Research Statement

Yu Yang (yu.yang@bears-berkeley.sg)

1 Background and Overview

My research is to provide a *hybrid solution package* to advance a *sustainable*, *flexible*, and *efficient* energy system from the perspective of *control*, *optimization*, *market design*. By proposing to integrate computation, communication and control into physical systems, Cyber-Physical System (CPS) technologies are transforming the way people interact with physical systems, just as Internet is altering the way people interact with information. People are no longer passively exposed to systems, but proactively interact with systems. Facing the severe global energy crisis, CPS technologies are rapidly penetrating energy system, advancing its transition towards Cyber-Physical Energy System (CPES).

Along the transition to CPES, energy system has been experiencing the rapid evolution: the electrification of transportation system (e.g., electric vehicles), the growing scale and integration (e.g., commercial heating, ventilation, air-conditioning system), and the emerging distributed renewable (e.g., wind power, solar power, hydrogen energy, etc.). These represent both challenges and opportunities for the transition. Particularly, *i)* the electrification of transportation system from the surge of electric vehicles (EVs) makes it possible to pursue carbon-free transportation, but poses the issue of handling the dramatic charging demand; *ii)* the growing scale and integration, such as the commercial heating, ventilation, air-conditioning (HVAC) system supplying multi-zones or rooms, makes it possible to improve the overall energy efficiency through coordination but faces the multiplied computational complexity; *iii)* the development of renewables can compensate the shortage of fossil fuels, but requires to address the volatile and non-dispatchable nature of supply.

To address the above issues, we need to empower the computation, communication, and control capabilities of CPES by deploying advanced control methods. However, CPES is a *hybrid* complicated networked dynamic system that faces various computational challenges:

1) *Multi-stage*: The evolution of CPES generally shows complex multi-stage dynamic process. For example, due to the thermal capacity, building shows delayed thermal effects. Besides, the energy demand is temporally coupled due to the presence of energy storage (e.g., electric vehicles, batteries, etc.). This implies the operation of CPES corresponds to multi-stage control and decision-making problems, which not only needs to consider the outcome for the current stage but also the long-term effects in the future.

2) *Uncertainties*: The dynamics of CPES suffer from various uncertainties which may arise from the energy consumption behaviors of occupants or the weather conditions that affect the thermal demand and renewable generation. To ensure the temporally and spatially dynamic balance of supply and demand under uncertainties is a challenging problem.

3) *Non-convexity*: The functioning of CPES imposes various non-linearity and non-convexity which may originate from the conversion of different energy types, transmission loss, and charging/discharging efficiency, etc. For example, the buildings' HVAC system involves the conversion of electricity and heat. The charging and discharging process of ES and EVs are subject to the efficiency. These bring non-linearity and non-convexity to the problem.

4) *Scalability*: CPES has the feature of large scale both in the subsystem and integration levels. This means scalable and computationally efficient solutions are required to ensure the timely response to the changes or disturbances.

To address the multiple challenging issues with the practice of CPES, my research has taken an effort in integrating the interdisciplinary theories and techniques including *reinforcement learning* (RL), *stochastic optimization*, *hierarchical control*, *decentralized optimization*, and *game theory*, etc., to explore a *hybrid solution package*. For example, I have combined RL with multi-agent distributed computation to achieve the synergy of EV charging with on-site renewable generation in building microgrid. Besides, I have integrated hierarchical control with decentralized optimization for commercial HVAC control to save energy and enhance human comfort. For the integration of renewable and ES technologies, I have combined stochastic optimization with game theory to design business models with high economic benefits. My works have been directly driven by the SinBerBest project with the top-prioritized target of saving energy, enhancing human comfort and exploring sustainability. My research progresses have already led to a number of publications on the prestigious transaction journals including TSG, TASE, TCST, etc.

2 Past and Current Research

2.1 Scalable EV Charging Scheduling [1–5]

The surge of electric vehicles (EVs) on the roads poses dramatic charging requests to be handled. Exploring a *friendly* manner to "fuel" EVs while relieving the grid stress has emerged as an urgent issue. The overall generating capacity of renewables has been proved to be fully or at least largely fill the EV charging demand, however it requires to address the issue of using volatile and non-dispatchable renewable supply to fulfill partially controllable demand. More specifically, to achieve the objective of best utilizing renewable generation to fill EV charging demand, we are required to optimize the charging processes of EVs to *temporally* and *spatially* align with the non-dispatchable renewable supply. However, there exist multiple computational challenges to be addressed: *i) Multi-stage*: the charging process of each vehicle corresponds to a multi-stage process subject to the occupant-based driving requirements; *ii) Uncertainties*: the uncertainties both originate from the EV charging demand and the distributed renewable generation; *iii) Scalablity*: the population of EV to be charged over each period is generally large. To address these computational challenges, we have combined reinforcement learning (RL) with distributed computation to provide an effective solution [1]. Decentralized or distributed computation has been acknowledged as an effective way to provide scalability, however achieving a specified *systematic* objective through decentralized or distributed computation has been the underlying challenge. For the microgrid formed by multiple buildings where buildings work as the intermediates for providing charging service, we have empowered each building to work as an agent to "learn" the optimal charging policies for the parked EVs based on historical data [1]. Particularly, to ensure convergence, we proposed a sequential "learning" algorithm for the building agents with performance guarantee. Since the marginal cost of renewable generation is minor, the proposed charging policies can lead to 70% electricity bill reduction for the buildings while not compromising the occupant driving requirements. Further, regarding the interactions between the EVs and buildings, we developed an EV-based decentralized charging algorithm by allowing the EVs to interact with the buildings through a dynamic charging price "signal". To ensure the convergence to the *systematic* objective, we proposed a dynamic charging price model triggered by the supply-demand gap. The convergence and convergence rate of the method was theoretically studied [2]. This decentralized charging algorithm is easy to be deployed for on-line charging scheduling due to the high computation efficiency of seconds and the communications only between the individual EV and the buildings.

2.2 Energy-Efficient HVAC Control [6–9]

The heating, ventilation and air-conditioning (HVAC) systems account for about 40–50% energy use in buildings for providing human comfort. The current way of HVAC operations not only suffer from the low energy efficiency but also are largely unsatisfied due to the discomfort. This raises our conscious to develop advanced HVAC control to enable *energy-efficient* buildings: *enhancing human comfort with least energy use.* Though the HVAC control has attracted extensive attention in the literature, the practice for commercial buildings still suffers from the computational challenges caused by system *complexities* and *scale*. The *complexities* mainly come from the energy conversion of different types within the dynamic process, posing non-linearity and non-convexity. The *scale* results from the integrated structure of commercial HVAC system that supplies multiple zones or rooms with thermal interactions. To overcome the computational challenges, we have combined relaxation technique with distributed computation by exploring the problem structure to provide a scalable solution [8]. The proposed decentralized method is scalable to the control of commercial HVAC system supplying 500+ zones and can reduce the electricity bill of HVAC system by about 19.3% while still maintaining the general comfortable temperature range $[24, 26]$°C. Further, to enhance human comfort, we proposed to jointly manage the thermal comfort and indoor air quality (IAQ, represented by CO_2) for HVAC control. This problem complexity is multiplied due to the two-dimensional parameters (i.e., temperature and CO_2) that couple the HVAC control. We have incorporated the relaxation technique, hierarchical control and distributed computation to provide a scalable solution to overcome the computational challenges [7]. We showed that the proposed control method can provide both thermal comfort and IAQ, which are closely related to working productivity and human health. More notably, it can further reduce the electricity bill of HVAC system by 8-10% compared with the separate management of thermal comfort and IAQ.

2.3 Distributed Renewable Integration [10, 11]

Achieving greater renewable integration is one of the critical issue facing the energy system transition. Energy storage (ES) has been acknowledged as one of the key technologies to achieve the target but still largely impeded by the high capital cost. Nevertheless, the economic benefits not only depend on the capital cost but also rely on the way we use it. This motivates us to study appropriate ES business models to enable higher renewable integration (i.e., increase the economic benefits of ES from local renewable integration). *Sharing economy* has been disruptive in transportation and housing systems. Such idea is naturally penetrating energy system for bringing in capital-intensive technologies like ES. However, different from other resources, the optimal sharing of ES corresponds to a multi-stage optimization problem which couples the optimal sizing and operation, making it non-trivial to achieve the stable and fair benefit or cost allocation among the different stakeholders. Considering the practice, we have studied two general sharing paradigms: *i) community ES sharing*, and *ii) third-party based ES sharing*. *Community ES sharing* requires to address the ES capital allocation among a group of cooperative users with local renewable generation that correspond to multi-step heterogeneous charging and discharging patterns. To address such issue , we have applied coalition game to capture the cooperative behaviors of building participants within the community and developed a fair *ex-post* cost allocation based on the *nucleolus* and constraint generation technique [11]. We show that the cost allocation mechanism is much more scalable than the existing methods due to the high computation efficiency (i.e., less than 1% over the existing methods). For example, it can handle the cooperation of 20+ peer participants within a community while the existing methods fail due to the exponential computation burden. Moreover, the proposed ES model can largely enhance the economic benefits for peer participants and enable higher utilization of local renewable generation. On top of that, we studied a more scalable and flexible sharing paradigm, referring to *third-party based ES sharing* that is led by an entity among its "consumers" [10]. This kind of ES models can unload the high initial cost from the consumers and enable the dynamic join and drop out. However, different from *community-based ES sharing* only with peer participants, this kind of ES models requires to address the benefit allocation among the stakeholder of asymmetric roles (i.e., the entity and its "consumers"). A number of existing works have studied similar ES sharing models but are deficient in ensuring the entity profitability and consumer incentives, which are critical for practice. To address such issue, we have proposed a quadratic price model based on the throughput of renewable storage over the contracted periods, which can achieve the objective of ensuring both the entity profitability and consumer incentives. The proposed ES sharing model can enable greater utilization of local renewable generation over the existing sharing models.

3 Future Works

Currently, we have mainly focused on improving energy efficiency of single buildings and enabling the buildings to consume renewable generation locally. One natural next step is to explore the interactions of end-users, buildings, and microgrids. From our perspective, three directions are closely related to the further practice of CPES and deserve deeper study and discussions.

3.1 Efficient P2P Energy Trading

The evolution of energy market from the top-down hierarchical structure to a consumer-centric decentralized structure is foreseeable with the presence of distributed renewable and ES technologies. Consumers are now transforming to prosumers, capable of both producing and consuming energy. Allowing the energy trading or sharing among prosumers is expected to further improve the *flexibility*, *efficiency*, and *self-consumption* of energy communities at orders. Therefore, one of our future works is to study the efficient peer-to-peer (P2P) energy trading market. Though there exists some related works, there are still a couple of important problems remaining to be addressed. For example, differing from the trade of other commodities that only couples the seller and buyer, the settlement of energy trading in virtual layer actually relies on the delivery of physical layer that undertaken by the grid operator. Besides, enabling free P2P trading could degrade the present profit of some stakeholders, such as the energy producer who may face profit loss due to the shrink of supply. Therefore, an efficient and effective P2P market requires to rethink the relationship of different stakeholders and explore the appropriate profit streams for them. For example, we may reward the grid operator for transmission with a network charge imposed on the P2P orders, etc. [12, 13]. However, how to design the network charge is an unresolved issue which determines the efficiency of the whole system.

3.2 Sharing and Trading of Information

The development of Internet of Thing (IoT) technologies, such as smart sensors and smart meters in energy system, are inducing massive data, which are important to support the operation of CPES. On one hand, data is important for system formulation; on the other hand, data are the fuels of many data-driven techniques, such as machine learning (ML). For energy system, the data are generally dispersedly collected and owned, and there is no motivation for the owners to contribute the data. Therefore, building a data market to enable the sharing or trading of data is expected to be a profound direction to advance the practice of CPES. This is expected to benefit both the data owners and the overall CPES operation. Data market has attracted increasing attention in machine learning (ML) context, such as the data valuation and selection based on Shapley value and Least core for the training accuracy of neural networks [14, 15]. However, the problem is quite different in energy system as it generally corresponds to the multi-stage operation of systems. In energy system context, some exploratory works have showed the economic benefits. For example, by incentivizing the users to sell their historical energy use data to the retailer can benefit both the users and the retailer [16]. However, such researches are still in deficient and at the very early stage, which requires to develop systematic data valuation and attribution for *multi-period* operation of energy systems.

3.3 Coordination of Multi-Energy System

Energy are present in different types, such as electricity, heat, fuels, etc. Typically, those types of energy are diversely required by buildings for making our life. Currently, the planning and scheduling of the different types of energy in energy systems are independent, leading to the low overall energy efficiency. The development of hydrogen technologies has destroyed the barriers for the conversion of different energy types, making it possible to develop multi-energy-coordination systems due to the two main technical advantages: *i)* there are multiple ways of producing and consuming hydrogen (e.g., generate heat or electricity, or burned, etc.); and *ii)* Hydrogen can work as energy carrier with high carrier value, no pollution when burned, long-term storage potential and easy long-distance transport. Therefore, using hydrogen as the medium to study the coordination of multi-energy system is expected to be a promising direction to further enhance the efficiency of energy system.

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