SunShot
U.S. Department of Energy

SHINES Program Review 2017

AGENT-BASED COORDINATION SCHEME FOR PV INTEGRATION (ABC4PV)

Awarded to *CMU, NRECA & Aquion Energy*
Presented by *Panayiotis Moutis, PhD (CMU)*

Presentation Outline

- Motivation
- Technical Objectives
- Team
- Approach
- Anticipated Outcomes
- Project Plan, Outcomes & Milestones Achieved in 2016
- Discussion

Motivation

- Increase penetration of photovoltaics, storage & demand response, ***jointly*** operating based on . . .
- Distributed (*scalable*) optimal (*cost effective*) control

➡ Gap between theoretical approaches and actual application

Need for a **testbed** for distributed algorithms,
a **testbed** for the application of PV integration and
a **testbed** of such algorithms in a practical environment

Technical Objectives

Project Goals

- Define proper set of active assets (PV, storage, loads) = "***Unit***"
- **Extend** & **Test** existing distributed optimal control algorithm
  - *Extend to* multiple assets per control point (PV, storage, switches)
  - *Test for* stability, robustness & malicious incidents
- **Verify** the real-world operation of 10 *units* on **test-bed**
  - *Install units* on end-customer households of a co-op feeder
  - *Define* testing protocols and cyber tools
  - *Determine* communication architecture (due to algorithm)
  - *Assess* algorithm optimality (due to extensions & framework)
- **Study** impact of storage system (notably, lifetime) on optimality

Team

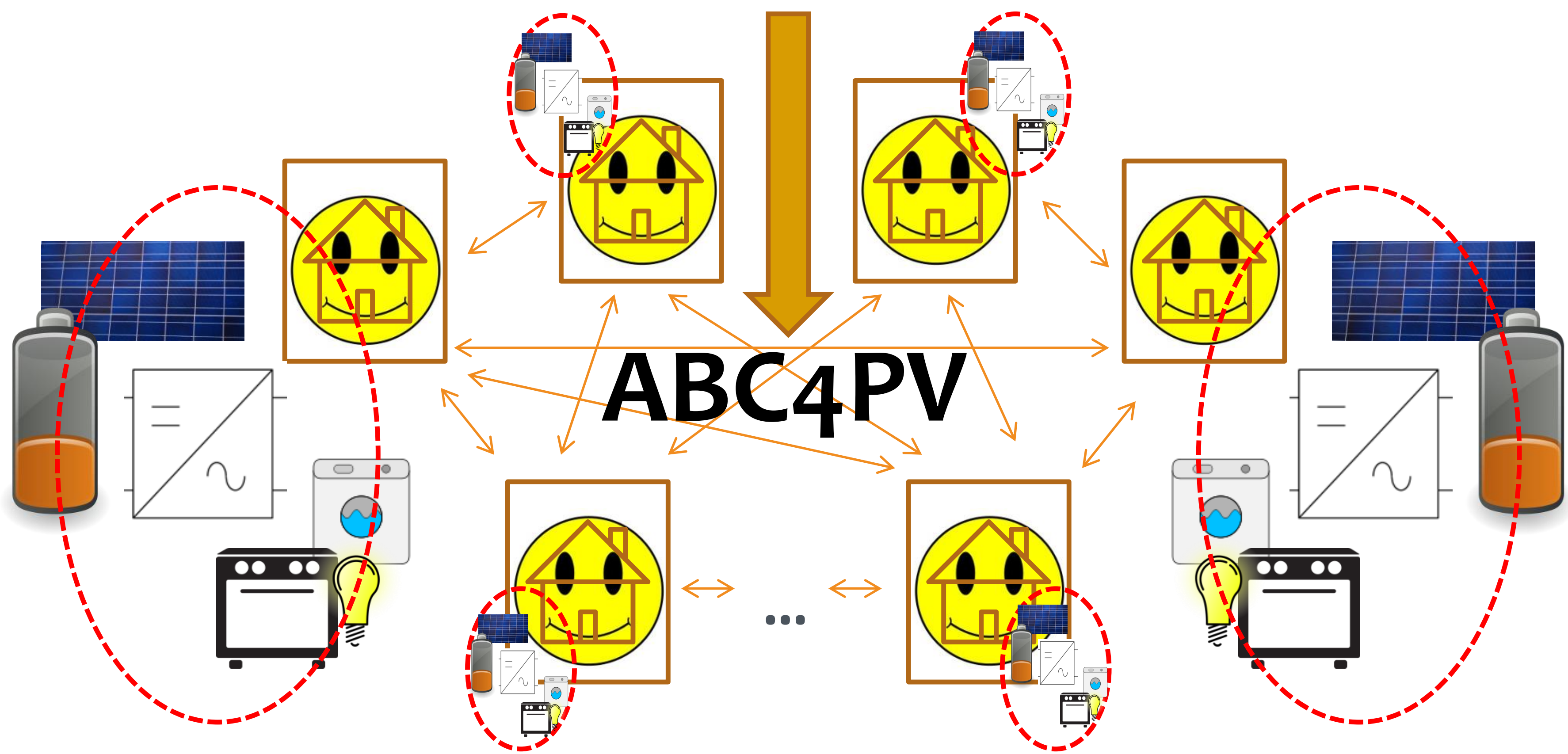
- CMU (S. Kar, G. Hug, J. Moura, P. Moutis, J. Whitacre)
  - Operating control framework
  - Efficacy assessment (simulations & software implementation)
- NRECA (C. Miller, A. Cotter, D. Danley, D. Pinney)
  - Testbed development
  - Standardization of unit equipment
- Aquion Energy (T. Madden, J. Whitacre)
  - Battery storage system physical integration and optimization

NRECA
A Touchstone Energy® Cooperative

AQUION ENERGY

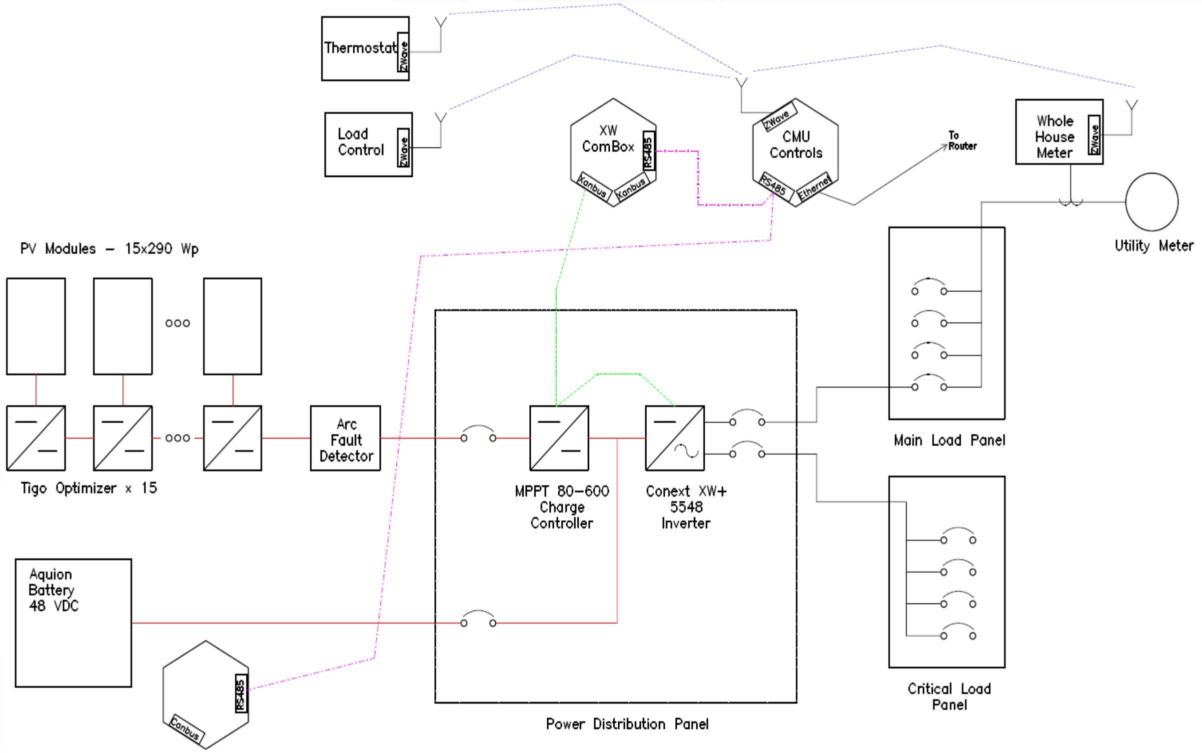
Carnegie Mellon University

Roadmap Approach:
- Determine “**unit**”
- Inter-unit **collaboration**



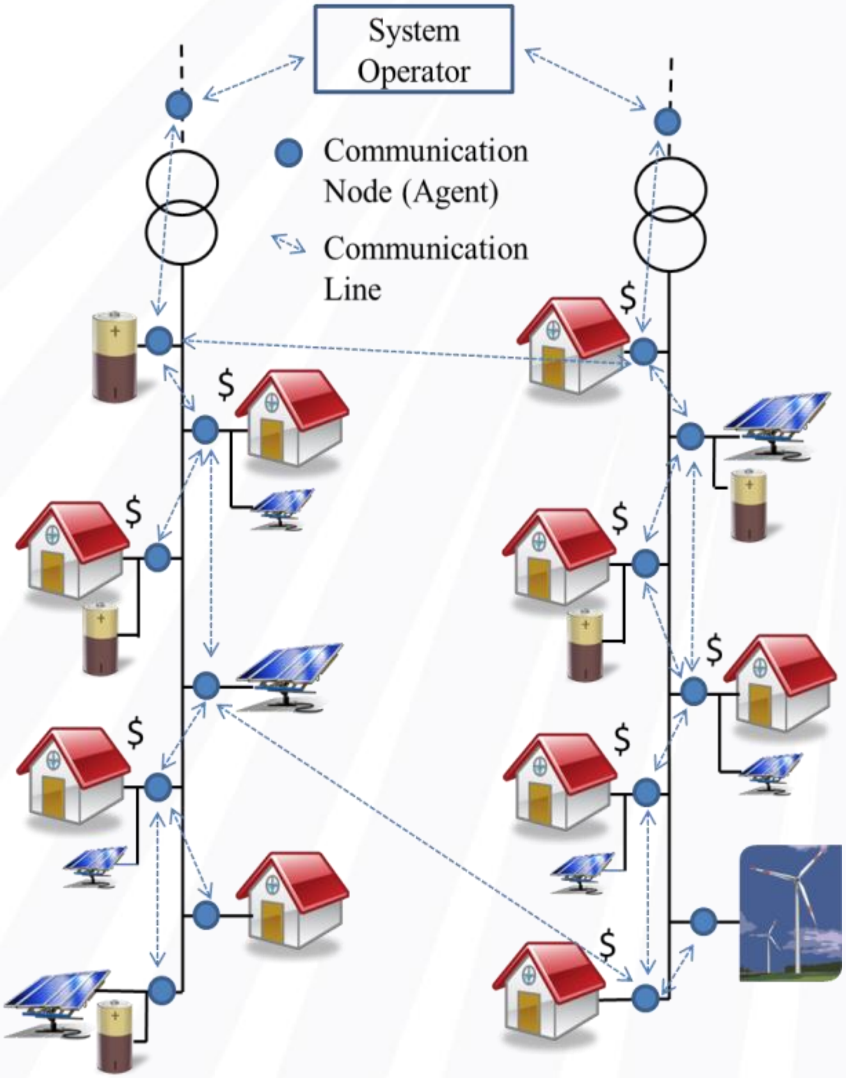
Approach: Unit-based integration and abstraction

- The ABC4PV **unit**
  - Max integration & combinational value
  - Plug-n-play capabilities
  - Assuming on high penetration (i.e. a large number of "units" has been deployed)



Approach: Inter-unit collaboration

- Agent-based distributed optimal control algorithm:
  - *Units* share information
  - System operator optional
  - Local calculations



Approach: Distributed optimization framework

- Form of updates
  - Mathematical formulation based on **<u>Consensus + Innovation</u>** approach:

$$\lambda_j^{(i+1)} = \lambda_j^{(i)} - \underbrace{\beta_i \sum_{l \in \omega_j} \left(\lambda_j^{(i)} - \lambda_l^{(i)}\right)}_{consensus} - \underbrace{\alpha_i \hat{d}_j^{(i)}}_{innovation} \qquad \left(\sum_{j=1}^{J} \hat{d}_j(\lambda_j) = 0 \right)$$

<u>consensus term</u>: Lagrangian multiplier representing the marginal cost
<u>innovation term</u>: -»- -»- for global constraint(s)

⟹ Low computational effort required

Considered Application:
- <u>Consensus</u> converges to cost optimality
- <u>Innovation</u> effect fades with convergence

Anticipated Outcomes

- Key Project Products (specific "artifacts")
  - Framework for a maximum value, plug'n'play *unit design*
  - Scalable and robust *distributed algorithm* for optimal control
  - Test-bed verified guarantees

- Major Outcomes (conceptual achievements)
  - Pathway towards efficient *integration of up to 100% solar (or distributed generation)* penetration on optimal control
  - *Functioning, adjustable & expandable test-bed* for distributed algorithms

Project Plan

- Distributed Control Methodology
  - Design and Development of Distributed Resource Coordination and Control Methodology (Years 1, 2)
  - Software Implementation of Algorithms (Years 1, 2)
  - Cybersecurity Assurance (Years 1, 2, 3)
- Testbed Development
  - Installation of Physical Components and Test-bed Setup (Years 1, 2)
  - Performance Testing in Test-bed (Years 2, 3)
- Functional and Economic Assessment and Optimization
  - Value of Solar (Years 2, 3)
  - Value of Storage (Years 2, 3)
  - Energy Storage Sub-System and Full System Assessment and Control Optimization (Years 2, 3)

Distributed Control Methodology Development

Task 1: Design and Development of Distributed Resource Coordination and Control Methodology

Subtasks

1. Modeling of Cost/Objective
   - Objective function of the optimization problem
2. Modeling of Constraints (Operational and Uncertainty)
   - Component operation constraints, e.g. min/max inverter power
   - Network constraints, e.g. line loading limits
3. Formulation of Iterative Distributed Control
   - Employ optimization algorithm to the problem
4. Performance Analysis and Real-time Guarantees
   - Benchmarking of convergence and time complexity
5. Simulation of Test-bed

Task 1: Design and Development of Distributed Resource Coordination and Control Methodology

Subtasks

1. Modeling of Cost/Objective
   - Objective function of the optimization problem
2. Modeling of Constraints (Operational and Uncertainty)
   - Component operation constraints, e.g. min/max inverter power
   - Network constraints, e.g. line loading limits
3. Formulation of Iterative Distributed Control
   - Employ optimization algorithm to the problem
4. Performance Analysis and Real-time Guarantees
   - Benchmarking of convergence and time complexity
5. Simulation of Test-bed

Objective Function

- Expresses total cost of coop feeder load demand energy, subtracting PV, storage & demand response contributions

$$\text{minimize} \left[\sum_{i\in\{loads\}} P_{i,L,t} + \sum_{i\in\{batteries\}} \frac{P_{i,RCh,t}}{n_i} - \sum_{i\in\{PV\}} P_{i,NM,t} - \sum_{i\in\{batteries\}} P_{i,DCh,t} \right]^T_{t\in[1,24]} \cdot [IF_t]_{t\in[1,24]} +$$

$$+ \sum_{t\in[1,24]} \sum_{i\in\{batteries\}} Dgd_{i,RCh,t} + \left[\sum_{i\in\{loads\}} P_{i,IL,t} \right]^T_{t\in[1,24]} \cdot [ILC_t]_{t\in[1,24]} -$$

$$- \left[\sum_{i\in\{PV\}} P_{i,Cntr,t} \right]^T_{t\in[1,24]} \cdot [Cntr_{PV,t}]_{t\in[1,24]}$$

Problem Constraints

Operating, system, policy, etc. . .

. . .

. . .

. . .

$$\underline{|S_{ij}|} \le |S_{ij}| \le \overline{|S_{ij}|} \qquad \underline{|v_i|} \le |v_i| \le \overline{|v_i|}$$

$$p_{ij} + i \cdot q_{ij} = v_i \cdot \left(v_i^* - v_j^*\right) \cdot y_{ij}^* \text{ and } P_i = \sum_j p_{ij} \text{ and } Q_i = \sum_j q_{ij}$$

Non-convex power flow equality constraint

Elaboration on Non-Convex Power Flow Constraint

- Relaxations lead to computationally tedious algorithms
- Existing linear approximations (DC & Decoupled) fail to consider the resistive nature of the distribution systems
- Two novel "resistive-aware" linear approximations developed

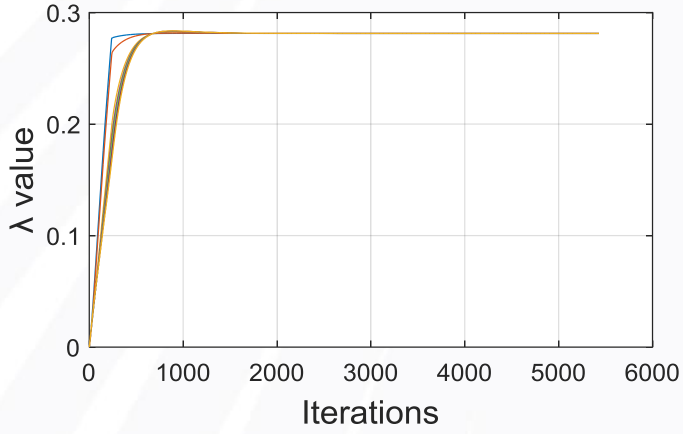
Novel linear OPF approximation indicative results

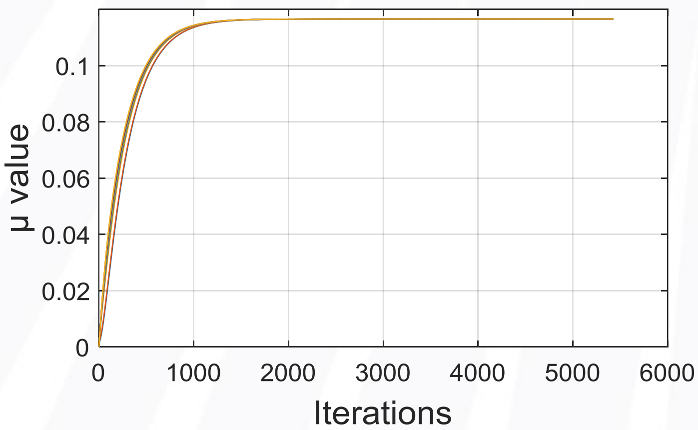
- 10-bus radial distribution feeder on ACSR-95 lines (9 loads & DG units)

Decoupled OPF		Novel linearized OPF		SDP-relaxed OPF	
V in p.u.	Angle (rad)	V in p.u.	Angle (rad)	V in p.u.	Angle (rad)
1.0000	0	1.0000	0	1.0000	-0.0000
0.9959	-0.0056	0.9949	-0.0034	0.9950	-0.0024
0.9792	-0.0281	0.9744	-0.0171	0.9743	-0.0125
0.9762	-0.0322	0.9707	-0.0196	0.9705	-0.0144
0.9750	-0.0338	0.9693	-0.0205	0.9691	-0.0151
0.9731	-0.0365	0.9669	-0.0222	0.9667	-0.0164
0.9723	-0.0377	0.9658	-0.0230	0.9655	-0.0170
0.9708	-0.0398	0.9640	-0.0242	0.9637	-0.0180
0.9703	-0.0406	0.9633	-0.0247	0.9631	-0.0184
0.9700	-0.0410	0.9629	-0.0249	0.9626	-0.0185

Novel linearized OPF approximation in C+I f/w results

Novel central		Novel on C+I	
V in p.u.	Angle (rad)	V in p.u.	Angle (rad)
1.0000	0	1	0
0.9949	-0.0034	0.99711	-0.0033843
0.9744	-0.0171	0.98521	-0.017112
0.9707	-0.0196	0.98302	-0.019603
0.9693	-0.0205	0.98226	-0.020528
0.9669	-0.0222	0.98087	-0.022189
0.9658	-0.0230	0.98024	-0.022955
0.9640	-0.0242	0.97925	-0.024232
0.9633	-0.0247	0.97886	-0.024679
0.9629	-0.0249	0.97860	-0.024934





Compared to the Decoupled OPF on C+I, novel OPF 30-60% faster

Brief note on the novel Battery operating cost model

Unlike simplified linear cost models of Battery Storage systems, a novel cost model has been developed

- Effect of CapEx depreciation accounted for

- Battery lifetime (throughput) expressed as a function of "usability"

More precise consideration of battery operating cost for similar control problems…

Task 2: Software Implementation of Algorithms

Subtasks

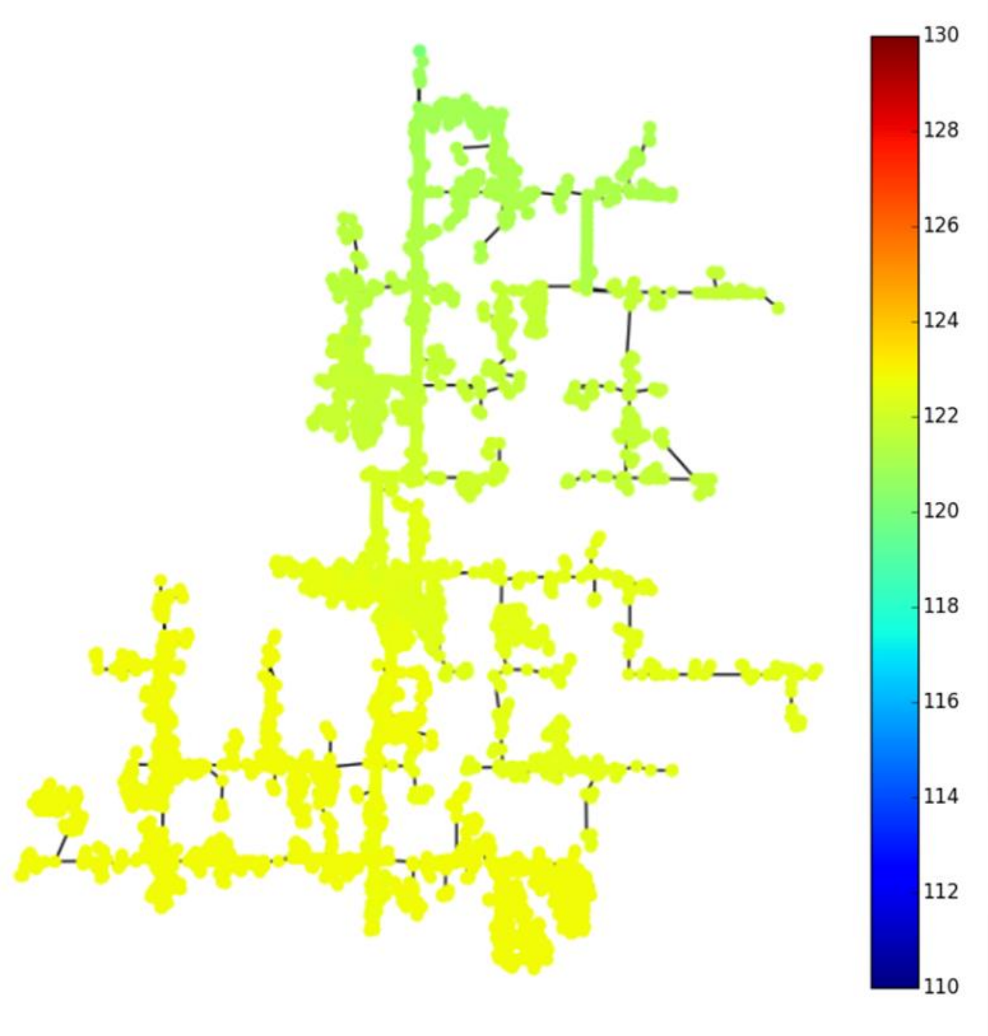
1. Network Design
   - Assessment of the selected coop feeder as the test bed
2. Implementation of Code on Embedded Site Controller and Communication
   - Validate performance of operation framework in simulation
   - Validate performance of operation framework *in situ*
3. Write Host Program to Collect and Format Data

Task 2: Software Implementation of Algorithms

Subtasks

1. Network Design
   - Assessment of the selected coop feeder as the test bed
2. Implementation of Code on Embedded Site Controller and Communication
   - Validate performance of operation framework in simulation
   - Validate performance of operation framework *in situ*
3. Write Host Program to Collect and Format Data

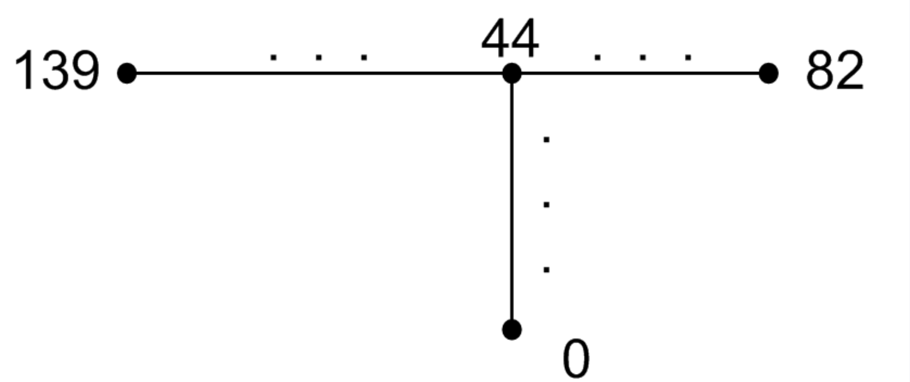
Indicative power flow output on CoServ feeder



Effect of distribution feeder design on power quality

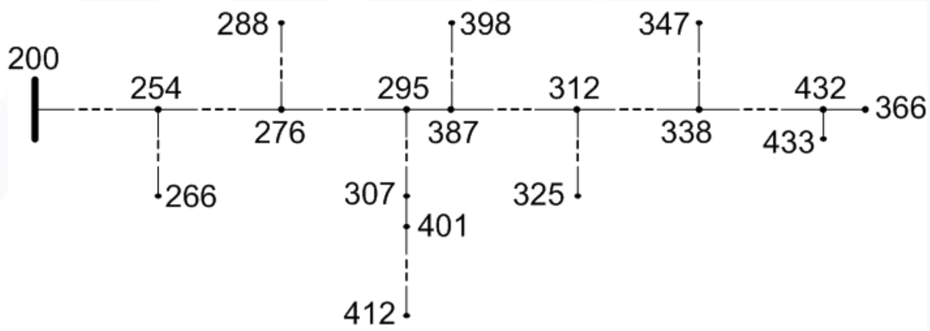
- Ikaria island (Greece)

R-22 feeder on peak load



- Rhodes island (Greece)

R-22 & R-26 feeders on installed (*not peak*) load



- Ikaria within power quality standard, Rhodes not (at various levels >50% installed)
- Distribution Networks usually oversized…

Task 3: Formulation of Iterative Distributed Control

Subtasks

1. Security Design
   - Analysis of cyber-security concerns and suggested measures
2. Secure Software Testing
   - Testing cyber-security performance of developed framework
3. System and In-Situ Testing
   - Cyber-security testing on the test-bed implementation

Task 3: Formulation of Iterative Distributed Control

Subtasks

1. Security Design
   - Analysis of cyber-security concerns and suggested measures
2. Secure Software Testing
   - Testing cyber-security performance of developed framework
3. System and In-Situ Testing
   - Cyber-security testing on the test-bed implementation

Testbed Development

Task 4: Installation of Physical Components and Test-bed Setup

Subtasks

1. Identification of Suitable Feeder
   - Promote project to candidate coop feeders
2. Design/Sizing of Devices
   - Determining exactly the components of each unit
3. Initial Deployment and Validation
   - Assessment of unit components (inter-)operability
4. Full Deployment and Validation
   - Unit fine-tuning based on cost assessment and final installation

Task 4: Installation of Physical Components and Test-bed Setup

Subtasks

1. Identification of Suitable Feeder
   - Promote project to candidate coop feeders
2. Design/Sizing of Devices
   - Determining exactly the components of each unit
3. Initial Deployment and Validation
   - Assessment of unit components (inter-)operability
4. Full Deployment and Validation
   - Unit fine-tuning based on cost assessment and final installation

Unit Design – Bill of Materials

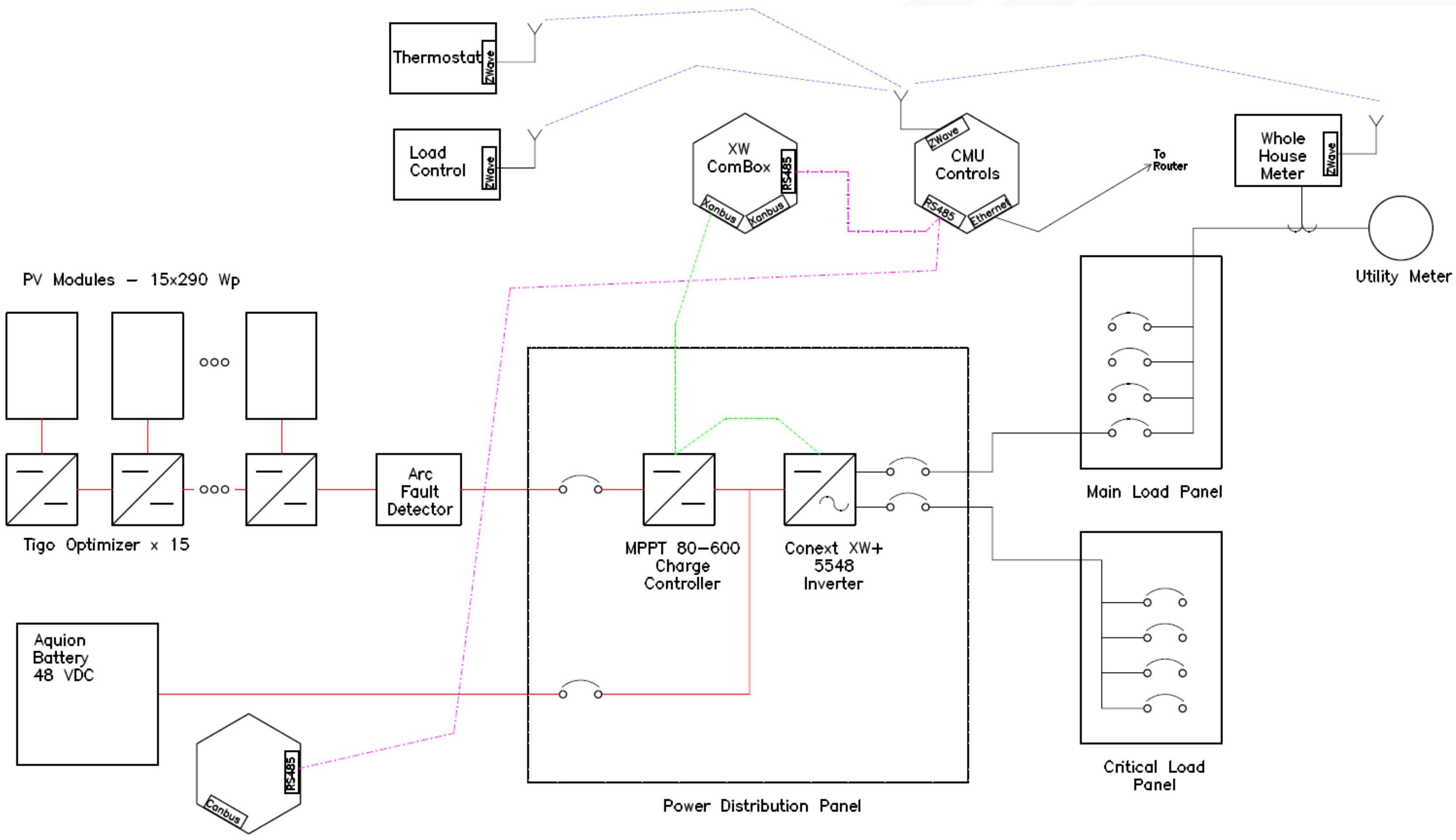
PV Subsystem			
Item	**Description**	**Manufacturer**	**Part #**
1.1	PV Module	Suniva	260 Wp
1.2	Racking	Rooftech	RT-[E]
1.3	Optimizer	Tigo	Tigo TS4L
1.4	Optimizer Comms / Rapid Shutdown	Tigo	Gateway
1.5	Arc Fault Detection	DC Sunvolt	ADU - Arc Fault Detection Module

Power Electronics Subsystem			
Item	**Description**	**Manufacturer**	**Part #**
3.1	Inverter	Schneider	Conext XW+ 5548-NA
3.2	Power Distribution Panel	Schneider	Conext XW+ PDP
3.3	Charge Controller	Schneider	XW-MPPT80-600
3.4	Control Panel	Schneider	Conext 865-1050-01
3.5	Comms Panel	Schneider	Conext 865-1058 ComBox
3.6	Battery Monitor	Schneider	Conext 865-1080-01
3.7	100A DC Breaker	Schneider	865-1070

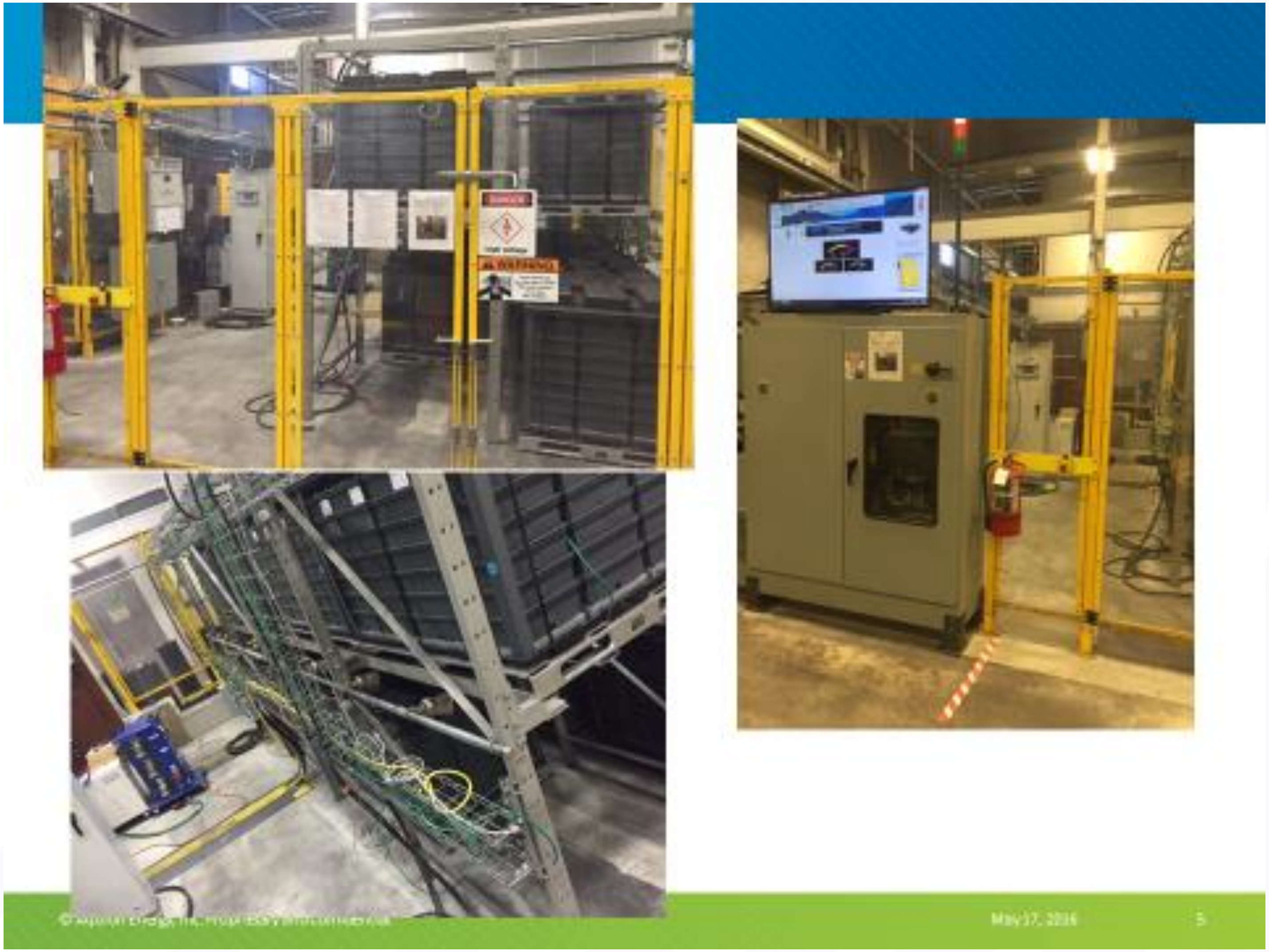
Battery Subsystem			
Item	**Description**	**Manufacturer**	**Part #**
2.1	Battery	Aquion	Aspen 48M
2.2	Battery BMS	Aquion	

Controls Subsystem			
Item	**Description**	**Manufacturer**	**Part #**
4.1	Whole House Monitor	RCS	Model EM52-ZW
4.2	Thermostat	RCS	Model TZ45
4.3	Load Control Relay	Evolve	Evolve LFM-20
4.4	Load Power Contactor	Elk	Heavy Duty Relay Contactor
4.5	Zwave Gateway	Vera	VeraEdge Z-Wave Controller
4.6	System Controller w/ enclosure	tbd	

Unit Design – One line Diagram



Unit equipment procurement & testing set-up



Formally quantified results at the end of 2016

- Average LCOE below $0.14/kWh (seasonal can spike)
  - Additional analysis to follow
- Power flow simulations on coop feeders (and others) determine dimensioning as main power quality factor
- Cybersecurity assurances procured and testing protocols determined
- Test bed (coop feeder) identified (*could* be revisited)
- Unit components, topology and design finalized
- Recharging/discharging tests successful
- Control & optimal algorithm operation tested

Dissemination actions

- Conference paper (S. Weerakkody, B. Sinopoli, S. Kar, and A. Datta, "…," *IEEE Conference on Decision and Control, 2016*)
- Journal submission (C. Wu, G. Hug, and S. Kar, "…," Submitted to *IEEE Transactions on Smart Grid*, Oct. 2016)
- P. Moutis' invited talks at Princeton Uni., CalTech, UCLA, UIUC
- Power engineering letter (P. Moutis, G. Hug, and S. Kar, "…," Submitted to *IEEE Transactions on Power Systems*, Nov. 2016)
- Conference publication (C. Wu, G. Hug, and S. Kar, "…," *American Control Conference* (To appear), May 24–26, 2017, Seattle, WA)

Questions?

Comments?