PV modules to the inverter, boosting DC/AC ratio to 1.85.
- 13% boost in NPV over AC battery system, since PV system produces a lot of excess DC power that cannot be captured by AC connected battery
- Possible reasons for high DC/AC ratio include levelizing system AC output throughout day, keeping plant AC output consistent over module lifetime, etc.

Conclusions

- A detailed model for PV plus DC-coupled batteries was developed in SAM and compared against an AC-coupled system
- Coupling a battery to the DC-side of a PV array to use a shared inverter can improve project economics and reduce losses due to clipping.
- Ability to model both system configurations can offer insight into which offers the best value for a given scenario.
- Model is open-source, summer release of SAM will include updated algorithms.

This work was authored by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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References

- [1] M. Hand, W. Cole, M. Maness, A. Eberle, et. al "2017 Annual Technology Baseline, National Renewable Energy Laboratory 2017 https://atb.nrel.gov/
- [2] GTM Research, "U.S. Energy Storage Monitor: 2017 Year in Review and Q1 2018 Full Report, GTM Research Report 2018
- [3] OpenEI, "International Utility Rate Database, online https://openei.org/apps/IURDB/rate/view/5927424d682bea6484cfded4. Accessed May 12, 2018