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Review

A New Electricity Infrastructure for Fostering Urban Sustainability: Challenges and Emerging Trends

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Abstract: The energy transition and sustainability are the critical challenges of our time, and cities are at the forefront of this transformation. As key players, these urban centers are pioneering innovative strategies to reduce carbon emissions, enhance energy efficiency, and promote renewable energy sources. Central to the transition is the role of electricity, which acts as a cornerstone in the "cocktail" of sustainable solutions. The development of an efficient and resilient "Electricity City Grid" is essential to support this shift. This article explores the target functions and challenges associated with designing and operating the Smart Electricity City Grid of the future. It delves into the infrastructural costs required for this transition and examines the economic and technical hurdles that must be overcome. Finally, the article looks ahead to the future of research in this field, highlighting the areas that will be crucial for the continued evolution and success of smart urban grids. Through this comprehensive analysis, we aim to suggest a roadmap for cities striving to achieve sustainability through advanced electrical infrastructure.

Keywords: electricity; infrastructure; sustainability; energy transition; cities

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1. Cities as the Key Players in the Transition Toward Sustainability

Cities are hubs of innovation, culture, and socio-economic opportunities, attracting people and investment and being in constant evolution. Nowadays, two of the main drivers for this evolution are the twin transitions, digital and green. At the same time, cities face many challenges, such as environmental degradation, adaptation to climate change, natural disasters, social inequality, demographic changes, and urban poverty. To address these challenges, cities need to adopt new approaches to urban planning and the management of the resources, as well as foster positive links with rural and peri-urban areas.

The United Nations has recognized the importance of cities for achieving the Sustainable Development Goals (SDGs), especially Goal 11, which aims to make cities and human settlements inclusive, safe, resilient, and sustainable [1]. The UN also calls for global actions to turn cities into "engines of sustainable development" by promoting resource efficiency, "green" infrastructures, low-carbon transport, and cultural and natural heritage preservation [2]. Moreover, the World Economic Forum highlights how cities can innovate to tackle climate change, e.g., by implementing Circular Economy models, Smart Grids (SGs), autonomous and non-autonomous Microgrids (MGs), renewable energy source (RES) integration, and Green Mobility solutions [3].

Cities are home to more than half of the world's population, and this share is expected to increase to 68% by 2050 [4]. As a consequence, cities consume a large amount of energy and produce a large share of CO_2 and pollutant emissions. According to a study by the International Energy Agency (IEA), cities accounted for about 75% of the final global energy consumption and 70% of energy-related CO_2 emissions in 2016 [5,6]. Moreover, a recent analysis by researchers at the University of Colorado Boulder found that just 25 mega-cities, mostly in Asia, produced 52% of the total urban greenhouse gas emissions in 2019 [7]. The study also revealed that cities in Europe, Australia, and the United States of America (USA) had significantly higher per capita emissions than cities in developing areas.

Also, Europe is deeply concerned with the strategic role of cities. It is worth to cite the "EU Mission: Climate-Neutral and Smart Cities" [8], that is, the European Mission for 100 climate-neutral and smart cities by 2030, also known as the Cities Mission. On 28 April 2022, the European Commission announced that 112 cities have been selected to take part in the Mission.

Some comparative figures for different countries are as follows [7]:

- China: the country with the largest urban population (831 million) and the largest urban CO_2 emissions (3.9 gigatons) in 2019; Beijing, Shanghai, and Tianjin were among the top 25 mega-cities with the highest emissions.
- India: the country with the second-largest urban population (461 million) and the fourth-largest urban CO_2 emissions (0.7 gigatons) in 2019; Delhi and Mumbai were among the top 25 mega-cities with the highest emissions.
- USA: the country with the third-largest urban population (274 million) and the second-largest urban CO_2 emissions (1.5 gigatons) in 2019; New York and Los Angeles were among the top 25 mega-cities with the highest emissions.
- Brazil: the country with the fifth-largest urban population (181 million) and the ninth-largest urban CO_2 emissions (0.2 gigatons) in 2019; Rio de Janeiro and Sao Paulo were among the top 25 mega-cities with the highest emissions.
- France: the country with the 21st-largest urban population (51 million) and the 18th-largest urban CO_2 emissions (0.1 gigatons) in 2019; Paris was among the top 25 mega-cities with the highest emissions.

Urban Energy Systems [9] are a major issue for cities, as they are rapidly evolving due to the pressure put on them by climate neutrality objectives, environmental pollution restrictions, technological changes, and the open possibilities from the extended digitalization of the same energy systems and the related markets. Big cities face the problem of connecting the changes in the energy systems with the rest of urban planning: mainly transport, waste, and building stock and the variations in the evolving profiles of industrial installations, services, social structures, and green areas in the city. Small-to-medium-size cities have to handle the limitations of their resources, both monetary and human. The shape and form that energy systems will take will be a crucial determinant of the cities of the future, as energy has a direct effect on health, on how to move around, on which activities can be deployed where, and, definitively, on the quality of life.

Based on these facts, one can defend that there is a special demand for reflecting on energy and sustainability in cities and especially on the intensification in the use of electricity as the more efficient energy carrier.

In the following section, we will discuss why electricity will play a central role in cities, as it will expedite their decarbonization and the abatement of pollution and will enable the more efficient use of energy.

Energy production and consumption in cities can be divided into local energy and imported energy. Local energy refers to the energy that is generated within the city boundaries, typically solar, wind, hydro, biomass, geothermal, or waste to energy. Imported energy refers to the energy that is supplied from outside the city, typically from coal, oil, gas, nuclear, or large-scale hydropower [10].

Traditionally, most cities have relied heavily on imported energy, especially fossil fuels, to meet their energy demand. This makes them passive consumers of energy, dependent on external sources and vulnerable to price fluctuations, supply disruptions, and environmental impacts. However, in the future, the role of local energy in cities is expected to increase as cities aim to become more active producers and managers of energy, enhancing their Energy Security, affordability, and sustainability. By 2040, solar and wind together are expected to contribute the largest share of the world's energy mix, according to a report by

McKinsey [11]. The share of local energy in cities varies depending on the availability of resources, the level of policy support, and the degree of public awareness and participation. Changes in local energy will affect the whole lifecycle: from generation to distribution to end use. Some examples of cities with high shares of local energy are Reykjavik (Iceland), which uses 100% geothermal and hydro power; Copenhagen (Denmark), which aims to become the world's first carbon-neutral capital by 2025; and Curitiba (Brazil), which has a high penetration of biofuels and waste to energy [12–14].

2. The "Cocktail" of the Transition and the Role of Electricity

Energy transition refers to the process of shifting from fossil fuels to low-carbon and renewable sources of energy in order to mitigate climate change and achieve the goals of the Paris Agreement [11].

The transition "cocktail" refers to the mix of energy commodities that will be used to meet the energy demand in different sectors and regions, depending on the availability, cost, and environmental impact of each commodity and, partially, also on the historical legacy of humanity's energy transitions [15,16].

The main energy commodities that are considered for the transition to obtain an ideal mix are gas, hydrogen, and electricity due to their characteristics, as summarized below [17]:

- Gas is the most widely used fossil fuel in the world, and it has a lower carbon intensity than coal and oil. However, gas still emits greenhouse gases and air pollutants, and its extraction and transportation can have negative environmental and social impacts. Therefore, gas is seen as a transitional fuel that can help reduce emissions in the short term, but it will need to be replaced by cleaner alternatives in the long term.
- Hydrogen is a versatile and clean energy carrier that can be used for various applications, such as heating, transport, industry, and power generation. Hydrogen can be produced from different sources, such as natural gas, biomass, or water, using different methods, such as steam reforming, gasification, or electrolysis. Depending on the source and method of production, hydrogen can be classified according to different colors and carbon footprints, ranging from grey (high carbon) to green (zero carbon). Hydrogen has the potential to decarbonize hard-to-abate sectors, such as steel, cement, and aviation, and support the integration of variable RESs, such as solar and wind, into the energy system.
- Electricity is the most efficient and convenient form of energy, and it can be generated from various sources, such as fossil fuels, nuclear, or renewables. Electricity can also be stored in batteries, pumped hydro, or using other technologies and transmitted and distributed through "grids" and "microgrids". Electricity can power various end uses, such as lighting, appliances, electric vehicles, and heat pumps. Electricity has the potential to decarbonize most of the final energy uses, especially in the building and transport sectors, and enable the digitalization and electrification of the economy.

It is also interesting to highlight that the transition can have either a multi-commodity or a mono-commodity perspective, as described in the following points:

- A multi-commodity perspective recognizes the diversity and complementarity of different energy commodities and aims to optimize the use of each commodity according to its comparative advantages and disadvantages, as well as the specific needs and preferences of each sector and region. A multi-commodity perspective can enhance the flexibility, resilience, and security of the energy system, as well as the social acceptance and affordability of the energy transition.
- A mono-commodity perspective focuses on the dominance and superiority of one energy commodity and aims to replace all other commodities with the preferred one as much as possible. A mono-commodity perspective can simplify the design, operation, and regulation of the energy system, as well as the coordination and integration of different actors and stakeholders. A mono-commodity perspective can also accelerate

the deployment and innovation of the preferred energy commodity and reduce the locked-in and stranded assets of the less preferred ones.

Electricity plays a central role in the framework of the energy transition by addressing the "Energy Trilemma" (Figure 1), which consists of three interlinked goals—Energy Security, Energy Equity, and Environmental Sustainability—as defined by the International Energy Agency [17].

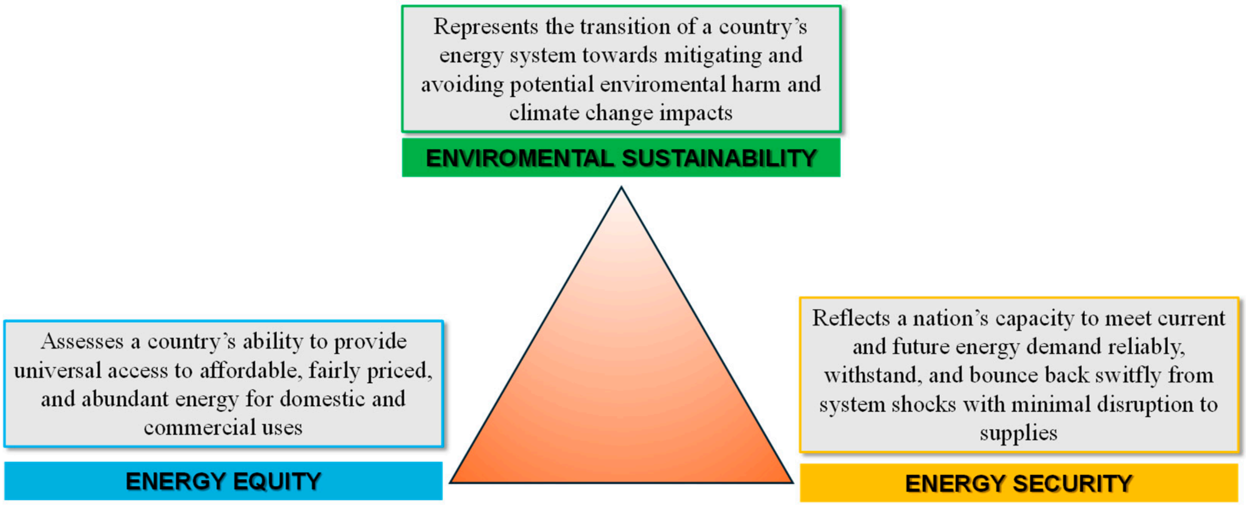

Figure 1. The Energy Trilemma [17].

In the following figure, some concepts that are useful to highlight how electricity helps to address each aspect of the Energy Trilemma are remarked:

Electricity supports Energy Security by enabling diverse energy sources, including RESs and nuclear energy, which can reduce dependence on fossil fuel imports and stabilize energy supplies [18]. Advanced grid management systems, battery storage, and demand-side management are essential in enhancing Energy Security through electricity. These technologies allow for reliable energy distribution, even when the supply varies due to intermittent RESs.

Electricity generated from RESs is becoming increasingly cost competitive due to technological advancements, scale economies, and policy support. This trend is helping to make sustainable electricity more accessible, increasing Energy Equity [19]. Additionally, advancements in Smart Grid technology and demand-response systems can reduce overall costs by improving energy efficiency and load management.

Electricity generated from renewable sources minimizes greenhouse gas emissions compared to fossil fuel-based energy, improving Environmental Sustainability [20]. Integrating renewable energy with Smart Grids, energy storage, and efficient demand-side management allows the electrical grid to accommodate cleaner energy, thus improving sustainability. The electrification of sectors like transport and industry also contributes to reducing overall emissions by shifting away from direct fossil fuel use.

According to the above remarks, it is possible to conclude that electricity is the key-commodity for the transition [19–22]. It is characterized by an "Electricity Triangle":

1. Local energy production from RESs;
2. Electricity-based distribution for energy;
3. Electric final uses.

Local energy production refers to the generation of energy within the city boundaries, mainly using RESs or combined-heat-and-power (CHP) plants. RESs include solar, wind, hydro, biomass, geothermal, or waste to energy, while CHP plants produce both electricity and heat from a single fuel source, such as natural gas, biogas, or waste.

Some possible city generators based on RESs or CHP are rooftop solar panels, which can provide electricity and hot water for buildings, reducing the dependence on the grid and the emissions from fossil fuels; wind turbines, which can harness wind energy and convert it into electricity on a small scale (e.g., micro-wind turbines); hydroelectric plants, which can use the water flow from rivers, dams, or canals to generate electricity, either on a large scale (hydropower plants) or on a small scale (micro-hydro plants); biomass plants, which can use organic matter, such as wood, crops, or waste, to produce heat, electricity, or biofuels, either on a large scale (biomass power plants) or on a small scale (biomass boilers); geothermal plants, which can use the heat from the earth's crust to produce electricity or heat, either on a large scale (geothermal power plants) or on a small scale (geothermal heat pumps); waste-to-energy plants, which can use municipal solid waste, industrial waste, or sewage sludge to produce electricity, heat, or biogas, either on a large scale (waste-to-energy plants) or on a small scale (anaerobic digesters) [23]; and CHP plants, which can use natural gas, biogas, or waste to produce electricity and heat simultaneously, either on a large scale (district heating networks) or on a small scale (micro-CHP units). This variety of potential sources provides flexibility to the planning and management of electricity generation [24,25].

The electricity-based distribution of energy is certainly the more critical element, since it requires rethinking and redesigning the current electricity distribution networks; in other words, it requires a significant infrastructural upgrade. In fact, all future scenarios see important factors changing the local electricity networks, such as: power injections potentially present at all grid buses (Distributed Generation—DG), the installation of (new) concentrated loads, such as charging stations for electric vehicles (EVs), an increase in the load level (power demand), concentrated and distributed storage, and new types of electricity consumption [26]. In addition, in terms of the patterns along which the electricity is consumed, the consumers' power profile is changing due to both power injection from PVs, with a marked reduction in the peaks around noon, and the availability of storage that enables a general reshaping of the profile and the so-called demand-side management (DSM) [27].

The electrification of final uses refers to the shift from fossil commodities to electricity in the energy end uses for various sectors, such as heating, cooling, transport, lighting, and industrial heat [28,29]. Electrification increases energy efficiency, reduces energy costs, and lowers greenhouse gas (GHG) emissions. Some examples of electrification of final uses are as follows: Electric Indoor Climate Conditioning, achieved by using electric heat pumps, which can provide heating and cooling by transferring heat from a low-temperature source (such as air, water, or ground) to a high-temperature sink (such as the interior of a building), while, in addition, electric cooling can be achieved by using electric air conditioners, providing cool air and dehumidification by transferring heat from a high-temperature source (such as a building) to a low-temperature sink (such as air); Electric Transport can be achieved by using electric vehicles running on batteries, fuel cells, or hybrid systems and reducing the emissions and noise caused by internal combustion engines; efficient lighting can be achieved by using LED lamps, which can provide high-quality and energy-efficient lighting and can reduce the electricity consumption and heat generation from incandescent or fluorescent lamps; and industrial heat can be achieved by using electric furnaces, boilers, or heat pumps, which can provide high-temperature heat for various industrial processes, such as melting, drying, or distillation, and can reduce the emissions and waste from fossil fuels.

3. "Electricity City Grid": Target Functions and Challenges

In order to discuss the paradigm of an "Electricity City Grid" (ECG), it is worth to preliminary introduce some considerations on the relationship among the following elements: city, electricity, and sustainability.

Cities are densely populated and require substantial amounts of electricity to power homes, businesses, transportation, and infrastructure [30]. This high demand often leads to increased energy consumption and strain on power grids. To manage this demand efficiently, cities are increasingly adopting Smart Grids (this concept will be widely discussed in Section 4 considering various viewpoints). These grids use digital technology to monitor and manage electricity flow, reducing waste, improving reliability, and integrating RESs into their power systems [31]. This not only helps in reducing carbon emissions but also enhances Energy Security, keeping the focus on sustainability. In fact, one of the most relevant aspects of a sustainable transition is the decarbonization process, i.e., the transition to RESs as the key factor for reducing GHG emissions.

Cities play a significant role in this transition by implementing policies that promote the use of clean energy [32]. At the same time, improving energy efficiency in buildings and infrastructure can significantly reduce electricity consumption. This includes retrofitting buildings with energy-efficient technologies and promoting sustainable development. This process is supported by Innovative Technologies, like Smart Meters, Energy Storage Systems, electric vehicles for both private and public transportation, as well as green spaces, which contributes to a more sustainable urban energy landscape, and, as a result, to sustainable urban planning [32,33]. That is why more effective urban planning can reduce energy consumption and enhance sustainability.

Additionally, cities must learn how to adapt themselves to climate changes by building resilient infrastructure that can withstand extreme weather events [34,35]. This includes investing in sustainable water management, waste management, and energy systems.

Local governments play a crucial role in implementing policies that promote sustainability [30,36,37]. This includes setting targets for renewable energy use, enforcing building codes, and incentivizing green technologies.

It is possible to conclude that the synergy between urban environments, electricity, and sustainability is essential for creating livable, resilient, and eco-friendly cities.

The concept of an ECG refers to the network of power lines, substations, transformers, and meters that deliver electricity from the generators to the consumers within a city.

The ECG plays a crucial role as the carrier and enabler of local energy, since it can integrate the local energy production from RESs or CHP plants into the grid, and balances the supply and demand of electricity; it facilitates the electrification of final uses in various sectors and enables the demand response and load management of electricity; it supports the development of an "active city", which can produce and consume its own energy, and participates in the energy market and grid services [38].

The following target functions must be implemented to allow the Electricity City Grid to perform its crucial role for the city's sustainability:

- Withdrawing the electricity produced by local generators, such as RESs or CHP plants, which can range from a small to medium scale, i.e., from kilowatts to tens of megawatts, as described in the previous section: This target function is important for enhancing the local energy production and reducing the dependence on imported energy, as well as for increasing the energy efficiency and lowering the emissions from fossil fuels. Some of the challenges faced by this function are the variability and intermittency of some RESs, the need for adequate grid connection and integration, and the potential for grid congestion and voltage fluctuations.
- Supplying electricity to all the loads in the framework of the electrification of the final uses, in particular heating, cooling, transport, lighting, and industrial heat, as discussed in the previous section: This target function is important for enabling the decarbonization and digitalization of the energy demand, as well as for improving the energy quality and affordability. However, this target function also poses some challenges, such as the increase in peak demand and load diversity, the need for Smart Metering and demand response, and the potential for power outages and cyberattacks.
- Allowing for the matching between generation and load at the lowest local level possible, such as within the prosumer side, for instance, in a building or a set of prosumers/buildings grouped in Energy Communities [39] or Positive Energy Districts [23]: This target function is especially important for optimizing the use of local

energy resources and minimizing the losses and costs of energy transmission and distribution, as well as for empowering the consumers and fostering the social and environmental benefits of the energy transition. The main challenges for this function are the coordination and regulation of multiple actors and stakeholders, the need for energy storage and grid flexibility, and the need to consider the potential for conflicts and inequalities.

- Allowing the setting of proper/new electricity market mechanisms based on traditional retail markets, but also targeting new markets both in terms of market structure (distributed community markets implemented throughout blockchain/electronic ledger) and pricing/regulatory schemes (spot pricing, incentives, etc.): This target function is important for creating a level playing field and a fair value for the local energy production and consumption, as well as for stimulating investments and the innovation and competition in the energy sector. This function encounters challenges such as the complexity and uncertainty of the market design and operation, the need for interoperability and transparency of the market platforms, and the potential for market failures and distortions.
- Managing the energy (electricity) dialogue, in terms of power/energy flows and electric interconnection variables, with the external energy-exchange infrastructure, such as the HV distribution and Transmission Networks: This function is also important for ensuring the security and reliability of the energy services at large, as well as for facilitating the integration and coordination of the local and regional energy systems. This target function also presents challenges, such as the technical and operational compatibility and interoperability of the different grid levels and components, the need for communication and information exchange, and the potential for grid instability and disturbances.

It is to be noted that when we discuss the security and reliability of energy services, generally, security is intended for transmission and reliability for distribution, but with the idea of an “active city”, security should also be discussed at the distribution level. This function is important for maintaining the quality and continuity of the energy supply and demand, as well as for preventing and mitigating the risks and impacts of natural or man-made hazards. This target sees challenges at the MV and LV distribution level, such as the definition and measurement of new security and reliability indicators and standards, the need for contingency and resilience planning, and the potential for cascading and systemic failures.

All the aforementioned “functions” at various levels require the availability of Energy Storage Systems (ESSs) and the proper integration of digital solutions in order to be correctly implemented [40–42].

ESSs are technologies or devices that can store energy for later use, either in the form of electricity or other energy carriers, such as hydrogen. ESSs can provide several benefits for the electricity distribution level, such as balancing the supply and demand of electricity, especially when there is a high penetration of variable RESs (such as solar and wind); providing ancillary services for the grid stability and quality, such as frequency and voltage regulation, spinning reserve, and black start; enhancing the resilience and reliability of the energy services, especially in case of grid disturbances, outages, or extreme events; reducing the losses and costs of energy transmission and distribution, especially during peak demand periods or congested network conditions; and enabling the participation and empowerment of the prosumers and Energy Communities, especially in terms of self-consumption, demand response, and market access.

There are different types of ESSs that can be suitable for the electricity distribution level, depending on the application, duration, and location of the storage. Some examples are as follows [41]:

- Batteries, i.e., electrochemical devices that can store and release electricity by converting chemical energy: Batteries can provide a fast and flexible response, high efficiency, and scalability. They can be classified into different categories, such as lead–acid, lithium-ion, sodium–sulfur, or flow batteries.

- Pumped hydro storage, i.e., a mechanical system that can store and release electricity by pumping water from a lower to a higher reservoir and then release it through a turbine: Pumped hydro storage can provide large-scale and long-duration storage, high reliability, and low operating costs. However, it requires suitable geographical conditions, the availability of water close to the city, and accurate studies of the potential environmental impacts.
- Hydrogen, i.e., a chemical system that can store and release electricity by using electrolysis to split water into hydrogen and oxygen, and then using fuel cells or turbines to convert hydrogen back into electricity: It can provide seasonal and inter-regional storage, high energy density, and multiple applications. However, hydrogen requires high capital costs, has low efficiency, and requires safety measures.

The interaction among the "two dimensions" of ESSs, namely the prosumer-scale ESSs (PESSs) and the utility-scale ESSs (UESSs), can be complex and dynamic, depending on technical, economic, and regulatory factors [43].

Some possible scenarios for the interaction of ESSs are as follows:

- PESSs can complement UESSs by providing local and distributed services, such as self-consumption, peak shaving, or backup power, and by reducing the burden on the UESSs, such as avoiding grid congestion, losses, or curtailment.
- On the other hand, PESSs can compete with UESSs by providing similar or superior services, such as frequency regulation, spinning reserve, or market participation, and by reducing the revenue or value of the UESSs, such as lowering the electricity price, demand, or grid fees.
- Finally, PESSs can cooperate with UESSs by providing coordinated and integrated services related to demand response, Virtual Power Plants, or Energy Communities and by increasing the efficiency or resilience of the UESSs, such as optimizing the energy dispatch, sharing the resources, or enhancing the grid stability.

The digitalization of electricity systems [44] has a crucial role and two main effects: it enables a better functioning of grids and paves the way for new services and market functions. It demands considerable investments and the parallel development of human resources, but digitalized power systems can better integrate distributed components (including RESs and ESSs), empower end users, support new architectures and modes of operation, better manage demand and supply, and also improve fault management. The main hindrances of digitalization are cybersecurity and data privacy, which have to be ensured as key priorities.

The target functions described in the present section are summarized in Figure 2 [45], which presents an overview of a future Smart City. This "vision" includes virtual energy markets, big data, and cloud computing-based data storage centers; moreover, the complex and sub-classified energy consumer and prosumer characteristics are presented.

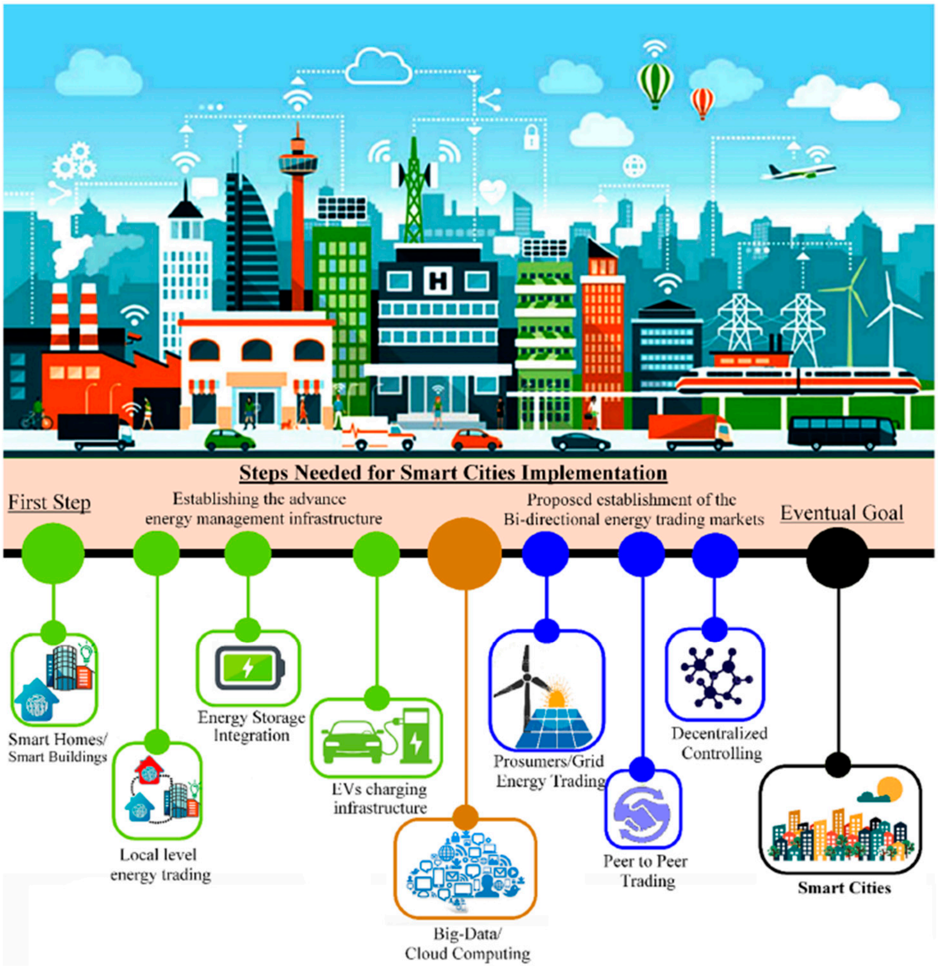

Figure 2. Overview of a future ECG adopting the target functions [45].

4. Design and Operation of the "Smart Electricity City Grid" of the Future

The paradigm of the "Smart Electricity City Grid" of the future can be designed in terms of Energy Balance and Power Balance.

Energy Balance and Power Balance are two different approaches that relate specifically to the operation and control of the electricity infrastructure. Energy Balance refers to the equality between the total energy input and output in the system during a specified time period [46], while Power Balance refers to the instantaneous equality between the total power generation and demand in the system [47].

The implications of Energy Balance and Power Balance in terms of operation and voltage/frequency control can be summarized as follows:

The operation of the Smart City Grid can be conceived in terms of Energy Balance intended as matching the electricity generated within the city grid with the related consumption, e.g., on an average monthly base, by exploiting the Transmission Network as a buffer that provides or withdraws the power mismatch between a city's generation and load. Otherwise, the operation can be designed in terms of Power Balance according to which the power generated by a city's generators must be instantaneously matched with the power withdrawn by loads. However, while maintaining the Energy Balance or the Power Balance as the basic criterion, the operation of the system requires to ensure security, stability, reliability, and efficiency of the system by means of appropriate Control Functions [26].

In this perspective, Voltage Control refers to the regulation of the voltage level in the system, which affects the performance and safety of the equipment and appliances connected to the system. Voltage Control requires the compensation of the voltage drops and fluctuations caused by the resistance, reactance, and capacitance of the transmission and distribution lines, the variability and intermittency of some RESs, and the diversity and dynamics of the loads. This is possible by controlling the active and/or reactive power injection/withdrawal at the nodes and fluxes through the lines of the system. Frequency Control refers to the regulation of the frequency value and its stability in the system, which is affected by the synchronization and operation of the generators and loads connected to the system. Frequency Control requires maintaining the Power Balance in the system, by compensating for the frequency deviations and disturbances caused by the mismatch between the power generation and demand, the inertia and droop of the generators, the faults and contingencies in the system, and the power exchange with other interconnected systems.

Having made this premise, which will be taken up again in the following section, one of the first ideas that is worth elaborating is the choice between the two innovative electricity distribution paradigms: Smart Grids and Multi-Microgrids Networks. This choice should be evaluated from the viewpoint of the operation impact on sustainability, social involvement, and the security of the supply because the paradigms have different advantages and disadvantages, as explained below.

The concept of a Smart Grid refers to the technologies and systems that, taking advantage of advanced digitalization, enable the two-way communication between field devices and control centers, as well as peer-to-peer communication, to manage the electricity grid, from the generation to the consumption level [48–50]. As defined by the European Commission, a Smart Grid is an "*electricity networks that can efficiently integrate the behavior and actions of all users connected to it—generators, consumers and those that do both—in order to ensure an economically efficient, sustainable power system with low losses and high quality and security of supply and safety*". The best-known approach to the structure of a Smart Grid is the Smart Grid Architecture Model (SGAM) [51]. It is composed of five layers: business objectives and processes; functions; information models; communication protocols; and components. This is an abstract view with interoperability as the key enabler. The aim of the model is to represent all components of a Smart Grid, with the five layers projected onto a two-dimensional plane, defining the so-called domains (i.e., the steps of the energy flows: Generation, Transmission, Distribution, Distributed Energy Resources, and Customer premises), and the zones (i.e., Process, Field, Station, Operation, Enterprise, and Market).

Additionally to the Smart Grid idea, the concept of a Multi-Microgrids Network (MMN) refers to a grouping of interconnected MGs, which refer to the local and distributed energy systems that can operate autonomously or connected to the main grid, using various RESs, ESSs, and loads [52,53]. In MGs, the electrical boundaries should be clearly defined, as they "act as a single controllable entity with respect to the grid" [54] and, for economic dispatching, generation units, and loads, they can be considered as a single entity [55]. The development of MMN requires new technologies for their control and protection, as they are more difficult to operate. On the one hand, MMNs can by useful for reducing the negative effects of the intermittency and variability of renewables, as well as for increasing service continuity; on the other, the interconnection of several Microgrids requires proper standards and protocols for ensuring their interoperability and cybersecurity, fitting approaches for their coordination, control and joint protection, with, for instance, efficient anti-islanding techniques. There have been proposals for many architectures and operational models for MMNs [56–58].

Getting back to the previous considerations about the possible operation of the Smart City Grid in terms of Energy Balance or in Power Balance mode, it can be observed that the two approaches can both be applied to Smart Grids, since according to the first one, the possible power mismatch between electricity generation and consumption can be matched by the Transmission Network that the Smart Grid is connected to. As said before, the second approach can provide power–frequency control, thus allowing for local frequency regulation that is necessary for the operation of an intentionally islanded (autonomous) Microgrid, also when intended as a part of a Multi-Microgrid infrastructure in which

Microgrids can operate in both autonomous or non-autonomous mode, according to the network operation requirements.

In conclusion, Smart Grids and Microgrids are two different concepts that can be complementary, with features depending on the context and the objectives. When considering Urban Energy Systems, the issue at hand, more than a discussion of the technologies, is to appraise the ways and means for satisfying the demand for energy services for the city's population while fostering the investments required for their implementation and operation. From this standpoint, Smart Grids provides the basis for an integrated view of the power system architecture, the enabling technologies (including Information and Communication), and the business processes; Microgrids provide a solid (and rapidly evolving) technical background for establishing the solutions for optimizing the distribution of resources and the overall energy management.

As for sustainability, Smart Grids can enhance the sustainability of the energy system by facilitating the integration of RESs, improving the energy efficiency, and reducing the emissions and losses from fossil fuels. Microgrids can also enhance the sustainability of the energy system by using local and renewable energy sources, optimizing the energy use, and minimizing the environmental impacts, providing services to the external network. However, both Smart Grids and Microgrids can also pose some challenges in terms of sustainability, such as the variability and intermittency of renewable energy sources, the need for backup and storage systems, and the potential for land use conflicts.

As far as social engagement is concerned, Smart Grids can enhance the social involvement of the stakeholders in the energy system by empowering consumers, fostering Energy Democracy, and creating new opportunities and benefits for society at large. However, Smart Grids see social challenges, such as the need for more education and awareness, the protection of privacy and data, and the potential for social exclusion and inequality. Microgrids can also enhance the social involvement of the energy system by providing prosumers and consumers with advanced technical solutions, fostering Energy Communities. However, Microgrids need to face social challenges too, such as the need for more coordination and regulation, the protection of rights and responsibilities, and the potential for conflicts and disputes.

Finally, security of supply of the energy system can be enhanced by Smart Grids by improving the reliability and resilience of the grid, preventing and mitigating the risks and impacts of natural or man-made hazards, and enabling demand response and load management. Smart Grids can also pose some security challenges, such as the complexity and uncertainty of the grid operation and management, the vulnerability to cyberattacks and sabotage, and the potential for cascading and systemic failures. Microgrids can also enhance the security of supply of the energy system by improving the reliability and resilience of the local energy system, e.g., enabling the self-consumption and the "islanding" mode of operation (off-grid operation). On the other hand, Microgrids can also pose some security challenges, such as the technical and operational compatibility and interoperability with the main grid, the vulnerability to physical attacks and vandalism, and the potential for isolation and dependency.

Generally speaking, radial and meshed networks are two different types of network topologies that can be used for the electricity distribution system. Radial networks have a tree-like structure, with a single path from the source to each load, while meshed networks have a loop-like structure, with multiple paths from the source to each load [48,59]. The comparison between radial and meshed networks in terms of reliability and protection system requirements can be summarized as follows:

Reliability refers to the ability of the network to deliver electricity to the loads without interruption or degradation. Radial networks have lower reliability than meshed networks, as they are more vulnerable to faults and failures and have less redundancy and flexibility. Meshed networks have higher reliability than radial networks, as they can isolate and bypass faults and failures, and have more redundancy and flexibility [59]. Protection system refers to the devices and schemes that detect and clear faults and failures and prevent or minimize the damage to the network and the equipment. Radial networks have simpler and cheaper protection systems than meshed networks, as they have less complexity and have less coordination and communication requirements. Meshed networks have more complex and expensive protection systems than radial networks, as they have more complexity and have more coordination and communication requirements [60,61].

It should also be considered that power flows distribution and power losses are two important aspects of the electricity networks, and they strongly depend on the network topology, radial or meshed.

Power flows distribution refers to the direction and magnitude of the power flows in the network, which affect the performance and efficiency of the network. Radial networks have unidirectional power flows from the source to the loads, while meshed networks have bidirectional power flows among multiple sources and loads [61,62]. Radial networks have simpler and easier power flows distribution than meshed networks, as they have less complexity and diversity of power flows. However, radial networks have less flexibility and controllability of power flows than meshed networks, as they have less capacity and diversity of power sources and loads.

Power losses refer to the amount of power that is dissipated or wasted in the network, which affects the cost and quality of the network. Radial networks have higher power losses than meshed networks, as they have different parameter values (resistance and reactance) of the transmission and distribution lines, more voltage drops and fluctuations, and more power quality issues. Meshed networks have lower power losses than radial networks, as they have less resistance and reactance of the transmission and distribution lines, less voltage drops and fluctuations, and less power quality issues [63].

The grid topology more suitable to implement a Smart Grid depends on the context and the objectives of the network. The main criteria to choose the grid topology for a smart grid are cost, performance, and flexibility [64].

Cost refers to the capital and operational expenses of the network, including the construction, maintenance, and operation of the network and the equipment. Radial networks have lower cost than meshed networks, as they have less infrastructure and equipment and less losses and congestion. Meshed networks have higher cost than radial networks, as they have more infrastructure and equipment and more losses and congestion.

Performance refers to the efficiency and quality of the network, including the power losses, voltage regulation, power quality, power factor, and reliability. As discussed in more details before, radial networks have lower performance than meshed networks, as they have more power losses, voltage drops, power quality issues, and power factor problems. Meshed networks have higher performance than radial networks, as they have less power losses, voltage drops, power quality issues, and power factor problems.

Finally, flexibility refers to the adaptability and scalability of the network, including the ability to accommodate changes in the load, generation, and network conditions [27]. Radial networks have lower flexibility than meshed networks, as they have lower capacity and diversity of load and generation and less controllability and reconfigurability of the network. Meshed networks have higher flexibility than meshed networks, as they have greater capacity and diversity of load and generation and more controllability and reconfigurability of the network.

It is possible to conclude that the Smart Electricity City Grid of the future must enable smart operation functions such as:

- Distributed Generation Control (prosumer and utility scale);
- Storage of Electricity (prosumer and utility scale);
- Demand-side management;
- Integrated operation of prosumers and Smart Grids (for overload relief and voltage/frequency control);
- Services to the connected national grid (the city as a provider of ancillary services);
- Dynamic prices and regulation (spot price and distributed markets).

Finally, some strategic areas valuable to promote the ECG, including the objectives and the possible actions needed, are reported in Figure 3, according to [30].

Figure 3. Areas for city-led action on inclusive clean energy for ECGs [30].

Nonetheless, as ICT systems progress at a rapid pace, one can expect to see in the next years novelties and more possibilities from digital technologies, with new applications of, for instance, Digital Twins, Artificial Intelligence, the Internet Of Things, Cloud Computing, etc.

5. The Electricity Infrastructural Costs for the Transition

The cost of transforming a radial electricity network into a meshed one depends on various factors, such as the size, location, and condition of the network, the type and number of equipment and devices, and the level and duration of the intervention [60]. Of course, the cost should be compared with the benefits of transforming a radial network into a meshed one, such as the increased reliability, performance, flexibility, and sustainability of the network, as well as the reduced losses, costs, and emissions of the network [65].

The electricity infrastructure costs afforded to implement the transition from the present distribution networks to the networks of the future according to the SGAM paradigm include the capital and operational expenditures for the deployment and integration of various technologies and systems, such as Smart Meters, Sensors, Communication

Devices, Control and Automation Devices, energy storage, Distributed Generation, and Software Platforms.

According to a study carried out by The Brattle Group, the total cost of implementing Smart Grids in the US from 2020 to 2030 is estimated to be around USD 338 billion, of which USD 233 billion is for transmission grids and USD 105 billion is for distribution grids [66]. The study also indicates that the cost of implementing Smart Grids depends on various factors, such as the size, location, and condition of the network, the type and number of equipment and devices, and the level and duration of the intervention. However, these costs should be compared with the benefits of implementing Smart Grids, such as the increased reliability, performance, flexibility, and sustainability of the network, as well as the reduced losses, costs, and emissions of the network. According to [66], the total benefits of smart grids in the United States from 2020 to 2030 are estimated to be around USD 694 billion, of which USD 476 billion is for transmission grids and USD 218 billion is for distribution grids.

According to a report written by the IEA [17], the global cumulative investment in Smart Grids from 2020 to 2030 is estimated to be around USD 1.3 trillion, of which USD 0.8 trillion is for transmission grids and USD 0.5 trillion is for distribution networks. The report also indicates that the investment in Smart Grids varies by region and scenario, depending on the level of ambition, policy support, and technology development. According to the IEA report, the global cumulative benefits of Smart Grids from 2020 to 2030 are estimated to be around USD 2.6 trillion, of which USD 1.6 trillion is for transmission grids and USD 1 trillion is for distribution grids [67].

6. A "Roadmap" for Electricity City Grid Development

The process of creating a possible roadmap to obtain a sustainable city through advanced electrical infrastructures and Smart Grid applications involves several key steps that are listed as follows [68,69]:

- Firstly, at the planning stage, it is necessary to conduct a Baseline Assessment, i.e., evaluate the current state of the city's electrical infrastructure, energy consumption patterns, and existing smart technologies. Then, it is essential to set Clear Targets, i.e., define sustainable goals, such as reducing carbon emissions, increasing energy efficiency, and integrating RESs.
- A "vision" of the infrastructure development must include a substantial upgrade in the electrical grids considering the transition from traditional grids to Smart Grids that, among the other previously described functions (Section 4), must enable two-way communication between utilities and consumers. In this perspective, it is crucial to deploy the Smart Metering paradigm by installing Smart Meters to provide real-time data on energy usage, helping consumers manage their power requirement more efficiently.
- Obviously, one of the most important targets is the integration of RESs according to the paradigm of Distributed Generation based on renewable sources. The future grids must be able to host RESs, such as solar, wind, etc., into the grid to reduce reliance on fossil fuels. This will also be possible thanks to an extensive use of Energy Storage Solutions by implement BESSs to store the excess energy generated from renewables for use during peak demand times.
- This can only be possible with the appropriate use of sensors, actuators, and other IoT devices to monitor and manage energy usage, water supply, waste management, and other city services. Smart Applications have to be created to allow customers to monitor their energy consumption, receive alerts, and optimize their electricity usage patterns.
- Other important steps of the roadmap are represented by the adoption of Big Data Management and Analytics as well as Cybersecurity Measures in order to (1) utilize big data analytics to process the vast amounts of data generated by Smart Meters

and IoT devices, providing insights for better decision making and (2) ensure robust cybersecurity protocols to protect the data and infrastructure from cyber threats.
- Even though the previously described steps can be technically feasible, they need to be enabled and supported by creating public awareness through proper campaigns with the aim of educating the customers about the benefits of Smart Grids and sustainable practices (e.g., through workshops, seminars, and digital platforms). and by providing incentive programs, since offering incentives for adopting energy-efficient appliances, installing solar panels, and participating in demand-response programs is a key factor for the success of the process as a whole.
- The development and implementation of appropriate policies and regulations to support the entire process will be crucial, especially to support the adoption of Smart Grid technologies and renewable energy integration. Proper Regulatory Frameworks will need to be established to ensure compliance with sustainability goals and standards.
- In order to maintain the safe operation of this complex system, it will be of basic importance to regularly monitor the performance of the Smart Grid and other sustainability initiatives and make necessary adjustments if needed.
- Research and innovation will continue playing a crucial role to explore new technologies and innovative solutions for further improvements.

By following a similar roadmap, cities can move toward achieving sustainability through advanced electrical infrastructures and Smart Grid applications, creating a more efficient, resilient, and environmentally friendly urban environment.

7. Future Research for Smart Electricity City Grids

Looking forward, what will the research for smart urban grids of the future entail?

The analysis of the future of energy systems in cities is central for our societies, as it will define our success in dealing with climate and environmental issues and setting the level of quality of life that will be feasible. The future of Urban Energy Systems in the long term is basically uncertain and unpredictable. This creates a tension between decisions that have to be made today, with unavoidable lock-in effects, and the openness to new solutions [70].

In this paper, we presented some of the main factors defining the problem, from technologies to costs. But several others will require similar consideration, for instance, externalities, investments, regulations, and policies. The following is a list of topics that we identify as central for Urban Energy Systems:

- New electricity paradigms, beginning from direct-current (DC) technologies;
- Energy storage technologies and their grid integration;
- Real-time issues, e.g., balancing power supply and demand in real time;
- Digitally related topics, such as monitoring the performance of resources (PV and storage) for better planning and operations, cybersecurity, and new digital applications [71,72];
- Distributed intelligence and multi-agent systems [73];
- Resilience, reliability, and security in local urban grids;
- New business models and new market regulation arrangements.

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