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More Circular City in the Energy and Ecological Transition: A Methodological Approach to Sustainable Urban Regeneration

Ginevra Balletto [1,*], Mara Ladu [1], Federico Camerin [2], Emilio Ghiani [3] and Jacopo Torriti [4]

1 Department of Civil and Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
2 Departamento de Urbanismo y Representación de la Arquitectura, IUU Instituto Universitario de Urbanística, Universidad UVA de Valladolid, 47014 Valladolid, Spain
3 Department of Electrical and Electronic Engineering, University of Cagliari, Via Marengo 2, 09123 Cagliari, Italy
4 School of Construction Management and Engineering, University of Reading, V Whiteknights, P.O. Box 217, Reading RG6 6AH, UK
* Correspondence: balletto@unica.it

Abstract: Cities consume over 75% of natural resources, produce over 50% of global waste, and emit 60–80% of greenhouse gases. The scenario that by 2050 two thirds of the world population will live in cities, highlights how cities are still responsible for the growing consumption characterized by linear economic processes, with the production of various types of waste. In this unsustainable framework, the Circular Economy offers the opportunity to shape the urban system by means of rethinking the possibility to produce and use goods and services, exploring new ways to ensure long-term prosperity. The Circular City paradigm contains in fact all the principles of the Circular Economy: recovery, recycling, and sharing. In particular, Circular City also introduces actions related to the development of renewable energy communities, use of green materials, CO_2 absorption approaches, and Proximity Cities. This work aims to develop a methodology to build a composite index (Circular City Index) capable of measuring the degree of implementation of urban policies that may enable an ecological transition of public assets. Circular City Index was applied to the military cluster of the city of Cagliari (Sardinia, Italy), a significant case study to guide circular policies in public properties for civil and military uses.

Keywords: circular city index; urban regeneration; renewable energy; ecological transition

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1. Circular, Green and Adaptive City

The Circular City is based on the dynamic principles of the circular economy [1,2]. In particular, with Circular Economy (CE) being a contested concept, a single universal definition of the CE is probably impossible, as the concept is also dynamic, constantly evolving [3] and interdisciplinary [4,5]. However, according to Paiho et al. (2020) [6]: "A circular city is based on closing, slowing and narrowing the resource loops as far as possible after the potential for conservation, efficiency improvements, resource sharing, servitization and virtualization has been exhausted, with remaining needs for fresh material and energy being covered as far as possible based on local production using renewable natural resources". Circular cities are the most suitable candidates to respond to the societal challenges tied to the rapid urbanization changes which project that by 2050 [7] over two thirds of people will live in cities, currently still predominantly anchored to the linear economy, or protagonists of the consumption of energy resources, as well as encourage a growing production of waste [8]. Cities, in fact, consume over 75% of natural resources, produce over 50% of global waste, and emit between 60 and 80% of greenhouse gases

[9,10]. In terms of solutions, cities attract creative talent and, thus, allow societal transformations toward sustainability in both the public and commercial sectors. Cities are among the most powerful entities that can impact development favorably if they transition to the circular city [11]. The Circular City is certainly not a new urban model [12], whose traces have been lost since the early stages of the industrial revolution, only to re-emerge in today's industrial 4.0 phase [13]. In particular, according to the definition of the Ellen MacArthur Foundation [14], principles of the Circular Economy can be found in all the urban functions of the circular city [15]. The Circular City therefore aims to eliminate the concept of waste air emissions to maintain value for performing goods and services; also, thanks to the support of the digital transition, the Circular City can generate prosperity, improve livability, and resilience [16–18]. The opportunities of the Circular City from storing carbon, recycled materials (concrete, lime, steel), renewable and sustainable energy with energy communities, proximity services to slow mobility are concentrated in urban regeneration [19,20]. The Circular City and the energy-ecological transition is the focus of the paper while the objective is to develop a methodological proposal of urban data analysis to implement a Composite Circular City Index to support integrated the pillars of the circular economy in three different urban scales. The case study is a large military area in Cagliari, Sardinia, Italy, located in proximity of a densely populated city neighborhood, which can be deployed for integrated use in sustainable urban energy regeneration. The manuscript is organized as follows:

- Section 2 provides a literature review that focuses on the challenge of the circular city in the twin transitions (Section 2.1); the energy demand in cities, developments and future challenges (Section 2.2); smart grid in the digital—energy transition (Section 2.3);
- Section 3 focuses on the materials, with particular attention to the management of public real estate in Italy (Section 3.1) and the current state of the military estate and energy transition (Section 3.2);
- Section 4 describes the proposed methodology to define the Key Performance Indicators (KPIs) used for Renewable Energy Communities (REC) (Section 4.1), the Circular City Index (Section 4.2) and the application to the study area (Section 4.3);
- Section 5 discusses the results of the case study;
- Section 6 contains the conclusion.

2. Literature Review

2.1. The Challenge of the Circular City in the Twin Transitions

Different transitions are in progress: the ecological one, and the digital-energetic, apparently distinct, represent the answer to the critical aspects of the complex city-territory and environment relationship, further aggravated by the recent health and delicate, environmental and energy emergency [21–23]. The European Union is trying to accelerate the transition from the current linear economy to a circular economy and consequently the quest for a circular city arises [24].

The circular economy is, in fact, considered a means to attain sustainable development goals (SDGs). Most of the relationships are straightforward, and here we mention a few that could be less immediate to spot:

1. SDG 4 (quality education): the circular transition is related to increased environmental and civic education of all the citizens, who must actively contribute to its implementation;
2. SDG 8 (decent work and economic growth): shifting the economic model from a linear one to a new one based on the low cost of materials, lack of externalities and costs and strong automation of processes toward a circular one based on maintenance, reuse, regeneration and recycle would create knowledge-based jobs not replaceable from robots;

3. SDG 9 (industry, innovation, and infrastructure): the circular economy represents an overall vision that shapes all specific initiatives (industry 4.0).

From a circular economy perspective, it is possible to consider the seven main pillars in the three main Urban Scales (US) (Figure 1): from the small scale (building), to the medium (buildings area) and the large scale (cluster of buildings).

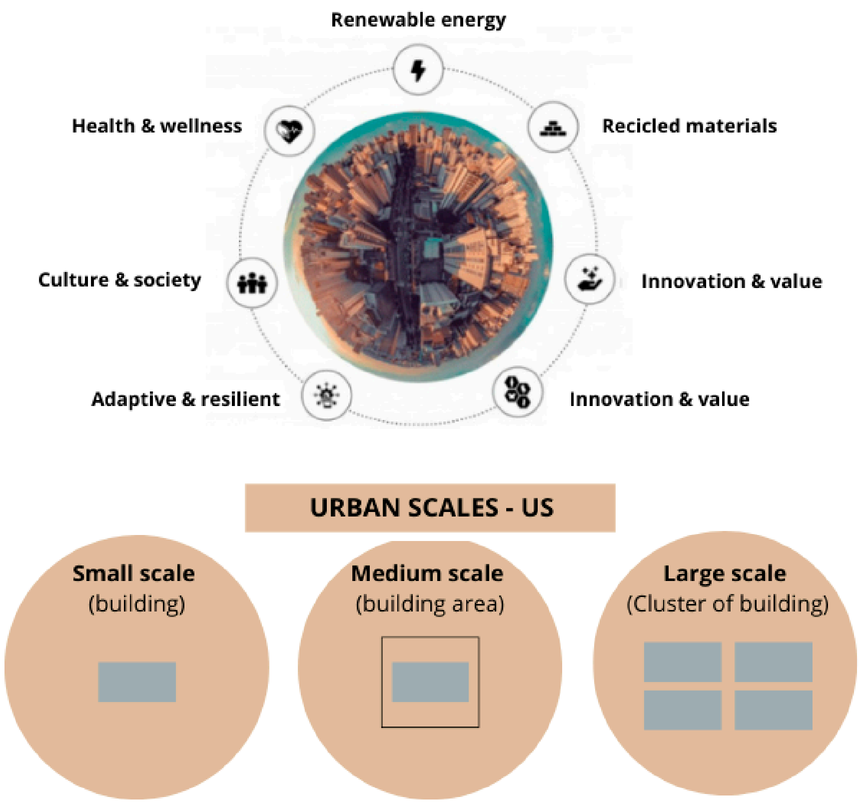

Figure 1. Pillars of the circular economy in relation to the three Urban Scales—US (Author: Balletto G., 2022).

The US represents the main dimension of the virtuous international cases of the circular city extrapolated from the literature [25–27]. Furthermore, increasing the urban scale (from small to large) of circular city projects favours the ecological energy transition from "building" to "district". This direct proportionality relationship constitutes an important added value to also guide the urban-scale size choices of regeneration policies. The use of the recycled materials is a transversal challenge supported by several studies. In this sense, the research project entitled "Materials for Building and Sustainable Infrastructure" (MEISAR project), which involved some authors of the present study, has been pivotal in addressing these challenges and developing an interdisciplinary approach on Construction and Demolition Waste (CDW) and secondary raw materials. The MEISAR project—https://meisar.org/en/ (accessed on 25 September 2022)—focused on several aspects, including the experimental investigation on the properties of concrete (resistance and durability) [28,29] and the analysis of methods for improving the microstructure of recycled concrete aggregate [30].

Finally, the use of the recycled materials is a strategic action of the six missions of Italy's recovery and resilience plan (PNRR) (innovation; digitalization; competitiveness; culture; and tourism; green revolution and ecological transition; infrastructures for sustainable mobility; education and research; inclusion and cohesion; health) which converge directly and indirectly towards circular city [25,26]. The PNRR is the plan approved in

2021 by Italy to relaunch its economy after the COVID-19 pandemic in order to allow the country's green and digital development. (European Commission, 2021 [24]).

2.2. Energy Demand in Cities: Developments and Future Challenges

Cities are at the forefront of developments in the energy field because of their increasing share in demand and changes in patterns of generation and consumption. With regards to trends in volumes of energy demand, according to estimates by the International Energy Agency (2008) [31] cities will account for 73% of the world energy demand of global electricity consumption by the year 2030. Cities are at the heart of developments relating to the move to extend electrification to areas of energy demand (i.e., heating and transport), which previously relied on fossil fuels [32]. In this context, fully electrified Smart Cities will experience the massive penetration of electric vehicles and heat pumps on every street and in every home [33], and a correspondingly massive increase in electricity demand [34].

A solution to match the increase in energy demand in cities consists of expanding the generation base associated with renewable energy supply, including from public assets such as those explored in this paper. These novel generation solutions may involve disused public properties and can be understood in the context of the integration of renewable energies in public sector buildings, including solar and geothermal energy [35].

At the same time, the presence of more renewable sources of electricity means that there will be less flexibility in generating electricity [36]. In order to overcome this challenge, a combination of smart grids and smart meters are supposed to provide the infrastructural basis for the delivery of flexible, affordable, reliable, and efficient power in cities [37]. "Smart" is an overused term, because it is mentioned in various contexts, sometimes even inappropriately; in the context of electrical systems, the term refers to the use of information technology, to communication systems, and to the whole set of sensors that can be used to detect data and actuators used to control systems in urban or suburban environments. The key aspect, however, that makes the systems smart is not the technologies themselves, because it is well known that all new technologies that are proposed are inherently smart. What is important is how the data are then collected from the ground and used both in real time and to do planning studies for the future. It is in this context that the demand for electricity in Smart Cities will involve the capacity to use energy in different locations at different times of day or year (via storage or by changing the timing of activity including whether it takes place at all); to switch fuels; to smooth or create peaks in demand; or, in the case of mobility, to re-arrange destinations and journeys in ways that reduce energy demand or congestion. Storing electricity, changing the timing of an activity, switching fuels, smoothing peaks in demand, increasing demand when renewables generation is available (for instance on sunny and breezy Sunday afternoons in the summer) are all examples of the challenges of energy demand in Smart Cities [38]. Cities will be confronted with complex decisions in relation to the mix of renewable sources, types of fuels, and levels of automation in demand management [39]. Changing patterns of energy generation and consumption are more likely to be adopted by wealthier urban populations and on an experimental basis by specific communities within the city [40]. For this reason, policies aimed at the expansion of electrification need to consider the portfolio of public assets—such as disused public properties—as ways to support energy transitions in equitable ways.

2.3. Smart Grid in the Digital—Energy Transition

As mentioned in the earlier sections of the manuscript, in order to achieve the electricity system decarbonization targets of the Sustainable Development Goals (SDGs) and the zeroing of greenhouse gas emissions by 2050, the European Union (EU) has placed particular emphasis on reducing energy consumption and improving energy efficiency in cities, supporting specific measures adopted by Member States to improve economic and environmental sustainability [41].

A paradigm shift toward a holistic, multi-generation approach can achieve more significant benefits by integrating energy infrastructure for electricity, natural gas, and district heating networks and by creating energy hubs in urban neighborhoods of future smart cities with smart grids. Planning and design of a city district therefore requires an interdisciplinary approach to planning, which must consider existing energy systems, analysis of building energy consumption (electric and thermal, for example), and the predicted development toward electric mobility. In this context, the participation in sustainable energy development of all stakeholders including citizens, institutions, and productive activities (e.g., small and medium enterprises) is one of the viable paths through the implementation of energy communities including renewable and non-renewable energy self-consumption user aggregates. In fact, energy communities, firstly outlined in the Renewable Energy Directive (RED II) [42], and in the Electricity Market Directive (IEM) [43], recently transposed to the Italian regulatory framework [44,45], introduce new legal entities in which citizens, "SMEs and local authorities, cooperate in the generation, consumption, distribution, storage, supply of energy, or in providing energy efficiency and the and service management (regardless of renewable energy) (e.g., CEC—Citizen Energy Communities), or citizens, SMEs and local authorities owns the objective of providing, through renewable energy production and sharing activities, environmental, economic and social benefits to the community" (e.g., REC—Renewable Energy Communities). In the future smart city, city district with RECs may supply public and residential electrical consumption, air conditioning, water heating and cooling, electric and thermal storage (heat pumps with tanks), transportation and public lighting, as well further energy services. The use of ICT and Internet technologies related to the smart grid development will help to control the electrical energy production of PV-plants, the electric vehicles charge/discharge, as well as to implement demand side integration (DSI) and demand side response [46].

In relation to qualitative and quantitative sustainability impact assessments and benefits of RECs, it is important to highlight that the electricity produced and fed into the public grid, consumed virtually by members of the energy community, is called shared energy and valued through an incentive tariff, identified by the Italian government. The incentive is paid by the Energy Services Manager (*Gestore dei Servizi Energetici*—GSE) directly to the energy community entity over a 20-year period. It is currently a premium tariff (equal to 100 €/MWh for self-consumption groups and 110 €/MWh for energy communities). Incentives are distributed internally among the members, according to rules established by them. A list of key indicators to evaluate the REC performance is analysed in Section 4.1. Within this framework, the presence of public administrations in the establishment of REC offers important opportunities. In particular, large public assets embedded into regeneration plans can significantly contribute to developing REC in a more extensive circular city approach. In this context, military sites are the focus of this work.

3. Materials

3.1. Public Real Estate Management in Italy

The Management of Public Real-Estate Assets (PREA) is an important issue at the core of international debate [47,48] and is gradually playing a prominent role in the implementation of public policies based on the circular economy paradigm.

As a matter of fact, the divestment phenomena of public properties relies on factors such as technological advances and new economic models, digitalization of public administration and changing geopolitical conditions after the end of the Cold War [49]. This situation solicits national and local governments to face the challenge of reusing a substantial number of buildings and areas that belong to different public bodies [50]. More precisely, the urban regeneration process oriented to improve the quality of the PREA, in terms of technological innovation and design, could contribute decisively to the implementation of the Circular City.

In the Italian context, the inadequacy of a comprehensive inventory on the current state of public assets, the frequent alternations between the political parties in government and the resulting lack of a clear long-term strategy has made the management of PREA a challenging issue [51,52]. Despite the idea of PREA as an unproductive resource [53], PREA may play an irreplaceable role as due to their testimonial and cultural memory value tied to the idea of nation and as a potential opportunity to create new income and provide public services [54].

Most recent initiatives aim to facilitate the transition of military properties to the status of semi-commons or commons [55], also through "Difesa Servizi Spa", an in-house company of the Ministry of Defence (MoD)—Law no. 191/2009 (2010 Budget Law), established to manage and enhance this specific portfolio [56]. "Difesa Servizi Spa" proposes on the real estate market those properties characterized by a marked vocation for dual use (civil and military use), which may be involved in regeneration projects, thus creating multiple benefits for investors and for the territory. Considering that the alienation of the asset is not permitted, properties remain in the full availability of the public owner in this type of real estate operation.

The purposes of the Green Barracks Project (GBP), launched by the Italian Army in 2019 to renovate the most strategic military sites across the national territory, are in line with this recent sustainable approach [57]. Among the 26 strategic military sites selected by the GBP project, two are located in the Sardinia Region. The cluster of military buildings located in the Municipality of Cagliari has been selected as a case study for this research (Section 4.2). With a total investment of 1.5 billion over 20 years, the GBP pursues two complementary objectives: to achieve higher levels of architectural quality; to define a new functional organization that allows to share socio-recreational and sports facilities with the local community and, therefore, to promote the 'dual use' of military sites and greater social inclusion [58]. In this sense, the GBP, if properly channelled and inserted into urban planning analysis and policies, can represent an opportunity to build new relationships between military sites and the city, within more comprehensive urban regeneration projects [59] according to the Circular City paradigm [60]. Within this national project, the energy transition of military estate constitutes a pivotal element worth analysing and a pillar for enabling the Circular City model.

3.2. Military Estate and Energy Transition

Military urban land may constitute a relevant opportunity for introducing ecological transition measures for the following reasons. The first is that the MoD is one of the largest landowners in Italy, so the availability of public-owned assets may facilitate these operations. The total surface dedicated to military use covers 783.05 km^2 and the military safety zones reach 451.76 km^2, for a total of 1234.81 km^2, being about 0.411% of the Italian territory [61]. The second is the wide variety of military settlements, which cover different use and location due to military purposes, from isolated administrative buildings to barracks, and from well-developed bases to training areas without any sort of infrastructure. The different kinds of settlements, such as airports, arsenals, barracks, naval bases, and warehouses, may be the ground on which to propose a variety of measures for urban and non-urban environments. The third is the particular characteristics of the internal morphology of a specific settlement, i.e., the barracks. Being introduced for soldiers' accommodation in the 19th century, the morphology follows specific architectural and urban schemes according to the international debate among military engineers [62]. The buildings were surrounded by wide open and green spaces, such as tree-lined avenues and squares, intended for circulation, training, and free time. These characteristics give military barracks the value of "self-sufficient cities" for the soldiers [63]. However, many barracks fail to meet modern architectural, energy, and technological standards and also find themselves in an unacceptable state of conservation for the military purpose of the 21st century [64]. At the end of the 90s the Italian government launched rationalization policies for the MoD in order to close thousands of military sites following geopolitical changes and the tendency to handover the management of public properties to local municipalities and private actors following neoliberal patterns [65]. The transfer from military to the civilian domain has resulted in multiple challenges for those responsible for their redevelopment and opportunities for the civil society to achieve an integrated urban regeneration [66]. Moreover, the rationalization policies aimed to create a smaller and significantly better estate that effectively supports the armed forces in accordance with current societal challenges, such as climate change and reducing expenditure in managing the assets. Among these challenges, the ecological transition is one of the most striking policies adopted by the MoD itself. Following a general trend occurring in Europe [67], the Italian Government embarked in 2019 on the Defense Energy Strategy [68], the implementation of which was entrusted to the "Defence Task Force for Real Estate Development, Energy and the Environment" in 2021. On this basis, the MoD officially launched the ecological transition of the military apparatus in the early 2022 [69] aimed at bettering energy efficiency and energy independence [70]. This new energy-oriented policy, in turn, is about containing expenditure, protecting the environment, and improving logistics and infrastructure sectors. The transition is fundamental to improve the energy performance of military buildings currently used by the MoD, which cover 760,000,000 m^2 of the Italian territory [71], for a total annual expenditure on electricity consumption of 127,000,000 €. Among the several actions of the Recovery Fund priorities aimed at the ecological transition of the MoD, the main priorities are two. First, the creation of smart military districts to maximize self-consumption and the energy flows. These new districts would result in the technological development of the districts' surroundings and the attraction of industrial interests and investments that would eventually benefit the economic and social development of the communities concerned [72]. Second, the Article 20 of Decree-Law 17/2022 (the so-called "Energy Decree") establishes that the MoD shall grant concessions or directly use military assets to install plants for the production of energy from renewable sources. The purpose of the regulation is the pursuit of national energy resilience, the sustainable growth of the country, and the decarbonisation of the energy system. Afterwards, the Article 9(1) of Decree-Law No. 50/2022 fully replaced Article 20(2) of Decree-Law No. 17/2022. This change regards the possibility to entrust to the MoD and the third-party concessionaires of military assets the power to set up national renewable energy communities, also with other central and local public administrations. In this sense, the present study proposes a methodological approach to build a composite Circular City Index (CCI) capable of assessing and monitoring the contribution of military sites in the implementation of the Circular City model.

4. Methodology and Data

4.1. Renewable Energy Communities (REC): The Key Performance Indicators (KPIs)

According to the literature review (Section 2), a list of key performance indicators (KPIs), is proposed to evaluate the REC performance and a comparison between the ex-ante scenario and the ex-post development scenario, as summarized in Table 1.

Table 1. Performance indicators used to analyse the REC—Renewable Energy Communities. Author: E. Ghiani (2022).

Performance Indicator	Description	Range
SCP (%)	Self-consumed over the total energy produced over a set period in the city district	0–50
STC (%)	Shared energy over total energy consumption of the community over a set period in the city district	0–50
EFET (%)	Ratio between energy fed to the grid and energy with-drawn from the grid over a set period	0–100
SCSTC (%)	Ratio between the sum of self-consumed and shared energy over the total energy consumption of the community over a set period	0–100

A more thorough description of the equations for evaluating the parameters used in the paper is reported in the following:

SCP is defined as the total energy self-consumed over the total energy produced by renewable generation plants for the period in analysis. This metrics is informative about the ability of instant physical self-consumption of the energy produced by the renewable generation plants in the city district.

$$SCP = \frac{\sum_j^N SC_j}{\sum_j^N TP_j} \cdot 100 \quad (1)$$

where: N is the number of periods over which the parameter is computed, SC_j (kWh) is the self-consumed energy over the j-th period and TP_j (kWh) is the total energy produced over the j-th period.

STC is defined as the energy used for the calculation of the sharing incentive over the total energy consumed by the community. The parameter thus defined provides information about the ability of the community to meet its energy needs through locally produced energy:

$$STC = \frac{\sum_j^N SE_j}{\sum_j^N TC_j} \cdot 100 \quad (2)$$

where: N is the number of periods over which the parameter is computed, SE_j is the total energy shared over the j-th period and TC_j is the total consumed energy over the period j-th and defined as the sum of the energy withdrawn from the grid and the self-consumed energy:

$$TC_j = ETG_j + SC_j \quad (3)$$

where: ETC_j is the energy withdrawn from the grid over the j-th period.

EFET is defined as the energy fed to the grid over the energy withdrawn from the grid. If greater than 100, the energy fed to the grid exceeds that withdrawn. This parameter gives a general idea whether the PV plant for the community is balanced.

$$EFET = \frac{\sum_j^N EFG_j}{\sum_j^N ETG_j} \cdot 100 \quad (4)$$

where EFG_j (kWh) and ETG_j (kWh) are, respectively, the energy fed and withdrawn from the grid over the j-th period.

SCSTC is defined as the ratio of the sum of the total self-consumed energy and the shared energy over the total energy need.

$$SCSTC = \frac{\sum_j^N SC_j + SE_j}{\sum_j^N TC_j} \cdot 100 \quad (5)$$

SCSTC has been designed with the aim to evaluate the ability of the community to satisfy its energy demand by self-consuming; self-consumption can be considered as an avoided expense whilst the shared energy is incentivized. Hence, the KPI relates quantities that can provide economic benefits to the community in relation to its total consumption.

On the other hand, if the interest is to evaluate the sustainability of the REC, it is possible to achieve such a result by jointly considering the EFET and SCSTC KPIs to understand whether the community is taking advantage of the economic incentives in relation to the energy locally produced and define the sharing of the benefits according to specific rules [46].

Furthermore, RECs are a legal entity operating in a city district: which is based on open and voluntary participation; whose shareholders or members who exercise control power are individuals, small and medium-sized enterprises (SMEs), local authorities, as per art. 31, paragraph 1 letter (b) of Legislative Decree 199/21; whose main objective is to provide environmental, economic or social benefits at the community level to its shareholders or members or to the local areas in which it operates.

4.2. The Circular City Index

The methodology is aimed to develop a Circular City Index based on a bibliometric analysis followed by an interpretative review of the literature as well as the KPIs used to analyse the REC (Section 4.1). The proposed Circular City Index is applicable for both ex-ante and ex-post scenarios in the different three urban scales (US) previously described (Section 2.1): Large; Medium and Small urban dimension. In particular, the proposed methodology is aimed at evaluating the Circular City Index, where the circular economy can become not only a moment of possible 'choice' but also the significant expression of the urban environment with multiple benefits—related to environment, health, and well-being, both individual and collective, in line with the objectives of the 2030 Agenda. The method is based on the 7 pillars of the circular economy declined by the 4 focuses and 10 key performance indicators that make up the circular city index (Table 2).

Table 2. Framework of pillars of circular economy, focus, SDGs, literature, and key performance indicators (KPIs) of Circular city. Author: G Balletto (2022).

Pillar of Circular Economy	Focus	SDGs	Literature	Key Performance Indicators (KPIs)	Ratio %
Recycled materials Innovation & Value	(1) Green and recycled materials	12	Omer, et al. (2022) [73] Balletto, et al. (2021) [74] Burghardt, et al. (2021) [75]	(1.1) All recycled material	UD/UD
Protects biodiversity Innovation & Value	(2) CO_2 uptake	13	Shafique, et al. (2020) [76] Furcas, et al. (2014) [77]	(2.1) Green area (2.2) Recycled materials (cement-lime)	UD/UD
Sustainable energy Innovation & Value	(3) REC	7	Carrus, et al. (2021) [78] Di Silvestre. et al. (2021) [79] Ghiani et al. (2019) [80]	(3.1) SCP (3.2) STC (3.3) EFET (3.4) SCSTC	UD/city district of REC
Culture & society Health and wellness Adaptive and resilient Innovation & Value	(4) 15 Minute and Proximity City	11	Moreno, et al. (2021) [81] Li, Z., Zheng, et al. (2019) [82] Balletto, et al. (2021) [83]; Badii, et al. (2021) [84]	Central places: (4.1) of movement (4.2) of welfare (4.3) of commerce	15 min of UD/city district of REC

Also, that city district of REC derives from art. 31, paragraph 1 letter (b) of Legislative Decree 199/21; whose main objective is to provide environmental and economic benefits.

The proposed focuses derive from a bibliometric analysis followed by an interpretative review of the literature and are (Table 2):

1. Green and recycled materials—in particular the concrete, plaster and steel;
2. CO_2 uptake- both from: green areas (phenomenon of photosynthesis) and cement and plaster (phenomenon of carbonation);
3. Renewable Energy Communities REC—City district;
4. 15 Minute City and Proximity services—accessibility to the main urban facilities.

Furthermore, the key performance indicators proposed are coherent and integrate the seven pillars of the circular economy at the basis of the prosperity of the urban ecosystem of the circular city [85] which by its nature intensifies the symbiosis in its urban system [86].

In fact, the urban ecosystem is a dynamic ecosystem that has similar interactions and behaviours as natural ecosystems. Unlike the natural ecosystem however, the urban ecosystem is a hybrid of natural and man-made elements whose interactions are affected not only by the natural environment, but also culture, personal behaviour, politics, economics and spatial planning [87].

The spatial and temporal scales at which a city operates mirror that of an ecosystem. In particular, an urban ecosystem is composed of an "… evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations …" that connect actors, activities, and artifacts [88].

To improve the integration between the components of the urban ecosystem to favor sustainable urban evolution [89] a synthetic index of circular city was developed, inspired by the Simpson index. Indeed, the Simpson index finds wide application in ecology to represent environmental ecological diversity, i.e., the represents an index of representativeness of an ecosystem.

The Simpson diversity index, used in statistics in the case of populations with a finite number (in the case of index D) of elements:

$D = 1 - \log \lambda$ (where D is between 0 and 1 and where λ corresponds to the Simpson concentration index in the case of a finite population.

$$\lambda = \frac{\sum_j Nj(Nj-1)}{N(N-1)} \tag{6}$$

$$D = 1 - log \sum_j \frac{Nj(Nj-1)}{N(N-1)} \tag{7}$$

where Nj indicates the number of j-th "species", specifically the key performance indicators of circular city.

The systematization of the literature referred to in Table 2 has made it possible to develop the CCI.

4.3. Study Area

The presence of abandoned or still-in-use military sites in urban areas or in close proximity to them is a particularly relevant issue in Italy and the specific military presence in Cagliari and Sardinia Region is relevant due to its pivotal role during the Cold War in the Mediterranean area [90,91]. The city of Cagliari is the capital of Sardinia Region and the most important cultural, economic, political, and administrative center of the Region. It has been a Metropolitan City since 2016, a new administrative structure of 17 municipalities. The Municipality of Cagliari hosts over 150,000 inhabitants, while the Metropolitan Cityspans over 400,000 inhabitants [92].

It plays a role as the major urban area in the Island, as well as a military headquarter for the simultaneous presence of important installations and bases of the different forces, namely, the Italian Army, Navy and Air Force. As a result, we can register important figures (58 units) of military buildings and barracks, offices, and residences, organized into clusters, with an extension of about 2 million m^2 in the urban area [93]. The present study focuses on the urban cluster of military buildings located in the Cagliari city, Sardinia, Italy (Figure 2), in a landscape context characterized by significant environmental components and geographic endowments [94], mixed with historical military settlement processes.

Figure 2. Cluster of military buildings in the city of Cagliari (Author: M. Ladu, 2022).

In particular, the cluster of military barracks of the GBP, consists of four units: three barracks complexes (MB01, MB02, MB03) and one area equipped with services and other facilities (MB04), with a total area equal to 279,981.325 m^2 (MB = military building; MB01 = 36,764.967 m^2; MB02 = 129,806.581 m^2; MB03 = 84,081.493 m^2; and MB04 = 29,328.315 m^2).

In line with the GBP objectives, which also provide for the mixed civil-military use of some portions, the urban regeneration of the barracks complex (cluster) is proposed, aimed at obtaining—within the circular city paradigm—the following actions: to use of green and recycled materials; to promote CO_2 uptake; to produce, use and share of the sustainable green energy (ICT, smart grid) and to foster the 15 Minute City and Proximity paradigms (urban design proposal).

In line with the Legislative Decree 199/21 on the use of energy from renewable sources, the proposed city district of REC (Figure 2) comprises the neighborhoods of La Palma, Quartiere del Sole, Sant'Elia Its main objective is to provide environmental, economic, or social benefits at the community level to its shareholders or members or to the local areas in which it operates. The Circular City Index was then evaluated andapplied to two different scenarios, "ex ante" and "ex post". From the endowment and spatial distribution of information (geo-database built by the authors in previous research [83,95] relating to the city of Cagliari, the following is obtained (Table 3).

Table 3. key performance indicators (KPIs)—Ex ante and ex post scenario. Author: Balletto G. (2022).

Key Performance Indicators (KPIs)	Ratio %	Ex Ante Scenario	Ratio %
(1.1) All recycled material	cluster/cluster	0	30
(2.1) Green area;	cluster/cluster	5	30
(2.2) Recycled materials (cement-lime);		0	80
(3.1) SCP	cluster/city district of REC	0	50
(3.2) STC		0	50
(3.3) EFET		0	90
(3.4) SCSTC		0	90
(4.1) Places of movement (local public transport, sharing mobility)	15 min area/city district	20	45
(4.2) Central places of welfare (school, park, health care)		21	42
(4.3) Central places of commerce (market, bar-restaurant, urban trade)		24	43

5. Results

Following a comprehensive literature review on the Circular City paradigm (Section 2.1), this study proposes a quantitative methodology to build a composite CCI based on the seven pillars of the circular economy and the four main topics (Green and recycled materials; CO_2 uptake; REC; 15 Minute City and Proximity City) chosen for the analysis. The proposed CCI is to be understood as the systematisation of the literature referred to in Table 2 within the paradigm of the circular city.

According to this approach, the CCI has been applied to the large urban scale in the city of Cagliari to assess the degree of circularity of the ex-ante and ex-post scenarios. The evaluation of the CCI referred to the 279,981,325 m^2 cluster of military buildings (001 MB–004 MB) included in the GBP (Section 3.1) and was developed through the combination of 10 KPIs in the Simpson formula.

The output data (Table 4) revealed the performance of the GBP regeneration strategies in terms of circularity, producing a significant increase in the CCI index. More precisely, regarding the challenge of the proximity city, the CCI grows from 0.81 (ex-ante scenario) to 0.98 (ex-post scenario), which is almost the highest performance. At the same time, the beneficiary population of the proximity city also increases from 12,126 to 16,937 inhabitants.

Table 4. Comparison of scenarios: CCI and Beneficiary population. Author: Balletto G. (2022).

	Ex-Ante Scenario		Ex-Post Scenario		
	CCI	Beneficiary population (proximity city)	CCI	Beneficiary population (proximity city)	Beneficiary population (REC—Renewable Energy Communities) city district [96]
Cluster of Military Buildings	0.81	/	0.98	/	
Beneficiary population	/	12,126	/	16,937	20,091

The isochrones of the 15 min city describe this phenomenon (Figure 3).

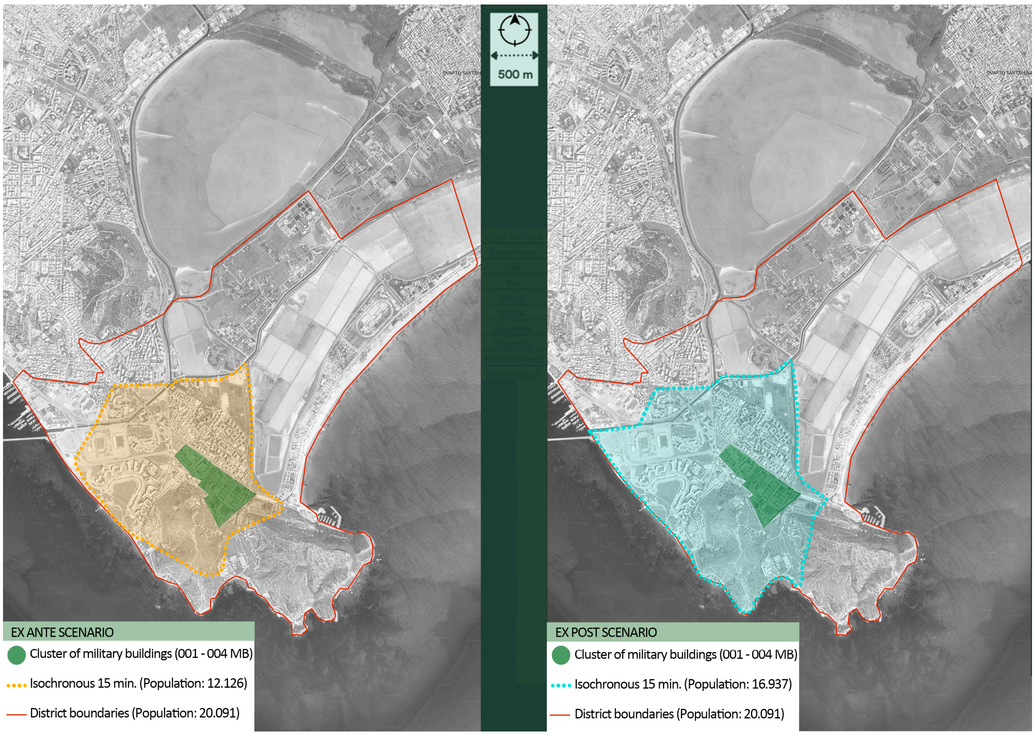

Figure 3. Isochronous 15 min by foot (ex-ante and ex-post scenario) related to the cluster of military buildings within the district boundary of the REC. Author: M. Ladu (2022).

Regarding the REC, the urban scale corresponds to the district area that the cluster of military buildings can satisfy in terms of energy production capacity (Figure 3). Table 4 shows that the beneficiary population of the REC exceeds 20,000 inhabitants in the ex-post scenario. This output cannot be assessed in the ex-ante scenario because the REC does not yet exist.

The main results, summarized in Table 4, highlight the role of the CCI in supporting the urban regeneration process at the large scale (building complex). As a matter of fact, the military cluster analyzed in Cagliari, due to its obsolescence, size, and urban location, requires strategic actions in line with the Circular City paradigm. These aspects are very important, especially if we consider that the draft of the new City Plan is ongoing. [97].

Moreover, the scenario assessment confirms the CCI as a useful tool in the main phases of the PREA management process:

- the cognitive phase, because it describes the ex-ante condition of PREA;
- in the urban and economic planning phase;
- in the design phase, as it supports design choices in coherence with the Minimum Environmental Criteria (MEC) [98], which in Italy should be respected in all interventions on PREA. The MEC are green criteria introduced to support public bodies in the ecological transition phase, which requires the implementation of the life-cycle approach in public governance;
- in the monitoring phase, which is after the conclusion of the regeneration project.

6. Conclusions

The ecological transition of existing urban military assets can provide a multi-faceted response to the challenges towards resilience and sustainability that society is currently facing and reducing dependency on fossil fuels wherever possible will contribute to the Governments' legal obligation to net zero greenhouse gas emission by 2050, taking advantage of new and emerging energy technologies as well as the new regulations for renewable energy production and sharing among citizens.

In this context, this paper develops an investigation along two main lines of research.

Firstly, the paper provides a comprehensive reflection on multiple use of military estate according to the Italian legislative framework and military estate rationalization policies. The analysis explores the regeneration strategies of military sites proposed by the Green Barracks Project (GBP) of the Italian Army that fits well with the pillars of the circular city. This approach allows the exploration of two dimensions of interventions, which can be summarized in the proximity city and renewable energy community models. In fact, the regeneration of military sites represents an opportunity to transform urban enclaves into transit nodes within a deeper network of material and immaterial relations with the city and into energy production hubs with an impact at different urban scales.

Secondly, the research provides a methodology to measure, evaluate, and monitor the degree of circularity of interventions from small to large scale (military cluster and district), consistent with those proposed by the GPB. The complexity of redeveloping military estate for both the military and civil society implies a multi-dimensional approach that led the Authors to build a composite Circular City Index (CCI) capable of assessing and monitoring the contribution of military sites in the implementation of the Circular City model. The CCI based its foundation on the seven pillars of the circular economy, the 4 main topics and the 10 keys performance indicators (KPIs) chosen for the analysis. The model is applied in an ex-ante and ex-post scenario with the aim of shedding light on the current condition of the military compound, defining the project and monitoring its performance once the regeneration measures have been implemented. The method also allows assessing the beneficiary population of the proximity city and renewable energy communities. This is a relevant aspect because proximity city and Renewable Energy Communities (RECs) coincides respectively with the 15 min isochrones (ex-ante and ex-post scenario) and the district area that the military buildings cluster can satisfy in terms of energy production capacity.

The choice to apply the CCI in the specific military cluster in Cagliari relied on the availability of data provided by GBP and the strategic location in the surroundings of urban neighborhoods.

The case study analysis of Cagliari has been pivotal in addressing a less-studied kind of public assets, which is still waiting for regeneration. These assets were not envisaged within ad hoc policies to address societal challenges in terms of territorial government.

The methodology approach proposal is exportable to other military clusters in urban areas and other public-owned sites with similar architectural and dimensional characteristics to the case study. In this sense, the regeneration of large military and public-owned assets may be an opportunity to create new urban centralities in terms of new functions for the civil society and potential energy production hubs serving local communities, in according to the pillars of circular city

The research presented here is intended to be the beginning of a broader interdisciplinary development that includes:

- the construction of an open dataset functional to the construction of CCI;
- a periodic review of key performance themes and indicators to improve the reliability of the CCI
- develop CCI integration processes within the framework of public policies for sustainable development (performance indicator)

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Glossary

CCI	Circular City Index
CDW	Construction and demolition waste
DSI	Demand Side Integration
GBP	Green Barracks Project
MB	Military Building
US	Urban Scale
MoD	Ministry of Defence
PREA	Public Real-Estate Assets
REC	Renewable Energy Communities
EFET	Ratio between energy fed to the grid and energy withdrawn from the grid over a set period
SCSTC	Ratio between the sum of self-consumed and shared energy over the total energy consumption of the community over a set period
SCP	Self-consumed over the total energy produced over a set period in the city district
STC	Shared energy over total energy consumption of the community over a set period in the city district.

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