Energy Efficiency in Smart Cities

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Cities are constantly facing major challenges, mainly due to continuous population growth and their diversion to urban living. These challenges depend on cities' geography and culture but, not exhaustively, are, namely: congestion management, excess pollution, resource usage, absence of satisfactory physical and social infrastructures, necessity to maintain continuous sustainable economic growth, and increasingly narrower energy and environmental obligations. The energy transition on the roadmap to a decarbonized economy can never be implemented effectively, both in terms of costs and timing, without energy efficiency being the priority, and cities will have a crucial role in such a process.

modeling tools smart cities electrification energy efficiency

1. Introduction

The United Nations Sustainable Development Goals (Ref. [1], with special prominence to SDG 11 [2], together with the New Urban Agenda [3], are catching international recognition to ensure a strong contribution from cities on the road to sustainability, in the pursuit to "Make cities inclusive, safe, resilient and sustainable" [4]. Human life is going through a crucial phase, where efforts to achieve a sustainable balance with the environment are becoming more challenging. A clear example was the agreement reached in the European Parliament to bring the European Union (EU) to climate neutrality, through the approval of the European Climate Law, transforming the political commitment of the European Ecological Pact to bring the EU to climate neutrality by 2050 into a binding obligation, as well as providing European citizens and businesses with the legal certainty and predictability they need to plan their investments during this transition. After the 2050 horizon, the EU's objective will be to achieve negative emissions.

Currently, the generation of electricity is increasingly based on renewable sources, so switching from technologies that use fossil fuels to those that use electricity will generally reduce greenhouse gases (GHG) emissions and the energy dependence of most of the Member States. With the energy transition on the roadmap to a decarbonized economy, the role of electrification is essential, but it can never be implemented effectively, both in terms of costs and timing, without energy efficiency being the priority. A set of opportunities for energy efficiency in buildings, transport, and industries will allow energy savings by switching from inefficient fossil fuel technologies to more efficient electrical technologies. They also provide financial, environmental, health, and property benefits. Therefore, electrification must be seen as an energy efficiency measure if energy savings are achieved. Energy efficiency ensures a key role, not only in global climate change mitigation, but also in increasing the security of energy supply, business competitiveness, and social welfare [5][6].

In harmony is also the European Commission, regarding the EU's climate targets that must be supported foremost by the energy-efficiency-first principle [7], at least since the publication of the Council Directive 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE), and thus far, with the publication of Directive (EU) 2018/2002, amending Directive 2012/27/EU on energy efficiency (EED) [8], that energy efficiency is part of an ambitious European legislative framework to stimulate the rational use of energy. In Europe, the absence of energy efficiency policies would have contributed to about 12% higher energy consumption in 2013 [9].

Other EU energy efficiency policies are the Energy Performance of Buildings Directive [10], Ecodesign Directive [11], Energy Labelling Regulation [12], and Regulations for the Reduction of the CO_2 Emissions of Vehicles [13]. The Energy Performance of Buildings Directive (EPBD—2010/31/EU) is the main European legislative instrument to promote the energy performance of buildings, regarding energy efficiency and renewable energies national requirements, and requiring Member States to implement an energy labeling system for buildings and define the technical requirements for nearly zero-energy buildings (NZEB). The Ecodesign Directive (2009/125/EC) to improve efficiency in energy-related products currently covers more than 30 product groups. The Energy Labelling Regulation (EU 2017/1369), on the indication by labeling and standard product information of the energy consumption and use of other resources by energy-related products, currently covers 18 different products, and the Regulations for the Reduction of CO_2 Emissions of Vehicles (EU 2019/631) sets CO_2 emission performance standards for new passenger cars and new vans in the EU.

As **Figure 1** shows, the European Union leads the world decarbonization process of the energy sector through a comprehensive legislative framework, which has been designed since 2015, providing strategic tools at the Member State level for the creation of the Energy Union, where energy planning is fundamental to fit all initiatives within the scope of energy efficiency, to identify the best way to achieve the national assumed objectives reflected in the Paris Agreement of 2015 [14]. Thus, there is a clear need for a deeper exploration of the role of energy efficiency in energy planning, since the impact is not limited to a decrease in final energy consumption, but also has an impact on the energy supply side, namely, the need for available power for electricity generation (thus contributing to an increase in the share of the final energy consumption that is ensured by renewable sources), the need for investments to reinforce energy transmission and distribution networks, and non-energy impacts, namely, those that promote the improvement of quality of life.

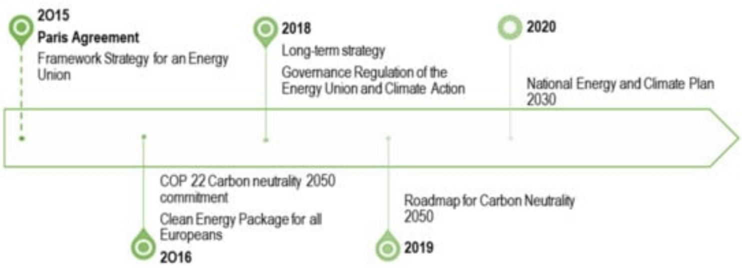

Figure 1. European Union decarbonization legislative framework since 2015.

Electrification is a key tool to change from fossil to decarbonized resources, namely, in the decarbonization of the building and transportation sectors [15]. However, this energy transition process involves a large increase in certain critical mineral needs [16]. In a scenario that meets the goals of the Paris Agreement, the participation of the energy sector in the total consumption of some key minerals increases significantly. Additionally, it is expected that electricity consumption will increase and since, currently, not all electricity generation can be based on renewable energy sources, it will be crucial that today's cities be smart in a short period and ensure efficiency on the final consumption. Therefore, energy efficiency should be the first fuel to be considered in this transition process [17][18][19][20].

2. Smart City Concept and Energy Efficiency

Different terms referring to similar concepts, namely, "Smart City", with "Sustainable City", "Future City", "Green City", "Resilient City", "Eco-City", "Low-carbon City", "Intelligent City", and "Digital City" being the most common [4][21][22][23][24][25][26][27][28][29]. The use of a combination of terms can also be observed, proposing or defining new concepts, occasionally for demarcation purposes, like, for example, the concept of "Smart Sustainable City" [27][30][31]. It can also be found terms used to highlight distinctive dimensions of their specific assessment such as the "Resilient City" or "Knowledge City" [4][29].

Although sometimes not exactly having the same focus, offering alternative development pathways in response to urban challenges [4], the use of different terms to address the "Smart City" concept has been generating terminological misunderstanding [25][32][33]. Nowadays, "Smart City" is probably the most prevalent and acknowledged wording among the majority of citizens, media, investors, companies, and public authorities [34]. Public authorities and the business sector, in general, are using this wording, as it is a buzzword comprehensible by the majority of the targeted stakeholders [27][34].

The increasing interest in "Smart City" and related concept terms are well documented in earlier bibliometric studies, which highlight its growth in scientific publications: Martin de Jong [29] refers to an exponential growth in the use of the "Smart City" term since 2009 when analyzing the period from 1996 to 2013, where "Sustainable City" had about two and a half times more retrieved articles. The same accelerating growth was also demonstrated by Wang [35] when analyzing the articles in the period from 1992 to 2016. In 2021, Schraven [4] extended the search until 2019, which covered the release of the UN's SDGs [1], the New Urban Agenda [3], and other more recent related initiatives. The bibliometric analysis of 35 different concept terms taken from a total of 148 revealed that "Smart City" and "Sustainable City" were the most used terms, with the first overcoming the second since 2012. "Smart City" has undoubtedly become the most investigated concept in recent years, being published in almost half (46%) of the total number of articles analyzed by Schraven [4] over the last 30 years, apparently due to the increasing adoption of smart technologies (IoT, big data, sensors, smart grids). Schraven [4] also realized that the two most-used terms have a very high level of co-occurrence with each other and significant co-occurrence with other terms, revealing their dominant position and influence, forming two clusters about "Sustainable City" (compact, low-carbon, green, and liveable—the "eco-cluster") and "Smart City" (intelligent, digital, future, ubiquitous, connected, and creative—the "techno-cluster"). Some more recent policy initiatives (e.g., "United for Smart Sustainable Cities" (U4SSC) [36] and the ISO 37122 standard for "Sustainable Cities and Communities—Indicators for Smart Cities" [37]) seem to try to contribute to the combination of the "Sustainable" and "Smart" city concepts, the overall goal of urban development defined in the first and the necessary technological resources to achieve it defined in the second [4].

There are similarities between the concepts of "Sustainable City" and "Smart City", but there are also some significant differences. Studies show that a "Sustainable City" is more focused on environmental and social aspects, while a "Smart City" is mainly focused on the technological, economic, and social aspects [38]. However, despite the low initial weight placed on the importance of environmental factors, the "Smart City" concept seems to be moving towards addressing sustainability issues. Traditionally, the "Smart City" has been interpreted as being more technology-focused instead, rather than the holistic conceptualization. Nevertheless, a holistic view of "Smart City" that includes, among many others, environmental issues is becoming more widespread recently. It is expected that the "Smart City" concept would leverage the technological infrastructure being deployed in an urban environment to deliver key "smart services", such as smart healthcare, smart homes, smart transportation, smart workplaces, smart government, and many others [39]. This perspective is found in academic literature [40][41][42] and regional or international organizations, such as the European Commission, the IEEE, and the United Nations.

The European Commission (EC) has a vision of smart cities that is beyond the simple use of technology and ICT. The EC points out that smart cities are more about the interaction between all cities' infrastructures with the aim of providing multiple benefits to different sectors. The EC [43] states that smart cities are *"Cities using technological solutions to improve the management and efficiency of the urban environment"*. It refers to the smart city as being *"a place where traditional networks and services are made more efficient with the use of digital and telecommunication technologies for the benefit of its inhabitants and business"*. It is also stated that *"a smart city goes beyond the use of information and communication technologies (ICT) for better resource use and fewer emissions. It means smarter urban transport networks, upgraded water supply and waste disposal facilities and more efficient ways to light and heat buildings. It also means a more interactive and responsive city administration, safer public spaces and meeting the needs of an aging population"* [43]. The IEEE has also a wider perception of the smart city concept in which technology is regarded as an enabler for an improved quality of life and to reduce environmental impacts [38]. The IEEE Smart Cities Initiative [44] states that *"a Smart City brings together technology, government and society and includes but is not limited to the following elements: A Smart economy, Smart energy, Smart mobility, Smart environment, Smart living, and Smart governance"* [44].

In "Smart Cities and infrastructure report" [45], the United Nations states that there is no standardized, generally recognized definition for the "Smart City" concept. It is although indicated as a reference on the report [45], the definition presented by the International Telecommunication Union (ITU) in 2014, after performing an analysis of about 100 different definitions. This definition was published on the ITU-T Y.4900 recommendations [46], with the following proposal: *"an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, the efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects"*. Even though this definition presented by the ITU [46] is actually for a "Smart Sustainable City", the United Nations uses it as a reference when citing the "Smart City" definition, asserting also that *"Governments and stakeholders need to work together to develop a common understanding of what Smart City means in their specific national and city-level contexts"* [45]. Currently, the United Nations refers to the "Sustainable Cities and Communities" term as a way to *"make cities and human settlements inclusive, safe, resilient and sustainable"* [47].

There is a wide variety of respectable studies aiming at the identification of the different dimensions of a "Smart City" [24][24][30][31][41][48][49][50][51]. They present different perspectives since the concept of a "Smart City" differs according to the different stakeholders, actors, and viewpoints of the literature [52]. In general, the literature points out the existence of seven main common different dimensions: People, Governance, Environment, Living, Mobility, Data, and Economy [24][30][41][48][49][50][51][52][53][54][55][56][57][58]. One of many common aspects is that energy and energy efficiency is considered one of the many sub-themes, usually inside the "Environment" dimension [41]. Considering all the multi-dimension concepts and all the different indicators inside them, energy efficiency concerns must be, directly or indirectly, taken into account and properly assessed on several of them when implementing a "Smart City" project. To have, for instance, an adequate and sustainable communications network (Data dimension), the efficiency of all the ICT equipment must be taken into account. Energy efficiency has to be considered in all technology-related dimensions, but even in the economy-related indicators, Energy Intensity is taken into account [49], which in some way is also related to energy efficiency. Almost all activities within cities require energy (i.e., transportation, work activities, security, entertainment, commerce, homes, etc.). Therefore, energy efficiency is becoming a crucial challenge for life in cities [59], and for the smart city implementations, that must be properly assessed.

With the increasing deployment of "Smart Cities", various smart city assessment tools with distinct evaluation indicators have been established [34]. These tools use different indicator sets for the overall assessment of a specific dimension of the smart city. Given that energy efficiency is usually integrated into the Environment dimension, it is important to properly evaluate the most adequate city energy systems modeling tools that can be used for a proper indicator calculation.

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