

## Article

# Embedding Circular Economy Principles into Urban Regeneration and Waste Management: Framework and Metrics

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**Abstract:** In a highly urbanised world, cities have become main centers of resource consumption and generation of waste. The notion of the circular economy (CE) identifies strategies for slowing and narrowing resource use through the prevention of waste, improvement of resource use, and substitution of the use of primary resources with recovered materials (and energy). The literature has recently started to explore the concept of circular cities, and a number of cities around the globe have adopted circular economy strategies. Urban regeneration can play a critical role in enabling more circular loops of resources and contribute to more sustainable urban environments; however, there is a lack of contributions in the literature that explore the circularity of urban regeneration projects. The aim of this research is to address this gap by providing a framework and metrics to embed circular economy principles into urban regeneration. The proposed framework and set of metrics are then applied to a case study in West London to quantitatively assess CE implications and point to opportunities to increase circularity. Three main scenarios are developed to assess resource impacts of different waste strategies. The maximizing recycling scenario suggests that over 65% recycling and just under 35% energy recovery could be achieved for the area. However, findings suggest potential trade-offs between strategies centered around energy recovery from waste and strategies that prioritise recycling of recyclable fractions from waste. The three scenarios are then assessed against the CE metrics proposed. Again, here, ‘maximising recycling’ better aligns with the proposed CE metrics and contributes to cutting around 50% of GHG emissions associated with management/disposal of residual waste while increasing opportunities for resource recovery. Finally, some conclusions are drawn pointing to pathways to maximise optimal resource use and infrastructural provision in urban regeneration.

**Keywords:** circular economy; urban areas; circular cities; urban regeneration projects; Material Flow Analysis; assessment framework; metrics for circularity



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## 1. Introduction

In a highly urbanised world, cities have become the main centres of resource consumption and generation of waste. It is expected that by 2050, two thirds of the world population will live in cities, and most of the world’s resources will be consumed in cities, which is expected to amount to 90 billion tonnes [1]. The notion of the circular economy identifies strategies for slowing and narrowing resource use through the prevention of waste, improvement of resource use, and substitution of the use of primary resources with recovered materials (and energy). The literature has recently started to explore the concept of circular cities, and a number of cities around the globe have adopted circular economy strategies. These strategies have different scopes and foci, which may cover waste management, resource use, transport, and planning [2].

The theoretical foundations of urban circularity can be drawn to the concepts of urban metabolism, industrial ecology and the ‘nexus,’ which emphasizes opportunities to

holistically explore the interactions across human-made and natural systems through flows of materials, energy, water, and land, and how these are shaped and mediated by technology choices, societal/institutional structures, and new business models [3]. The novelty of the circular economy (CE) concept lies in the emphasis on disruptive processes that enable more restorative use of resources rather than relying solely on efficiency and incremental improvements. This requires moving away from the current linear model of production and consumption to a circular one, where products, components, and materials are kept at their highest utility and value [4,5]. The concept of the CE aims to ‘keep products, components, and materials at their highest utility and value at all times’ [6], distinguishing between technical and biological cycles. It is conceived as a continuous positive development cycle that aims at preserving and enhancing natural capital, optimising resource yields, and minimising system risks by introducing fundamental changes to the way finite stocks and renewable flows are managed, moving away from linear wasteful processes to circular and regenerative loops [7]. CE has applications at every scale from the micro business scale to the macro scale of circular looping of global resources. It is important, though, that there is coordination across the scales to generate drivers that act consistently towards circularity at different levels. Ultimately, the CE seeks to decouple global economic development (not necessarily measured as GDP) from finite resource consumption and environmental impact [6].

The strategic dimension of CE has not always been adequately acknowledged. In Europe, the CE policy discourse still revolves mainly around waste and a narrow view of resource management [7]. However, as emphasised by Ghisenilli et al. (2016) [8], CE approaches should not be seen as ‘more of the same’, but as a radical new perspective based on system thinking with a focus on ‘radically alternative solutions, over the entire life cycle’. This is, of course, much more challenging and requires a new set of tools and guidelines to understand resource flow and impacts and to evaluate effectiveness of integrated solutions. Urban regeneration projects are of special interest, as they can set the basis for future resource use patterns and lock in infrastructural pathways for the next 20–30 years. However, contributions addressing changes in urban fabric, patterns of resource use, and infrastructural dotation are still scarce and fragmented.

This paper aims to contribute to filling this gap by providing an analytical framework and set of metrics to evaluate the application of CE principles exploring circular destinations of waste in the context of urban regeneration projects and identifying infrastructural needs from a CE perspective. The methodological approach has been applied to the case of the Old Oak Common and Park Royal area (OOPR) in West London, which is undergoing the largest urban regeneration project in Europe.

Section 2 provides an introduction of the application of CE principles at the urban level, key approaches, and main challenges. Section 3 describes the analytical framework proposed and describes the main methods. Section 4 applies the methodological framework to the case study of the OOPR and looks at projected resource flows and current local policies and proposes CE metrics for circular resource use. Section 5 discusses the main results and provides some recommendations based on the findings to maximise CE opportunities in the area and draws some conclusions around waste management planning in urban regeneration projects and the proposed framework.

## 2. CE Principles at the Urban Scale: Findings from the Literature

Application of CE principles at the urban level has attracted substantial attention in the literature in recent years. There has been increasing interest in identifying the potential that CE could bring to cities and regions, and a few pioneering cities and regions have started to design and implement strategies and roadmaps for the transition to the circular economy [2]. However, assessment of these initiatives is problematic, as most are still at very early stages of design or implementation. Cities such as Amsterdam and London have defined route-maps for the transition to circularity. At a regional and national level, Catalonia, Scotland, and Denmark have pioneering processes for advancing circularity. To

date, though, evaluation of the outcomes of these initiatives and frameworks for assessment is still an area that requires further attention.

The literature has addressed the specific challenges of CE at the urban level. Petit-Boix et al. (2018) [2] and Predenville et al. (2018) [9] highlight that, while the number of cities in Europe and elsewhere which have adopted CE strategies/policies has grown exponentially, the specific strategies and approaches adopted vary widely, reflecting a myriad of CE definitions and implementation perspectives. Moreover, CE strategies tend to fall within a range of different approaches to transition towards more sustainable cities. However, without referring specifically to CE, De Jong et al. (2015) [10] identified at least 12 distinct concepts (zero-waste cities, circular cities, etc.) with, in many cases, overlapping dimensions, which lack clear definitions, boundaries, and operationalization tools.

Practitioner approaches such as the RESOLVE framework [4,5] have been proposed to identify areas of potential to increase circularity at the urban level. However, some authors have looked at this proliferation of practitioner-led frameworks with reservation. Williams (2019) [11] argues that current circular urban approaches do not capture the complexity embedded in urban systems without adequately acknowledging the interactions between spatial, socio-economic, and natural systems operating at different dynamics and scales. A better understanding of these interactions based on data-rich frameworks seems to be a requisite to move from merely incremental interventions to more radical disruptions of current systems. In this line of thought, Calverio de Ferreira and Nerini (2019) [12] propose a CE city multi-layer framework that is supported by a system of metrics divided by areas that differentiate between 'inner' and 'outer' circles. However, as noted by Prendeville et al. (2018) [9], 'major investments' required to leap from linear to circular urban systems are absent in current strategies, creating a gap between ambition and capability.

Urban waste management has been at the core of some of the circular economy strategies at the urban level [2]. Concerns around lack of circularity of current predominant waste management have been emphasised in the literature [13–15]. Most of these contributions point to a myriad of factors limiting the ability of waste management systems to retain material value and recover energy from waste [16]. Some of the contributions focus on specific interventions, such as that of Lee et al. (2021) [17], which explore the role of informal urban recycling networks in South Korea through the use of urban informatics, while other contributions focus on specific material streams, such as Construction and Demolition Waste (CDW) [14,18]. In these analyses, the complex interactions between different groups of stakeholders [16] or the lack of incentives to boost innovation in waste management [15] are highlighted as key challenges and barriers associated with the transition towards a CE in waste management at the urban level.

Metrics for the circular economy have also sprouted as a result of the policy uptake of the concept. Saidani et al. (2018) [19] provide a comprehensive review of existing metrics at different scales, scopes, and levels. Similarly, Ekins et al. (2019) [20] analyse circularity metrics and note the steady development of frameworks to measure CE at the urban level developed in recent years. Ferreira and Fuso-Nerini (2019) [12] propose a CE-monitoring framework for cities by looking at different sectors of the city and areas covering energy, water, and materials. China has developed a harmonised system for indicators at the city level that cover aspects from pollutant emissions to material and waste management. In Europe, several municipalities have also developed their own systems of indicators to assess their CE performance (i.e., Amsterdam, Peterborough, among many others), but there is lack of harmonisation of CE metrics across different initiatives and different levels [21]. Metrics based on urban metabolism approaches have also been reviewed in the literature. Ravalde and Keirstead (2017) [22] propose performance-based metrics derived from urban metabolism and exergy approaches to quantify multi-resource flows in cities and investigate pathways for sustainable resource use. Thomson and Newman (2018) [23] explore how urban metabolism approaches can be employed to assess the sustainability of different urban fabrics. Gao et al. (2020) [24] use System Dynamics and

Material Flow Analysis to develop scenarios to quantify the potential impact of circularity strategies and propose a CE index at the regional level to assess the performance of the system over time. However, to date, we are unaware of specific research that applies Material Flow Analysis (MFA) to evaluate waste management alternatives in the context of urban regeneration projects.

The review of the literature has pointed to gaps in the understanding of opportunities and trade-offs associated with CE waste management strategies at the urban level and the selection of waste–resource technology–infrastructure fixes, especially in the context of regeneration projects. Urban regeneration projects are critical from at least a double perspective. On the one hand, they involve changes in the use of land with implications of material flows and transformation of city functions; on the other hand, urban forms shape city infrastructures, fundamentally altering potential for the circularity of urban resource flows. From a CE transition perspective, urban regeneration can unlock or limit circularity transformation towards the future. This paper proposes a methodological framework and CE metrics to assess the degree of circularity associated with alternative recovery options for urban waste streams in the context of urban regeneration projects.

The proposed approach in this paper is tested for the Old Oak and Park Royal (OOPR) regeneration project (West London, UK) as representative of large-scale urban regeneration projects in Europe. The proposed approach combines MFA and scenario development to identify flows of resources and potential for CE transformation. The paper aims to contribute to (1) a better understanding of the opportunities for embedding circularity at the urban scale in the context of regeneration projects (described in Section 3) and (2) identifying urban specific metrics to track progress towards the CE in the area of waste management and resource recovery (described in Section 4.4).

### 3. Materials and Methods

The research design proposes an analytical approach based on the modelling of resource flows, using MFA and scenario development techniques, to assess different technology/treatment pathways for urban waste streams and provides an estimation of carbon implications associated with the different scenarios. A system of CE metrics is then proposed to assess alternative strategies of resource recovery and their alignment to CE principles. The description of the resource flow model and key assumptions are discussed in Section 3.2 and the Supplementary Materials (SM). The development of scenarios is described in Section 3.3 and the analytical development of CE metrics and overall proposed methodological framework are discussed in Section 3.4. The methodological framework has been tested in a case study of OOPR.

#### 3.1. Selection of the Case Study: OOPR Regeneration Project (London, UK)

The methodological approach proposed has been tested in a case study. The case study method allows for an in-depth exploration of urban resource dynamics in a specific context and allows for highlighting the linkages between actor decision-making/planning strategies and resource flows. The case study selected is a large-scale urban regeneration project in West London (UK). A purposive approach to case selection was adopted, as this case was relevant from several perspectives: (1) the case is representative of other urban regeneration projects in Europe; (2) it highlights possible trade-offs across alternative solutions to land use and waste management; and (3) it may offer some insights into the opportunities connected to the better integration of waste recovery facilities into high-density urban developments. In sum, the case study contributes to portraying explicit choices in urban regeneration projects with regards to waste management options and their implications for circularity.

#### 3.2. Material Flow Analysis (MFA)

The report uses Material Flow Analysis (MFA) to describe resource flows in the OPDC area and identify opportunities to increase circularity through recovery of waste.

Material flow analysis is a system-based tool for identifying and characterising flows and stocks within a system boundary [25]. It is based on the principle of mass conversation, which builds on the laws of thermodynamics, where inputs to the system should equal outputs to the system plus additions to the stock. The MFA provides a picture in time of the resources flowing into a system; the outflows of the system, including dispersion, pollution, and waste [26]; and additions to stock. Both flows and derived indicators use mass units to quantify material implications of the socio-economic/industrial/urban metabolism. There are different types of MFA. Economy-wide MFA has been used in this analysis, following the EUROSTAT methodology [27]. Although economy-wide MFA is generally used at a higher level of aggregation [28], its application at the urban and even sub-urban scale is not new and links with the field of urban metabolism [29,30]. MFAs have been graphically represented using Sankey diagrams (built using the web-based ‘sankeymatic’ tool), which have their origin in thermal engineering and allow the provision of an intuitive overview of resource flows in a system [31]. MFA is a powerful tool to understand underutilised resources and leakages from the urban system into the environment and to identify opportunities to optimise the functioning of socio-economic systems and reduce their entropy.

### 3.2.1. System Boundaries

The system boundary for the analysis encompasses a large area (650 ha) in central-west London, which expands across four London Boroughs (Brent, Ealing, Hammersmith, and Fulham). The area has been designated by the Greater London Authority as a strategic development area to be managed by a London Mayoral Development Corporation (Old Oak Park Royal Development Corporation: OPDC). The OPDC acts as the planning functional body to facilitate London’s regeneration of large areas across the city. The Development Corporation has several statutory powers (e.g., relating to infrastructure, regeneration strategies, land acquisitions, design of interventions, planning regulations, and financial assistance). For the purpose of the analysis here presented, the boundary considers the whole of the regeneration area and works on basis of the projected number of residents and the worker population. The regeneration project will be undertaken in different phases, with the total construction processes expanding over a period of 32 years. Therefore, it has been assumed that Construction & Demolition (C&D) waste arising will be distributed over a period of 32 years.

### 3.2.2. The Flows

Given the focus of the study on waste management options and following the EURO-STAT [27,32] MFA methodology, flows of resources are considered only from the waste generation stage. The scope is restricted to material out-flows in the form of solid waste and its destination.

Waste generation data are based on projections for the regenerated area based on Greater London Authority (GLA) projections, where available, or more local or regional data for the UK on waste arising and the destination of waste. Specific data sources are indicated in the tables and Supplementary Materials (SM).

Estimations of GHG associated with energy consumed in the area are out of the scope of this MFA.

### 3.2.3. MFA as a Tool to Assess CE Opportunities

In this paper we propose exploring the use of MFA as a tool for mapping out potential CE opportunities for waste management in an urban area. Up to now, there has been little research in the use of tools such as MFA to inform policy making and planning decisions at the local level. This works though builds on a large body of literature that uses economy-wide MFAs as a tool for assessing degree of circularity globally, regionally, or in specific sectors [33–35]. However, applications at the local level to assess circularity of waste management destinations in the context of urban regeneration projects are still



underdeveloped. MFA is useful in describing the flows of materials into a (local) system and identifying areas where resources can be used in more optimal ways. Over time, MFA can also be useful to assess the overall use of resources of the system, management of stocks, and evaluation of waste generation trends. From a circular economy perspective, MFA is relevant tool to identify loops of materials and opportunities to re-circulate materials within the system boundary.

MFA also provides a measure of the scale of the social metabolism and indicates changes over time. In fact, one problematic aspect of current CE approaches is that system scale, critical for system sustainability, is poorly addressed. The sustainability of a circular system can be compromised if the scale of the systems increases over time [34].

### 3.3. Scenario Development

Departing from the MFA, different alternatives to incorporate CE considerations in the regeneration project were explored using scenario analysis. Three scenarios were developed: (1) Business as Usual (BAU), (2) maximising energy recovery (Max ER), and (3) maximising recycling rate (Max Recycling). The BAU scenario provides the baseline for projected waste generation in the area. It also provides detail about the composition of the waste and main destination. Departing from the baseline, two scenarios are proposed. The first scenario is more aligned with the circular economy core principles, as it maximises recycling and recovery of nutrients (in the case of biological waste) and materials (for the technical cycle). The second scenario aims for energy self-sufficiency and maximises energy recovery from waste. Waste-to-energy capability has grown substantially in Europe in recent years. In this case, it recovers energy in waste and in some cases, such as Anaerobic Digestion (AD) or composting, also recovers nutrients in biological waste; however, it does not retain the functionality of the material streams as scenario 1 proposes. Of course, practical solutions would require a combination of the two, but for clarity, both scenarios are presented independently.

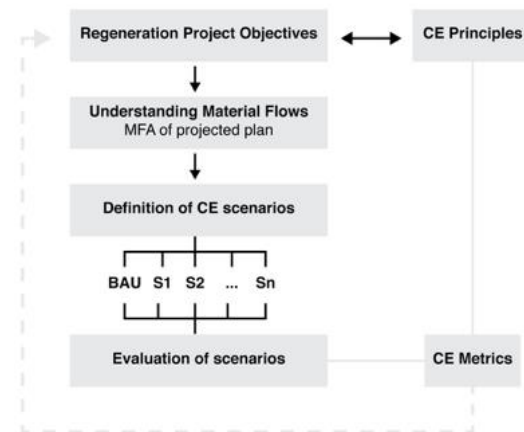
To create the scenarios, the waste generated from different sectors was first broken down to material composition (as detailed in Section 4). Material categories are not entirely harmonised across household (HH), commercial and industrial (C&I), and construction and demolition (C&D) waste due to the following reasons: (1) material composition differs across sectors and (2) limitations of data, which are subjected to different material categorisations (EUROSTAT waste database provides harmonised data across material categories but is not available at the local level). Information on waste destinations was then gathered from local statistics and was used to develop the BAU scenario. Assumptions were then taken to create the other two scenarios, based on (a) benchmark data (recovery and recycling rate at the national level) and (b) technical feasibility of the options (discussion of the assumptions is included in the Supplementary Materials).

For construction and demolition waste, information on material types was very limited. This is because waste generation from construction and demolition is often very site-specific, and there are not good data on the material composition and destination of waste from the sector. Aggregated figures for recycling are often quoted but do not reflect the diverging recycling rates of different materials. The data sources and main assumption for the generation of scenarios are described in more detail in the analysis section.

### 3.4. Development of an Integrative Framework

Based on the combination of tools described above an overall framework for evaluation of CE options in urban regeneration projects has been proposed. The framework departs from the understanding of the objectives of the urban development/regeneration project and the interconnections with CE principles. MFA is used to map flows of resources required for the regenerated area and to then generate scenarios that combine different options for increasing circularity. In case study analysed, the exploration of alternatives has focused on recovery options from waste, but the framework could also be used to examine different options with implications for masterplanning and for selecting design decisions.

The evaluation of scenarios has been assessed through the use of metrics to measure the performance of the scenarios against CE principles. Finally, the results of the analysis are fed back into the planning/regeneration process to better align this with the CE principles. Figure 1 below describes the proposed framework.



**Figure 1.** Framework for assessing circularity of urban regeneration projects. Source: authors elaborated.

#### 4. Findings: Analysis of CE Opportunities in an Urban Regeneration Project

##### 4.1. Background of the OOPR Case Study: Urban Regeneration Policies

OOPR area, in West London (UK), has been classified as a strategic development area by the Greater London Authority. To oversee the regeneration project and act as main planning authority, a new planning figure, a development corporation was created (Old Oak Park Royal Development Corporation, OPDC). The OPDC has been granted planning powers by the 2011 Localism Act, which introduced the planning figure of Mayoral Development Corporations and the 2016 Housing Planning Act, the OPDC being the second of this kind. The corporation acts as a local planning authority for the area with statutory powers to manage infrastructures, land acquisition, and financial incentives, as well as to develop the local plans. In the Old Oak and Park Royal area, the Corporation is also the lead landowner, with the transfer of 97 publicly owned hectares transferred to OPDC [36].

The 650-hectare project aims at creating a beyond-state-of-the-art development that promotes healthy, smart, and sustainable urban communities, providing quality living space, jobs, and enhancement of local ecosystems, and has become one of the largest urban regeneration projects in Europe. The project constitutes a transport hotspot where Cross-rail (interurban expansion of the rail network) will meet with the UK National Rail network, and it is also linked with the High Speed 2 (HS2) line with a new station in Old Oak Common. This development will allow for connecting different parts of London and the north of the UK. The project is driven by the need to provide new homes and employment opportunities in West London to meet the increasing demand for housing. The project aims to create 25,500 new affordable homes, generate 65,000 employment opportunities, and bring £7 billion to the UK's economy [36].

The project aspires to become an exemplar for 'sustainable and healthy large-scale development' and a referent for circular economy and sustainable use of resources. Circular economy principles have been embedded in the strategic policies that inform the local plan. SP2 specifically states that proposals should support 'good growth' through 'promoting resource efficiency and the principles of the circular and sharing economy'. The local plan also considers within 'environmental and utilities policies' a policy on waste (EU6) and a policy on circular and sharing economy (EU7). The EU6 refers to apportion targets (waste management infrastructures to deal with waste generated in the area) and to the need to relocate current waste management activities that conflict with the land use changes of the

regeneration. Application to new waste management facilities may be considered if they help to move waste up the waste hierarchy. The local policy also places great emphasis on supporting energy decentralisation and bio-waste treatment, such as AD and other forms of Energy from Waste (EfW). It specifies that, according to the London Plan carbon intensity floor emissions performance standard, new EfW infrastructures would need to meet the minimum threshold of 400 g/kWh electricity, and the feedstock would need to be 100% organic or residual waste. The policy also considers impacts associated with transport of waste and the need to minimise it through several approaches, including working with local partners and considering using rail and water transport options. With regards to C&D waste arising during the construction phase, the plan makes specific reference to the target of 95% landfill diversion in construction sites, the need to develop secondary material markets, and opportunities arising from working with local recycling facilities. Finally, the document recognises the challenge to achieve recycling targets for household and commercial waste in inner-city dense developments and proposes working with developers to ensure sufficient space for segregation and storage is provided in apartments to achieve the Mayor of London target of 65% recycling.

Policy EU7 focuses on circular and sharing economy and indicates that major development proposals need to provide a statement indicating how CE principles have been met. A number of opportunity areas are listed, including food (and potential to use it to produce biochemicals and electricity), water, energy (including EfW), materials, fabrication, mobility, transport, communal space, maker and mender spaces, skills sharing, logistics, flexible design, digital platforms, waste, and smart monitoring. The policy is quite ambitious in terms of the scope but provides little detail as to how this may be achieved. In terms of waste, it reiterates the need for segregation and separate collection of recyclables and an emphasis on minimisation, without indicating how this would be achieved.

#### *4.2. Resource Flows and Composition of Waste to the OOPR*

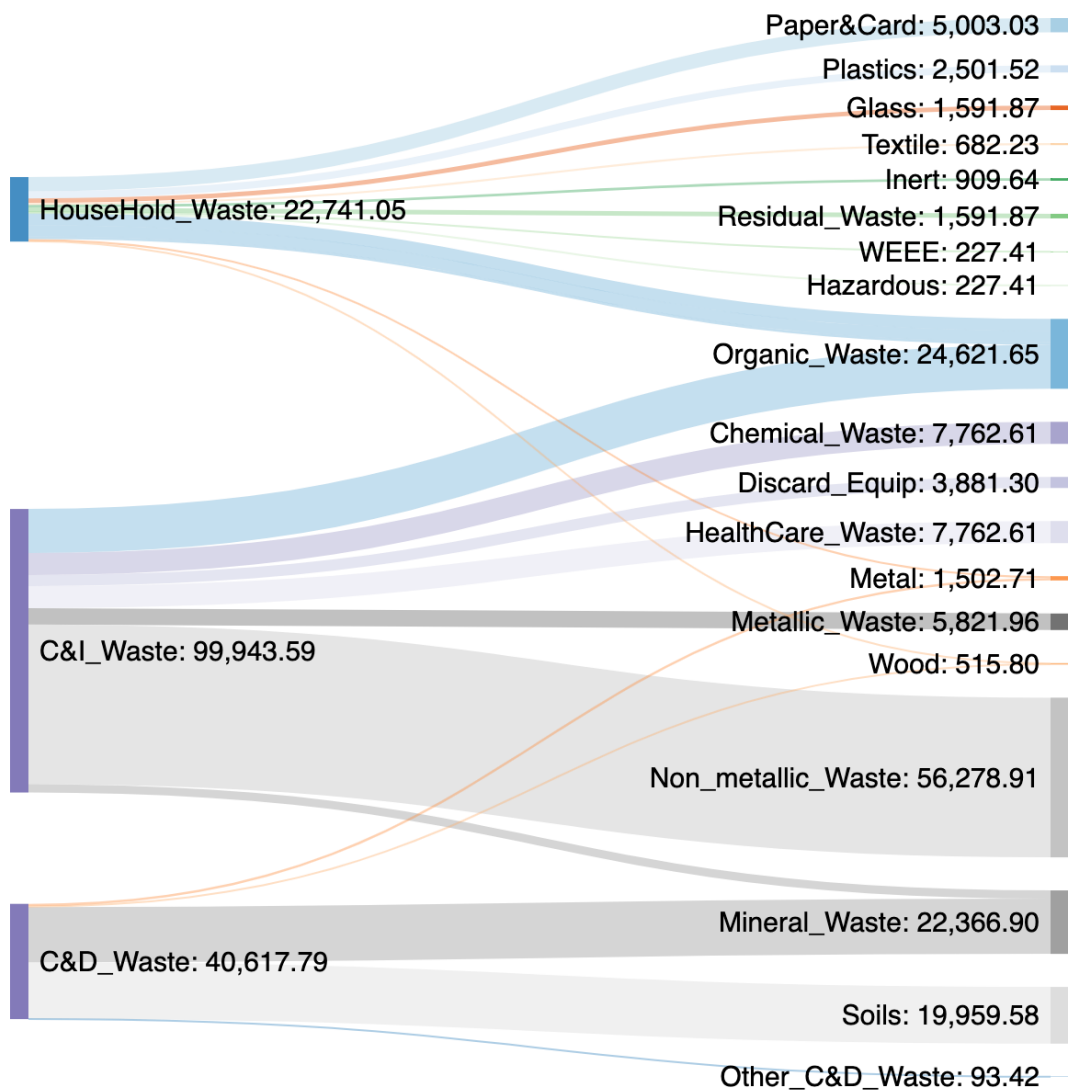
A report by OPDC (2017) [37] included quantified resources into the regenerated area and projected volume of waste. However, to assess circular opportunities, further breakdown with detail of waste composition is needed. Therefore, the work here presented quantified the annual projected waste composition of the regenerated area, waste destinations, and defined metrics to assess potential for recycling and energy recovery based on benchmarks by material waste stream. Assumptions and details of data sources made for the quantification of flows of MFA are included in the Supplementary Materials. Figure 2 visually represents the composition of waste flows of the OOPR area.

#### *4.3. Assessment of the Development Scenarios*

##### *4.3.1. Scenario Development*

Departing from the estimation and composition of waste presented above, three scenarios have been developed to quantify the material and energy recovery potential of different strategies for waste management: (1) business as usual (BAU); (2) maximising energy recovery and (3) maximising recycling rate. For the construction of the scenarios, estimation of potential reusability, recyclability, and suitability for energy recovered was estimated based on best practice benchmarks as detailed for each of the scenarios and described in the Supplementary Materials. Details of the calculations are provided in the Supplementary Materials.

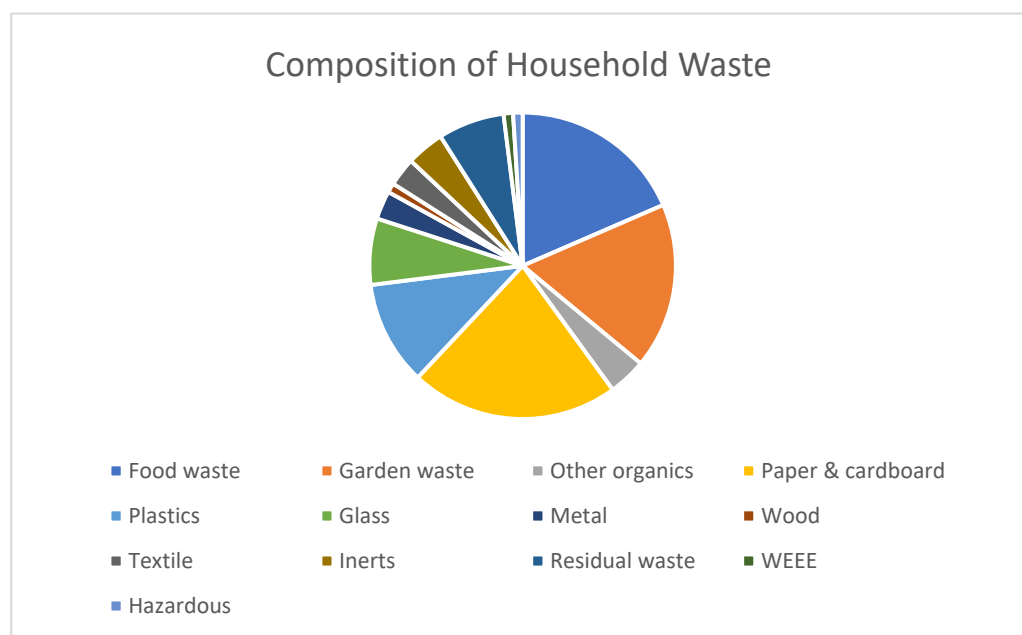




**Figure 2.** OOPR Composition of waste flows (estimated for one year). Source: author generated.

#### 4.3.2. Household (HH) Waste

Figure 3 provides detail of composition of HH waste. Table 1 below summarises projected recycling and energy recovery for household waste under the three proposed scenarios. Detailed information about the waste composition, the amount of waste generated, and data sources for three scenarios can be found in the Supplementary Materials. Current recycling levels vary substantially across different materials, but for all HH, waste recycling is around 46%. However, current policy commitments require achievement of at least 70% recycling by 2030, which is the assumption made for the scenario 3, maximizing recycling. Scenario 2 proposes energy recovery as the main destination of HH waste to recover energy from waste.



**Figure 3.** Composition of household waste. Source: authors elaborated.

**Table 1.** Household waste with three scenarios.

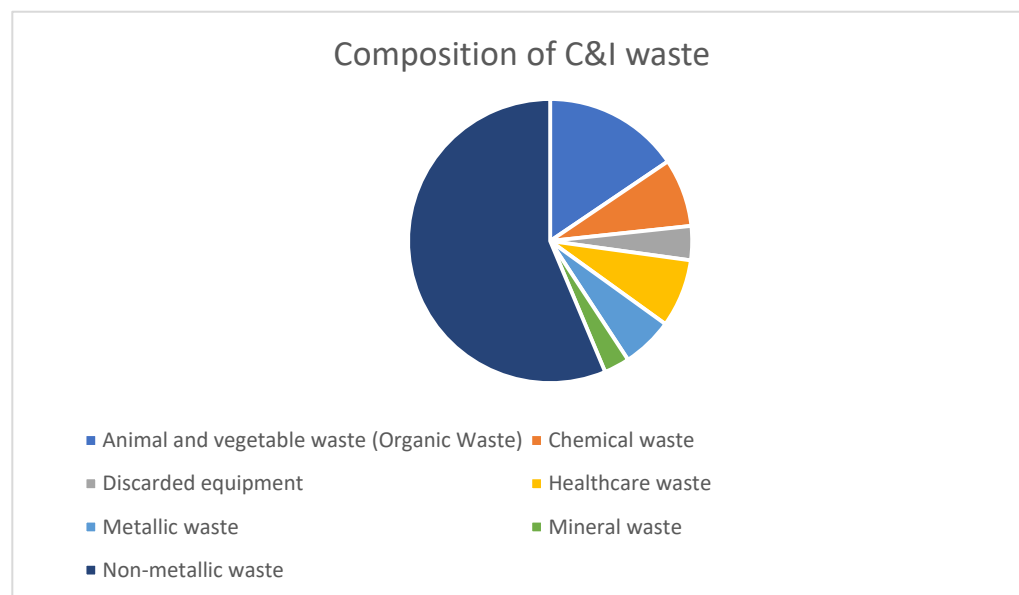
Waste Composition	Amount		Sc. 1—Business as Usual		Sc. 2—Maximising Energy Recovery		Sc. 3—Maximising Recycling	
	Tonne pa	%	Recycle (%)	ER (%)	Recycle (%)	ER (%)	Recycle (%)	ER (%)
Food waste	4207.10	18.50	56.00	42.24	0.00	96.00	70.00	30.00
Garden waste	3979.69	17.50	27.00	70.08	0.00	96.00	70.00	30.00
Other organics	909.64	4.00	0.00	96.00	0.00	96.00	70.00	30.00
Paper & cardboard	5003.03	22.00	66.00	32.64	0.00	96.00	70.00	30.00
Plastics	2501.52	11.00	37.00	60.48	0.00	96.00	70.00	30.00
Glass	1591.87	7.00	63.00	35.52	0.00	96.00	70.00	30.00
Metal	682.23	3.00	55.00	43.20	0.00	96.00	70.00	30.00
Wood	227.41	1.00	0.00	96.00	0.00	96.00	70.00	30.00
Textile	682.23	3.00	38.00	59.52	0.00	96.00	70.00	30.00
Inerts	909.64	4.00	0.00	96.00	0.00	96.00	70.00	30.00
Residual waste	1591.87	7.00	0.00	96.00	0.00	96.00	0.00	100.00
WEEE	227.41	1.00	0.00	96.00	0.00	96.00	70.00	30.00
Hazardous	227.41	1.00	0.00	96.00	0.00	96.00	0.00	96.00
<b>Total</b>	<b>22,741.06</b>	<b>100.00</b>	<b>45.95</b>	<b>56.76</b>	<b>0.00</b>	<b>96.00</b>	<b>65.10</b>	<b>34.90</b>

Source: authors elaborated. List of assumptions in Supplementary Materials.

#### 4.3.3. Commercial and Industrial (C&I) Waste

Figure 4 describes composition of C&I waste. Table 2 below summarises projected recycling and energy recovery for C&I waste under the three proposed scenarios. Two main material streams within C&I waste are non-metallic waste, which includes plastic, packaging, paper, textiles and other non-metallic fractions, and organic waste, including animal and vegetable waste. Maximum energy recovery and recycling rates are based on the potential recyclability and energy recovery potential of different material streams

within C&I waste, as described in the SI. Given the more homogenous nature of C&I waste, recycling potential is higher than 85% compared to the 56% of the BAU scenario. This points to a substantial unrealised potential for increasing recycling. Energy recovery could also be increased substantially by reducing waste-to-landfill and other non-circular destinations, as estimated in scenario 2.



**Figure 4.** Composition of C&I waste. Source: authors elaborated.

**Table 2.** C&I waste with three scenarios.

Waste Composition	Amount		Sc. 1—Business as Usual		Sc. 2—Maximising ER		Sc. 3—Maximising Recycling	
	Tonne pa	%	Recycle (%)	ER (%)	Recycle (%)	ER (%)	Recycle (%)	ER (%)
Animal and vegetable waste (Organic waste)	15,525.22	15.53	45.06	3.76	0.00	87.11	95.30	0.00
Chemical waste	7762.61	7.76	26.56	6.07	0.00	52.14	46.78	5.36
Discarded equipment	3881.30	3.88	75.64	0.12	0.00	89.56	97.68	0.00
Healthcare waste	7762.61	7.76	0.24	4.01	0.00	89.24	4.19	85.05
Metallic waste	5821.96	5.82	75.44	0.35	0.00	80.60	87.89	0.00
Mineral waste	2910.98	2.91	41.63	0.36	72.81	12.74	91.38	0.00
Non-metallic waste	56,278.91	56.31	65.69	1.67	4.19	76.91	91.42	0.00
Total	97,032.60	100.00	56.25	2.41	4.62	78.66	84.27	7.23

Source: authors elaborated. List of assumptions in Supplementary Materials.

#### 4.3.4. Construction and Demolition (C&D) Waste

Figure 5 describes the composition of C&D waste. Table 3 below summarises projected recycling and energy recovery for C&D waste under the three proposed scenarios. Given the composition of C&D waste, potential for recovery relies mainly on increasing recycling from current rates of around 70% to over 90% estimated in scenario 3. Here, in scenario 2, Energy Recovery is only suitable for materials with high calorific value, such as wood and plastics.



Figure 5. Composition of C&D waste. Source: authors elaborated.

Table 3. C&D waste with three scenarios.

Waste Composition	Amount		Sc. 1—Business as Usual		Sc. 2—Maximising ER		Sc. 3—Maximising Recycling	
	Tonne pa	%	Recycle (%)	ER (%)	Recycle (%)	ER (%)	Recycle (%)	ER (%)
Mineral	19,455.92	47.90	86.40	1.20	90.00	5.00	90.00	1.20
Soils	19,959.58	49.14	56.90	0.00	90.00	0.00	90.00	0.00
Metal	820.48	2.02	99.80	0.00	99.80	0.00	99.80	0.00
Wood	288.39	0.71	64.60	24.40	0.00	100.00	90.00	10.00
Other	93.42	0.23	52.00	1.01	0.00	100.00	90.00	10.00
Total	40,617.79	100.00	71.94	0.75	89.35	3.34	90.20	0.67

Source: authors elaborated. List of assumptions in Supplementary Materials.

#### 4.3.5. Cross-comparison of Scenarios

The three scenarios provide a comparison of different routes to enhance resource recovery across different material streams generated by different sectors (HH, C&I, and C&D). The comparison of scenarios 2 and 3 with BAU highlights substantive unrealised recovery potential of resources. The BAU scenario for household, C&I, and C&D waste shows that is a large proportion of resources that does not achieve optimal recovery, and there is significant room for increasing recycling and/or maximising energy recovery.

For HH waste, there are opportunities to increase recycling across all main types of waste, with significant gaps in garden and organic waste, textiles, plastics, and electronics, when comparing the current rate against maximum recoverable fractions. While a full evaluation of the scenarios using life cycle assessment was out of the scope of current research, increasing recycling and energy recovery present, in most cases, benefits compared to landfills or incineration without energy recovery.

Similarly, C&I shows significant room for improving recovery rates across different material streams, especially organic waste, metal, and mineral fractions. Although current recycling rates are substantially higher than for HH waste, the more homogenous nature of C&I waste and its volume creates opportunities for increasing recycling, as illustrated in scenario 3, with an average recycling rate of over 85%. Incineration with energy recovery could also recover the calorific content of some of the C&I waste streams. Maximising recovery, through both recycling and incineration, could contribute to emission savings.

Finally, for C&D, current levels of recovery through recycling are higher than for HH and C&I waste, meaning that gaps between the BAU and the CE scenarios are smaller. This is explained by the recyclability of the large majority of the metal and mineral fractions of C&D waste but also with specific legislative and voluntary initiatives adopted in recent years.

Most elements of the mineral fraction can be recycled, depending on the level of segregation, cross-contaminations, and technology in percentages close to 100%. Examples are asphalt, ceramics, and tiles. Recycled asphalt can be used and mixed with new asphalt. Denmark has achieved a 100% recycled asphalt [38]. Other fractions such as ceramics, tiles, and masonry, also part of the mineral fraction, have reported recycling rates between 40 and 85%. Gypsum is also part of the mineral fraction of C&D waste, and the recycling rate has increased substantially in recent years. The main problem to recover gypsum from C&D waste is contamination and segregation at the source. In 2010, England and Wales adopted a Quality Protocol for recycled gypsum defined by end-of-waste criteria for the use of waste plasterboard to produce recycled gypsum. Gypsum waste can be reintroduced in a variable % for the substitution of virgin gypsum in the production of plasterboards. The introduction of the Quality Protocol developed a secondary market for gypsum and increased the demand for waste plasterboard, which traditionally had been landfilled. The protocol specifies the end of waste criteria that, if met, would mean that the material ceases to be waste and becomes a by-product/resource. Soils can be used mainly for backfilling but also as a sub-base for roads, construction projects, and production of recycled aggregates.

Wood recycling is currently high at over 64%. This is, in general, for all sectors of activity, although a note of caution should be added that this percentage may be lower for C&D waste according to sector experts. Energy recovery is currently around 25%. Wood waste can be recycled and used in the production of derived timber products, for energy recovery, and in other forms of material recovery, including landscaping, animal bedding, or composting. In the case study, the C&D waste wood fraction could be used to produce energy in the gasification plant but could also be recycled if segregation at source is effectively implemented. The potential recycling of waste can be set at 90%, although consideration should be taken to the level of contamination of the material. In some cases, preparation of the material is required to be used in derived timber products (i.e., removing the contaminated fraction).

#### *4.4. Waste Infrastructures for Realising CE Objectives*

Currently the OOPR area is a net importer of waste in the Greater London area. The area concentrates currently seven waste facilities, including a waste transfer station, metal reclamation, and C&D waste treatment. Most of them are relatively small, with less than one hectare of land, with two main plants: a metal recycling plant (4.4 hectares) and an HH and C&D waste facility (3.9 hectares). The re-developed area falls into the boundaries of the boroughs of Brent, Ealing, Hammersmith, and Fulham, and, therefore, the OOPR plan needs to ensure that the area complies with the waste apportionment targets [35].

According to the MFA shown in Figure 2, total yearly projected waste for the area is 160,391 tonnes. This includes three main types of waste streams: household waste, C&I waste, and C&D waste. The largest waste recycling plant in the area currently segregates different waste fractions for recycling and produces refuse-derived fuel (RDF) from residual waste. RDF constitutes around 22% of the plant's current outputs. RDF is a renewable fuel created by shredding and drying out combustible waste [39] with calorific value, which is mainly made up of plastic film, paper, splinters, of wood and cardboard. Current RDF produced in the UK is mainly shipped to the North of Europe, mainly Sweden, Germany, and Holland, but there may be opportunities to use this more locally to generate energy in the future.

Plans for the area include the possible development of a gasification plant. Gasification technology operates in an oxygen-starved environment to produce heat for pyrolysis



reactions, resulting in the generation of syngas that can be sold or used to generate electricity in the reactor [40]. This technology is an economically and environmentally appealing alternative to avoid landfilling [40] and has been implemented in other parts of London (Barnett, LSIP). Gasification plants can treat MSW, sorted or unsorted, to convert it into energy. The gasification plant in the OOPR development could work on two main types of feedstock: wood chips and RDF from the waste recycling plant. The area currently produces around 500 tonnes of waste wood and 72,218 tonnes of RDF, which could yield values of around 7.2 MW a year (based on an estimation of gasification performance from Ishaq et al. (2020) [41]). This could cover a substantial part of the electricity demand of the developed area and generate surplus of heat. However, for it to be feasible, the plant will need to maintain a steady stream of wood waste, which may rely on imports of wood from other parts of London. Similarly, RDF production would represent over 45% of the total waste produced by the area and, therefore, could compete with the recycling fractions with calorific value (plastics, cardboard, paper), which are also more suitable for recycling unless other residual waste fractions are imported to produce RDF. Therefore, maximizing energy recovery for renewable energy generation may reduce attainment of recycling targets or import of waste from other areas. Being a net importer of waste in such a densely populated area may create additional frictions, such as congestion and air pollution, especially if waste is delivered by trucks.

The use of composting technologies and Anaerobic Digestion (AD) to treat all organic waste streams in the area could also generate opportunities to recover nutrients and generate biogas and heat and electricity. Anaerobic digestion is a well-tested technology that includes the biological oxidation of organic matter to produce biogas and digestate [42]. Examples of operative AD plants in London are multiple. For example, the Riverside AD facility in East London upgrades biogas to produce biomethane that is injected in the national grid, producing 550 Nm<sup>3</sup> biogas/hr from 36,000 tonnes of waste [43]. Small scale AD has also been adopted as community projects in other parts of London. According to our own calculations, presented in Figure 2, the OOPR area could be generating around 24,000 tonnes of organic waste, combining organic fractions from household waste and C&I waste.

Enhancing the understanding of resource flows can help to better evaluate the need, mix of technologies, and plant capacity in the planning of waste management infrastructure in the area. In the case of OOPR, it is important to highlight potential trade-offs between recycling and EfW destinations, unless the area receives waste from adjacent areas, which may create pressures related to transport and commercial and residential functions.

#### *4.5. CE Metrics for Urban Regeneration Projects*

Metrics for tracking progress CE in cities have been developed in recent years, as noted above. Although there are abundant indicators for measuring CE in cities, it is unclear what their contribution to the planning of waste management infrastructures is. Urban regeneration projects aim to enhance urban spaces socially, economically, and environmentally, but consideration of resource flows and waste management-associated requirements are not always well understood to ensure that the areas maximise resource recovery from waste.

Building on the three CE principles proposed by EMF (2016) [44] and based on the analysis of the case study presented above, CE urban metrics are proposed here, see Table 4. The objective of the metrics is specifically to provide guidance in urban regeneration projects and infrastructure planning, which may complement broader CE monitoring frameworks for cities [2]. The metrics have been calculated for the case study to be able to draw some conclusions with regards to their ability to provide guidance in decision-making processes related to urban regeneration.

**Table 4.** CE principles and key metrics for OPDC.

CE Principles	Key Metrics	Case Study OOPR		
		Scenario 1. BAU	Scenario 2. Max ER	Scenario 3. Max Recycling
Principle 1: Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows	Renewable electricity VS total electricity demand (%)	8.0	160.0	8.8
	Renewable heat VS total heat demand (%)	12.8	101.4	14.2
	Unutilised waste VS total waste generation (%)	34.78	14.35	9.27
Principle 2: Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles	Recycling VS total waste production (%)	58.05	25.42	83.05
	Reuse VS total waste production	Medium	Low	High
	Nutrient recovery potential	Medium	Low	High
	Energy recovery potential	Medium	High	Low
Principle 3: Foster system effectiveness by revealing and designing negative externalities	GHG emissions associated with residual waste (ton CO <sub>2</sub> eq. pa)	10,503.73	6418.05	4612.05
	Waste requiring disposal (tonnes per year)	55,785.89	23,021.23	14,866.49

The first principle relates to conservation of natural capital and the controlling finite of stocks. Here, metrics defined provide an overview of the share of renewable energy (as both electricity and heat) and rate of unutilised waste (i.e., landfilling). The first two metrics are associated with the controlling of finite stocks and balancing renewable sources, while the last one provides an estimate of natural capital loss through lack of waste utilisation. Energy recovery from waste allows for the generation of electricity and heat from renewable sources (waste), avoiding electricity from finite resources (fossil fuels). Metrics here may suggest that scenario 2 (Maximising Energy Recovery) can contribute towards achieving principle 1 but also would negatively impact material resource recovery, which can be maximised in the CE (recycling) scenario.

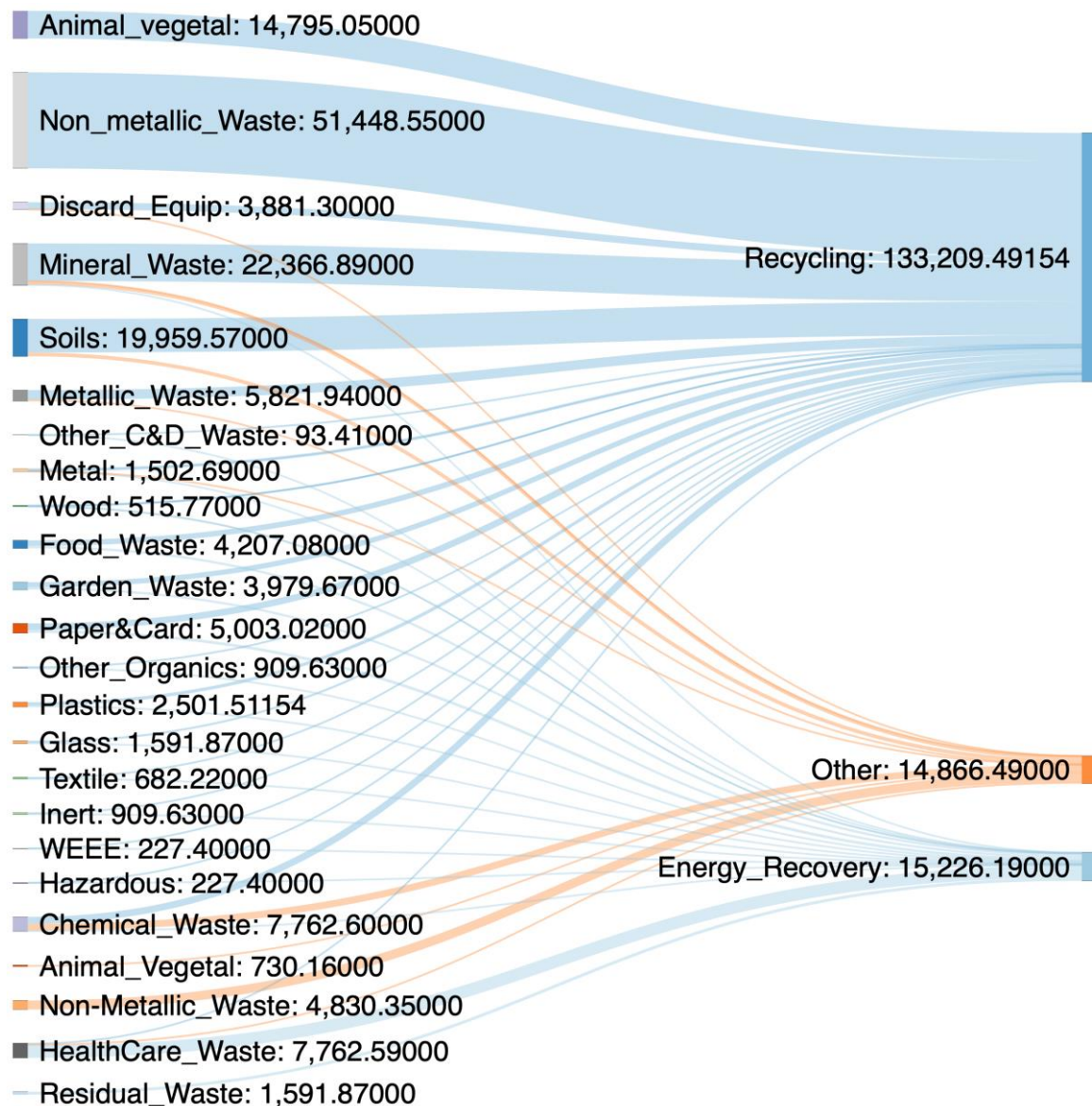
Related to principle 2, ‘optimising resource yields’ four main metrics have been proposed: (1) share of recycling, (2) share of reuse, (3) nutrient recovery potential, and (4) energy recovery potential. All three scenarios have been assessed against these three metrics. The ‘maximising recycling’ scenario scores better in all metrics except for energy recovery.

Finally, for principle 3, related to ‘system effectiveness’, two metrics have been proposed, one related to overall GHG emissions and one to waste disposal. Scenario 3, ‘maximising recycling’, offers the largest potential, both in terms of minimising GHGs and reducing landfill and waste disposal.

As a concluding remark, Scenario 3, ‘maximising recycling’, shows better alignment with CE principles and potential to contribute to the transition to the CE. This scenario places the emphasis on waste prevention (i.e., reuse) and recycling. Energy recovery also plays a role in reducing residual waste. However, further life cycle assessment studies would be required to quantify impacts across different impact categories associated with alternative recovery pathways. The findings also suggest that maximising energy recovery from waste as a source of renewable energy may create trade-offs for recycling maximisation. Applied to the case study, the metrics suggest that a focus on waste prevention and maximisation of reuse, recycling, and nutrient recovery may potentially better align with

CE principles and, thus, should inform planning of waste infrastructures needs to limit energy recovery options for recyclable waste streams.

Quantification of the potential opportunities for resource recovery through recycling in scenario 3, 'maximising recycling,' are shown in Figure 6.



**Figure 6.** Recycling opportunities in the OPDC area by type of waste stream in tonnes p.a. Source: authors' own elaboration. Sankey generated using Sankeymatic.

## 5. Discussion of Results and Conclusions

As major hubs of resource consumption, cities are critical players in the transition to the CE. Although the concept of CE has attracted a lot of enthusiasm and political commitment, large scale examples of urban transformation towards circularity are still rare. In this paper, a large-scale urban regeneration project in West London has been selected as a case study to examine different alternatives to better align urban regeneration projects and waste infrastructure planning with CE principles. Embedding CE principles in urban regeneration is critical, as planning choices made will lock in pathways for urban transformation in the future.

The framework proposed is aimed to support the introduction of CE considerations in urban regeneration projects to unlock circular pathways of resource use in cities. For this,

we proposed an iterative process for aligning urban regeneration against CE principles, based on data analysis and exploration of alternatives. In the case study, we showed that while CE principles were reflected in some of the policies and areas of intervention, such as waste management, these considerations were not clearly embedded in the planning of recovery and waste management infrastructures, and there was a lack of integrated vision across actions and policies areas with resource implications. For example, in the selected case study, the waste policy is governed by the waste hierarchy principle, but the energy policy places great emphasis on energy self-sufficiency, mainly EfW, compromising some of the opportunities for reuse and recycling, as the analysis has shown.

The research has departed from an MFA study that describes future waste arising and composition of waste in the area, taking into account proposed land use changes and construction processes. The waste flow model compared a BAU scenario against two other scenarios providing an assessment of material implications of different possible waste-treatment routes that require an alternative mix of management infrastructures. The BAU scenario also highlighted that several opportunities related to nutrient recovery, recycling, and energy recovery are not being currently exploited. Departing from the BAU, two more scenarios were developed: (1) the ‘energy recovery maximising’ scenario and (2) the ‘maximising recycling’ scenario. The three scenarios have been assessed against a proposed set of metrics for the CE in the context of urban regeneration projects. The findings suggest that the ‘maximising recycling’ scenario is the one that better aligns with different dimensions of the CE.

The case study findings are in line with previous literature findings suggesting a disconnect between CE strategies at local level and urban regeneration and infrastructure plans [8]. It also suggests that CE approaches have focused on the management of waste and overlooked impacts of land use changed in resource use [2]. While the scope of the proposed framework is limited to the exploration of recovery options for urban waste streams, as suggested by Williams (2019) [11], more layers need to be added to the analysis to better represent how the material system interacts with the wider institutional settings and socio-economic systems. In line with this, the proposed framework could also be expanded to better reflect how design solutions, land use changes, and nature-based solutions could be integrated at the urban scale to modify input and output of material systems by reducing consumption of virgin materials and generation of waste. A comprehensive assessment also needs to consider the contextual elements of the regeneration project and how it connects with broader city and regional systems, considering challenges regarding the alignment of circularity interventions at different urban and regional or supra-regional levels [9].

The analysis provides insights into the implication of different combinations of technology choices for end-of-life treatment of waste in regeneration plans. The case study is representative of a large category of urban regeneration that combines different land use, including residential, office, and industrial land uses. In the case of study selected, the regeneration plan reduced land associated with waste infrastructures, manufacturing, and commercial activities for a larger share of residential and office space. Depending on the scale of the project, this may have profound implications in the overall urban metabolism and ability to transform waste into resources that are fed back into the city. The case study also highlighted potential trade-offs into conventionally labelled ‘CE options’, such as recycling and EfW. These choices are not always well understood in terms of resources implications but may lock the technological pathway for the transition towards the CE in the long term, as investments in large scale waste management infrastructures are expected to have a 20–30-year time horizon. It is thought important to highlight that those other important socio-economic aspects, such as pay-off times, alignment with established waste collection and segregation systems, policy objectives and targets, and investment risks, play an important role in shaping the feasibility of different technological choices for waste management, increasing the complexity of socio-technological choices in urban regeneration projects.

Implications for urban planning policy highlight the need for a better integration of resource flow analysis in planning practice to ensure CE implications associated with land use changes, resource recovery, and infrastructure planning enable rather than prevent more circular use of resources in cities. This needs to be better represented in policy objectives and targets but also importantly backed up by methodological approaches, tools, and metrics that allow to assess adequacy of planning interventions against CE principles. The proposed framework here may provide a first step in this direction.

In conclusion, this study proposes a CE framework for urban regeneration and some metrics to understand the implication of different resource management options at the urban scale. The case study helps to test the framework and provides insights into the material flows and analytical elements and evidence to assess suitability of different technology choices for waste recovery. Further research is needed to better assess design choices and add detail to the interaction between the socio-economic and environmental layers of the analytical framework proposed.

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