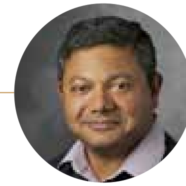
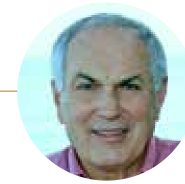
Stanford | Bits & Watts

Stanford Precourt Institute for Energy

Annual Review 2019

AN ECOSYSTEM FOR DIGITAL GRID TRANSFORMATION





A LETTER FROM THE BITS & WATTS CO-DIRECTORS

It has been an exciting year for Bits & Watts at Stanford. As we all know, the electricity grid is undergoing a once-in-a-century transformation. The mission of Bits & Watts is to engage in research, education and outreach to help anticipate and navigate that change; this report highlights our 2019 achievements in support of this mission. This is truly an exciting and opportune time for the industry; it is also a challenging time.

After a year-long preparation, we launched a new research focus on Electrification of Transportation. And this past year we initiated the idea of "flagship research challenges" to address high priority research questions. Our first foray into this realm is the EV50 project, imagining and researching the issues surrounding a 50% penetration of electric vehicles in a country's or region's transportation fleet. You can read more of our flagship program, EV50, on Pages 6 - 8.

We have continued to strengthen our research portfolios in infrastructure planning, business innovation, and customer empowerment. Three new seed grant projects were funded in the area of power electronics and intelligent controls. This report also highlights some successful collaborations between Stanford faculty and industry members on specific mutual research interests.

The utility workforce is aging and the industry is facing a skills gap in training qualified employees for the future grid. In 2019, we advanced our Smart Grid Seminar to focus on Electrification and offered a new course, Battery Systems for Transportation and Grid Services. We continued to extend our annual education program to industry members and collaborated with Stanford Center for Professional Development on the Energy Innovation and Emerging Technologies Certificate. Many industry members have also assigned their researchers to work as visiting scholars with specific and relevant Stanford faculty.

We are pleased that we have been able to initiate a postdoctoral research fellow program. This program brings the most promising newly minted PhDs to Stanford for an intensive two-year mentorship with Stanford Faculty. This addresses one of our key goals: training the researchers of tomorrow. We are grateful to the State Grid Corporation of China for funding our first postdoctoral fellows and we look forward to expanding the program.

We were also able to cultivate productive engagement between Stanford and the community. The weekly Bits & Watts Community Forum provides an opportunity for the Stanford research and industry communities to gather in an informal setting, network and discuss the latest ideas and news about grid research and innovations.

With your support and contribution, our initiative gained additional resources for research. Shell and Portland General Electric joined the Bits & Watts family in August 2019 with a significant commitment to the digital grid transformation.

This report presents not only our ongoing research education efforts but also vital partnerships with our industry members. We hope it inspires you to join us in the conviction that, together, we are digitally transforming the 21st Century Grid.

Arun Majumdar
Co-director, Bits & Watts Initiative
Co-director, Precourt Institute for Energy
Jay Precourt Professor, Mechanical Engineering

Charles D. Kolstad
Co-director, Bits & Watts Initiative
Senior Fellow, Institute for Economic Policy Research (SIEPR)
Professor, Economics

> "Our energy systems reflect our ambitions for progress and our values for how we get there. New technologies and policies, the result of research and development, enable that pursuit."
>
> —GEORGE SHULTZ
> *Chair, Energy Policy Task Force, Hoover Institution, Stanford University*

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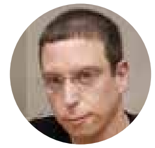

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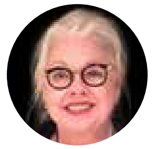

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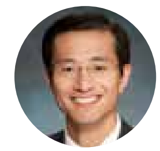

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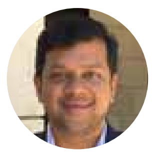

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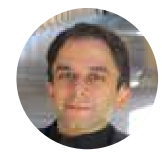

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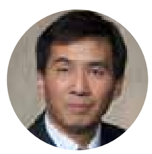

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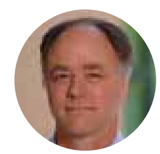

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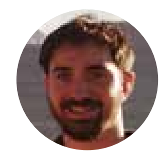

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RESEARCH HIGHLIGHTS

> "The first challenge was to bring down the cost of wind, solar and other forms of distributed power. The next challenge is to create an integrated system. We must develop the right technologies, financial incentives and investment atmosphere to take full advantage of the lowering costs of clean energy."

—STEVEN CHU

Stanford Professor, Nobel laureate, former U.S. Energy Secretary

Robust Infrastructures and Holistic Planning: Robust infrastructures (transmission, distribution and energy storage) will enable the delivery of clean energy to customers and expand the ways that clean energy is used.

WESTERN INTERCONNECTION DATA ANALYTICS PROJECT (WIDAP)

PIs: Dian Grueneich (Stanford), Sally M. Benson;
Co-PIs: Maury Galbraith (Western Interstate Energy Board)
Grace Anderson (California Energy Commission)

The Western Interconnection Data Analytics Project (WIDAP) is a joint effort between Bits & Watts and the Western Interstate Energy Board (WIEB) to better understand the changing nature of electricity generation in the Western United States.

WIDAP is an unprecedented effort to analyze millions of data points about the historical operation, generation, and emissions of Western power plants. The WIDAP team built and analyzed a 15-year database (2001-2016), with over 85 million observations of the changing Western grid, from historical data made public by the United States Environmental Protection Agency. The publicly available WIDAP database covers almost 600 fossil-fired electric generating units in the Western Interconnection (WI).

The WIDAP research demonstrates dramatic shifts in fossil-fired generation and emissions in the WI and makes publicly available the WIDAP Toolkit, for use by policymakers and other stakeholders interested in analyzing the evolving changes in generation in the WI.

Seed Grant Project 2018-2019

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PROBABILISTIC GRID PLANNING WITH VARIABLE GENERATION AND STORAGE

PI: Sanjay Lall; Co-PI: Dimitry Gorinevsky;
Student: Weixuan Gao

Renewable energy has a large and increasing impact on the grid. Solar and wind generation are non-dispatchable and bring random variability. To compensate, more energy storage is getting connected to the grid. New probabilistic analysis tools are required for managing risk and grid cost with new storage and variable generation growing at scales beyond anything seen before.

Professors Lall and Gorinevsky explored a method of analyzing grid reliability with such variable generation resources. Their team has developed machine learning algorithms for probabilistic analysis of grid reliability with variable generation resources, including renewables and storage. A software tool called RAPIER (Risk Analysis and Prediction for Integrated Energy from Renewables) is currently under development as well.

The key contribution of the project is machine learning modeling of key variable patterns induced by distributed and variable energy resources. Using these probabilistic models, adequacy of the resource mix can be assessed more accurately and with less effort than by using existing approaches.

Seed Grant Project 2018-2019

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GRID-LEVEL ENERGY STORAGE: TOOLS FOR CHARACTERIZATION, DESIGN OPTIMIZATION, AND TECHNOLOGY EVALUATION

PI: Simona Onori; Co-PI: Seongbeom Lee; Student: Kevin Moy

Lithium-ion batteries are widely used as energy storage systems for renewable grid applications at considerable expense. Adequate mathematical models are critical to operate, design, and optimize battery systems and should have a substantial impact on battery cost, performance, and usability. However, to date, most battery models used in renewable grid applications are based on oversimplified models. Such simplistic models do not allow for a robust optimization routine. Adopting physics-based models will allow for maximizing the penetration of renewable energy sources by identifying proper chemistries and aging models for each grid application. It will also provide an insight into developing new materials at the same time.

Capacity/power fade is a critical consideration in renewable grid markets. Two key benefits of adopting physics-based models are to: i) minimize over-stacking and under-utilization of battery systems; and ii) maximize the battery life by implanting proper aging mechanisms for each grid application—such as frequency regulation and peak shaving. To maximize these advantages, we must identify characteristic battery duty cycles under frequency regulation signal and peak shaving, develop accurate physics-based electrochemical-aging models, and investigate more grid-prone chemistries.

Various chemistries of Li-ion batteries—which produce different performances—are widely available today. The proposed physics-based approach accounts for internal states of the battery systems, providing high-prediction accuracy and thereby achieving better reliability and resilience. This can maximize the penetration of renewable grid energy resources by identifying optimal deployment strategies which will significantly contribute to affordability, thus enabling further decarbonization of the grid.

Seed Grant Project 2019-2020

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Business Innovation and Customer Empowerment: Business innovation, policies supporting customer control and end-user technologies will recast the relationship between consumers and the electric grid.

USING BEHAVIORAL ECONOMICS TO FORECAST ENERGY CONSUMER ENGAGEMENT AND RESPONSE

PIs: Brian Knutson, Nik Sawe

Understanding how changes in messaging influence information processing and downstream decisions surrounding environmental and energy behaviors is key to how the public views and responds to energy-efficient programs, policies, and products. This interdisciplinary project identifies how messaging can be changed in ways that improve public support and engagement with energy-efficient programs and policies.

Working with researcher Nouschka Veerman, we have written a report on integrating neuroscience with behavioral economics findings on decision-making to inform energy policy. This expands on our work published earlier in the year in Behavioural Public Policy (Sawe 2019). In 2019, we created a neuro-linguistic programming (NLP) tool to test how different terms would perform on social media.

The NLP tool can be used to suggest new replacement terms that are likely to positively engage readers. These terms can then be tested to a deeper degree. Continued iteration will determine how to create effective messaging that improves public support and adoption of environmental and energy policies.

Seed Grant Project 2018-2019

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UTILITY BUSINESS MODELS AND TECHNOLOGICAL OBSOLESCENCE

PI: Michael Wara

Utility business models are predicated on recovering the costs of long-lived, capital-intensive, investments over 25 to 40 years. Rapid technological changes at the grid edge threaten this paradigm, creating increased premature obsolescence risk. How should we alter current rate-making processes to de-risk the utility business model for rapid grid-edge evolution? What can we learn from previous instances of rapid technological change/ premature obsolescence in other regulated industries that can inform the electric utility context today? How might changes to utility cost recovery practices impact the competition between electric utilities and distributed energy resources (DER)?

This project seeks to achieve the following goals: assess current depreciation practices across the electric utilities in the most rapidly growing DER markets; evaluate current depreciation-related controversies in light of issues raised by technological change; develop case studies of economic and legal consequences of rapid technological change in other regulated industries (rail, telecoms, street cars, etc.); and initiate a conversation in the electricity policy community about how to price risk of technological obsolescence in order to avoid creation of stranded assets.

Seed Grant Project 2018-2019

OPEN INNOVATION AND THE SEARCH FOR DIGITAL SOLUTIONS: STRATEGIC DIFFERENTIATION

PI: Stephen Comello; Co-PIs: Ann-Kristin Zobel (University of St. Gallen), Lukas Falcke (University of St. Gallen)

Large firms with legacy systems that operate within established industries, such as electric utilities, are increasingly searching for— and deploying—digital solutions across various dimensions of their business models. Digitalization presents multi-dimensional opportunities to innovate business models in search of new ways to create and capture value. Large Open Innovation (OI), especially formations that leverage the agility and specialization of start-ups, is a notable approach for corporations to search for new digital solutions and gain capabilities in the process.

This project offers a working framework for the pathway a corporation may take to pursue increasingly ambitious and disruptive digital solutions within an OI setting. We show that collaborative intensity, knowledge exchange, development workload, and pilot completion time —among other dimensions—are differentially affected by the interaction of solution focus and complexity, for both the corporation and collaborating start-up(s).

As utilities intensify their capability search strategies with respect to digital solutions, efficient collaborative processes will increase the absorptive capacity of these firms to assess, deploy, and scale such solutions. At the same time, such efficient collaborative processes will benefit the start-ups with which they co-develop solutions, by right-sizing the pilot/point of connections through matching expectations, resources, and business and technical requirements, among others.

Seed Grant Project 2018-2019

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Power Electronics and Intelligent Control: The widely networked inverter-based distributed energy resources and intelligent controls will help against intermittency and large ramps from renewables in the most cost-effective way.

GRID-HOME EFFICIENCIES ENABLED BY LOCAL ENERGY STORAGE

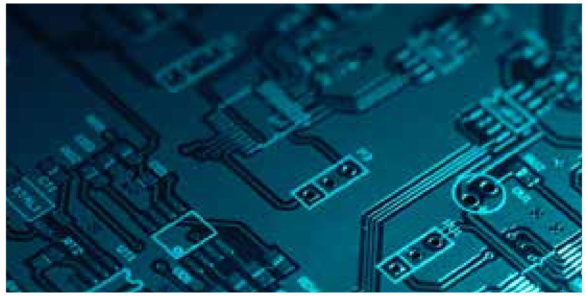
PI: Nick Bambos

Rapid developments in distributed energy storage (home battery units) are enabling substantial resilience and efficiency gains on the power grid. That much distributed energy/power storage can be a game changer for the smart power grid and extract efficiency and resilience gains on many fronts.

Professor Bambos and his team investigated a two-tier communication and control architecture for leveraging local energy storage. It comprises a power control gateway (PCG) for each home and a power server (PS) for each neighborhood. The PCG controls in-home functions (e.g., schedules tasks on smart appliances and selects between battery and grid for drawing power from) while the PS controls cross-home functions by communicating with the PCGs and coordinating them across homes.

The objective is to systematically design and optimize such an architecture and evaluate the grid efficiencies enabled (e.g., peak suppression, disaster recovery) via modeling, analysis, optimization, and simulation. Of key importance is how to learn the statistical profiles of power tasks in the home and jointly schedule them across multiple residences.

Seed Grant Project 2018-2019



ULTRAFAST CIRCUIT BREAKERS WITH WIDE BANDGAP GALLIUM NITRIDE TECHNOLOGY

PI: Srabanti Chowdhury; Co-PIs: Juan Rivas-Davila, Rohith Soman, Bhawani Shankar

Renewables are creating a critical challenge concerning circuit protection. The overload capability of converter-based renewable power sources is limited by the thermal-electrical budget of the semiconductor chips inside the converters. The semiconductor devices typically cannot sustain a fault current more than two or three times the nominal current for more than a few tens of microseconds, even with overdesigns.

This seed grant funded project seeks to develop a novel class of ultrafast, autonomously operated, self-powered, bidirectional Solid-State Circuit Breakers (SSCB) using wide bandgap (WBG) semiconductors with a nearly tenfold reduction in response time and eventually more than a tenfold reduction in system cost. These devices will be designed as bi-directional transistors to serve the SSCB requirement. The proposed gallium nitride (GaN) devices will focus on developing SSCB for two current/voltage ratings which cover the most common distribution-level AC voltages and emerging DC voltage standards. We expect to reduce conduction losses by more than a factor of two. The WBG SSCB technology benefits fast-growing renewable energy sectors—such as PV or wind power systems or any converter- interfaced microgrids—by developing novel Solid-State Circuit Breakers (SSCBs) using WBG semiconductors to protect distribution level renewable power systems from short circuit faults. Increasing protection speed by a factor of ten will provide true protection for renewable power systems.

Seed Grant Project 2019-2020

ESTABLISHING A DIAMOND-BASED DEVICE PLATFORM FOR HIGH POWER ELECTRONICS

PI: Srabanti Chowdhury: Student: Kelly Woo

Constraints on the abilities of photoconductive switches are holding back the integration of multiple high-power sources into a single electricity supply network—a “smart grid”—hindering the deployment of renewable energy resources. The main problem of photoconductive switches is their short lifespan resulting from voltage and current overloads, as well as heating at those high-power levels.

Our research aims to determine if diamond devices can outperform other semiconducting materials for high-power electronics applications. Diamond is an ideal material for high-power and high-temperature electronics. The properties of interest relevant to power electronics are large bandgap energy, high breakdown electric field, high carrier mobility, and excellent resistance to radiation. The high thermal conductivity and size advantage of diamond devices could potentially lead to a performance-over-cost advantage compared to other wide bandgap semiconductors (SiC, GaN, and Ga2O3).

This research studies the optical excitation and reaction in diamond as a function of phosphorous and/or nitrogen doping. This will help identify the potential and the challenges of building a photoconductive switch in the diamond platform. We are investigating if controllable phosphorus doping can be combined with thick diamond layers grown on a single crystalline diamond to achieve 2 kV and higher voltage class p-i-n diodes, and also exploring n-type doping, leveraging it to establish foundations for 1) p-n junction-based devices, and 2) optically triggered switches/photoconductive switches.

Our work, if successful, will create a building block for enabling a grid-level power electronics platform using diamond with photoconductive switches. The ultra-high breakdown field would enable much thinner structures for the same voltage limit. This translates directly into several performance advantages, as well as reduced system cost.

Seed Grant Project 2019-2020

Electrification of Transportation: EV50 is a Bits & Watts flagship program designed by Stanford and industry members to understand the engineering, economic, and policy implications of the dramatic transformation of our transportation sector to 50% electrification and beyond. Click here to learn more

> "As an energy company with business activities that cut across the electricity value chain, Shell values the breadth and depth of the Bits and Watts initiative. Research insights in technologies, economics, operations, regulation, policy and consumer behavior, as well as engagement with faculty, students, and other members, complements and accelerates our internal R&D programs. In particular, the integrated nature of the EV50 program provides a unique perspective to develop the roadmap for the transition to EVs at scale."
>
> —AJAY MEHTA
> *General Manager, Shell New Energies Research & Technology*

BUSINESS MODEL FOR CHARGING SERVICE PROVIDERS

PI: Ram Rajagopal; CoPIs: Arun Majumdar, Charles Kolstad, and Liang Min; Student: Marie-Louise Alt

Charging electric vehicles at home or the workplace is usually not time critical. This allows considerable potential to shift or manipulate charging in order to take advantage of lower electricity prices, manage consumption peaks, or provide ancillary services. Charging Service Providers (CSPs) can potentially provide those services while serving their clients. Yet, to our knowledge, existing business models take only limited advantage of these opportunities.

In this project, we develop a business model for a CSP. Similar to a cell phone plan, we design contract menus where drivers can buy a mileage plan and allow the CSP to control drivers' charging according to the conditions of the contract type. Contracts address different types of drivers, including for instance drivers with varying degrees of risk aversion or expected driving ranges. We evaluate the economic value of such a business model. Apart from a theoretical analysis and simulation, we hope to validate our results and assess customer choices regarding contract menus in a field experiment.

This work analyzes potential value streams and business models in the EV charging market. We hope to inspire new services which are able to unlock synergies of the power and transportation systems, enabling customer-centric charging while decreasing system operation costs and improving the integration of renewable energies.

THE VALUE OF TIME IN INTERCITY TRAVEL: EVIDENCE FROM CARPOOLING CHOICES

PI: Charles Kolstad; Co-PIs: Nicolas Astier and Xavier Lambin

Even with so-called fast-charging technologies, the refueling of electric vehicles (EV) remains significantly slower than for their gasoline counterparts. However, increasing further charging speed is costly both in terms of charging infrastructure and battery degradation. A key challenge in the EV industry is thus to assess how fast DC chargers need to be to support the transition towards EVs.

Ultimately, the optimal design of fast-charging stations depends on the extent to which drivers value time in their intercity travel. This project intends to assess this value in a credible setting, leveraging revealed-preference information from choices made by the users of a large carpooling platform.

Working on a rich dataset should enable to get values of time differentiated by route characteristics (e.g. length, rural/urban, etc.), time of the day, or even ultimately countries. Such knowledge would represent a key input to design a cost-efficient charging network across large geographical areas.

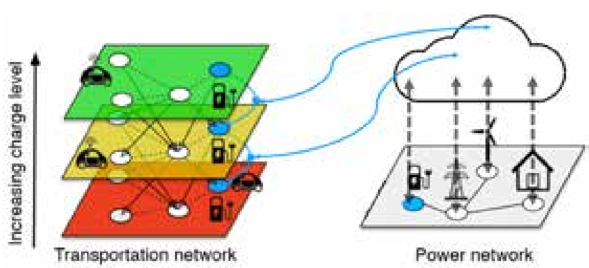
AUTONOMOUS EV FLEET COORDINATION

PI: Marco Pavone; Co-PI: Ram Rajagopal; Student: Justin Luke

Electrification and autonomy are driving down the total cost of ownership for vehicle fleets. Presently, autonomous electric vehicles (AEV) are being developed for fleet applications such as passenger mobility, delivery, and medium-range trucking. While the grid impact for these future electric fleets is not well understood, autonomous fleets have the advantage of highly controllable routing and charge scheduling compared to privately owned, human-operated EVs. With intelligent control, AEV fleets can not only avoid negative social externalities like exacerbated road congestion and overloaded grid infrastructure, but also play an active role in increasing transportation system efficiency and providing grid services.

This project develops a tool that computes the optimal placement and charging rate of EV charging stations in an urban setting with high penetration of autonomous EVs and PV solar installations. The optimal siting is determined jointly with the routing and charging of the fleet as a network flow problem, seeking to minimize infrastructure costs, electricity costs (including demand charges), and travel costs while observing road and power flow constraints. At a later stage, the optimization will integrate with the cloud-enabled grid overlay project which will communicate dynamic charging bounds to the fleet operator, allowing for online operation of the fleet while obeying grid constraints without needing to compute grid power flow in real-time.

Charging infrastructure is the coupling link between power and transportation networks, thus determining optimal station placement is necessary for planning of power and transportation systems. This tool will be purposed to provide rigorous analysis and simulation results to inform key industry players and policymakers in both systems.



LONG RANGE PLANNING FOR EV50: WHAT IS THE FUTURE DEMAND FOR CHARGING?

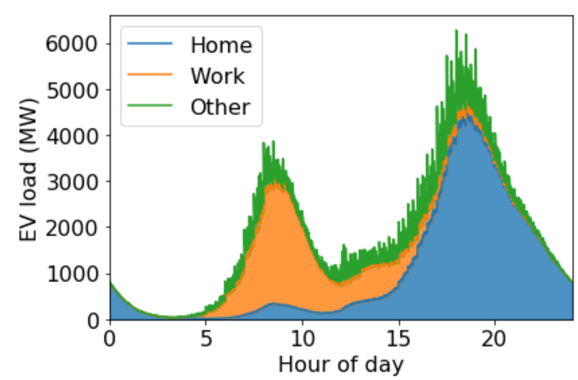
PI: Ram Rajagopal; Co-PI: Liang Min; Student: Siobhan Powell

To prepare for the future envisioned by EV50, a crucial first step is developing forecasts and scenarios. Forecasts of EV load will enable us to quantify the energy and capacity impacts of fast charging, study long-term grid planning, and define a framework for other key EV50 projects. The picture of EV charging in 2030 and beyond is affected by a multitude of uncertainties. The adoption of fast charging, changing rate schedules and market structures, drivers' choice to charge on-the-go rather than at work or at home, changing driver profiles, available charging infrastructure, new charging technologies drawing power at higher rates, and longer-range vehicles are all important variables that will impact the EV load of the future.

With this project we propose to develop a set of detailed, up-to-date, realistic scenarios for how these effects may play out in California and other regions around the world. Large sets of charging, mobility, and census data will be mined to understand key driving patterns and factors in charging behavior. These factors will be used to project future changes and reflect a range of behavioral and technical constraints on the load, including charger input and the impact of infrastructure constraints. The scenario generation will be data-driven and utilize a graphical modeling framework to capture the uncertainties, assumptions, and conditioning of the features impacting EV load.

With case-studies in California and other regions, a wide range of scenarios will be presented in publications exploring the large-scale potential impacts of EV charging. We will also develop and publish an open-source software tool implementing the model. An online interface will allow readers to interact with the model, alter assumptions, and generate new scenarios. We believe this will help communicate the uncertainties and assumptions impacting the scenarios, as well as offer insights to inform planning processes for a range of stakeholders.

> "Successfully integrating high levels of EV penetration into the energy ecosystem is a complex and important problem to solve. The Bits & Watts program is in a unique position to draw together the multidisciplinary teams to provide the strong, independent thought leadership required to address these problems."
>
> —CAMERON BRIGGS
> *Head of Future Energy, Origin Energy*



One possible scenario for the future electricity demand from private EV drivers in California

ONLINE LEARNING AND MANAGEMENT OF BATTERY SYSTEMS

PI: Nicolas Bambos; Co-PI: Ram Rajagopal; Student: Ilai Bistritz

The battery pack is the heart of the electric vehicle (EV). With better management of the battery, we can both improve the range and the health of every EV. The main task of the battery management system (BMS) is to balance the state of charge (SOC) of the different cells in the battery pack. To date, state-of-the-art cell balancing algorithms assume highly accurate SOC estimation which can only be achieved using model-based control solutions. Unfortunately, electrochemical models of batteries are too costly and are still not reliable enough to be used for cell balancing in practice. As a result, the prevalent method today is passive cell balancing, in which cells with an excess of charge just release it as heat. Passive cell balancing is not energy efficient and complicates the thermal management of large battery packs, risking a thermal runaway. This compromises safety.

Our project proposes a simple consensus-based cell balancing algorithm that does not assume any knowledge of the electrochemical model of the battery. Instead, our algorithm only uses SOC estimates from online measurements to make small and careful sequential balancing decisions. Our plan is to establish mathematically that our algorithm balances the battery even with very noisy SOC estimates. For the second step we will consider the more challenging case where balancing is done while the battery is charging or discharging. Balancing while charging can accelerate the charging rate, relying on the balancing mechanism to protect the cells from overcharging. The third step is to study the safety and reliability of our algorithm in simulations, which should also support the theoretical findings.

Compared to existing approaches, our model-free cell balancing method only requires a simple circuit and much cheaper sensors. As such, it has the potential to make active cell balancing practical. In contrast to passive cell balancing, active cell balancing is much faster and energy efficient. This enhanced energy efficiency both increases the range of the EV and allows for larger SOC margins that protect the health of the battery.

ALGORITHMS FOR FAST-CHARGING STATION MANAGEMENT

PI: Abbas El Gamal; Co-PI: Ram Rajagopal; Students: Lily Buechler, Emmanuel Balogun, Thomas Navidi

Increasing deployment of fast-charging stations will have significant impacts on power distribution systems by increasing voltage violations and accelerating transformer aging and battery degradation. At the station level, these effects depend on the integrated modeling and control of all system components: charger power electronics, transformers, battery storage, driver behavior, the distribution system, and other distributed energy resources.

This project will focus on the development of station-level modeling and simulation capabilities. This will require the development of component-level models that can be calibrated from real data and the underlying physics and then integrated into a station-level simulation. These models will be used to develop optimization and control algorithms to address various operational objectives, such as reducing demand charges and energy costs and mitigating battery and transformer degradation as well as distribution system impacts.

This platform will be used to analyze various use cases, such as using co-located stationary storage to absorb power fluctuations from unpredictable fast charging. The tools developed from this project could aid utilities with charging station grid interconnection and help charging station providers reduce system costs while mitigating grid impacts. Consequently, this project will minimize demand spikes, which in turn reduces generation loads and carbon emissions in our fight against climate change.

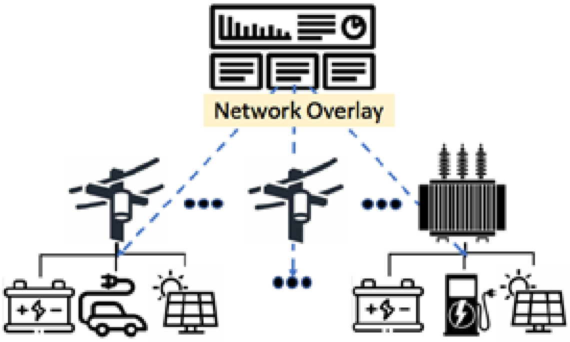
ELECTRIC VEHICLE CHARGING: NETWORK OVERLAY

PI: Guru Parulkar; Co-PIs: Ram Rajagopal, Arun Majumdar, Charles Kolstad, Nicholas Bambos; Students: Thomas Navidi, Emmanuel Balogun

Future EV charging demands, particularly fast charging, will require coordination between EV chargers, power networks, and vehicles to manage reliability of the grid. Such coordination requires information exchange across multiple devices and stakeholders in the system.

Purely centralized coordination would require data and objectives from all stakeholders in the system to be known by the coordinator. This is not practical as it does not satisfy the autonomy of each stakeholder in the system. Alternatively, traditional decentralized coordination approaches would require each charging facility—or even individual chargers—to be aware of the physical power network topology, transformer, and communication network constraints preventing the scaling of the solution. Instead, we propose designing a virtual overlay that decouples the utility power network and edge devices.

The overlay will enable edge devices to make their own local decisions while incorporating simple local constraints that ensure the voltage and transformer reliability of the network. Furthermore, virtual local storage manages unexpected local fluctuations. The network overlay also enables the information sharing necessary to design a variety of critical applications for the EV ecosystem, including green route planning of vehicles, dynamic pricing for the distribution system, and forecasting power and traffic.



Sponsored research projects allow for more in-depth collaborations between Stanford faculty and industry members on specific mutual research interests. Bits & Watts works closely with both industry members and the Stanford faculty to understand what the interests are and cultivate the collaborations by consistently facilitated conversations and engagements.

> "Reducing emissions from the transportation sector is critical to helping California achieve its climate and air quality goals. Bits & Watts provides an important and impartial platform for stakeholders to convene and develop system-wide, open-source approaches to electrify this sector."
>
> —ROY KUGA
> *Vice President, Grid Integration & Innovation*
> *Pacific Gas and Electric*

EMPOWERING THE CUSTOMER THROUGH DATA SCIENCE

PI: Ram Rajagopal; Co-PIs: June Flora, Hao Wang, Oskar Triebe, Chad Zanocco, Chin-Woo Tan, Gonzague Henri (Total) and Dimitra Ignatiadis (Total)

In recent years, utilities began deploying smart meters for residential customers unlocking a large amount of data. The first use case was billing automation, but with the development of data science, cloud computing and cheaper data storage we can now develop new use cases and generate more value from this data.

In this project, Total and Stanford look at different data science techniques that could increase customer engagement. This project has two parts: algorithms and behavioral science.

During this first year of collaboration, the team focused on developing the algorithm part of the project, the second year focusing more on the application and interactions with clients.

The following topics were investigated this year: monthly energy consumption forecasting, EV detection from AMI data, load disaggregation, activity detection, applying behavioral sciences to energy, federated clustering (privacy ML), and applying deep learning to time series.

Among the main results: the monthly bill forecasting task was completed, many update presentations were made to Total, an innovative alternative to standard load disaggregation looking at disaggregating activities rather than appliances was proposed, and a promising approach to bridge the gap between time series and deep learning was developed. In order to maximize customer engagement, a review of behavioral techniques that could be applied to the energy sector was completed.

CLOUD ELECTRICITY STORAGE

PI: Ram Rajagopal, Co-PIs: Ramesh Johari, Mohammad Rasouli, Tao Sun, Camille Pache (RTE) and Patrick Panciatici (RTE)

Electrical batteries are able to provide a wide range of services to the electricity system, at all levels of the grid, from the residential consumer to the system operator. With the rapid increase in battery integration with the grid, a better understanding of their potential for business is crucial.

This project studies an innovative business model for the usage of centralized electrical batteries by market players and small individual users, called Cloud Storage. In particular, we focus on two important but challenging problems: how batteries can be shared by end users, as well as other grid services, and to what extent users change their electricity consumption after having battery storage capability.

Empirical tests showing the effectiveness of both models were conducted based on a consumption data set comprising half a million households in California, combined with grid congestion data sets from RTE, the French Transmission System Operator. The future work of this project will be to study optimal contract designs for individual users in the proposed Cloud Storage framework given the estimation of users' consumption behavior.

> "The research cooperation with Stanford continues to be an eye-opener for us. Findings have helped us understand collaboration dynamics and patterns from new and useful perspectives."
>
> —STEFAN PADBERG
> *Managing Director, innogy New Ventures*

SHORT-TERM SOLAR PV PREDICTIONS WITH COMPUTER VISION AND DEEP LEARNING

PI: Adam Brandt; Students: Yuchi Sun, Vignesh Venugopal

Solar PV electricity generation is rapidly growing across the globe. The volatility of cloud movement introduces significant uncertainty in short-term solar power, which can complicate the operation of modern power systems.

Professor Brandt and his team incorporated over one year of 360-degree high-resolution sky video into computer vision models (convolutional neural network, CNNs) to predict 15-minute ahead output from a co-located PV array. They explored different methods of data pre-processing and test methods from the broader deep learning community to improve the ability of the models to ingest and interpret heterogenous data inputs (e.g., historical sky images and historical PV output).

The team is now partnering with Dubai Electricity and Water Authority (DEWA) to further demonstrate the technology at DEWA's photovoltaic Solar Park.

OPEN INNOVATION IN THE ELECTRICITY INDUSTRY: A MULTI-YEAR EXAMINATION OF THE FREE ELECTRONS PROGRAM

PI: Steve Comello; Co-PIs: Ann-Kristin Zobel (University of St. Gallen), Lukas Falcke (University of St. Gallen)

The electricity industry is undergoing structural changes due to a confluence of forces that can conveniently be summarized as the "Four Ds": decarbonization, digitalization, decentralization and deregulation. While this energy transition holds the promise of new technologies, business models, and competitive landscapes, the journey for any firm toward these endpoints is highly uncertain. This is true for both incumbents and new entrants. Incumbents may have assets, experience, and capital; however, the "business as usual" deployment of these capabilities may not enable these firms to thrive in the future. New entrants may have agility, ideas, and cutting-edge knowledge, but not necessarily the experience and resources to build, test, and deploy their solutions economically or at scale. In response, incumbents and new entrants may overcome their strategic constraints and complement each other in an open innovation (OI) environment in order to co-develop mutually beneficial solutions.

The Free Electrons (FE) program — a novel utility-backed innovation ecosystem — is a manifestation of such an OI environment. Now in its 4th year, it has brought together 10 utilities and 57 startups from across the world within a structured setting, where each is encouraged to form beneficial collaborations to test solutions, gain knowledge, and build critical relationships through a mediated, cohort-based approach. Researchers from the Stanford Graduate School of Business and the University of St. Gallen have been examining the Free Electrons program since inception, exploring such dimensions as: (i) OI collaboration formation, (ii) OI goal negotiation among heterarchical firms, (iii) effective OI program design, (iv) digital technology piloting strategies, and (v) OI program effects on startup success trajectories.

Research on FE continues to be a fruitful, rewarding relationship, where academia and industry support each other in developing findings that advance both practice and theory for the electricity industry and beyond. As an example, results from a study focusing on OI design were used to enhance FE program delivery and the subsequent academic manuscript was recently awarded "Best Paper" at the 80th Annual Meeting of Academy of Management.

VISDOM: VISUALIZATION & INSIGHT FOR DEMAND OPERATIONS & MANAGEMENT

PI: Ram Rajagopal; Co-PIs: June Flora, Chin-Woo Tan, Sam Borgeson

Improved understanding of consumers would enable utilities to target customers more effectively for demand-response and energy efficiency programs. It would also help distribution system operators manage consumption over small geographical areas. New sensors, advanced telecommunication, and smart meters supply the data to better understand the consumer, but a clear picture of actual energy use habits has been missing.

Visualization & Insight for Demand Operations & Management (VISDOM) is an open-source, web-based platform and architecture for load analysis and management. The goal of VISDOM is to enable researchers and practitioners to more easily interpret and learn from demand-side data and to apply those insights to improving demand-side management for the smart grid. It analyzes raw electricity use data and additional diverse data sources — like geographic, demographic and weather information — for unprecedented understanding of customer behavior. By incorporating standard statistical methods as well as newly developed and published algorithms, VISDOM allows a deeper understanding of load data from unconventional angles. VISDOM's open-source software is being developed with several major utilities and demand-response companies. It incorporates statistical methods, new algorithms, and machine learning in a graphical interface that is easy to use. In addition, VISDOM enables response modeling for each customer segment. This helps evaluate planned changes by revealing how customer segments will respond to signals and to what degree. VISDOM is now being used by more than 10 US utilities and an additional 15 utilities worldwide.

CLICK HERE TO LEARN MORE

Shared Facilities to Create and Demonstrate the Digital Transformation for the 21st century Electricity Grid

Stanford University is a living laboratory. The Campus Energy system, along with many other labs across campus, provide a contained and integrated platform upon which Bits & Watts researchers and industry affiliate members can create and demonstrate both individual technologies as well as integrated systems solutions.

BITS & WATTS LAB

The Bits & Watts lab features two smart energy homes. In the first home, we have a full set of electric appliances, an electric energy storage unit, a water heater and solar PVs on the rooftop of our building. The second home allows us to simulate the impact of thousands of various of smart appliances or distributed energy resources. These two homes are connected to a grid emulator, which allows both homes to exchange power with the grid in both sending and receiving. The lab allows faculty and students to develop and test customer-sited distributed energy resources (DERs) technologies individually or as an integrated system to enhance grid flexibility and thereby ensure reliable, safe, affordable, and sustainable electric service for customers.

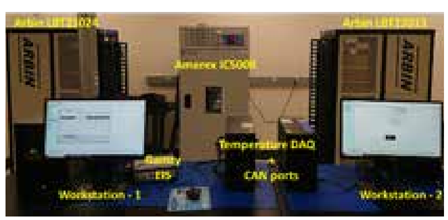
Professors Ram Rajagopal and Abbas El Gamal's team has successfully used the lab to demonstrate an end-to-end, opensource system that enables real-time coordination of utilities' centralized large assets with millions of distributed resources. It integrates embedded sensing and computing, power electronics, data analytics, and networking with cloud computing.

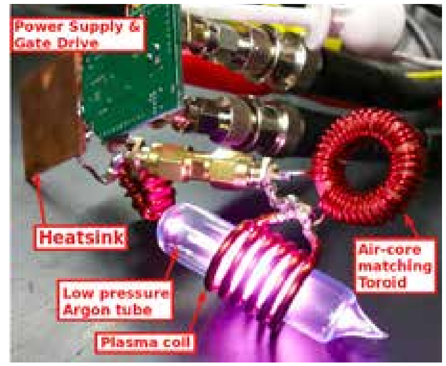
STANFORD ENERGY CONTROL LAB

The Stanford Energy Control Laboratory (SECL) led by Simona Onori is aimed towards physics-based and data-driven modeling, control, optimization, diagnostics, and prognostics of advanced energy storage systems for automotive and stationary storage applications. It tackles fundamental questions to both improve efficiency and longevity of existing energy systems — and at the same time optimize the development of the new-generation energy systems with the ultimate goal to accelerate the transition to clean energy grid and transportation.

It works closely with major industry players, academicians from domestic and international universities, and practitioners in the field of transportation and utility grid.

The laboratory consists of state-of-the-art battery testing equipment capable of performing real-time battery charging and discharging experiments with accurate programming control and fast data acquisition. It includes two Arbin systems, an Electrochemical Impedance Spectroscopy (EIS), and an auxiliary system to measure cell temperature and enable Controller Area Network communication.





SUPERLab

The Stanford University Power Electronics Research Lab (SUPERLab), led by Juan Rivas-Davila, researches the areas of scalable renewable energy integration, robust EV charging, and next-generation transmission and distribution systems. In particular, it explores new solutions and circuit topologies to leverage the advantages of wide-bandgap (WBG) power-semiconductor devices.

In an ongoing collaboration with the Stanford Center for Automotive Research (CARS), the SUPERLab is developing a next generation electric vehicle (EV) charging system that could one day wirelessly charge electric vehicles with order-of-magnitude improvements in efficiency, charging speed, and convenience compared to today's EV charging systems. The SUPERLab is developing power electronics that can intelligently and efficiently stabilize the grid, enabling a pathway towards a future electric grid built on renewable energy and power-electronics interfaced resources.

STANFORD'S CENTRAL ENERGY FACILITY

Stanford's Central Energy Facility (CEF) includes three large water tanks for thermal energy storage, a high-voltage substation that receives electricity from the grid, and an innovative heat recovery system that takes advantage of Stanford's overlap in heating and cooling needs. CEF, which doubles as a teaching tool, is powered completely by electricity, which Stanford has committed to procure from renewable sources.

The Bits & Watts SGCC Fellowship PhD student, Jacques de Chalendar, and his advisor, Sally Benson, developed planning and controls software to explore how the CEF can reduce costs, control the campus carbon footprint, and provide energy services to the power grid while simultaneously meeting the campus energy needs. With the help of the engineers and operators at the CEF, Chalendar also recently led a megawatt-scale experiment to participate in Pacific Gas & Electric's Capacity Bidding Program and test the campus's demand response capabilities.

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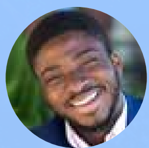
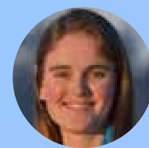
EDUCATION HIGHLIGHTS

STUDENTS

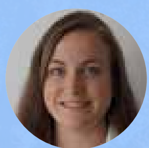

Emmanuel Balogun

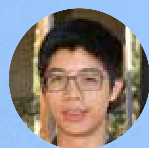

Ilai Bistritz


Lily Buechler


Jacques de Chalendar

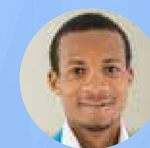

Weixuan Gao


Marie-Louise Alt


Justin Luke

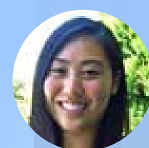

Kevin Moy

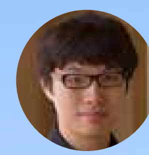

Thomas Navidi

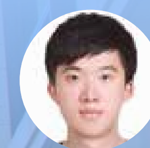

Olamide Oladeji


Siobhan Powell


Yuchi Sun


Kelly Woo


Jiafan Yu


Guanzhou Zhu

The digital grid of the future integrates technology, economics, business, and policy. Yet the education of industry experts has generally not interconnected these domains. Bits & Watts pursues a two-pronged education strategy:

1. Help industry executives broaden the expertise required for a holistic, data-driven approach to transforming the grid and give input on new research areas

2. Produce a new generation of Stanford graduates with a holistic and integrated understanding of emerging grid trends to continue the transformation

Industry Education: Bits & Watts has established a professional development program for executives of sponsoring organizations. This program includes lecture-style education modules and the Energy Innovation and Emerging Technologies Certificate (EIET) for executives to extend their knowledge in subjects outside their main area of expertise. Bits & Watts members are also able to assign their researchers to work at Stanford as visiting scholars.

Student Education: Bits & Watts provides full-time Stanford graduate and undergraduate students interested in the electricity industry with curricula of relevant courses for depth within their discipline and breadth in other disciplines. In 2019, we advanced our flagship Smart Grid Seminar (CEE 272T/EE292T) to focus on Electrification and offered a new course, Battery Systems for Transportation and Grid Services (CEE 292X/EE 292X).

ELECTRICITY MARKET DESIGN TO SUPPORT ITALY'S ENERGY TRANSITION

Visiting Scholar: Federico Quaglia, Head of Energy Operation Analysis and Studies at Terna. Stanford collaborators: Frank Wolak, Christoph Graf

Despite the distance, Italy and California have similar power systems in terms of their fundamentals (yearly consumption, peak load, solar and wind penetration) but very different electricity market designs. The California electricity market is based on a multi-settlement Locational Marginal Pricing (LMP) market, where energy and ancillary services are co-optimized and virtual bidding is allowed in the day-ahead energy market. On the other hand, the Italian market (in line with the European target model) is based on a zonal market, where energy is procured considering limited system constraints and ancillary services are procured afterwards in a dedicated market.

I spent 6 months at Stanford working with Professor Frank Wolak to identify the main sources of inefficiencies in the Italian market, assess the benefits of a potential switch toward a LMP market design and discuss its compatibility with the current European legal and regulatory framework.

Some of the key analysis and findings are an empirical assessment of the "inc/dec game" in the Italian market and competitive benchmark models estimating annual inefficiencies up to 2 billion euros (~10% of total costs). Project outcomes, summarized in a technical report, are currently supporting Terna in its discussions with the Italian Regulatory Authority in the context of the ongoing process for reviewing the Italian electricity market.

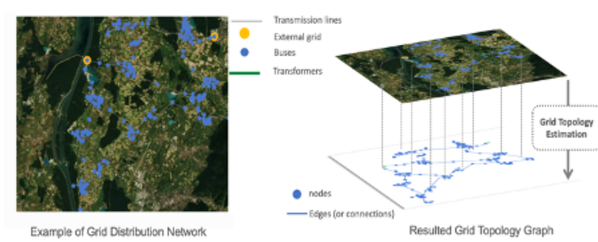
ESTIMATING DISTRIBUTION GRID TOPOLOGIES USING GRAPHICAL MODELS

Visiting Scholar: Ahmed Mabrouk, Research Scientist at Engie. Stanford collaborator: Ram Rajagopal

I am a research scientist at the R&D department of Engie, a French multinational electric utility company. I came to Stanford as a Data Scientist Engineer visiting scholar and not in my wildest dreams could I have imagined how much I would learn within a short period of time, how many different challenges I would tackle and how unique the people I would work with would be.

I have to come to appreciate how digital technologies, especially Artificial Intelligence (AI), can revolutionize the energy sector by improving the efficiency and control of the devices around us. Under the direction of Professor Ram Rajagopal at Stanford, I learned how I can apply these same principles to the distributed energy system. This project provided me with such a wide range of skills and abilities to propose new data-driven methodology to enhance the grid topology reconstruction using observational IoT data.

Benchmark networks IEEE 8-bus and 123-bus were used in the experimentation phase. We investigated the reliability of our methodology by considering the accuracy of the returned topologies. This has been done by a direct comparison between the estimated topologies and those of the true networks. The results obtained show an accuracy higher than 95%. We plan to extend our study to larger grid networks.



Example of Grid Distribution Network — Resulted Grid Topology Graph

STATE GRID CORPORATION OF CHINA SPONSORED FELLOWSHIPS

Bits & Watts founding member, State Grid Corporation of China, generously provides gift support for graduate and postgraduate fellowships focused on creative, multidisciplinary research projects that explore new directions for the digital grid transformation. Meet our graduate fellowship recipients.

JACQUES DE CHALENDAR

I joined the Energy Resources Engineering Department at Stanford University in 2014 as a Masters student to work on a micrometer-scale physics problem, aiming to better understand the long-term security of geologic carbon sequestration. Through discussions with fellow researchers and literature, I then became progressively engaged in my current work as a doctoral candidate to help shape the role of electrified and flexible urban energy systems in a decarbonized world. Throughout, I have been applying state-of-the-art computational tools to energy and carbon management problems.

The project I am currently working on focuses on tracking power system emissions in time, space and through electricity exchanges. This work was recently published in the Proceedings of the National Academy of Sciences. I am currently working on a real-time implementation of the tools we have built in this context.

Parallel to my pure research activities, my experience with the campus energy management systems has put me in a position to regularly advise the campus management as well as faculty committees as they seek to update the design of the current system to accommodate their future energy needs (cooling, heating, power).

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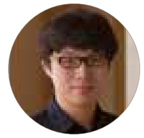

JIAFAN YU

In 2007, the documentary, *An Inconvenient Truth* made me aware of the challenge of climate change and I began to dream of contributing to a more sustainable society. I had already been working on the development of higher efficiency and lower cost solar cells.

My research focuses on integrating state-of-the-art artificial intelligence tools. Solar panels now account for over 10% of the total electricity generation in some U.S. states, such as California. But policymakers, utility companies, and engineers still find it difficult to put an accurate number on the country's total solar power installation, let alone to describe what factors make solar power thrive in certain areas and not others. I am developing a scalable deep learning tool, DeepSolar, that scans high definition satellite imagery across the U.S. to obtain accurate data on distributed solar panels' location and size. Analyzing over a billion high-resolution satellite images we found 1.47 million solar rooftop installations in the United States, a much higher figure than previously estimated. By combining this data set with socioeconomic data, we give unprecedented insight into the societal trends that drive solar power adoption.

DeepSolar is now a publicly available database for energy stakeholders to further uncover solar deployment patterns, build comprehensive economic and behavioral models, and ultimately support the adoption and management of solar electricity. In the future, I plan to create a better mechanism to provide more liquidity to the electricity market and connect the existing wholesale market and the emerging peer-to-peer retail market.

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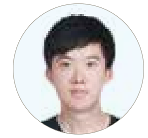

GUANZHOU ZHU

I first became interested in the field of renewable energy when I worked on graphene-based supercapacitor in my undergraduate research under the guidance of Professor Richard Kaner at the University of California, Los Angeles. With the growing need for clean energy to replace fossil fuels, I found myself very motivated to work in the renewable energy field. After coming to Stanford University for my Ph.D. studies, I decided to shift my research focus to battery storage, as the energy transition depends on technologies that allow the inexpensive temporary storage of electricity from renewable sources.

My Ph.D. research focuses on developing new types of batteries that are safe and possess a long cycle life, high energy density and high capacity. My current research is on developing a novel electrolyte for aluminum batteries.

Aluminum batteries are very safe to operate compared to lithium-ion batteries. In addition, aluminum batteries can withstand a much faster charge-discharge rate without sacrificing its capacity to a great extent. However, the operating voltage of the battery is limited by the voltage window of its electrolyte. Therefore, in order to further improve aluminum batteries, my current research is on developing an electrolyte that can withstand a much wider voltage window while maintaining the advantageous properties of aluminum batteries.

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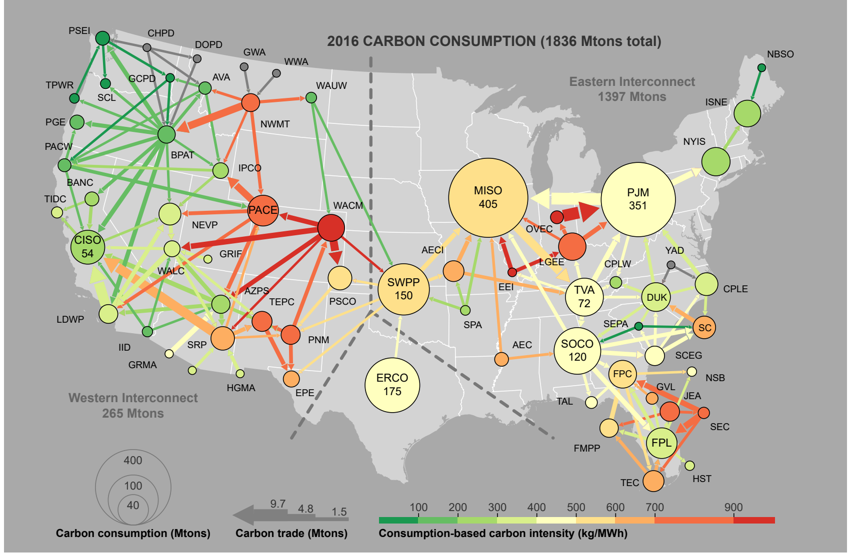

TRACKING EMISSIONS IN THE U.S. ELECTRICITY SYSTEM

PHD Student: Jacques A. de Chalendar: Advisors: Sally M. Benson, and John Taggart

The environmental quality of the electricity flowing through electric grids varies by location, season and time of day. About 30 percent of U.S. greenhouse gas emissions come from power plants that generate electricity by burning fossil fuels. Understanding electricity consumption and production patterns is a necessary first step towards reducing the health and climate impacts of associated emissions.

In this work, data from three publicly available sources have been combined to produce the first hourly emissions data set for the 66 balancing authorities in the US. The economic input-output model is adapted to track emissions flows through electric grids and quantify the pollution embodied in electricity production, exchanges and ultimately consumption for the sixty-six continental US Balancing Authorities (BAs). The novel, hourly and BA-level dataset we generate and release leverages multiple publicly available datasets for the year 2016. Our analysis demonstrates the importance of considering location and temporal effects as well as electricity exchanges in estimating emissions footprints. While increasing electricity exchanges makes the integration of renewable electricity easier, importing electricity may also run counter to climate change goals and citizens in regions exporting electricity from high emission generating sources bear a disproportionate air pollution burden. For example, 40% of the carbon emissions related to 2016 electricity consumption in California's main BA were produced in a different region. From 30 to 50% of the sulfur and nitrogen oxides released in some of the coal-heavy Rocky Mountain regions were related to electricity produced that was then exported.

Having precise data to untangle the complex flow of carbon is essential for policymakers hoping to address climate change. Whether for policymakers designing energy efficiency and renewable programs, regulators enforcing emissions standards, or large electricity consumers greening their supply, greater resolution is needed for electric sector emissions indices to evaluate progress against current and future goals. This new tool will also give large corporations a more rigorous way to monitor electricity use and reduce their carbon footprint.

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ENERGYATLAS (DEEPSOLAR) MAPS OUT NEARLY ALL U.S. SOLAR PANELS

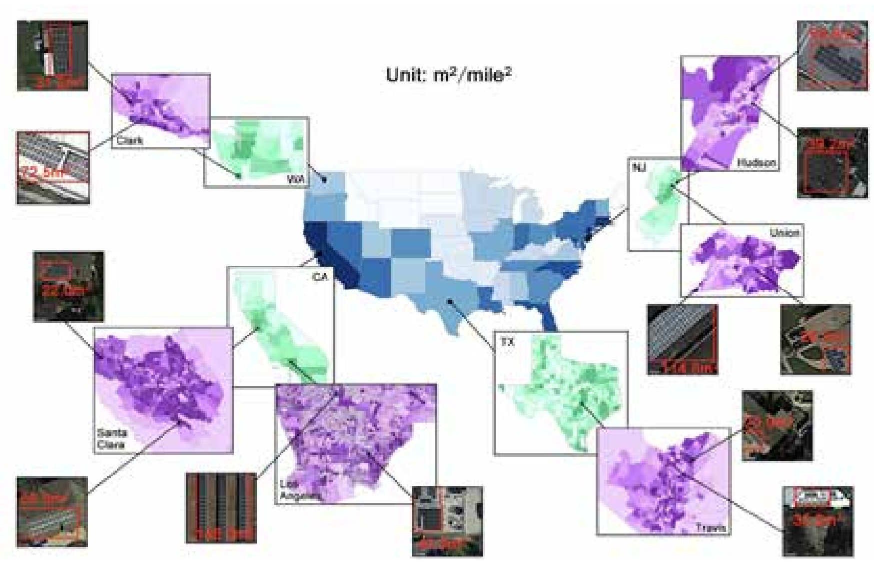
PhD Students: Jiafan Yu and Zhecheng Wang. Advisors: Ram Rajagopal and Arun Majumdar

Knowing where, what and how much distributed energy resource (photovoltaic, wind, storage, etc) has been installed is enormously useful in this time of pivotal change in the electricity industry. Jiafan Yu and Zhecheng Wang aim to develop automated tools to map, analyze, and maintain a comprehensive and highly granular energy atlas.

The first stage of EnergyAtlas, DeepSolar, is a deep learning framework that analyzes more than a billion high-resolution satellite images and identifies nearly every solar power installation in the 48 contiguous United States. Their analysis found 1.47 million installations, which is a much higher figure than either of the two widely recognized estimates. The data is publicly available on the project's website They also integrated U.S. Census and other data with their solar catalog to identify factors leading to solar power adoption. For example, they found that household income is important, but only to a point. Above $150,000 a year, income quickly ceases to play much of a role in people's decisions. By combining this data set with socioeconomic data, DeepSolar gives unprecedented insight into the societal trends that drive solar power adoption.

"We can use recent advances in machine learning to know where all these assets are, which has been a huge question, and generate insights about where the DER adoption is going and how we can help get it to a more beneficial place," said co-advisors Ram Rajagopal, associate professor of civil and environmental engineering, and Arun Majumdar, professor of mechanical engineering.

CLICK HERE TO LEARN MORE



BATTERY SYSTEMS FOR TRANSPORTATION AND GRID SERVICES

In recent years, battery systems have dramatically improved due to innovations in electrochemistry, materials, cell and battery pack design, modeling and control algorithms, and power electronics. Bits & Watts associated faculty, Professors Ram Rajagopal and Abbas El Gamal, developed this new course that provides an introduction to the design, modeling, analysis, and operation of battery systems for transportation and grid services. Specialists from Stanford, other academic institutions, national labs and industry cover all aspects of engineering and operating battery systems.

This course covers cell technologies, topology selection, thermal and aging management, safety monitoring, AC and DC charging, and operation control/optimization. Industry experts introduce students to the state of the art of each topic and provide a holistic view of the subject to those planning to research, design, analyze, model or just learn about battery systems. The course, CEE 292X/EE292X, is intended for graduate students in engineering or related disciplines, and engineers in industry who wish to design battery systems, model them from data, integrate them into applications, or just learn about them.

ENERGY INNOVATION AND EMERGING TECHNOLOGIES CERTIFICATE

The Stanford Energy Innovation and Emerging Technologies Program supports professionals currently working in energy fields to broaden or update their understanding of this complex field and gain insights into the trends and driving forces that will determine what the energy sector looks like a decade from now. Courses examine emerging technologies, policies, economics, finance, management, and behavioral science that will transform how we obtain, distribute, store, and use energy. This program brings together top Stanford faculty and Silicon Valley researchers who are responsible for discoveries in technologies ranging from battery design to solar panels.

Current offerings include:

- Building Energy Efficiency: Technology Policy & Finance
- Planning for a Sustainable Future with Wind, Water and the Sun
- Economics of the Clean Energy Transition
- Solar Cells
- Energy Storage
- Nuclear Energy – Why, How and Prospects
- Behaviorally Informed Design for Energy Conservation
- Past, Present and Future of Fossil Fuels

An *Energy Innovation and Emerging Technologies* Certificate Certificate, can be earned by completing any four courses within the program. Each course is self-paced and includes online video lectures, readings, and exercises. Completion should take roughly 3-4 hours per course depending on familiarity with the topic. These courses are available to Bits & Watts Affiliate members at a 10% discount.

ANNUAL INDUSTRY EDUCATION PROGRAM

On May 14-15, 2019 Bits & Watts hosted its annual education module. The goal of the Industry Education Program is to help industry participants broaden expertise required for a holistic, data driven approach to transforming the grid. This two-day intensive program featured lecture style courses and immersive learning. This year's program covered *Blockchain for the Energy Sector* and *Using Data Thinking and AI for Transforming the Electric Grid*.

Blockchain for the Energy Sector covered the fundamentals of blockchain technology, introduced smart contracts, and provided insights to help navigate the ecosystem of blockchain applications and services. He also covered the technological maturity and economic promise of blockchain based applications by analyzing a few implemented energy use cases including, among other things, congestion management in electricity distribution grids (emobility) and electricity wholesale trading (OTC).

Jens Strüker, managing director of the Institute of Energy Economics at the Fresenius University of Applied Sciences in Frankfurt led the *Data Thinking and AI for Transforming the Electric Grid* module. This course addressed utilization of large scale structured and unstructured data brought about by the adoption of renewables at the supply side, the emergence of mobile and stationary storage and connected consumers at scale. It covered data thinking, a systematic process to produce value from data, key AI technologies and their applications to the electric grid with prototypical problem statements and their solutions. Takeaways were the ability to understand where AI can play a critical role in your organization and a process to identify specific problems and solution opportunities.

CONVENING HIGHLIGHTS

"Two revolutions are driving our industry – renewable electricity sources and digitalization; and they are intersecting. The combined dynamics are driving unparalleled functional changes, particularly with the development of energy grids and their interconnections. The electric power system is at the center of this digital revolution. State Grid Corporation of China (SGCC) will continually support the Bits & Watts Initiative to embrace the new quantum leap of energy grids – "Internet of Energy.""

—MENGRONG (SHIRLEY) CHENG
President of State Grid US Representative Office

BITS & WATTS COMMUNITY FORUM

The Bits & Watts Community Forum is a regular gathering for the community of Stanford students, faculty, and researchers interested in the future of energy and/or doing work on the future electric grid. The Forum provides an opportunity for Stanford research and industry communities to gather in an informal setting, network and discuss the latest ideas and news about grid research and innovations. Engineers, lawyers, policy experts, economists, and psychologists are invited to participate.

Each meeting has a featured presenter from this broad constituency who shares briefly about their work, or what they are passionate about in the field, to spark conversations. The Community Forum generally takes place on Thursday evenings during Stanford term time. Bits & Watts provides complimentary food and drink to nourish our community and to encourage student attendance.

2019 Speakers Included:

- Lara Pierpoint, Exelon: Innovation at Big Utilities, and Career Path: from Academia to Government
- R. V. Guha, Google: Data Commons
- Vik Chaudhry and Kaitlyn Albertoli, Buzz Solutions: Artificial Intelligence and Predictive Analytics Solutions for Smarter Power Line Inspections
- Zhecheng Wang, Stanford: Deep Solar
- Nicola Peill-Moelter, VMware: VMware Microgrid
- Michael Wara, Stanford: Customer Resilience in a wildfire prone state
- Ram Rajagopal and EV50 Team, Stanford: Enabling beyond 50% adoption of Electric Vehicles
- Jessica Bian, Grid-X Partners, IEEE President Elect: Women in Power
- Will Paxton, Ford Motor Company: An electrifying future with Ford

SMART GRID SEMINAR

Many diverse issues need to be tackled if the electric grid is to be modernized using a holistic approach. Bits & Watts' Smart Grid Seminar (SGS) provides experts from startups, research institutes and large corporations to familiarize seminar participants with the challenges and advances in grid data analytics, economics, market design, battery storage, electrified transportation, power electronics, renewable energy integration, and system operations and resiliency. The speakers are renowned scholars from academic institutions or industry experts in power and energy systems. This seminar is offered quarterly as a 1-unit seminar course, CEE 272T/EE292T for interested students and lectures are open to interested members of the community.

More than 100 people attended a seminar on batteries with a Tesla senior engineer. Generally, participants wanted to learn about data utilization, solutions to real world problems, and the evolution of new technologies. The top research subjects were batteries and electric vehicles – including their evolving market structure and operations.

Our 2020 spring quarter SGS will be presented as an online webinar and focus on cyber-security.

2019 Speakers Included:

- Mandeep Waraich, Google: Application of Artificial Intelligence in Industry
- Chen-Ching Liu, Virginia Polytechnic Institute & State University: Grid Resiliency
- Dai Wang, Tesla Inc.: Battery Storage
- Yingchen Zhang, National Renewable Energy Laboratory: Predictive Analytics
- Jing Li, MIT: Compatibility and Investment in the United States Electric Vehicle Market
- Mahnoosh Alizadeh, UCSB: Safety-constrained Learning Algorithms for Demand Management
- Haiwang Zhong, Tsinghua University: Demand Response
- Karim Farhat, Pacific Gas and Electric, Vehicle Grid Integration
- Aleksi Paaso and Calvin Zhang, ComEd, Utility Work on DER Integration
- Mark McGranaghan, EPRI: The Digital Transformation of the Electric Power Industry

MAJUMDAR TESTIFIES TWICE BEFORE THE CONGRESS ON ENERGY R&D

The Senate Committee on Energy & Natural Resources examined opportunities for energy innovation to address global climate change in April. A diverse set of experts, including Arun Majumdar, told the committee that to address climate change the federal government should play a bigger role in both energy policy innovation, and energy research and development.

Majumdar told committee members that research targets should include: large-scale energy storage at one tenth of the cost of today's lithium-ion batteries; small modular nuclear reactors at half the construction cost of today's reactors; using renewable electricity to produce hydrogen from water instead of natural gas; affordably capturing carbon dioxide for making useful products; as well as innovations for low-carbon construction and agriculture. In February, Majumdar and others advocated tripling the budget of the Department of Energy's Advanced Research Projects Agency Energy to $1 billion. Also, they told the House Committee on Science, Technology & Space's Subcommittee on Energy, Congress could increase both the budgets and the effectiveness of the DOE's five applied energy offices and its Basic Energy Sciences program. Majumdar was the founding director of ARPA-E.

KOLSTAD SPEAKS AT GEIDCO CHINA-AFRICA FORUM

The Global Energy Interconnection Development and Cooperation Organization (GEIDCO), with its permanent office in Beijing China, is a non-governmental organization dedicated to promoting the establishment of a global energy interconnection system to meet the global demand for electricity in a clean and green way. GEIDCO recently seeks to develop untapped generation resources, such as hydropower in the Congo basin of Africa. In November 2019 GEIDCO hosted a conference focusing on Africa's role in this Global Project. It was attended by many, including many prominent representatives from African countries. Charles Kolstad was invited to participate and present insights on the economic dimensions of the ambitious project.

Kolstad's remarks noted the breathtaking ambition of the GEIDCO project and connected past experience with dams built in developing countries to spur economic development. Two examples from the 1960s are the Akosombo dam in Ghana and the Aswan dam in Egypt. Both projects have had real economic benefits but also have led to unanticipated consequences, both in terms of the propagation of disease and the difficulty in leveraging economic development from the projects. Assuring the security of generating and transmission resources is also a non-trivial challenge. The remarks were a combination of praise for the ambition of the project, combined with notes of caution, based on past experience developing hydro resources and power transmission lines in developing areas.

ENABLING BEYOND 50% PENETRATION OF ELECTRIC VEHICLES

On October 29, 2019, over 100 Stanford professors, students, and a select group of industry leaders and policymakers convened at Stanford to explore major opportunities and obstacles in electricity infrastructure development to enable beyond 50% penetration of electric vehicles (EV). Bits & Watts Co-director, Arun Majumdar, opened the workshop and laid out a series of challenges for the workshop panels and participants. Two Bits & Watts founding members, State Grid Corporation of China and Pacific Gas and Electric, shared their goals for the electrification of transportation in China and California respectively. In 2030, China's EV stock will reach 80 million and the power of all EV batteries will exceed 1 billion kilowatts. California has a goal of 5 million ZEVs on the roads by 2030 and 250,000 EV charging stations by 2025.

Twelve panel presentations addressed various aspects of emerging technologies, policy issues, and market potential. A number of important opportunities were identified through three facilitated panel discussions focused on market segments represented by utilities, automakers, and charging networks. Assembly member, Phil Ting, NRDC Attorney, Max Baumhefner, and former CPUC commissioner, Nancy Ryan participated in a fascinating EV policy fireside chat moderated by Charlie Kolstad. A key message delivered by them was that the current California policy for charging infrastructure for 2025 is insufficient. They would like to see more research on building out EV charging infrastructure.

Participant comments and questions in response to panel discussions raised many high-priority challenges and opportunities. The discussion, especially between the various stakeholders, was substantive, open and terrific! It highlighted things that are being resolved, and many other open issues that need to be addressed in our EV50 research program (page 6-8).

2020 LOOK AHEAD

Looking back at 2019, we can say with confidence that it has been a year full of substantive progress. Some of it came from the momentum that has been building since the launch of the Bits & Watts initiative four years ago. Particularly exciting for us, however, is the launch of focused research challenges, which have been guided by feedback and strategic dialogue with our global industry members. Our first effort of this type is our research program focused on Electrification of Transportation, which is highlighted by the flagship project called EV50 . In 2020 Bits & Watts will be continue to be guided by translating industry feedback into research and educational programs that involve our students, post-doctoral fellows and staff, in close engagement with our industry partners.

One of the strategic research areas that we have identified for 2020 is Grid Resilience and Security. Research in this area will forge collaborations and partnerships to address key challenges and opportunities in microgrids, cybersecurity, and electricity sector climate resilience. We are taking several actions to launch this research area including more seed grant investments, a new student summer internship program, and a focused Smart Grid Seminar series on grid resilience and security.

We are piloting a new partnership model – a Member Collaboration program – which provides a more agile and flexible platform for industry members to partner with Stanford researchers in projects that address issues of interest to a significant subgroup of members. These projects will build upon existing research and translate them into real-world applications at member demonstration sites.

Expanding the presence of members involved in “Bits” will be a core focus from the member engagement perspective. As a start, we will partner with our members to co-host a workshop “Digital Grid – Integrating Customer DERs”. The workshop will convene utility, information technology, and academic leaders to develop the research roadmap on a standardized data platform to interface customer DERs with the grid. Finally, to strengthen industry education, we are pleased to offer two new continuing education courses: Transforming the Grid and Electric Vehicles, in addition to our existing offerings.

This annual report is published during the global pandemic of COVID-19. This unprecedented event has led to a rapid digital transformation and widespread adoption of digital formats by many businesses. This change has already affected Bits & Watts; by moving our Smart Grid Seminar online, we have expanded our participation by over 100%. We hope to leverage this change and use this time to accelerate the transition.

Charlie Kolstad and Arun Majumdar, *Co-Directors* | Liang Min, *Managing Director*

BITS & WATTS INITIATIVE AFFILIATE MEMBERS

EPRI ELECTRIC POWER RESEARCH INSTITUTE

ENGIE

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HITACHI

innogy

origin

PG&E Corporation

Portland General Electric

RTE

SIEMENS

SMUD Powering forward. Together.

国家电网公司 STATE GRID CORPORATION OF CHINA

Terna

ABOUT US

Bits & Watts is a Stanford University initiative focused on developing innovations for the 21st century electric grid—a new grid paradigm that is needed to incorporate large amounts of clean power and a growing number of distributed energy resources, while simultaneously enabling grid reliability, resilience, security and affordability.

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