Integrated Distribution System and Urban District Planning With High Renewable Penetrations

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Abstract

Recent efforts to reduce energy consumption and greenhouse gas emissions have resulted in the development of sustainable, smart districts with highly energy efficient buildings, renewable distributed energy resources (DERs), and support for alternative modes of transportation. However, there is typically little if any coordination between the district developers and the local utility. Most attention is paid to the district's annual net load and generation without considering their instantaneous imbalance or the connecting network's state. This presents an opportunity to learn lessons from the design of distribution feeders for districts characterized by low loads and high penetrations of DERs that can be applied to the distribution grid at large. The aim of this overview is to summarize current practices in sustainable district planning as well as advances in modeling and design tools for incorporating the power distribution system into the district planning process. Recent developments in the modeling and optimization of district power systems, including their coordination with multi-energy systems and the impact of high penetration levels of renewable energy, are introduced. Sustainable districts in England and Japan are reviewed as case studies to illustrate the extend to which distribution systems planning has been considered in practice. Finally, newly developed building-to-grid modeling tools that can facilitate coordinated district and power system design with utility involvement are introduced, along with suggestions for future research directions.

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Caption: Engaging the local utility and including electrical distribution system design in district master planning can reduce costs and improve performance of sustainable urban districts with high penetrations of renewable energy, but new research tools are needed to facilitate an integrated design. *Source:* `fujisawasst.com/EN/`

Introduction

Efforts to reduce greenhouse gas emissions worldwide have become an area of global concern with agreement on at least some targets and time lines for their reduction (*Paris Agreement*, 2015). The European Union, for instance, aims for an 80%–95% reduction in greenhouse gas emissions by 2050 compared to 1990 levels (European Commission, 2011). To achieve these targets, particular focus has been placed on energy end-use reductions in buildings—in the European Union, buildings are responsible for 40% of total emissions (*Clean Energy for All Europeans*, 2016), requiring the building sector to achieve a reduction of at least 88%–91% to contribute to the 2050 target (European Commission, 2011). Further, more than one-quarter of the projected 2050 E.U. building stock is yet to be built. To exploit the huge savings potential of the building stock to meet climate goals worldwide, significant reductions in energy usage are required—through both better design and operations along with increased building energy generation from renewable sources.

Within this landscape, zero energy buildings (ZEBs) have proven to be key players by directly addressing challenges regarding energy efficiency, renewable energy generation, and energy management. A ZEB's energy consumption, and related greenhouse gas emissions, must be close to zero on an annual basis (Atanasiu & Attia, 2011; Peterson, Torcellini, & Grant, 2015; European Union, 2010). Notably, the European standard EN15603:2008 recommends a yearly weighted primary energy balance, preferably also showing monthly or shorter time intervals rather than only an annual basis (European Committee for Standardization, 2008). This is achieved through stringent design or thorough retrofitting for high energy efficiency combined with on-site renewable energy generation and careful management of energy storage system operations and building services. A completely electric ZEB with electric cooking and heating demand additionally avoids localized emissions, improving urban air quality. Moreover, ZEBs have inspired the development of net zero energy districts (ZEDs), which use spatiotemporal smoothing of load and generation from these buildings for improved efficiencies. In addition to building-level improvements, ZEDs take advantage of efficiencies of scale, including district energy systems that harness renewables and waste heat (Polly et al., 2016). ZED design presents an opportunity to achieve energy balance at the community level, which can contribute significantly to reaching the emissions-reduction targets.

Concurrently with these developments in building and urban planning, electric power systems have been undergoing a transformation. The introduction of large amounts of renewable energy and distributed energy resources (DERs) are driving a shift from centralized to localized energy generation. In particular, the rise in distributed solar photovoltaics (PV) is rapidly changing the way in which electricity distribution systems are designed, operated, and regulated. Although early DER adoption has been consumer-driven without any centralized or long-term planning, the increasing penetration levels of distributed renewable energy necessitates updated distribution system design to mitigate potential challenges such as voltage violations, reverse power flows, and inappropriate protective equipment responses. Within a ZED design, there are opportunities for achieving efficiencies of scale through holistic designs for distribution systems with high renewable penetration levels rather than treating interconnection on a case-by-case basis. Additionally, the introduction of renewable DERs in the power sector complements building energy usage reductions to achieve emissions targets at the district or city level.

Because of these combined developments, the fields of urban district planning and electric distribution design have significantly changed during the last two decades. Although these two areas have been developing relatively independently of one another from an academic perspective, further implementations have driven the need for an integrated process for sustainable urban development with electric distribution system design and planning. The integrated treatment of these concepts has the potential for both economic savings as well as the further incorporation of additional technologies that can reduce greenhouse gas emissions; however, current practice typically excludes distribution system design considerations during ZED planning. Energy balancing is assumed to take place on an annual horizon, which neglects any instantaneous power imbalances between a district's renewable DERs and its load. This can lead to a variety of challenges, such an unanticipated curtailment, expensive grid reinforcements, or violations of voltage limits or line ampacity ratings. By specifically designing the distribution system along with a ZED's load and generation assets, many of the challenges can be mitigated at lower costs compared to designing the district and distribution systems separately. This requires both fostering utility involvement as a stakeholder during ZED planning as well as improved modeling tools to facilitate an integrated approach.

This overview introduces opportunities for an improved, integrated district and electric distribution system planning process by reviewing current practices and research in the two fields. First, current standard practices in sustainable urban district planning are reviewed, including DERs, district services, and transportation; in general, current urban planning does not fully consider the power system. Then, recent research on power system design that would be appropriate during district-scale urban planning is introduced, followed by newly developed combined buildings-to-grid models that integrate these two planning stages together. To illustrate the extent to which power system planning has or has not been incorporated during the design process, two sustainable district case studies are presented. Finally, the authors conclude with some additional recommendations for future directions to improve integrated urban-distribution system planning.

Sustainable District Planning Practices

Over time, sustainability aspirations in urban planning such as healthy living, reduced carbon emissions, and general environmental stewardship have culminated in the idea of the net zero energy district. A variety of ZED definitions have been proposed (Carlisle, Van Geet, & Pless, 2009; Marique & Reiter, 2014; Koutra, Becue, Gallas, & Ioakimidis, 2018; Aghamolaei, Shamsi, Tahsildoost, & O'Donnell, 2018), generally motivated by a combination of two objectives: a desire for more stringent carbon emission reductions and a developing concern for energy security, including self-sufficiency and community resiliency. A general definition for a ZED is a district that generates as much energy as it consumes over an annual horizon, but ZEDs focused on carbon emissions may also aspire to be "zero carbon districts," completely eliminating on-site fossil fuel consumption or using carbon credits to offset remaining emissions (Carlisle et al., 2009). ZEDs more focused on energy security may allow for some on-site gas co-generation or diesel back-up because of the added energy surety they provide. For purposes of measuring its performance and success, a ZED definition might encompass all annual energy consumption in terms of electricity, heating and cooking energy, and transportation, or it might be more focused, for example, only on electricity demand (Aghamolaei et al., 2018). The question of how to treat transportation that originates, ends, or stops in the district is an unresolved question, and is often excluded from ZED definitions for ease of accounting (Aghamolaei et al., 2018). Of interest here, a ZED with a net zero electrical system can be defined as a district that generates enough electricity from renewable resources to offset its consumption from the grid at large. For the purposes of this paper, which focuses on electric utility involvement in district planning, we use the term ZED loosely when referring to districts with very high renewable energy penetrations and (near) net zero electrical systems, regardless of where the district chooses to draw its boundaries for carbon and energy accounting in terms of gas consumption, transportation, etc.

As the demand for ZEDs emerges, the district planning process is evolving as well. District planning now extends beyond basic sustainability principles to include measures such as ultra-low energy buildings, significant distributed renewable energy resources, multiple energy vectors, district thermal loops, and the integration of mobility energy (Polly et al., 2016). This section introduces current practice for some of these major district planning steps, shown in Fig. 1 for a typical planning process. Each of these aspects impacts electricity usage and thus the requirements on the distribution system; as district energy systems become more complex and interconnected, it is increasingly important to consider these impacts from the early design stages and from the standpoints of both cost and operational stability. However, a typical district planning process does not consider the distribution

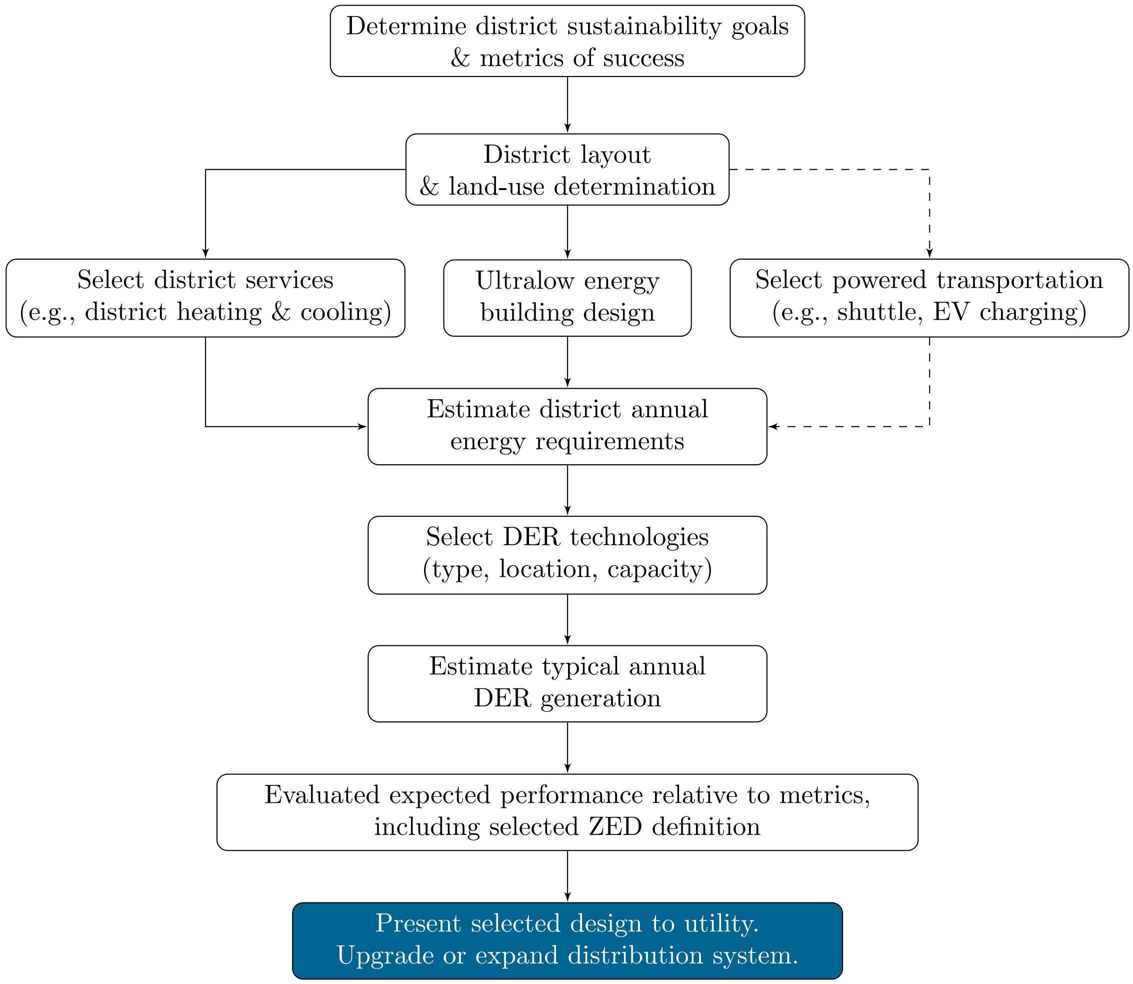

Figure 1: A typical sustainable district design process with limited utility involvement, in which electrical demand and generation are treated on an annual time horizon, neglecting grid impacts. Transportation may or may not be included in the district's performance goals, as it can lead to ambiguous energy accounting. The distribution system design is added on near the end of the process, once most of the design decisions are made.

system design until late in the planning process after the other district elements have been selected, as shown in Fig. 1. While this district planning process is broadly intended for new, "green field" district developments, the design measures are applicable to retrofit or expand "brown field" developments as well, but the additional constraints of existing infrastructure may render some options less effective or impractical. In those instances, it is even more important to engage the utility from an early stage and model those constraints in planning tools. In that vein, later sections describe how this design process might be improved with earlier utility engagement and integrated distribution system design.

District Planning: Energy Master Planning

Commonly, sustainable district development begins with a district master plan conceived by urban planners and master developers. The master plan articulates the district vision and development principles, including guidelines and standards for site design, minimal sustainability targets, key architectural design elements, landscaping design, and signage. In response to growing support for ZEDs and other developments with high levels of energy efficiency and renewable energy, a focus on “energy master planning” has emerged to supplement the typical district master plan and ensure that all key energy planning elements are fully considered. In response, the U.S. Department of Energy has launched the Zero Energy District Accelerator (Zaleski, Pless, & Polly, 2018) to accelerate this trend. Where sustainability goals might now extend to self-sufficiency and community resiliency, the integration of distributed generation and energy storage for both net zero energy and enhanced energy surety is a key community value to be included in planning efforts.

However, a lack of integrated energy planing and modeling tools that include optimal strategies across the district sectors and scales has limited the effectiveness of zero energy master planning to date. To realize the full potential of district energy master planning, planning tools and approaches are needed that unlock renewable energy economies of scale; maximize load diversity to reduce capacity requirements for central heating, ventilating, and air-conditioning and energy storage systems; enable access to centralized waste heat capture resources; and leverage centralized decision-making. For example, investment in district-scale waste heat recovery and thermal energy storage must consider the balance between district system infrastructure costs and best-in-class energy-efficiency measures that further reduce building loads.

All of the technical planning efforts must be paired with a practical governance and ownership model for how the district energy system will be financed, owned, and operated, including its new gas and power lines, district heating and cooling loops, generation and storage assets, monitoring and communications hardware, and protective or regulatory equipment (Bouton, Newsome, & Woetzel, 2015). For the electricity system, a major new concern in this regard is the ownership of and operational responsibility for renewable DERs, including both communal generation and storage assets as well as roof-top PV or in-building battery systems. Options range from customer control of their behind-the-meter energy assets to third-party aggregation to centralized utility ownership and control, funded through rate-based investments (*2016 State of the Electric Utility Survey*, 2016). The selected ownership model will largely dictate how the energy assets are operated and whether net zero energy operation is possible, so resolving the ownership question is critical to the rest of the energy master plan.

District Planning: Distributed Energy Resources

Sustainable district planning has typically involved the inclusion of DERs to offset at least some all of the district's electrical load. In recent years, the driving force behind DER integration has been customer adoption of PV on residential and commercial buildings (Gagnon, Margolis, Melius, Phillips, & Elmore, 2016). In addition to PV, storage technologies such as lithium-ion batteries have seen increased deployment in recent years, which can complement the variability and uncertainty of renewable DERs such as PV. Other DER options include distributed wind generation, small-scale hydropower, geothermal heat pumps, fuel cells, and demand-side management (Jiayi, Chuanwen, & Rong, 2008); diesel generators, while not zero carbon, can contribute to local energy security if that is of high priority. However, as customer installation of PV has emerged as the dominant mechanism for DER deployment, there has been relatively little centralized planning regarding DER siting and sizing at the distribution level.

By including DERs within district master planning, a higher DER penetration could be achieved more efficiently compared to the current piecemeal process. In the case of PV, the first planning concern is to ensure sufficient access to solar radiation for PV installations on rooftops, large covered parking canopies, and in community-scale arrays. To that end, the district master plan might allocate land use areas for community solar and lay out buildings to minimize shading from one building to the next. Incorporating these siting concerns into urban planning is intended to ensure adequate DER power generation, but these steps are likely insufficient to achieve very high DER penetration rates without also tailoring the electrical distribution system to the district's unique needs.

High penetrations of DERs fundamentally change the operating paradigm of distribution grids. Renewable DERs such as PV are variable, uncertain, nondispatchable, and, in large numbers, can disrupt the unidirectional power flow from transmission to end users, all of which pose challenges to utility operations. Power injection from large numbers of DERs can overload power lines and cause overvoltage violations if left unaddressed. Other important concerns include reactive power support, reverse power flow into substations, wearing of voltage regulator taps because of variability, and changes to transmission market models (Katiraei & Agüero, 2011; Tonkoski, Turcotte, & El-Fouly, 2012). When a large DER installation is proposed, the utility will typically require a study to assess the impacts of the new installation on these concerns before permitting the interconnection. If the results show that the installation cannot be adequately supported by current infrastructure, the utility might disallow the planned DERs, require the developer to pay the incremental infrastructure costs, or be forced to bear those costs itself, based on local regulations and practice. Therefore, a ZED should engage the local utility from the early planning stages to develop a more holistic energy master plan that anticipates and mitigates these expected grid impacts to efficiently and cost-effectively achieve the full benefit of the district's DERs.

District Planning: Heating, Cooling, Water, and Waste Services

The master plan can address other services, such as waste management and water, heat, and gas networks, which might interact with the electrical infrastructure. Water interactions with the electrical system have typically been limited to correctly sizing electrical infrastructure to support the anticipated pumping load based on the locations of the water supply and wastewater treatment plant; looking forward, water pumping is a large dispatchable load that could be incorporated into future demand response efforts.

More notably, thermal (both heating and cooling) and gas networks can be tightly entwined with the electrical system (Sayegh et al., 2017). Over time, the technology for district heating systems has continually improved by reducing the hot water supply temperature (from 100-200°C to <70°C), resulting in energy savings due to reduced transmission

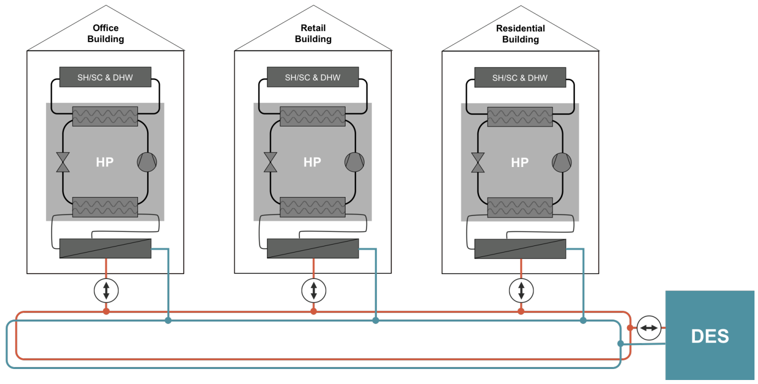

Figure 2: Fifth-generation district heating and cooling network layout. Each building serves its space heating (SH) and cooling (SC) loads through its own heat pump (HP), allowing temperature independence from the primary loop, fed by the district energy system (DES).

losses and ability to add new heating sources to the district system. Although the original heat sources were oil- or coal-fueled steam boilers (von Rhein, 2018), heating networks have evolved over time to use combined heat and power (CHP), and eventually geothermal, biomass, waste incineration (Lund et al., 2014), and solar thermal (Winterscheid, Dalenbäck, & Holler, 2017). CHP plants can provide heat as well as electricity at high efficiencies. Using biomass or local waste as a CHP fuel source rather than natural gas can further reduce the district's carbon footprint; however, increased recycling and composting have reduced the combustible content in municipal waste, and local air quality concerns have reduced the feasibility of waste incineration or co-generation. On the other hand, lower district heating loop temperatures enable even more carbon-free heating sources, such as wastewater heat recovery (Polly et al., 2016) and data center waste heat (Wahlroos, Pärssinen, Manner, & Syri, 2017).

Modern district thermal systems merge district heating with cooling as well and can be installed in regions with highly variable climates. These two-pipe or single-pipe systems can directly utilize the rejected heat of the cooling loads in the district (Fig. 2). Unfortunately, there have been comparatively fewer advances in cooling sources. Absorption chillers can be used if there is high temperature waste heat, otherwise, heat rejection for district cooling is typically accomplished with mechanical cooling, cooling towers, or cooling ponds (Lake, Rezaie, & Beyerlein, 2017). Modern "fifth-generation" district heating and cooling (5GDHC) networks use lower supply temperatures (10°C to 25°C), which can vary seasonally to optimize energy efficiency (Fedrizzi, 2017; ETH Zürich, 2017). The low supply temperatures require boosting the temperature for space heating and domestic hot water preparation, typically accomplished with a reversible water-to-water heat pump in each of the buildings, allowing each building the freedom to meet its heating or cooling load independently of the loop temperature and to both consume and produce heat.

In conjunction with a district thermal network, seasonal thermal storage systems (STES) may allow shifting surplus solar energy collected during the summer months to the winter months (Griffiths & Colclough, 2015). STES systems heat a storage medium with excess solar energy, and then extract the low-grade thermal energy to serve domestic hot water and space heating needs at a later time. In regions with significant heating demand such as Northern Europe, this is an important technology for utilizing variable renewable energy sources, especially in zero energy districts where a large degree of independence from the electric and natural gas grids is desired (Griffiths & Colclough, 2015). Commonly, STES systems heat soil directly through boreholes drilled in the ground; other systems exchange heat with aquifers or storage tanks or pits filled with a storage medium. Inversely and less commonly, ice storage can help serving cooling needs during warm days (Griffiths & Colclough, 2015). Successful examples of STES include Brædstrup, Denmark (`http://www.solarge.org/index.php?id=1646`), the Drake Landing Solar Community in Canada (`https://www.dlsc.ca`), and Suffolk One, a college in East Anglia, England (`http://www.e-hub.org/concrete-solar-collector.html`), which each combine solar thermal collection with borehole STES. At Drake Landing, the ground can reach temperatures in excess of 70°C, which is used to heat the houses passively.

Clearly, the reliance of 5GDHC systems on electrically driven heat pumps offer a prime opportunity for tight design integration between the thermal and the electric distribution infrastructure. These 5GDHC networks may unlock resources for electric demand flexibility by proactively shaping thermal heating and cooling loads in an urban built environment to anticipate and respond to renewable energy availability changes. Even so, there are still significant barriers to the practical implementation of district energy systems, such as a limited knowledge base, the necessity of complex partnerships, and unclear cost/benefit allocation (Cooper & Rajkovich, 2012). Another open question is determining the optimal balance between investing in building energy efficiency to reduce consumption versus investing in district thermal systems to provide high-efficiency generation, given that these systems can be very expensive. Nonetheless, districts with multi-energy technologies like 5GDHC networks and CHP plants are being developed and are already relatively common in Europe. Districts with stringent carbon emissions targets could push one step further, replacing natural gas infrastructure completely through all-electric heat pump heating and electric or induction residential and restaurant cooking systems, which would require committed community buy-in because of the popularity of gas cooking. Such measures would significantly impact the electrical load profile and thus the distribution system, but as yet, complete district electrification is an academic study rather than a practical reality. Regardless, the coordinated planning of a district's interconnected gas, thermal, and electrical systems in the energy master plan can achieve significant efficiency benefits and open new opportunities for operational flexibility.

District Planning: Transportation

Typical district master planning for transportation aims to facilitate the flow of people within and across the district boundaries with adequate pedestrian malls and sidewalks, bike lanes, and group and public transportation infrastructure, in addition to personal vehicle accessibility (Kenworthy, 2006; Coates, 2013). Car-share, ride-share, and automated bus infrastructure can incentivize the reduction of personal vehicles (Chance, 2009); integrated smart phone applications can facilitate group mobility. Similarly, easy access to public transportation can complement pedestrian byways to reduce vehicle congestion and transportation emissions. From a holistic neighborhood perspective, public, multimodal transportation centers can also function as network hubs for economic development and community activity (Kenworthy, 2006).

In addition to reducing the use of personal vehicles overall, an emerging planning concern is the accommodation of an increasing penetration of electric vehicles (EVs). The preferred locations and extent of EV charging infrastructure is an evolving question. When integrating EVs into the district's buildings, the building type and location dictate the desired charging infrastructure and the relative impact of charging on the building performance and load profile. At the grid level, the parallel growth in electric vehicles can help or hinder grid reliability as the distribution system is transformed by renewable DERs (Mwasilu, Justo, Kim, Do, & Jung, 2014). The high power requirements and timing of EV charging can stress grid infrastructure, particularly when exacerbating peak loads. On the other hand, power electronics and car batteries can provide grid services, with manufacturer support; at this time, EV grid support has not yet gained widespread industry adoption. Therefore, the grid performance is strongly impacted by the EV charging controls, and new business models and electricity markets might develop in the future to ensure stable operation.

District Distribution System Design

Currently, the district energy master planning process generally overlooks the distribution system design, missing an opportunity to engage utilities and regulators as stakeholders in the planning process. As a result, a tension can develop between a community's efforts to become energy independent and its assumed dependency on the local utility for instantaneous balancing and grid stability services. The grid infrastructure and local regulations will impact whether the district can practically achieve net zero energy operation for its electricity system – for example, DER curtailment may be required during overvoltage events or to minimize reverse power flows. By engaging the local utility and regulators, technical and regulatory solutions can be developed to accommodate the ZED's unique operating needs, be mutually beneficial for the utility, and not detrimentally impact other customers. Although a discussion on DER operating regulations and local rate structures is beyond the scope of this overview, recent academic work has progressed modeling and analysis methods that would be appropriate to incorporate during the energy master planning phase of a ZED distribution system. This section will provide an overview of these modeling and design approaches and their relevance to district-scale design.

Distribution Design: Expansion Planning and Operational Optimizations

Typically, two types of studies are particularly relevant during the system design phase: expansion planning and operational models; additional guidance on conducting these types of studies can be found in (Holttinen, 2018). In the district planning context, expansion planning can be thought of as the placement and sizing of new storage and DERs on the distribution feeder. Operational models typically determine the dispatch of generation to meet forecasted load. Modeling operations during the course of a year can illuminate trends in operating costs, emissions, or voltage regulation performance. In reality, these two optimization problems should inform each other: the results of the expansion planning form the basis of the operational model, and the success of the daily or yearly operation should inform whether additional assets or grid reinforcements are required. With increasing penetrations of nondispatchable variable and uncertain renewable resources, it is increasingly important to include operational models that capture the weather dependency of renewable generation during expansion planning decision-making. As a result, an increasing number of studies consider these problems together using bilevel optimization methods to consider both capital costs and operating costs simultaneously (Saldarriaga, Hincapié, & Salazar, 2013; Mashayekh, Stadler, Cardoso, & Heleno, 2017; Morvaj, Evins, & Carmeliet, 2016).

In general, optimization problems like these can be formulated as mathematical problems with linear and/or non-linear equations to describe the system, including the behavior of the DERs, the flow of power throughout the distribution network, and the investment cost of adding new assets. Expansion planning and operational problems frequently contain binary variables as well as continuous variables, due to binary choices like whether or not to build a new generator. In these cases, the optimization problems are formulated as mixed-integer linear programs (MILP) or mixed-integer nonlinear programs. Additionally, although minimizing capital investment and operational costs is usually the primary goal, it is not the only consideration. In the case of a ZED, the key requirement might be minimizing annual net electricity import. Other considerations might include minimizing carbon emissions, system losses, or voltage fluctuations. As a result, these problems are often studied as multiobjective optimizations, commonly solved with genetic or other evolutionary algorithms (Maroufmashat, Sattari, Roshandel, Fowler, & Elkamel, 2016; Lo Cascio, Borelli, Devia, & Schenone, 2017; Moradi & Abedini, 2012). For a particular development, a multiobjective optimization can inform decision-making by characterizing the trade-offs among the project's critical goals, such the trade-off between minimal cost and minimal operating emissions.

A few ongoing improvements to operational and expansion planning optimizations are particularly relevant to ZEDs. Within operational models of distribution systems, which have low-voltage lines and potentially unbalanced single- and two-phase lines, an AC power flow is required to accurately characterize system losses and compliance with voltage regulations and line capacity constraints. This necessitates modeling the grid infrastructure, including line impedances. At present, some district-scale studies take a simplified view of the distribution network (Best, Flager, & Lepech, 2015) or ignore it altogether (Wakui, Kinoshita, & Yokoyama, 2014; Lo Cascio et al., 2017). In many cases, the network is modeled by assuming that the power into and out of a line is equal, which thereby ignores voltage impacts and losses; some studies simplify further by looking solely at annual generation and load. As stated before, designing a ZED under these assumptions might be a poor indicator of how it actually performs because of unanticipated DER curtailment or grid stability issues. Other recent studies are directly studying these concerns by including complete network models within distribution system design (Saldarriaga et al., 2013; Babacan, Torre, & Kleissl, 2017; Moradi & Abedini, 2012; Morvaj et al., 2016).

As an additional concern, most operational models are conducted by solving for the system's steady-state operating point at hourly intervals, which is too coarse to capture the variability of nondispatchable renewable generators. In a traditionally designed distribution feeder, rapid changes in supply can cause voltage fluctuations that increase wear and tear on mechanical voltage regulation equipment such as load tap changers (LTCs); voltage excursions might also exceed regulatory limits during mechanical LTC delays or because of an insufficient range of tap settings. For an urban ZED with mostly uniform weather exposure, minute-by-minute variability will have a significant impact on operating conditions. Nonetheless, it is still common to use hourly time steps for distribution system modeling with renewable DERs, partially because of a lack of fine-resolution weather input data. Recently, however, district design studies have been emphasizing the use of weather data with increments of 1–15 minutes (Molitor, Groß, Zeitz, & Monti, 2014; Babacan et al., 2017; Protopapadaki & Saelens, 2017). Unfortunately, high computation time is a second impediment to using fine-resolution time-series data, but methods are also being developed to analyze an entire year's data without prohibitive computation time or unacceptably large errors (Deboever, Grijalva, Reno, Zhang, & Broderick, 2017; Mather, 2017).

Operational optimizations should also be robust to some level of uncertainty in both the load and renewable energy generation. At the district level, recent academic work has addressed renewable DER uncertainty with agent-based models, stochastic optimizations, and rolling optimization horizons (Silvente, Kopanos, Pistikopoulos, & Espuña, 2015; Kuznetsova, Li, Ruiz, & Zio, 2014). For instance, because weather forecasts are increasingly uncertain during longer time horizons, a rolling-horizon optimization continually recalculates for each time point given the most up-to-date forecast rather than calculating once with a day-ahead forecast. By developing these new tools to address uncertainty, excessive DER curtailment can be avoided.

Additional modeling methods will be described in the following sections, but expansion planning and operational optimizations remain the fundamental research problems. These other modeling strategies can be thought of as building blocks to better represent system constraints or desired behavior within these optimizations.

Distribution Design: Microgrid Approaches

A microgrid is an interconnected set of generators and loads that can appear as a single, controllable entity to the network at large. For a certain area to operate as a microgrid, it must have sufficient local generation, storage, regulation, and control equipment to serve its own critical loads, allowing it to either remain grid-connected or to disconnect and operate as an autonomous island during contingency events. Microgrid research commonly focuses on remote or rural applications where self-sufficiency is paramount, but interest is growing in applying microgrids to urban power systems. In general, community microgrids can benefit from security in the event of grid outages or cyberattacks, enhanced resiliency and reliability because of local supply and control, and increased efficiency and renewable energy penetration while also reducing congestion on the rest of the grid (Bahramirad, Khodaei, Svachula, & Agüero, 2015).

Within the scope of microgrid applications, a district could play different roles at multiple scales. In a simple sense, a self-sufficient district might operate as a microgrid to the grid at large, able to respond to requests for net import or export of energy or to provide certain reliability functions. At a finer scale, a district might be an aggregator of smaller microgrids in a hierarchical multi-microgrid (Gil & Peças Lopes, 2007), as shown in Figure 3. In a multi-microgrid application, an additional intermediate control layer might increase the district's flexibility at a cost of increased complexity. For example, that additional flexibility can be leveraged to alleviate stressed conditions, such as branch overflows or overvoltages (Vasiljevska, Peças Lopes, & Matos, 2012). Although multi-microgrid control is a recent area of research, it is important to note that almost all multi-microgrid implementations are at the research demonstration stage (Xu et al., 2017).

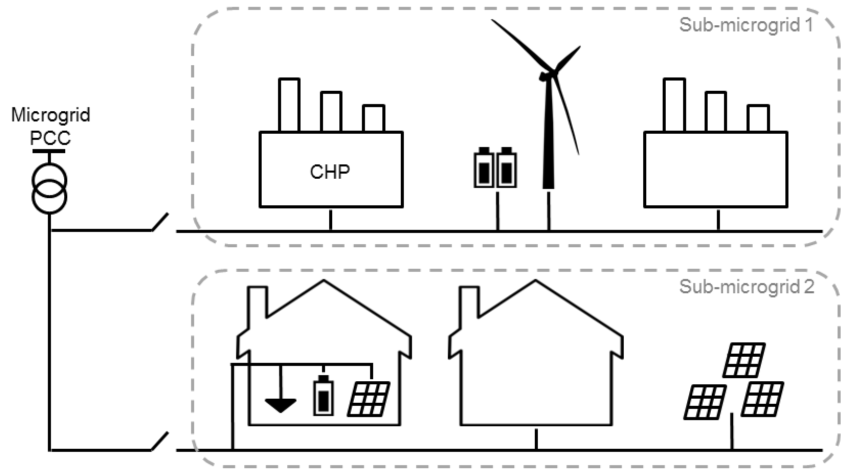

Figure 3: Example implementation of a hierarchical multi-microgrid, within a district application.

Regardless of topology, several practical challenges remain in the face of wide-scale district microgrid implementation. In addition to the physical build-out of the microgrid infrastructure, there are major concerns of high capital costs, investment recuperation, and questions of ownership by the consumers, utility, and third-parties (Bahramirad et al., 2015). Consensus must be reached on the ownership of the microgrid's DER assets and control infrastructure as well as the utility rate case applied to the microgrid. These questions are common to ZEDs as well and must similarly be resolved to facilitate their widespread development.

Distribution Design: Multi-Energy Systems Analysis

In addition to building a zero net energy electricity system, sustainability-minded ZEDs might aim to achieve carbon neutrality, reduced water consumption, energy security during disasters, or other sustainability metrics. Such a holistic approach requires attention to the interactions among power, water, gas, heating, cooling, and other local networks. For example, a community trying to achieve carbon neutrality by eliminating gas demand for cooking and heating might require houses and restaurants to install electrified cooking equipment and heat pumps while designing an electric power system capable of meeting the additional load. To achieve sustainability goals and better system efficiencies in general, recent research has been devoted to the simultaneous design and operation of these interconnected systems; this is the purview of multi-energy systems analysis.

In a multi-energy system, primary fuels—including natural gas, biomass, hydrogen, and electricity—are converted into usable energy vectors, such as heating, cooling, and electricity. The intermediary technologies might include CHP, electric heat pumps, absorption chillers, engine-driven chillers, Stirling engines, fuel cells, and others (Mancarella, 2013). A commonly studied multi-energy system compromises electricity and gas networks with or without the addition of a district heating network. Classical power systems analysis, such as the optimal power flow problem, can be extended to include these other networks in an "integrated power flow" problem (Geidl & Andersson, 2007; Liu, Wu, Jenkins, & Bagdanavicius, 2016). The integrated power flow can be applied during operational optimizations to extract additional system efficiency from the flexibility provided by multiple energy vectors (Clegg & Mancarella, 2016). For example, a system with a CHP plant and an electric heat pump can meet a certain heating demand with varying inputs of gas and electricity, depending on fluctuations in gas and power prices or availability.

Within multi-energy systems analysis, a popular modeling tool is the energy hub, which represents an element's inputs and outputs as well as storage and conversion capabilities in terms of the multiple energy vectors (Geidl & Andersson, 2007). As demonstrated in Figure 4, the inputs to an energy hub—such as gas, biomass, and electricity—are related through an efficiency conversion matrix to its outputs, such as electricity and heat. The various hubs are connected by the energy carrier networks, enabling simulation of carrier flows throughout the system. The energy hub is a useful abstraction tool that can then be used in the context of other modeling and design methods discussed here, such as operational (Deng et al., 2016) and expansion planning (Zhang, Shahidehpour, Alabdulwahab, & Abusorrah, 2015; Orehounig, Evins, Dorer, & Carmeliet, 2014; Orehounig, Mavromatidis, Evins, Dorer, & Carmeliet, 2014; Orehounig, Evins, & Dorer, 2015) optimizations. Like microgrids, energy hub design might be useful at multiple scales for ZED developments. Individual buildings could be conceived as energy hubs interacting within the district, and the district could present itself as an energy hub to the energy system at large—analogous to a multi-microgrid in a single-carrier power system design (Martínez Ceseña & Mancarella, 2016). For more information, an introduction to multi-energy systems modeling is available in (Mancarella, Andersson, Peças Lopes, & Bell, 2016), and a review of relevant multi-energy system tools is presented in (van Beuzekom, Gibescu, & Slootweg, 2015).

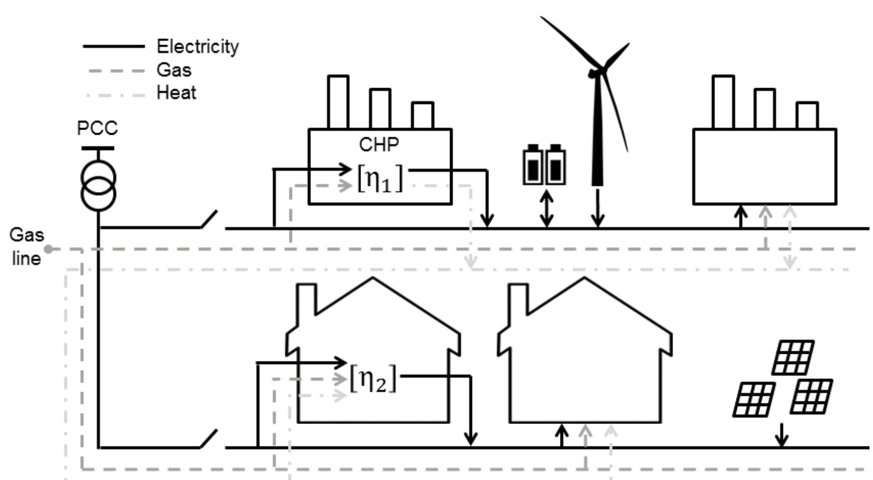

Figure 4: An example district modeled as a multi-energy system. The inputs and outputs of an energy hub, such as a single building or group of buildings, can be related through an efficiency conversion matrix, η.

Distribution Design: Hybrid Methods

Although each of these modeling techniques is useful individually, integrating these approaches could provide additional opportunities for flexibility, resiliency, and self-sufficiency. Although microgrids typically address only the electricity network, recent research has started to integrate microgrids or multi-microgrids with multi-energy systems while optimizing both the system's design and operation (Wouters, Fraga, & James, 2015). Multi-energy systems analysis can also be used in concert with multiobjective optimizations for the design of multi-energy districts (Maroufmashat et al., 2016). Similarly, these two lines of inquiry can be further combined for the optimization of a multi-energy microgrid (Mashayekh et al., 2017). Such hybrid methods are building blocks in the path toward more comprehensive and innovative district power system design tools that are useful during energy master planning. The next section also addresses opportunities for further tool integration by modeling both building loads and the power system endogenously.

Integrated District and Distribution System Design

While the distribution design techniques described above have received attention from the research community, they have not in general been applied during the district master planning process. Rather than the linear flow of decision-making in a typical district master plan illustrated by Fig. 1, an improved design process might be similar to that shown in Fig. 5. The electric utility is engaged at a much earlier step to aid in the selection, sizing, and placement of generation technologies and collaborate with other utilities serving heating, cooling, and gas needs in an iterative design process to achieve a highly efficient energy system while proactively addressing operational challenges. From the point of view of research and analysis tools, this necessitates significant workflow automation.

A handful of research groups have recently begun developing building-to-grid integrated simulation tools that model both building loads and power system infrastructure endogenously. These include the Integrated District Energy Assessment by Simulation (IDEAS) library developed at the University of Leuven (Baetens et al., 2012; Van Roy, Verbruggen, & Driesen, 2013; De Coninck, Baetens, Saelens, Woyte, & Helsen, 2014; Protopapadaki & Saelens, 2017); the MESCOS framework (Molitor et al., 2014); the modeling environment developed by the Urban Energy System group at Osaka University (Kusakiyo, Yamaguchi, & Shimoda, 2013; Fujimoto, Yamaguchi, & Shimoda, 2017); and the optimization framework proposed by Morvaj *et al.* (Morvaj et al., 2016; Morvaj, Evins, & Carmeliet, 2017). By modeling building measures, such as demand response and efficiency, as well as power system enhancements, such as recabling and voltage regulation equipment, utilities can compare demand-side and supply-side investment options side by side. Note that these new frameworks include detailed electrical infrastructure models for power flow calculations and analysis of grid reliability impacts rather than simplified network models. Several also include the option of multi-energy systems analysis to look beyond the electricity grid itself for further performance benefits. To demonstrate the value of these integrated frameworks, (Baetens et al., 2012) compares net zero energy design at the building level to the neighborhood level to account for economies of scale and network impacts and finds that both ZEB and ZED performance is highly dependent on the distribution system build-out.

By developing and testing open-source building-to-grid integrated modeling tools, future research can create building blocks for utility planning to improve both the design and operation of ZEDs. During the energy master planning process, building-to-grid integrated tools can first be applied in infrastructure design. Once a particular design has been selected, the model's operational optimization can be used to investigate sensitivities to control upgrades, such as smart inverter functions, electric vehicle charging strategies, and building demand response. At the next level of complexity, there is opportunity to close the loop by feeding information about power system operations back into the building operations. Rather than a linear flow of information from predicted building loads to power system design, a feedback loop would modify building behavior based on current grid status to provide flexibility. From a research perspective, this would require modeling and design tools with a highly integrated work-flow; however, in a practical sense, grid-to-building feedback necessitates implementation of building sensors, control devices, and several communications layers that are not yet widely deployed. Additionally, building-to-grid modeling can be seen in the context of a broader integrated modeling process like that proposed in (Manfren, Caputo, & Costa, 2011), including data collection and pre-processing, design post-processing sensitivity and uncertainty analysis, and economic profitability and life-cycle impact analyses. An example workflow integration of part of this process is available in (Fuchs et al., 2016), but on the whole, a computational framework integrating these many design stages together is presently lacking. Additional development of comprehensive planning frameworks from the research community can help enable communities to translate their sustainability rhetoric and climate change goals into technical solutions.

Sustainable District Case Studies

To illustrate the sustainable district design practices introduced above, two case studies are reviewed: BedZED in the United Kingdom and Fujisawa SST in Japan.

BedZED, Hackbridge, UK

The Beddington Zero (Fossil) Energy Development (BedZED) is an environmentally friendly mixed-use development built in 2000-2002 in Hackbridge, United Kingdom, by architect Bill Dunster and the social enterprise BioRegional Development Group (Figure 6(a)) (`www .zedfactory.com`). The basic tenet of ZEDfactory design is that the district residents should generate no more than their fair share of sustainable carbon emissions and consume no more than their fair share of national sustainable resources (Dunster, Simmons, & Gilbert, 2008). In pursuit of this design objective, BedZED illustrates the typical pattern of community stakeholders measuring their performance based on annual sums or averages—in this in-stance, targeting emissions of no more than 2.1 tons CO_2 and an ecological footprint of less than 2 global hectares per person per year (Dunster et al., 2008); a person's ecological footprint is the area of biologically productive land and water that generates the resources they consume and processes their waste (`https://www.footprintnetwork.org/`).

Based on these goals, the district-level design focuses on infrastructure for cycling,

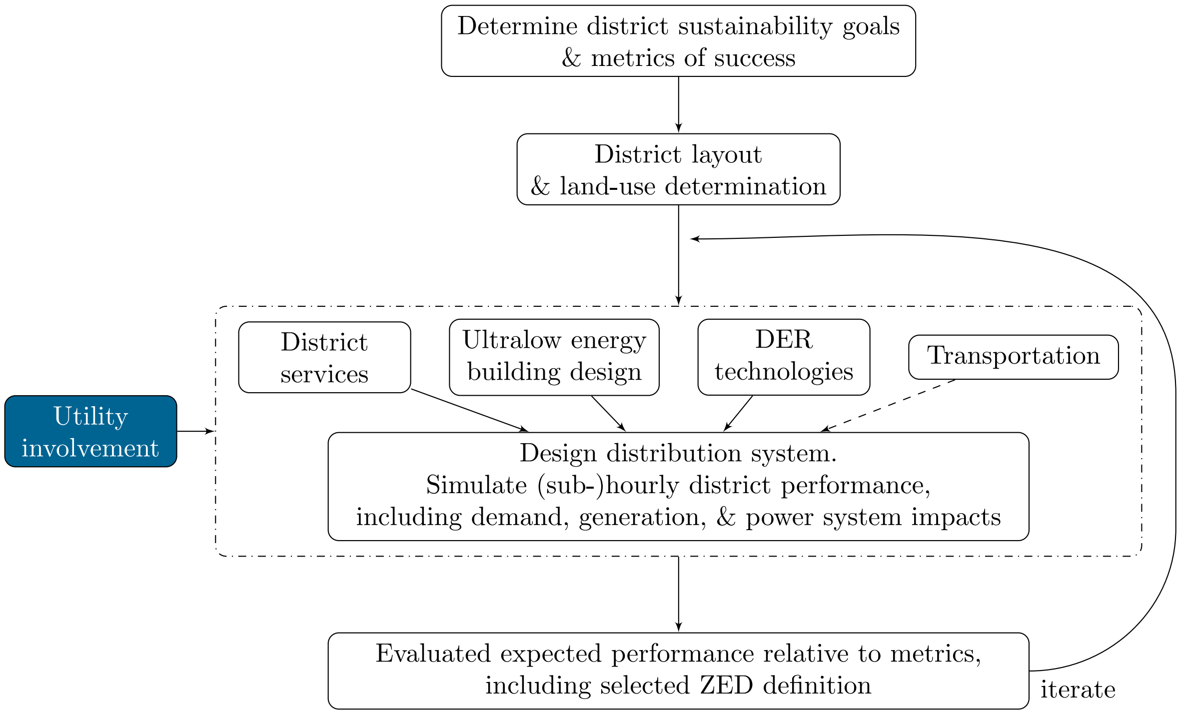

Figure 5: An integrated district design process, in which the electric utility is involved from early stages to enable coordinated design of the district loads, generation, distribution system, protective equipment, and communication equipment, if needed. District load and generation are treated on a finer than annual time scale during the design process to ensure grid impacts are probably assessed, given the high renewable penetration.

biodiesel or electric vehicles, and public transit; growing spaces to reduce food miles; and integrated work spaces to reduce commuting distance. Building efficiency measures include high passive solar gain, super insulation, thermal mass provided by dense concrete, passive ventilation with heat recovery, and reduced-flow taps and showers (Dunster et al., 2008; Lazarus, 2006; Chance, 2009). Once load-reduction measures have been implemented, the remaining load is offset by micro-generation by microturbines and PV (Dunster et al., 2008). The district also has a heating and hot water system supplied by wood chip-fueled CHP or a main gas condensing boiler if the CHP is not used. In these measures, the BedZED planning process addressed each of the typical district planning elements described above, but leaves opportunity for intentional utility collaboration and the incorporation of distribution system design. The following case study illustrates some next steps forward in this regard.

Fujisawa Sustainable Smart Town, Fujisawa, Japan

A corporate-municipal collaboration spearheaded by Panasonic Corporation is currently developing a sustainable residential district in Fujisawa, Japan, called Fujisawa Sustainable Smart Town (Fujisawa SST) (Figure 6(b)). Unlike BedZED, Fujisawa SST is not directly pursuing a net zero energy benchmark – the town's major sustainability goals are to reduce carbon emissions by 70% compared to 1990 levels and water use by 30% compared to 2006

(a) (b)

Figure 6: (a) BedZed Eco-village, Hackbridge, London, England. *Source: Tom Chance, Bioregional* (b) Fujisawa Sustainable Smart Town, Fujisawa, Japan. *Source:* `fujisawasst .com/EN/`

levels for general facilities. This 19-hectare development is 68% complete with 1,600 residents as of July 2017, with plans to be complete with 3,000 residents by 2020. The information presented here is gathered from (*FujisawaSST Concept Book*, 2017) and personal communication with a Panasonic representative (Okawara, 2017). Fujisawa SST's district master plan, which is lead by Panasonic and to which the other collaborators contribute, envisions a communal Internet-of-things employing Panasonic's smart technologies as the underlying infrastructure to allow the residents to grow their community as they see fit (Tokoro, 2015). In each house, a home energy management system tracks power, gas, and water consumption, controls in-home generation and storage, and accesses transportation services, such as car-sharing reservations.

From the power system perspective, Fujisawa SST includes some less common features because of a collaboration between Panasonic and the local gas and electric utilities, as well as the community's prioritization of energy security. In the wake of the Great East Japan Earthquake in 2011, which removed approximately one-quarter of Japan's energy supply, power network resiliency has received national attention, including the decentralization of energy supply (Marnay et al., 2015). In addition to a 100-kW communal PV system, all houses in Fujisawa SST have rooftop PV and 75% also have an ENE-FARM cogeneration fuel cell. The ENE-FARM processes gas into hydrogen, then the fuel cell cogenerates hot water and electricity. This in-home cogeneration is more popular in Japan than in Europe or the United States, where district heating typically receives more attention. For added energy security, the homes are equipped with battery storage sized to supply at least 3 days worth of backup power. The assets are owned by the homeowners, who determine their operating strategy. Although it is economically preferential to sell excess PV power back to the grid, Panasonic has incentivized storing energy by offering a warranty extension on the battery.

To support the high DER penetration in the neighborhood, the Tokyo Electric Power Company (TEPCO)—Fujisawa SST's local electric utility—has implemented a few extra protective measures. A step voltage regulator manages reverse power flow from excess PV generation back into the rest of the distribution system. Also, to avoid overvoltage conditions because of high local PV generation, each home is equipped with a power controller that manages generation should the system voltage exceed the limit preconfigured by TEPCO. The collaboration with local utilities to provide adequate protective measures for the town's high renewable generation is a promising step forward for utility integration in energy master planning. Next steps could include monitoring the home power controllers during operation to determine the impact of PV curtailment on the development's goals.

Case Study Comparisons

In future sustainable developments, lessons learned from previous developments can be leveraged – for the case studies here, their strengths include BedZED's pursuit of net zero energy and Fujisawa SST's intentional inclusion of distribution system protections. However, in both case studies, the annual accounting approach can be challenging from a power systems perspective when the electric grid is treated like infinite storage capable of perfectly time-shifting the district DERs' overgeneration to times of undergeneration. Although Fujisawa SST has emphasized on-site storage for emergency backup, neither case study has not prioritized or investigated on-site storage for peak shaving or instantaneous net zero energy balancing during regular operations. Considering performance metrics with a finer time granularity might capture operational challenges and further illustrate the need for a higher level of utility engagement. Promising steps are being made in this direction, such as Fujisawa SST's collaboration with TEPCO and other local utilities to proactively address grid resiliency and voltage regulation. However, in future developments, there is opportunity to more fully integrate the distribution system design approaches described above into the district planning process so that the electric reliability in-district can be ensured, and negative impacts on neighboring customers and unnecessary infrastructure costs can be avoided.

Summary and Future Research Directions

In the first few generations of sustainable urban districts, it has been feasible for the community stakeholders to require the utility or distribution system owner to layer a feeder design on top of the community design, overbuilding as needed to accommodate regulation needs. This overview introduces current district planning practices including such aspects as distributed energy resources, district services, and transportation. These planning practices typically focus on district load and generation on an annual basis, without accounting for instantaneous imbalance or grid impacts that interfere with this idealized view. However, as the occurrence of ZEBs, ZEDs, and other low-load/high-DER developments increases, it will not be prudent to assume that the local electric grid can support each new development without specialized and concurrent power system design. There is opportunity to co-optimize the build-out and operation of the energy supply system and district loads to achieve improved efficiencies, not only mitigate undesirable impacts after the fact. To that end, this overview also introduces relevant academic research in multi-energy systems analysis, energy hubs, microgrid approaches, and mixed-integer linear programs for operational and expansion planning optimizations, which can be integrated into future district planning processes.

Recent advances in integrated building-to-grid models that facilitate for simultaneous district planning and distribution system design are introduced and recommended for additional future research. As these integrated frameworks are developed, they are recommended to include a variety of control options to investigate a major concern in ZED development: asset ownership. For example, in a centrally controlled district within a vertically integrated utility, it might be practical for DER assets to be owned by the utility and to be operated in concert. Within an energy market, the customer on whose land the assets are located might have primary control, and agent-based models might be more appropriate to simulate the potentially conflicting behaviors from distributed building-level control. In a multi-energy system, there could be multiple energy service providers interacting; on the other hand, there could be opportunity for a utility to expand its service menu to include other energy vectors, such as gas or district heating, to provide effective and efficient operation of the multi-energy assets. Modeling control strategies that reflect these ownership arrangements are required to analyze the resultant performance.

Although the development of these district-level models is most directly applicable to ZED development, the broader purpose of such research is to improve distribution system performance in the face of a changing power landscape. ZEDs can be seen as testbeds for new distribution system designs with very high DER penetrations, and the lessons learned through integrated district design can be extrapolated to accommodate the rising DER penetrations in the distribution system at large.

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