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Electrifying Lives with Community Empowerment

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World Bank's ambitious 'Agenda 2030' includes seventeen Sustainable Development Goals (SDGs) with 'Energy' being the major SDG that interlinks others. Globally, there are about three billion people living in energy poverty, and over one billion people with no access to electricity. Electricity availability is critical for health care delivery, access to clean and safe water, boosting education (which is one of the most important instruments for poverty reduction), obtaining inexpensive and safe lighting and economic empowerment. Regarding economic empowerment, electricity can increase household per capita income by 39 percent as businesses operate at higher levels of productivity. Farmers can also run cleaner irrigation systems and processing machines that improve their yields and thus, their income. So far, only 1.8 million people have gained tier-2 energy access by using off-grid electrical services. To address energy poverty, new strategies are needed to scale energy access solutions 1000x.

Being an initiative of the IEEE (Institute of Electrical and Electronics Engineers) Power Electronics Society (PELS) that is supported by the IEEE Foundation, IEEE Empower a Billion Lives (EBL) Competition is a biennial global competition aimed at fostering innovation to develop new age solutions for alleviating energy poverty worldwide. The solutions are expected to be scalable, regionally relevant, holistic, and leverage 21st century strategies/technologies with declining cost. Among the more than 450 teams that have registered, more than 130 innovative proposals were accepted for evaluation during the inaugural online round. Eighty-two teams were subsequently invited to the Regional Rounds that took place on five continents in 2019. The competition was open to student groups, small and medium-sized companies, research laboratories, international corporations and non-profit organizations.

'Power@NUS' team, comprising of researchers from SinBerBEST and National University of Singapore, participated in this competition. They focused on elevating the living standard of the energy-poor eastern-segment of Sumba Island, Indonesia by leveraging on the electrification potential with the objective of supporting community empowerment. The island's main occupation is agriculture, fishing and producing Ikat textiles (Ikat is a dyeing technique used to pattern textiles that employs resist dyeing on the yarns prior to dyeing and weaving fabrics). All these occupations are labour intensive. The team's survey with villagers revealed their demand for electricity and their perception that electricity can improve their living conditions as well as income. The team took into account the regional context, expectations of the inhabitants and their occupations while designing a technical solution, evaluating its potential impact and proposing a robust business model.

Technical Solution

A community grid based on renewable energy sources (solar and wind) was proposed to supply electricity and empower employment creation in the village. This microgrid not only strives to maximize the renewable energy usage (solar and wind) but also has a diesel generator-set to provide uninterrupted power to the critical loads during contingencies, thus making the system resilient. The loads have been categorized as (i) income generating loads, (ii) household loads, and (iii) public service loads. A schematic of the proposed system for a community consisting of 50 families with installed capacity of 97 kWh/day and estimated installation cost of $90,000 is shown in Figure 1. The utility-based electrification model has the provision for collecting electricity usage data at the unit, as well as, at the utility-grid level via economic metering-systems, which would enable data analysis for modelling the time-based energy needs of the community and thus plan energy dispatch as well as pricing in an adaptable manner. Electricity supply was provided through three-phase AC systems which enables consumers to: 1) purchase standard AC appliances available from multiple vendors (ensuring low prices), 2) operate easily (used by majority of people) and 3) protected from electrical hazard (due to safe and easier protection equipment). Further, AC systems allow supply of higher quantum of electricity compared to DC systems, thus capable of a quicker transition to a community with high electricity access. Even in situations of subsequent integration with the utility, all the investments made can be utilized without significant alterations.

Impact Evaluation

The community based electrification model enables the inhabitants to have access to various services such as refrigeration, transportation, mechanization of cottage-industry. The refrigeration systems were designed to enable storing of local cash crops such as coffee, hazelnuts, and cashews through periods of low prices as well as prevent wastage of perishable items such as fishes. Additional revenue per refrigeration container (typically 20 x 8 x 8 cu. ft.) is estimated to be up to $2,500 per month dependent on the item that is stored. Similarly, there is a projected socio-economic impact due to income generation through cottage industries, electrical maintenance, and transport systems which will not only help supplement the income of target communities but can also help to diversify their income sources. It is estimated that additional income for the community through these sources to be $3,000 per month.

The proposal also includes services such as provision for lighting in community schools, reverse osmosis (RO) drinking-water, and energy needs of basic rural health-centers (medicine refrigeration, life-saving equipment). An estimated 1500 litres per day of purified drinking water can be supplied to the community for 50 families.

The total impact of the community microgrid in terms of employment generation and empowering indigenous entrepreneurship can reach up to 10,000-13,000 USD per month (for a community of 50 families) apart from other community services that are being included in the set of provisions.

Business Model

The business model was designed to be scalable and flexible, such that on one hand the local economy expands with the generation of employment and sustainable entrepreneurship opportunities, whereas, on the other hand investors can perceive enough flexibility to be interested. The infrastructure assets created would be owned by investors and would be leased to the operating committee for utilization. The investment would be recovered through monthly instalments that include both loan repayment and interest. The business model has also taken into consideration, the different associated risks such as defaulted cold storage, e-tuk-tuk (tuk-tuk: a three-wheeled motorcycle taxi for cheap public transportation) charging or cottage industry and inefficiency in billing and collection system.

Field Testing

Power@NUS emerged as winners along with 23 other teams in the regional-round and progressed to field-test their solutions, and to compete in the Global Final. The field testing has been divided into two parts: (i) testbed emulation, and (ii) on-field impact study.
For the technical validation of the proposed solution, SinBerBEST's nanogrid-testbed at CREATE Tower, National University of Singapore was utilized. On-site data for various sources and typical load profiles in Sumba Island have been collected for the emulation of the various components in the community microgrid for different scenarios (cloudy, partially cloudy and sunny days). The experimental setup of the nanogrid-testbed is shown in Figure 2 with the various emulators for sources and loads clearly labelled.

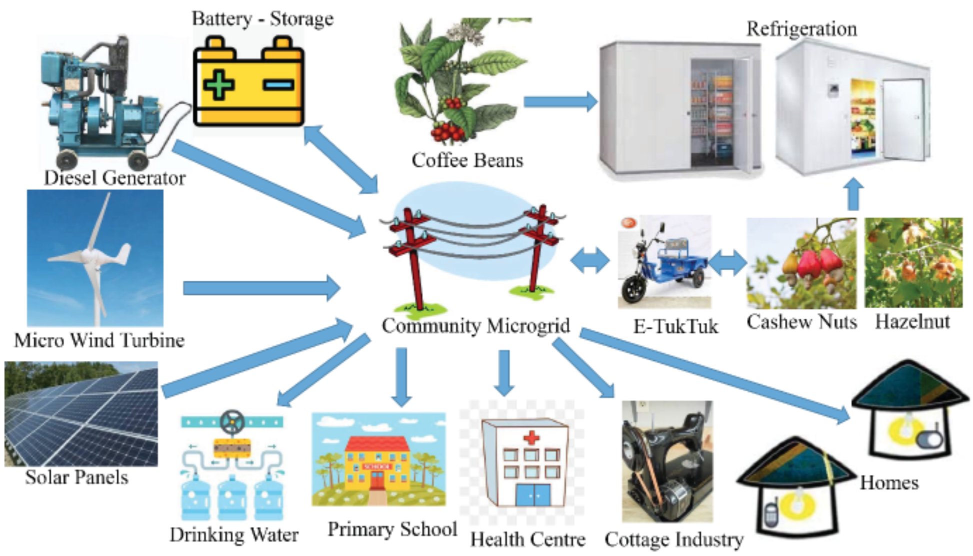


Fig. 1 Block diagram of the system which shows the major sources of generation and the three categories of load

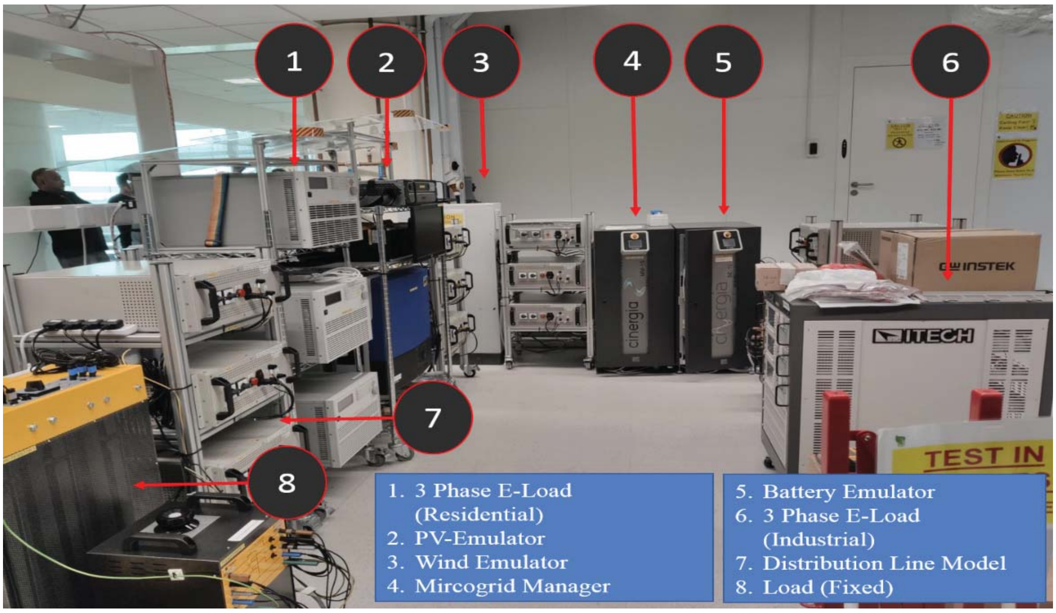


Fig. 2 Setup of the testbed for emulating the community microgrid at SinBerBEST, CREATE

The team worked closely with a collaborator Alva Energy, Indonesia, to understand the impact of their solar-based nanogrid project on the residents of Kampung Tanah Kudumuka, a small village in Sumba island. With a total installed capacity of 1.2kWp, the nanogrid is designed to supply 19 households with four community kitchens and one community hall 'Balai', as shown in Figure 3. The total cost for the nanogrid is 6300 USD with approximately 80% of it recovered by company CSR & Maybank's program named 'empowering youth'. The nanogrid's impact on the community has been multi-dimensional with allowing educational and handicraft related activities to be carried out after sunset, and improvement of community health and hygiene via water filtration system , avoidance of safety and health hazards associated with kerosene flames usage and ease of phone charging for emergency and business. Through feedback, the inhabitants have appreciated the contribution of electricity in uplifting their living standards and have since developed a sense of responsibility towards the installation.

Conclusion

The 2019 IEEE EBL concluded on October 3rd, 2019 in Baltimore, USA along with the IEEE ECCE 2019 conference, where global finalist teams from all over the world showcased their groundbreaking innovations. The Power@ NUS team presented the technical, business and social aspects of setting up an economic community microgrid based on renewable energy sources in the island of Sumba, Indonesia. The team also shared their experiences from the field trials and the associated business and social impact aspects. At the global final, team members interacted with the representative from international agencies working in this domain such as the World Bank Group, Millennium Challenge Corporation, and others. The team successfully showcased this proposal for a sustainable community based electrification as a solution for alleviating energy poverty along with subsequent community empowerment and gained valuable insights from the feedback received at the global final round.

Fig. 3 Installations in Sumba Island, Indonesia

Acknowledgement

The team would like to acknowledge the support of Electrical Machines and Drives Lab (EMDL) at the Department of Electrical and Computer Engineering, NUS, Alva Energy (Indonesia), SinBerBEST at CREATE and Solar Energy Research Institute of Singapore (SERIS) during the course of the project.




Maintaining Thermal Comfort and IAQ *via* Two-Level Distributed HVAC Control to Save Energy Cost

Yu Yang, Seshadhri Srinivasan, Guoqiang Hu, Costas J. Spanos

Both Indoor Air Quality (IAQ) and thermal comfort influence human health and working productivity in buildings. They are closely tied to buildings' Heating, Ventilation, and Air-Conditioning (HVAC) systems, which have been acknowledged as a major building energy component. While thermostat settings have been widely perceived in HVAC control to maintain thermal comfort [1-2], there is little awareness on IAQ. In some situations, the HVAC energy cost saving target may be achieved at the expense of awful IAQ. Therefore, it's imperative to jointly consider IAQ and thermal comfort while investigating energy-efficient HVAC control.

However this is challenging as: i) there are conflicting objectives and constraints imposed by energy saving target, and the thermal comfort and IAQ requirements. For example, a good IAQ generally requires sufficient outdoor fresh air infusion and zone mass flow rates, which may result in the violations of lower zone temperature bounds and the high energy cost. Another challenge is ii) the intrinsic non-linearity and non-convexity caused by the complex HVAC system behaviors. Here, both the energy cost and the system (i.e., temperature and CO_2) dynamics are non-linear with respect to the HVAC control inputs. Lastly, iii) the various couplings both arising from inter-zone heat transfer and zone recirculated air implies that both the zone temperature and CO_2 dynamics are coupled with each other. Overall, we will have to face a complex non-linear and non-convex optimization problem (NP hard) to simultaneously maintain IAQ and thermal comfort while achieving the energy cost saving target. In such case, even looking for a feasible operation point is computationally intractable as we need to tackle two bundles of coupled complex non-linear constraints that are related to temperature and CO_2, respectively.

Motivated by the requirement for a scalable and computationally efficient method for the above situation, this project develops a two-level distributed model predictive control (MPC) for HVAC system to achieve thermal comfort and IAQ simultaneously while reducing energy cost. The main idea of the method is inspired by the special structure of the problem, i.e., the temperature and CO_2 dynamics are independent, which allows to decompose the problem into two levels (i.e., upper and lower level) and tackle the two bundles of non-linear and non-convex constraints for temperature and CO_2 separately. To be specific, the upper level control activates zone temperature controllers to compute the optimal zone mass flow rate to satisfy thermal comfort while reducing energy cost. Subsequently, the lower level control starts zone CO_2 controllers to optimally regulate the computed zone mass flow rates from the upper level as well as the fresh air infusion to achieve the desirable IAQ metric. Fig. 1 illustrates the main ideas of our two-level distributed method (TLDM) for HVAC control. As both the upper and lower level control can be implemented in a distributed manner with zone level computations, the proposed method is scalable and computationally efficient.

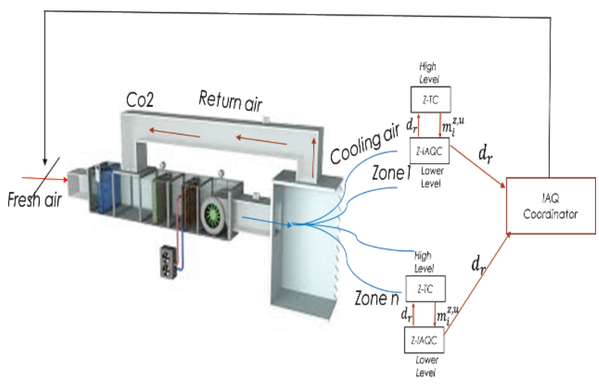
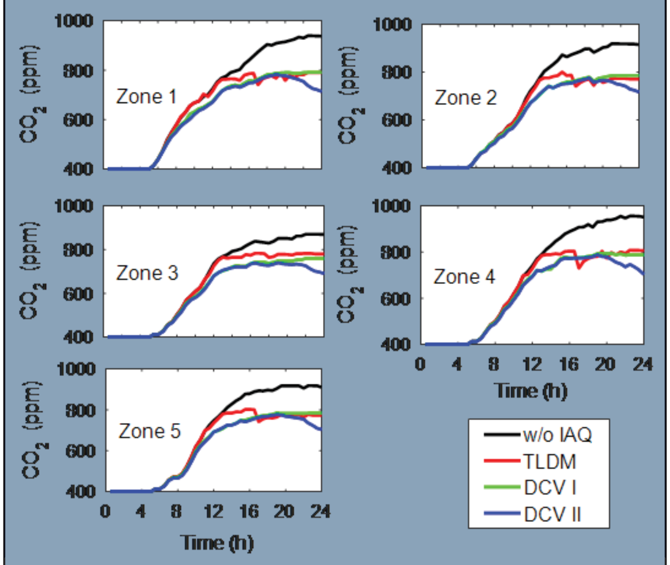


Fig. 1 Two-level Distributed MPC

We report the performance of the proposed method on a number of numeric case studies, i.e., a benchmark (5 zones), medium case (10, 20 zones) and large cases (50, 100 zones). First, to illustrate the advantages of the proposed method in energy cost saving and computation efficacy, we compare it with (i) centralized method (optimal solution), (ii) w/o IAQ [1], and (iii) the commonly-used demand controlled ventilation strategies (DCVs) (i.e., DCV I and DCV II) 1. The numeric results on HVAC energy cost, average stage computation time and the guarantees of thermal comfort (TC) and IAQ are shown in Table I. By investigating the benchmark, we note that except for w/o IAQ, both the thermal comfort an IAQ can be maintained by the other methods as exhibited in Fig. 2. Particularly, the proposed method is well-marked either by the energy cost reduction and the computation efficiency improvement. Specifically, by comparing with the centralized method, we note that the sub-optimality in energy cost saving is around 4%.This is negligible compared to the computational advantages gained. Besides, the proposed method apparently outperforms the widely-used DCVs with a 7.0% reduction in energy cost. Moreover, the proposed method is supposed to be more preferable in practice as it allows to dynamically adjust the ventilation rate on-line in contrast to the DCVs that generally depend on off-line regulation of the occupancy and space ventilation rate.

Fig. 2 Zone CO_2 concentration (Benchmark)



Further, the scalability and capability of the proposed method for large buildings are demonstrated through the medium and large cases, which becomes computationally intractable for the centralized method. Similarly, through comparisons with the currently widely-used DCVs, we see about 8.0%-9.8% (DCV I) and 8.1%-10.2% (DCV II) in energy cost savings with the proposed method while maintaining the same level of thermal comfort and IAQ.

Table I Simulation results

Method	Benchmark		Medium		Large		TC	IAQ
	5		10	20	50	100		
	Cost (s$)	Time (s)	Cost (s$)	Cost (s$)	Cost (x10^3s$)	Cost (x10^3s$)		
w/o IAQ	245.03	2.11	387.0	887.12	2.54	5.80	√	×
Centralized	247.15	575.07	-	-	-	-	√	√
DCV I	276.23	-	447.42	1015.50	2.91	5.49	√	√
DCV II	274.99	-	440.42	1020.60	2.92	6.31	√	√
TLDM	257.02	5.21	407.32	939.83	2.65	6.36	√	√

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Demand Response for Commercial Buildings



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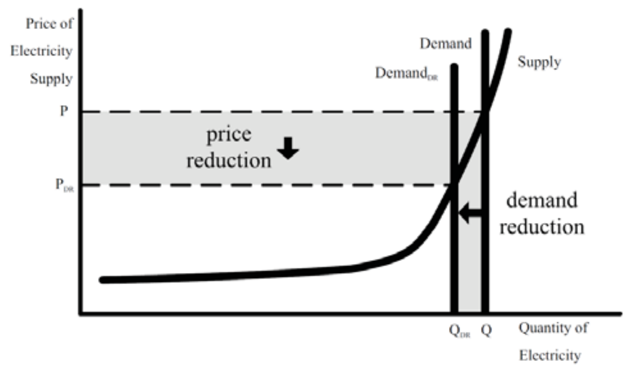
Most electricity customers see electricity rates that are based on averaged electricity costs and bear little relation to the true production costs of electricity as they vary over time. Demand Response (DR) is a program established to motivate changes in electricity use by end-users in response to changes in the price of electricity over time, or to give incentive payments designed to induce lower electricity use at times of high market prices or when grid reliability is affected (DOE, 2006). As an example, Baltimore Gas and Electric (BGE) has been aggressively involved in DR since the 1980s. The program offered customers US$10 per month during the summer (June–September) for allowing BGE to install a switch on the air conditioner, and it achieved enrollment of about 250,000 customers in 20 years Hamilton and Gulhar, 2010). The benefits of DR include: (i) enabling efficient demand and supply balancing, (ii) enhancing grid resilience, (iii) encouraging market participation from demand centres, and (iv) avoiding capital-intensive capacity addition for the power grid.

Energy Market Authority (EMA) of Singapore has introduced a DR programme which enables contestable consumers to reduce their electricity demand voluntarily, in exchange for a share in the system-wide benefits, in terms of reduction in wholesale energy prices as a result of their actions (EMA, 2018). It is depicted graphically in Fig. 1. This system includes the demand side bidding concept which allows consumers to indicate their “willingness to consume” electricity at various price points of time by adjusting their loads in response to real-time supply and demand conditions (EMA, 2013). This improves the overall efficiency of the market and avoids overloading of electrical infrastructure.

Fig I Representation of price reduction in the market with respect to demand reduction



Commercial buildings consume significant portion of electricity in the developed countries. Buildings consume around 31% of total electricity in Singapore (Chua et al., 2013). Similarly, commercial buildings consume around 36% of the total electricity in the United States of America (DOE, 2011). The demand flexibility from commercial buildings can be utilized to provide demand response (DR) services. The big challenge for the smart grid is how to coordinate an ever-growing number of intelligent devices and systems within buildings for DR services, especially in the transactive energy framework. Transactive Energy (TE) is defined as “a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter” (GridWise Architecture Council 2015). The benefits of TE based DR are discussed in Table 1.

	One-Way Communications	Two-way Communications
Local Decisions	Price Reaction + Full use of response potential + No privacy issues - Uncertain system reaction - Market inefficiency	Transactive Control + Full use of response potential + Certain system reaction + Efficient market + No privacy issues
Centralized Decisions	Top-Down Switching - Partial use of response potential - Uncertain system reaction - Autonomy issues	Centralized Optimization + Full use of response potential + Certain system reaction - Privacy & Autonomy Issues - Low Scalability

Table I Comparison of energy management frameworks for DR (Kok K, Widergren S, 2016)

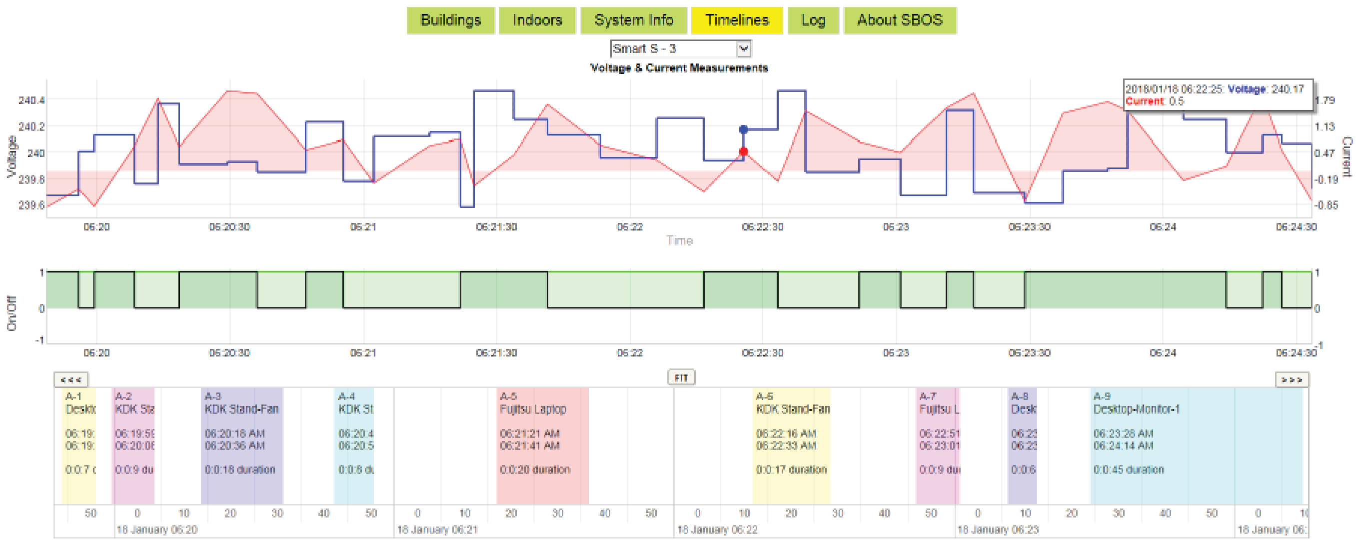


Fig. 2. Real-time web-interface showing plug-load identification and contextualization using SEOS. Since the appliance/equipment information is automatically available for SEOS, DR scheme using several appliances can be done more intelligently, and in a robust manner.

We have earlier developed the Smart Electrical Socket/ Outlet (SEOS) (Krishnanand et al., 2018) for low-cost automation and plug-load management in buildings. A GUI for demonstration of the plug-load information accessed by SEOS is shown in Fig. 2. Such intelligent devices are enabling technologies for DR participation and support transactive controls through our proposed Building Energy Management Systems (BEMS) (Chandra et al., 2018). We are also working on a transactive market based control algorithm for air-conditioning and mechanical ventilation(ACMV) systems. The proposed control approach is designed considering the general requirements of the Energy Market Authority (EMA) Singapore's DR program.

DR enables inexpensive conversion of passive demand centres (including commercial buildings) to active participants in grid operations as discussed above. Thus, DR is expected to be a game changer, and main driver of Smart Grid innovations. Considering the huge potential from commercial buildings for DR, we are leveraging plug-load and ACMV control to support this transition.

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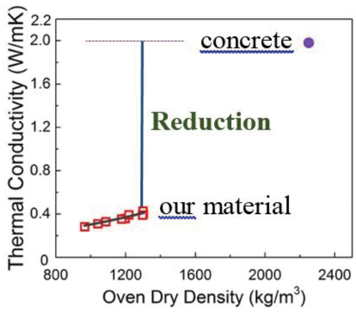
Paulo Monteiro, Hong Zhang, Liya Yu

Development of Multi-Functional Energy-Efficient Concrete for Building Facades

a)



b)

In a symbiotic research between NUS and Berkeley, Prof. Paulo Monteiro (U.C. Berkeley) and Profs. Min-Hong Zhang and Liya Yu (NUS) have developed exciting a multi-functional energy-efficient concrete for building façades (Fig.2). The first phase was to develop new ultra-lightweight cement composites with low thermal conductivity and high specific strength for energy efficient buildings. To achieve this milestone, the team incorporated a coal-industry byproduct called cenospheres into the concrete. These small spheres are hollow but have a hard shell so it was possible to reduce the specific density and the thermal conductivity without compromising the strength of the material. Indeed, the researchers obtained 28-day compressive strengths up to 70 MPa, more than enough to satisfy very demanding structural requirements. The thermal properties of these multi-functional concrete are given in Fig.1a.

Fig.1 **a)** Thermal conductivity as a function of oven dry density and **b)** TiO2 coating of the building façades for pollution reduction and self-cleaning.

The second phase was to develop functionalized TiO_2 that can be integrated with the ultra-lightweight low thermal conductivity concrete. The formulation allows airborne pollutants to be mitigated which provide a cost-effective alternative to enhance ambient environment of large cities in the tropics. This approach is easier to be implemented compared to tightened emission standards and ambient air quality standards. This also enables existing and future buildings in large cities to contribute to a sustainable environment. The new materials utilize solar energy to degrade three types of criteria airborne pollutants, SOx, NOx and particulates. The concrete treated with the TiO_2 coating becomes self-cleaning. The experiments showed that the specimens coated with silicate containing 15% TiO_2 showed satisfactory degradation efficiency in laboratory accelerated tests up to 2500 h of simulated UV irradiation, simulating the condition of at least 2.4 years based on a tropical warm and humid condition, indicating its durable performance (see Fig.1b).

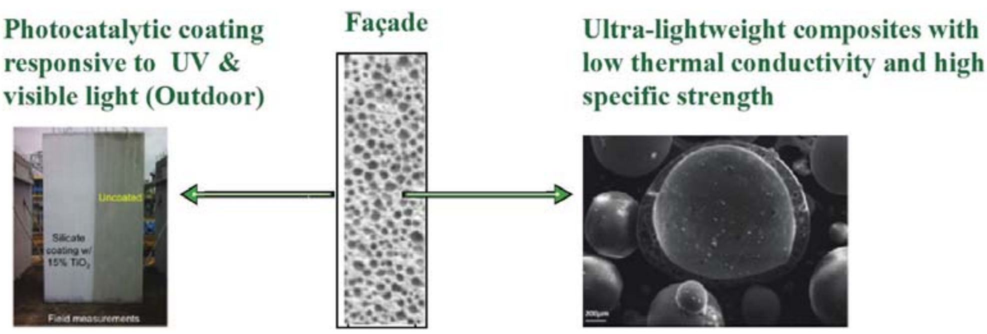
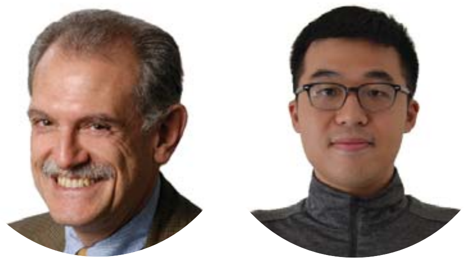


Fig.2 A new generation of concrete with low thermal conductivity, ultra-low specific density, high strength and self-cleaning capability

Designing Building Control Systems as Cyber-Physical Systems



Alberto Sangiovanni Vincentelli, Baihong Jin

The design of HVAC systems is crucial for reducing energy consumption in buildings. As complex cyber-physical systems, HVAC systems involve three closely-related subsystems – the control algorithm, the physical building and environment, and the embedded implementation platform (Fig. 1).

In the traditional top-down approach, the design of the HVAC control algorithm is done without explicit consideration of the embedded platform. The underlying assumption is that the computation and communication capabilities of the embedded platform are sufficiently performing for any type of control mechanism. However, with the advent of more complex HVAC control algorithms for energy efficiency, the use of distributed networked platforms, and the imposition of tighter requirements for user comfort, this assumption on the embedded platform is no longer valid. Various aspects of the platform, including sensor accuracy and availability, communication channel reliability, and computing power of embedded processors, may have a significant impact on the quality and cost of a BAS. For instance, a BAS with an MPC algorithm as its control logic has different computation power requirements compared to a BAS with simple bang-bang controller as its control logic. Thus, the design of the control algorithm should take into account the configuration of the implementation platform and vice versa, i.e., the control algorithm and the embedded platform should be co-designed, as proposed in this project (Maasoumy et al. 2013a).

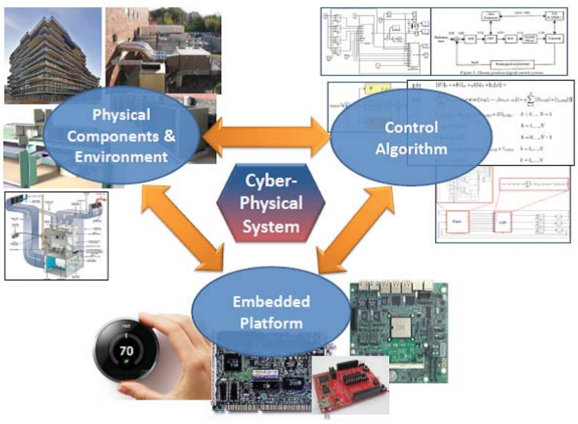


Fig. 1 As complex cyber-physical systems, HVAC systems involve three closely-related subsystems - the control algorithm, the physical environment and the embedded implementation platform.

We used the reduced order model (or meta-model) obtained as part of the process is reused for automated calibration of the high fidelity building energy model from which it was derived. The advantage of a meta-model is that it returns function evaluation in a fraction of a second as opposed to the high fidelity model, which takes several minutes to simulate. Furthermore, the meta-model is obtained in a simple analytical form. Consequently, it can be easily manipulated and used in various optimization algorithms. This approach provides a reliable and fully automated way to assess first order parametric sensitivities in building models. Higher-order sensitivities are computationally more expensive to evaluate.

Once we identify how model uncertainty affects the performance of a model-based controller such as MPC, then we can solve the co-design problem that we introduced earlier in this chapter. Here we review our co-design approach presented in Maasoumy et al. (2013a) that analyzes the interaction between the control algorithm and the embedded platform through a set of interface variables – in particular sensing accuracy (Fig. 2). Six control algorithms are analyzed that take into account the sensing error, and the relation of control performance and cost is modeled versus sensing error. The relation of embedded platform cost versus sensing error is captured by analysis of the collected data from a test-bed. Based on these models, the co-design of the control algorithm and the temperature sensing subsystem of the embedded platform is performed to optimize with respect to energy cost and monetary cost while satisfying the constraints for user comfort level.

In Maasoumy et al. (2013b) via extended real-scale experiments, we observed that modulating the fan speed of HVAC systems for extended periods of time with the existing control algorithms can lead to discomfort and does not allow optimizing the amount of flexibility provided by a building. Hence, in Maasoumy et al. (2014a), we proposed to re-design the control algorithm, and considered commercial buildings whose HVAC systems are controlled by an MPC scheme running an optimal control problem at each time step k. Typically, the MPC aims at minimizing the total energy cost (in dollars). In an SF scenario, such cost must account for the reward received from the utility because of the building flexibility in energy consumption.

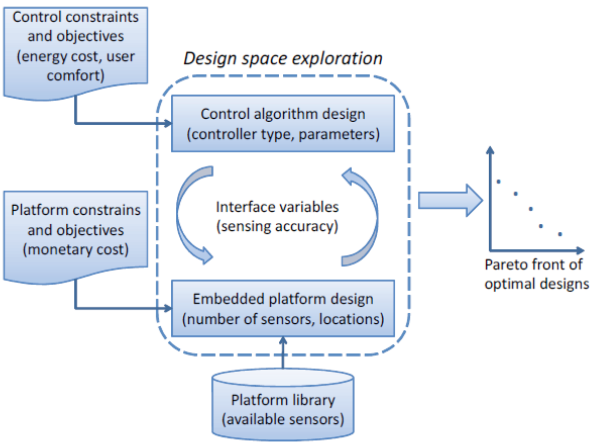


Fig.2 Co-design framework for HVAC systems

In Maasoumy et al. (2014a), we identified and quantified the concept of "flexibility". Then, a contractual framework between the utility and the building operator was designed so that the building can "declare" its flexibility and be rewarded for it. Finally, a control algorithm was proposed that allows the operation of building under this framework. At-scale experiments were carried out to demonstrate the high potential of commercial buildings as a source of flexibility and the feasibility of the proposed algorithm. Clearly, by obeying the utility power consumption signals, the building may consume more or be in a worse state at the end of the Hc time slots with respect to a conventional demand-following protocol. The flexibility declared by the building operator would then be significant only if:

- it is enough to be effectively exploited for frequency regulation services (Maasoumy et al. 2014b), and
- the reward from the utility is appropriate for the building.

The schematic of the entire system architecture is shown in Figure 3. The solid-line arrows correspond to the baseline power flow. The ancillary power flow is represented by a dashed-line arrow.

In Maasoumy et al. (2015), we proposed a dynamic contractual framework that in real-time analyzes the requirements of the grid on one side, and requirements of the building on the other side, and performs optimal operation of the whole system while taking into account the state and input constraints of both building and grid and governs this interaction through a set of interface variables and constraints. We used the concept of assume-guarantee contracts to formalize the requirements of the grid and the building subsystem as well as their interface. At the building level, such formalization leads to the development of an optimal control mechanism to determine the HVAC energy flexibility while maximizing the monetary incentive for it. At the grid level, it allows formulating a model predictive control scheme to optimally control the ancillary service power flow from buildings, while integrating constraints such as ramping rates of ancillary service providers, maximum available ancillary power, and load forecast information. To simplify the problem, we abstracted into one grid agent all the players beyond the aggregator, such as the wholesale market players and the generation units, and denote as buildings the demand-side service providers that deal with the aggregator. They then focus on grid and buildings as the two sides of the supply-demand spectrum, by abstracting all the intermediate entities involved in the chain from power generation to power consumption. More recently, in Maasoumy and Sangiovanni-Vincentelli (2015), we illustrated how the two building and grid side controllers can interact seamlessly in a single framework with multiple time-scales of different sub-systems. We defined two markets, namely the flexibility trading market (FTM), and the wholesale electricity market (WEM). Aggregator plays the role of an interface between these two markets. To address the challenges originating from this distributed and hierarchical system, in Maasoumy et al. (2015), we resorted to a Contract-Based Design (CBD) methodology.

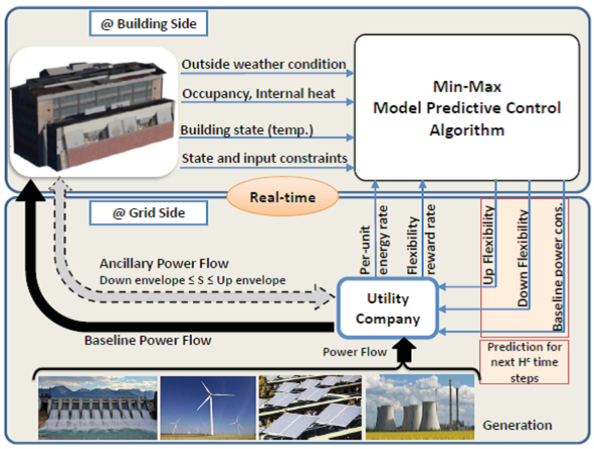


Fig.3 Schematic of the grid architecture and contractual framework proposed in Maasoumy et al. (2014a).

CBD has recently emerged as a compositional paradigm for the design of complex systems, emphasizing the concept of interface and requirement formalization to facilitate system integration and provide formal support to the whole design flow Nuzzo et al (2015). We then provided an integrated design framework for MPC synthesis, which can combine and subsume both the approaches in Maasoumy et al. (2014a, 2014b). The advantage of our contract-based methodology with respect to previous works is threefold:

- it enables compositional design of the building and the grid MPC schemes, so that they can be independently implemented while still guaranteeing that their integration is correct;
- it allows extending the approaches in Maasoumy et al. (2014a, 2014b) to highly distributed architectures,

including a large number of control areas and buildings, in a scalable way;

- it supports automatic synthesis of embedded control software directly from assume-guarantee specifications.

In Aksanli et al. (2014), we demonstrated a framework composed of distributed smart buildings and energy generation. Here we demonstrated the feasibility of such real-time communication and control among several grid nodes and building nodes. We studied the effects of smart building controllers on the grid frequency and stability via an experimental approach, using ad-hoc controller for the grid node, while the controllers on the building sides ranged from simple bang-bang controllers whose only objective was to keep the temperature within a comfort zone, to more sophisticated min-max MPC controllers that at the same time keep temperatures within the comfort zone and maximize building capacity for ancillary service when the capacity is needed most. Managing the aggregation of a large number of heterogeneous loads to achieve a desired response, in the case of large scale demand-response programs as in Fig. 4, still remains to be a challenge, especially at a fast time scale.

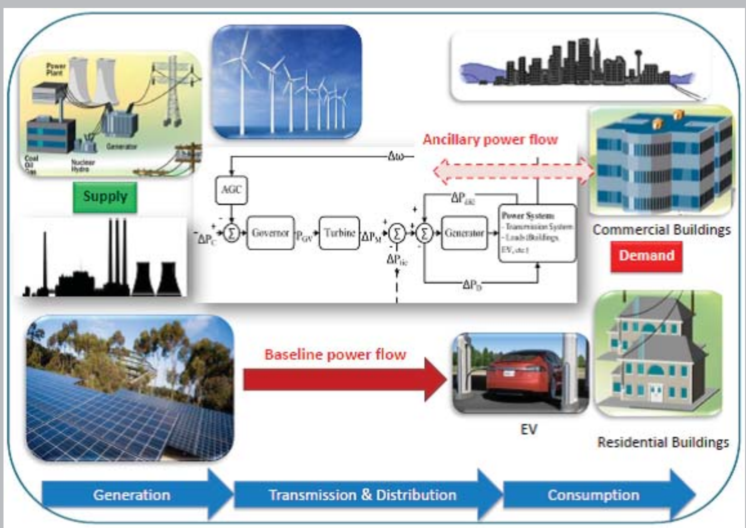


Fig.4 As influential players in the smart grid domain, buildings have a significant role in its operation. One of the services that buildings will provide to enhance the operation of the smart grid is ancillary services to help frequency regulation through automated demand response events.

In Jin et al. (2015), we presented a system-level modeling and control design approach for Demand Response (DR) management in smart grids, by following a contract-based methodology. Given a set of flexible DR loads, capable of adapting their power consumption upon external requests, Jin et al. (2015) find a strategy for an aggregator to optimally track a DR requirement by combining the individual contributions of the DR components. In their framework, both the design requirements and the DR components' interfaces are specified by assume-guarantee contracts expressed using mixed-integer linear constraints. Contracts are used to formulate an optimal control problem which is solved repeatedly over time, in a receding horizon fashion. The effectiveness of the methodology for a set of DR components including fans and pumps was illustrated.
To counteract the variability of RES, in Hanif et al. (2015), we proposed provision of flexibility from the demand side as a viable option. Here we discussed how the heating, ventilation and air conditioning (HVAC) system, mostly installed in medium to large sized office buildings, can provide demand side flexibility. A model predictive control (MPC) scheme in a receding horizon environment was deployed to provide an economic operation of the building, while respecting comfort constraints of dwellers. Furthermore, robustness is introduced in the doing so, the controller is also evaluated with respect to its sensitivity towards economic and technical constraints. The National Electricity Market of Singapore (NEMS) is used as a case study and challenges of integrating demand side flexibility in the grid were pointed out.

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SinBerBEST Nanogrid

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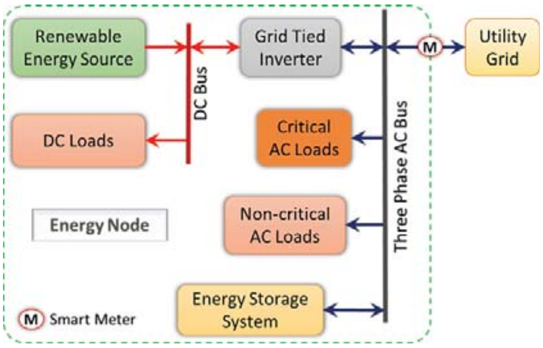


Fig.1 Schematic of an Energy Node Instance

In conventional grids of gigawatt to terawatt capacity, electrical energy flows from power producers to consumers. With increase in distributed power generation, microgrids of a few megawatt capacity have motivated the idea of prosumers – consumers who are also producers of electrical energy. For buildings, this decentralization of power goes a level further to form nanogrids having capacities ranging from a few kilowatts to hundreds of kilowatts. In a highly urbanized setting such as Singapore, study of nanogrids form an important part of the search for energy sustainability.

Modern buildings have multiple electrical resources, including renewable energy sources, energy storage devices, flexible loads and utility connection. Coupled with the new energy pricing plans and schemes of the deregulated market, these physical assets present new opportunities for nanogrid service provider to save energy, reduce operational costs, avoid carbon emissions and improve lifestyle. In SinBerBEST (SBB), this is explored by treating buildings conceptually as Energy Nodes (Fig. 1). Energy Nodes represent electrical components within a building and their electrical interconnections, which are programmatically managed through software.

The SBB nanogrid testbed, as shown in Fig. 2, is configured for experiments in building-to-building and building-to-grid interactions proposed by Theme-B.

The objectives include:

- Design of distributed and scalable control strategies for Demand Response (DR), i.e. offsetting power demands as requested by the utility grid.
- Study the role of building-level electrical resources in displacing reserve capacity and providing other ancillary services within a Transactive Energy (TE) framework.
- Investigate connection of multi energy nodes to share energy resources as a cluster of buildings.

Fig.2 SinBerBEST Nanogrid TestBed

SBB nanogrid has been successfully used by Power@NUS team to conduct experiments for global finals of Empower a Billion Lives (EBL) competition at the IEEE ECCE 2019. A GUI for the energy node is shown in Fig. 3. The main devices in the setup are:

Photovoltaic (PV) Emulator: TerraSAS (600V DC/ 17A) emulates the dynamic electrical behaviour of a terrestrial PV solar array. It offers low output capacitance and high closed loop bandwidth to match with the modern Maximum Power Point Tracking (MPPT) algorithms.
Grid Emulator: California Instruments MXi 30 delivers up to 30 kVA three phase outputs in AC mode, with option to defined voltage waveform. In sink mode it can regenerate up to 100% of the rated output power back to the utility grid.
Battery Emulator: Cinergia BE10 is a bi-directional power source to emulate different kinds of battery such as Lead acid, Lithium, Li-ion as well as Redox Flow Vanadium. Rated Power is 10kVA, 9kW, Rated Output Current 45A (DC), Output Voltage 0-750 VDC.
DC/AC Inverter: Sunny Tripower 12000TL is equipped with two separate MPPT at two inputs to work as a multi-string inverter, converting direct current of either one or two PV arrays into alternating current. Voltage Input is up to 1000 VDC, 3 phase output up to 440 VAC, and Maximum Power 12 kVA.
DC/DC Converter: 2 units of Schaefer C4877KZ with power of 10kW offers a setting system at rated voltage up to 800VDC and bipolar voltage output of -190VDC/+190VDC. Programmable AC Electronic Load: Two 3-phase programmable loads are connected in nano-grid are the ITECH AC/DC electronic load (Model IT8617) and the star-connection of 3 units of Chroma 63800 series.
Passive AC Load: 3-phase resistors and inductors are present for powers 3.3kW and 2.2kVAR respectively.
Bidirectional Converter: Cinergia MM15 allows the connection with AC and DC resources to balance generation, consumption and storage. It is compatible with several DC storages such as Li Ion, Lead-acid, VRLA, and battery

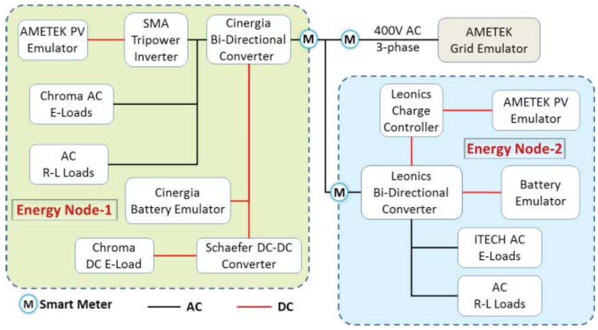


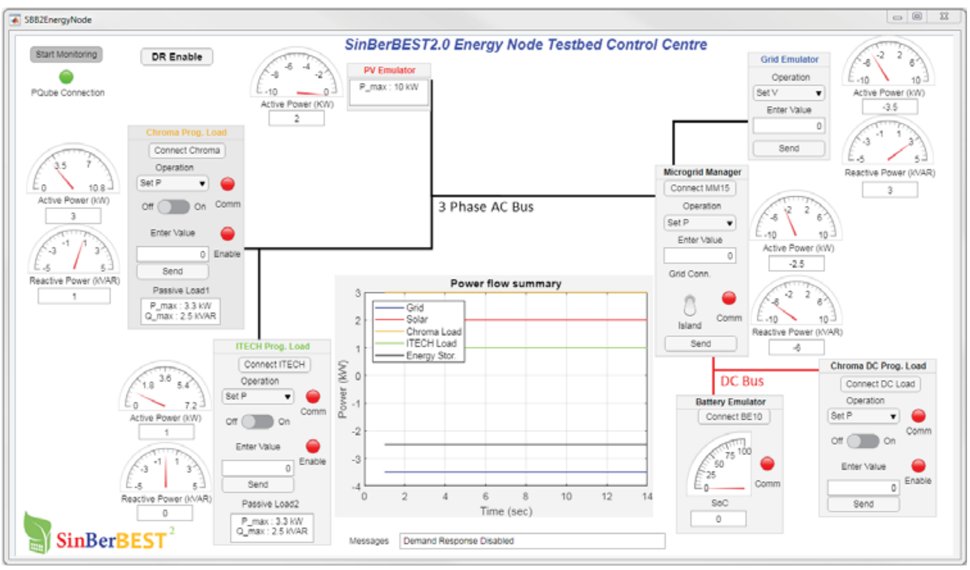
Fig.4 Nanogrid structure with two energy nodes. PQube3e hardware is used for electrical metering.

emulator. The voltage of storage system is up to 750 VDC. Rated power is 13.5kW, 15 kVA with rated current of 20A for AC and 60A for DC.

While an energy node has already been configured, the final two-node structure being setup is represented in Fig. 4. The nanogrid is conceived as a system of energy node subsystems that exercise both autonomy and mutual coordination in their electrical operations. For the purpose of demand side management (DSM) studies, SBB nanogrid has capabilities for emulating a) demand variation b) renewable energy variation (photovoltaic generation) c) energy storage variation, and d) islanded operation.

The challenge of a nanogrid is to have a cyber-physical system such that programmatic coordinated control of the components of the energy nodes yields expected behaviors. This requires a Nanogrid Control Centre (NCC) that holistically views the combination of individual electrical operations within the context of nanogrid power-flows, stability requirements, economic objectives, grid services etc. Such software-defined behaviors of the nanogrid make transactive energy control possible, which is the anticipated paradigm shift for having smarter grids and digitalized services.

Fig.3 Instance of a Graphical User Interface (GUI) developed for the nanogrid with one energy node and the grid



Interview With **Dr Gao Yidan** *and* **Dr Yang Yu**

Dr Gao Yidan and Dr Yang Yu joined SinBerBEST as researchers working in the area of building façade and building automation and control respectively. We were impressed by the expertise of these two scholars especially as they relate to computer simulations in building domain knowledge. Their technical abilities and the relevance of their past research made them ideal addition to the SinBerBEST's research team. We asked them about their past experience, current research and their hopes for the future.

Can you briefly describe your education background?

Yang: I received my bachelor's degree from Huazhong University of Science and Technology, Wuhan, China in 2013 and obtained my PhD degree from Tsinghua University, Beijing, China, in 2018. Since then, I have been working as a postdoctoral researcher in BEARS working under Professors Hu Guoqiang and Costas Spanos.

Gao: I obtained my bachelor's degree from Southeast University in China and my PhD degree in Nanyang Technological University in Singapore. Upon graduation, I joined the SinBerBEST program to work under Theme C under the supervision of Professor Khalid Mosalam.

How did you get into this field?

Yang: I have taken up automation as my major subject during my college years. Due to how it is closely linked to humans' life, this topic has spurred my strong interest. Moreover, the past decades have witnessed the proliferation of information technologies. This excites me as the great opportunities that are presented in front of us, allow researchers like me to use automation technologies to help create a better and smart future for people.

Gao: My PhD in NTU is mainly focussed on advanced statistical modelling and random process research. I am now working in the field of sustainable building energy field where there are many uncertainty problems in long term consideration. Thus, my background is very relevant and useful to the program. Also, by applying my numerical simulation work into the building sector, I hope that I will be able to grow in this field as a researcher and contribute meaningfully as a person.

What drew you to SinBerBEST?

Yang: After I got my PhD degree, I received an advertisement on recruitment opportunities under SinBerBest from my professor. I found the project description to be very interesting and I believe I am able contribute to it, therefore I took the opportunity.

Gao: I was a postdoctoral research fellow in Nanyang Technological University before I came here. I gave a seminar in NUS and by chance my topic got the interest of some research staff in SinBestBEST. Recommended by some professors, I came here to try to contribute my knowledge to the research team here.

How does your work at SinBerBEST build on your past research?

Yang: The main research focus of my PhD is to research on optimization-based control method that includes decentralized optimization, reinforce learning, stochastic optimization and data-driven analysis, etc., with their applications to smart grid and building energy system. This background makes it possible for me to develop efficient and scalable control techniques to facilitate energy-efficient buildings, which is one of the main research targets of SinBerBEST program.

Gao: The advanced statistical model that I am developing will be applied into the building domain. With this new model, the building energy simulation results will be more close to real situation.

How can your research benefit people working in the building and other industries?

Yang: My research promoted the creation of an energy efficient building whilst still providing a more comfortable environment for people. For example, one of my research topic now is on designing energy-efficient control methods for heating, ventilation and air-conditioning systems in buildings. Such smart control methods are not only hopeful to help reduce the electricity bills but also promising to maintain a better working environment with comfortable temperature and indoor air quality for people. However, the practical implementations need the support of new communication and computation technologies. This both provide new challenges and opportunities to the technology industries.

Gao: Currently my work in SinBerBEST is trying to provide a novel and smarter computational platform for holistic design applied to novel façade concepts. All the uncertainties will be described in the most realistic manner through random variables, stochastic processes and random fields.

What are your longer term goals?

Yang: My long-term goal is to become a faculty member in a university.

Gao: I hope to hone my expertise and continue working as a researcher in a research institute. I also hope to become a faculty member in a university. Also, I hope that what I am doing may help make the world better.

SinBerBEST

The SinBerBEST program, funded by the National Research Foundation (NRF) of Singapore, is a research program within the Berkeley Education Alliance for Research in Singapore (BEARS). It comprises of researchers from University of California, Berkeley (UCB), Nanyang Technological University (NTU) and National University of Singapore (NUS). SinBerBEST's mission is to advance technologies for designing, modeling and operating buildings for maximum efficiency and sustainability in tropical climates. This newsletter, published quarterly, is to showcase the excellence of SinBerBEST faculty, post doctoral fellows and students.

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