Department: Head
Editor: Name, xxxx@email

Telecom-to-Grid: Supercharging 6G's Contribution for Reliable Net-Zero

Ferheen Ayaz
Department of Computer Science, City St. George's, University of London, UK

Maziar Nekovee
6G Lab, University of Sussex, UK

Amani Faya Ibraheem
College of Computer Science, King Khalid University, Kingdom of Saudi Arabia

***Abstract*—The future of 6G communications envisions a revolutionary framework where mobile base stations (BSs) extend beyond traditional connectivity by supporting innovative applications and opening opportunities for smart and reliable energy management solutions. Equipped with backup batteries and energy-efficient designs, these BSs can store and manage surplus energy, providing uninterrupted service to the power system during high demand periods. Considering the dispatchable capacity of backup batteries of BSs, this article discusses the evolving frameworks of Telecom-to-Grid (T2G) and Telecom-to-Vehicle (T2V) energy exchange. The concept is further illustrated with a use case where bidirectional energy transfer between Electric Vehicles (EVs) and BSs takes place to ensure reliable energy supply in a disaster-affected area. The article concludes with the discussion of associated research challenges and opportunities pertaining to the proposed framework.**

■ **THE RECENT** environmental global goals have brought a significant inclination of industries towards renewable and clean energy. One of the major aims of proliferation of renewable energy sources is achieving net-zero, that is, building a community where at least as much energy is produced as it is consumed with zero or negligible emissions [1]. The role of 6G communications is crucial for achieving net-zero. For example, reliable and seamless communications among energy sources, suppliers and consumers can make smart grid more responsive, adjusting dynamically to demand fluctuations and reducing energy wastage [2].

One of the key features of future energy systems enabled by 6G is decentralized energy management with distributed sources. The increasing electricity demands have aggravated the burden of main power grid. It is extremely challenging for a grid to balance demand and supply with renewable resources alone. Therefore, small-scale distributed energy sources are emerging as a cost-effective solution to meet the growing energy demands in an environment-friendly manner. Unlike traditional large-scale power plants, microgrids or nanogrids, and distributed energy storage systems (ESSs), such as batteries acquiring energy from solar panels at rooftop of a building or surplus energy in electric vehicle (EV), offer localized energy solutions without requiring extensive infrastructure. The 6G connectivity is essential for managing these distributed resources, enabling real-time monitoring and control, seamless peer-to-peer (P2P) energy transactions, and the integration of Artificial Intelligence (AI) technologies for optimized energy management. In this context, 6G networks can integrate Internet of Things (IoT) devices in energy management systems, enabling detailed data collection and analytics to drive predictive maintenance, estimate energy consumption and forecast supply from distributed sources, such as EVs, regulate grid supply and reduce its operational costs.

Utilizing EVs as distributed and flexible energy sources during high demand periods is already a well-established concept enabled by Vehicle-to-Grid (V2G) technology [2]. Bidirectional V2G energy exchange transforms EVs from consumers of energy into dynamic contributors to the power grid. By enabling EVs to store surplus energy and feed it back into the grid, V2G systems offer a dual benefit: they provide a new energy storage solution and support grid stability. The concept of prosumerism has been effectively supported by V2G. Entities in a power system which both consume and provide energy, such as EVs, are typically referred as prosumers. Nevertheless, 6G's advanced connectivity and features can play a key role in supporting prosumerism by enabling more efficient P2P energy exchanges in V2G networks. 6G can enable secure and private transactions between EV owners, energy providers, and other consumers, fostering a trusted decentralized and participatory energy economy.

Despite significant contributions of 6G towards net-zero, it is an inevitable fact that expected the progression towards fast data rates, low latency and wide network coverage is ultimately leading to rising energy demands and huge carbon footprints. Therefore, wireless communications industries across the globe are now considering energy efficiency and sustainability amongst the most important design metrics of 6G systems. Green 6G networks incorporate various energy-efficient techniques, such as, Reconfigurable Intelligent Surfaces and sleep mode management in BSs. These efforts are worth considering as one of the major steps in the journey towards net-zero.

Overall, the shift towards energy-efficient networks and reliable connectivity provided by 6G are both indispensable for developing a flexible, resilient, and sustainable infrastructure, crucial for achieving net-zero goal and ensuring energy security. Additionally, there is a promising opportunity that lies with the backup batteries of 6G mobile base stations (BSs) without causing an unbearable overhead in terms of infrastructure. We first present the added advantages of this concept as compared to other approaches of prosumerism, its three possible implementations, and relevant considerations for a practically feasible framework. A use case highlighting its application in post-disaster management with the help of digital twin (DT) is proposed followed by a discussion of associated challenges, associated technological innovations and research directions, and conclusion.

BASE STATIONS AS ENERGY PROVIDERS

A BS typically has a backup battery of certain power capacity for providing uninterrupted supply in case of power outage. It usually remains idle or underutilized, unless in specific cases such as power disruption due to an incident or when a BS performs a high-power consuming computing task. Recent dispatchable capacity of BS can give rise to promising bidirectional Telecom-to-Grid (T2G) and Telecom-to-Vehicle (T2V) energy exchange as an emerging new application of 6G proliferation.

The rollout of 6G will bring tremendous upgrades and densification in infrastructure, such as installation of large number of BSs across a region. The world is already witnessing small steps towards this huge shift. Chinese operators have installed a total of 3.28 million BSs nationwide as of the end of November 2023. Further plans include extending the network coverage, commercialization of 6G in 2030, with standardization expected to commence in 2025. By 2025, the expected number of BSs in China is 8.28 million [3]. More BSs will consequently have more backup batteries and therefore higher dispatchable capacities. The major advantage of BS over an EV as an energy provider is that it is already powered by the grid and its battery is mostly used as a backup source in case of main power failure. Also, with recent trend towards energy-efficient systems, a BS can potentially save its backup energy for another prosumer. Furthermore, supply from T2G and T2V can also be made more sustainable than the energy from other battery-based systems. It is because a battery retired by an EV has typically sufficient energy capacity and can be re-used as a backup battery of BS [4].

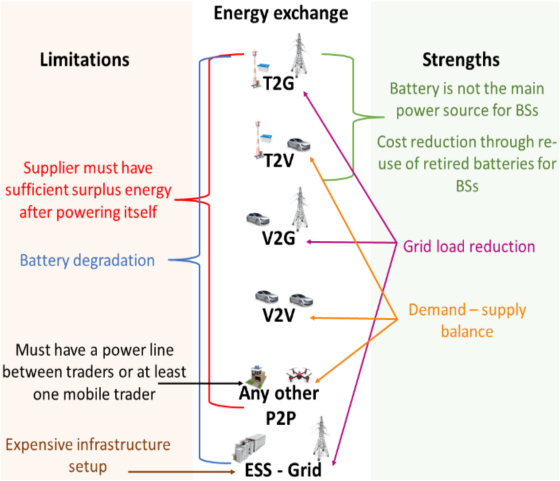

Figure 1. Limitations and strengths of different energy exchanges in future 6G networks.

Figure 1 illustrates the limitations and strengths of various forms of energy exchanges envisioned for future 6G networks including T2G, T2V, V2G, vehicle-to-vehicle (V2V), other P2P exchanges among various prosumers, such as a homes, Unmanned Aerial Vehicle (UAV) and Energy Storage Systems (ESSs) specifically set up to support grid during high demand periods. Motivated by the additional strengths of T2G and T2V highlighted in Figure 1, we consider this energy exchange as a useful vertical application of 6G BS. However, with millions of BSs and EVs, the implementation of T2G and T2V energy exchange will come with its own set of implementation challenges such as potentially disrupting the telecom infrastructure if not planned carefully, record-keeping of original energy source, energy management, finding the best buyer and seller match and dynamic pricing. We present the following three ways to implement T2G and T2V exchange.

Grid Centralized T2G

As shown in Figure 2(a), in a grid centralized T2G, the bidirectional energy exchange takes place only between BSs and grid. The grid-centralized T2G energy exchange is evaluated in [8] with a case study on IEEE-33 node system which shows that at most 50% of backup battery of a BS is dispatchable when communication traffic is low. When a feeder experiences a failure, BSs can utilize their backup batteries to serve as an uninterruptible power supply during the restoration process. Once the restoration is complete, BSs receive power from an alternative intact feeder. This integration of tie-lines and backup batteries greatly enhances the reliability of the power supply to BSs. The backup battery of a BS can be charged during off-peak hours. BS can supply energy back to the grid at peak demand hours. Dynamic pricing mechanisms can be implemented for the telecom companies, which may earn profit by buying energy for their BSs at a lower price and selling it back at a higher price. In a grid centralized exchange, EVs are able to acquire energy only through a grid and not directly from a BS. Therefore, a grid-centralized T2G reduces communication overhead between BSs and EVs. As a trade-off, some energy is wasted as a transmission loss which could be saved if EVs were to travel directly to the BSs for a T2V exchange.

Cloud based Virtual Power Plant (VPP)

As shown in Figure 2(b), a VPP, usually located in the cloud of an Internet-of-Energy (IoE) network aggregates decentralized energy resources like solar panels, wind turbines, and ESSs, all managed through a unified control system. The integration of distributed P2P resources in a VPP enables dynamic and flexible energy management. Additionally, 6G supports scalable solutions, accommodating the growing number of decentralized energy resources and expanding VPP capabilities to meet future energy demands. Both EVs and BSs can sell their surplus energy to a VPP and the exchange can be taken place directly thereby avoiding the additional transmission loss occurring in T2G. A case study of using VPP for regulating user-side energy as a backup when the external power grid fails in the industrial park is presented in [9]. A VPP can record information, optimally manage the resources and find the best buyer-seller match. Mathematical or machine learning algorithms and other information handling techniques such as database servers or blockchain can be incorporated with the VPP for privacy-preserving smart energy management. A use case of this type of energy management is described in [10], where EVs also perform edge computing tasks for BSs during energy transfer. Quantum algorithm is used by the VPP for energy-efficient optimization. However, the energy consumption of the optimization algorithm rises with the increase in number of EVs. As we anticipate a huge increase in EVs in near future, a completely decentralized energy management solution can be more suitable and less time consuming.

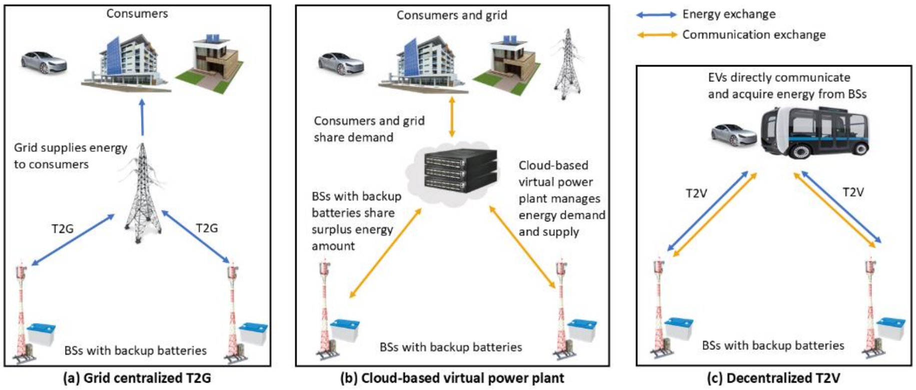

Figure 2. Implementation approaches for T2G and T2V energy exchange.

Table 1. Comparison of implementation approaches for T2G and T2V energy exchange.

Approach	Advantages	Disadvantages	Modeling requirements
Grid-centralized T2G	Privacy preserving with low communication overhead	Associated with high transmission loss and chances of disruption due to power failure	Dynamic pricing strategies
Cloud based VPP	Efficient, scalable and optimized energy management	High computation complexity with increasing number of EVs	Optimization and matching algorithms
Decentralized T2V	Does not require third party for communication or energy transfer	More vulnerable to cyberattacks and high communication complexity	Incentive strategies such as game theoretic based modeling to promote honest and cooperative energy exchange

Decentralized T2V

As shown in Figure 2(c), in a decentralized T2V energy exchange, BSs can share energy directly with the EVs and vice-versa. This approach enhances the flexibility and resilience of energy systems and is independent of grid supply availability and failures. Decentralized T2V reduces the management burden of traditional power systems and centralized aggregators. A direct T2V exchange prevents additional transmission loss involved in T2G. However, it may require exchange of multiple messages between BSs and EVs to negotiate and agree on energy amount and prices. Therefore, a reliable communications system is necessary for EVs and BSs to share their demands, available energy, locations and prices. Its use case is described in the next section.

Table 1 provides the comparison of the pros and cons and basic design requirements of each implementation approach for a profitable energy exchange system. Regardless of the implementation approach, it is important to consider the following points for a practical and economically feasible exchange

- Utility of both buyer and seller should be positive.
- Battery degradation cost, traveling cost of EV and time consumed during energy exchange should be taken into account while calculating the utility.
- Expected load and energy consumption of a BS should be considered for estimating the energy threshold that a seller BS must keep to fulfill its own needs, such as some backup energy to run in case of unexpected power disruption.
- An EV should have sufficient energy in its battery to travel towards a BS.
- The buyer should be able to verify source of energy being transferred, keeping in view the net-zero goal.

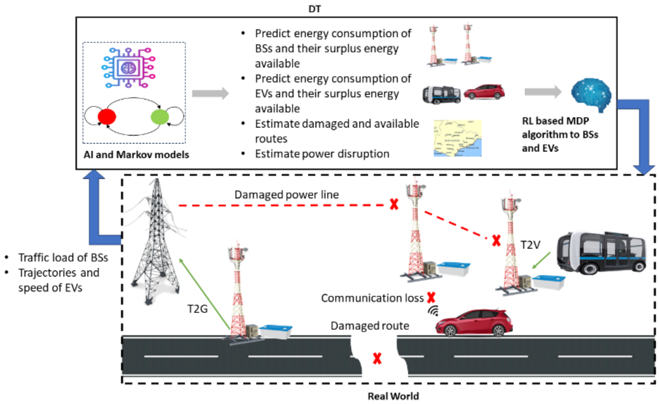

Figure 3. Use case of post-disaster decentralized T2V energy exchange.

USE CASE OF POST-DISASTER T2G AND T2V EXCHANGE

System Setup

In this section, we evaluate the application of bidirectional T2G and T2V exchange of a 6G network in post-disaster situation. As shown in Figure 3, it consists of BSs, EVs and a cloud simulating DT of the network by continuously monitoring the entities and estimating energy demands and available supply in case of disaster.

We assume two kinds of damages caused by a disaster. Firstly, a route through which an EV travels towards a BS can be blocked. Secondly, power disruption may occur due to which a BS will not be able to share its energy or even lose communication if all the energy in its backup battery is exploited. A continuous time Markov process models the state of these damages.

Utilities and Optimization Algorithm

We define SW as the Social Welfare of the system which is the sum of utility of a buyer and seller in an energy exchange. If surplus energy is available, a BS or EV sells it in return of the following utility

$$U_s = p_s e_s - p'_s e_s - p_t e_t, \quad (1)$$

where p_s is the selling price of the energy amount e_s, p'_s is the price at which e_s was originally acquired and p_t is the price of energy e_t which was consumed in traveling towards a buyer if the seller is EV. The utility of buyer is

$$U_b = (\gamma \log(1 + e_s) / SoC_b) - p_s e_s - p_t e_t, \quad (2)$$

where γ is the adjustment coefficient, SoC_b is the State of Charge of buyer's battery. It is aimed to maximize SW considering positive utilities of both buyers and sellers and availability of undamaged routes for an optimized energy exchange.

A Reinforcement Learning (RL) based Markov Decision Process (MDP) optimization algorithm is trained in the cloud to select the most appropriate BS for energy exchange which maximizes their SW. Regular monitoring of SoC and energy consumption of EVs and BSs is ensured by DT to estimate demand and available surplus energy which both entities can offer. The action set of RL algorithm for EVs available to exchange energy is comprised of BSs which act as buyers in case of power disruption or sellers otherwise. The reward of each action is resulting SW. It is likely that two or more EVs are matched with the same BS. In this case, the highest energy amount being exchanged is given preference. If no match between BS and EV takes place, then energy is exchanged with grid. The RL algorithm is continuously updated as EVs travel. The EVs regularly receive updates so they can execute the algorithm independently in case of disaster.

Performance Evaluation

The performance of use case is evaluated using Python with 500 EVs simulated on the map of East Sussex. The traffic simulation is performed using tool called Simulation of Urban Mobility [11]. The open-source datasets are used including historical data of floods in East Sussex, UK to model the damage rate of routes in the area [5] and the traffic load and energy consumption of BSs [6]. AI models defined in [2] and [7] are utilized to estimate the demand and availability of surplus supply for EVs and BSs respectively. The battery capacity of EV and BS is assumed as 40 kWh and 30 kWh respectively. The SoC of EV is assumed as a random variable following lognormal distribution [12]. Simulations are performed for one hour.

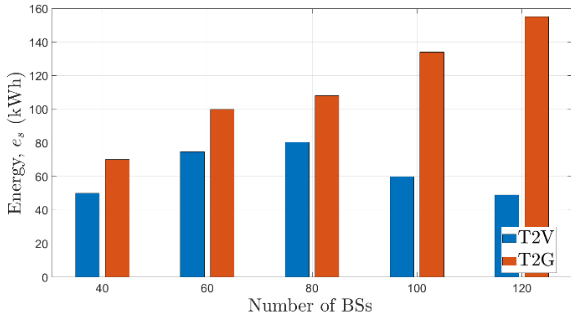

Figure 4. Energy exchange with BS as a seller.

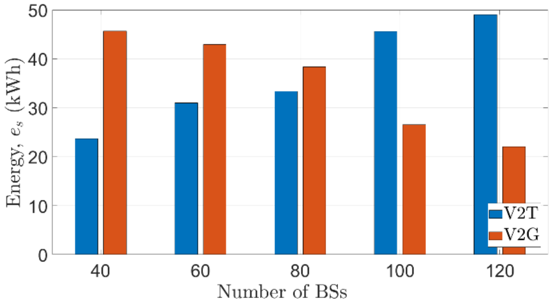

Figure 5. Energy exchange with EV as a seller.

Figure 4 shows the total energy exchange taken place with seller BSs. The energy transferred from BS to grid (T2G) is higher than T2V. It is because EVs have to pay additional travel cost which result in decreased utility. The increase in T2G energy and number of BSs is proportional. However, there is an optimum number of BSs when T2V energy exchange is highest. Few BSs are not sufficient to provide enough energy to EVs. As BSs increase, most of their energy is shared with grid.

Figure 5 shows the energy transferred from EVs to either BSs, i.e., Vehicle-to-Telecom (V2T) or grid, i.e., V2G. V2T rises as the number of BSs increase ultimately leading to a decrease in V2G. It is possible that a power line from grid to BS is damaged due to a disaster. In this scenario, the advantage of V2T is two-fold. It ensures smooth running of BS and also reduces transmission loss.

CHALLENGES

The implementation techniques, design considerations and constraints discussed in this article are crucial to make the most of the proposed T2G and T2V energy exchange. However, there are still several challenges and open research issues that need to be addressed before practical execution of this framework.

Energy Consumption and Power Outage Models

The primary purpose of backup batteries is to provide uninterrupted supply to BSs and avoid connectivity issues and failures. Ensuring resilient and reliable communications is one of the core objectives of 6G. Therefore, it is must that a backup battery of BS has enough capacity remaining to run itself in case of main power failure, even after it has supplied a portion of its energy to a grid or another prosumer. Intelligent computing techniques are required to estimate the energy consumption of a seller BS considering its traffic load, fluctuations in the supply it receives from grid, and expected disaster or incident which may cause power disruption. Adaptive decision-making solutions are also needed to regulate T2G and T2V exchanges or completely stop when required. It is worthwhile mentioning that some sophisticated AI solutions demand massive energy and computational resources. Therefore, it is also important to create energy-efficient AI models considering the net-zero goal. Furthermore, a T2V energy exchange may not be plausible for small BS (pico or femto cell). However, in outdoor deployment scenarios their ~~its~~ backup batteries can ~~y can~~ be used for low-powered devices, such as UAVs [13], while in indoor scenarios they can be used for wireless power transfer to ~~ly charging~~ IoT devices.~~.~~

Optimal Location of BSs

The location and distance among BSs are crucially important to provide network coverage. However, the optimal locations ensuring reliable connectivity may not be favorable for energy provision. The EV charging locations and number of charging zones are critically planned and set up according to the demand trends of a certain area. However, a BS serving as an energy provider can possibly be present at a low-demand location and its battery backup may remain underutilized. Nevertheless, a BS location must be selected according to 6G network requirements. For utilizing backup battery of a BS which is not ideally located as a seller, it is recommended to implement battery dispatching and swapping services run by mobile nodes including EV cars, motorbikes and UAVs. However, this concept is only feasible if the energy consumed and cost incurred in traveling of mobile nodes do not result in a significant decrease or negative utility of buyer or seller.

Security and Privacy

The energy management systems involving BSs would be prone to cyberattacks compromising either communications, energy or both. 6G is expected to incorporate quantum communication and computing technologies, providing unprecedented security for data transmissions. Unauthorized access to cloud-based aggregators or VPPs, can be countered with quantum-resistant cryptography, ensuring only authorized entities gain access. Additionally, for a complete net-zero system, it is also important to balance trade-off between energy consumption and security. Quantum computing usually consumes small power and has a low carbon footprint [10]. Furthermore, the issue of selfish behavior, where prosumers might withhold surplus energy, can be managed by creating effective incentive mechanisms that discourage such actions. Moreover, the risk of unauthorized access to private information, like EV charging patterns or routes, can be mitigated through privacy-preserving information exchanges using blockchain.

TECHNOLOGY EVOLUTION AND FUTURE DIRECTIONS

The future scope of the proposed T2G and T2V energy exchange extends beyond battery management solutions and can benefit technology evolution in several impactful ways.

Wireless Power Transfer (WPT)

An EV has to travel to a BS for charging or discharging. The related energy consumption and cost may not result in a high profit T2V exchange. Also, the immobile prosumers can only take part in energy exchange through a grid which is prone to transmission losses. One of the reliable solutions to avoid travel for EVs and implement direct wireless power transfer (WPT) between a BS and an immobile prosumer. Recent research aims to increase the output power, reduce associated costs and minimize the effect of WPT on radio transmissions. WPT is often considered as more sustainable and environment-friendly as it eliminates cord usage. However, WPT is still in its infancy and can only be availed when the source and receiver are just few meters apart. One of the more futuristic applications of 6G is holographic beamforming, which can enable highly efficient wireless energy transfer [14, 15].

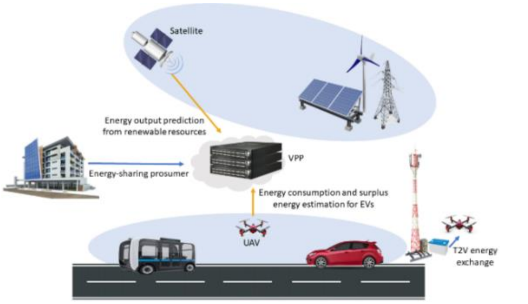

Figure 6. Integrating non-terrestrial network with 6G-enabled terrestrial energy management system.

Integrated Terrestrial and Non-Terrestrial Networks for Collaborative Energy Management

6G aims to integrate terrestrial and non-terrestrial networks. It can enable satellite-based comprehensive energy management systems with the ability to monitor and control energy resources and prosumers across a large area, as shown in Figure 6. Such integration could facilitate collaborative coordination of energy resources regulated by multiple authorities, optimizing their use and ensuring a balanced supply across different regions. Also, the integration of terrestrial and non-terrestrial networks can include UAVs for surveillance and acting as mobile BSs. They can also charge themselves using the backup batteries of BSs.

Virtual Energy Management Interfaces

Virtual realization of 6G networks for real-time monitoring is an evolving concept. One of its popular examples is DT which we have already discussed. Apart from disaster, it can also simulate various other scenarios, such as a road accident, allowing BSs and EVs to predict and prepare for future demands and potential disruptions by leveraging ultra-reliable and low-latency massive Machine Type Communications (mMTC) and advanced edge computing capabilities. With unsupervised learning, DT can become more accurate over time, leading to proactive rather than reactive energy management strategies.

Human-Device Interfaces in Energy Management

6G is expected to enhance human-device interfaces through technologies like augmented reality (AR) and virtual reality (VR). In energy management, these interfaces could provide intuitive and immersive ways for prosumer to monitor and control energy systems. For instance, a 6G operator can use AR glasses to visualize real-time energy flows and system statuses of BS before deciding to sell energy.

Figure 7. Future research directions highlighting 6G contributions and technological innovations towards net-zero.

Figure 7 shows different aspects where 6G can support achieving net-zero and distributed energy exchange including BSs. The items indicated in red are not currently implemented by 5G and identify promising research directions and technological innovations.

CONCLUSION

In this article, the potential of BSs for a reliable net-zero community is highlighted. The T2G and T2V energy exchange is evolving as a promising concept to reduce grid burden and maintain demand-supply balance. The implementation approaches and important considerations for the practical feasibility of the proposed framework are also discussed. A use case of employing T2G and T2V energy exchange in post-disaster situation is presented. The associated challenges and future research directions incorporating latest 6G technologies are pointed. While many of the future research opportunities regarding 6G in energy management are still theoretical, their potential to revolutionize energy management and distribution is significant.

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