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Perspective

Technologies and Strategies to Support Energy Transition in Urban Building and Transportation Sectors

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Abstract: More than half of the world population live in urban settlements which are responsible for a large share of energy consumption and, consequently, carbon emissions. The transition towards a more sustainable urban environment requires a change in paradigm in terms of how we design and manage our cities. Urban areas require innovative technologies and strategies to reduce energy consumption and carbon emissions, and to be included in comprehensive plans encompassing all technical, social and economic dimensions which characterise cities. This involves the transformation of urban contexts, with a focus on local and urban-level mitigation measures, such as the construction of positive energy buildings, deployment of renewable energy, promotion of a sustainable mobility, creation of resilient urban infrastructure, implementation of circular economy and recycling practices, etc. The present article provides a perspective on the sustainable energy transition in cities, focusing on the building and transportation sectors. Furthermore, insights on supporting mechanisms and innovative management strategies are presented.

Keywords: cities; renewable energy; energy efficiency; positive energy districts; urban transports; funding mechanisms; project management

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1. Introduction

Cities are home to more than half of the world population and they account for about 75% of carbon emissions and between 60 and 80% of energy consumption [1]. It has been estimated that about two-thirds of the global population will be residing in urban settlements by 2050 and, as outlined by the Sustainable Development Goals (SDG), a significant overhaul in the construction and administration of urban areas is required to foster a sustainable transition in cities [2]. With a large concentration of energy consumption and complex infrastructure, cities require innovative technologies and strategies to support a successful energy transition.

The complexity of the urban environment—where several sectors with different energy and material demands, features and needs—makes the development of comprehensive sustainable policies encompassing technical, social and economic aspects quite challenges [3,4].

Therefore, the implementation of energy transition strategies deeply involves the transformation of urban contexts according to high-level guidelines, forming city energy plans, which should establish measurable sustainable targets and specify actions encompassing all technical, economic and social dimensions. This requires a focus on local and urban-level mitigation measures, including the construction of positive energy buildings, deployment of renewable energy systems (RES), promotion of sustainable mobility, creation of resilient urban infrastructure, implementation of circular economy and recycling practices, among others [5–8].

Notwithstanding, successfully implementation of sustainable measures in urban areas also requires establishing effective mechanisms to support the diffusion of new renewable-based technologies and energy efficiency strategies [9]. Funding schemes, tailored to the specific urban needs identified in city energy plans, should be introduced. Such mechanisms need to be designed to tackle economic and financial barriers which limit the uptake of sustainable strategies at the urban-level, especially those related to economically disadvantaged population and areas where critical infrastructure are located. Furthermore, effective management structures at both policy and implementation levels should be established to foster the adoption of new renewable-based technologies and efficiency strategies by stimulating knowledge generation and technology transfer among relevant city stakeholders [10].

The present work is intended as a perspective paper, thus offering a commentary of the authors' vision in different sectors relevant for energy transition in cities.

Among the different sectors, the present article outlines some of the most relevant aspects of the sustainable energy transition in cities related to buildings and transportation sectors. In particular, building retrofitting strategies and the electrification of heat demands in the building sectors (Section 2), the role of photovoltaic solar systems in city areas (Section 3) and the emerging definition of positive energy districts Section 4 are discussed. Furthermore, technologies for sustainable urban transportation and strategies for their integration with the building sector are presented in Section 5. Finally, Sections 7 and 8 address the main supporting mechanisms and innovative management strategies to foster the uptake of sustainable energy technologies in urban areas.

2. Building Retrofitting and Electrification of Heat Demand

The building sector accounts for over 40% of the primary energy demand, with an expected increasing trend in the next future [11], and for about 36% of all greenhouse gas emissions. Energy policies and regulations, such as the Energy Performance of Building Directive and the Energy Efficiency Directive [12,13], have been introduced by the EU to establish energy performance standards for new constructions and to foster the energy renovation of the existing building stock. Despite efforts to meet net zero-energy building standards for new constructions, only a small fraction of existing buildings (about 1%) are renovated each year in Europe [14]. A retrofitting strategy, as defined by Rey [15], involves a set of interventions aimed at improving the building energy performance, guided by an architectural approach and optimised through the coordination of building envelope upgrades and technical installations. Apart for reducing the overall primary energy consumption, this process can lead to other external benefits—such as, from end-users point of views, the improvement of occupants' thermal comfort and the increase of the building market value—while also reducing the reliance on fossil fuels and enhance the overall security of the energy supply at a larger scale [16].

In the context of building retrofitting strategies, several key pillars can be depicted:

- building envelope improvement: being one of the most common strategies adopted to reduce the energy consumption for heating and cooling, it consists of limiting the energy losses through vertical walls, roof, floors and windows to reduce the building energy demand.
- energy system replacement and renewable energy integration: upgrading old heating, ventilation, and air conditioning systems with more efficient technologies can reduce

the primary energy consumption. Moreover, the exploitation of renewable-based technologies for energy generation—such as thermal and photovoltaic solar panels, geothermal heat, wind power, etc.—can contribute to decreasing the reliance on fossil fuels, thus reducing overall carbon emissions.

- monitoring and control optimisation: the installation of energy management systems for demand-side management (DSM), based on smart sensors and optimised control algorithms, can help reduce system inefficiencies while also providing fault detection services. Furthermore, DSM systems can unlock new features such as demand flexibility [17], in which energy demand and generation can be decoupled (e.g., by means of energy storage [18]) and optimised to reduce costs and carbon emissions. The implementation of demand response (DR) programs, in which building electricity demand profiles are adjusted to provide ancillary services to the national grid, is an example of novel services which can be provided by smart building blocks [11].

The electrification of heat consumption is one of the main strategies for the decarbonisation of the building stock and to support the energy transition of urban settlements in Europe. According to this, a comparison of the cost of electricity-based technologies and traditional natural gas boilers was developed in [19], where a case study on the city of Bilbao was analysed by considering different configurations. Results showed that a combination of PV plants and heat pumps is the optimal solution for covering the heating demand with lowering carbon emissions. Other authors focus their attention on identifying retrofitting strategies for the building envelope to reduce the overall thermal demand required for heating and cooling. To this aim, the utilisation of phase change materials (PCMs) as an innovative solution for urban energy regeneration and reduction in thermal loads is discussed in [20]. The work presents a solution based on the Passivhaus strategy and nature-based solutions at the urban-level which was demonstrated through a digital twin of a district of Valencia.

Notwithstanding, the deployment of retrofitting measures in buildings require capital expenditures which, in some cases, can be relevant. Often barriers to the renovation of buildings, especially multi-storey ones, are related to the specific social and economic conditions of owners or tenants. This is particularly true for shrinking cities as noted in [21]. The introduction of funding mechanisms is therefore fundamental to make energy retrofitting investments more affordable and accessible to building owners and encourage the uptake of energy-efficient upgrades. Governments may provide grants and subsidies in the form of tax credits or tax deduction to encourage energy retrofitting projects, particularly for building owners with limited financial resources. Otherwise, energy-efficient mortgages can allow building owners to finance energy-saving upgrades as part of their mortgage, making retrofitting more accessible and affordable. Furthermore, another possible solution for overcoming financial barriers, specifically those due to the upfront investment costs of energy renovation, is the promotion of on-bill schemes as discussed in [22]. Generally, a mix of public and power funding, where finance institutions and public authorities coordinate their efforts to guarantee access to funding for building renovation projects is needed.

3. The Role of Photovoltaic (PV) in Urban Areas

Solar renewable energy systems have the potential to supply a substantial part of the energy demand in cities. One of the most widespread technologies to exploit solar energy in urban areas is photovoltaic (PV), which can be integrated into existing buildings by recovering unused surfaces such as roofs or façades. Several studies have analysed the potential energy production from PV systems in several cities worldwide. Typically, three main approaches can be adopted [23]:

- *constant-value methods*: a simple approach that makes an assumption about the percentage of a building's rooftop that can be used to host solar panels. This assumption is then applied to the entire building stock to estimate the total area available for PV deployment. Although this method can represent a useful approach to obtain fast estimates of rooftop availability, the lack of validation and consideration for specific nuances in each building can lead to oversimplifications and inaccurate results.

- *manual selection*: at the highest level of resolution, this method involves examining individual buildings to identify the total rooftop area suitable for PV installation and to calculate their potential energy generation. Aerial photography is one source used to provide visual information about the most appropriate locations for rooftop PV installations, while manual selection provides the most accurate estimate of the total rooftop area suitable for PV, it is also the most time-consuming and resource-intensive approach.
- *GIS-based methods*: geographic information system (GIS) tools—which allow designers to store, manage, analyse, and visualise geographic data and information—is a powerful approach for analysing and mapping spatial relationships and patterns in urban areas [24]. This allows the identification of suitable rooftops for photovoltaic (PV) installations in urban areas by analysing various factors and criteria that influence the feasibility and performance of a PV installation, such as roof geometry, orientation, shading, structural capacity, proximity to electrical infrastructure, etc. The results of the analysis can be used to create a comprehensive and systematic assessment of the available rooftop surfaces for PV installation in an urban district and prioritise PV deployments based on their efficiency and production potential.

The current literature provides several examples of assessment of PV installation potential in urban settlements. For instance, Gómez-Navarro et al. [25] carried out a comprehensive analysis of the potential PV production for Valencia in Spain by exploiting suitable building rooftops. The results showed that the exploitation of the available rooftop surface would allow the coverage of about 37% of the power demand of the city. A subsequent study [26] expanded the analysis to the profitability of PV installations based on several regulation scenarios, showing that the inability to sell energy when revenues are greater than purchases represents one of the main limitations to reducing the levelised cost of electricity (LCOE), since a net metering system is not currently allowed in Spain. Enabling this would allow an increase in the payback by about one-third.

Based on 3D city models, Rodríguez et al. [27] estimated the solar photovoltaic potential at an urban and regional scale in Seville (Spain). The findings of the study demonstrate that attaining substantial yearly rates of electricity supply for numerous municipalities is feasible in certain scenarios, with some even exceeding 100%. By utilising all accessible rooftop space, there is a technical potential to cover 77% of the region's electricity consumption and an economic potential of 56%, focusing solely on roofs with high irradiance. Similarly, Arcos-Vargas et al. [28] examined self-sufficient renewable energy supply in metropolitan areas, presenting a methodology to assess the capacity of urban areas to sustain themselves with publicly available data. Their research revealed that the majority of renewable energy originates from roof- (72%) or ground-mounted PV facilities in the surrounding urban areas (25%), with a small contribution from biogas generated from wastewater.

The role of GIS tools in assessing the suitability and penetration potential of PV systems in urban areas has attracted particular interest over the last few years since they can effectively contribute to the development of integrated urban energy policies, as well as support decision-making actors in prioritising sustainable investments. A comprehensive review on the methods for estimating rooftop solar PV potential at the urban scale using GIS tools is presented in Gassar and Cha [24]. The authors reviewed and classified GIS-based methodologies and their potential applications at both small and large scales, while also discussing the limitations and future developments in the field, such as machine learning integration. For instance, Mansouri Kouhestani et al. [29] evaluated the rooftop PV potential in Lethbridge (Canada) from both technical and economic points of view, adopting a multi-criteria GIS-based approach. Results showed that the electricity generation potential of the city is more than 300 GWh/year, corresponding to about 38% of its yearly electricity demand, while more than 96% of the identified locations are economically feasible. The authors emphasised that the methodology and findings presented could aid in making well-informed policy decisions regarding the allocation of resources to implement renewable energy generation.

Figure 1 shows the result of a GIS based approach integrated with machine learninn for the estimation of the PV generation potential in the city of Geneva. Finally, it is worth mentioning the potential integration of solar PV in building façades. The advancements in module and cell technology have elevated PV systems to a new level, where they can be integrated into a building's design as functional architectural elements. This is referred to as building-integrated photovoltaic (BIPV). This approach involves using PV modules as sunscreens or replacing traditional building materials with PV modules as glazing surfaces. On the other hand, building-applied photovoltaic (BAPV) refers to the deployment of integrated PV system to an existing building. Vertical PV systems, despite receiving lower levels of direct sunlight and having a suboptimal angle of incidence, are relatively immune to the negative effects of soiling agents, such as snow or dust, and have the potential to be self-cleaning during rain, thus necessitating less maintenance [30]. For instance, Baumann et al. [31] experimentally analysed a PV system with bi-facial PV modules installed on vertical surfaces in combination with green roofs. The results showed that, despite the presence of shading and low albedo factors, the 9 kWp installation was capable of achieving generation values close to south-facing PVs in the same location. This allows to increase the overall surface available for PV installations in cities, while also creating opportunities for building renovation and energy communities in urban districts.

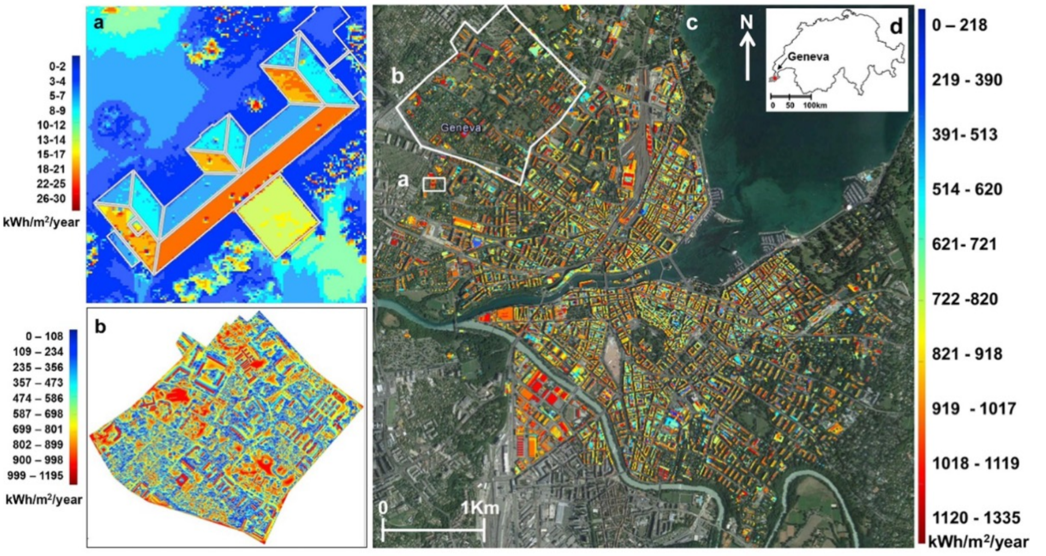

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Figure 1. Estimation of the annual average solar PV generation from rooftops in Geneva (Switzerland) calculated using a GIS-based approach integrated with a machine learning approach. The machine learning algorithm classifies the typology of the roof by estimating the PV generation potential. (**a**) Single building level, (**b**) district level, (**c**) city level. Reprinted with permission from Mohajeri et al. [32]. Copyright 2017, Elsevier Ltd. (**d**) location of the city within the country.

In conclusion, the potential for using photovoltaic systems to generate renewable energy in urban areas can be significant. Results from studies carried out in several cities around the world indicate that significant amounts of electricity demand can be met through the exploitation of rooftop surfaces for PV installation. Generally, the assessment of solar PV potential is a necessary step to identify suitable locations among city buildings, while also to analyse the techno-economic performance of the PV installations. GIS-based methods have been shown to be a valuable tool to conduct such analyses, which can be used for establishing policies regarding investment in renewable energy generation.

4. Positive Energy Districts

Positive energy districts (PEDs) are sustainable urban development initiatives that strive to produce more energy than they consume by utilising a combination of renewable energy sources and energy-efficient buildings and infrastructure. PEDs promote the transition towards a circular and low-carbon economy in urban settings, with the ultimate objective of reducing greenhouse gas emissions and supporting sustainable urban development. The main goal is to establish self-sufficient communities that are better equipped to handle energy price fluctuations and supply disruptions. In addition, excess energy generated in PEDs can be shared with neighbouring districts to meet their energy requirements, enabling areas with high potential for renewable energy production to supply areas with lower production capabilities.

As discussed in Brozovsky et al. [6], a PED is defined as "*a district with annual net zero energy import, and net zero CO_2 emission working towards an annual local surplus production of renewable energy* " according to the definition given in the European SET Plan Action 3.2 Smart Cities and Communities Implementation Plan. PEDs are integrated in the urban context in order to enhance its energy security and flexibility, while also reducing energy poverty. The key principle in PED is to keep their energy consumption lower than their generation. However, it is important to highlight that a positive energy district may not necessarily correspond to a net-zero climate emission districts and that careful considerations and quantitative assessments should be carried out to identify opportunities and limitations at district level [33].

When discussing PEDs it is extremely important to define its geographical boundaries since they represent the line of interaction with the energy system outside the PED [34], whereas all the components within the boundary, i.e., demand, supply, and storage units, represent the key aspects of the PED.

As reported by Casamassima et al. [35], PEDs can be analysed according to the *sustainability triangle*, i.e., by encompassing techno-economic, environmental, and social dimensions. In particular, they focus on six sub-dimensions (spatial aspects, energy balance, environment, energy efficiency, land use and social aspects), which are individually analysed.

- **Spatial aspects** attain the geographical boundary of the PED which is relevant to determine the inflow/outflow of energy, as illustrated in [34].
- **Balance aspects** focus on the energy balance of the district which should be positive, zero or nearly zero. On the other hand, to define a balance, it is relevant to establish the time resolution of the balance, e.g., monthy, yearly, etc., since the balance may have different values.
- **Environmental dimension** is mainly linked with the emission from PEDs. Formally, PEDs do not have any emission reduction goals since their definition is more focused on energy targets. On the other hand, since PEDs are based on RES, the implicit assumption is that they have the ambition to limit the PED carbon footprint.
- **Energy efficiency** is a funding principle of PEDs which assumes that the district energy demand is minimised and the remaining part is then covered with RES.
- **Land use** is a critical aspect of PEDs. Usually land is scarcely available in highly urbanised areas; thus, it can be problematic to find a location for the technical facilities required (e.g., RES installation, storage, etc.). It is necessary to determine the trade-off between the technical installations and other social uses (e.g., sport facilities for youth, aggregation points for elders, etc.). The principle is that optimisation and inclusiveness of public spaces must be ensured.
- **Social aspects**, according to [35], can be mainly linked to the principle of energy justice. The establishment of a PED implies that the neighbourhood is in good condition with energy-efficient buildings. Usually, these conditions are not verified in poorer suburban areas, thus there is the risk that the development of PEDs would go against the inclusiveness principle.

Figure 2 illustrates the boundaries of the different positive energy "modules", from building to district. Social aspects were heavily emphasised by Sareen et al. [36] who summarised ten questions concerning PEDs. In particular, they focused on the involvement of stakeholders, including citizens first and then all the other actors. In fact, it is a common opinion that the gradual involvement of citizens, since the inception of a possible PED idea, is extremely complicated to accomplish. Thus, municipalities are called upon to develop significant actions for building a positive attitude towards PEDs, while also to carry out a revision of urban governance models to make them more adequate for managing very innovative and unique projects such as PEDs.

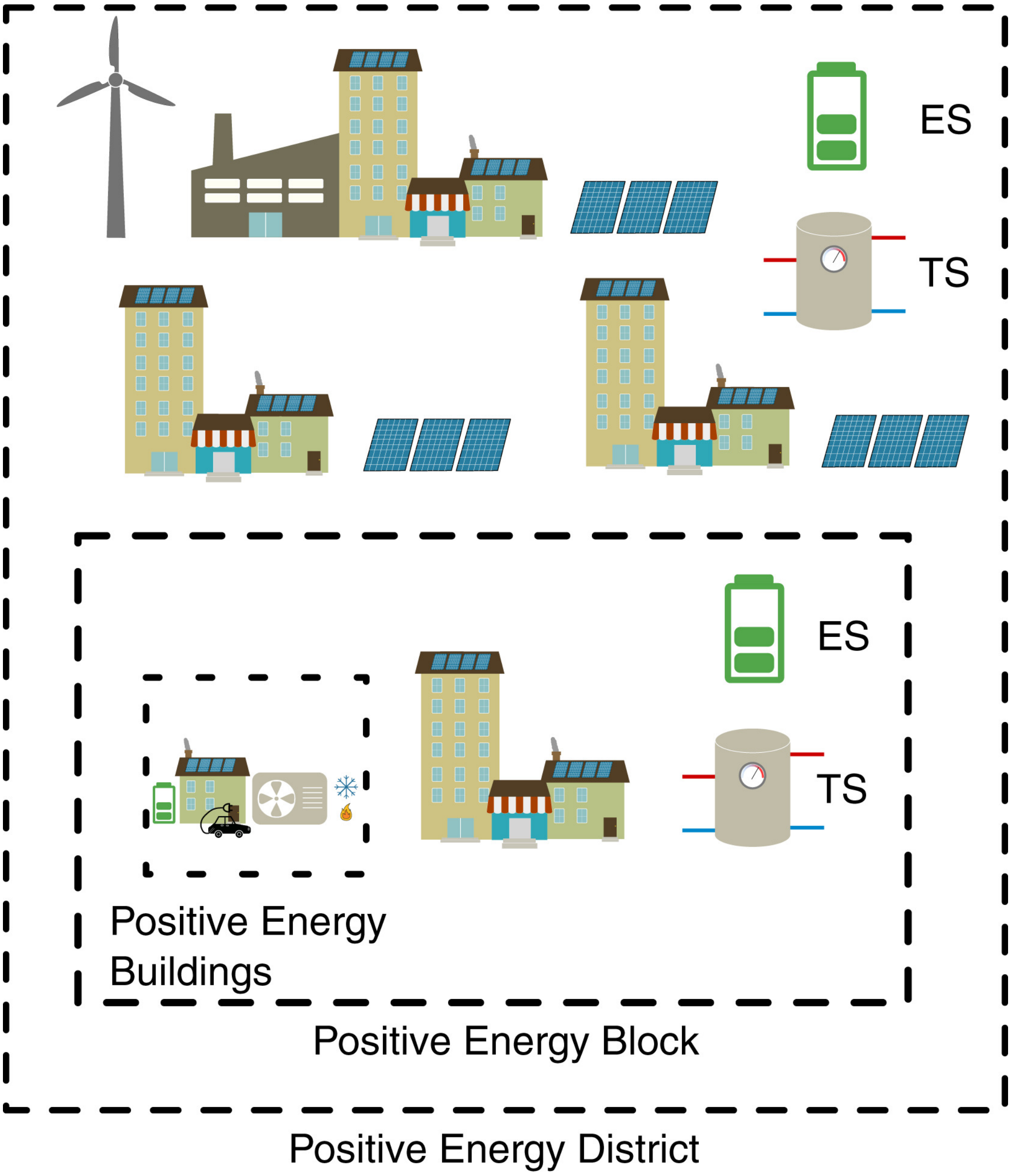

Figure 2. Schematic of geographical boundaries for positive energy districts in comparison with positive energy buildings and positive energy blocks. Reprinted with permission from Casamassima et al. [35]. Copyright 2022, the authors under CC BY 4.0 licence.

Based on their extensive literature review, Koutra et al. [37] concluded that gaps exist in the governance systems, participatory processes for citizens, and bottom-up approaches for creating synergies and co-creating standards for PED design and deployment. Additionally, the analysis of these processes highlights the need for a strategic plan that incorporates social, technical, financial, and regulatory elements. However, a significant challenge also lies in ensuring data accessibility and compatibility.

The social dimension of PEDs is a recurrent topic in the literature explored by Gouveia et al. [38], who focused on the possible implementation of PEDs in historical districts. Gouveia et al. [38] recalled that most of the PED projects have been implemented in new districts, where it is easier to plan and build all the necessary facilities. On the other hand, reaching the EU Green Deal targets requires to also target historical parts of cities, representing the larger majority of the building stock in the EU.

According to [38], PEDs could represent an opportunity of urban regeneration for these districts in compliance with the principle that "nobody should be left behind". As a consequence of possible urban regeneration due to PED, energy poverty would decrease since the energy is self-generated.

Recognising the importance of the existing building stock in the development of PEDs, Bruck et al. [39] proposed a methodology for determining the value of retrofitting the building stock in an electrified PED. Their results suggested that retrofitting is essential for the success of PEDs in cold climates and densely urbanised areas such as northern European cities. Similarly, Aparisi-Cerdá et al. [40] illustrated a PED development project on the waterfront of Valencia (Spain). Different scenarios and strategies were analysed, showing that there are huge opportunities to develop PEDs in coastal Mediterranean cities.

Finally, a step-by-step calculation procedure to establish PEDs was reported by Gabaldón Moreno et al. [41]. The methodology comprises eight relatively simple steps which can support the decision-making process of municipalities interested in PEDs development.

5. Sustainable Transports

A sustainable transportation system is vital in decreasing urban energy consumption and promoting a low-carbon economy. In recent years, the contribution of the transport sector to greenhouse gas (GHG) emissions has significantly risen, surpassing 20.8% and ranking as the EU's second most significant emission source [42]. Studies have shown that the adoption of green transport technologies, such as electric vehicles and alternative fuels, can significantly reduce energy savings and emissions. For example, the International Energy Agency report shows that the widespread adoption of electric vehicles could reduce global oil demand by 2.5 million barrels per day by 2030 and up to 13 million barrels per day by 2050 [43]. Additionally, a study by the European Environment Agency found that a shift towards sustainable mobility, including electric vehicles and alternative fuels, could result in a 60% reduction in transport-related greenhouse gas emissions by 2050 [44]. Regarding the benefits of retrofitting the transportation sector with sustainable solutions, a report by the United Nations Environment Program found that implementing sustainable transport solutions could save up to $70 trillion in infrastructure investments and fuel costs by 2050 while reducing global carbon emissions by up to 90% [45]. Combining green transport technologies, such as hydrogen-powered vehicles, EVs, drones, and electric mobility as a service solution (MaaS), can lead to huge opportunities in fostering the sustainable transition in urban areas [5]. However, these technologies require adequate infrastructure integrated with the built environment, such as charging networks, refuelling stations and landing pads, particularly in large cities. Integrating buildings and transportation sectors through the combination of district co-generation units and green transport has the potential to significantly reduce carbon emissions in urban areas and optimise fuel consumption [46]. Future technologies, such as autonomous vehicles and drones, can reduce city energy consumption and emissions. However, their deployment is limited by social, economic, and technological barriers [47].

Another area of intervention is reducing the transport demand since private cars remain the most popular transportation across countries. The COVID-19 pandemic has had a significant impact on transportation and mobility patterns globally. The restrictions on movement and social distancing measures put in place in many countries have reduced travel demand, particularly for non-essential travel. This reduction was due to a combination of factors, including the closure of workplaces and schools, the cancellation of events, and restrictions on international travel. One critical change that emerged during the pandemic is the rise of flexible and hybrid working models. These models allow employees to work from home or alternate between working from home and the office, reducing the need for daily commuting. This change has the potential to lead to a long-term reduction in travel demand, which could have significant benefits for the environment, public health, and urban congestion. The pandemic has demonstrated that transport demand can be reduced without affecting economic development, which is a critical lesson that policymakers should consider. The reduction in travel demand during the pandemic has not caused significant economic disruptions; some businesses have even reported increased productivity due to remote working. However, it is important to note that the transport needs of city dwellers go beyond just commuting to work, and policies to reduce demand should consider other factors, such as leisure travel and access to essential services. Governments should prioritise incentives for sustainable transport behaviour and infrastructure development that supports green transportation instead of mandating mobility restrictions. For example, governments can provide tax incentives for companies that adopt flexible and hybrid working models or invest in public transportation systems, bike lanes, and pedestrian-friendly infrastructure [48]. The use of big data and technology can support the optimisation of green transport and the reduction in demand, but privacy, cyber-security, and data reliability remain concerns.

Poor public transportation, insufficient community planning, and regulations in developing nations can lead to exorbitant travel times and expenses. Conversely, high levels of motorisation and private vehicle usage in these countries may result in economic, social, and environmental challenges. Generally, a sustainable transport system requires a combination of technologies such as micro-mobility solutions, EVs, car sharing and a data-driven infrastructure to promote sustainable mobility behaviours. Furthermore, a reward system can incentives sustainable mobility, and big data can be used to optimise road capacity and forecast demand. Decisive policies and actions may be necessary to promote sustainable transport addressing the climate change emergency and health constraints.

6. The Case of Megacities

An emerging topic related to the energy transition in cities is mega-cities, i.e., large urban agglomerations with more than 10 million inhabitants, which are increasing especially in emerging countries, as observed in [9]. The decarbonisation of buildings in megacities is pivotal for achieving decarbonisation in urban areas since they have large untapped potential [49]. Commercial buildings offer many opportunities for decreasing energy consumption and reducing carbon emissions. By applying the generalised Divisia index method, a study on Chinese megacities [49] highlighted that the main drivers for carbon emissions are value-added from the service sector, gross domestic product, and energy consumption. Based on this, it appears relevant to decouple carbon emissions from economic growth. According to Bianco and Sonvilla [22] a decoupling effort in Chinese megacities has been observed starting from 2009.

Megacities face a significant challenge to ensure a sustainable and sufficient energy supply to support their diverse activities. To address this issue, Ram et al. [50] conducted a case study proposing a transition to 100% renewable energy in New Delhi. The study provided a technology-rich analysis that covers the power, heat, transport, and desalination sectors. The findings demonstrate that New Delhi and its surrounding areas can potentially reduce their primary energy consumption by more than 40%, while also reducing energy costs by over 25%. These benefits were also linked with a decline in greenhouse gas emissions, air pollution, and associated health expenses.

Various approaches can be employed to determine the most effective routes towards achieving energy transition in urban areas. In 2010, China initiated a low-carbon city pilot policy aimed at promoting green development and energy transition through carbon dioxide emission reduction and environmental quality improvement [51]. Results from a study encompassing 253 cities indicate that the low-carbon city pilot program was successful in hastening energy transition. These cities also generated positive spatial spill-over effects on energy consumption and energy intensity. Similarly, pilot projects have been launched in order to test innovative strategies, technologies and concepts. An analysis of five European cities, namely Maia, Reykjavik, Kifissia, Kladno and Lviv, was developed in Fatima et al. [52]. Data were collected through field activities such as interviews, workshops, etc. Authors concluded that new forms of governance are necessary to implement innovative strategies and new business models, allowing for the development of innovative approaches such as PEDs. Similarly, an analysis of the wind energy potential for Gdansk (Poland) was developed in Aydin et al. [53]. The analysis considered the installation of innovative city-type wind turbines to generate electricity for the city. This increased the transmission efficiency, since there were short physical distances between generation and consumption. The paper shows that city-type wind turbines can be successfully used in Gdansk by avoiding the usual problems connected with large wind turbine installations.

7. Supporting Mechanisms for the Diffusion of Green Technologies in Urban Contexts

Facilitating the widespread adoption of green technologies requires the establishment of supportive measures to attract investment when high upfront costs impede the uptake of such technologies, either due to their immaturity or the lack of established learning curves. An example of such measures is the feed-in tariffs, implemented throughout the EU to encourage the installation of renewable energy systems [54]. Supportive measures are also required in stagnant market contexts, which typically remain unresponsive to profitable investment opportunities due to existing biases that prevent players from accurately evaluating them [55].

Wang et al. [56] highlighted the importance of three mechanisms, feed-in tariffs (FiTs), renewable portfolio standard (RPS), and emission trading schemes (ETS), in the development of RES for power generation. FiTs serve to increase the developmental pace of RES capacity, since the generated power is paid at an established price which allows the investment to be paid back. FiTs are usually calibrated on the capital expenditure (CAPEX) of the incentivised technology. RPS is a mechanism based on the minimum quantitative share of renewables that energy suppliers must guarantee in their portfolio. In this way policymakers are assured the defined objectives are fulfilled. The focus is on the supplier rather than the final users, so the system is easier to manage. Finally, ETS is a system based on establishing a market for carbon emissions, thus carbon emissions are subjected to extra costs and the system is supposed to evolve towards low-carbon technologies. FiTs, RPS, and ETS all have specific implications in the urban context since all the technologies they support can be integrated into the urban environment.

On the other hand, FiTs and RPS seem more effective since ETS only involve a limited amount of end-use sectors [56,57]. For instance, municipalities, with an appropriate regulatory context, could impose specific RPSs to local distributors. Xin-gang et al. [58] offers an example of how FiTs can be used to promote biogas technologies. Biogas production plants are significant in the urban context, since they can process the organic fraction of urban wastes to produce biogas by recovering methane that would have been released naturally into the atmosphere as a consequence of the natural degradation of organic wastes. This is very relevant for urban contexts since this process is a virtuous example of a circular economy.

To fulfil national targets, such as the EU targets of 2020, 2030, and 2050, cities are pivotal since they represent most of the consumption and have a large potential to integrate sustainable technologies. Schenone and Delponte [59] highlighted the importance of urban energy planning to define clear objectives to reach through specific initiatives and support mechanisms implemented at the city level. Delponte and Schenone [60] also stressed that energy planning should be organically embedded into the urban planning process of cities in order to enhance sustainability.

Another area of extreme importance for improving the sustainability in cities is the building energy retrofitting. For instance, Bianco and Marmori [61] estimated that the appropriate implementation of energy-efficiency measures on the Italian residential building stock could save 100 TWh of primary energy per year. Based on this, it is fundamental to develop adequate support schemes or business models for sustaining these investments. Within this framework, Brown [62] examined five different approaches for creating energy-efficiency measures in the building industry, namely the atomised market model, market brokerage model, one-stop-shop, energy services agreement (ESA), and managed energy services agreement (MESA). These models range from traditional methods employed by energy service companies (ESCOs), such as ESA and MESA, to more cutting-edge tactics, such as the one-stop-shop, providing an all-encompassing, turn-key solution for a variety of investment levels.

Similarly, Tingey et al. [63] described six possible types of local authorities energy service models, municipal in-house, energy performance contractor model, municipal (or district) energy company model, local third sector business model, district energy concession contract model, and municipal energy utility model. Notwithstanding, resources are necessary to develop and deploy these programs. Furthermore, a general program does not exist suitable for all cases, thus it is necessary to build a program according to the local context and issues. Stuart et al. [64] analysed the successes obtained through ESCO-based models in supporting energy efficiency in the USA. It is important to mention that ESCO models are very effective when applied to large properties or infrastructures, such as airports, train stations, large office buildings, hotels, etc. For small buildings or flats the models do not work since the transaction costs can be very high in proportion to the investment, and the scheme results are very complicated with respect to the implemented measures.

For small properties an innovative approach can be represented by on-bill programs [22]. These programs are generally offered by utilities alone or in cooperation with financial institutions. They aim at overcoming the market barrier due to the high upfront costs for energy-efficient residential dwellings. The utility provides the upfront cost for deploying the efficiency measures while the user will pay back the CAPEX on the bill. This mechanism has been in place for more than 30 years in the USA with very successful cases. Oppositely, in the EU there are only a few initiatives, the UK Green Deal was a case of failure [65]. Finally, Delponte et al. [66] mentioned the importance of non-energy benefits brought by energy-efficiency measures and the need to include them in the overall assessment of each case. Non-energy benefits can drive the willingness of final users, especially in residential dwellings, of energy-efficiency retrofitting.

8. Innovation Management in Urban RES Development

The field of innovation management provides an important perspective on how to manage the development and implementation of new technologies, services and processes based on RES. Previous studies have pointed out that innovations based on RES are one of the most important contributions when it comes to environmental benefits in the construction sector [67]. Many challenges need to be addressed when it comes to implementing new ideas based on RES. From an innovation management perspective, both economical, environmental and sustainable aspects need to be addressed in an integrated way during the innovation process.

In the early stages of renewable energy transition, or in the fuzzy front-end of the innovation process, it is important to combine different skills and build trust. Leadership and management provide the baseline when balancing between degrees of freedom, tasks and outcomes of the project. Compared to more traditional innovation projects, the focus on RES adds an extra element of innovation management. The traditional process of innovation usually focuses on the business target of costs and efficiency in the process and to a large extend the financial output of the investment. However, innovation projects that include RES need to target the sustainable aspects during the process as well as the important outcomes. Some of the challenges when targeting RES implicate difficulties when transforming the goals into practice. For instance, the transition towards zero-emission buses in public transport is viewed as an important step towards a better climate in urban areas, but the adoption is slow due to economic and technological barriers. However, it could be argued that institutional innovations need to be considered as the first step of targeting new collaborations and business models to boost development, also providing new technical solutions [68].

It is clear that RES adoption requires powerful regulations and policies that provide guidelines for implementation at both the local and national level [69]. Innovations that address RES are essential, but the process towards the solution in many cases involve a high level of uncertainty, especially when it comes to the environmental benefits. The transition towards RES is often considered without including the environmental attributes, which could be understood as a barrier to RES adoption [69].

Adding to the complexity of the innovation process of many different participants from different fields, one also needs to address the end-user perspective in order to make a successful transition. It is clear that many challenges exist when developing renewable energy solutions, such as technological, economic, socio-cultural, institutional and sustainable barriers, but some of these problems tend to be linked to poorly attributed dissemination of renewable energy technologies, implying the need to co-create solutions with stakeholders and the end-user. The development in Europe over time indicates that RES consumption in households is rising, but some differences have been identified during 2004–2019 [70]. The RES growth is visible in several EU countries, but in some countries there is a tendency of stabilisation and even signs of decline, indicating the necessity to enforce RES policies at the national level [70]. Furthermore, the national context and geographical location need to be addressed in the development of RES policies and guidelines. For example, countries in central and eastern Europe tend to use bio-fuels, while western European households are more likely to install efficient systems (e.g., heat pumps) and renewable-based energy systems (e.g., thermal solar panels, biogas-based boilers and biofuels) [70].

Furthermore, having the pre-conditions in place before unlocking RES adoption is not enough to ensure deployment. During the adoption process, it is crucial to pay attention to challenges that could emerge during their implementation. For example, Razmjoo et al. [71] pinpointed the lack of technical analysis of environmental impacts in the assessment process of RES adoption. Similar conclusions have been drawn by Tseng et al. [69] which revealed that "*institutions and policy, technical analysis, and environmental impact are the causal attributes supporting RES adoption, while institutions, policy adoption and technical analysis are causal attributes hindering RES adoption*" [69].

Innovation management in urban RES development need to address prior conditions such as policies and regulations that stimulate new cooperation and sustainable business model innovations. When a new institutional setting is implemented, the focus needs to be on the innovation capabilities to accelerate RES adoption, e.g., the ability to transform knowledge and ideas into RES-based solutions for the benefit of the partners involved and its stakeholders [10,69].

Innovation capabilities can accelerate the development of RESs during the innovation process [72]. Two different strategies have been identified, one addressing more radical innovations, implying new product solutions for new markets, and more incremental innovations addressing the improvements of existing products and services to make them more efficient, faster and/or cheaper for end-users. The chosen strategy also needs to be aligned with the organisation (including structure, management, culture, etc.) and the process (co-creation team), requiring education and learning assessments in several fields such as innovation management, RES technologies (both new and modified technologies) but also techniques and methods to generate technical, economical and sustainable analysis. Furthermore, leadership will be one important cornerstone during the transition phase, to address the dynamic and uncertain process towards RES adoption.

9. Conclusions

Cities have a crucial role in achieving a sustainable future due to their high contribution to global carbon emissions and energy consumption. To achieve this, urban areas must undergo a transformation that emphasises local and urban-level mitigation measures. This includes implementing innovative technologies and integration strategies that aim to reduce energy consumption and emissions. Additionally, comprehensive plans must consider all technical, social, and economic dimensions of cities. This paper examined the transition towards a more sustainable urban environment, with a focus on the building and transportation sectors.

The decarbonisation of cities requires the implementation of strategies aimed at reducing building energy consumption through measures such as building retrofitting and electrification of heat demand. These measures typically focus on improving the building envelope to minimise energy losses to the external environment and replacing less efficient generation systems with more efficient and/or renewable energy systems, such as solar photovoltaics. Recent trends emphasise the importance of efficient demand-side management systems to optimise energy consumption and generation in buildings, unlocking the potential of energy flexibility and resulting in reduced carbon emissions and operational costs.

Over the last decade, the concept of PEDs has attracted a lot of attention from researcher and policymakers. PEDs are urban areas where the balance between energy generation and consumption is positive (e.g., they generate more energy than what they consume). A PED is typically created by a combination of energy-efficient buildings, RESs, and smart grid technologies. However, developing PEDs in urban areas is a complex task, since several dimensions, e.g., geographical, environmental, land usage, technological and social aspects, need to be taken into account. As outlined by different authors, several gaps exist in the governance systems, participatory processes for citizens, and bottom-up approaches for creating synergies and co-creating standards for the design and implementation of PEDs, which require establishing comprehensive strategic plans tailored to each specific contexts.

The integration of the building and transport sectors has been recognised as a promising strategy to achieve sustainable urban development and mitigate the environmental impacts of urban areas. By combining efforts in both sectors, urban districts can achieve significant reductions in carbon emissions and energy consumption, while also promoting efficient land use and more sustainable transportation patterns. This is particularly important in megacities, which are often characterised by high population densities, intense economic activities, and significant transportation demands. In these contexts, the integration of the building and transport sectors can help optimise energy use and transportation infrastructure, reducing congestions and pollution, while also enhancing the overall quality of life for urban residents. Furthermore, this integration can foster the development of more resilient and adaptable urban systems, better prepared to cope with future challenges related to climate change and energy security.

In this context, innovation management plays an important role in managing the development and implementation of RES-based technologies, services, and processes, considering economic, environmental, and sustainable aspects during the innovation process. First, regulations and policies on both local and national levels, thus considering national context and geographical location, are essential pre-conditions for RES adoption. However, some challenges are linked to poorly attributed dissemination of renewable energy technologies, requiring co-creation solutions with stakeholders and end-users. During the adoption process, technical analysis of the environmental impacts and challenges that could emerge are essential. Education and learning assessments in innovation management, RES technologies, and techniques to generate technical, economical, and sustainable analysis are necessary. Leadership is an important cornerstone during the transition phase to address the dynamic and uncertain process towards RES adoption.

Finally, the paper highlighted the importance of establishing effective supporting financing mechanisms to support the diffusion of green technologies. These mechanisms should be designed to attract investments for novel green technologies as well as to tackle the financial barriers which limit the uptake of sustainable strategies at an urban level, especially those related to economically disadvantaged population and areas where critical infrastructure are located.

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