Harnessing Resource and Demand Flexibility for Energy Management in Urban Micro-grids

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***Abstract*—Successful adoption of distributed clean energy resources requires the enhancement of system flexibility from both the generation and the demand side. This paper presents a case study on the Punggol Digital District of Singapore exploring both distributed generation, storage, and demand side flexibility. The distributed generation resources investigated include rooftop photovoltaic systems and waste-to-electricity generation via hydrogen and fuel cell technology. In the urban use case, the local demand to be served far exceeds the local distributed clean energy generation potential. Therefore in this context, flexibility is the key added value of collective self-consumption, which could be leveraged as a valuable grid service in the city-state to support the integration of variable renewable energy resources. In this context, this work presents the assessment of the flexibility that can be provided by the cooling demand and electric vehicles by the control of respective demand-side resources.**

***Index Terms*—District cooling, Flexibility, Waste-to-energy, Self-consumption, Thermal modeling, Transactive energy management**

I. INTRODUCTION

A. Energy context in South East Asia

The energy landscape of the region and their respective energy targets determine the need for resources on the flexibility axes of the markets in the region. This section gives an overview of the flexibility requirements that may arise in Southeast Asia with the energy trends and a review of market participation possibilities of such resources.

The Southeast Asian energy market is growing at a steady pace due to the economic growth and urban development in the region. The average increase in electricity consumption is growing steadily by 4 % annually [1]. It is one of the few regions in the world where the coal-fired generation capacity is still growing, with about 20 GW still under pre-construction and construction phase, as stated in the 2020 IEA report [1]. This is indeed a unique challenge to balance the decarbonization efforts and still meet the growing energy demands.

The ASEAN region has a high target of integrating renewables, and one of the solutions explored is interconnection as a Southeast Asian power grid allowing cross-border trade of electricity, which could reduce cost and emissions [2]. The region is also targeting a diverse energy mix to supply the growing demand due to rising concerns on decarbonization and energy security. Continued reliance on fossil fuels raise concerns on energy security with the fuel supply and the economic burdens of importing or exporting the net supply, in addition to the undeniable impact on the environment. Hence, by diversifying energy resources by investment in variable renewables like PV and wind, and simultaneously improving the energy efficiency of existing energy supplies are being extensively looked at in the region. This is evidently seen by investment initiatives and the rapidly reducing cost of PV and on-shore wind as the market matures.

The rapidly changing energy system in the local context from dispatchable generation to an intermittent generation landscape requires grid enhancements for operational stability. Tapping on the demand side flexibilities to support in relieving of grid constraints is indeed a valuable resource locally. This work discusses a case study of harnessing of such distributed

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generation and demand side flexibilities in the urban energy context in Singapore.

B. Urban micro-grids

The significance of flexible generation and demand is growing in cities with the increased adoption of variable renewable energy resources stressing the conventionally built electric network. Flexible and dispatchable resources that are sustainable are limited, and hence the need to adopt a bi-directional generation-demand balancing strategy.

The PRIMO (Platform for Interconnected Micro-grid Operation) project [3] was launched in 2020, funded by the Energy Market Authority of Singapore to study and develop methods for coordination of local energy systems in the Punggol district of Singapore as grid-connected networked micro-grids for an organized integration of energy resources.

The study area includes an institution campus with rooftop PV system and waste-to-energy generation of hydrogen from waste collected locally. Electricity is planned to be generated from hydrogen by a fuel cell. The waste-to-energy generation is considered to be dispatchable with a hydrogen storage tank. In this work, we do not consider bi-directional flexibility of the fuel cell and hydrogen storage by electrolysis considering the economic viability. On the other hand, the centralized cooling system and electric vehicle charging facility comprise the controllable loads, while the rest is non-controllable demand. In addition, a battery energy storage system is considered to be present for additional flexibility to the micro-grid. Similarly, the industrial campus micro-grid is also considered to have rooftop PV, a battery storage system, and flexible demand.

In this paper, we present briefly our results focusing on the flexibility potential on the demand side and its potential to generate value by participation in the energy market.

II. FLEXIBLE RESOURCES

In this urban micro-grid context, the local demand is much higher than the energy resource potential at all times. Hence, PV as a resource is limited and must be completely utilized and therefore no curtailment flexibility is considered in this work.

A. Waste-to-Energy

Waste-to-energy (W2E) is one of the distributed energy resources (DERs) studied in the PRIMO project. Even though a W2E installation is not planned for the PDD at this point of infrastructure planning, there is still an interest to take it as a case study to understand its challenges and potential as a DER. It may play an important role in providing a sustainable local energy supply for urban districts. In Singapore, approximately 7700 ton/day of solid waste is incinerated at the four existing W2E plants [4]. The incineration process reduces the waste volume by 90 % and supplies around 2 % of the national electrical power need [5]. There is a perpetual waste source that provides the opportunity to treat waste near the source and return useful products such as molecules and energy to the local community. Near-source and decentralized treatment reduces transportation of waste and its products across the island city, hence reducing transportation emissions, cost, and risks associated with the goods (i.e., odor, explosiveness, and toxicity). A system optimization study on the efficiency of centralized and decentralized municipal waste management systems in the Singapore context showed that the decentralized waste management system could halve the operation cost and reduce the land capacity fragmentation and transportation fleet size by 74 % and 15 %, respectively [6].

In this study, hydrogen is identified as one of the potential molecules to be produced from waste. It is a zero-carbon emission fuel for transportation. The hydrogen economy has also picked up its momentum recently with major support from the government and business sectors in its logistics (i.e., refueling, transportation of fueled vehicles, and cost reduction strategy in hydrogen production) [7]. High-purity hydrogen can be produced and stored to buffer variable renewable power generation (e.g., from offshore wind farms), providing robust on-demand local electricity generation [8].

As a decentralized W2E plant, it usually does not have the luxury of huge waste-holding capacity. The process of starting up and shutting down a thermochemical plant needs time and is often complex before it can achieve an efficient steady state. It also relies on batteries for excess power storage. The thermochemical route via gasification is selected for this study to produce syngas, followed by hydrogen enrichment with water gas shift and purification stages. Syngas production from municipal waste gasification, compared to pyrolysis process, is a proven technology and with many plants built globally. There have been studies looking into hydrogen as a robust energy storage option. Synergetic control and economic optimization of a micro-grid were modeled around a multi-energy storage system [9] which includes hydrogen generation from electrolyzers and being stored for power generation by fuel cells. Power generation by hydrogen fuel cells for micro-grid application can be operated independently of the hydrogen generation mode, which marks its robustness.

B. Battery Energy Storage Systems (BESSs)

BESSs play an important role to improve reliability and resilience of power systems [10]–[12], allowing greater penetration of intermittent DERs into the power system [13], [14] and providing economic benefits to micro-grid operators by participating in ancillary services and/or energy arbitrage [13]. In [12], the authors studied the application of BESSs to improve resilience of distribution systems to natural disaster by effectively scheduling BESS discharge during outages. In [15], the impact of the power quality on the grid when connecting to intermittent renewable resources was investigated. The authors found an improvement in power quality of the grid by smoothing and stabilizing power generation from the resources. In [13], different strategies for managing grid-connected BESSs were studied for primary control reserve and energy arbitrage. In [16], the economic benefits of BESSs for providing peak shaving in an islanded micro-grid were assessed.

C. Demand Side Flexibility

In [17], the home energy management system “Forsee” was introduced along with a concept for user inputs of desired indoor air temperature. In this software framework, the system collects a data set of comfort and schedule preferences in order to learn and forecast user behavior. An optimal scheduling algorithm is then deployed to harness the determined DSF potential. A similar approach is pursued in [18]. The work [19] proposes a user interface for V2G systems, where the user can choose between different operation modes and input their EV charging requirements. The underlying charging scheduling algorithm is able to interpret these inputs as constraints in its optimization problem.

III. DEMAND SIDE FLEXIBILITY

First, the operational mode of demand side flexibility (DSF) systems can be divided into 1) flexible operation and 2) fixed operation. Fixed operation refers to the traditional control mode which aims to maximize user comfort. Flexible operation describes the control mode where system operation is determined by an optimal scheduling algorithm for cost minimization subject to user comfort constraints.

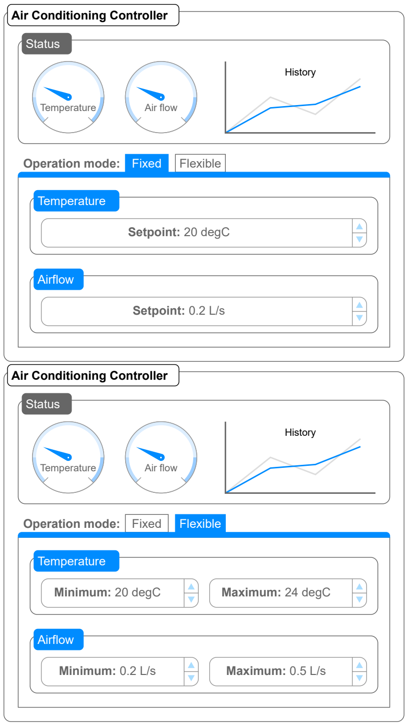
The spatiotemporal DSF in air-conditioned buildings describes the flexible cooling demand due to centralised air-conditioning systems in the Punggol Digital District (PDD) area. The DSF in air-conditioned buildings arises from the inherent thermal energy storage in the building structure, e.g. walls and floors, which can be utilised to defer cooling demand while keeping within occupants’ comfort and indoor air quality (IAQ) requirements. To this end, the required user inputs for DSF in air-conditioned buildings are:

- **Availability** schedule which refers to the projected availability of the system for flexible operation rather than fixed operation.
- **Temperature preference** captures the desired temperature set point as well as minimum and maximum limits which characterize the thermal comfort.
- **Air flow preference** describes the IAQ requirement through desired air flow set point; minimum and maximum values.

For vehicle-to-grid (V2G) systems, the flexibility is restricted by electric vehicle (EV) charging demand and V2G participation preference. The latter describes the preference to participate in uni-directional V2G, i.e., smart charging, or fully bi-directional V2G. Correspondingly, the required user inputs for V2G-enabled EV charging are:

- **Availability schedules** which capture the envisioned departure of a vehicle from the charger as well as availability of the system for flexible operation.
- **Energy demand** captures the amount of energy the user requires to be charged and additionally the maximum charge which should not be exceeded, where the latter only becomes relevant for bi-directional V2G.
- **V2G participation** describes the willingness to participate in full bi-directional V2G, rather than just uni-directional V2G/smart charging.

In order to address the aforementioned requirements, the user interfaces (UI) for DSF in air-conditioned buildings and V2G systems are proposed to focus on comfort preferences and schedules. The information pane on the UI is used to communicate passive measurements and notifications to the user, whereas the control pane would capture all interactive components of the user interface.



Operation mode: Fixed

Setpoint: 20 degC

Setpoint: 0.2 L/s

Operation mode: Flexible

Minimum: 20 degC Maximum: 24 degC

Minimum: 0.2 L/s Maximum: 0.5 L/s

Fig. 1. User interface for DSF in air-conditioned buildings.

Figure 1 represents the proposed user interface wire frame for DSF in air-conditioned buildings. In the status pane, current measurements of temperature and air flow are provided, which serves to enable the user to relate their perceived comfort to the quantitative parameters. In the control pane, the user would be presented with different options depending on the selected operation mode. In fact, the selection of the operation mode itself serves as an input to the system, as it indicates the availability for flexible operation. In the fixed operation mode, inputs for temperature and air flow are restricted set points, whereas the flexible operation mode allows the input of a permissible range.

The proposed user interface wire frame for V2G systems is depicted in Figure 2. Here, the status pane includes information on the charged energy and current charging power. The user can choose between fixed and flexible operation mode to indicate their willingness to participate in smart charging and V2G. In the fixed operation mode, the energy demand is the only input, where the earliest departure time will be determined by the system. In the flexible operation mode, the energy demand input is split into minimum and maximum value. Further, the expected departure time is now provided as

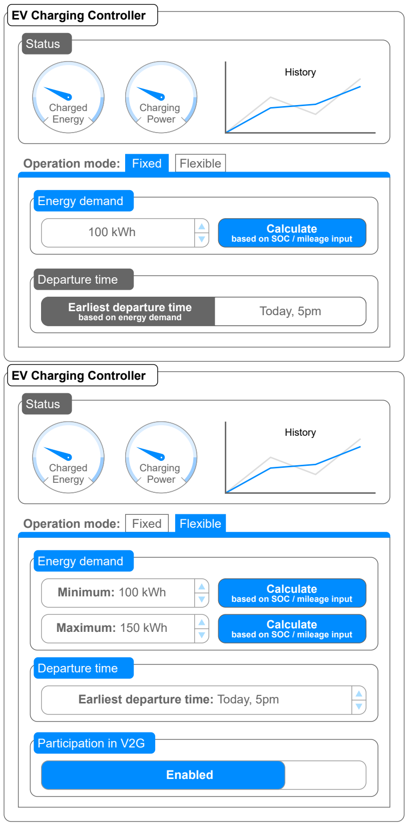


Fig. 2. User interface wire frame for DSF in V2G systems.

an additional input in addition to the selector for participation in bi-directional V2G.

A. *Flexibility from Cooling demand*

To express DSF in air-conditioned office buildings, a state space model representation is chosen as presented in [20].

Of each building, geometry, height and number of floors are acquired. This is complemented with the specific internal heat gains due to occupants and comfort constraints. Then we use the Control-oriented Building Model (CoBMo) presented in [21] which expresses the relationship between the cooling demand of the air-conditioning systems and the indoor air climate with consideration for interactions of the building with its environment, its occupants and appliances.

DSF can be characterized by the ability to defer load for a particular time period. To this end, the maximum load reduction for a fixed time period with respect to the baseline load is proposed as an indicator for DSF. The load reduction potential represents the maximum load reduction which is feasible for a given load reduction time period while still respecting the comfort constraints. The load reduction time period is the fixed time period during which the load curtailment is being enforced. Figures 3 and 4 depict the average and maximum load reduction potential time series across all PDD buildings for different values of load reduction duration. The load reduction potential clearly decreases with increased load reduction duration. Furthermore, the average load reduction potential is higher during working hours since the PDD area consists largely of commercial and educational buildings. The peak load reduction potential is observed in morning and evening hours, which can be explained with the reduced occupancy during those time periods allowing for a higher level of curtailment.

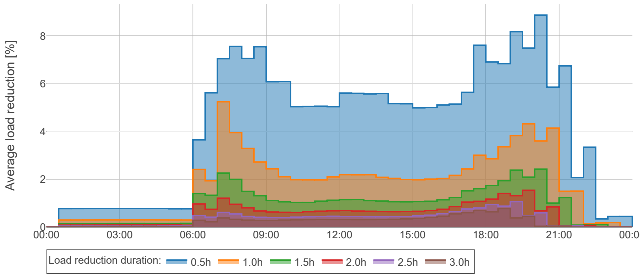


Fig. 3. Average load reduction potential time series.

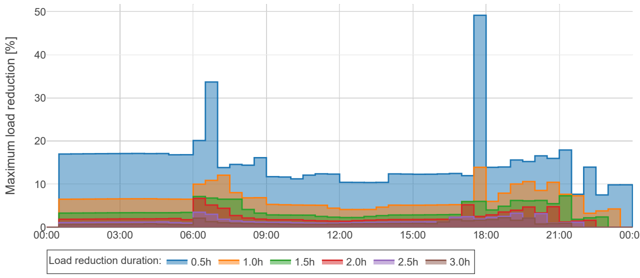


Fig. 4. Maximum load reduction potential time series.

B. *Flexibility from Electric Vehicle Charging Stations*

DSF of flexible EV chargers is enabled by the V2G capabilities of chargers and vehicles. V2G capabilities can be categorised into 1) smart charging/unidirectional V2G as well as 2) V2G charging/bidirectional V2G. Here, smart charging refers to ability to control the charging power demand schedule, whereas V2G charging describes the ability to control the bidirectional exchange of electric power between the vehicle and the electric grid, i.e. both charging and discharging.

In order to estimate the DSF potential of EV chargers, in the PDD area, we developed an EV charging model. This model takes the following time series inputs: maximum permitted charging and discharging power at each charging station, maximum value of aggregated charged energy across all vehicles, aggregated energy demand of all departing vehicles. Note that these properties are proxy variables for availability, energy demand and V2G participation of the vehicles.

With the developed EV charging model, an exemplary study was conducted for one PDD carpark to determine the optimal charging power schedule to minimize energy cost based on the Singapore wholesale electricity price. To this end, figures 5 and 6 provide the charging power over the course of one day for unidirectional and bidirectional V2G. For bidirectional V2G, the optimal charging power is close to the maximum possible charging power between 5:00 a.m. and 10:00 a.m., as well as between 5:30 p.m. and 7:30 p.m. Wholesale electricity prices are highest between 8:30 a.m. and 12:00 p.m., as well as between 6:00 p.m. and 10:00 p.m. Bidirectional V2G allows for better utilization of high-price periods.

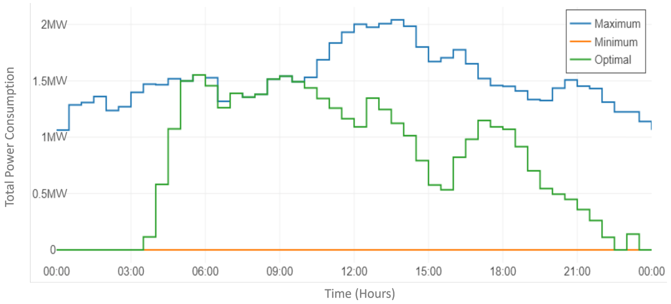


Fig. 5. Charging energy demand for unidirectional V2G.

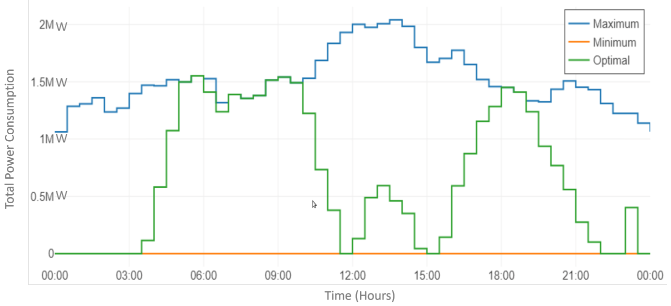


Fig. 6. Charging energy demand for bidirectional V2G.

IV. CONCLUSION

In this paper, an overview of the flexibility potential on both the demand and supply side in the study area of the PRIMO project was presented. Flexibility is important for operating micro-grids with fluctuating renewable generation and unpredictable loads such as uncontrolled EV charging. Realizing such a system comes with challenges. It takes a lot of effort to analyze the flexibility potential even of a small micro-grid. Moreover, there are privacy issues since the analysis of flexibility potentials could allow to identify energy usage patterns of customers. Policy and regulatory changes are required to enhance active customer participation in demand response.

REFERENCES

[1] International Energy Agency, "Electricity market report - december 2020 - developments in south east asia," International Energy Agency, Tech. Rep., 2022.

[2] J. Stich and T. Massier, "Enhancing the integration of renewables by trans-border electricity trade in ASEAN," in *Proceedings of the 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. Brisbane: IEEE, Nov. 2015.

[3] K. Zhang, S. Troitzsch, T. Massier, R. Migné, E. S. P. Teh, V. K. Advani, M. Cassat, Y. Xu, and K. J. Tseng, "Towards city-integrated distributed generation: Platform for interconnected micro-grid operation (PRIMO)," in *Proceedings of IECON 2020 – The 46th Annual Conference of the IEEE Industrial Electronics Society (IES)*. Singapore: IEEE, Oct. 2020, pp. 3791–3796.

[4] National Environmental Agency (NEA) Singapore, "Waste statistics and overall recycling," 2019. [Online]. Available: https://www.nea.gov.sg/docs/default-source/our-services/waste-management/waste-recycling-statistics-2016-to-2019.pdf

[5] Energy Market Authority, "Energy transformation," 2021. [Online]. Available: https://www.ema.gov.sg/singapore-energy-statistics/Ch02/index2

[6] E. Kuznetsova, M.-A. Cardin, M. Diao, and S. Zhang, "Integrated decision-support methodology for combined centralized-decentralized waste-to-energy management systems design," *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 477–500, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1364032118308165

[7] International Energy Agency, "The future of hydrogen: Seizing today's opportunities," International Energy Agency, Tech. Rep., 2019.

[8] D. F. Recalde Melo and L.-R. Chang-Chien, "Synergistic control between hydrogen storage system and offshore wind farm for grid operation," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 1, pp. 18–27, 2014.

[9] F. Garcia-Torres and C. Bordons, "Optimal economical schedule of hydrogen-based microgrids with hybrid storage using model predictive control," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 8, pp. 5195–5207, 2015.

[10] H. Xie, X. Teng, Y. Xu, and Y. Wang, "Optimal energy storage sizing for networked microgrids considering reliability and resilience," *IEEE Access*, vol. 7, pp. 86 336–86 348, 2019.

[11] J. Marqusee, W. Becker, and S. Ericson, "Resilience and economics of microgrids with PV, battery storage, and networked diesel generators," *Advances in Applied Energy*, vol. 3, p. 100049, 2021.

[12] E. Galvan, P. Mandal, and Y. Sang, "Networked microgrids with rooftop solar PV and battery energy storage to improve distribution grids resilience to natural disasters," *International Journal of Electrical Power & Energy Systems*, vol. 123, p. 106239, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0142061519342553

[13] C. Brivio, S. Mandelli, and M. Merlo, "Battery energy storage system for primary control reserve and energy arbitrage," *Sustainable Energy, Grids and Networks*, vol. 6, pp. 152–165, 2016.

[14] B. Cárdenas, L. Swinfen-Styles, J. P. Rouse, A. Hoskin, W. Xu, and S. D. Garvey, "Energy storage for a high penetration of renewables," in *2019 Offshore Energy and Storage Summit (OSES)*, 2019, pp. 1–10.

[15] J. Mundackal, A. C. Varghese, P. Sreekala, and V. Reshmi, "Grid power quality improvement and battery energy storage in wind energy systems," in *2013 Annual International Conference on Emerging Research Areas and 2013 International Conference on Microelectronics, Communications and Renewable Energy*, 2013, pp. 1–6.

[16] E. Lobato, L. Sigrist, and L. Rouco, "Use of energy storage systems for peak shaving in the spanish canary islands," in *2013 IEEE Power & Energy Society General Meeting*, 2013, pp. 1–5.

[17] X. Jin, K. Baker, D. Christensen, and S. Isley, "Foresee: A user-centric home energy management system for energy efficiency and demand response," *Applied Energy*, vol. 205, pp. 1583–1595, Nov. 2017.

[18] Y. Ozturk, P. Jha, S. Kumar, and G. Lee, "A personalized home energy management system for residential demand response," in *4th International Conference on Power Engineering, Energy and Electrical Drives*. IEEE, May 2013, pp. 1241–1246.

[19] H. Krueger and A. Cruden, "Integration of electric vehicle user charging preferences into vehicle-to-grid aggregator controls," *Energy Reports*, vol. 6, pp. 86–95, May 2020.

[20] K. Zhang, S. Troitzsch, S.-Y. Zhang, E. S. P. Teh, L. Subramanian, and T. Massier, "Transactive energy in an urban environment: A case study of local generation and flexibility potentials in a Singaporean urban district," *Frontiers in Energy Research*, vol. 9, Mar. 2021.

[21] S. Troitzsch and T. Hamacher, "Control-oriented thermal building modelling," in *Proceedings of the 2020 IEEE PES General Meeting*. Montreal, QC, Canada: IEEE, Aug. 2020, pp. 1–5.