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Wireless energy: Paving the way for smart cities and a greener future

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ABSTRACT

The significance of energy stability in urban development has increased as the use of intelligent devices continues to expand and extreme weather poses a threat to the integrity of electric networks. Wireless power transfer technology is well-known for its dependability, security, and adaptability, and has reached billions of market share in China alone in the cell phone and electric vehicle sectors over the past decade, with the electric vehicle wireless charging market expected to grow at a compound annual growth rate of over 30% by 2023. Combining WPT with renewable energy, electric vehicles, and recharge infrastructure is a promising new application for smart city development. This paper examines the history, characteristics, and six classifications of WPT technology through the lens of urban development, in addition to its successful implementations in seven contexts, such as portable devices and transportation, based on a survey of 161,425 papers. We propose a dependable and efficient research-to-application life cycle for high-power WPT operations, which is capable of achieving efficiencies of approximately 90 percent at approximately 50 percent of the original cost. In addition, the significance of incorporating WPT technology, renewable energy sources, and urban infrastructure into the design of sustainable cities is highlighted. This study determined that WPT is advantageous for promoting the construction of space and ground photovoltaic plants, as well as photovoltaic rooftops, and also serves to accelerate the promotion of electric vehicles, smart devices, and charging roads. The findings of this study cast light on three problem areas and six future prospects of WPT, as well as its multifaceted benefits in terms of energy, the environment, and the social economy of sustainable cities.

1. Introduction

More than half of the world's human activity, energy consumption and carbon emissions occur in cities, and this proportion is increasing [1]. To combat the worsening of the energy crisis, global warming, and air pollution, sustainable-development cities are moving towards digitalisation, intelligence and low carbon emissions [2]. Massive intelligent devices will transform data, renewable energy, and cutting-edge technology in the energy systems and civilizations of the future [3]. We have witnessed the rapid development of a large number of portable electronic devices, household smart appliances, industrial robots and new electric vehicles (EVs), and the traditional methods of charging via wires and the use of battery power supplies have placed significant pressure on energy supply safety and stability in smart cities in terms of industrial

Abbreviations: CPT, Capacitive power transfer; EV, Electric Vehicle; EC-WPT, Electric field coupling wireless power transfer; HIL, Hardware in the Loop; IoT, Internet of Things; MCI-WPT, Magnetic coupling inductive wireless power transfer; MCR-WPT, Magnetic coupling resonance wireless power transfer; MPT, Microwave power transfer; OPT, Optical power transfer; UPT, Ultrasonic power transfer; UAV, Unmanned Aerial Vehicle; WPT, Wireless power transfer.

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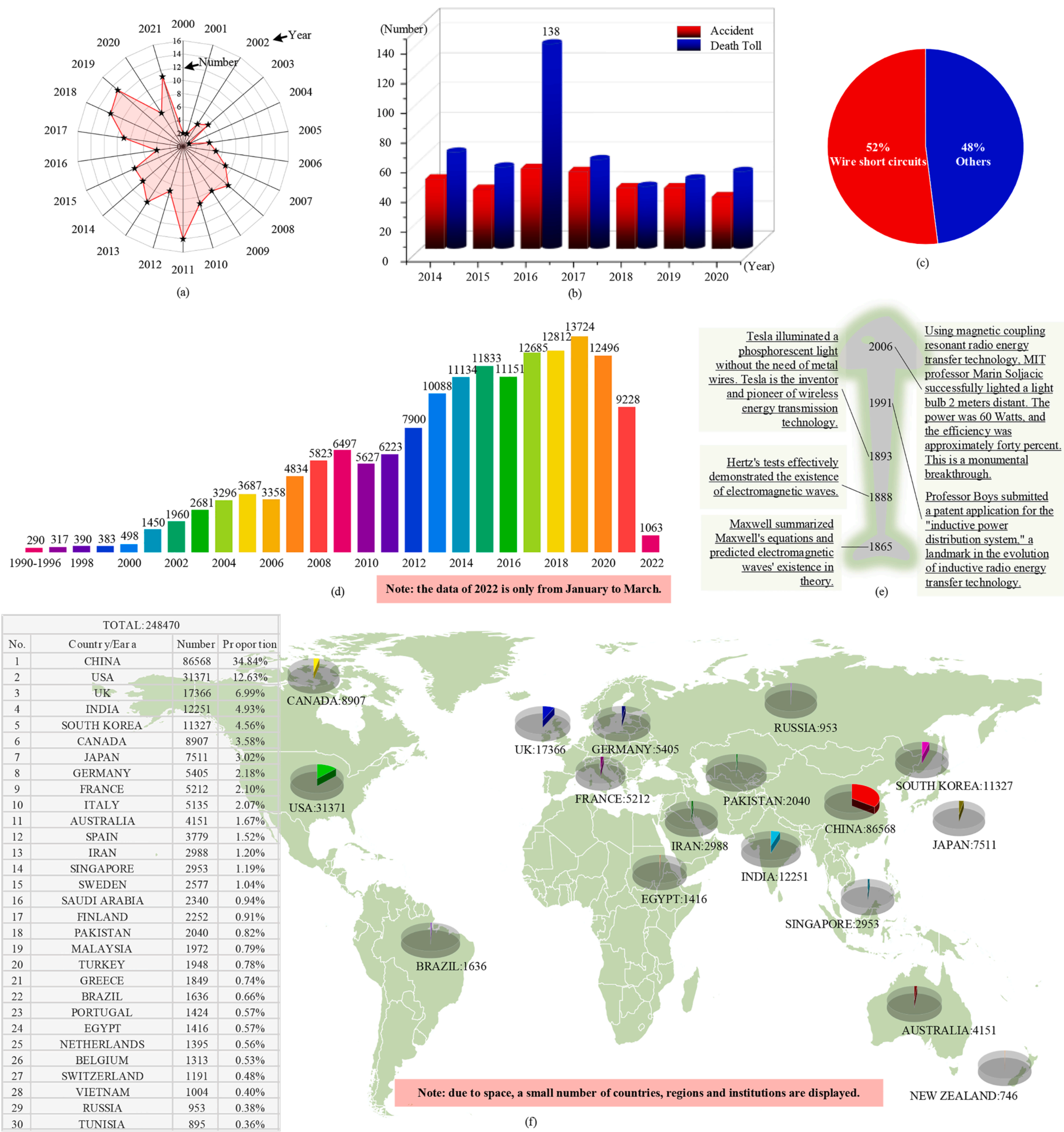
production, domestic life, transportation and special operations [4].

Large-scale intelligent devices help smart cities become more digital, information based, green and sustainable. However, potential electrical charging hazards have also become a concern [5]. As depicted in Fig. 1 (a), power equipment and transmission lines caused more than 90% of the 150 significant power outages over the past three decades, affecting hundreds of millions of people and costing billions of dollars [6]. The most significant issue is that metallic wires pose safety risks [7]. Metal wires degrade and threaten power security. Metal wires can be fatal in high-temperature, high-voltage, or unusual power-consumption situations, such as the seabed, mines, outer space, the chemical industry, and warehouses. As indicated in Fig. 1 (b), the China National Energy Administration reported multiple power-generation incidents in recent years, resulting in many deaths and much economic property damage [8]. Natural calamities, ageing equipment and design faults caused most electrical-shock and fire mishaps. Wire short circuits caused 52% of Chinese fires in 2019 (Fig. 1 (c)) [9]. In addition, metal wires present both adaptability and practicality concerns, and large-scale devices exacerbate the problem [10]. Transmission wires severely limit working distance and range, especially for flexible industrial robots. Power-line improvements and equipment relocation are also difficult.

Compared to wired power transmission, wireless-power-transfer (WPT) technology offers safety, convenience, flexibility, energy efficiency, a wide application range and low maintenance costs in



TOTAL:248470			
No.	Countr y/Ear a	Number	Pr opor tion
1	CHINA	86568	34.84%
2	USA	31371	12.63%
3	UK	17366	6.99%
4	INDIA	12251	4.93%
5	SOUTH KOREA	11327	4.56%
6	CANADA	8907	3.58%
7	JAPAN	7511	3.02%
8	GERMANY	5405	2.18%
9	FRANCE	5212	2.10%
10	ITALY	5135	2.07%
11	AUSTRALIA	4151	1.67%
12	SPAIN	3779	1.52%
13	IRAN	2988	1.20%
14	SINGAPORE	2953	1.19%
15	SWEDEN	2577	1.04%
16	SAUDI ARABIA	2340	0.94%
17	FINLAND	2252	0.91%
18	PAKISTAN	2040	0.82%
19	MALAYSIA	1972	0.79%
20	TURKEY	1948	0.78%
21	GREECE	1849	0.74%
22	BRAZIL	1636	0.66%
23	PORTUGAL	1424	0.57%
24	EGYPT	1416	0.57%
25	NETHERLANDS	1395	0.56%
26	BELGIUM	1313	0.53%
27	SWITZERLAND	1191	0.48%
28	VIETNAM	1004	0.40%
29	RUSSIA	953	0.38%
30	TUNISIA	895	0.36%

Fig. 1. Electrical safety incidents and a synopsis of wireless power transfer's (WPT's) global expansion: (a) the annual number of power outages, (b) the number of power-safety accidents and fatalities in China from 2014 to 2020, (c) the components of these accidents, (d) the annual number of academic research articles, (e) WPT milestones and (f) the countries and areas performing WPT technology research.

transmitting electrical energy [11]. WPT has a wide range of manufacturing and life applications in wireless-power smart-city construction [12]. WPT, renewable energy and large-scale intelligent equipment will promote low-carbonisation, digital and intelligent transformation, sustainable city development and urban-energy-system and infrastructure construction [13,14]. In our scientific study, we present a comprehensive survey of WPT technology and illustrate its rapid global expansion (Fig. 1 (d-f)) [15,16], including the number of academic research articles published each year, the countries or regions conducting WPT research and significant milestones in the evolution of WPT [17]. WPT's use in portable devices [18], household appliances, transportation, robots [19], and applications underwater [20] and in outer space attest to its ubiquity. Photovoltaic-wireless power charging stations [21], wireless charging roads [22], and wireless charging for EVs [23] have demonstrated the enormous potential of WPT technology in promoting renewable energy resources and urban infrastructure development. Consequently, to promote smart cities in a safe and sustainable manner, we combine WPT, renewable energy sources, large-scale intelligent equipment and urban infrastructure construction and propose the concept of a wireless-energy green city.

The second section provides a summary of six major WPT technologies and their technical characteristics and applications in the context of sustainable urban development. To encourage the research and development of large-scale, high-power apparatuses, Section 3 proposes a novel, efficient and reliable WPT research-to-application lifecycle. In Section 4, a comprehensive review of seven applications of WPT in the construction of renewable and sustainable cities is presented, and a new application for smart-city construction that integrates WPT with renewable energy, EVs and charging infrastructure is proposed. In Section 5, this paper discusses the sustainable benefits of WPT, in terms of energy, the environment, and the social economy, for sustainable urban development and construction, along with its three current challenges and six future prospects.

2. The classification of WPT in terms of constructing a sustainable city

WPT has been developed from a variety of non-contact power-transmission systems [24,25]. Fig. 2 (a) shows a typical WPT system. As shown in Fig. 2 (b), based on the underlying principle involved, WPT technology can mainly be divided into six groups: magnetic coupling inductive wireless power transfer (MCI-WPT), magnetic coupling resonant wireless power transfer (MCR-WPT), electric-field coupling wireless power transfer (EC-WPT), microwave wireless power transfer (MPT), optical power transfer (OPT) and ultrasonic power transfer (UPT) [26,27]. Table 1 provides a comprehensive overview of the six technologies. In sustainable urban construction that uses renewable energy to generate electricity, we can choose WPT technology methods based on power-transmission conditions and energy acquisition needs in various scenarios [28,29].

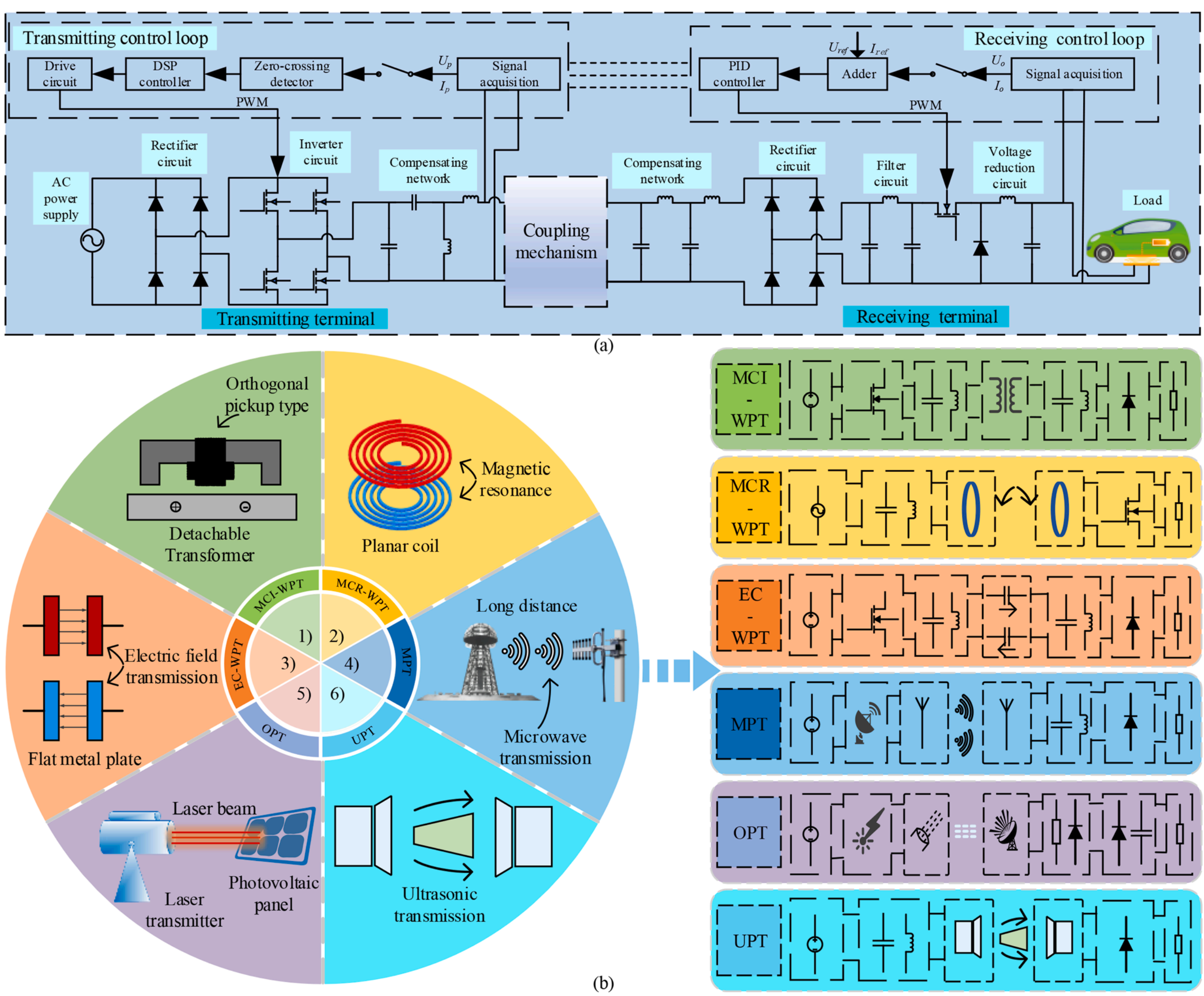


Fig. 2. Classification of WPT technologies: (a) typical system composition, (b) six types of WPT technology and their representative system compositions.

Table 1
The main applications of six WPT methods in cities.

Category	Body	Working frequency	Transmission distance	Advantages and disadvantages	Examples
MCI-WPT	Electromagnetic wave	Tens to hundreds of kHz	A few millimeters to tens of millimeters	Easy-to-use, 99% effective. Large magnetic flux leakage, short transmission distance, quick transmission efficiency degradation, and stringent alignment.	Ioannis Karakitsios presented a power transmission efficiency control system for EV dynamic induction charging [47]. H.Dinis et al. said that WPT technology can reliably power implantable electronic devices, with inductive coupling being the most established and recognised way [48]. Yue Chuanyu et al. remotely powered the implanted glucose sensing device at 2 cm using inductive coupling [49]. DIEGO MASOTTI et al.'s inductive power system (IPT) can give 100 W of consistent power to mass handlers in industrial automation plants [50].
MCR-WPT	Electromagnetic wave	MHz to hundreds of MHz	A few centimeters to hundreds of centimeters	No radiation, interference protection, and efficient medium-distance transmission. Same resonance frequency, simple error, bad performance.	Antimahesh et al. stated that magnetic coupling resonant wireless power transfer charging technology has a large EV market [51]. The intelligent greenhouse sensor's power supply problem was solved by Wook Kim et al.'s 'closed-loop' magnetic resonance wireless power supply system, which forms a large uniform magnetic field and evenly distributes power in the case of multiple secondary coils [52]. Zhang Ziqi's fractional time-sharing control-based wireless power transmission technique for household equipment in intelligent buildings enabled TV and mobile phone time-sharing resonant charging [53].
EC-WPT	Electric field	Tens of kHz to hundreds of MHz	Centimeters to hundreds of centimeters	Simple, lightweight, thin, affordable, low electromagnetic interference, and can pass metal obstacles. High power and high frequency are difficult. High coupling voltage causes safety accidents easily, although the technology is immature.	Yang Lei et al. developed a four-board submarine CPT system for AUVs [54]. Luo Bo et al. developed a magnetic-electric hybrid curve power transmission system for wireless railway train power transfer [55]. Masaya Tamura et al. used capacitive WPT to power the intravascular implant device [56].
MPT	Electromagnetic wave	300 MHz-300 GHz	Hundreds to thousands of meters	Directed, long-distance transmission. Low reception power, complex antenna layout, low transmission and conversion efficiency.	RubenHidalgo-Leon et al. suggested microwave radio frequency wireless power transfer for intelligent building wireless sensor network nodes [57]. Hu Biao et al. presented an asymmetric resonance-based long-distance high-power microwave wireless power transfer system that can remotely power fuel-free aircraft and urban UAVs [58].
OPT	Electromagnetic wave	Wavelength around 800 nm	Tens of meters to thousands of meters	Excellent directivity, high energy density, convergence, and aperture with low divergence. Low transmission distance, high alignment precision, high air transmission loss, underdeveloped technology.	Lasers and 60% photoelectric converters allow Russian rocket and space businesses to charge mobile phones 1.5 km afar [59]. Huang Chunming of China presented a resonant beam method for optical fibre wireless power transmission to overcome the power transmission challenges of the Internet of Things (IoT) and mobile electronic devices and achieve safe and high-power beam power transmission [60].
UPT	Mechanical wave	20 kHz to several MHz	Hundreds to thousands of meters	Aviation and medical power supply without electromagnetic interference. Its limited transmission efficiency and environmental dependence make the technology immature.	Jiang Liming and colleagues suggested using ultrasonic-induced wireless energy collecting to power nano-devices and implantable medical systems [61]. Fu Hailing et al. proposed ultrasonic wireless power transfer for embedded condition monitoring devices in civil infrastructure, industrial machinery, and other fields [62].

MCI-WPT is an innovative transformer-based technology that operates without magnetic resonance coupling [30,31]. MCI-WPT is the epitome of efficiency and power [32], and it can power domestic appliances and portable electronic devices with unmatched efficiency and potency. **MCR-WPT** was created by combining the ideas of MCI-WPT and strong magnetic resonance [33,34]. Long-distance MCR-WPT's high-efficiency properties have ushered in a new era in terms of the widespread application of WPT technology in EVs, home appliances and intelligent urban buildings. The energy carrier for **EC-WPT** technology, also known as capacitive power transfer (CPT) and capacitive coupling power transfer (CCPT), is a high-frequency electric field [35,36]. EC-WPT can be applied to implanted medical electronic devices, electric locomotives on urban traffic railways and wireless power sources for undersea electric equipment, among other applications [37]. **MPT** technology is a far-field WPT technology that allows information transfer and energy transmission to occur simultaneously [38,39]. As a technique for long-distance wireless power transmission, MPT is well-suited for power transmission between space power stations and urban power grids, as well as for providing a the remote, wireless power supply to unmanned aerial vehicles (UAVs), wireless sensor networks and other urban devices [40,41]. **OPT** technology is a long-distance wireless-power-transmission method based on lasers [42]. OPT has been extensively studied in power transmission for urban power systems and the provision of a long-distance power supply for power equipment, and it can provide power for UAVs, satellites and other mobile electrical facilities [43]. However, its sensitivity to cloud cover, fog and precipitation hampers the development and use of OPT technology [44]. One short- and medium-range WPT technology is **UPT** [45]. UPT is suitable for power transmission in metal-enclosed situations, such as high-temperature, high-pressure, radioactive, toxic or implanted equipment, as well as providing power for urban medical treatment, specialised chemical and bio-industrial equipment and environmental sensors, due to its unique technical advantages [46].

3. A novel research-to-application life cycle

Hardware in the Loop (HIL), a real-time simulation, is increasingly used in motor control [63]. HIL offers security, affordability and efficacy for large-scale high-power WPT experiments [64]. In Fig. 3 (a), the lifecycle is shown to have three stages: laboratory testing, simulation and real-world testing, and application testing. A Chinese-Ministry-of-Education-approved power-electronics experiment platform based on the Speedgoat controller proves that this study-to-application lifecycle works [65]. The investigation used a 50 kW inductive-power-transmission platform (Fig. 3 (b)).

Unlike prior methodologies, Part 2 of the inventive lifecycle from research to application comprises real-time modelling and testing. The rapid verification of control algorithms, controllers and power circuits is achievable, particularly for experiments involving high power and risk. The research and development procedure's dependability and efficiency are improved, while its mistake rate, cost and duration are reduced.

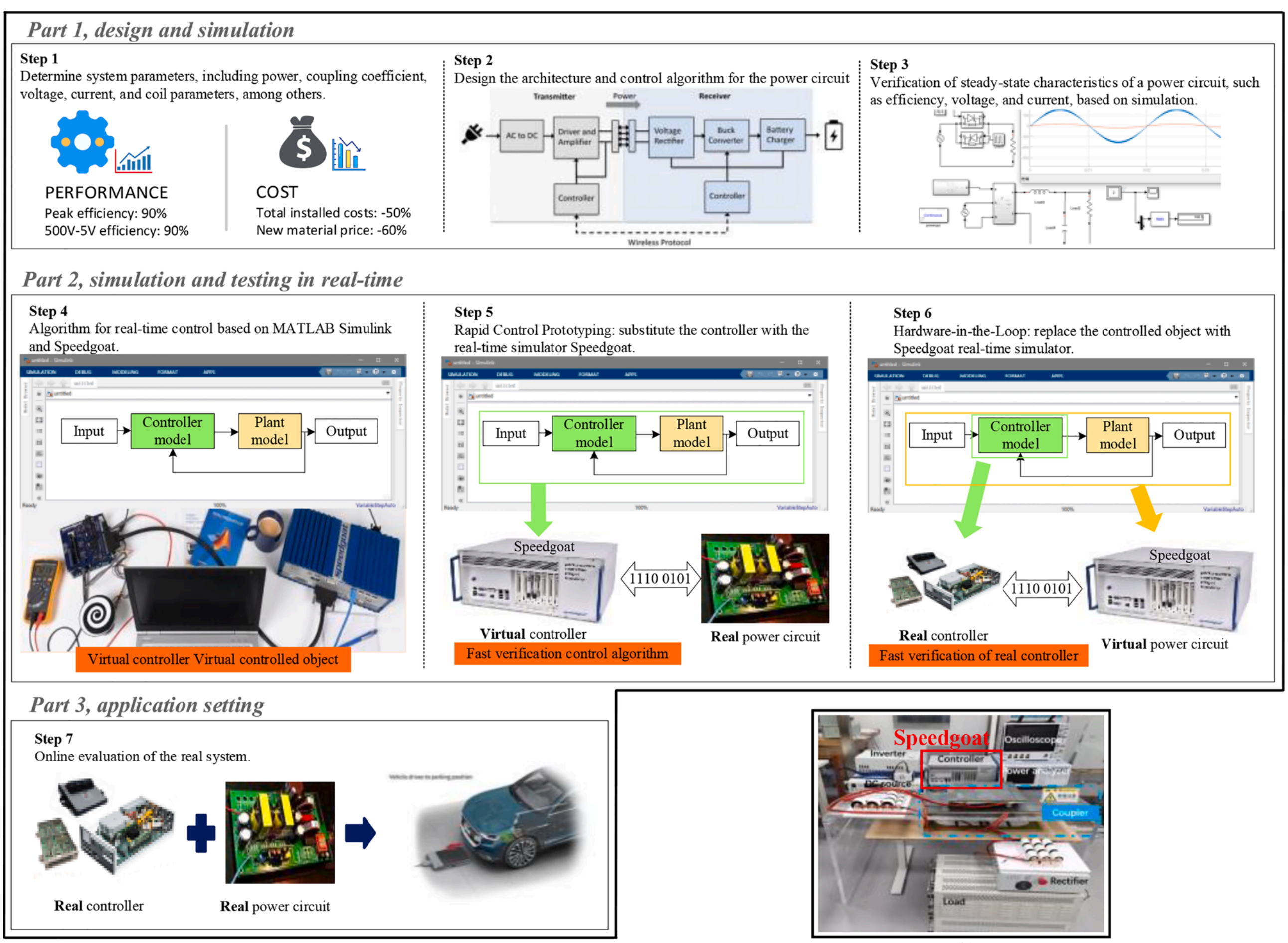
4. Application of WPT in transforming renewable energy and building sustainable cities

Given its unrivalled excellence, WPT technology is widely used in all aspects of social production and daily life in the building of wireless-power cities, particularly in portable electronic equipment and electric cars [66]. As shown in Fig. 4 (a), China's wireless charging industry has grown steadily since 2015, with mobile phones constituting a significant share of the market [67]. As shown in Fig. 4 (b), the penetration rate for the wireless charging of EVs in China has increased annually since it was first recorded in 2018 [68]. Fig. 4 (c) displays the applications of WPT technologies, which play a key role in human society.

4.1. Seven significant applications of WPT in wireless-power cities

We summarize seven major applications of WPT in various fields of urban construction. These seven fields will be discussed in detail in this section, and the application examples inspired by this study are summarised in Table 2.

1) Portable electronic equipment: Due to the rapid growth of intelligent technology, laptops, mobile phones and digital cameras are now essential to daily life [69]. However, cable-charging and battery-power-supply techniques are portable electronics' most important limitations, and the many power interfaces and chargers limit user



(a) (b)

Fig. 3. Research-to-application: (a) A research-to-application lifecycle; (b) 50 kW inductive-power-transfer platform.

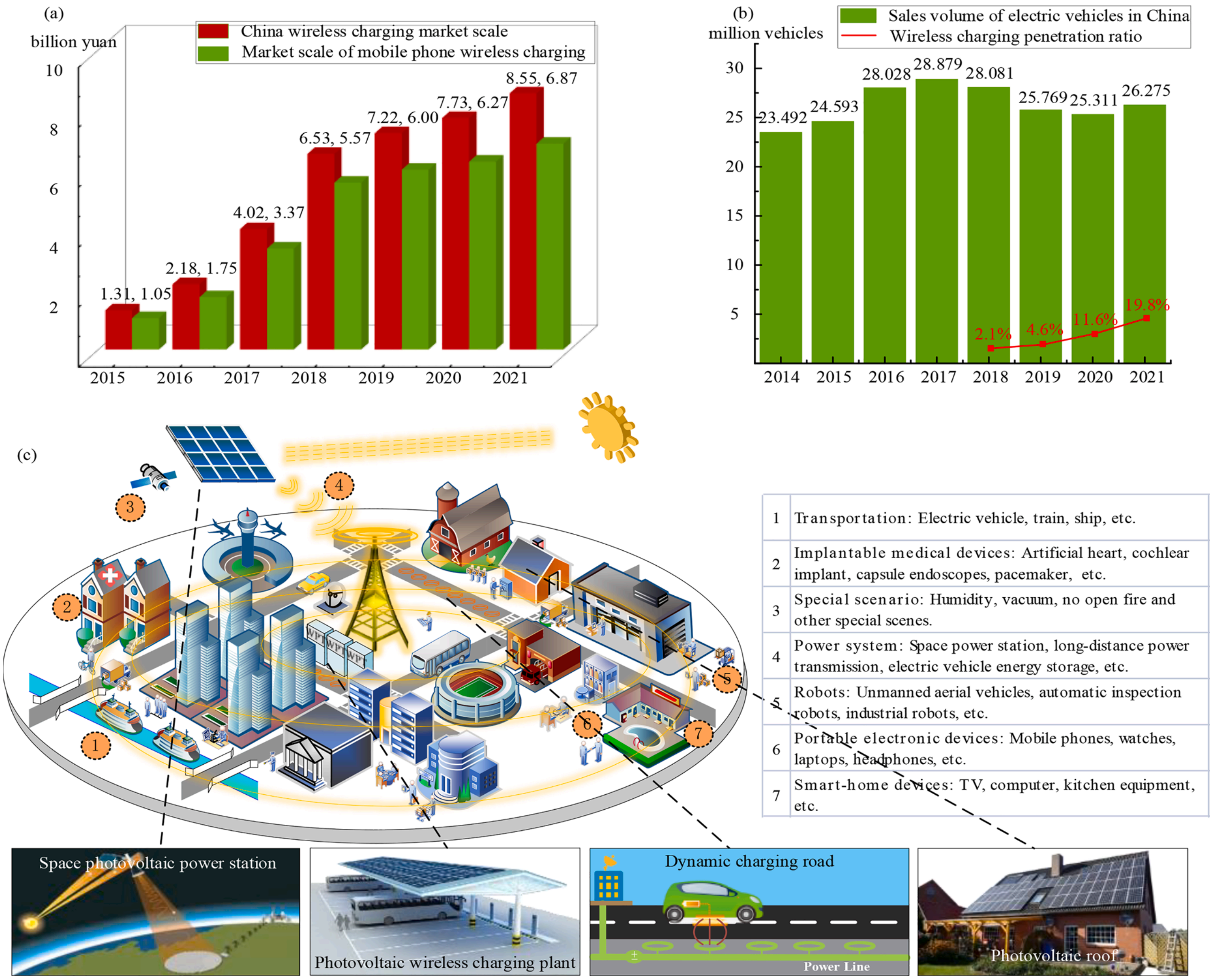


Fig. 4. Marketisation of WPT technology: (a) China's wireless charging market scale and mobile phone wireless charging market scale, (b) sales volume of EVs in China and its wireless charging penetration and (c) WPT technology in human culture and its significant applications.

flexibility [70]. WPT allows portable electronics to use a wireless charging network at any place and any time [71]. Because Apple introduced an intelligent wireless-charging device in September 2017, WPT technology has been used in over 90 mobile phone models [72]. Wireless power consortium (WPC) research predicts that the global wireless charging market for wearable and smart devices will grow between 2017 and 2026 [73,74].

2) Smart home equipment: As the pace of smart-city construction quickens, people are paying increasing attention to smart houses [75]. The intellectualisation of televisions, kitchen appliances, light bulbs, domestic robots for cleaning floors and other equipment makes it difficult for wired charging to meet the convenience demands of individuals regarding smart goods [76]. WPT can make the placement and power supply of intelligent appliances more flexible, practical and humanised. Xiaomi's space-separation charging method, available as of 2021, is capable of 5-watt long-distance charging for many devices within a few-meter radius [77].

3) Implantable medical devices: Increasingly, electronic equipment, such as artificial hearts, cochlear implants, wireless capsules and intestinal robots, are being utilized in medical therapy to compensate for the faults of human organs as medical research and technology advance [78]. However, the power supply issue regarding these implantable medical devices has become the most significant barrier to their use. Whether *in vivo* or *in vitro* batteries are utilised for power supply, patients may be exposed to the risk and discomfort of surgery or infection [79]. The WPT non-contact power-supply method can successfully address the issue of patients undergoing surgery in terms of changing batteries for energy storage, and implantable electronic devices can be charged in a painless, secure and dependable manner [80].

4) Robots: With the advancement of science and technology, UAVs, inspection robots, industrial robots and other types of robots have been researched in an effort to replace humans in dangerous, demanding and repetitive heavy labour [81]. Charging is the most common method of powering robots. However, the connected charging option burdens the robot significantly [82]. Frequent plug-in charging has a significant impact on the performance of a robot, as well as its working time and efficiency. WPT can effectively increase a robot's operating distance and working time, as well as ensuring its continuous task fulfilment [83].

5) Transportation: The energy crisis and the quickening pace of the energy transition have motivated nations across the world to vigorously develop and commercialise electric-powered vehicles [84]. In urban areas, automobiles, buses, industrial transport vehicles and railway vehicles are rapidly being replaced by electric locomotives, and the charging mechanism of electric locomotive batteries is one of the most significant factors impeding their rapid development [85]. The cable-charging method not only occupies a considerable amount of urban territory but also affects convenience and mobility due to its lengthy charging time and fixed-point charging queues. WPT can significantly

Table 2
Seven main WPT main application scenarios.

Application scope	Typical applications	Main technologies	Examples
Portable electronic devices	Portable computers, mobile phones, digital cameras, wireless mice, Bluetooth headsets, etc.	MCI-WPT, MCR-WPT, MPT.	S.Nandakumar of India has built a wireless power transmission technology for portable devices and established a battery management system based on the IoT to monitor the voltage, temperature, and charging status of batteries [111]. China's Li Yanjun et al. put forward a greedy heuristic and PSO-based solution test to wirelessly charge users' wearable devices in two-dimensional areas [112].
Smart-home devices	Televisions, kitchen appliances, vacuum cleaners, illumination bulbs, home robots, etc.	MCI-WPT, MCR-WPT, MPT.	Wool Lee of the United States proposed an efficient multi-scale WPT system based on metamaterials and applied it to smart homes [113]. Zahra Katbay of the United States integrates WPT technology with IoT -enabled intelligent houses and offers a reverse Tx array that may be used to power several static or dynamic household equipment [114].
Implantable medical devices	Cardiac pacemakers, artificial hearts, cochlear implants, wireless capsules, intestinal robots, etc.	MCI-WPT, MCR-WPT, MPT.	Tommaso Campi of Italy has designed an implantable WPT power supply system that can supply energy to various devices [115]. Mengyi Village in China proposed a wireless power transmission system with two parallel opposed coils, which can improve the low-power transmission efficiency and power transmission stability of capsule robots or other implantable medical devices [116].
Robots	UAVs, inspection robots, industrial robots, etc.	MCI-WPT, MCR-WPT, MPT.	Eun S. Lee from South Korea proposes a series of segmented wireless charging methods that increase the transportation robot's adaptability and enable it to do its efficient continuous transportation work [117]. Gong Wenlan et al. of China designed a coupling mechanism with a switchable topological structure, which simplified the wireless charging system of robots and realized two-phase constant current and constant voltage charging [118].
Transportation	EVs, electric buses, industrial transport vehicles, railway vehicles, etc.	MCI-WPT, MCR-WPT.	Brandon Regensburg of Cornell University devised a kilowatt class air gap CPT system with a specific matching network for wireless charging of EV, which may achieve high power transmission density and high efficiency [119]. The Korea Railway Research Institute's ES Lee created a WPT system for a pre-charging circuit of SST in railway vehicles [120]. Iran's ArmanFathollahi proposed an electric truck model with a dynamic WPT positioning route, which can be used in multi-warehouse and multi-product delivery supply chains [121].
Power transmission	The space power station, tesla tower, Yagi-Uda antenna, etc.	MPT, OPT.	The space solar power plant proposed by Dr. Peter Glaser of the United States collects solar energy in space and sends it to the ground by microwave or laser for conversion into electrical energy [97]. Japan's Shuichi Obayashi invented a UAV inductive charging device for overhead transmission line inspection [122].
Special scenario	Space, undersea, mines, warehouses, factories, etc.	MCI-WPT, MCR-WPT MPT, OPT.	Lin Chi et al. of China first proposed the concept of the underwater wireless rechargeable sensor network and developed a series of charging schemes for a three-dimensional underwater environment [123]. Wangxin et al. of China proposed a new WPT with a double-layer parallel coil model, which can be used to provide remote power supply for electronic equipment on rotating machinery such as helicopters and aero engines [124].

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Table 2 (*continued*)

Application scope	Typical applications	Main technologies	Examples
			MohitAngurala of India uses multiple nodes WPT to overcome energy-related problems in wireless sensor networks under medical and industrial detection [125].

reduce the charging time for electric locomotives, lower the vehicle's total weight and cost and increase transit flexibility [86].

6) Power transmission (WPT mode)**:** The building of power lines limits the power-transmission distance and power-supply range, and high-voltage power-transmission lines can pose safety risks regarding urban power consumption [87]. MPT, OPT and other far-field WPT methods can be widely used in power generation, transmission, transformation and consumption due to their advantages in terms of long-distance power transmission [88,89]. They can provide long-distance power transmission to equipment in cities and effectively avoid the problems posed by the difficult installation and maintenance of power lines and a lack of power supply in remote areas, including isolated islands [90].

7) Special scene space: Sliding friction and metal conductor charging technologies have certain disadvantages, such as the difficulty of in line installation, sliding wear, the limited working area of the equipment, contact between metal wires and sparks, carbon deposits and the exposure of conductors to special working environments, such as the seabed, mines, warehouses and factories [91]. These disadvantages increase the safety risks for power equipment and personnel working in harsh environments [92]. WPT technology can ensure the power supply for electrical equipment in the above-mentioned special settings, making the work safer and more efficient [93].

4.2. WPT's role in urban infrastructure construction combined with renewable energy

The most alluring combination for use in the building of a wireless-power city is WPT technology, renewable energy and urban infrastructure. WPT technology can be used to promote the application of renewable energy in urban power grids and the integration of dispersed energy resources and controllable loads, such as wind turbines, photovoltaics, diesel generators and energy-storage systems, in a microgrid infrastructure [94], especially solar-energy applications [95]. In this section, the combination of WPT with renewable energy and urban infrastructure construction is introduced [96], and the relevant research applications are compared and analysed in Table 3.

4.2.1. Promoting the application of renewable energy

WPT is conducive to accelerating the application of renewable energy in urban construction; relieving the crisis and pressure resulting from accelerated energy consumption and promoting the construction of space photovoltaic power stations and space photovoltaic transmission systems, distributed photovoltaic power stations and urban photovoltaic roofs.

1) Space photovoltaic power station: In 1968, Glaser proposed the idea of a solar power satellite (SPS), and nations throughout the world began research on space photovoltaic power systems [97]. WPT makes it technically feasible to transport the electrical energy produced by a space photovoltaic power station to a ground grid in order to supply customers with electricity. MPT and OPT are the two forms of WPT being employed in space photovoltaic power-transmission systems [98,99].

Table 3
Main WPT applications in wireless-power-city construction.

Application scope in the city	Typical applications	Main technologies	Examples
Renewable energy	Space photovoltaic power station	MPT, OPT	Lasers or microwaves can be used to transmit electric energy from space to the earth [126]. The photoelectric conversion efficiency of the space power station is much higher than that of the ground solar power station because there is no atmosphere, diurnal variation, and other influencing factors [127].
	Renewable energy wireless charging station	MCI-WPT, MCR-WPT, MPT	Photovoltaic systems can be integrated into EVs and charging stations to realize the efficient utilization of renewable energy [128]. A renewable energy grid-connected dynamic wireless charging system integrating photovoltaic and wind energy is proposed, and the charging cost is greatly reduced [129].
	Photovoltaic roof	MCI-WPT, MCR-WPT, MPT	Solar energy could be used to supply a significant portion of the energy needs of EVs by installing photovoltaic equipment on their roofs [130]. A systematic modelling framework was developed to study photovoltaic roofs with different roof availability and to propose peak shaving strategies to reduce peak loads and carbon emissions [131].
Infrastructure	EVs, electric bicycles, electric buses, etc.	MCI-WPT, MCR-WPT, EC-WPT	The methods and technologies for EV wireless charging are reviewed [132]. The parameters of the primary and the secondary coils were selected and optimized by using COMSOL Multiphysics finite element software [133]. The WPT technology in EV applications is evaluated from two perspectives of technology and sustainability [134].
	UAV, sensor networks, and other industrial robots	MCI-WPT, MCR-WPT, MPT, OPT	The feasibility evaluation of the laser-based wireless power transmission

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Table 3 (*continued*)

Application scope in the city	Typical applications	Main technologies	Examples
	Wireless charging station, wireless charging road, etc.	MCI-WPT, MCR-WPT	(WPT) mechanism in UAV applications is theoretically studied to increase its working time [135]. The persistent task of charging the batteries of unmanned intervention drone formations is achieved by supplying power through on-site wind turbines to a charging station employing resonant WPT [136]. [137] discussed the advantages of building roads and station charging with the help of solar panels. In [138], an innovative design of partially magnetized pavement is proposed, which improves the charging efficiency of wireless power transmission of EVs by 1.5% −13.3%.

2) Ground photovoltaic power station: The ground photovoltaic power station has become one of the ideal choices for energy transformation in many areas, and it is currently one of the most prevalent ways to use solar energy to generate electricity in cities [100]. Using MCI-WPT, MCR-WPT, MPT, and other technologies, photovoltaic and wireless charging technologies for EVs can be coupled [101].

3) Photovoltaic roof: With the acceleration of urbanization, population increases will lead to a land shortage, and the importance of large-scale photovoltaic power stations will be emphasised. People are keenly interested in photovoltaic roof power generation [102,103]. Utilising MCI-WPT, MCR-WPT, MPT, and other technologies is beneficial in terms of security and flexibility and resolving the conflicts involved in photovoltaic-power-station land usage.

4.2.2. *Accelerating the construction of urban infrastructure*

WPT facilitates flexible energy acquisition for electric equipment, such as new-energy EVs and intelligent drones, as well as the creation and implementation of charging infrastructure, such as charging stations and charging highways. It plays an essential role in enhancing quality of life for inhabitants and reducing urban transportation congestion.

1) Electric vehicles: Electric transportation has significant energy and environmental sustainability benefits. Electrical charging safety is the most urgent issue given the expansion of large-scale green EVs, electric buses and industrial electric locomotives. WPT contributes to the resolution of the issue of safety and flexible energy extraction for electric cars [104,105].

2) Intelligent devices: With the development of smart cities and the improvement of living standards, the applications of intelligent devices, such as UAVs, sensor networks and other industrial robots, can be found everywhere. However, like EVs, their applications are also limited by battery capacity and endurance, making it difficult for them to complete homework tasks continuously and efficiently [106]. WPT offers a flexible charging mode for intelligent devices and guarantees their continuous, efficient and stable operation [107].

3) Charging road: Due to the limits of battery capacity, cruising range is one of the most significant obstacles to the development of green EVs, electric buses and industrial electric locomotives [108]. Electrified roadways with WPT technology can supply EVs with power continually while maintaining their mobility [109,110]. This alleviates people's concerns about the long charging times and the cruising range of automobiles, as well as safety issues when charging in inclement weather, and it provides a new research direction regarding the development of charging infrastructure.

5. Discussion

5.1. *Sustainable benefits*

In this section, we will further analyse and discuss the sustainable value and significance of WPT technology in terms of building more sustainable cities that have more renewable energy based on energy policy, environmental impact and the social economy.

5.1.1. *Energy policy analysis*

WPT technology may speed up the electrification process and the achievement of the UN's sustainable development goals by boosting renewable energy use and city building. The 2022 sustainable development target report prioritises 'affordable clean energy', 'sustainable cities and communities' and 'climate action' [139]. WPT technology can boost renewable energy deployment by building space photovoltaic power plants, transmission systems, distributed power plants and urban photovoltaic rooftops [140].

Cities are where people live, work and produce greenhouse emissions. Sustainable cities and communities will better address population increase and climate change. WPT's efficient mix of technology, renewable energy and urban infrastructure has inspired new ideas for sustainable cities and communities [141]. The use of WPT technology in new-energy EVs, portable electronic devices and charging roads improves public transportation, residents' quality of life, the use of renewable energy to create a wireless city and smart cities' sustainability. WPT aids in creating 'sustainable cities and communities' [142].

Fossil fuels are now contributing to the release of the most greenhouse gas emissions ever, intensifying the greenhouse effect and causing climate disasters, such as severe heat, cold, droughts, and floods, which have a major impact on society. Affordable renewable clean energy must be deployed more quickly. WPT technology promotes the use of renewable energy in urban construction and power systems [143]. We can reduce the climate catastrophe and the pressure generated by rapid fossil energy consumption through implementing 'Climate Action', the Paris Agreement, and other renewable-energy development goals.

Thus, the use of wireless-power-transfer technology in sustainable-city construction benefits wireless-power cities and renewable energy development. The government could offer incentives and subsidies to encourage energy and electricity firms to build WPT technology in sustainable cities. Energy policy guidance can help enterprises better use their advanced technology and management experience, reduce the cost of technology investment projects, improve their core competitiveness, popularise WPT technology and renewable energy, promote renewable energy consumption and sustainable city development, and realise 'affordable clean energy'. It also helps to achieve 'affordable clean energy', 'sustainable cities and communities', and 'climate action' goals.

5.1.2. *Environmental effect analysis*

The use of wireless-transmission technology in sustainable-city development can improve urban planning and construction. The deployment and use of wireless-transmission technology in sustainable-city construction will greatly reduce the materials, land, energy and emissions needed to build an electric-energy-transmission system, including cables, poles and transmission towers [144]. This can reduce the area occupied by many urban-energy-system infrastructures, improve the utilisation of effective land resources in urban construction, optimise a city's spatial layout and planning and reduce the consumption of materials and energy during infrastructure construction and the potential pollution of urban land and water resources by laying cables.

Accelerating the use of WPT technology in sustainable urban construction will help upgrade urban intelligent energy systems; realise urban energy informatization, intelligent management and monitoring [145]; ensure an efficient and stable urban energy supply; reduce unnecessary energy consumption and waste; lower urban construction carbon emissions [146] and promote sustainable urban low-carbon economic development [147]. WPT and renewable energy will hopefully accelerate the development of new energy-related technologies such as EVs; promote sustainable-city construction, green innovation and intelligence and promote environmental optimisation in urban construction.

5.1.3. Social-economy analysis

WPT technology promotes sustainable-city construction by converting renewable energy sources, such as photovoltaic sources, into electrical energy resources with resource utilisation value through infrastructure such as photovoltaic charging stations and roofs, as well as supplying energy to EVs and other electrical equipment. Widely deploying charging infrastructure for renewable energy sources meets the growing energy demand of cities and the demands of urban residents for urban energy services, effectively reduces the use of fossil fuels in urban economic production and construction, relieves the pressure of primary energy consumption in urban construction and alleviates the energy crisis caused by energy poverty [148]. Increased renewable energy consumption will also reduce greenhouse gas production and emissions in urban construction, which reduces climate change and adds social value to sustainable-city construction [149]. Therefore, the promotion of renewable energy by WPT technology in sustainable city construction will achieve a double harvest of social and economic benefits for the construction of sustainable cities, and the sustainability of renewable energy will also bring the sustainable growth of social and economic benefits to the construction of sustainable cities.

As an emerging intelligent technology, WPT can simultaneously transmit information and energy by combining wireless sensor networks and wireless communication technology [150]; promote intelligent and informative urban smart-energy systems [151]; enhance smart grid energy dispatching, utilisation and power supply quality and promote the sustainable development of the economy in sustainable-city construction [152]. From the perspective of industrial value, renewable energy input in sustainable-city construction is sustainable, cheaper than primary energy consumption and friendlier to the environment and air. Specifically, it can reduce greenhouse gas emissions and comprehensive environmental management costs. WPT technology will also boost new energy businesses, such as EVs, and provide urban-development jobs [153].

5.2. Main challenges

Currently, WPT technology is immature. Breakthroughs in the technology itself are needed so as to achieve space power stations, ultra-long-distance transmission and high-power transmission. Numerous advancements can be made in circuit network topology [154], coupling mechanisms [155], electromagnetic shielding [156], control strategies [157], signal transmission [158], electromagnetic compatibility [159], frequency band occupation [160] and technical standards [161]. However, in this age of important worldwide development, science, technology, information and energy have changed drastically [162,163]. WPT faces opportunities and challenges in terms of renewable energy, enormous intelligent devices, a variety of new-energy EVs, large-scale electric bicycles and other applications. Thus, three important application issues are highlighted in terms of accelerating WPT research and implementation in sustainable cities:

Impact on a new power system: Massive wireless charging infrastructure and the ubiquitous charging and discharging of EVs will have a substantial effect on the electrical grid [164]. Continuous load variation, asymmetric load-reactive power demands and harmonic pollution will be highlighted.

Urban safety and human health problems: The implementation of WPT on a wide scale in many settings, such as urban traffic, domestic life and industrial production, will pose potential risks to urban safety and public health [165,166]. Further emphasis will be placed on issues such as continuous high-frequency electric and magnetic fields, continuous electromagnetic-field-radiation leakage, eddy current loss and particularly the destructive scattering of microwave and laser light. Consequently, electromagnetic safety and energy leakage regarding WPT represent the obstacles to its widespread deployment in urban industrialisation.

Energy coordination and management in the wireless network: WPT is capable of one-to-one, one-to-many and many-to-many energy transfer, which is one of its defining properties. The wireless energy acquisition of numerous portable electronic gadgets, EVs, wireless sensor networks and other electric loads will be very unpredictable, as will the grid-connected power generation of renewable energy sources such as wind energy and solar energy. The two-way matching of uncertain power generation and load poses significant difficulties for urban energy management [167]. Realising the energy coordination and management of the WPT charging network, as well as coordinating the energy supply and energy extraction of renewable energy and electric load on demand, is, therefore, one of the necessary means of realizing the widespread application of this technology in urban areas [168].

5.3. Future directions

To accelerate the incorporation of WPT into our social production and daily routines, we must continue to invest in research and development. Beyond that, here are six intriguing avenues that merit further investigation:

Integration of emerging technologies: Emerging technologies, such as 5G, AI, peripheral computing, IoT, and intelligent algorithms, have the potential to open new frontiers for WPT technology [169]. We must continue to investigate power transfer and wireless charging innovations for a variety of intelligent devices.

Acceleration of wireless-power city construction: The installation and construction of wireless charging base stations, charging piles and charging roadways can revolutionise how urban transportation and industrial machines are powered [170]. Optimal site selection, capacity determination and power distribution will be of paramount importance in this endeavour.

Wireless power bidirectional transmission technology: Bidirectional WPT can transform EVs into essential elements of urban power grids and even facilitate optimal power-system dispatching [171]. Therefore, research into this technology is essential.

Embrace renewable energy: To combat resource depletion and the greenhouse effect, we must implement renewable energy sources as soon as possible [172]. WPT technology can play a significant role in advancing this trend. For example, solar-powered photovoltaic wireless charging stations and optimised urban power infrastructure enhance overall efficiency.

Harmony with a new power system: Integrating a high proportion of renewable energy into the power infrastructure presents a number of obstacles, including an unstable power supply and high costs. Similarly, large wireless charging devices and intelligent electric devices must contend with weighty load requirements [173]. Using grid-interactive building networks and intelligent software solutions, we must promote harmony between WPT technology and new power systems in order to ensure a sustainable energy future.

Advancement of global accessibility: Finally, it will be crucial to guarantee the global accessibility and widespread implementation of this technology, including in developing regions. Attaining this objective will necessitate concerted efforts to reduce costs, enhance overall deployment and improve the end-user experience through user-friendly interfaces and security protocols.

We can unlock the full potential of WPT technology and drive a more sustainable, equitable and technologically advanced future for our cities, and beyond, by pursuing these innovative initiatives.

6. Conclusion

In recent decades, global urbanisation has developed rapidly. However, because of the world's energy and carbon emissions, rapid urbanisation has created several energy, socio-economic and environmental issues, and the development of renewable energy and sustainable city construction is imperative. In recent years, research on WPT technology has advanced significantly and is likely to become the predominant charging method in the future. This paper reviews 161,425 papers published in the last 30 years about WPT technology, analyses the historical process of WPT technology-development from the perspective of urban-construction development and proposes a new concept of the wireless-energy green city by combining WPT technology with sustainable energy and urban infrastructure construction, thereby making smart-city construction safer, lower in carbon emissions and more sustainable. The primary findings and contributions of this study are as follows:

- WPT technologies can be categorised primarily into six groups, specifically MCI-WPT, MCR-WPT, EC-WPT, MPT, OPT, and UPT. Six varieties of WPT can be implemented in numerous contexts, including implantable medical devices, urban construction, wireless sensing networks and EVs. This paper analyses and describes the characteristics of these six WPT technologies in terms of their transmission medium, operating frequency, transmission distance, advantages and disadvantages and demonstrates the viability of the proposed scheme.
- A new lifecycle from research to application is proposed, consisting of three stages: laboratory testing, simulation and actual testing and application testing. In this study, a 50 kW inductive transmission power electronics experimental platform based on a Speedgoat controller can reach about 90% efficiency at a fraction of the cost of the original platform. The application of this method will result in the development of large-scale, high-power apparatus that is safe, efficient, and inexpensive.
- WPT technology can be applied to sustainable urban development in seven primary areas, including portable devices, intelligent home appliances, implantable medical devices, transportation, robotics, power transmission, and space. The review addresses the major aspects of sustainable urban construction, and its findings can provide applicability scenarios for the research proposals and methods presented in this paper.
- A new application is proposed for the effective incorporation of WPT technology with urban infrastructure and renewable energy. The study concludes that WPT technology can not only promote the construction of new energy facilities, such as photovoltaic power plants, and accelerate the development of renewable energy in cities but also accelerate the development and widespread adoption of EVs and charging roadways. This study offers a novel approach to the design of intelligent and sustainable cities.
- WPT technology can promote a sustainable urban economy and renewable energy industry; accelerate the upgrading of a smart energy system; aid in the development of a green, low-carbon city; increase new-energy jobs and initiatives and promote social harmony. The sustainable advantages of WPT technology in terms of the energy-related, environmental and socioeconomic aspects of urban construction will facilitate its further incorporation into urban development and construction.
- Current obstacles to WPT technology include the impact on new power systems, urban safety and human health issues, as well as energy coordination and management within wireless networks. Various renewable energy, EV and charging-road implementations will face these obstacles, as demonstrated by the research presented in this paper. The challenges presented will also further accelerate the research and implementation of WPT in sustainable cities.
- The six future paths for sustainable wireless are as follows: the integration of emerging technologies, the acceleration of wireless-power-city building, wireless power bidirectional transmission technologies, embracing renewable energy, harmony with the new power system and the promotion of global accessibility. The innovative initiatives proposed in this study provide researchers with future directions and perspectives that will facilitate the accelerated incorporation of WPT technology into society.

This study proposes that the integration of WPT technology, renewable energy and infrastructure in wireless cities has significant application potential. However, the scope of this study is limited to the integration of WPT technology with novel photovoltaic energy sources in urban infrastructure, such as photovoltaic power stations, photovoltaic rooftops and charging roads. Future researchers can contemplate expanding the integration of WPT technology to include additional renewable energy sources and emerging technologies in additional sectors, such as wind and geothermal energy.

In conclusion, this research provides an innovative development orientation for the integration of WPT technology and sustainable urban development and broadens our cities' and the planet's horizon of possibility. This research contributes to the achievement of sustainable development objectives, such as 'affordable clean energy', 'sustainable cities and communities' and 'climate action'. Future researchers can use the new concept of the wireless-energy city proposed in this work and new applications of WPT technology, combined with renewable energy and urban facilities, as a foundation for research that will contribute to the development of a more technologically advanced, environmentally friendly and sustainable smart city.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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