Statement of Research

Sanmukh Rao Kuppannagari
https://sanmukh.github.io

The urgency of global warming is propelling several governments into adopting ambitions targets on the portion of electricity generated from renewable energy resources. The traditional paradigm of centrally administered power plants supplying energy to a large portion of consumers is rapidly being transformed into complex distributed system with limited central control. This is being driven by the proliferation of modern small-scale Distributed Energy Resources (DER) such as photo-voltaics, wind turbines, and home energy storage solutions such as Tesla Powerwall. The energy output of these distributed energy resources is highly variable, hard to predict, and depends on the time of day, season, and even the prevailing weather conditions. As a result, operators are facing significant difficulties due to continually increasing frequency of supply-demand mismatches which can lead to catastrophic failures in the grid if not regulated quickly.

Further increase in the proliferation of DERs in response to the government targets will only exacerbate the difficulty of grid operators and make the reactive nature of regulation ineffective. Because of the discrete configuration space of DERs, the optimization landscape is highly multi-dimensional and consists of non-convexities and mixed integer constraints. Novel solutions which can handle this complex optimization space are needed to pro-actively schedule the DERs to enable smooth transition to a 100% renewable energy powered grid.

The focus of my research is to develop data-driven algorithmic techniques for **fast scheduling of DERs with efficient and provable worst-case guarantees under prediction uncertainties** to enable the grid operators make this transition. These include approximately optimal scheduling algorithms for DERs with discrete complex power injections [EENERGY19, Thes18, TOSN18, ISGT18, BuildSys17, ICCS16], reinforcement learning algorithms to control systems with unknown dynamics [IoTDI19, BuildSys19], and a flow graph based scheduling framework to aid utility operators in deploying Mobile Energy Storage Solutions (MESS) [LOCS19, SUST18]. I have demonstrated the effectiveness of these techniques on USC Microgrid, in collaboration with the Los Angeles Department of Water and Power (LADWP), as part of the DOE-sponsored Smart Grid Demonstration Project [IJCAI16]. Through this and future research — by leveraging my expertise in optimization theory, discrete approximation algorithm design, Reinforcement Learning — I hope to develop novel, environmentally responsible solutions to the challenges resulting from rapid urbanization and population growth enabling transition to reliable and sustainable **Autonomous Cyber Physical Energy Eco-Systems** of the future.

Current Research

Approximate Scheduling of DERs with Discrete Complex Injections

DERs such as PVs, controllable loads, storage and EVs exhibit discrete control configurations. Grid operations with these DERs require fast optimization over non-convex, mixed integer feasible space. As we show in [ISGT18], existing heuristic solutions which do not provide theoretical worst case guarantees on constraints violations (supply-demand mismatch) can lead to unbounded errors ranging from 2-95%.

To address this issue and enable fast optimal scheduling of DERs, we developed a suite of approximation algorithms that minimize cost objectives and provide worst case guarantees on constraint violations. A few examples of such algorithms include:

Scheduling DERs to Achieve Target Output Under Prediction Model Uncertainty
Objective: Given a set of DERs, with each associated with a set of control options, and each control option for each DER associated with a cost and a complex power output prediction, the objective is to schedule the DERs to minimize cost, ensure that collectively the DERs achieve the complex power target and reduce the uncertainty (target shortfall) due to the stochasticity of the prediction model.
Result: We developed a dynamic programming based two-stage stochastic decision making polynomial runtime complexity algorithm that outputs a solution which with probability $1-\delta$ has a cost within $1+o(\varepsilon)$ of the optimal and uncertainty within $2+o(\varepsilon)$ of the optimal while requiring only $\theta(\lambda^2\varepsilon^{-2}\log|X|\log\frac{1}{\delta})$ samples from the prediction model, where $\delta > 0.5$ is a probability parameter, $|X|$ denotes the size of input and λ is a problem parameter which bounds worst case uncertainty of the model [EENERGY19, Thes18].
Scheduling DERs with Fairness
Objective: As before, with added constraint that over a horizon, no DER should output more than a pre-defined budget value to ensure equitable contribution in grid operations from all DERs.
Result: We developed a linear programming rounding based polynomial runtime complexity algorithm which outputs a minimum cost solution and which in the worst case violates the target constraints and budget values by a factor of 2 [BuildSys17].

Reinforcement Learning based DER Scheduling

Reinforcement Learning (RL) has found widespread success in decision making in systems with unknown dynamics. The dominant paradigm for application of RL in smart grids is to train an independent RL agent for each DER in the grid. This paradigm produces optimal results for the individual DERs but, as we show in [IoTDI19], leads to severe grid constraint violations.

We addressed these limitations by developing novel techniques for safe exploitation in decision making and exploration in learning. For safe exploitation, we developed a co-operative RL framework in which each DER is associated with a RL agent and a co-operation agent based on low complexity knapsack approximation algorithm combines the output of the DER agents in each interval to ensure that the constraints are met. We showed empirically that our approach performs cost optimal DER scheduling while encountering close to zero constraint violations [IoTDI19]. For safe exploration, we ensured that the action sampling is performed as a bounded random walk to reduce the probability of constraint violations [BuildSys19].

Flow Graph based Scheduling Framework for Mobile Energy Storage Systems

Traditionally, Energy Storage Systems (ESS) have been used to implement a plethora of cost reduction techniques for smart grid operations such as temporal supply-demand shifting, frequency regulation, voltage regulation etc. However, the stationary nature of ESS limits their flexibility, potentially leading to low utilization and risk being a stranded asset. Thus, we explored the use of Mobile ESS in implementing such cost reduction techniques in a grid consisting of multiple microgrids [LOCS19, SUST18]. Scheduling Mobile ESS is challenging as in addition to generating the temporal charging/discharging schedule of each ESS, spatial assignment of mobile ESS to micro-grids needs to be produced.

We addressed this problem by designing a flow graph model for scheduling mobile ESS. The flows in the graph represent the temporal and spatial assignment of the mobile ESS as well as their charging/discharging control options. We then developed greedy path based algorithms which are either optimal [SUST18] or provide a $\frac{1}{e}$ (sub-modularity) approximation [LOCS19] to the problem under appropriate assumptions.

Future Directions

My future vision is to enable development of **Autonomous Cyber Physical Energy Eco-systems**. I define them as diverse Internet-of-Things (IoT) enabled physical infrastructure systems where energy plays a major role (such as smart grids, smart buildings, urban mobility (self-driving EVs)) interconnected at the 'Cyber' level — the control and monitoring is performed by computer-based algorithms. These eco-systems are characterized by synergies and inter-dependencies between various layers (physical infrastructure systems).

The current monitoring and control in these systems is segregated, sporadic, and requires significant human involvement. With the rapid pace of urbanization, this is becoming unsustainable. My research will focus on developing a holistic framework for these eco-systems which senses the environment, updates its internal model of the environment and decides actions to maximize objectives such as cost or social welfare — thus making these eco-systems **autonomous**. Such a framework will require two main components:

Data Driven Environment Model: The complex unknown dynamics of the environment will require us to rely on data driven techniques for modeling the environment. The vast amount of data obtained from IoT based sensing devices provides great opportunities for the same. However, several challenges exist: (i) Fast accurate inference on the complex model is needed to obtain live system status in real-time, and (ii) partial observability of assets will reduce the accuracy of the model. I have done some preliminary research on developing data driven approaches for improving real time PV observability [EENERGYW19, PREP20] and for generating synthetic timeseries load and generation data in smart grids [SGCOMM18]. I will further build upon this research to develop novel data driven solutions for modeling the complex environment of Cyber Physical Energy Eco-systems.

Real-time Scalable Optimization Framework: Decision making in these eco-systems will require algorithms which perform cross layer optimization targeting multiple objectives and constraints. The optimization framework will need to react rapidly to the changes in the environment. Thus, fast decision making is needed. Scalability is needed to handle the large and growing number of assets in the environment. This will expose a rich set of problems both from a theoretical perspective and a practical stand point. I see an opportunity to make foundational contributions to both the theory of decision making and its application to real world environments.

My research will enable transition to efficient, reliable and scalable *Autonomous Cyber Physical Energy Eco-systems* by developing tractable computing solutions in these 'Cyber' based eco-systems. My research will be instrumental in developing sustainable, environmentally responsible solutions in these eco-systems. I believe that my expertise in optimization theory, discrete approximation algorithm design, Reinforcement Learning and my knowledge in the domain of smart grids will serve me in developing novel as yet unheard solutions which will play a positive and hopefully significant role in tackling climate change, sustainability and urbanization which are key challenges of the 21st century.

References

[PREP20] Chung Ming Cheung, Sanmukh Rao Kuppannagari, Ajitesh Srivastava, Rajgopal Kannan, and Viktor K Prasanna. "Behind-the-Meter Solar Generation Disaggregation Using Consumer Mixture Models". In: *Preparation for a suitable journal* (2020).

[EENERGYW19] Chung Ming Cheung, Sanmukh Rao Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Towards Improved Real-Time Observability of Behind-Meter PhotoVoltaic Systems: A Data-Driven Approach". In: *Proceedings of the Tenth ACM International Conference on Future Energy Systems*. ACM. 2019, pp. 447–455.

[EENERGY19] Sanmukh Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Approximate Scheduling of DERs with Discrete Complex Injections". In: *Proceedings of the Tenth ACM International Conference on Future Energy Systems*. ACM. 2019, pp. 204–214.

[LOCS19] Ajitesh Srivastava, Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Minimizing Cost of Smart Grid Operations by Scheduling Mobile Energy Storage Systems". In: *IEEE Letters of the Computer Society* 2.3 (2019), pp. 20–23.

[BuildSys19] Chi Zhang, Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Building HVAC Scheduling Using Reinforcement Learning via Neural Network Based Model Approximation". In: *Proceedings of the 6th ACM International Conference on Systems for Energy-Efficient Built Environments*. ACM. 2019.

[IoTDI19] Chi Zhang, Sanmukh R Kuppannagari, Chuanxiu Xiong, Rajgopal Kannan, and Viktor K Prasanna. "A cooperative multi-agent deep reinforcement learning framework for real-time residential load scheduling". In: *Proceedings of the International Conference on Internet of Things Design and Implementation*. ACM. 2019, pp. 59–69.

[ISGT18] Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "NO-LESS: Near optimal curtailment strategy selection for net load balancing in micro grids". In: *2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*. IEEE. 2018, pp. 1–5.

[TOSN18] Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Optimal Discrete Net-Load Balancing in Smart Grids with High PV Penetration". In: *ACM Transactions on Sensor Networks (TOSN)* 14.3-4 (2018), p. 24.

[Thes18] Sanmukh Rao Kuppannagari. "Discrete Optimization for Supply Demand Matching in Smart Grids". PhD thesis. University of Southern California, 2018.

[SUST18] Athanasios A Rompokos, Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Minimizing Cost of Load Matching in Multiple Micro-Grids Using MESS". In: *2018 IEEE Conference on Technologies for Sustainability (SusTech)*. IEEE. 2018, pp. 1–7.

[SGCOMM18] Chi Zhang, Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Generative adversarial network for synthetic time series data generation in smart grids". In: *2018 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*. IEEE. 2018, pp. 1–6.

[BuildSys17] Sanmukh R Kuppannagari, Rajgopal Kannan, and Viktor K Prasanna. "Optimal net-load balancing in smart grids with high PV penetration". In: *Proceedings of the 4th ACM International Conference on Systems for Energy-Efficient Built Environments*. ACM. 2017, p. 27.

[IJCAI16] Sanmukh R Kuppannagari, Rajgopal Kannan, Charalampos Chelmis, and Viktor K Prasanna. "Implementation of Learning-Based Dynamic Demand Response on a Campus Micro-Grid". In: *The 25th International Joint Conference on Artificial Intelligence*. IJCAI-Demo Track. 2016.

[ICCS16] Sanmukh R Kuppannagari, Rajgopal Kannan, Charalampos Chelmis, Arash S Tehrani, and Viktor K Prasanna. "Optimal Customer Targeting for Sustainable Demand Response in Smart Grids". In: *Procedia Computer Science* 80 (2016), pp. 324–334.