

Commercialization

Powernet is meant to solve a critical need, so from the outset we have been establishing key allies to ensure rapid adoption of the technologies develop. SLAC, the U.S. Navy, Google and the University of Florida are our research partners.

In time, we will team up with manufacturers of home batteries, solar panels and other residential energy devices on technical compatibility; with companies that could commercialize our devices; and with grid operators and utilities to integrate with our Cloud Coordinator. Making the core control and optimization algorithms open source will create a platform that many private companies can further develop and customize.

Internally, as part of the project, we will perform cost-benefit analyses of Powernet under several use cases. Based on actual data, the formal method will quantify Powernet's value.

Industry and academic advisory boards

Powernet's advisory boards ensure that our work is geared toward practical, scalable, economical and scientifically sound solutions.

The initial entities participating in the industry advisory board include:

- Amberkinnetics
- Autogrid
- City of Palo Alto Utilities
- Kisensum
- Nest
- Pacific Gas & Electric
- Sacramento Municipal Utility District
- San Diego Gas & Electric
- Schneider Electric
- Solar City
- Southern California Edison

The academic advisory board comprises:

- Anjan Bose, Washington State University
- Munther Dhaleh, MIT
- Steven Low, Caltech
- Pravin Varaiya, UC-Berkeley

We are actively engaging with several other strategic entities as potential partners and advisors.



Funded by the U.S. Department of Energy's Advanced Research Projects Agency-Energy

PARTNERS:



CONTACTS:

Principal Investigator: Ram Rajagopal
ramr@stanford.edu

Project Coordinator: June Flora
jflora@stanford.edu

powernet.stanford.edu

CO-INVESTIGATORS:

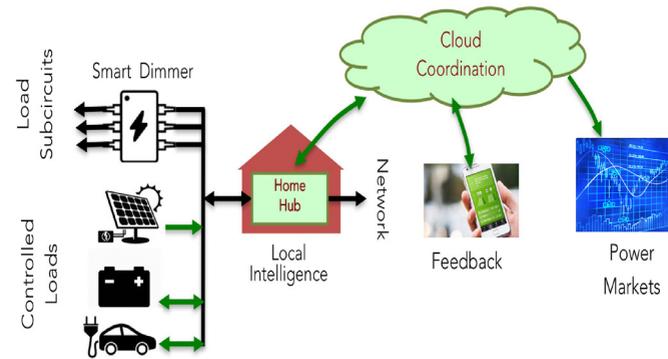
- Arun Majumdar
- Steven Chu
- Abbas El Gamal
- Juan Rivas
- Sila Kiliccote (SLAC)
- Sean Meyn (University of Florida)



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STANFORD UNIVERSITY



Picture a world where most of the electricity we use is renewable, affordable and reliable. Imagine consumers making this possible by occasionally and automatically selling electricity to the grid or delaying use, usually without even noticing.

Much work is needed to create this future, but the electricity paradigm that has served us for more than a century must fundamentally change. Power plants fueled mostly by fossil fuels simply ramping up and down to meet demand must be replaced by solar and wind generators that are less controllable.

Fortunately, today's sensors, power electronics, algorithms and data science can help the grid manage extensive renewable generation and make the most of new, local energy resources, like residential solar power, home batteries and flexible consumer demand. This could shrink the need for massive energy storage facilities, standby natural gas-fired generators and long-distance transmission lines.

The Powernet project is developing integrated hardware and software to aggregate and control local energy resources. Our layered architecture should enable networked neighborhoods by the thousands to participate in wholesale electricity markets as both buyers and sellers to keep the lights on at the lowest cost. We are also working to make this system attractive and easy for consumers to use, while preserving privacy.

In a preliminary study, we showed that 10,000 homes can provide up to three megawatts of local capacity. Powernet is developing the tools necessary for 125 million U.S. homes to capture that capacity economically. If successful, we will have contributed significantly to building a clean, reliable and affordable electricity future.

Ram Rajagopal

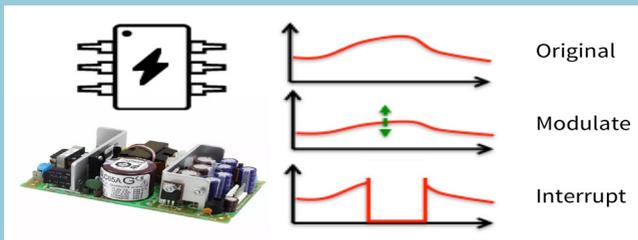
Principal Investigator, Powernet
Stanford University



Powernet is an end-to-end, open-source system that will enable real-time coordination of utilities' centralized, large assets with millions of distributed resources. It integrates embedded sensing and computing, power electronics, data analytics and networking with cloud computing. The Powernet research project, begun in 2016, is part of ARPA-E's Network Optimized Distributed Energy Systems program.

Smart Dimmer Fuse

Powernet's novel Smart Dimmer Fuse (SDF) will replace traditional home circuit breakers to control electricity use based on residents' preferences, while also improving safety. The device will include power electronics needed for the load curtailment capability, and sensing and processing for high-fidelity load measurements.



SDFs will be installed at the breaker panel for key subcircuits. For each of these subcircuits, the device measures the voltage and current, and can control the subcircuit voltage. Additionally, the new fuses will detect faults and provide greater safety than thermal-magnetic breakers in use today.

SDFs can curtail the power of controllable loads through voltage or current control, based on consumer settings. First-level reductions are generally unnoticeable, like pausing electric water heaters, air conditioning systems and refrigerators, especially when nobody is home or not typically bathing. When electricity prices rise to the point at which residents have indicated they can live with more noticeable load reductions, SDF actions include dimming lights or suspending the running of a clothes dryer.

The new fuses will also be critical in helping the Home Hub to identify what appliances are on each subcircuit. This learning will be critical to the success of Powernet, which relies on determining and predicting loads and their controllability. The Home Hub will use the SDF load models to plan demand-side rescues for optimization

within the home and for the Cloud Coordinator. A full picture of residential resource availability requires both the instantaneous controllability and accurate forecasting of consumption at a subcircuit level.

Home Hub

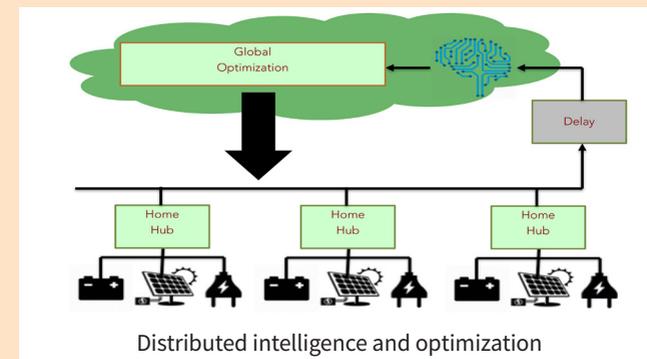
Powernet's Home Hub will enable consumers to control their energy consumption, participate in aggregation services, save money, and make the most of their home batteries, solar panels and other devices. Home Hubs will help the broader electricity system operate reliably and at least cost by reacting automatically to changing system requirements and coordinating residential resources to supply grid services such as ramp following and regulation.

Based on learned consumer choices and electricity prices, for example, the Home Hub will know whether output from a solar panel should be used, stored or sold, and then act accordingly. Individual consumers will gain increased control over their assets conveniently while also acting on their environmental values. They can subscribe resources to participate in aggregate services for the grid that compensate consumers according to wholesale market needs and pricing.

The hub's hardware will include a computing unit that runs the software and optimization algorithms. This unit also will have wired and wireless communication capabilities to collect data from sources within the home and outside.

Each home's distributed energy resources, i.e. battery storage and solar generation, and SDFs will communicate and be controlled by the Home Hub. It will also be able to control plug-level devices, like washers and dryers, if the devices have wireless capabilities.

The Home Hub's software will collect and process data for learning user preferences, communicating with the Cloud Controller and detecting anomalies. The hub will also include an interface for users to monitor and control their system from web applications and mobile devices. Having access



to round-the-clock circuit level power information in the home allows additional analysis and alert functions, if the consumer desires. Examples include recommendations on electrical rate choices and alerts for abnormal conditions.

Cloud Coordinator

Powernet's Cloud Coordinator will optimize net load for a given area and for each Home Hub within the area to minimize total cost or achieve coordination goals such as ramp following or regulation. In addition to communicating with homes, the cloud-based platform will use signals from electric utilities and grid operators—regulation reserves, ramp rates, market prices, etc.—and grid data, such as voltage, frequency, and phase at distribution and transmission levels.

The Cloud Coordinator solves a multi-period economic optimization. The optimization is resolved every 30 minutes to a few hours using a rolling horizon control, with the updated information collected from the homes. When the grid operator requests regulation or ramp following, the optimization includes an additional term in the objective function penalizing deviations from regulation or ramp signals. The goal of the cloud coordinator is to identify feasible trajectories that respect global network constraints.

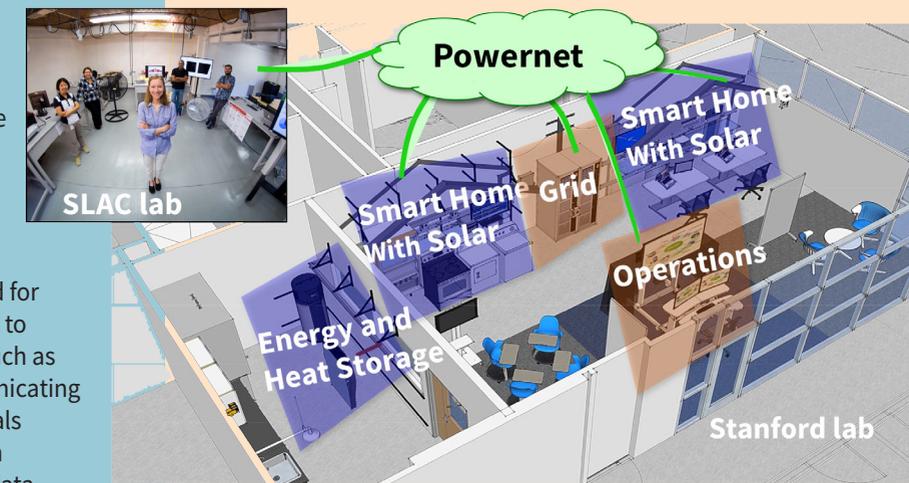
The Cloud Coordinator computes the global power balancing trajectory for the whole Powernet system. A new net load sent by the coordinator or changes within a specific home introduced by its residents triggers the optimization at the Home Hub. The home hub optimization happens at a higher time resolution and in real-time. It does not require knowledge of the network. This two-level optimization preserves the home's privacy, because only net load curves and available storage are shared with the Cloud Coordinator.

When tracking regulation signals from the grid operator, the Cloud Coordinator will incorporate deviation penalties and forecasted demand, resulting in a modified control of a Home Hub's net loads and storage. Market-based payments incentivize the consumer to share for these purposes.

Integration and Validation

Powernet researchers will develop and test the fully integrated end-to-end system in two connected laboratories and, ultimately, with a set of homes on a U.S. Navy base. One laboratory is in the engineering quad of Stanford's main campus, and the other is the GISMo lab at SLAC National Accelerator Laboratory.

The laboratories will use hardware-in-the-loop



simulation. They will include physical energy assets—solar power generators, energy storage devices and home appliances—using Smart Dimmer Fuses and Home Hubs. They will also use virtual, heterogeneous homes. The Cloud Coordinator, in turn, will operate within a software platform simulating the broader grid, load forecasts and economic data necessary for system optimization in real time. Researchers will first test a small group of homes focusing on the physical integration of the system. Next, they will use a group of 10,000 simulated homes based on actual utility data.

The simulations will validate the physical and processing responses of the Powernet system to such changes as price fluctuations, deviations from generation and load forecasts, and dynamic consumption in individual homes. Researchers can control the virtual grid to test multiple and rapidly shifting scenarios. This system could also test proposed new policies and electricity rate structures to see if outcomes meet expectations.

After the hardware-in-the-loop simulations, Powernet will be tested with residents of a naval base. In this phase, the Cloud Coordinator will likely interact in real-time with the local utility and the larger transmission grid operator.

