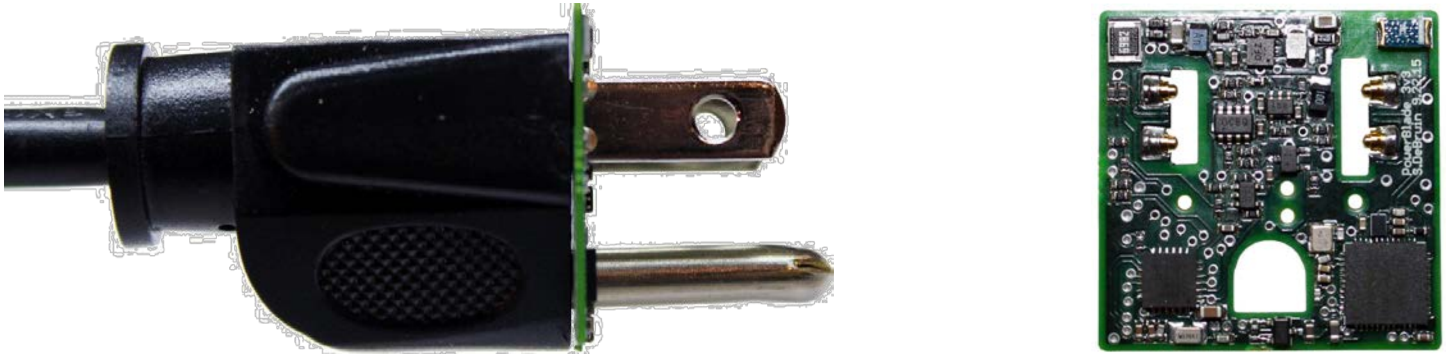
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Low-Cost Identification and Monitoring of Diverse MELs in Residential and Commercial Buildings with PowerBlade



UC Berkeley | Lawrence Berkeley National Laboratory | National Renewable Energy Laboratory

Prabal Dutta, Associate Professor

prabal@berkeley.edu

Project Summary

Timeline:

Start date: January 1, 2018

Planned end date: December 31, 2020

Key Milestones:

1. $10-12 sensor unit cost in volume (Q2)
2. Cloud DB schema and queries (Q4)
3. Sensor accuracy verification (Q4, Q6)
4. Scaling sensor manufacturing (Q5)
5. Field deployment and analysis (Q8)

Budget:

Total Project $ to Date:

- DOE: $0
- Cost Share: $0

Total Project $:

- DOE: $2,025,000.00
- Cost Share: $225,095.00

Key Partners:

Lawrence Berkeley National Laboratory (LBNL)
National Renewable Energy Laboratory (NREL)
CubeWorks, Inc

Project Outcome:

- Automatically identify/monitor miscellaneous electrical loads (MELs) across a representative sample of homes in two geographies.
- Provide a blueprint and proof-of-concept for a cost-effective, scalable, MEL monitoring and identification system.

Team

Prabal Dutta
UC Berkeley
Focus: Sensors, Networks, Analytics

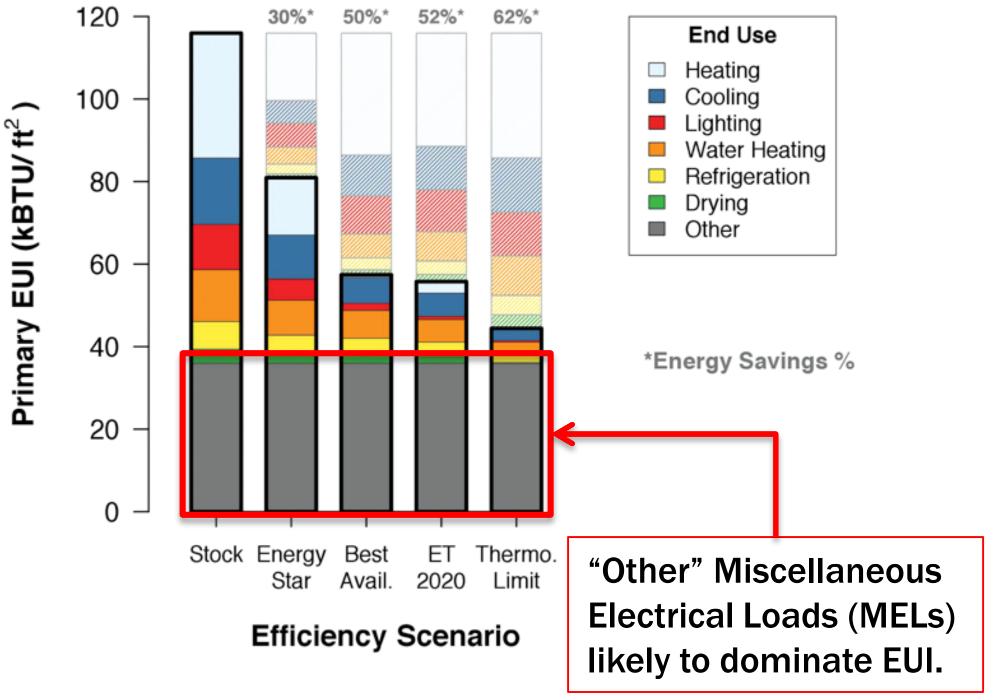
Rich Rrown
LBNL
Focus: Design Testing & Validation

Lieko Earle
NREL
Focus: Deployment Design & Execution

ZhiYoong Foo
CubeWorks
Focus: Nano-power Timekeeping

- Dutta is a leader in dense, large-scale, low-power sensor systems and networks.
- Brown is a leader in characterizing and addressing MEL energy use in buildings.
- Earle is a leader in field testing, including for the Building America Program.
- Foo is a leader in nano-power “smart dust” sensor technologies and components.

Challenge: MEL Monitoring and Identification



*Energy Savings %

“Other” Miscellaneous Electrical Loads (MELs) likely to dominate EUI.

Source: U.S. Department of Energy, Quadrennial Technology Review (QTR): An Assessment of Energy Technologies and Research Opportunities, Sep. 2015.

The Problem

- MELs are a large and growing fraction of end-load EUI
- MELs are fragmented so little visibility into them today
- Hard to identify “offenders” given wide mix of MELs
- No good solution to identify and characterize MEL energy use and usage patterns

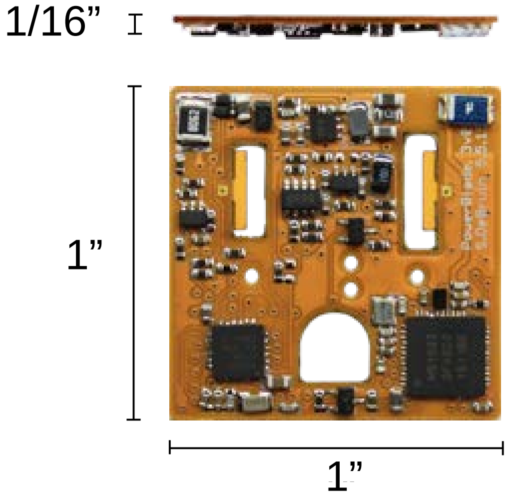
Approach: PowerBlade at Every MEL

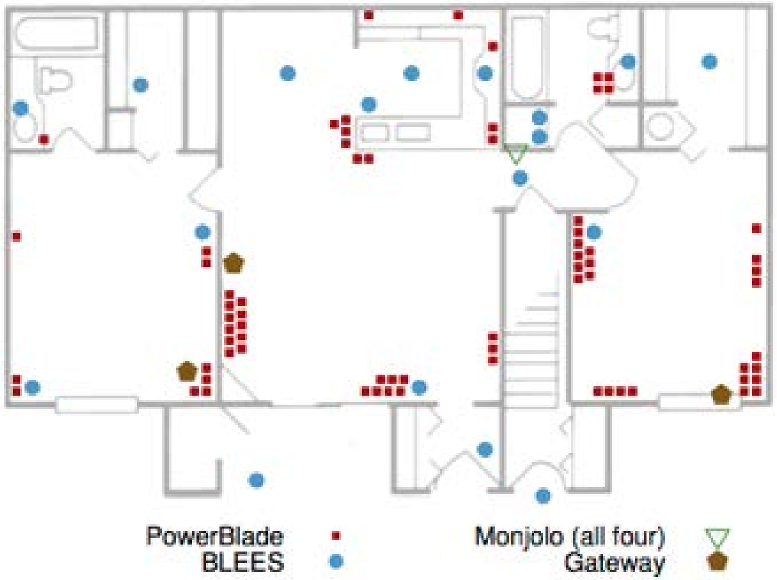
Our Solution

- A small and ubiquitous sensor
- Attaches to every MEL plug-load
- Identifies and monitors every MEL
- In 200-500 residential dwellings
- Using advanced data analytics
- Enabling unprecedented density

Technical Risks/Challenges

- Achieving target cost
- Ensuring metering accuracy
- Ensuring load identification accuracy
- Reliably delivering date to cloud



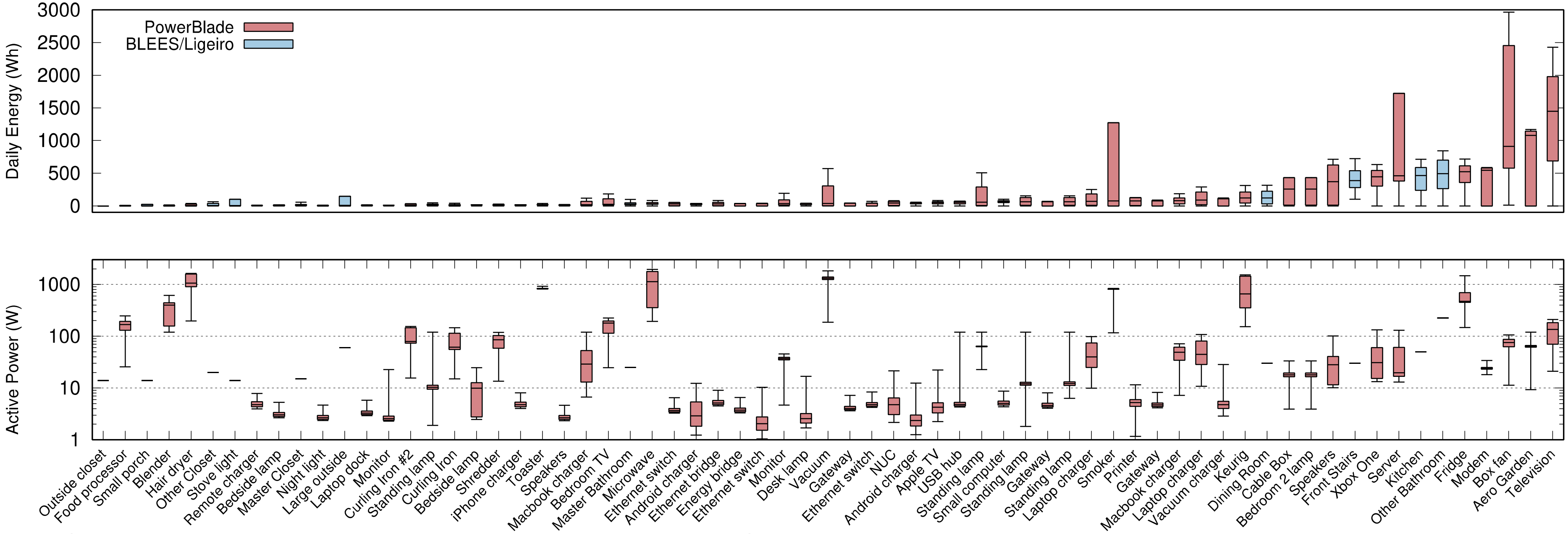


S. DeBruin, B. Ghena, Y.-S. Kuo, and P. Dutta. PowerBlade: A low-profile, true-power, plug-through energy meter, In *Proc. of the 13th ACM Conference on Embedded Networked Sensor Systems (SenSys’15)*, pp 17–29, 2015.

Impact: Inventory MEL Usage and Trends

Advantages, Differentiation, and Impact

- Small size and dense deployment enable novel analytics and new insights
  - The six devices that that draw the most power (> 500 W)
  - Collectively account for a small fraction of total energy use (2.9%)



S. DeBruin, “Enabling Visibility Into Building Energy Consumption Through Novel Metering Designs and Methods,” Ph.D. Dissertation, University of Michigan, 2017.

Impact: Inventory MEL Usage and Trends

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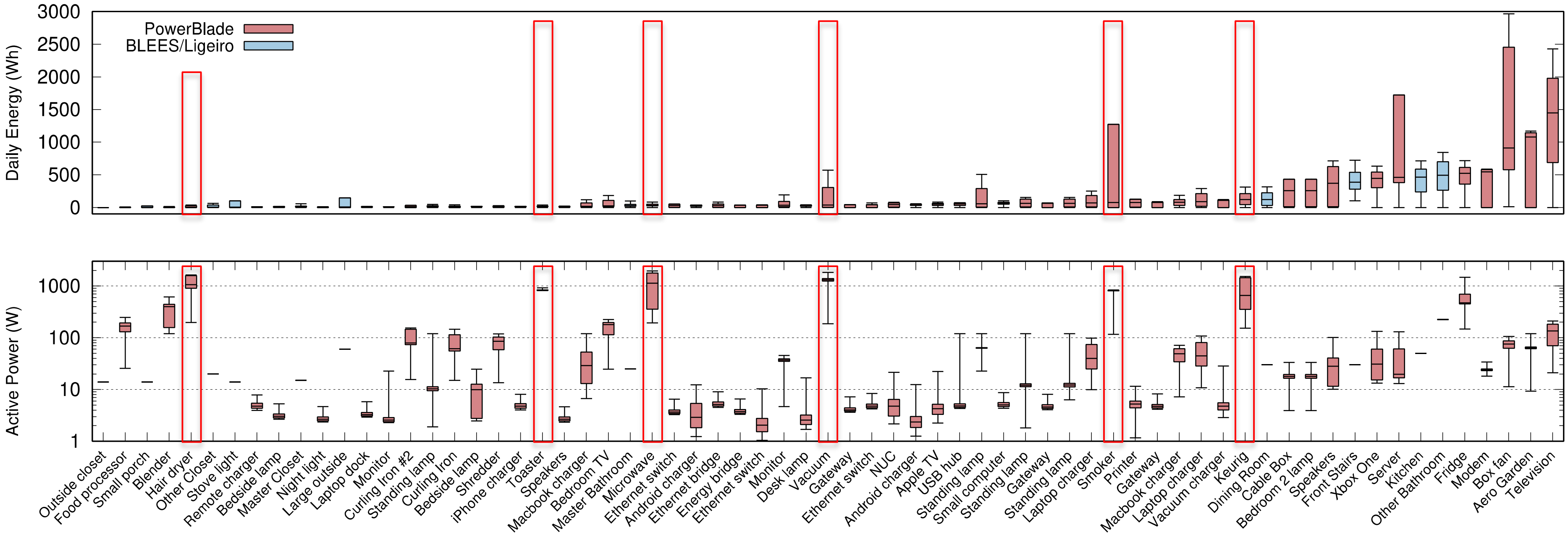

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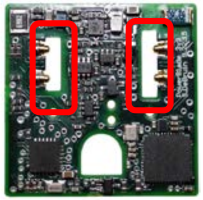
Progress: Low Cost Sensors (Tasks 1 & 3)

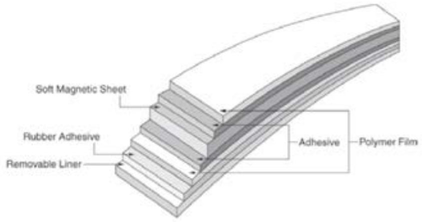
- Analysis of PowerBlade sensor yielded three design issues

  - Issue 1: Insufficient insertion depth with short plugs
    - Many older appliances/lamps have short plugs that barely meet standard
    - Prevalent in older homes, especially with well-used receptacles
    - Reducing insertion depth by an additional 1/16” to 3/32” is an issue
    - Issue is less likely in newer homes and with newer loads



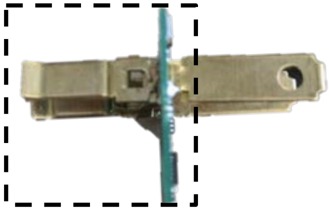
  - Issue 2: Insufficient creepage and clearance tolerances
    - Tolerance between high-voltage and low-voltage circuits too small
    - Mainly an issue since PCB design is open-air design and exposes signals
    - Easily mitigated via PCB change or changing dielectric (e.g. overmolding)

  - Issue 3: Magnetic interference from noisy loads
    - Caused by highly inductive/noisy loads
    - Magnetic field affects sense electronics
    - Requires magnetic shielding to reduce impact
    - Mu-metal tape/shielding offers one possible route



Progress: Potential Mitigations to Issues

- Option 1: PowerBlade++
  - Creepage → Change PCB, overmold to increase isolation
  - Interference → Use mu-metal shield to reduce susceptibility
  - Insertion Depth → Include extension cord for when needed



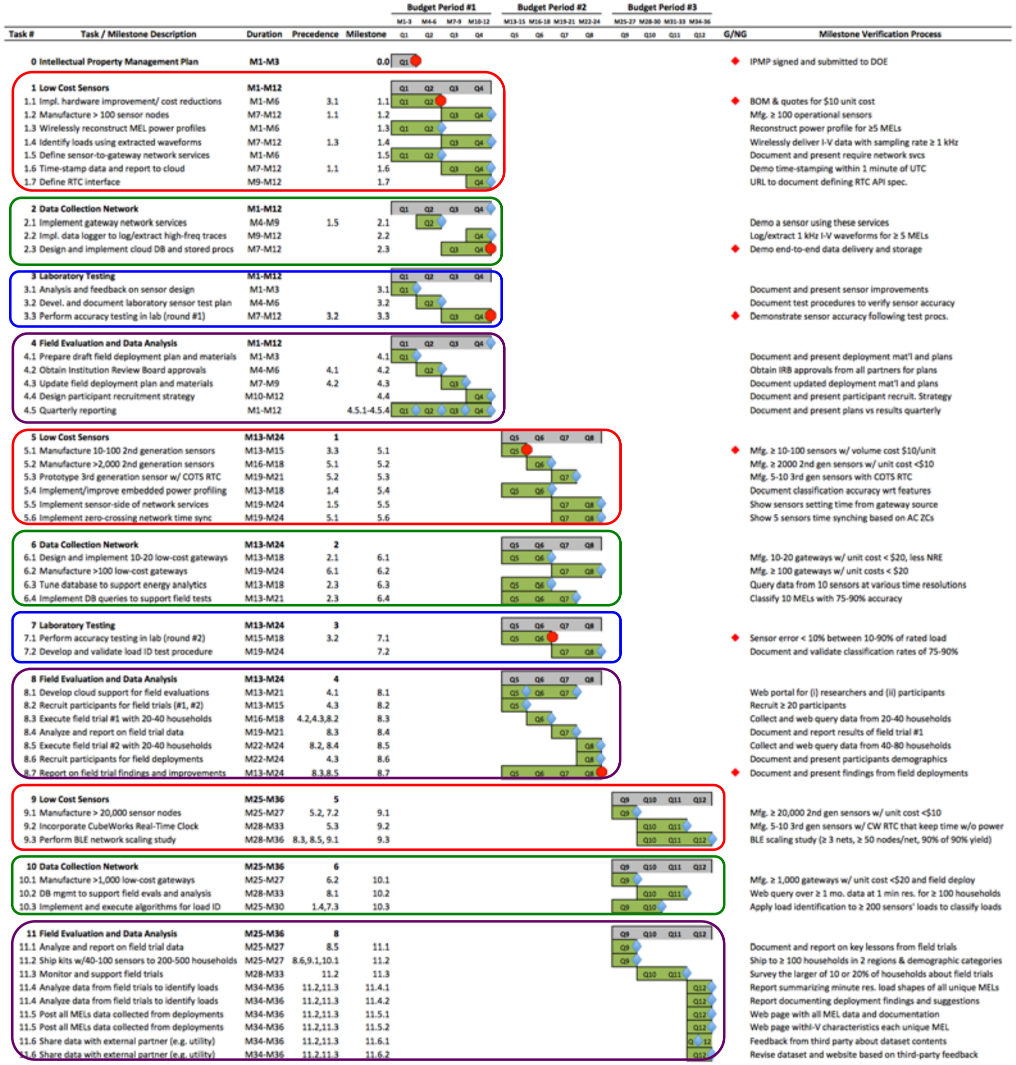
- Option 2: PowerCube
  - Creepage → Change PCB, overmold to increase isolation
  - Interference → Use mu-metal shield to reduce susceptibility
  - Insertion Depth → Add standard receptacles and prongs

- Option 3: PowerCord
  - Creepage → Change PCB
  - Interference → Use mu-metal shield to reduce susceptibility
  - Insertion Depth → Integrate into standard plug housing

Stakeholder Engagement

- NIST
  - Interested in available COTS/R&D MEL metering technologies
  - Project will adopt a variation of NIST-designed testing procedures
  - Project will supply sensors to NIST for independent verification
- Residential homeowners/occupants
  - Interested in understanding energy usage and reduction pathways
  - Engage with Boulder residents; leverage NREL ⇔ Boulder relationship
  - Tune & test deployment strategies with local sites; then scale up
- Electric Utilities
  - Interested in helping ratepayers reduce demand, replace appliances
  - Project will supply potentially actionable data at the level of homes
  - Project will engage with stakeholders through contacts at local utilities
- State and National Laboratories
  - Interested in understanding, monitoring, and regulating MELs
  - Project can provide key missing data for decision-making and policy
  - Project will engage with stakeholders through meetings and on-site visits

Remaining Project Work



					Budget Period #1				Budget Period #2				Budget Period #3					
					M1-3	M4-6	M7-9	M10-12	M13-15	M16-18	M19-21	M22-24	M25-27	M28-30	M31-33	M34-36		
Task #	Task / Milestone Description	Duration	Precedence	Milestone	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	G/NG	Milestone Verification Process
0	**Intellectual Property Management Plan**	**M1-M3**		0.0	Q1												◆	IPMP signed and submitted to DOE
1	**Low Cost Sensors**	**M1-M12**			Q1	Q2	Q3	Q4										
1.1	Impl. hardware improvement/ cost reductions	M1-M6	3.1	1.1	Q1	Q2											◆	BOM & quotes for $10 unit cost
1.2	Manufacture > 100 sensor nodes	M7-M12	1.1	1.2			Q3	Q4										Mfg. ≥ 100 operational sensors
1.3	Wirelessly reconstruct MEL power profiles	M1-M6		1.3	Q1	Q2												Reconstruct power profile for ≥5 MELs
1.4	Identify loads using extracted waveforms	M7-M12	1.3	1.4			Q3	Q4										Wirelessly deliver I-V data with sampling rate ≥ 1 kHz
1.5	Define sensor-to-gateway network services	M1-M6		1.5	Q1	Q2												Document and present require network svcs
1.6	Time-stamp data and report to cloud	M7-M12	1.1	1.6			Q3	Q4										Demo time-stamping within 1 minute of UTC
1.7	Define RTC interface	M9-M12		1.7				Q4										URL to document defining RTC API spec.
2	**Data Collection Network**	**M1-M12**			Q1	Q2	Q3	Q4										
2.1	Implement gateway network services	M4-M9	1.5	2.1		Q2												Demo a sensor using these services
2.2	Impl. data logger to log/extract high-freq traces	M9-M12		2.2				Q4										Log/extract 1 kHz I-V waveforms for ≥ 5 MELs
2.3	Design and implement cloud DB and stored procs	M7-M12		2.3			Q3	Q4									◆	Demo end-to-end data delivery and storage
3	**Laboratory Testing**	**M1-M12**			Q1	Q2	Q3	Q4										
3.1	Analysis and feedback on sensor design	M1-M3		3.1	Q1													Document and present sensor improvements
3.2	Devel. and document laboratory sensor test plan	M4-M6		3.2		Q2												Document test procedures to verify sensor accuracy
3.3	Perform accuracy testing in lab (round #1)	M7-M12	3.2	3.3			Q3	Q4									◆	Demonstrate sensor accuracy following test procs.
4	**Field Evaluation and Data Analysis**	**M1-M12**			Q1	Q2	Q3	Q4										
4.1	Prepare draft field deployment plan and materials	M1-M3		4.1	Q1													Document and present deployment mat'l and plans
4.2	Obtain Institution Review Board approvals	M4-M6	4.1	4.2		Q2												Obtain IRB approvals from all partners for plans
4.3	Update field deployment plan and materials	M7-M9	4.2	4.3			Q3											Document updated deployment mat'l and plans
4.4	Design participant recruitment strategy	M10-M12		4.4				Q4										Document and present participant recruit. Strategy
4.5	Quarterly reporting	M1-M12		4.5.1-4.5.4	Q1	Q2	Q3	Q4										Document and present plans vs results quarterly
5	**Low Cost Sensors**	**M13-M24**	**1**						Q5	Q6	Q7	Q8						
5.1	Manufacture 10-100 2nd generation sensors	M13-M15	3.3	5.1					Q5								◆	Mfg. ≥ 10-100 sensors w/ volume cost $10/unit
5.2	Manufacture >2,000 2nd generation sensors	M16-M18	5.1	5.2						Q6								Mfg. ≥ 2000 2nd gen sensors w/ unit cost <$10
5.3	Prototype 3rd generation sensor w/ COTS RTC	M19-M21	5.2	5.3							Q7							Mfg. 5-10 3rd gen sensors with COTS RTC
5.4	Implement/improve embedded power profiling	M13-M18	1.4	5.4					Q5	Q6								Document classification accuracy wrt features
5.5	Implement sensor-side of network services	M19-M24	1.5	5.5							Q7	Q8						Show sensors setting time from gateway source
5.6	Implement zero-crossing network time sync	M19-M24	5.1	5.6							Q7	Q8						Show 5 sensors time synching based on AC ZCs
6	**Data Collection Network**	**M13-M24**	**2**						Q5	Q6	Q7	Q8						
6.1	Design and implement 10-20 low-cost gateways	M13-M18	2.1	6.1					Q5	Q6								Mfg. 10-20 gateways w/ unit cost < $20, less NRE
6.2	Manufacture >100 low-cost gateways	M19-M24	6.1	6.2							Q7	Q8						Mfg. ≥ 100 gateways w/ unit costs < $20
6.3	Tune database to support energy analytics	M13-M18	2.3	6.3					Q5	Q6								Query data from 10 sensors at various time resolutions
6.4	Implement DB queries to support field tests	M13-M21	2.3	6.4					Q5	Q6	Q7							Classify 10 MELs with 75-90% accuracy
7	**Laboratory Testing**	**M13-M24**	**3**						Q5	Q6	Q7	Q8						
7.1	Perform accuracy testing in lab (round #2)	M15-M18	3.2	7.1					Q5	Q6							◆	Sensor error < 10% between 10-90% of rated load
7.2	Develop and validate load ID test procedure	M19-M24		7.2							Q7	Q8						Document and validate classification rates of 75-90%
8	**Field Evaluation and Data Analysis**	**M13-M24**	**4**						Q5	Q6	Q7	Q8						
8.1	Develop cloud support for field evaluations	M13-M21	4.1	8.1					Q5	Q6	Q7							Web portal for (i) researchers and (ii) participants
8.2	Recruit participants for field trials (#1, #2)	M13-M15	4.3	8.2					Q5									Recruit ≥ 20 participants
8.3	Execute field trial #1 with 20-40 households	M16-M18	4.2,4.3,8.2	8.3						Q6								Collect and web query data from 20-40 households
8.4	Analyze and report on field trial data	M19-M21	8.3	8.4							Q7							Document and report results of field trial #1
8.5	Execute field trial #2 with 20-40 households	M22-M24	8.2, 8.4	8.5								Q8						Collect and web query data from 40-80 households
8.6	Recruit participants for field deployments	M22-M24	4.3	8.6								Q8						Document and present participants demographics
8.7	Report on field trial findings and improvements	M13-M24	8.3,8.5	8.7					Q5	Q6	Q7	Q8					◆	Document and present findings from field deployments
9	**Low Cost Sensors**	**M25-M36**	**5**										Q9	Q10	Q11	Q12		
9.1	Manufacture > 20,000 sensor nodes	M25-M27	5.2, 7.2	9.1									Q9					Mfg. ≥ 20,000 2nd gen sensors w/ unit cost <$10
9.2	Incorporate CubeWorks Real-Time Clock	M28-M33	5.3	9.2										Q10	Q11			Mfg. 5-10 3rd gen sensors w/ CW RTC that keep time w/o power
9.3	Perform BLE network scaling study	M28-M36	8.3, 8.5, 9.1	9.3										Q10	Q11	Q12		BLE scaling study (≥ 3 nets, ≥ 50 nodes/net, 90% of 90% yield)
10	**Data Collection Network**	**M25-M36**	**6**										Q9	Q10	Q11	Q12		
10.1	Manufacture >1,000 low-cost gateways	M25-M27	6.2	10.1									Q9					Mfg. ≥ 1,000 gateways w/ unit cost <$20 and field deploy
10.2	DB mgmt to support field evals and analysis	M28-M33	8.1	10.2										Q10	Q11			Web query over ≥ 1 mo. data at 1 min res. for ≥ 100 households
10.3	Implement and execute algorithms for load ID	M25-M30	1.4,7.3	10.3									Q9	Q10				Apply load identification to ≥ 200 sensors' loads to classify loads
11	**Field Evaluation and Data Analysis**	**M25-M36**	**8**										Q9	Q10	Q11	Q12		
11.1	Analyze and report on field trial data	M25-M27	8.5	11.1									Q9					Document and report on key lessons from field trials
11.2	Ship kits w/40-100 sensors to 200-500 households	M25-M27	8.6,9.1,10.1	11.2									Q9					Ship to ≥ 100 households in 2 regions & demographic categories
11.3	Monitor and support field trials	M28-M33	11.2	11.3										Q10	Q11			Survey the larger of 10 or 20% of households about field trials
11.4	Analyze data from field trials to identify loads	M34-M36	11.2,11.3	11.4.1												Q12		Report summarizing minute res. load shapes of all unique MELs
11.4	Analyze data from field trials to identify loads	M34-M36	11.2,11.3	11.4.2												Q12		Report documenting deployment findings and suggestions
11.5	Post all MELs data collected from deployments	M34-M36	11.2,11.3	11.5.1												Q12		Web page with all MEL data and documentation
11.5	Post all MELs data collected from deployments	M34-M36	11.2,11.3	11.5.2												Q12		Web page withI-V characteristics each unique MEL
11.6	Share data with external partner (e.g. utility)	M34-M36	11.2,11.3	11.6.1												Q12		Feedback from third party about dataset contents
11.6	Share data with external partner (e.g. utility)	M34-M36	11.2,11.3	11.6.2												Q12		Revise dataset and website based on third-party feedback

- Low-Cost Sensors
  - Y1: Hitting target cost $10
  - Y1: Hitting target accuracy
  - Y1: Address design feedback
  - Y2-3: Scale up: 100→1-2K→ 10-20K
- Data Collection Network
  - Y1: Hitting target cost $20
  - Y1: Sensor ⇔ gateway protocols
  - Y2-3: Scale up: 10 → 100 → 500
- Laboratory Testing
  - Y1: Testing plans and procedures
  - Y1-2: Metering and load ID accuracy
- Field Evaluation and Data Analysis
  - Y1: Getting IRBs & plans finalized
  - Y2: Recruiting participants
  - Y2: Field trials (20-40 homes)
  - Y3: Deployments (200-500 homes)
  - Y3: Data collection & sharing

Thank You

UC Berkeley | LBNL | NREL | CubeWorks

Prabal Dutta, Associate Professor
prabal@berkeley.edu

REFERENCE SLIDES

Project Budget

Project Budget: $2,250,095.00 (total) project budget (start date: 1/1/2018)
Variances: Below BP1/Q1 spending target due to contracting delays.
Cost to Date (1/1 - 2/28): $28,493.93 (govt. share) + $9,276.82 (cost share).
Additional Funding: None.

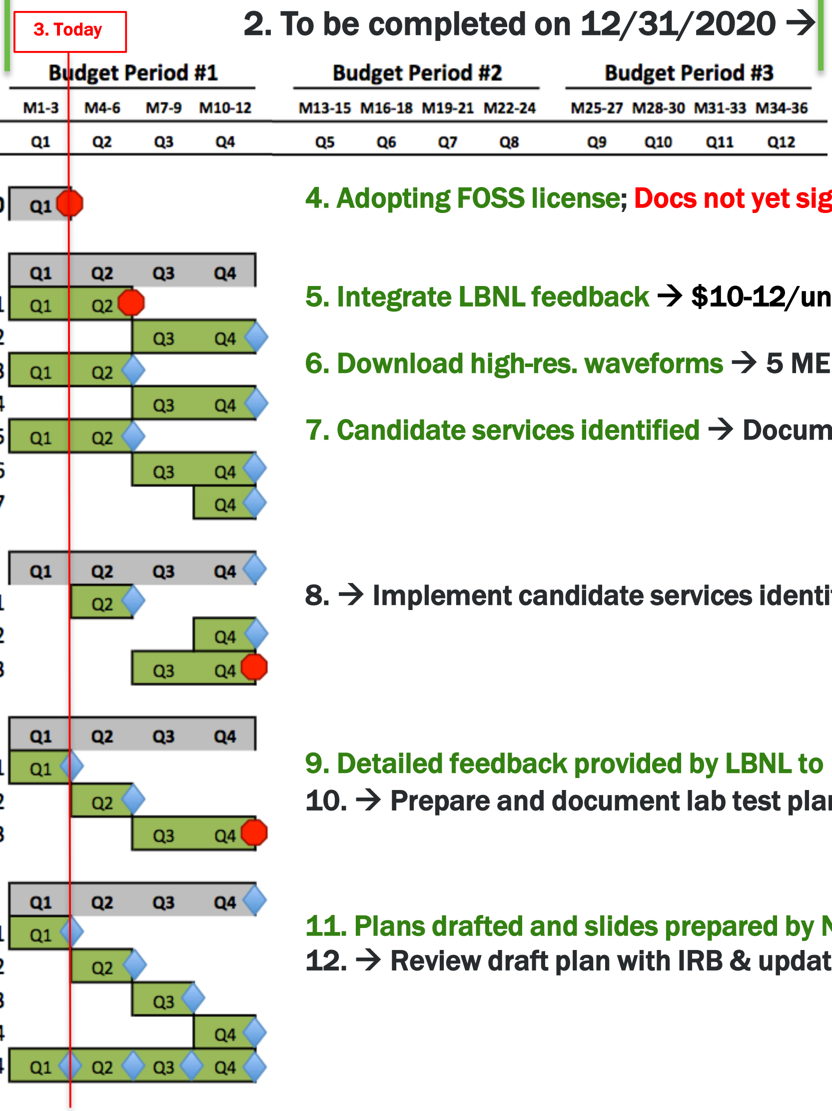
Budget History					
FY 2017 (past)		FY 2018 (current)		FY 2019 – FY 2020 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$0	$0	$700,001	$77,812	$1,324,999	$147,283

Project Plan and Schedule

← 1. Started on 1/1/2018

2. To be completed on 12/31/2020 →

Task #	Task / Milestone Description	Duration	Precedence	Milestone
0	**Intellectual Property Management Plan**	**M1-M3**		**0.0**
1	**Low Cost Sensors**	**M1-M12**		
1.1	Impl. hardware improvement/ cost reductions	M1-M6	3.1	1.1
1.2	Manufacture > 100 sensor nodes	M7-M12	1.1	1.2
1.3	Wirelessly reconstruct MEL power profiles	M1-M6		1.3
1.4	Identify loads using extracted waveforms	M7-M12	1.3	1.4
1.5	Define sensor-to-gateway network services	M1-M6		1.5
1.6	Time-stamp data and report to cloud	M7-M12	1.1	1.6
1.7	Define RTC interface	M9-M12		1.7
2	**Data Collection Network**	**M1-M12**		
2.1	Implement gateway network services	M4-M9	1.5	2.1
2.2	Impl. data logger to log/extract high-freq traces	M9-M12		2.2
2.3	Design and implement cloud DB and stored procs	M7-M12		2.3
3	**Laboratory Testing**	**M1-M12**		
3.1	Analysis and feedback on sensor design	M1-M3		3.1
3.2	Devel. and document laboratory sensor test plan	M4-M6		3.2
3.3	Perform accuracy testing in lab (round #1)	M7-M12	3.2	3.3
4	**Field Evaluation and Data Analysis**	**M1-M12**		
4.1	Prepare draft field deployment plan and materials	M1-M3		4.1
4.2	Obtain Institution Review Board approvals	M4-M6	4.1	4.2
4.3	Update field deployment plan and materials	M7-M9	4.2	4.3
4.4	Design participant recruitment strategy	M10-M12		4.4
4.5	Quarterly reporting	M1-M12		4.5.1-4.5.4



4. Adopting FOSS license; Docs not yet signed

5. Integrate LBNL feedback → $10-12/unit

6. Download high-res. waveforms → 5 MELs

7. Candidate services identified → Document

8. → Implement candidate services identified

9. Detailed feedback provided by LBNL to UCB

10. → Prepare and document lab test plan

11. Plans drafted and slides prepared by NREL

12. → Review draft plan with IRB & update