

Towards Net-Zero Base Stations with Integrated and Flexible Power Supply in Future Networks

Hao Yuan*, Guoming Tang*, Teng Liang, Deke Guo, Yi Wang

Abstract—The energy consumption and carbon emissions of base stations (BSs) raise significant concerns about future network deployment. Renewable energy is thus adopted and supplied to enable the net-zero (or zero-carbon) BS. However, due to severe inconsistency between renewable energy generation and power demand, the conventional one-to-one power supply architecture could cause a large waste and low utilization of renewable energy. In this article, we design a many-to-many power supply architecture for BSs, to maximize the utilization of renewable energy. More specifically, we strategically group multiple renewable energy generators into virtual cells to serve multiple BSs in an integrated way, thus minimizing the inconsistency between the renewable energy generation and power demand. To fine-tune the power mismatch between power supply and demand in each virtual cell, we propose software-defined techniques to flexibly control the discharging/charging of a battery energy storage system. Illustrative results from a case study demonstrate that a high renewable energy utilization can be achieved with the proposed architecture and mechanisms.

Index Terms—Net-zero base station, renewable energy supply, battery energy storage system

I. INTRODUCTION

WITH recent large-scale deployment and commercialization of 5G networks, researchers have started to consider the next-generation network vision in 6G era. Compared to the 5G network, 6G is expected to provide much higher frequency bandwidth (e.g., mmWave and 1-3 THz) and lower transmission latency (within 1 ms) to the end users, and support more emerging applications like multi-sensory XR, connected robotics and autonomous systems. For the mobile network base station (BS), as illustrated in Fig. 1, besides the terrestrial and fixed BSs as in 5G, the 6G network is also said to include mobile BSs, air BSs, low-orbit satellites (LEO) and CubeSats [1]. This would make the future network cover broader areas and fulfill more destinies.

In the future 6G network, due to the denser BS deployment (as the signal range of 6G BSs is shorter), more IoT device connections and higher frequency bandwidth adoptions, the power demand of future network would be much higher than the current 5G network. Particularly, for future mobile applications driven by AI techniques, BSs would be equipped with high computing and communication capabilities, to cope

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with the high computation and data rate demands. Such an upgrading of BSs, however, must trigger intensive power demand and supply in the radio access network (RAN). As a matter of fact, the power consumption of current 5G BSs is $2\times$ to $3\times$ larger than the 4G ones [2]. A more detailed comparison on energy-related features among different network generations is summarized in Table I.

With energy sources dominated by fossil fuels, the operation of future 6G BSs would incur enormous carbon footprints, as well as negative environmental impacts. It obviously does not comply with the worldwide “green” revolution calls [3]. Therefore, out of the social responsibility for environmental conversation, it is urgent to find a more sustainable way to alleviate the environmental impacts of extremely high energy consumption in future networks.

Owing to the continuous decline of material expense and installation cost for renewable energy generators (REGs) (e.g., a 61% cost reduction of the solar equipment from 2010 to 2017 [4]), the renewable energy has been promoted dramatically over the past decade. As a result, the mobile operators have deployed large numbers of REGs for (solar and wind) energy harvest in supplying the communication facilities.

A. Net-Zero BS: Concept and Challenges

Recently, driven by the pervasive renewable energy supply and low-carbon footprint target, the concept of *net-zero* (or zero-carbon) is promoted and introduced into several sectors, e.g., net-zero buildings and net-zero datacenters [6]. For a net-zero building or datacenter supported by on-site renewable energy harvesting, the total amount of energy consumed by the building or datacenter in a specific billing cycle (e.g., one month) is equal to or less than the amount of renewable energy generated by the on-site REGs, thus resulting in zero carbon emission.

With the large-scale BSs deployed in 5G and to be deployed in 6G, corresponding concerns on high energy consumption and carbon emission have already been highlighted. Thus, in this article, we propose the concept of *net-zero base station* (or net-zero BS), which pursues zero carbon emission in operating the BSs, i.e., the power supply from traditional power grid is completely offset by that of renewable energy.

As the net-zero BS is a brand new concept in the communication domain, we are faced with several challenges in its design and operation. **Firstly**, although the net-zero concept has been well explored before, there is no readily-available solutions for our RAN scenario. Thus, how should we design the architecture of net-zero BSs, and how could we operate

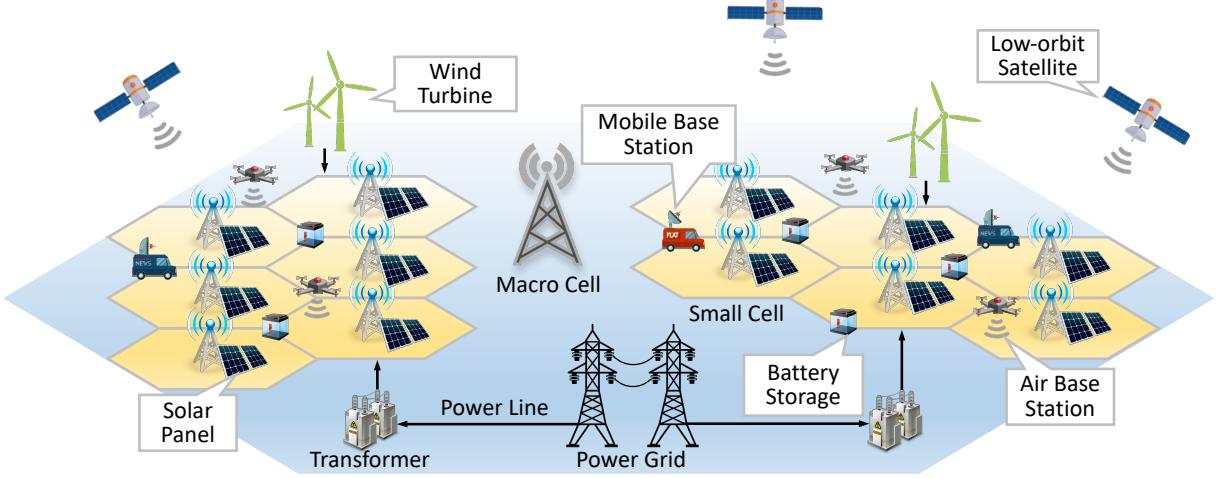


Fig. 1. A vision of the future 6G network, consisting of (terrestrial and fixed) macro and small BSs, as well as mobile, air and space ones. For green communication purpose, renewable energy would become the major power supply of all BSs in the future networks.

TABLE I
COMPARISON OF DIFFERENT GENERATION NETWORKS FROM THE GREEN COMMUNICATION PERSPECTIVE.

Feature	3G	4G	5G	6G
#BS sites (global)	3.3 millions	7.6 millions	11.2 millions	20+ millions
AVG. power per BS	1.7 kW	1.3 kW	3.7 kW	5+ kW
Propagation loss	Few loss	Large loss	Severe loss	Massive severe
BS density	4-5 BSs/km ²	8-10 BSs/km ²	40-50 BSs/km ²	100+ BSs/km ²
Carbon footprint per mobile end	20 kg	23 kg	31 kg	40+ kg
RAN power consumption	49 TWh	77 TWh	86 TWh	100+ TWh
#Antennas of BS	2	8	20	100+
OPEX	Low	High	High	Very high

*Some data of 3G/4G/5G are referred to [5]. As 6G standards are currently not disclosed, corresponding data are estimated based on available information.

them towards a (near) zero carbon emission? Basically, we need to think over the above problems and give answers for the first time. **Secondly**, due to the intermittent generation of solar or wind energy, most probably the power demand at the BSs are not consistent with the on-site renewable energy supply. For example, it is normally to see that the solar energy is abundant in the noon, while the power demand of the BSs in the residential area is high in the evening. Such a power mismatching between demand and supply could lead to a low utilization of renewable energy, making the net-zero target hard to realize if not impossible. Adding battery energy storage system (BESS) to the system could help alleviate the mismatching. Nevertheless, besides cutting down the energy storage cost, how to operate the BESS in terms of battery discharging/charging decisions is the **third** challenge, given that both energy supply (of REGs) and demand (of BSs) are uncertain and hard to precisely predict.

B. Our Ideas and Contributions

In this work, we pursue high energy and cost efficient wireless network communications by providing the net-zero BS design and operations. Making use of the widely deployed REGs in different types, we aim to design new architectures and mechanisms and provide an integrated and flexible power supply to the BSs in future networks.

Specifically, we first design the power supply architectures of the net-zero BS system, including the across-cell architecture for integrated power supply and in-cell architecture for flexible power supply. Then, we propose two-phase power supply operations under the designed two architectures, respectively. In phase-I, we strategically match and integrate the REGs and BSs into several virtual cells (as applied in the microgrid scenarios [7]). Accordingly, the aggregate renewable energy generation could be consistent with the aggregate power demand in the same virtual cell as much as possible. In phase-II, within the virtual cell formed in phase-I, the BESS is controlled in a software-defined way to fine-tune the power mismatching between the power supply and demand by proper discharging/charging operations, thus further approaching the net-zero BS target.

The rest of the article is organized as follows. In Sec. II, we propose the architecture design of net-zero BSs. In Sec. III, we give the two-phase operations of net-zero BSs. We evaluate the proposed architectures and mechanisms by a case study in Sec. IV and conclude the article in Sec. V.

II. ARCHITECTURE DESIGN OF NET-ZERO BSs

A. Background and Motivation

In the past decade, the material expense and installation cost of REG have declined dramatically, resulting in a rapid

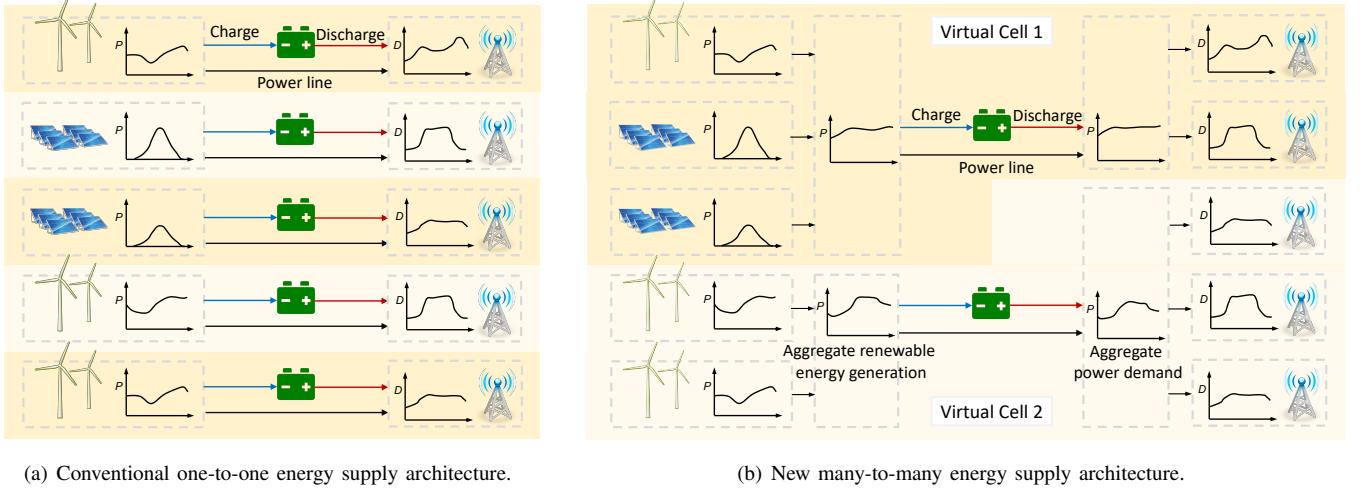


Fig. 2. Two renewable energy supply architectures. The many-to-many architecture of (b) has the advantage over the one-to-one architecture of (a) at integrating different types of REGs and BSs into (two) virtual cells to match the power demand and supply and thus improving the renewable energy utilization.

payback period of REG investments. For example, it is reported in [8] that, the cost payback for current solar energy has ranged from 3 to 4 years, and wind energy has an even faster payback period of 3 to 4 months. This makes the REG a great potential in energy-saving and replacement of fossil fuel.

It thus has inspired the mobile operators to deploy on-site REGs (e.g., solar PVs or wind turbines) and harvest renewable energy as the auxiliary supply to the power-hungry BSs, as illustrated in Fig. 1. The solar energy has been harvested to power the BSs in many places, and in some developing countries it occupies $> 8\%$ of the total energy usage of the BS system [9]. Wind energy harvesting (WEH) systems are also developed and exploited to sustain the operation of wireless sensor nodes.

Nevertheless, current one(REG)-to-one(BS) supply architecture would result in a low utilization of renewable energy, as the generation of the renewable energy is typically inconsistent with the BS power demand. As illustrated in Fig. 2(a), both the intermittent generation of solar/wind energy and user behavior related BS power demand contribute to the mismatching between the supply side and demand side. A battery storage could be leveraged to rectify the supply curve by temporary discharging or charging. To achieve the net-zero target, however, the storage capacity should be as large as the biggest magnitude of the mismatching, which could bring a huge BESS installation cost.

B. Across-Cell Architecture: Supply-Demand Power Matching

Instead of the one-to-one architecture, we propose a many(REGs)-to-many(BSs) renewable energy supply architecture, as illustrated in Fig. 2(b). Generally speaking, by strategic selection of distributed REGs and BSs across all cells, we could form some desired virtual cells (VCs), in each of which the aggregate power supply curve of REGs is roughly consistent to the aggregate power demand curve

of BSs. With such an across-cell power supply architecture, the power supply-demand mismatching appeared in the one-to-one scenario could be much alleviated, thus leading to a significant increase of renewable energy utilization.

Note that the selection of REGs and BSs in forming virtual cells could be based on the historical data, e.g., the average renewable energy generation at each REG and the periodic power demand curve at each BS. In Sec. III-B, we will disclose more details on how to make use of such information to make the selection and design optimal REGs-to-BSs matching across existing cells. Particularly, we name the optimal supply-demand matching *phase-I operation* towards the net-zero BSs in this article.

C. In-Cell Architecture: Software-Defined Power Supply

As will be introduced in Sec. III-B, the VCs are formed based on historical power supply and demand measurements in the long run. Consequently, the many-to-many matching between energy generation and energy consumption could not be perfect in each temporary slot. To this end, we further design the power supply architecture in each VC. Specifically, a software-defined power supply mechanism is proposed to control a BESS's charging/discharging operations, so as to approach the net-zero target in each VC.

The architecture and detailed design of a software-defined power supply system in each VC are shown in Fig. 3. Three major components are included in the design: *supply part*, *demand part* and *control part*.

- **Supply Part:** In the VC, several types of REGs (e.g., solar panels, wind turbines and so on) are distributed in different areas and have different energy generation patterns. By integrating renewable energy generations of those REGs, an aggregate power supply with a particular form could be provided to the control part and deliver in proportion to the power demand at each BS in the VC.
- **Demand Part:** The power demand of each BS in this VC is mainly determined by its location (e.g., residential area,

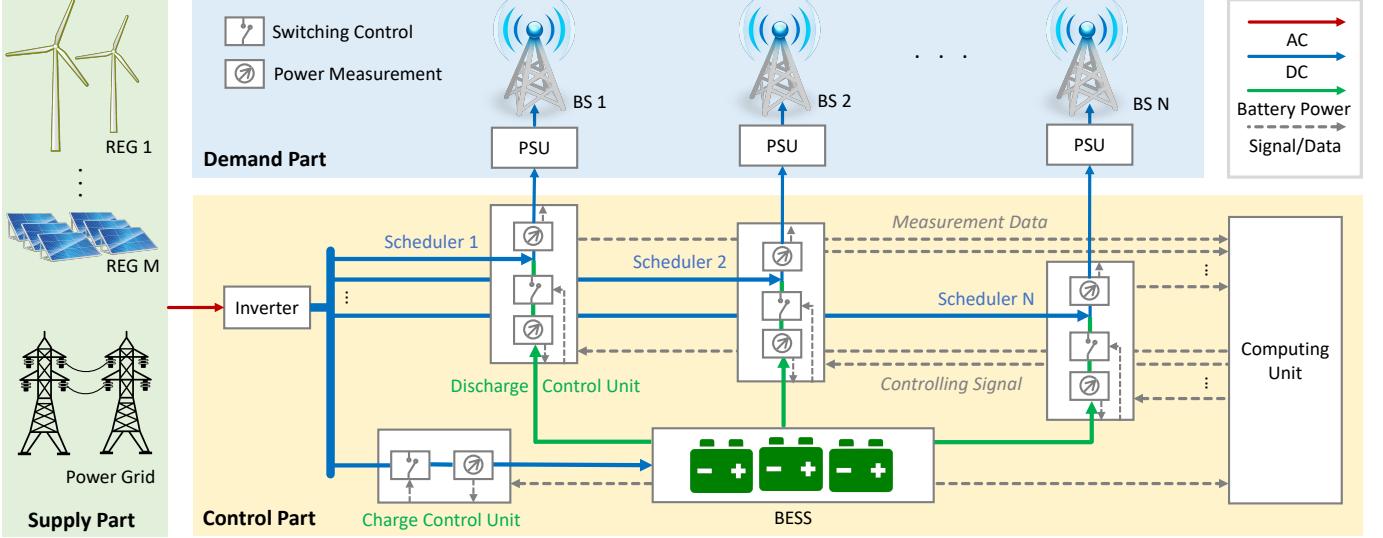


Fig. 3. Detailed design of the in-cell power supply architecture in a virtual cell, including supply part, demand part, and control part. A software-defined power supply mechanism is applied to further reduce the supply-demand power mismatching, where the control part controls the energy allocation and the BESS discharging/charging operations through the schedulers.

office area, or comprehensive area). Through the control part, the energy from REGs or power grid is transmitted to the power supply unit (PSU) of each BS.

- **Control Part:** This is the core component of the software-defined power supply architecture, which controls the energy allocation and the BESS discharging/charging operations. Generally, with the information of energy storage, power demand and supply, the computing unit makes decisions on i) which power source (REGs or power grid) to choose, ii) whether discharge/charge the battery and iii) how much energy to be discharged/charged. These decision signals are then delivered to the schedulers and charge/discharge control units for power supply operations in the VC.

With the fine-tuned power supply via the above software-defined mechanism, it is expected that the renewable energy utilization could be further improved, thus closer to the net-zero BSs target. More details on the software-defined power supply with BESS will be disclosed in Sec. III-C. Particularly, we name the software-defined power supply mechanism *phase-II operation* towards the net-zero BSs in this article.

III. OPERATIONS OF NET-ZERO BSs

In this section, we first introduce relevant entities involved in the designed architectures, and then present the details about the aforementioned two key phases in approaching the net-zero target.

A. Involved Entities

1) *Renewable Energy Generators:* We consider multiple REGs deployed to supply the power of BSs in our scenario, including the solar PVs, wind turbines, etc. These REGs could be installed along with the BSs in an embedded way or deployed near the BSs independently [10]. For the renewable

energy generation at each REG, we could measure it with dedicated power meters and keep record of the information with a discrete time model, e.g., by every time slot of Δ_t . Additionally, the location (latitude and longitude) of each REG is also recorded and used for later operations.

2) *Base Stations:* The target network considered in our scenario consists of multiple BSs (only fixed BSs are considered for simplicity), each with a location recorded. The BSs may have varying power demand patterns, as the power demand pattern of a BS is related to the mobile traffic demanded by the particular user group within the BS's coverage. And the magnitude of a BS's power demand is determined by the volume of traffic load. Thus, for a given time slot, we could infer the power demand of a BS from its traffic load volume in the corresponding time slot. In a long run, with the observation that the traffic demand pattern is normally periodic (with a cycle of one day), the incurred power demand at each BS is periodic and with a relatively stable pattern [11].

3) *Battery Storage:* As mentioned in the architecture design, BESS can be leveraged to regulate the mismatching between REG power supply and BS power demand. Specifically, under the aforementioned across-cell architecture, we assume that there are several BESSs deployed at the preset presence of points (PoPs). As the number of REGs and BSs could be larger than that of PoPs, one BESS can connect to multiple REGs and BSs (as illustrated in a VC in Fig. 2(b)). Within a VC, after an optimal supply-demand matching (the phase-I operation introduced later), the aggregate power supply of REGs is expected to be consistent and close to the aggregate power demand of BSs. Therefore, a small storage capacity in each VC could be sufficient, much reducing the BESS installation cost in the one-to-one architecture (as shown in Fig. 2(a)). Furthermore, to lower the computational complexity in the software-defined power supply (the phase-II operation introduced later), we could adopt a discrete state of charge

(SoC) model of battery and operate on multiple equal-spaced SoCs (e.g., 10%, 20%, ..., 100%).

B. Phase-I: Optimal Supply-Demand Matching

1) *Supply and Demand Modelling:* Given the above considerations for the involved entities, we first need to determine the connections between the REGs and the PoPs, i.e., the many-to-many relationships. From the modelling perspective, the connection relationships of REGs-BESS and BESS-BSs could be modeled by a supply matrix X and a demand matrix Y , respectively. For the supply matrix, each element $x_{i,j}$ is a binary value representing whether a specific REG is connected to a specific BESS; for the demand matrix, the element $y_{i,j}$ is also boolean and represents whether a specific BESS is connected to a specific BS. Recall that we have already recorded the historical information of renewable energy generation from REGs and power demand at BSs. Thus, for any given relationships of REGs-BESS (i.e., supply matrix X) and BESS-BSs (demand matrix Y), the supply-demand power mismatching in a cycle (e.g., one-day period) could be computed accordingly.

2) *Optimal Matching:* Given the above modelling for the supply and demand, an optimization problem could be formulated to minimize the mismatching between the aggregate renewable energy supply of REGs and the aggregate power demand of BSs during the entire billing cycle (e.g., one-month or one-year period). At this phase, we only consider the long-term supply-demand matching. That is to say, we can simply treat the volumes of power supply and demand as deterministic values (by referring to the average values of the historical data) and thus pursue a (coarse-grained) optimal supply-demand matching solution in the long run. Specifically: $\operatorname{argmin}_{\{X,Y\}} \sum_{p=1}^P \sum_{t=1}^T \delta_p(t)$, where $\delta_p(t)$ is the supply-demand mismatching at the p -th BESS (total number is P) in the t -th time slot (total number is T). The above optimization problem belongs to the mixed-integer linear programming (MILP), which could consume a lot of time to find the optimal solution, especially when the problem scale is large. Fortunately, in practice the number of REGs and BSs connecting to one battery cannot be large [12]. Thus, with some off-the-shelf MILP solvers, we could tackle the optimization problem efficiently.

3) *Further Constraints:* We also consider some practical constraints in the supply-demand matching optimization process. First, for some geographical or spatial limitations, the BESS capacity may not be allowed too large and should be under certain limits. Second, due to the power loss during the power transmission, the power line distance between the REG and BESS, as well as that between the BS and BESS, should be no longer than a predefined maximum length.

Note that we could solve the above optimization problem in an off-line way, by using the historical data gathered at the REG supply side and the BSs demand side. The results from the problem (i.e., the supply/demand matrices) give the concrete instruction in forming the optimal VCs in the long run.

C. Phase-II: Software-Defined Power Supply with BESS

As we make use of the long-term historical data for the REGs-BSs pairing, the supply-demand matching could not be perfect. For example, the temporary renewable energy generation, e.g., in the future one hour, could not be exactly the same as the expected power demand at BSs. Therefore, in phase-II we leverage the BESS to fine-tune the (minor) mismatching via discharging/charging operations, thus further promoting the renewable energy utilization.

1) *BESS Modelling:* In each VC, to eliminate the supply-demand mismatching as much as possible, we need to find the optimal BESS discharging/charging schedule in each time slot. Therefore, for an arbitrary PoP p , we define the battery discharging/charging schedule operation at time slot t as $Z_p(t)$, where positive and negative values represent discharging and charging charge amounts, respectively. With the optimal solution from phase-I, we are able to obtain the (expected) renewable energy generation and power demand in each time slot of the whole cycle. Therefore, for any given BESS discharging/charging schedule, the supply-demand power mismatching could be computed accordingly.

2) *Optimal Discharging/Charging:* Given the above modelling of BESS, an optimization problem could be formulated to minimize the power mismatching between the supply side (i.e., the renewable energy plus energy storage) and the demand side (i.e., the power demand) during the entire billing cycle in each VC. Specifically, the optimization problem could be written as: $\operatorname{argmin}_Z \sum_{p=1}^P \sum_{t=1}^T \eta_p(t)$, where $\eta_p(t)$ is the supply-demand mismatching at the p -th BESS in the t -th time slot. As we have assumed, the battery SoC is discretized so that the solution space would be much shrunk. And thus similar optimization skills in phase-I could be applied here for optimal discharging/charging operations. In practice, the temporary power supply and demand within a VC could fluctuate around their historical means and hard to precisely predict. In this case, the discharging/charging schedule obtained from an off-line optimization process (using the historical data as inputs) might not yield the optimal results. To address this concern, some online learning approaches could be applied, e.g., a deep reinforcement learning (DRL) based method has been used for online BESS discharging/charging scheduling [13].

3) *Further Constraints:* We further consider some practical considerations during the discharging/charging operations. First, in order to prevent the battery from over-discharging/charging, the discharging/charging amounts (i.e., Z) should be within a specific range. Second, the discharging/charging operations should be constrained by the maximum charging/discharging rates. Third, as the discharge cycle of battery is harmful to its health, especially a deep discharge cycle, we also need to limit the maximum depth of discharge (DoD) of the BESS.

In our design of phase-II operation, the control of the BESS (discharging and charging operations) is separated from its correlated hardware like the REGs and BSs, which makes the power supply within the VC work under a software-defined way. Such a software-fined power supply mechanism

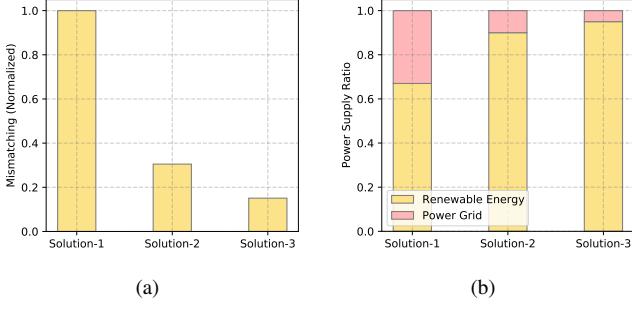


Fig. 4. Overall outcomes: (a) normalized power mismatching resulting from different solutions; (b) Renewable energy utilization resulting from different solutions.

is expected to further spur the renewable energy utilization towards the net-zero target.

IV. A CASE STUDY

A. Experimental Setup

1) *Scenario*: In this case study, 100 BSs and 100 REGs are considered as the target network. For the BESS, 10 battery PoPs are assumed within the target network area. To investigate different power supply patterns, we set two types of REGs equipped with solar panels (50%) and wind turbines (50%), respectively. Also, to include diverse power demand patterns, we set three types of BSs deployed in the residential area (20%), office area (50%), and comprehensive area (30%), respectively.

2) *Datasets*: We set the entire cycle T and time slot Δt as one-day period and 0.25 hour, respectively. Accordingly, the historical renewable energy generation data and power demand data from [11], [14] are adopted, which could represent the average power supply and demand patterns in a long run.

3) *Benchmarks*: We compare the solution of our two-phase net-zero BSs operations with that from the architecture without supply-demand matching, i.e., Fig. 2(a) vs. Fig. 2(b). Specifically, the results from the following three solutions are compared:

- Solution-1: BS power supply under the one-to-one architecture without power matching.
- Solution-2: phase-I BS operation with optimal supply-demand power matching.
- Solution-3: phase-I operation plus phase-II operation of software-defined power supply with BESS.

4) *Optimization Solver*: To tackling the two optimization problems in the two-phase operations, we use PuLP with a CBC solver to find the optimal solutions for both phase-I and phase-II. As the problem scale is relatively small, the applied solver can find the optimal solutions efficiently (within a few minutes on a low-end desktop in our implementation).

B. Results and Analysis

1) *Overall Outcomes*: Fig. 4(a) shows the mismatching results of three different architectures during the entire cycle. As we can see, the traditional one-to-one renewable energy

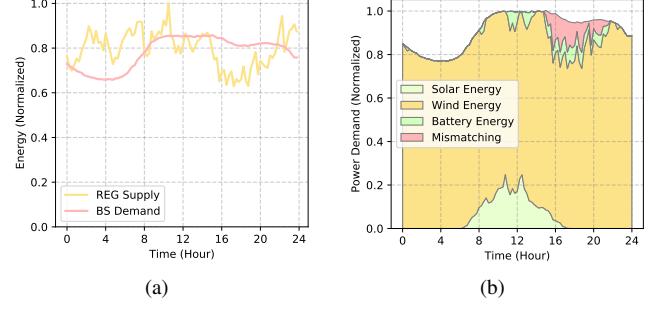


Fig. 5. Local observations: (a) supply-demand matching with 1 solar panel, 9 wind turbines and 10 BSs in an example VC; (b) power supply components from the REGs and BESS in an example VC.

supply architecture (solution-1) has the highest mismatching and worst performance. With operation in phase-I, compared to solution-1, the mismatching from solution-2 could reduce to 31% by optimal supply-demand matching. With the two-phase operations, the mismatching from solution-3 could further reduce to 15% aided by the BESS discharging/charging regulation. Fig. 4(b) shows the comparison of renewable energy utilization. After phase-I and phase-II operations, the renewable energy utilization could be improved to 90% and 95%, respectively.

2) *Local Observations*: Fig. 5(a) shows the matching result after phase-I operation from one example VC, in which 1 solar panel, 9 wind turbines and 10 BSs are deployed (the resulting group sizes in each VC are between 8 and 12 for BSs and REGs). As we can see from the figure, in most of the time the REGs can provide sufficient renewable energy to the BSs, whereas there still exists a minor mismatching between the power supply and demand. Then, as shown in Fig. 5(b), with the operation of phase-II, the BESS could compensate the power mismatching via proper discharging/charging and thus further improve the renewable energy utilization. Eventually after the two-phase operations, only 2.4% of the total power demand is mismatched and satisfied by the power grid.

V. CONCLUSION

In this article, we proposed the concept of net-zero BSs for future wireless network and provided corresponding design architectures and operation mechanisms. The zero-carbon target of BSs was approached by two-phase power supply operations in eliminating the power mismatching between the REGs' supply and BSs' demand. For phase-I, an optimal supply-demand power matching mechanism was presented to largely reduce the mismatching of paired REGs-BSs. For phase-II, a software-defined power supply mechanism was developed to fine-tune the supply-demand mismatching, through flexible BESS discharging/charging controlling. Results from a case study demonstrate that, compared to the conventional one-to-one power supply architecture, the renewable energy utilization rate in our net-zero BS system could reach up to 95%.

In the future, we plan to extend our work in more directions. For example, the net-zero BS system could be adapted to the mobility scenario, where the renewable energy generation

and power demand rely on the environment heavily. In that case, adaptive matching and BESS scheduling mechanisms should be studied to tackle much uncertain power supply and demand. Besides, how to design incentive policies or marketing mechanisms to facilitate the proposed power supply architectures (such as [15]) is also an interesting problem for the future work.

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