Towards City-integrated Distributed Generation: Platform for Interconnected Micro-grid Operation (PRIMO)

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***Abstract*—This paper describes the PRIMO project which aims at defining, modeling and simulating an operation platform that facilitates market participation of interconnected microgrids (MGs) in the distribution grid market. High penetration of distributed energy resources (DERs) not only increases the complexity of distribution grid operations but can also bring new services and value streams. To this end, interconnected MGs to provide coordination between DERs and distribution grid brings key benefits to improve the social welfare efficiency. The proposed platform comprises physical system modelling tools, and communication interfaces between two hierarchical levels comprising i) distribution grid-to-MG, ii) MG-to-MG energy/flexibility exchange, aiding in the result interpretation and practical realization. Leveraging from the decentralized organization, the operational autonomy and information privacy of each MG is protected.**

***Index Terms*—Real-time market, ancillary service, urban-microgrids operation**

I. INTRODUCTION

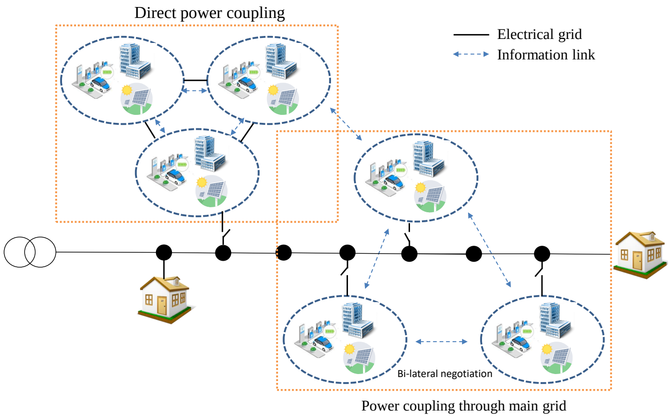

Fig. 1. Interconnected MG System. The power coupling can be either through the main grid or direct interconnection between the MGs.

A MG is defined as a localized small-scale power system, which is able to manage its power supply, distributed energy resources (DERs), and loads within the given electrical boundary. MGs make use of locally available resources and, hence, could reduce their dependence on the main grid to serve on-site loads, particularly, when contingencies are encountered. The emergence of MGs spurs interest for exploiting the benefits of DERs through the utilization of advanced management and control strategies. Currently, small-scale generators based on intermittent sources are not involved in grid operations and the major concerns for rejecting their participation often include the small size and unreliability of distributed generators (DGs) [1]. Through the concept of a MG, the DGs and aggregated flexible loads (FLs) can be clustered to form larger market players and provide ancillary services, e.g., frequency control, voltage control, spinning reserve, black start support [2]. The MGs can either be connected to the main grid or be interconnected to form a multi-MG (MMG) system, where in both cases a competitive market can be established for the multiple MGs to benefit the social welfare of the underlying system. A schematic of a typical interconnected MGs system is depicted in Fig. 1.

A. Related work and projects

Some practical examples [3], [4] include the interconnected MGs on the campus of the Illinois Institute of Technology and its adjacent community Bronzeville [3], where the optimal energy management mechanisms for interconnected MGs are exploited. Another example is the Oncor MG project near Dallas, wherein 4 sub-MGs are able to operate independently or jointly [5]. A MG energy market is established for the Brooklyn MG [6], wherein an internal P2P energy market within the MG is implemented and technologies like blockchains are tested to enable transactions between small-scale prosumers. The interconnected MGs are not the same as the traditional power distribution network. The flow of power is bidirectional from one MG to another MG or to the distribution grid and the change in network topology can be frequent in interconnected MGs. If implemented and managed properly, interconnected MGs can provide a variety of benefits to electric power utilities and consumers in terms of supply efficiency, security, and reliability [7], [8]. In the scope of their market participation, the interconnected MGs are proposed in the literature to participate in the local distribution system operators (DSO) market [7], [9] which can act as virtual power plant with each MG's controller having direct control over its resources.

B. Platform scope

To emphasize on the MG-to-MG coordination as well as the interaction of MGs to the main grid, we conceptualize the platform for interconnected micro-grid operation (PRIMO) with this project funded by the Singaporean Electricity Regulator in order to address the market integration of interconnected MGs as well as the interplay with MG control system in an urban environment. The PRIMO project aims to provide platforms at two hierarchical levels. A transactive platform is established at a higher level acting as a market place to enable inter-microgrid energy/flexibility trade and also electricity trade to the main grid. At a lower level, a MG operation platform is designed to capture the optimal prosumer behavior of the MGs and handle the physical control challenges while managing the energy flow within the MGs.

C. Assumptions

Consider the settings in Fig. 1, where each MG is operated by a microgrid operator (MGO) which owns, manages, and imposes centralized control over its DER assets, loads, and the switchgear located at the point of common coupling (PCC). Furthermore, the following assumptions are mode for the platform design.

- There are existing markets at the main grid (e.g. DSO market) which are implemented in two time scales (day-ahead and real-time). The transactive platform can be, hence, implemented in two time scales accordingly. The transactive platform can interact with the main grid market directly or indirectly (through spatial/temporal arbitrageur).
- MGOs are price-taking, utility maximizing agents. In light of this, the multi-MG coordination and the prosumer market participation can be organized by a centralized auction based on economic dispatch or decentralized optimization process that can be interpreted as a Walras' process towards market equilibrium. To support the assumption of a competitive market for consumers, the arbitrageur is considered to be introduced to increase the market liquidity.
- The local demand in the MGs are assumed to be primarily met by the electricity supply from the main grid. Hence, load flexibility is considered to be an important product that can be either provided to the main grid or exchanged between MGs.
- Definition of interconnection does not strictly require the direct physical connection between MGs. The connection can also be realized through the main grid where the grid usage pricing [10] may occur for the energy exchange between MGs. In both cases, grid codes are to be complied when connecting to the main grid.

II. PLATFORM FOR INTERCONNECTED MGS OPERATION

PRIMO is designed to address the need of a dedicated coordinated platform to enable the market participation of interconnected MGs in an urban environment. It comprises optimization, physical modelling software tools together with the communication interfaces. Note that external regulations are imposed by market regulators and grid codes, whereas the platform focuses on the market behavior and the operational side of the MMG system. An overview of its components is summarized in Fig. 2. The description of each component is detailed in the following.

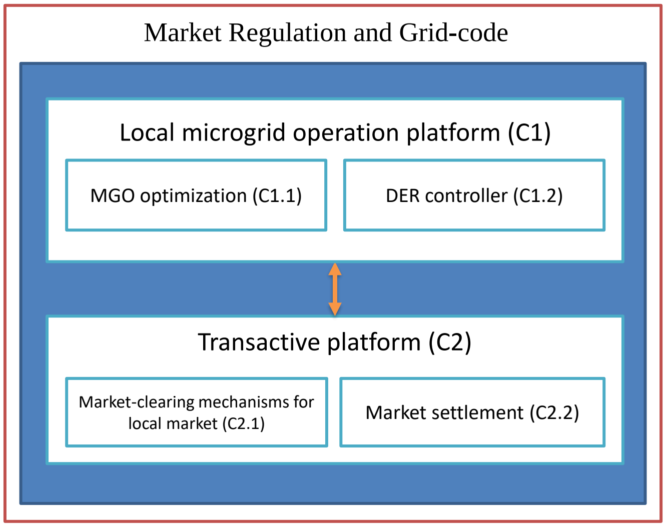

Fig. 2. Overview of PRIMO components.

A. Local microgrid operation platform (C1)

The local microgrid operation platform comprises MGO optimization modules that makes long term decisions on their market-participation behavior and short-term decision on dispatch scheduling, schedule tracking of the local DER assets.

1) Microgrid optimization (C1.1): Under the assumption that the MGOs are price takers and utility-maximization agents, the MG aggregation problem can be formulated as a cost minimization problem for energy exchange subject to the local energy balance, grid constraints, DER constraints, uncertain quantities (loading, generation profile, prices, etc.). Appropriate approaches include stochastic programming, robust optimization, and distributionally robust optimization [11].

The MGs are modeled as three-phase radial networks that each have a root node with index 0 and n PQ nodes. The essential modeling steps of the network include the derivation of the three-phase admittance matrix that can be denoted as $\mathbf{Y} \in \mathbb{C}^{3(n+1)\times 3(n+1)}$, based on the topology of the network, the π-model of the transmission lines, and alternative passive network devices. The connection of the sources/loads can be distinguished into wye- and delta connections. Then the load flow problem within the MG can be solved based on the fixed-point method as in [12]. It is worth mentioning that a linearized

AC grid model may be a tractable model to provide sufficient accuracy to capture the nature of the small-scale MG while neglecting the losses [13], [14]. Reconfigurations may need to be taken into account if the MGs are directly interconnected. For multi-time-period operation planning, time-coupling constraints of FLs and energy storage systems (ESS) should be taken into account. The considered DERs include HVAC (heat ventilation and air conditioning), photovoltaic (PV), electrical vehicle (EV) charging stations, and waste-to-energy (W2E) technologies.

Another important aspect is modeling the uncertain quantities. Loading profile, DG output, and price signals usually rely on forecast data, wherein the resulted schedule may not be feasible if the uncertainty nature of these quantities remains unconsidered. Some studies have shown that it is reasonable to model the uncertainty of the prices, loading profile, DG generations prediction by a Gaussian random variable. Hence, it is assumed that the distribution of the forecast data of these quantities (denoted as γ) can be described by normally distributed random values, i.e., $\gamma, \delta \sim \mathcal{N}(\gamma^{\text{est}}, \xi^2)$. Furthermore, the forecast value is assumed to be equal to the averaged value $\gamma^{\text{est}} = \gamma^{\text{avg}}$. Recent work applies data-driven modelling techniques, like regression model, to model these uncertain quantities.

Once the dispatch schedule is determined, the local MG controller is to use the available resources to deliver any contracted schedule for each market interval as well as the sub-hourly contract tracking while complying with the grid code. Particularly, the aim of the sub-hourly contract energy tracking of an MG is to minimize the energy difference between the scheduled and actual generation, that is to say, in the end of each contract interval (half an hour), MG should be controlled to reach the predetermined scheduled value. In addition, there may be ramping limits and additional requirements to the MG to be able to remain connected. This is due to the occurrence of generators' output clapping, change of load demand, and inaccuracy of forecast. The actual generation output and demand of the MGs may deviate from the prediction or schedule when approaching the settlement time, resulting in the energy difference between the schedule and actual transaction, i.e., the unbalanced energy. Consequently, the DSO may enforce a high rate charge for the imbalance energy. To minimize the imbalance cost, MGOs should resort to their controllable resources to control the energy imbalance to the contract during the intra-day operation to avoid penalty cost. Hence, a market-interval (half an hour) is further divided into 4 sub-hourly epochs with each epoch lasting 7.5 min to solve this optimal closed-loop control problem.

2) DER Controller (C1.2): Distributed energy resources (DERs) are defined as all electric assets connected to the local MG, which are further distinguished into fixed DERs and flexible DERs. On the one hand, fixed DERs such as uncontrollable generators including solar photovoltaic systems as well as conventional electric loads due to lighting, appliances and industrial processes cannot be controlled by the MGO. On the other hand, flexible DERs such as controllable generators, e.g., W2E plants, flexible loads, e.g., HVAC systems, district cooling systems and V2G-enabled EV charging systems, and energy storage systems allow direct control from the MGO and therefore are dispatched through the operation problem in C1.1.

To this end, the DER controller is responsible for 1) providing the other components with a physical model as well as the operational limits of the DER system and 2) interfacing the low-level control systems of DER assets to track the operational schedule provided by C1.1. For fixed DERs, the mathematical model merely consists of a prediction of the generation or load schedule, whereas for flexible DERs a detailed formulation of the system dynamics is incorporated.

Because the optimal operation problem is expected to be formulated as a convex numerical optimization problem, all DER models and constraints are expressed in terms of linear equations. To conveniently standardize the formation of the DER models, the state space form is utilized, where each DER model is expressed as:

$$\begin{aligned} \boldsymbol{x}_{t+1} &= \boldsymbol{A}\boldsymbol{x}_t + \boldsymbol{B}^c\boldsymbol{c}_t + \boldsymbol{B}^d\boldsymbol{d}_t \\ \boldsymbol{y}_t &= \boldsymbol{C}\boldsymbol{x}_t + \boldsymbol{D}^c\boldsymbol{c}_t + \boldsymbol{D}^d\boldsymbol{d}_t \end{aligned} \tag{1}$$

The vectors $\boldsymbol{x}_t$, $\boldsymbol{c}_t$ and $\boldsymbol{d}_t$ are the state, input and disturbance vectors for FL f at time step t. The matrices $\boldsymbol{A}$, $\boldsymbol{C}$ are the state and output matrices, and $\boldsymbol{B}^c$, $\boldsymbol{D}^c$, $\boldsymbol{B}^d$, $\boldsymbol{D}^d$ are the input and feed-through matrices, on the control and disturbance vectors respectively. The operational constraints are imposed by imposing upper and lower bounds onto the output vector $\boldsymbol{y}_t^{min} \leq \boldsymbol{y}_t \leq \boldsymbol{y}_t^{max}$. For example, for energy management system in a flexible building, these bounds can be obtained by the temperature limits that provides the sufficient comfort for the inhabitants of the building accordingly. The respective control variables are the considered as the switch signals of the HVAC systems. The formulation of the operational constraints $\boldsymbol{y}_t^{max}$, $\boldsymbol{y}_t^{min}$ will depend on the system setup of the DER as well as on the consumer preference whereas the disturbance time series $\boldsymbol{d}_t$ will depend on environmental and consumer interference with the DER. Therefore, the DER controller must 1) provide an interface for the consumers to set their operational preferences and 2) generate predictions of DER disturbances.

B. Transactive Platform (TAP) (C2)

To implement the system physically, a web-based platform shall be established to provide a local market place information and to enable transactive activities between different entities as shown in Fig. 3. It is supposed to be operated by an independent operator (possibly DSO) to publish profile, forecast data including distribution grid electricity price forecast (see, e.g., [15]), grid usage prices (see, e.g., [10]) and additional grid information like the operational schedule. MGOs can either trade directly with the DSO in the market place or trade with other MGOs by getting information on the supply/demand of alternative market participants including other MGOs on the platform. If the transaction is based on bilateral contract between MGOs, MGOs are obligated to report to DSO about the contracted quantity to DSO. The PRIMO does not specify any

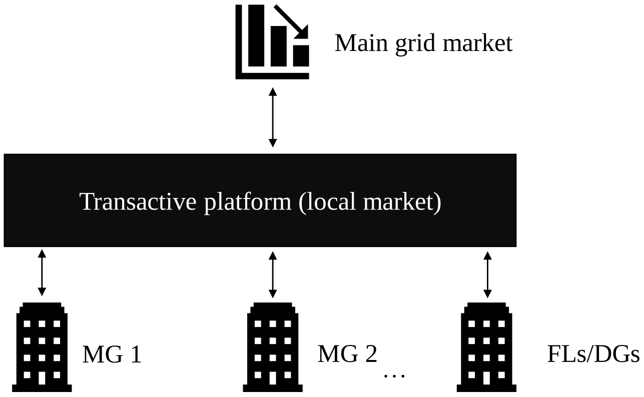

Fig. 3. Market structure.

particular transactive data structures like blockchain. It rather focuses on the market-clearing mechanisms and required data flow.

1) Market-clearing Mechanism for MMG Exchange (C2.1): The market-clearing mechanism on the transactive platform generally differentiates between two scenarios: 1) price-taking MGOs and, 2) price-making MGOs. For price-taking MGOs, the assumption ensures that the market at the distribution grid level is sufficiently competitive to prevent additional gain of profits by strategic behavior. In this scope, energy/flexibility trade between MGOs can be based on coordinated behavior. Hence, the market-clearing mechanism can be implemented to maximize the overall social welfare based on the welfare theorem in classical microeconomics. Moreover, distributed optimization protocols, e.g., alternating direction method of multipliers (ADMM) [16], which also serve as competitive market mechanisms, can also be utilized to solve the social welfare problem for the MMG system. This requires each MGO to fully comply with the protocol.

By removing the assumption of the price-taking MGOs, the objective of the problem formulation of the MGO remains the same as to maximize their individual surplus. The interaction between MGOs, however, has to be modified accordingly to model their strategic-bidding behavior. For this purpose, game-theoretical approaches are particularly useful for analyzing strategic behaviors. Mathematically speaking, game theoretical approaches comprise a broad category of games to model the decision-making process in a competitive scenario and clear the energy/flexibility trade between multiple MGOs. Game theory can be categorized into i) non-cooperative games and, ii) cooperative games. Each category of games can be used to model different decision-making processes in various scenarios. Consequently, policies and new financial products can be introduced accordingly to improve the market efficiency and social welfare based on these analysis.

2) Market Settlement (C2.2): The proposed platform considers multiple market clearing during a day. The day-ahead energy market enables the market participants to commit to electricity purchase/selling one day before the operating day, which can potentially reduce price volatility for the real-time market. The real-time market serves as the real-time adjustment of the committed dispatch schedule of the MG system. In total, two financial settlements will be produced for each point on the time scale. From a long-term perspective, blockchain and other distributed data technologies can be exploited to enhance the data security and lower the operational risks.

C. Example

We use the following example to illustrate a typical day-ahead market-clearing process and the information flow in Fig. 4. Prior to the day-ahead market-clearing, the transactive platform obtains and publishes necessary market data from the DSO and market participants. Based on this data, the MGO solves its optimization problem as a prosumer and decides upon its market participation strategies (trade with DSO, exchange with other MGOs, or both). Once the decision has been made, the MGO will submit the bids to different market places. For the DSO market, the market will be cleared by the DSO centrally for the contracted quantity and prices. For a bilateral market, the market will be either cleared by the transactive platform centrally or based on the negotiation results on a bilateral basis. Consequently, the DSO shall be informed by all the bilateral contracts. The MGO will set their control strategies for the next day accordingly. Note that a real-time market can be implemented in a similar manner to accommodate the uncertainty of the day-ahead planning.

III. STUDY AREA

A. Overview

In the scope of PRIMO project, a study area is determined as the Punggol Digital District (PDD), Singapore, scheduled to operate from 2023 onwards, wherein it is planned to model the interconnected MGs operation within this area. Based on the design data, modeling and simulations will be first carried out to study the generation and flexibility potentials and the proposed transactive platform shall be able to provide the essential coordination services between various MGOs, DERs, and regulatory bodies.

The PDD brings together the Singapore Institute of Technology (SIT)'s campus and the Jurong Town Council (JTC)'s business park spaces within the new community of at least 2000 families in Punggol North. The infrastructure and services available in phase 1 of the PDD include a public transportation hub (i.e. Mass Rapid Transit (MRT) and bus interchange); retail and commercial sectors (i.e. F&B, shopping malls); services (i.e. childcare, community services) and workspaces (i.e. offices, co-working, prototyping workshops). The land which is 50 hectares in size would offer 28,000 jobs in digital economy, a place to work and study for 12,000 students and 500 academic staff. The peak load of this study area is taken as 50 MVA for the phase 1 of SIT and JTC only. An overview of the study area is depicted in Fig. 5. The PRIMO project would consider the digital capability of the PDD in managing and optimizing power dispatch including the following systems that will be deployed in this location:

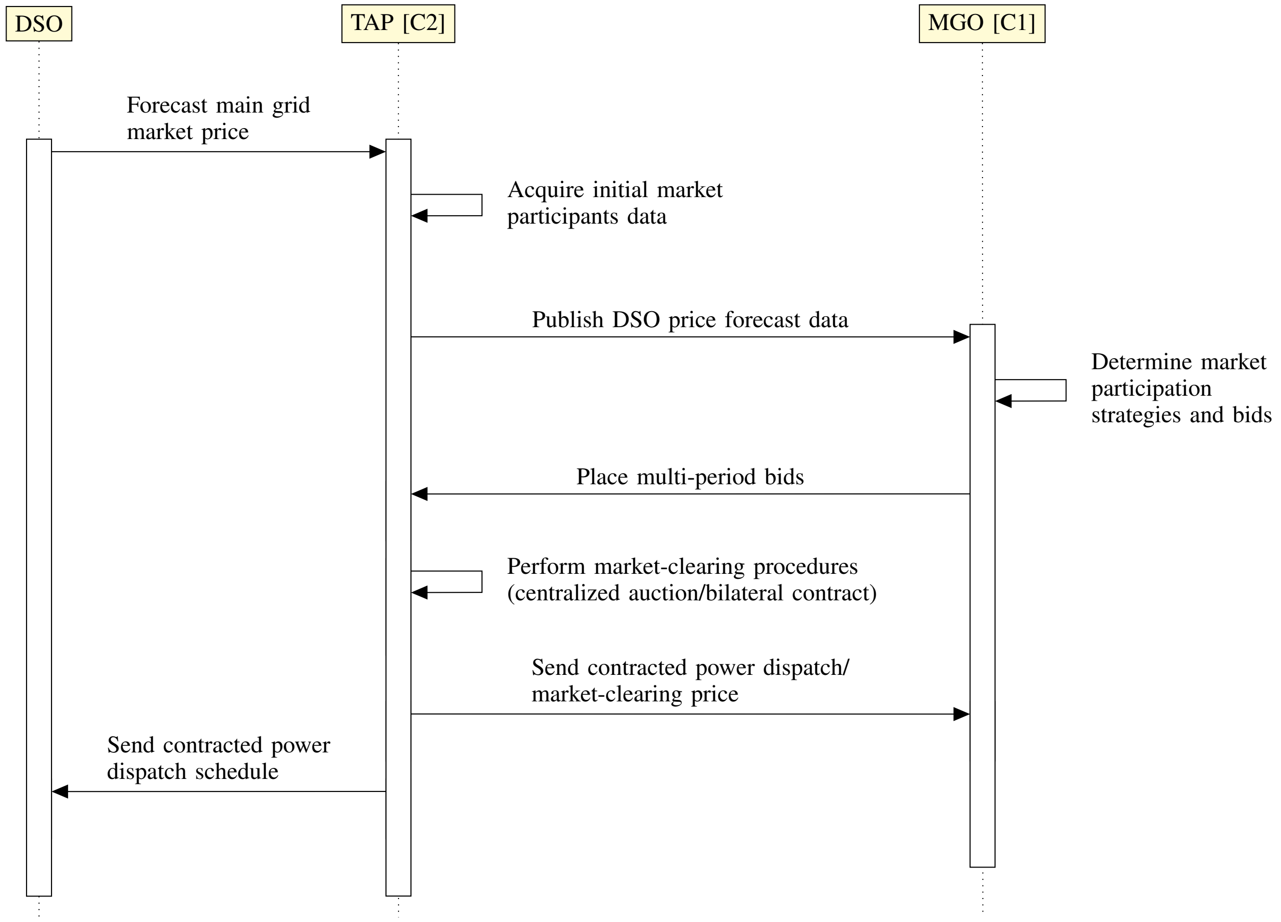

Fig. 4. Sequence diagram for interconnected microgrids participation in day-ahead market.

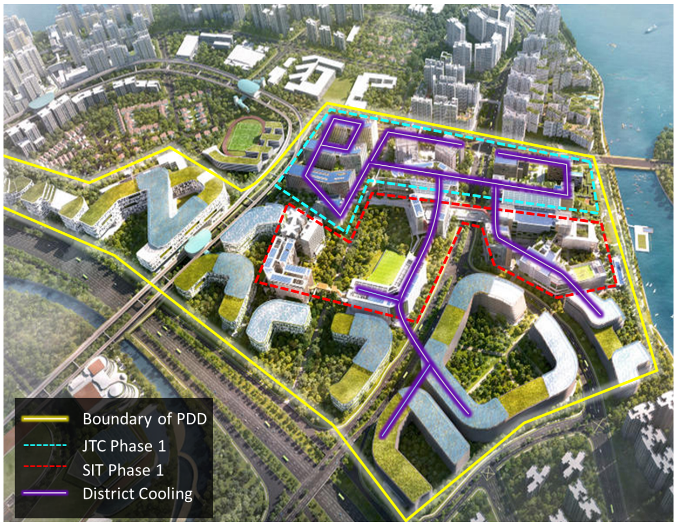

Fig. 5. Punggol digital district planning area in Singapore.

- A MG located at SIT campus with PV generation and energy storage systems. The PV system at SIT campus (phase 1) alone could generate $1.3\,\mathrm{MWp}$ with its $11\,500\,\mathrm{m}^2$ of PV cells. Additional PV generation in the JTC Business Park (phase 1) is of equivalent capacity. It is also envisioned that PV cells would be installed on roof tops of most buildings in the PDD area.
- In this study, the co-optimization of power and cooling in this project will cover a total of $108\,\mathrm{MW}$ cooling capacity for SIT Phase 1 and JTC CC1, CC2 and CC3. Flexible operation of the chiller system may be made more efficient through thermal storage generated during off-peak periods.
- The JTC business park (phase 1) in the PDD has a Pneumatic Waste Collection System (PWCS) to collect waste through a district-wide underground vacuum-pipe network. The PRIMO project envisions a decentralized W2E plant, adjacent to the PWCS, to generate electricity and to recover heat as DER. It is estimated that 40,000 people will be working and studying in the PDD. The combined general waste generation in the first phase of PDD is estimated to be 20 ton/day. With a conservative net heating value of 7MJ/kg, there is potentially 140 GJ of energy to be recovered as electricity (11.7 MWh) and heat (63 GJ/day). PRIMO project will look at the potential of gasification as W2E technology to generate fuel which can be stored and provide on demand energy supply to the

MG. Operation window and power conversion response profile will be part of PRIMO's optimization study.

- Smart metering technologies will be deployed in this study area that allow consumers to adopt clean and renewable sources of energy, and also to participate in demand-supply cost optimization (i.e. charging of electric vehicles and selling of stored electricity to the grid), but also facilitate greater energy efficiency and savings for end customers.
- The private EV charging demand was derived from a household mobility survey and it was shown that it could offer significant peak shaving potential when considering V2G capabilities.

Based on the received data of the study area, models will be established for the aforementioned systems to solve the respective optimization problem in Section II. In terms of controller design, the integration of flexible electric loads is an important step towards dealing with intermittent renewable generation. In recent years, the advances in model predictive control (MPC) have inspired research into energy efficient thermal building control. With MPC, the scheduling problem of HVAC systems can be formulated as an inter-temporal optimization problem aimed at minimizing operational costs, i.e. energy costs, subject to comfort requirements, enabling DSF with indirect control through the energy price. The ability of MPC to consider dynamic energy prices has further led to research into how buildings can offer demand side flexibility to the power system operator. Hence, the deployment of MPC for DER control will be tested for the study area.

B. Deployment of transactive platforms

The local MG operation and transactive platforms will be developed based on the modeling results and market analysis of the study area. Specifically, the operation platform can be deployed for the SIT MG management as well as other potential MGs in an urban environment. For the transactive platform, there are other prosumer agents besides the MGOs, which are considered to be the building aggregators, charging station aggregators, and DCS operators. They can utilize the local electricity market place to maximize their individual surplus. Overall, the transactive platform will be developed to settle the market transactions between the prosumers in this area in coordination with the main grid electricity market.

IV. CONCLUSION AND OUTLOOK

Moving towards grid decentralization, an integrated platform for operation of interconnected MGs and their market integration into a local energy market are proposed in this work. With the proposed platform, local MG operators and other prosumers in the local market preserve their autonomy in the energy management while economic efficiency of the overall system is achieved. In the beginning phase of the project, it will be focused on the modeling of the study area, whereby the demand/supply characteristic, flexibility potentials will be accessed and analyzed. Based on this, potential commodities and market organizations to enable the transactive platform design will be investigated and defined that in line with the current electricity market settings in Singapore. Future work comprises the investigation of the incorporation of peer-to-peer electricity trading and the regulatory work to enable the deployment of the platform.

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