UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI SCIENZE CHIMICHE

CORSO DI LAUREA MAGISTRALE IN SUSTAINABLE CHEMISTRY AND TECHNOLOGIES FOR CIRCULAR ECONOMY

TESI DI LAUREA MAGISTRALE

Title: “Tracking Circular Economy Principles in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change”

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Statement of originality

I, Nadezhda Ushakova, hereby declare that the work presented in this dissertation, titled "Tracking Circular Economy Principles in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change" is entirely my own original work. I affirm that it has not been fully or partially submitted previously in any other Italian or foreign university for assessment purposes.

I further confirm that the content of this dissertation is the result of my own intellectual endeavors, and I have appropriately cited all sources used. This work does not infringe upon the intellectual property rights of any third party, and its contents do not constitute plagiarism.

I understand the consequences of submitting work that is not my own and affirm the honesty and integrity of this academic contribution.

Nadezhda Ushakova

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Abstract

Climate change is an urgent global challenge that requires transformative circular transitions, making the integration of circular economy (CE) principles essential. The study examines the integration of circular economy (CE) and related concepts in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, specifically within The Working Group III contribution–*Climate Change 2022: Mitigation of Climate Change.* Through keyword analysis and quantitative review of selected chapters, the study summarizes how circular economy principles are addressed across specific sectors like energy, buildings, transport, urban systems, industry and cross-sectoral perspectives. Findings indicate that even though circular economy is not the central focus of IPCC AR6, it is recognized as a climate change mitigation strategy that facilitates the decarbonization and supports transition away from fossil fuel dependence. Beyond emissions reduction, CE also aligns with Sustainable Development Goals (SDGs), reinforcing its broader relevance in climate discussions. The future work includes the expanded analysis of global chapters of IPCC AR6 with a focus on policies, investment, international cooperation, innovation, and frameworks for accelerating the sustainable transition.

Chapter 1– Introduction and aim of the thesis

Climate change is defined as a significant long-term shift in temperature and weather patterns on Earth and remains the most influential global issue. Even though the shift can be caused by natural changes like sun activity or volcanic eruptions, from the 1800s the phenomenon is largely driven by anthropogenic activities that generate and release greenhouse gases into the atmosphere (United Nations, n.d). Afterwards, these gases trap sun radiation and prevent heat from escaping, thus leading to rising temperatures and warming the planet. According to United Nations reports, climate change causes a variety of consequences including more severe storms, increased drought, a warming rising ocean that affects natural biodiversity by loss of species, and human beings by food shortage, health risks, poverty and displacement (United Nations, n.d).

According to the Paris Agreement, a legally binding international treaty on climate change, the goal is to hold “the increase of global average temperature below 2°C above pre-industrial levels (1850-1900)” and make an effort “to limit the temperature increase to 1.5°C above pre-industrial level” by end of 21st century to avoid the worst climate impact and maintain a livable climate. However, the community of researchers claim that with the current trend, the temperature increase can reach 3.1°C of warming by the end of the century, without immediate actions (UNFCCC, 2015).

To overcome the environmental challenges, the European Union established the European Green Deal, a set of proposals to reach climate neutrality by 2050 by implementing the green transition. The green transition stands for the sustainable economic model while ensuring that socioeconomic systems stay within planetary boundaries (European Commission, 2019). Therefore, green transition can no longer accommodate the linear economy system, where the resources are extracted to make a product and eventually end up as waste. It stands for the necessity of shifting toward the circular economy system, where materials and products are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling and never become waste and nature is regenerated. Circular economy (CE) is a strategic action towards tackling climate change as it decouples economic activity from consumption of finite resources (Ellen MacArthur Foundation, n.d.).

The main United Nations body responsible for science related to climate change is the Intergovernmental Panel on Climate Change (IPCC). The IPCC was established to provide policymakers with scientific assessments regarding climate change, potential risks, mitigation and adaptation options. The main activities of the IPCC are the preparation of assessment reports, special reports, and methodology reports and then communication of the findings to the communities. The IPCC reports are the guidelines for policymakers, governments, scientists, environmental organizations, and the general public for evidence-based insights for making climate-related decisions (IPCC, n.d.). The latest IPCC report includes the Sixth Assessment Report (AR6) with contributions by its three Working Groups and a Synthesis Report:

- The Working Group I contribution–*Climate Change 2021: Physical Science Basis* (IPCC, 2021)
- The Working Group II contribution–*Climate Change 2022: Impacts, Adaptation and Vulnerability* (IPCC, 2022)
- The Working Group III contribution–*Climate Change 2022: Mitigation of Climate Change* (IPCC, 2022)
- Climate Change 2023: Synthesis report (IPCC, 2023)

The IPCC Sixth Assessment Report (AR6) is the first IPCC report which acknowledged the importance of the circular economy for climate change. Therefore, the objective of this work is to assess to what extent the circular economy and CE-related concepts are addressed in the report.

According to the literature review conducted, several papers were found providing a critical review of the IPCC 6th Assessment Report, however, none of them focused on circular economy strategies, which highlights the novelty and relevance of the work conducted.

To reach this goal, this work is organized as follows:

- Keyword analysis of IPCC Sixth Assessment Report to identify relevant chapters;
- Discussion of circular economy and related concepts within each identified chapter;
- Quantitative and qualitative analysis followed by discussion of key findings.

Chapter 2– Methodology

The methodology aims to distinguish the perspective from which the Intergovernmental Panel on Climate Change 6th Assessment Report (IPCC, 2023) addresses the circular economy concept.

To make this assessment the keyword research analysis was conducted across the IPCC Sixth Assessment Report. The initial set of keywords was chosen based on the Ellen MacArthur Foundation Circular Economy glossary (Ellen MacArthur Foundation, n.d.), which defines the meaning of the commonly used terms in the circular economy domain. Specifically, it includes the terms: “circular economy, anaerobic digestion, biological cycle, composting, durability, finite materials, lifespan, linear economy, maintain, non-virgin materials, recyclability, recycle, redistribute, refurbish, regenerative production, remanufacture, renewable energy, renewable materials, repair, repairability, reuse, reverse logistics, sharing, technical cycle, virgin materials”.

To determine their relevance within the scope of this investigation, R programming language was utilized for every keyword search in each of The Sixth Assessment Report (AR6) contributions, therefore allowing to objectively identify the report of interest.

The analysis was conducted through the Google Colab service, which allows the running of R scripts in the cloud-based environment of the University of Padua The R programming language was used to extract the text from PDF versions of the IPCC report. The following steps were implemented:

1. Required packages:

```
library(pdftools)(R Core Team, 2020)
library(stringr)(Wickham, 2019)
library(dplyr)(Wickham et al., 2021)
```

The `pdftools` command was used to extract the text from PDF files, while `stringr` and `dplyr` were responsible for processing the text and matching keywords.

2. Introduction of keywords and reports for analysis:

```
pdf_files <- c( "CL2021.pdf", "CL2022Ad.pdf", "CL2022Mit.pdf", "CL2023.pdf")
keywords <- c("circular economy", "anaerobic digestion", "biological
cycle","composting","durability",
"finite materials","lifespan", "linear economy","maintain","non-virgin
materials","recyclability","recycling",
"redistribute","refurbish", "regenerative
production","remanufacture","renewable energy","renewable materials",
"repair", "repairability","reuse","reverse logistics","sharing","technical
cycle","virgin materials")
```

In the code, *Climate Change 2021: Physical Science Basis* is noted as “CL2021”, *Climate Change 2022: Impacts, Adaptation and Vulnerability*– “CL2022Ad”, *Climate Change 2022: Mitigation of Climate Change*– “CL2022Mit”, *Climate Change 2023: Synthesis report* – “CL2023”.

3. Counting keyword occurrences inside IPCC AR6 reports:

```
count_keywords_in_pdf <- function(pdf_text, keywords) {
  results <- setNames(numeric(length(keywords)), keywords)
  for (keyword in keywords) {
    total_count <- 0
    for (page_text in pdf_text) {
      total_count <- total_count + str_count(tolower(page_text),
tolower(keyword))
    }
    results[keyword] <- total_count
  }
  return(results)
}
```

The function `count_keywords_in_pdf` iterates through all the pages taking the text content of the PDF and a vector of keywords. Then it applies `str_count` to identify matches and returns the total count for each keyword.

4. Storage and analysis of results:

```
all_results <- data.frame(matrix(ncol = length(pdf_files) + 1, nrow =
length(keywords) + 1))
colnames(all_results) <- c("Keywords", pdf_files)
all_results[1, 1] <- "Keywords"
all_results[2:nrow(all_results), 1] <- keywords

for (i in seq_along(pdf_files)) {
  pdf_file <- pdf_files[i]
  pdf_text <- pdf_text(pdf_file)
  keyword_counts <- count_keywords_in_pdf(pdf_text, keywords)
  all_results[2:nrow(all_results), i + 1] <- as.numeric(keyword_counts)
}
all_results
```

The function `data.frame()` creates the empty matrix structure with a specified number of rows and columns, where the first column is filled with keywords using `all_results[]`. The loop iterates over the PDF files, extracting text with `pdf_text()` and applying `count_keywords_in_pdf()` to count occurrences of keywords. The results are stored in the data frame and include the keywords count for each report.

The results of the keyword analysis via R programming language are summarized in Table A.

Table A. Keyword Occurrences across IPCC AR6 Reports.

Keywords	**CL2021**	**CL2022Ad**	**CL2022Mit**	**CL2023**
Circular economy	0	0	239	0
Anaerobic digestion	0	0	27	0
Biological cycle	0	0	1	0
Composting	0	0	12	0
Durability	0	0	25	0
Finite Materials	0	0	0	0
Lifespan	1	0	24	1
Linear Economy	0	0	0	0
Maintain	38	41	138	10
Non-virgin materials	0	0	0	0
Recyclability	0	0	13	0
Recycling	17	2	291	5
Redistribute	17	1	5	1
Refurbish	0	0	33	0
Regenerative production	0	0	0	0
Remanufacture	0	0	8	0
Renewable energy	13	9	857	13
Renewable materials	0	0	3	0
Repair	0	0	30	0
Repairability	0	0	1	0
Reuse	4	1	83	1
Reverse logistics	0	0	0	0
Sharing	11	18	355	10

Table A. Keyword Occurrences across IPCC AR6 Reports (Continued).

Technical cycle	0	0	2	0
Virgin materials	0	0	6	0

The *Climate Change 2022: Mitigation of Climate Change* report (code CL2022Mit, in Table A) had the highest number of keyword occurrences. The most frequently used CE-related keywords were “renewable energy” (857 occurrences), “sharing” (355 occurrences), “recycling” (291 occurrences), “circular economy” (239 occurrences), “maintain” (138 occurrences), and “reuse” (83 occurrences). Keywords with a count of less than 50 were considered less significant and, hence, excluded from further analysis.

In addition to the Ellen MacArthur Foundation Circular Economy glossary, several keywords were chosen based on the academic literature of Geissdoerfer et al., (2017), Merli et al., (2018), Romero-Perdomo et al., (2022), Kirchherr et al., (2023). All of the authors frequently referenced “waste” as a keyword for their research, while “sustainability”, “life cycle assessment” and “efficiency” were the common keywords for Geissdoerfer et al., (2017), Merli et al., (2018) and Romero-Perdomo et al., (2022). To understand the relevance of these terms, their frequency in *CL2022Mit* was analyzed using R programming language. The results showed “waste” (914 occurrences), “sustainability” (1132 occurrences), “life cycle assessment” (103 occurrences), and “efficiency” (1941 occurrences), therefore justifying the use of these keywords for further analysis.

Since *Climate Change 2022: Mitigation of Climate Change* report (code CL2022Mit, in Table A) had the highest number of CE-related keywords, the next objective was to identify the main chapters that most extensively address the concept of the circular economy.

The same R-based analysis with an updated list of keywords was then conducted across the chapters of *Climate Change 2022: Mitigation of Climate Change* (code CL2022Mit, in Table A). The results were summarized in Fig. A to provide a visual representation of keyword distribution.

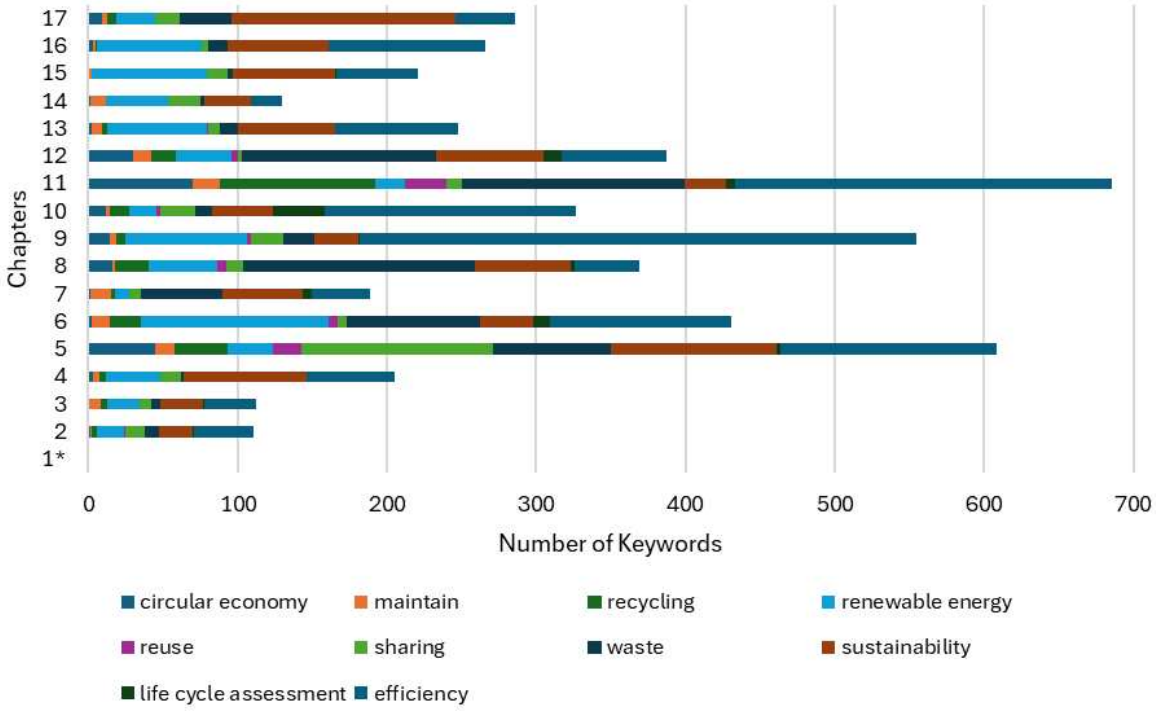

Figure A. The distribution of keywords across chapters of Climate Change 2022: Mitigation of Climate Change Report: Chapter 1 (Introduction and Framing), Chapter 2 (Emissions Trends and Drivers), Chapter 3 (Mitigation Pathways Compatible with Long-term Goals), Chapter 4 (Mitigation and Development Pathways in the Near to Mid-term), Chapter 5 (Demand, Services and Social Aspects of Mitigation), Chapter 6 (Energy Systems), Chapter 7 (Agriculture, Forestry and Other Land Uses (AFOLU)), Chapter 8 (Urban Systems and Other Settlements), Chapter 9 (Buildings), Chapter 10 (Transport), Chapter 11 (Industry), Chapter 12 (Cross-Sectoral Perspectives), Chapter 13 (National and Sub-national Policies and Institutions), Chapter 14 (International Cooperation), Chapter 15 (Investment and Finance), Chapter 16 (Innovation, Technology Development and Transfer), Chapter 17 (Accelerating the Transition in the Context of Sustainable Development).

Chapter 1 (Introduction and Framing) was excluded from the analysis as it serves as an overview of the report and therefore not particularly relevant to the discussion. The chapters with keyword occurrences of more than 300 were chosen for future analysis due to the relevance and page limitations of the thesis. The seven most relevant chapters for deeper analysis included: Demand, Service, and Social Aspects of Mitigation (Chapter 5), Energy (Chapter 6), Urban Systems and Other Settlements (Chapter 8), Buildings (Chapter 9), Transport (Chapter 10), Industry (Chapter 11), Cross-Sectoral Perspective (Chapter 12).

Chapter 3–Circular Economy and related concepts across selected chapters

Chapter 3 examines selected chapters of IPCC AR6 to analyze the extent to which circular economy (CE) concepts are incorporated and the ways they are addressed. Each chapter is reviewed individually to provide a structured discussion.

3.1 Demand, Services, Social Aspects of Mitigation – IPCC AR6 Chapter 5

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the total number of occurrences in IPCC AR6 Chapter 5 is over 300, where "circular economy"–45, "recycling"–35, "renewable energy"–31, "reuse"–19, "sharing"–128, "waste"–79, "sustainability"–111, "life cycle assessment (LCA)"–3, "efficiency"–144.

3.1.1. Introduction

The chapter elaborates on the impact of demand-side solutions on climate change mitigation actions. Demand-side solutions are based on social aspects including customer behavior, lifestyle and are coupled with production systems and infrastructure leading to the growth of a socio-technical perspective. It is important to highlight demand-side solutions as they contribute to Sustainable Development Goals in terms of human well-being and help to stay within planetary boundaries (Keyßer and Lenzen, 2021). Overall, this chapter is focused on the implementation of the ASI concept, "Avoid", "Shift", and "Improve" as service-related mitigation strategies. "Improve" refers to enhancements of efficiency in available technologies. For example, in the context of transportation, the framework can be applied in a way: shifting to more efficient transportation means (from personal vehicles to fast bus service) and reducing carbon intensity by utilizing renewable energy for public transportation (Creutzig et al., 2016a). However, successful implementation of the ASI model can be distinguished with proper infrastructure, financial investments and political systems supporting mitigation actions.

3.1.2 Mapping the Opportunity Space

ASI framework categorizes the mitigation actions for the continuous elimination of waste in delivering service systems. "Avoid" provides opportunities to reduce waste and unnecessary demand for service provision through teleworking, avoiding long-hour flights, changing dwelling size, and avoiding food with a short life span. "Shift" strategies focus on meeting service demand by reducing resource use, lifecycle energy and emissions through the following strategies: transitioning to multi-family dwellings (reduction of material intensity per unit floor area (Ochsendorf et al., 2011)), adopting low-carbon materials to reduce resource intensities (e.g. use of blended concrete (Scrivener and Gartner, 2018), shifting to additive manufacturing to decrease material waste (Huang et al., 2016, 2017). “Improve” strategies enhance the efficiency of existing systems, reducing energy and material waste.

One type of waste that contributes to GHG emissions is food waste, which accounted for 8-10% of GHG emissions from 2010 to 2016 (Mbow et al., 2019). Most food waste comes from consumers, necessitating behavioral changes, including meal planning, avoiding over-preparation, and utilizing leftovers (Gunders et al., 2017; Schanes et al., 2018). Reducing food waste will lead to 0.1–5.8 $GtCO_2$-eq mitigation potential and further reduce energy, land, and materials demand.

In the transportation sector, effective waste reduction strategies can include light-weighting vehicles (Fischedick et al., 2014) and avoiding using carbon-intensive materials (Das et al., 2016; Hertwich et al., 2019; IEA, 2019b). In the building sector, waste reduction can be achieved with material efficiency strategies such as 3D printing for geometry optimization and minimization of materials in structural elements to improve circularity (Mahadevan et al., 2020; Adaloudis and Bonnin Roca, 2021). Service efficiency strategies aim to avoid the material demand by the dematerialization of packaging (minimizing the use of the material in packaging design) (Worrell and Van Sluisveld, 2013) and introducing “products as services” (transforming products into long-lasting service) (Oliva and Kallenberg, 2003), therefore aligning with material efficiency and circular economy principles.

Overall, implementing CE strategies can lead to significant changes, such as:

- Infrastructure changes can enhance product reusability and recyclability and using CO_2-neutral materials can lead to material efficiency.
- Shifting from products with short lifespans to long-lasting products can reduce emissions and resource use by 29% by 2050.
- Improved recycling and resource efficiency could cut 3 $GtCO_2$-eq in 2050 (Van Vuuren et al., 2018; IEA, 2019a).

According to the Low Demand Scenario[1], the behavior and technological changes using ASI strategies in combination with digitalization and circular economy will lead to delivering decent living standards and in the meantime reduce global final energy demand to 245 EJ in 2050 (Grubler

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[1] mitigation scenario that envisions a future where global final energy demand is significantly reduced through lifestyle changes, efficiency improvements, and technological innovations rather than relying solely on supply-side decarbonization

et al., 2018). Digitalization, sharing, and the circular economy are considered transformative megatrends for climate change mitigation (Material Economics, 2018). The sharing and circular economy are interconnected concepts that include practices such as reuse, repair, recycling, and waste scavenging. Digitalization can benefit the circular economy by improving material management through waste exchanges (businesses trade unused waste between each other) and industrial symbiosis (use of businesses' waste as resources).

However, the sustainability aspect of digital service implication depends on several factors: energy demand of digital infrastructure; efficiency gain, through the increase of system-level energy and resource efficiency (Wilson et al., 2020b); energy, material and waste management standards for ICT devices (Belkhir and Elmeligi, 2018; Malmodin and Lundén, 2018); and potential rebound effect (unsustainable demand growth) (Wadud et al., 2016). The fast spread of digitalization consequently leads to the increase of e-waste, which is the most rapidly growing domestic waste stream (Forti et al., 2020).

The sharing economy is a model that proposes the sharing of assets in between without transferring the ownership. The concept became widely spread also thanks to the increase in digitalization and the occurrence of online platforms, which make the sharing of underused items and services more convenient. The sharing economy involves the following aspects:

- Extending Product Lifespan: with the help of the sharing economy principle, consumable products become long-lasting (durable) goods resulting in "product service" (Fischedick et al., 2014).
- Shared mobility: Sharing assets (car, bicycle, e-scooter) facilitates the decrease of GHG emissions if it substitutes more GHG-intensive travel (Shaheen and Cohen, 2019). In addition, it alters consumer behavior from "ownership of personal transportation to demand fulfilment" (Mi and Coffman, 2019).
- Shared accommodation: Shared housing provides efficient resource use per capita due to the shared use of heating, lighting etc (Voytenko Palgan et al., 2017).

Shared economy strategies are also related to the "Avoid" and "Shift" strategies of ASI by reducing energy and material consumption while providing similar or improved services.

Circular economy strategies facilitate the reduction of energy and material consumption while delivering the same level of service with lower environmental impact. The most common definition of circular economy was formulated by the Netherlands Environmental Assessment Agency in 2018 by addressing ten circularity strategies: Refuse (R0), Rethink (R1), Reduce (R2), Reuse (R3), Repair (R4), Refurbish (R5), Remanufacture (R6), Repurpose (R7), Recycle (R8), and Recover energy (R9) (Potting et al., 2018). A key goal is to maintain the value of the products when they reach the end of life (Linder and Williander, 2017) through initial design which ensures recyclability after use (de Coninck et al., 2018), while service-oriented strategies try to reduce lifecycle emissions (Creutzig et al., 2018). Main examples include the reuse of building materials in construction (Shanks et al., 2019), remanufacturing of products to ensure durability, and recycling improvement to reduce upstream resources (IEA, 2019b; IEA, 2017b). Despite all the benefits of CE, research concerning its effect on climate change mitigation remains limited, thus during the systematic literature review performed by Cantzler et al., (2020), 3,244 peer-reviewed articles were found concerning CE, however, only 10% of them address the relation between CE and climate. Furthermore, among CE strategies recycling remains the most investigated in comparison with reuse and reduce strategies (Cantzler et al., 2020).

It is worth acknowledging that several constraints exist concerning the effectiveness of CE, including:

- Thermodynamic limits of recycling: Recycling is limited by material degradation (quality loss) and mass conservation principles, and requires a large amount of energy (Cullen, 2017).
- Demand outpacing efficiency gains: Global materials and energy demand might increase disproportionately to the improvements of supply chains, therefore making CE insufficient strategy on its own (Bengtsson et al., 2018). Currently, only 6.5% of all processed materials come from recycled sources and since 44% of materials are used for energy generation, they are not recyclable reinforcing the need for eco-design (Haas et al., 2015).
- Impact on cost-effectiveness: Some CE strategies are considered cost-effective but require a significant energy supply, leading to an increase in energy intensity as well as a reduction of labor intensity due to automation. Proper institutional framework should be established to balance profitability and sustainability (Moreau et al., 2017).
- Regional disproportions: The occurrence rate of different CE strategies including recycling, reuse, and refurbishing vary significantly between developed and developing countries (McDowall et al., 2017).

The effective implementation of CE strategies can result in a reduction of more than 6 $GtCO_2$ emissions in 2030 (Blok et al., 2016). However, achieving this potential requires prioritizing material reduction as merely substituting materials or refurbishing buildings may still increase emissions (Castro and Pasanen, 2019; Eberhardt et al., 2019). Tax reforms that shift the burden from labor to raw material extraction and greenhouse gas (GHG) emissions could further drive the adoption of CE practices. A reduction of 50 % of GHG emissions in industry between 2010 and 2050 can be accomplished with a combination of innovative strategies and a reduction of primary input (Allwood et al., 2010).

CE strategies align with the "Avoid" strategy for primary materials. They enhance human well-being by reducing environmental harm and saving financial resources by lowering consumption needs. However, the rebound effect[2] should be taken into account, as reducing the consumption of one product may lead to increasing consumption of another product (Castro et al., 2022). The discussions regarding the Circular Economy are usually focused on technological advancement ("Improve") and waste minimization ("Avoid"), while "Shift" related to consumer behavior receives less attention. One of the reasons can be that initially circular economy is related to industrial ecology, which puts more attention on material systems rather than end users. By shifting the focus from the supply to the demand side, customers are seen as users who interact with businesses to meet their needs, making behavioral adoption crucial (Hobson, 2019).

Overall, the circular economy framework has a significant potential for climate change mitigation, however, this potential can be limited if industry and decision-makers do not prioritize the reduction of raw material use. CE strategies, including recycling and extending the lifetime of a product remain thermodynamically limited and at a small scale as long as demand for raw material continues to rise. Despite the growing amount of literature concerning CE, there is still a significant gap concerning the understanding of the overall influence of some CE strategies. Moderate agreements exist on CE and sharing economy can lead to a reduction of resource use and GHG emissions, however, the scale of potential savings is still uncertain.

3.1.3 Governance and Policy

Demand-side mitigation measures have a significant untapped potential, but current policies prioritize "Improve" (technological efficiency) over "Avoid" (waste reduction) and "Shift" (alternative materials, sharing economy) (Dubois et al., 2019; Moberg et al., 2019). Demand-side mitigation policies are often insufficient, fragmented and robust to achieve climate goals (Mundaca et al., 2019; Moberg et al., 2019).

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[2] refers to situations where improvements in resource efficiency lead to increased overall consumption, thereby offsetting the anticipated environmental benefits

Several countries started to implement stronger measures within this domain, including prohibitions on fossil fuel heating and substituting it for lower carbon options. However, policymakers prefer incentives and awareness campaigns rather than stricter regulations, because policies concerning behavior and lifestyle changes have a perception of being riskier for policymakers (Rosenow et al., 2017; Moberg et al., 2019). Accelerating demand-side transitions require a broader policy mix including all ASI and ensuring a comprehensive governance framework (Kern et al., 2017; Rosenow et al., 2017; IPCC, 2018). Transitions in developing countries will also require stronger administrative capacities and providing financial and technical support (UN-Habitat, 2013; Creutzig et al., 2016b).

To systematically integrate demand-side approaches, the Avoid-Shift-Improve framework provides a structured way to categorize policies across sectors and services, identifying key areas where obstacles may arise. The introduction of Avoid-Shift-Improve framework will help to categorize demand-side policies by sectors and services identifying main areas for potential obstacles.

Table 3.1.3. Policy tools for Mitigation: Initiatives and Strategies by sectors (IPCC, 2022).

Mitigation option	**Incentives**
"Avoid"	
Reduce/ avoid food waste	Raise consumer awareness of food waste; establish a clear well-defined labelling system (Wilson et al., 2017); support R&D for packaging improvement to extend life (Thyberg and Tonjes, 2016); charge households for excess food waste
Sharing economy	Subsidies for sharing services providers (Jung and Koo, 2018)
"Shift"	
Multifamily housing	Regulations regarding land use to promote higher-density living (Geffner, 2017)
Material-efficient product design, packaging	Establish standards for embodied carbon for buildings (IEA, 2019c)
Architectural design with shading and ventilation	Incentives to increase urban density, buildings with lower surface-to-volume rations, and better shading (Creutzig et al., 2016a)

Table 3.1.3. Policy tools for Mitigation: Initiatives and Strategies by sectors (Continued).

"Improve"	
Use low-carbon materials in dwelling design	Increase of construction/demolishing waste recycling; incentives to put recovered materials at higher value (Nußholz et al., 2019)
Better insulation and retrofitting	Financial support from banks; labelling of building and heating systems (Ortiz et al., 2019; Sebi et al., 2019); energy use disclosure (Sebi et al., 2019)

Policy coordination is critical to balance demand-side and supply-side measures and manage infrastructure interdependence to avoid trade-offs. As an example, Germany's policies on renewables started with funding for research, development and demonstration (RD&D), followed by subsidies and large-scale projects with feed-in tariffs for the utilization of solar power (Jacobsson and Lauber, 2006), therefore resulting in industrial growth of solar and wind energy. An example of successful policy coordination is the phase-out of inefficient incandescent light bulbs (ILBs) in Europe. The transition from inefficient incandescent light bulbs (ILBs) to energy-efficient lighting, such as CFLs and LEDs, was facilitated by coordinated policies which increased public awareness, provoked voluntary actions and helped to frame ILBs associated with energy waste. Therefore, a combination of technological development and proper regulations can work together to facilitate actions for climate change mitigation.

3.2 Energy Systems – IPCC AR6 Chapter 6

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 6: "circular economy"–2, "recycling"–21, "renewable energy"–126, "reuse"–6, "sharing"–6, "waste"–89, "sustainability"–36, "life cycle assessment (LCA)"–11, "efficiency"–122.

3.2.1. Introduction and recent trends and developments in energy systems.

The chapter focuses on energy system being the largest source of carbon dioxide emissions, therefore the reduction of which is specifically important for climate change. Currently, global electricity is mainly supplied by oil, coal and natural gas with considerably smaller renewable energy share (IEA, n.d.) However, the future scenario suggests the shift towards solar, wind and biomass sources for generating electricity (Fig 3.2.1).

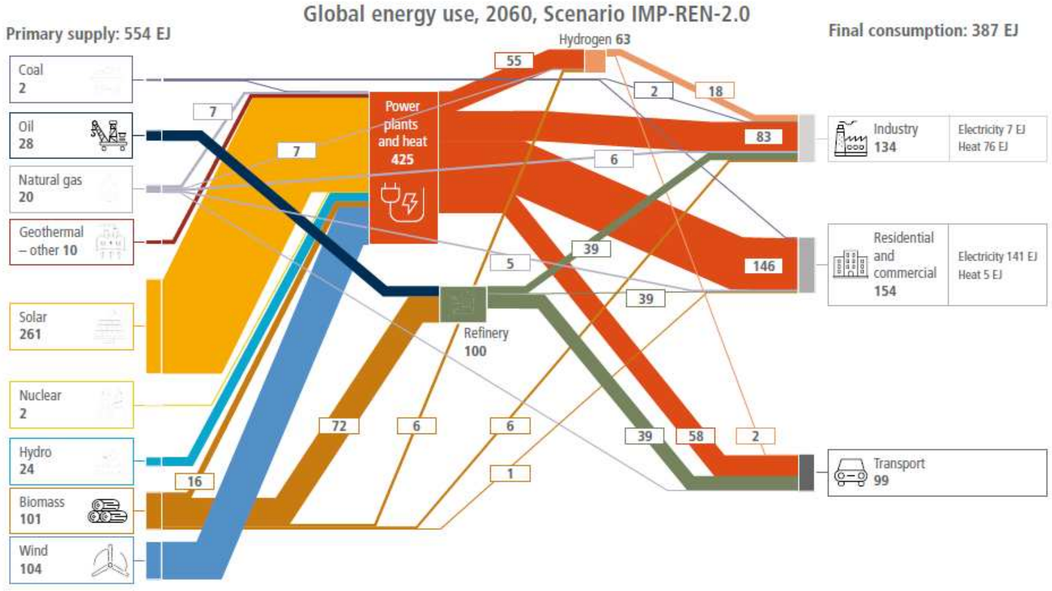

Figure 3.2.1. Prediction of global energy flow by 2060 (IPCC, 2022).

The recent energy system trends and developments suggest the following:

- Total global energy emissions continue to grow with a decreasing rate. If the current trend of energy emissions' growth remains the same, the global temperature change by the end of this century will not be just limited to 2°C. The emissions of the global energy systems based on fossil fuels increased by 1.1% yearly from 2015 to 2019 (IEA, 2021d). However, the energy intensity has been gradually decreasing since 2015 (IEA, 2020b), with this reduction in EU linked to the increase of renewable electricity production (Dyrstad et al., 2019).
- The total global energy demand and production continue to grow with the decreasing rate. Between 2015 and 2019, renewable energy (excluding hydropower) increased at an annual rate of 12%, however, their share in total primary energy supply remains low (2.2% in 2019, up from 1.5% in 2015).
- Energy systems continue to change under the influence of non-climate factors. By 2019, 90% of global population received access to electricity (IEA, 2020c), though this access was granted mostly by use of fossil fuels, however the amount of people receiving electricity from renewable sources continue to grow. The energy security concerns led to the increase of investments into renewable energy generation on a domestic scale (Konstantinos and Ioannidis, 2017). The costs of renewable energy sources decreased drastically, making on-grid renewables the most affordable option to ensure universal access to electricity by 2030.
- One of the goals is to eliminate the usage of coal, however, only a modest decrease has been achieved so far (IEA, 2024). The reduction of coal use is mainly driven by the reduction of

renewable energy costs. Many countries in Asia suspended new projects for coal plant expansion due to environmental constraints and the deployment of renewables. In the USA, old coal-fired power stations were replaced by half of gas and half of renewables, while in the EU mostly by renewables.

- There has been a significant increase in the use of solar and wind energy, however, the total share in the global energy supply remains relatively low. Between 2015 and 2019, the global wind and PV capacities increased by 70% and 170% respectively. In 2019, the total share of both in global electricity generation increased to 8% (2.5% solar, 5.5% wind) from 5% in 2015 (IEA 2021a). The cost of PVs, offshore wind and onshore wind dropped by 60%, 32% and 23% respectively since 2015. Solar PVs accounted for 99% of total solar capacity, while onshore wind accounted for 95% of total wind capacity. The rapid expansion in solar and wind capacities stands for the potential of these technologies in mitigation of climate change. Success will depend on the speed of solar and wind power integration into electricity grids.
- There has been a growth of other low-carbon energy sources excluding solar and wind. Since 2015 low-carbon energy sources including hydropower, geothermal, and bioenergy continue to grow (IEA, 2017; IEA, 2021a). Hydroelectric share is estimated to be 16% of global electricity generation (IEA, 2017; IEA, 2021a). From 2015 to 2019, the geothermal energy sources electricity generation increased on 0.05 EJ/yr. Bioenergy share in total electricity generation was 2.4% in 2019 (IEA, 2017; IEA, 2021a). Overall, in 2019 the total share of electricity produced by low- and zero-carbon technologies was 37% of global electricity.
- The reduction of battery prices facilitates their deployment of electricity. Prices of lithium-ion batteries (LIB) declined dramatically in the last decade alone, showing the decrease by 90%, which promoted their wider applications in energy systems, especially systems for renewable energy generation (IEA, 2021a; Ziegler and Trancik, 2021). The total amount of batteries connected to grid increased from 0.6 GW to 10 GW between 2015 and 2019 (IEA WEO, 2019; IEA, 2020c). Although pump-storage hydropower systems dominate the total installed energy storage capacity accounting by 90% in 2019, since 2015 90% of new energy storage capacity added to the grid has come from battery (LIB) energy storage systems (IRENA, 2019a; IEA, 2020c).
- Energy policies continue to change and evolve. Feed-in tariffs, tax incentives and renewable portfolio standards play an important role in attracting investments in the renewable energy sector (Wall et al., 2019). In addition, carbon pricing is a significant tool for the promotion of these renewable energy sources (Best and Burke, 2018). Subside-free investments in renewable energy, such as wind offshore are becoming more widely spread because its

funding through Power Purchase Agreements (PPAs) (Jansen et al., 2020; Frankfurt School-UNEP Centre and BNEF, 2020).

Globally, USD150 billion/yr is being contributed to the total renewable subsidy annually (IEA 2018b). However, the estimation shows that the amount spent on renewables is half the amount spent on fossil fuels subsidies (IEA, 2018b).

3.2.2 Mitigation Options

Renewable energy is well known for its significant potential in mitigating the climate change impacts. The most promising of them include solar energy, wind energy and waste-to-energy, the potential of which is assessed in Table 3.2.2.

Table 3.2.2. Renewable energy resources and their potential for mitigation.

Characteristics	**Energy sources**
	Solar Energy
Technical potential	It is estimated to be 1080 EJ/yr for solar PV, while for concentrating solar power (CSP) it is 162-295 EJ/yr (Dupont et al., 2020).
Environmental impact	GHG emissions: PV produces significantly less GHG emissions in comparison with fossil fuels. Life cycle analysis (LCA) estimates that with improved manufacturing efficiencies the GHG range is 18–60 gCO_2 kWh^{-1} (Wetzel and Borchers, 2015).
Material demand	Primary materials include silicon, glass, copper, aluminum, and silver. Materials have substitutes, can be recycled, none of them are critical or scarce (IEA, 2020e).
Recycling/ end of life Material efficiency	PVs' lifespan is about 30 years, then modules can be recycled allowing reuse of 83% of components (Ardente et al., 2019). End-of-life PV is predicted to account for 10% of global e-waste by 2050 (Stolz and Frischknecht, 2017). Solar cells consist of 70% of glass by mass which is easy to recycle. To increase recycling rate policy incentives are required. The market value for recovered materials is estimated to be low except for copper and aluminum, therefore not being able to justify recycling

Table 3.2.2. Renewable energy resources and their potential for mitigation (Continued).

	(Den et al., 2019). In addition, recovery maximization of valuable materials such as silicon, silver and aluminum is prioritized (Heath et al., 2020). Implementation of new designs and materials can facilitate the reduced use of resources and increased efficiency. In the past 10 years, the passivated emitter and rear cell (PERC) design has been widely spread leading to efficiency increase over aluminum backing (Blakers, 2019; Green, 2015).
	Wind Energy
Technical potential	The amount of potentially exploitable wind energy resources accounts for 2005-2580 EJ/yr, which exceeds global electricity demand by 20-30 times in 2017 (IRENA, 2021a).
Recycling/ end of life Material efficiency	Wind energy is dependant on use of two rare earth elements (REEs) like neodymium and dysprosium (Pavel et al., 2017; Li et al., 2020b). Transition to wind energy will increase the demand for these elements, which is the issue of concern of potential supply disruption (World Bank, 2020). In order to reduce the need in strategic materials, magnets can be removed from turbines, however, it can affect the efficiency and productive cost (Månberger and Stenqvist, 2018).
	Waste-to-Energy approach for energy recovery from waste in form of heat, fuel, electricity (Zhao et al., 2016).
Technical potential	In 2019, the overall capacity of WTE incineration facilities was estimated to 310 million tonnes/ yr (UNECE, 2020). The treatment of waste can reduce the volume of waste by 80%-90% and mass by 70%-80% (Haraguchi et al., 2019).

By implementing renewable energy options for energy demand satisfaction, financial investments in energy storage infrastructure is crucial for efficiency maximization. The adoption of energy storage facilitates the use of energy excess for the future or at a different location. If renewable energy integration doubles by 2030, the total storage capacity can triple reaching 0.043-0.055 EJ (IRENA, 2017b)

Batteries are showing the potential for energy storage as they provide rapid response time and can be used for voltage support and frequence regulation, therefore facilitating the better integration of renewables into electricity grids (Stbac and Aunedi 2016). However, battery waste is considered to be hazardous, the proper recycling of batteries is essential to address sustainability issues (Harper et al., 2019). Liquid air energy storage (LAES) enables daily storage of electricity as well as waste heat capture from industrial processes. Thermal energy storage (TES) allows to capture and reuse waste heat, therefore increasing the efficiency of industrial processes. Hydrogen, especially "green" hydrogen produced from renewable sources as solar and wind energy, supports renewable energy integration by enabling long-term electricity storage (Schmidt et al., 2017).

It is also important to emphasize that demand-side measures are crucial to reduce carbon emissions into energy systems, therefore users should implement a wide range of actions including:

- Use of renewable energy sources by producing their own (installation of PV), buying shares in projects and, or choosing providers of renewables.
- Use of technologies for energy storage to meet the demand when energy production is low.
- Change behavior towards circular economy includes reduction of waste, promoting refurbishment, sharing products so that fewer new products are used.

The change of behavior towards circular economy can be influenced by number of factors like:

- People are usually more inclined to adopt changes in behavior for mitigation purposes (energy efficiency, material efficiency), if this behavior can lead to more individual benefits, such as financial, comfort, independence in energy supply (Wolske and Stern, 2018).
- People are more likely to engage in behaviors that bring positive and, or, meaningful feelings (Steg, 2016).
- People tend to adopt renewable energy technologies more if their social circle expects them to do so (Palm, 2017).
- People who care more about the environment are more likely to act towards energy efficiency, material efficiency and renewable energy generation (Steg, 2016).

3.2.3 Net-zero Energy Systems

The introduction of technologies for zero-emission or net-negative-emissions electricity systems will require a shift to renewable energy sources including wind, solar, hydroelectric, bioenergy. There is a significant potential for achieving high shares of renewable energy (more than 75%) to satisfy hourly electricity demand, especially with variable renewable energy like wind and solar (Blanford et al., 2021; Denholm et al., 2021). The challenges however exist for high penetration of wind and solar energy, such as variability and uncertainty in generation (Cole et al., 2017). The possible solutions include the following:

- Energy storage. Technologies such as batteries and pumped hydro are crucial for managing supply and demand (Balducci et al., 2018; Bistline et al., 2020a).
- Demand Management. Improvements in energy efficiency and demand response can help align demand with renewable supply (Imelda et al., 2018a; Bistline, 2021a).

- Sector coupling. Higher electrification of the end-use sectors and adoption of synthetic fuels (such as hydrogen) have been considered vital for integrating renewables into all sectors (Davis et al., 2018; Ueckerdt et al., 2021).

Overall, net-zero energy systems prioritize energy efficiency more as a cost-effective strategy to reduce energy demand and maintain service level (DeAngelo et al., 2021). Efficiency in net-zero energy systems is predicted to be used in different sectors. For example, efficiency improvements in industry can be achieved increasing the usage of recycled materials, technological advancement in heat efficiency as well as heat waste for pumps, etc.

The global transition to low-carbon energy systems involves increasing investment in renewable electricity, especially in solar and wind generation technologies and expanding energy storage capacity. The total global investment in renewable electricity (mainly solar and wind) is estimated to be USD340 billion/yr. Many countries support the introduction of financial schemes like federal income tax credits and feed-in-tariffs to promote residential solar PV installment (Wolske and Stern, 2018). Moreover, people tend to accept mitigation options as renewable energy projects more if they or public organizations participate in decision-making process (Perlaviciute and Squintani, 2020).

Although transitioning to 100% renewables is feasible, the economic value of additional capacity typically decreases at higher penetration levels, requiring regulatory and market adjustments to ensure resource efficiency (Denholm et al., 2021; Millstein et al., 2021).

3.2.4 Benefits of low-carbon energy systems on Sustainable Development Goals

The increasing integration of renewables such as solar PV, wind and batteries is largely driven by falling costs. Strategies to ensure energy efficiency and energy conservation align with strategies for sustainable development. Many studies claim that energy efficiency has a large potential to be untapped in demand and supply (Lovins, 2018; Méjean et al., 2019). Increased efficiency and energy conservation will lead to more sustainable energy production and consumption (SDG 12, Responsible Consumption and Production). Reducing the extraction of resources is another important contributor to SDG 12.

The public perception of solar PV has improved due to the positive linkage between sustainable development goals and climate change mitigation strategies, making it the most acceptable among other major mitigation options. The use of PV power for water pumping technologies can lead to reduction of energy consumption and lead to promotion of SDG 6, Clean Water and Sanitation. In combination with SDG 7, Affordable and Clean Energy, the increase of renewable energy technologies will result in potential employment opportunities in the energy sector and increased urge for skilled workers. Moreover, withholding fossil fuels will improve air quality (SDG 3, Good Health and Well-being) and consequently decrease the rate of premature deaths (He et al., 2020; Li et al., 2020c).

3.3 Urban Systems and Other Settlements – IPCC AR6 Chapter 8

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 8: “circular economy”–16, “recycling”–22, “renewable energy”–46, “reuse”–6, “sharing”–12, “waste”–155, “sustainability”–64, “life cycle assessment (LCA)”–3, “efficiency”–43.

3.3.1 Introduction, trends and benefits for Sustainable Development Goals

The chapter is mainly focused on urban systems and settlements and how their spatial organization influences GHG emissions, as well as how urban infrastructure can contribute to better mitigation. Urban areas accumulate GHG mostly because of size of population, urban economy and GHG embodied inside infrastructure and products (USGCRP, 2018).

Urban mitigation strategies lead to greater sustainability contributing to SDG 11, Sustainable Cities and Communities. Urban mitigation strategies such as electrification based on renewable energy will be beneficial for outdoor and indoor air quality improvements (Kjellstrom and McMichael, 2013), consequently leading to avoidance of premature deaths (SDG 3, 7). Measures of waste management and recycling of wastewater can generate economic benefit (SDG 6, 12). Recycling wastewater can reduce the cost of renewal of plants for wastewater treatment (Nisbet et al., 2019). Moreover, the energy from waste-to-energy systems can compensate for wastewater management expenses (Colenbrander et al., 2017; Gondhalekar and Ramsauer, 2017).

Furthermore, urban planning and construction affect the amount of GHG emissions to be released. The design of buildings and infrastructure affects the number of materials and energy to be used, energy demand, and long-term emissions (d’Amour et al., 2017). A study covering 700 urban areas concludes that by 2050, GHG emissions can be decreased from 14 $GtCO_2$-eq to 1.8 $GtCO_2$-eq by application of mitigation measures. The reduction will come from buildings (58%), transport (21%), material efficiency (15%), waste (5%) and decarbonized electricity. Electrification and connecting different sectors inside urban infrastructure can lead to the higher introduction of renewable energy sources into the energy grid.

3.3.3 Urban Mitigation Options

Mitigation measures can be applied at different urban levels from households, such as increasing energy efficiency for appliances, to city and regions. Local reduction of emissions can promote a decrease on a bigger scale through proper use of materials and energy, better efficiency of infrastructure.

Spatial planning is a crucial factor for establishing sustainable urban infrastructure, which also includes heating and cooling systems (UNEP IRP, 2020). Low-temperature systems, utilizing the renewable energy, or waste heat, can avoid reliance on carbon from fossil fuels, while proper eco-design can lead to further improvement of system efficiency (Dominković and Krajačić, 2019). Electrifying heating and cooling networks can cut emissions by 65% (De Chalendar et al., 2019).

In urban areas measures for energy efficiency can be promoted by building codes, retrofitting and renovation. Electrification and renewable integration offer major advantages:

- The 54%-95% of CO_2 emissions reduction can be achieved by utilizing of all-electric vehicles (EVS) and roof-top photovoltaics (PVs) systems alone (Brenna et al., 2014; Kobashi et al., 2021).
- Electrification allows the absorption of large shares of renewable energy in mobility, heating and cooling. By connecting the efficient building clusters with smart thermal grid in heating and cooling systems, higher implementation of renewable energy in urban energy systems can be achieved (Lund et al., 2014; Lund et al., 2017).
- It is easier to increase the use of renewable power in urban areas with high densities. Urban electrification can decrease renewable energy waste by adjusting energy time-of-use on smart systems (O'Dwyer et al., 2019).
- By increasing demand-side flexibility, urban systems can support 100% renewable energy systems (Thellufsen et al., 2020).
- Smart grids can result in GHG emissions from 10 to 180 $gCO_2\ kWh^{-1}$ depending on several factors, including renewable energy penetration (Moretti et al., 2017).

Electrification technologies still possess certain trade-offs which can be minimized by circular economy practices combined with good governance and international cooperation. Electrification technologies should be undergone material recycling to reduce potential social and environmental costs (Gaustad et al., 2018; Sovacool et al., 2020). Circular economy strategies are crucial to create supply chains with the closed-loop by utilizing material recovery, reuse, recycling and repair. For instance, PV CYCLE program[3] resulted in a reduction of 30,000 metric tons of waste from renewable technologies.

Engineered timber can also be used in mid-rise urban buildings for broad substitution of steel and concrete, therefore transforming buildings from GHG emitters to carbon sinks. Biomass-based structured materials as timber store carbon from forests, decreasing reliance on emission-intensive materials like steel and concrete. Broader implementation of agroforestry measures can help balance forestry and agriculture, while recycling and reusing timber material from dismantled buildings. Practices supporting material reuse and design for disassembly will make the solutions more durable (Churkina et al., 2020).

Waste is the impactful source of GHG emissions, which remains the second largest urban emissions contributor, after the energy sector (Lu and Li, 2019; Nisbet et al., 2019). Municipal authorities hold the responsibility for waste management and remain the key for city-level efforts to reduce related emissions (Zaman and Ahsan, 2019). However, assessing the impact of mitigation measures is challenging because of varying system definitions and difficulties in tracking avoided waste (Matsuda et al., 2018).

Socio-behavioral changes in terms of urban infrastructure are required as well for effective waste separation at source and implementation of waste hierarchy (Sun et al., 2018a; Hunter et al., 2019) and the former can also improve reduction of emissions related to transportation (Oliveira et al., 2017). Decentralized waste management systems encourage people to better sort the waste at source, thus making the benefits more visible (Linzner and Lange, 2013). Additionally, public acceptance increases as cost for citizens is reduced, and a larger awareness campaign of waste management is established (Slorach et al., 2020).

However, waste composition and generation can vary depending on the region, therefore requiring different activities in waste disposal terms on the sides of both institutional and infrastructure. The prioritized measures include either reduction of waste generation and waste to energy transformation

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[3] European initiative focused on the collection, recycling, and sustainable disposal of photovoltaic (PV) solar panels

or transformation into other products in circular economy (Calderón Márquez and Rutkowski, 2020; Fatimah et al., 2020). Waste collection, recycling and composting rates, waste treatment techniques are different depending on the location, even the areas with the same urbanization rate can generate different waste per capita depending on various economic, cultural, and policy-related factors (Kaza et al., 2018).

To maximize the benefits of the waste management sector in energy recovery, material reuse, and emissions reduction, the implementation of innovative policies is essential (Jiang et al., 2017). Without intervention, municipal solid waste is projected to reach 3.4 Gt by 2050 globally (Kaza et al., 2018). The transformation of informal waste recycling[4] activities into structured programs can enhance the distribution of costs and benefits, support public awareness, and improve low-carbon waste management strategies (Conke, 2018; Grové et al., 2018; de Bercegol and Gowda, 2019). Balancing centralized and decentralized approaches is key to addressing the challenges of integrating informal waste workers into formal systems. The waste management sector also presents significant opportunities for employment and economic growth, with an estimated 45 million jobs by 2030, particularly when informal labor is transitioned into value-added recycling and resource recovery roles (Coalition for Urban Transitions, 2020; Soukiazis and Proença, 2020).

Overall, to alleviate the use of resources and upstream emissions the measures regarding waste minimization, prevention and management should be more widely implemented (Harris et al., 2020). Integrated waste management allows to maximize the potential of mitigation measures; therefore, emissions can be decreased due to: reuse and recycling of materials to avoid upstream emissions; changes in land use to ensure avoidance of emissions (also from waste disposal); avoidance of primary energy use. Waste generation can be decreased with the combination of proper technologies, infrastructure, behavioral changes according to waste hierarchy.

Considering the waste-to-energy potential, it depends on the technological pathway to be undertaken, and its role in waste management practices (Alzate-Arias et al., 2018; Islam, 2018), while on the side of food waste management, recycling and reduction at source will require also changes in socio-behavioral side (Gu et al., 2019). Moreover, recycling of nutrients from waste and reuse of wastewater are included into strategies for urban food production.

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[4] refers to waste management activities that are not officially regulated, recognized, or integrated into formal government or private sector waste systems

To summarize, urban mitigation strategies include two main categories: clean energy, sustainable transport, construction and coupling via electrification (Waheed et al., 2018); urban design, urban form, spatial planning and their synergies (Wang et al., 2017; Privitera et al., 2018). Material efficiency strategies can be more beneficial if they are applied by cross-cutting sectors, which implies utilization of less material by down-sizing or light-weighting, prolonged use of materials, substitution, improved recycling, reuse, remanufacturing, recovery. By establishing light-weighting design in buildings, GHG emissions related to materials can be reduced by 20% (UNEP IRP, 2020). GHG emissions can be decreased, and resource impact can be reduced by combining strategies of resource efficiency and strategic densification.

3.3.4 Governance, Institutions, and Finance

Potential trade-offs of electrification can be minimized by local governments by implementation of circular economy strategies. These strategies include financial and institutional support, partnerships between producers and consumers, therefore increasing recycling efficiency by providing a path from consumer waste to producer (Fratini et al., 2019).

In 2020, over 830 cities across 72 countries had established renewable energy targets, with more than 600 of these cities aiming for 100% renewable energy (REN21, 2021).

3.3.5 Integrating Mitigation Strategies for Different Urbanization Typologies

The largest GHG emissions can be archived by repurposing, retrofitting the buildings, as well as electrifying energy systems. The retrofitting of buildings alone can lead to emissions reduction of existing stock by 30-60% with the estimation in some cases up to 80% (Creutzig et al., 2016a; Ürge-Vorsatz et al., 2020).

A significant effect in energy saving and emissions reduction can be achieved by ensuring both behavioral and structural changes (Zhang and Li 2017). The better sustainability of urban systems can be ensured by implementing social and ecological innovations and as the result provide decoupling of economic growth and energy use (Hu et al., 2018; Ma et al., 2018). Cross-sector actions including increasing the efficiency of urban infrastructure, reducing waste by use of circular waste, and expansion of public transport can lead to transforming urban areas into hubs with sustainable mobility and renewable energy (Lin et al., 2018).

On the human resources, or labor, side, the involvement of multidisciplinary teams of specialists composed of architects, engineers as well as representatives of environmental institutions can lead to strengthening of decision-making at all policy level and therefore increase to energy efficiency and widen the use of renewable energy (Mrówczyńska et al., 2021).

Rapidly growing cities with developing infrastructure can prevent future emissions by proving the urban planning, electrifying all sectors including transport, heating, cooling, as well as different recycling systems, among others.

Urban areas should be built differently, planning a reduced use of materials, innovative energy-driven urban design, while lowering impact on land use. This perspective can be summarized in a demand minimizing approach to energy and material use. The effective measures can include material substitution, lightweighting, renewable energy use, material efficiency to ensure more sustainable urbanization. Furthermore, new cities can utilize lifecycle assessments for analysis of materials and renewable energy use in order to avoid ecosystem disruption and energy use (Ingrao et al., 2019). Integration of urban planning, energy electrification, renewable energy use for heating and cooling systems, circular economy can provide additional beneficial effects on improving air quality and therefore health and well-being (González-García et al., 2021). The positive effects from GHG emissions measures can be achieved for water quality by implementing efficient water use and recycling (Kim and Chen, 2018).

3.4 Buildings – IPCC AR6 Chapter 9

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 9: “circular economy”–14, “recycling”–6, “renewable energy”–81, “reuse”–3, “sharing”–22, “waste”–20, “sustainability”–30, “life cycle assessment (LCA)”–1, “efficiency”–373.

3.4.1 Introduction

This chapter introduces the importance of the Sufficiency, Efficiency, Renewables framework (SER, hereafter) as a high-potential mitigation strategy. Overall, SER aims to tackle the causes, symptoms, and consequences of human activities' environmental impacts. It follows a hierarchical structure, where sufficiency stands first and followed by efficiency and renewable.

“Sufficiency” is defined as avoiding the demand for energy and materials over the life cycle of buildings and goods while delivering decent living standards within the planetary boundaries (Saheb, 2021b; Princen, 2005). Efficiency is directed towards the improvement of energy and materials intensity. The renewables pillar addresses the reduction of carbon intensity in energy supply. An example of sufficiency is the decrease in housing size by repurposing the existing buildings and applying cohousing, therefore reducing the demand for material in construction and the demand for energy for lighting, heating, and cooling (Duffy, 2009; Heinonen and Junnila, 2014).

3.4.2 New Developments in Emission Trends and Drivers

Building management systems play a crucial role in optimizing building operations by integrating renewable energy, energy-efficient air conditioning, and solar photovoltaic power for cooling (Burnett et al., 2014). Additionally, new technologies such as Building Information Modelling (BIM) are essential for assessing the environmental impact of buildings (Lambertz et al., 2019).

A key challenge in reducing greenhouse gas (GHG) emissions in buildings is addressing major energy demand trends, including cooling energy, electricity use, and digitalization energy demand. Sufficiency measures, such as designing smaller, well-insulated buildings, can significantly lower energy consumption. Renewable-powered air conditioning can further reduce emissions, while electrification remains an effective decarbonization strategy—provided it is supplied by renewable energy sources (Ruhnau et al., 2020). Notably, the share of data centers powered by renewable energy is steadily increasing (Cook et al., 2014). Additionally, 3D printing in construction has the potential to minimize material waste (Dixit, 2019). Applying sufficiency measures could limit demand growth from 4% to 1.5% (Ferreboeuf, 2019).

To assess the trends and future projections of GHG emissions in buildings, the International Energy Agency (IEA) has proposed several scenarios:

- IMAGE-Lifestyle-Renewable (LiRE) scenario: Focuses on limiting building floor area per capita, increasing electrification, and expanding renewable energy in the energy mix (Detlef Van Vuuren et al., 2021).
- Resource Efficiency and Climate Change-Low Energy Demand (RECC-LED) scenario: Examines the role of resource efficiency in emission reduction.

Key drivers of GHG emissions include population growth, sufficiency, efficiency, and renewable energy adoption. Between 1990 and 2019, sufficiency policies in developed countries helped stabilize material use, while renewable energy use expanded in developing regions. However, in 2019, global energy demand from buildings reached 128.8 EJ, accounting for one-third of total energy consumption, with solar thermal and geothermal energy contributing only 1% of this demand. Looking ahead to 2020-2050, different IEA scenarios predict varying impacts on emissions, with renewable energy playing a central role in emission reduction. The successful implementation of sufficiency measures, electrification, and renewable energy integration will be key in shaping a low-carbon building sector for the future.

3.4.3 Technological Mitigation Options

Buildings are becoming more energy efficient which leads to the reduction of operational energy demand, therefore the importance of embodied energy and embodied carbon in building materials is growing (Ürge-Vorsatz et al., 2020). The most prominent building materials including steel possess the highest embodied energy (32-35 MJ kg–1) in comparison with masonry, and wood. Buildings can be considered as carbon sinks in terms that wood material stores a significant amount of carbon compared to emissions generated during its production. However, some materials as concrete generate a lot of carbon during the production process and have minimal storage capacity (Sanjuán et al., 2019; Churkina et al., 2020).

With the reduction of emissions from energy used in buildings, the share of emissions associated with the production process of materials used for construction is becoming larger therefore the embodied emissions are an important factor in the building sector's total emissions (Röck et al., 2020). Embodied emissions can be lowered by implementing material efficiency measures: improving building design, light-weighting of materials, substitution of materials for alternatives with lower carbon, reuse of building components (Pamenter and Myers, 2021; Pauliuk et al., 2021). Further reductions in embodied emissions can be achieved by slower growth in floor area per capita (sufficiency), reduction of material mass (material efficiency), and decarbonizing material production using renewable energy sources.

According to Attia et al., (2017), Enongene et al., (2017), and Baloch et al., (2018), lighting energy accounts for 19% of global electricity consumption. Several studies highlight the correlation between improving the energy efficiency of lighting appliances and decreasing energy consumption.

Considering Positive Energy or Energy Plus Buildings[5], the integration of renewables in the buildings should follow a step-by-step approach. The priority should be set on demand reduction by utilizing sufficiency measures and maximizing energy efficiency to cut energy consumption. As soon as demand is reduced, the implementation of renewables will allow the buildings to become prosumers-producers and consumers of energy (Sánchez Ramos et al., 2019). The decreased price of photovoltaics and the integration of energy storage are significant factors to enable the widespread adoption (de Gracia and Cabeza, 2015). Additional renewable energy sources are considered as well and include photovoltaic/thermal (Sultan and Ervina Efzan, 2018), solar/biomass hybrid systems (Zhang et al., 2020b), solar thermoelectric (Sarbu and Dorca, 2018), solar-powered sorption systems for cooling (Shirazi et al., 2018), and on-site renewables with battery storage (Liu et al., 2021).

3.4.4 Behavioral Mitigation Options

Regenerate, Share, Optimize, Loop, Virtualize, Exchange (ReSOLVE) framework highlights non-technological circular economy solutions like sharing, virtualizing and exchanging. These aspects still remain less studied in CE applications (CE100, 2016; ARUP, 2018).

Even though consumers are interested in the advantages of RES, implementation limitations still exist in terms of economic and governmental support. Technical issues remain for novel technologies, and stakeholders should establish capacities (Mata et al., 2021a; Musonye et al., 2020)

The circular and sharing economy is becoming more perceived as an innovative approach by consumers, even though technical and regulatory challenges are still a limitation for broader use and difficulties exist regarding demonstration to consumers and supply chain (Pomponi and Moncaster 2017; Hart et al., 2019). Governmental support is required to establish a proper system of standards and regulations, especially regarding taxes for waste reduction and recycling (Rachel and Travis, 2011; Ajayi et al., 2015; Volk et al., 2019).

3.4.5 Global and Regional Mitigation Potentials and Costs

This section analyses the literature regarding the potential of GHG emissions in buildings in different countries based on the SER framework. The sufficiency approach is the novelty for the current report and even though most of the studies claim sufficiency to be an important option for Developed

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[5] is designed to generate more energy from renewable sources than it consumes over a specified period, typically one year

Countries, it is also important for Developing ones. It addresses the reduction of inequality and poverty by providing sufficient living standards for the whole population.

Combining measures such as energy efficiency and renewable energy concludes that when energy demand is low, there is a greater choice of low energy supply options and therefore such a sequencing is more advantageous. (Rogelj et al., 2018). The introduction of the sufficiency approach is computer to ensure a minimum of 1.4 $GtCO_2$ emission reduction, while energy efficiency technology–5.6 $GtCO_2$, renewable energy–1.1 $GtCO_2$ in the future

Although a significant number of studies justify that implementation of the sufficiency approach can lead to a large share of the potential for developed countries, no robust cost assessment is provided, indicating that the costs can be very low. (Cabrera Serrenho et al., 2019). The cost estimation of renewables at a large scale remains difficult as well due to the parameters of different building types (Horváth et al., 2016; Fina et al., 2020).

3.4.6 Links to Adaptation

With the increase in temperature, the efficiency of solar photovoltaic panels decreases, however, the effect is considered to be relatively small, making PV an effective renewable energy technology to adapt to climate change.

Several studies conclude that the increase in energy demand is due to the change in future climate. Higher cooling might be needed, therefore leading to the widening of energy demand and higher emissions (Wan et al., 2012; Li et al., 2012). An increase in the energy efficiency of cooling appliances can reduce energy needs as well and limit the possible GHG emissions (Davide et al., 2019; Bienvenido-Huertas et al., 2020; Bezerra et al., 2021). The same effect can be achieved by utilizing renewable energy sources such as PV (Salom et al., 2014; Grove-Smith et al., 2018).

The climate effect on buildings might lead to increasing maintenance interventions, altering further the embodied energy and carbon footprint related to material production, transportation and end-of-life (Rasmussen et al., 2018). Sufficiency, energy efficiency and renewable can facilitate improvements in building resilience and reduce the impact on energy systems.

3.4.7 Links to Sustainable Development Goals

Mitigation actions in buildings result in not only significant emissions reductions, thus contributing to SDG 13, Climate Action, but support also circular economy principles by improved resource management (SDG 12, Responsible Consumption and Production) and energy efficiency (SDG 7, Affordable and Clean Energy). Moreover, measures contribute to substantial macroeconomic and social well-being (SDG 8, Decent Work and Economic Growth). The mitigation measures in buildings can therefore affect overall the consumption rates of natural resources (SDG 12, Responsible Consumption and Production). Implementing energy efficiency can result in resource savings of lower final energy demand in the residential sector (SDG 7, Affordable and Clean Energy) (Teubler et al., 2020). The embodied energy of buildings might as well be reduced due to the use of local and sustainable building materials (SDG 11, Sustainable Cities and Communities) (Hashemi et al., 2015; Cheong and Storey 2019).

3.5 Transport – IPCC AR6 Chapter 10

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 10: “circular economy”–12, “recycling”–13, “renewable energy”–19, “reuse”–2, “sharing”–24, “waste”–11, “sustainability”–41, “life cycle assessment (LCA)”–34, “efficiency”–169.

3.5.1 Introduction and connection to SDG

The chapter examines the role of transport for mitigation of climate change and includes the review of technologies, fuels and conditions enabling transport decarbonization. This is done, also referring to the seventeen sustainable development goals, including 169 targets and 232 indicators, some of which emphasize the importance of sustainable transport strategies (United Nations, 2017; Lisowski et al., 2020). The SDGs connected to the transport sector are summarized in Table 3.5.1.

Table 3.5.1 Transport and interconnections with Sustainable Development Goals (IPCC, 2022).

Earth precondition	**Sustainable resource use**	**Social and Economic development**
SDG 13 (Climate Action)	SDG 7 (Clean Energy), SDG 12 (Responsible Consumption & Production)	SDG 8 (Decent Work & Economic Growth), SDG 9 (Innovation & Infrastructure), SDG 11 (Sustainable Cities & Communities)

Table 3.5.1 Transport and interconnections with Sustainable Development Goals (Continued).

-Reduction of GHG emissions along the value chain (well-to-wheel) -Development addressing minor emissions -Sustainable transport -CE applied to transport (Farzaneh et al., 2019)	-Use of renewable energy -Energy efficiency in transport -Reduced material consumption during production of vehicles -Closed loop carbon cycle connected to CE (SLoCaT, 2019)	-Decarbonized public transport -Positive economic growth due to resource efficiency -Transport manufacturers are key drivers of changing role of transport-related labor (Peden and Puvanachandra, 2019; SLoCaT, 2019; Xu et al., 2019)

3.5.2. Trends and Changes in Transport Sector

The increase of transport electrification is one of the major ways to reduce GHG emissions. Many strategies are categorized based on the Avoid-Shift-Improve approach (Taptich et al., 2016). In this context, "Avoid" focuses on reduction of transport via minimizing the travel distances, promotion of efficient transport via price/demand management. "Shift" emphasizes the change from high-emitting to low-emitting transport and improvement of navigation apps. "Improve" discusses reductions of emission per km travelled via changes for cleaner fuel, electric vehicle incentives (Lutsey and Sperling, 2012; Gota et al., 2015). In addition, behavioral changes play a key role in the decarbonization of the transport sector. Personal income influences transport choices, but additional factors such as environmental values, gender, age, social status have particular impact (Simićević et al., 2020).

Shifting demand patterns towards public transport can help decarbonize the transport sector, but this effect can be achieved if complemented with a mix of urban policies, taxation frameworks as well as digital services able to make public transport more attractive.

Considering that cars are still preferred as transportation type; it is important to improve their performance to ensure proper decarbonization. The improvements in transport electrification, including the use of EV, can be beneficial. However, choice of EV is affected by a variety of factors including personal perceptions, infrastructure availability, policies, cost and duration of charge, among many others (Liao et al., 2016).

The issue of extensive material use and its impact on the environment leads to increased importance of the circular economy (Bleischwitz et al., 2017) also within the transportation domain. The principles of CE include material efficiency, recycling, reuse and EPR. Circular economy can be applied to the transport sector by ensuring dematerialization via reducing the material use in the production process. Therefore, the transport sector can reduce the material use and reduce the weight of products leading to increased efficiency. 3-D printing technologies proposed new potential for dematerialization through reduction of transport emissions by providing localized production (d'Aveni 2015; UNCTAD, 2018).

In the context of transport, the sharing economy is the fastest growing concept in comparison with circular economy and digitalization, which includes car/bike/e-scooter sharing (Greenblatt and Shaheen, 2015). The concept is assumed to lead to a decrease in demand and increased efficiency. Carpooling is found to result in a 12% reduction in emissions. However, the concerns exist considering commercial shared vehicle services (ex. Uber) as they optimize personal comfort more than shared culture (ITF, 2020a; ITF, 2020b).

In the context of transport sector, digitalization is also considered and addressed in terms of teleworking, therefore reducing the transport demand. However, additional changes can be ensured with the improvements in smart mobility, which includes the synergies of technologies such as ICT, internet of things and big data. Internet of things sensors can improve the fuel efficiency of vehicles, thus reducing CO_2 emissions (Taiebat and Xu, 2019). New applications and app-based platforms in combination with smart city planning can incline users towards shared transit. Blockchain technologies can enable the use of local solar microgrids, where solar energy can be shared between vehicles, therefore support urban regeneration (Green and Newman, 2017). Vehicles automation can increase efficiency (Massar et al., 2021). Moreover, there is an increasing interest in use of drones in delivery services (Stolaroff et al., 2018).

3.5.3 Transport Technology Innovations for Decarbonization

Electrification of transport is a crucial method to reduce GHG emissions, which require proper electrical energy storage systems (EES). The main interest of application is presented by the rechargeable lithium-ion batteries (LIB). The demand for the batteries is projected to increase even more in the future, therefore related resource extraction should be well- managed. Circular economy methods as reuse and recycling of LIB could help to reduce demand for extraction. However, difficulties still exist associated with remanufacturing of batteries for second life (Ahmadi et al., 2017), establishing proper regulations and ensuring design for recyclability (Harper et al., 2019).

In the broader context of reducing transport emissions, the shift towards electric vehicles plays a significant role. Light-duty vehicles for passenger transport is the main mode of citizens transportation and it is responsible for the biggest share of transport emissions globally (IEA, 2019d). The mitigation of sector emission could be achieved by BEV (battery electric vehicle), HEV (hybrid electric vehicle), plug-in HEV. The mitigation ability is highly dependent on electricity mix used to charge the batteries. The greatest effect can be achieved by using low-carbon electricity. However, alongside this shift, the growing popularity of SUVs (sport utility vehicles), which represented about 39% of all vehicles sold in 2018 (IEA, 2019d), presents additional challenges. Lightweighting of such LDV involves the use of advanced materials like aluminum, carbon fiber, polymer composites (Hottle et al., 2017). These materials can be difficult to recycle and maintain the high performance (Meng et al., 2017).

Both HEV and PHEV technologies are using combustion engines, and the use of biofuels can offer a good solution for mitigation of GHG emissions. Biodiesel and renewable diesel fuels can lead to significant emissions reduction for buses and passenger rails, while battery electric rails can be a future option. Alternative fuel vehicles remain more expensive than traditional ones, however the increases of cost for fuel can enable alternative fuel technologies to become more attractive.

When finally approaching the hard to abate sectors, Sustainable Aviation Fuel (SAF) has a growing interest for research as an alternative option for kerosine. SAF includes bio-based fuels that can be produced from crops, crop residues, wood products, waste fats, oil (Staples et al., 2018). Research claims that use of bio-derived fuels can result in emission reduction from 2% to 70% (Staples et al., 2018).

3.5.4 Enabling Conditions

Even though the main focus of the chapter is on technological innovations, socio-behavioral aspects should not be neglected including the new trend for future economy as circular economy, shared economy and dematerialization. The efficiency of the measures will depend on priorities set by governmental policies. There are many positive developments for implementation of EV technologies into buses, trucks and rail transport. However, demand for critical material for batteries production should be taken into account. EV's are dependent on renewable resources including wind, solar and hydro in order to generate power, this could have effects on resources, land and water use. Improved power generation capacities as well as establishment of charging stations is required for EV. Biofuels could be used for each type of transport; however, its feasibility is still questionable.

Manufacturing process of LIB and other renewable power technologies require use of critical materials. In the case of LIB, the focus should be put on recycling batteries and improving design fo recyclability, therefore closed-loop system can be beneficial to decrease the pressure for critical minerals in the future.

3.6 Industry – IPCC AR6 Chapter 11

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 11: "circular economy"–70, "recycling"–104, "renewable energy"–20, "reuse"–28, "sharing"–10, "waste"–149, "sustainability"–28, "life cycle assessment (LCA)"–6, "efficiency"–253.

3.6.1 Introduction, New Trends in Emissions and Industrial Development

This chapter examines the impact of the industrial sector, including mining, manufacturing, construction and waste management, on GHG emissions. The industrial sector is the major contributor to climate change considering direct and indirect fuel-combustion emissions, emissions from processes and waste (Sharma, 2023).

As industrial production expands to meet growing societal and economic demands, the use of diverse materials has increased significantly. Economic development has always been associated with the production of goods with desired performance and characteristics. The increase in the production of multi-purpose goods skyrocketed the use and implementation of diverse materials. Given that industrial development and material use are found to be directly related to GHG emissions, related sub-key factors such as demand growth (population, GDP per capita), material efficiency (material stock intensity of GDP, primary material extraction per material stock), circularity (secondary materials per material stock), energy efficiency (energy per materials), fuel switching (GHG emissions (direct energy) per energy), electrification (GHG emissions (indirect energy) per energy), feedstock carbon intensity (GHG emissions (other) per materials) are central for the study and improvement of the relation

Among these factors, material efficiency stands out as a particularly effective approach to reducing emissions while maintaining economic productivity. Material efficiency is an effective tool, which is defined through the concept of dematerialization, which involves the principle of demand reduction along with maintaining adequate living standards (Hertwich et al., 2019; Hertwich et al., 2020). The “dematerialization multiplier” stands for the idea that less amount of materials will be used for building in-use stock in the future, therefore the material stock and GDP growth will be decreased (Pauliuk et al., 2021).

Stock intensity of materials, such as wood, plastic, paper, iron/steel, copper, aluminum, concrete, asphalt, aggregate, bricks, and glass, must be properly addressed since recycled materials contributed to the demand for stock building materials only by 10% of material input (Krausmann et al., 2017, 2018; UNEP and IRP, 2020). Mapping the state of the art, the potential for recycling and circularity has been recognized but only recently started to be exploited.

Considering “end-of-life” concept, remanufacturing and construction waste generated from accumulated stocks indicates a recycling rate still being 10% of inputs (Mayer et al., 2019). It highlights the fact that “limited circularity was engineered into accumulated stocks” (Circle Economy, 2020), which means that existing stocks were not designed with circularity in mind, did not taking the product’s end-of-life scenario into account. Substituting the linear approach with the circular one results in the fact that less primary material will be used in total material input.

Recycling is addressed through several concepts which are the overall recycling rate, all-scrap ratio and end-of-life scrap ratio. In the context of steel, the overall recycling rate is 85% (Gielen et al., 2020; IEA, 2021b), which indicates that this percentage of steel waste generated is returned to the system. Meanwhile, the all-scrap ratio of steel production varies between 35% and 38%, ranging from 22% in China to 83% in Turkey (BIR, 2020) The ratio of end-of-life scrap decreased from 30% (1995-2010) to 21-25% (after 2010) (Gielen et al., 2020; Wang et al., 2021).

The poor progress in material efficiency and lack of representation of material efficiency in climate and energy policies depend on many factors. The ones related to circular economy are lack of political focus and industrial lobbying, lack of coordinated policy across institutions and no incentives to exploit reusing, remanufacturing and recycling (Skelton and Allwood, 2017; Gonzalez Hernandez et al., 2018b; Hilton et al., 2018).

Industrial energy efficiency is already a working strategy for the reduction of GHG emissions. In 2000-2019, energy use per ton of extracted materials fell by 20% and consequently by 15% in 2010-2019 with the energy intensity decline by 15% in 2000-2018 (IEA 2020b, a). The significant positive results were distinguished by the application of the best available technologies and use of recycled materials (metals, paper and cardboard).

Once industries widely implement the best available technologies, the energy use per unit of production decreases. However, at some point, the market becomes saturated, which stands for the fact that all producers have the most efficient technology available. After that, further energy reduction will become difficult to achieve unless transformative new technology enters the market. In this case, the focus can be shifted to secondary used (recycled) materials. The improvement in recycling rates will result in significant energy use reduction along the whole production chain. Another important claim is that synergy between material efficiency and energy efficiency (referred to as resource efficiency) will deliver more savings than implementation of energy efficiency alone (Gonzalez Hernandez et al., 2018b). The example of secondary steel-making justifies the above-mentioned fact by reducing the need for virgin material (material efficiency), reducing the production energy and resulting in higher exergy (effective energy) in comparison with primary production (energy efficiency), therefore lowering GHG emissions.

3.6.2. Technological Developments and Options

Material efficiency is framed as a strategy to reduce GHG emissions by optimizing material use throughout the whole production chain including design, manufacture, use and end-of-life. The design stands for optimization through minimization of material use and incorporation of eco-design principles like durability, reusability, repairability and the possibility of recycling at the end of life, which focuses on creating goods with minimal environmental impact. The use stage promotes the extension of the product’s life via repairing, upgrading and modifying as well as the promotion of shared use. At the end-of-life stage, products should be recovered or recycled through improved remanufacturing.

Even though material efficiency strategies are effective tools for the reduction of GHG emissions, changes should be applied throughout the different stages of the supply chain involving different stakeholders, it makes the process more challenging. Historically the concept of material efficiency was usually under-represented in the context of climate change but recent advancements in material flow modelling help to integrate material efficiency into climate scenario modelling (Grubler et al., 2018; Allwood 2018). First, over the years the researchers could create material-flow maps for energy-intensive materials including steel, pulp and paper, and petrochemicals therefore allowing them to trace back the emissions released and identify key intervention points for material efficiency.

Using the combination of material efficiency with energy efficiency analysis will result in a more sustainable impact (Gonzalez Hernandez et al., 2018b).

The International Energy Agency (IEA) claims that under the material efficiency scenario, the industrial energy demand will be reduced by 17% in 2040 (IEA, 2015). As well as Material Economics also predicts that circular economy and resource efficiency could decrease by half the 530 $MtCO_2$ yr^{-1} emitted by materials sectors in the EU by 2050 (Material Economics, 2019). Therefore, integration of synergy of material efficiency interventions with energy efficiency analysis might be an effective combination to be implemented into climate scenario modelling.

When assessing instead circular economy, the section addressed this concept to close the loop for material and energy flow through strategies for more efficient use and minimization of waste (Geng et al., 2013). Key strategies include the design of durable products with components that can be reused, recycled or remanufactured (Wiebe et al., 2019), therefore the virgin material processing which releases GHG intensively can be reduced. For example, aluminum recycled materials are more energy efficient, requiring only 5% of the energy needed for primary production. However, not every recycling process, such as chemical recycling of plastics, can be energy efficient.

The circular economy strategies regarding industrial waste can be implemented at three levels:

- Micro level applies to single firms, especially multinational companies. The typical CE strategies at this level include carrying out cleaner production, implementation of eco-design, environmental labelling as well as conducting process synthesis, and green procurement. An example can be the design of more recyclable plastics in the chemical industry. The main barrier at that level is that recyclability is expanding to the markets without recycling capacity (Mah, 2021), such as absence of recycling infrastructure: collection systems, sorting plants and recycling centers (Wiebe et al., 2019; Soo et al., 2021). It justifies the fact that improving recycling alone will not be efficient without a working system as well as policy incentives.
- Meso level covers the cooperation of three or more firms, which are usually defined as industrial parks. Typical CE measures implemented here include sustainable supply chain and industrial symbiosis. They are considered to be energy and material-efficient due to reduction of virgin materials and waste from by-product exchanges among companies. Moreover, the properly selected location can facilitate the use of renewable energy technologies. In addition, waste prevention at the top of the "waste hierarchy" is highlighted

at this level as it can lead to systematic change within industries, thus making it easier to scale the solution.

- The macro level is represented by urban symbiosis, which is defined as using waste from cities as raw materials for energy sources for industrial operations (Sun et al., 2017). This synergy is beneficial due to the geographical proximity for material transfer. The challenge at this level is not only to ensure proper waste management but also to preserve the values of specific waste streams. Also, the creation of data-sharing platforms is important for spreading CE technologies between different stakeholders to facilitate potential synergies.

Energy efficiency is a significant mitigation strategy for tackling climate change issues. Energy efficiency is still restricted in energy-intensive industries like steel (Pardo and Moya, 2013; Kuramochi 2016; Arens et al., 2017), so fundamental process changes are required to reach deep Decarbonization. Several technological advancements, like digitalization and implementing high-temperature heat pumps facilitate energy efficiency improvements. However, since many industries already own the best available technologies (BATs), the thermodynamic limit of efficiency is approached (Gutowski et al., 2013).

In this context, there is a growing focus on utilizing waste heat as a means to further enhance energy efficiency. A big potential for using waste heat to develop high-temperature heat pumps is mentioned. The circular economy concept of “Reduce, Reuse, Recycle” is applied to improve energy and heat efficiency in the industrial sector (NEDO, 2019). “Reduce” refers to decreasing heat by providing proper thermal insulation, “reuse” refers to recovering heat waste, and “recycle” refers to using waste heat for power generation.

While these methods contribute to reducing energy consumption, the integration of digital technologies is playing a key role in refining energy management. Energy management systems (EMS), standardized under ISO-50001 and specified as an approach for energy optimization across organizations (Biel and Glock, 2016; Tunnessen and Macri, 2017). Energy management is being enhanced by the integration of digital technologies such as sensors, machine learning, virtual reality and other simulation technologies, all of which can improve energy efficiency (Rogers, 2018).

Alongside digital advancements, the transition to low-carbon energy sources remains a central strategy for reducing greenhouse gas emissions. The principle of electrification and fuel switching means that industries will implement the transition from GHG-intensive energy carriers like coal, natural gas, and petroleum products to lower-emitting biofuels, solar heating, and net zero synthetic hydrocarbons. The most used renewable biofuel includes solid biomass from wood chips, lignin or pellets. Some feedstocks from biofuel can originate from agricultural and food waste, however the production scale is limited. To increase the production rate of biofuel biomass should be supplied from higher cellulose feedstock like wood waste.

As the focus shifts to cleaner energy solutions, the role of carbon capture technologies also becomes crucial in achieving net-zero emissions. In the chapter carbon capture and storage (CCS) is defined as requiring return of carbon dioxide from combustion or other processes (IEA, 2019g). Carbon capture and utilization (CCU) is defined as locating at the place of capturing from one process and being reused for another (Tanzer and Ramírez, 2019). CCU captures carbon dioxide and converts it into products (chemicals, synthetic fuels, building materials).

These strategies, along with energy efficiency measures, must work together to reduce overall demand for resources and improve sustainability. This section analyses the interactions between service demand, material and energy efficiency, circular economy, electrification and fuel switching and CCU/CCS. These strategies are not sequential, however the reduction of demand or materials efficiency will reduce the need to implement the following ones.

Ultimately, designing for efficiency and sustainability from the outset can significantly improve the circular economy's impact. CE is mainly addressed here from design point to be materially efficient, easy to recycle at the starts, therefore ensure proper treatment in the end in terms of recycling or sustainable disposal (Murray et al., 2017; Korhonen et al., 2018). The value chain’s efficiency is maximized when the product’s design is considered beforehand rather than retrofitting later (Bataille, 2020a). The strategies can be considered on example of building design, where the following factors should be taken into account like: the possibility of integration of solar PV, use of steel and concrete where it is needed, substitution of some materials, use of easy-to recycle plastics or disposable materials for interior design, possibility of use for multiple purposes during the life time, easy retrofitting, the reuse of parts, high-purity recycling of components and so on.

In the context of this holistic approach, energy efficiency plays a key role in enabling the transition to clean electrification. Energy efficiency enables clean electrification and reduces the need for material-intensive energy, CCU and CCS infrastructures (IEA, 2021a). Energy efficiency and electrification are deeply interconnected because the switch to electricity from fossil fuels generally leads to increased energy efficiency.

Table 3.6.2. The potential roles of different sectors in mitigation strategies (IPCC, 2022).

Sector	**Material efficiency (ME)**	**Circular Economy**	**Energy efficiency**
Architectural and engineering firms	Development of design tools, material flow mapping	Implementation of design for repurpose, reuse, recycling	Retain sharing of knowledge and high expertise
Industry	Minimization of industry scrap, design for durability	Implementation of design for reuse, recycling, use of recycled feedstock, promotion of industrial symbioses	Sustain energy management systems
International bodies	Modification of international standards	Regulations for managing waste, recycling	Maintain sharing or knowledge and practices
Regional and national government	Improvement of guidelines, building codes and standards	Regulations for product design, collection of material-flow data	Pursue policies for energy efficiency like standards, labels
Civil society	Strengthen the awareness and lobbying	Engagement into monitoring and standards	Monitor progress

3.6.3 Sectoral Mitigation Pathways and Cross-sector Implications

The mitigation options are specified in Table 3.6.3 to specific industrial sectors including steel, cement and concrete, chemicals, light manufacturing, aluminum and other non-ferrous metals, pulp and paper.

Table 3.6.3. Cross-sectoral implementation of mitigation measures.

Sector	**Mitigation strategies**
Steel	Improvement of energy efficiency by 15% can be achieved in BF-BOF process by increasing the share of secondary materials: use of end-of-life scrap; increase quality of steel recycling. Additionally, the reduction of emissions can be distinguished by material efficiency (e.g., more targeted steel use) and usage of the product more intensive (e.g., sharing cars). Material efficiency can reduce the demand for steel and cement by 48% in EU by 2060 (Material Economics 2019). Globally secondary steel production is 40-56% by 2050 (IEA, 2019b). Some coal inputs can be substituted by biofuel.
Cement and Concrete	The significant progress in energy efficiency has been achieved by moving from wet to dry kilns with calciner preheaters. Material efficiency measures include better mixing, sizing of aggregates, substitution of cementitious material. However, the significant changes in material efficiency will require re-education of producers, engineers, and users.
Chemicals	Even though energy efficiency has improved significantly over the past decades, the heat and steam for production of primary chemicals still create cause large share of emissions. This energy can be substituted by bioenergy, low-carbon electricity using electric boilers (Saygin and Gielen, 2021). The electrocatalysis of carbon monoxide is a promising technique for future electric recombination of waste into new intermediates (De Luna et al., 2019). Lifecycle emissions can be decreased by closing the material loop from designing product for remanufacturing, reuse, recycling to chemical recycling, which produces recycled feedstock to replace virgin materials (Rahimi and García, 2017; Smet and Linder, 2019). However, the most studied chemical recycling is pyrolysis, which is energy intensive, therefore can lead to even larger emissions than energy recovery (Meys et al., 2020). Considering the drawbacks of chemical recycling, CCS systems with waste combustion plants can be utilized. Alternative recycling options include polymer selective chemolysis, hydrocracking or catalytic cracking (Ragaert et al., 2017). Biomass feedstock is another effective measure for reduction of lifecycle emissions. Considering measures for treatment of plastics, the waste-to-energy help to reduce the emissions more than generally used plastic incineration (from 5% to 13%), while recycling remains low because of insufficient collection systems, sorting centers, contaminations in recycled plastics, heterogeneity of plastics used in packaging (Ive Vanderreydt et al., 2021).
Light manufacturing and industry	According to (Madeddu et al., 2020), 78% of industrial energy in Europe can be electrified, direct solar energy can be used as an energy source. There is a significant potential in industrial clusters

Table 3.6.3. Cross-sectoral implementation of mitigation measures (Continued).

	in terms of energy savings (e.g., the heat can be passed from facility to facility).
Aluminum and other non-ferrous metals	Even though the numbers remain low, aluminum waste is being reused and recycled at the end of life. If aluminum is not contaminated, recycling of it requires 1/20 of energy of primary production and can achieve 20-25% (Haraldsson and Johansson, 2018). Processing non-ferrous material requires further increase of material efficiency and recycling of existing stock.
Pulp and paper	The pulp and paper industry is low-emitting industry if the feedstock is sustainably sourced (Tanzer et al., 2021). The industry can be further easily decarbonized by energy efficiency, electrification (e.g., use of high-temperature heat pumps) (Ericsson and Nilsson, 2018). Bio-residues, which are currently used for energy internally, can be utilized as carbon source for chemicals in the future (Meys et al., 2021).

3.6.4 Industrial Infrastructure and Sustainable Development Goals

Table 3.6.4 addresses the co-benefit of circular economy and related principles like material efficiency, energy efficiency, industrial waste management on Sustainable Development Goals.

Table 3.6.4. Circular Economy and related concepts impact on Sustainable Development Goals.

Sustainable Development Goals	**Material Efficiency and Demand Reduction**	**Circular Economy and Industrial Waste**	**Energy Efficiency**
SDG 3: Ensure health and well-being		The strategies lead to reduced pollution and environmental hazards, leading to enhancement of public health and minimization of health risks (Geng et al., 2012; Bonato and Orsini, 2017).	
SDG 6: Ensure clean water and sanitation	Material efficiency may decrease the impact on environmental systems (Olivetti and Cullen, 2018). It can be distinguished by the reduction of wastewater, reduction of water usage on production (use of recycled materials instead of virgin ones), and reuse of water at different stages of the production cycle.		
SDG 7: Ensure access to sustainable energy		The fuel for several industries can be derived from waste (Chatziaras et al., 2016).	By ensuring a clean, affordable and reliable energy supply, the need to produce other types of

Table 3.6.4.Circular Economy and related concepts impact on Sustainable Development Goals (Continued).

			energy and providing the infrastructure is reduced therefore resulting in optimization of current energy use.
SDG 8: Promote sustainable economic growth and decent work	Implementation of material efficiency strategies such as remanufacturing, repair, and recycling may lead to the creation of new business models and, therefore, new jobs and economic opportunities.	New business models based on circular economy require the establishment of new job positions (Antikainen and Valkokari, 2016), therefore resulting in sustainable economic growth, and innovations in business and industrial sectors (Pieroni et al., 2019).	The improvements in energy efficiency directly result in economic growth and, therefore, the promotion of new job positions. Moreover, energy efficiency directly leads to the reduction of fossil fuel, which leads to an improvement of air quality in industrial areas, results in more comfortable working conditions (Williams et al., 2012).
SDG 9: Build sustainable infrastructure and foster innovation	Material efficiency aligns with the goal by implementing strategies like reusing, remanufacturing, and recycling (Allwood et al., 2011) which lead to the enhancement of infrastructure, industry and innovations (Mathews et al., 2018).		
SDG 11: Create sustainable and resilient cities		Circular economy may indirectly influence the goals by establishing new networks between industrial sectors and local communities, as well as increasing public awareness regarding environmental issues.	The sustainability of the cities can be increased since less energy is needed for the materials production and less energy supply infrastructure is required (Di Foggia, 2018).

Table 3.6.4. Circular Economy and related concepts impact on Sustainable Development Goals (Continued).

SDG 12: Ensure sustainable production and consumption	Material efficiency is directly related to the goal as it supports the reduction of the need for virgin materials and waste reduction by improving the processes along the lifecycle of a product. Material efficiency promotes the usage of circular economy principles during production processes for industrial sectors (Olivetti and Cullen, 2018).		
SDG 13: Combat climate change and its impacts	The fact that material efficiency is a significant option for climate change mitigation in heavy industries still has to be fully acknowledged (Dawkins et al., 2019).		
SDG 16: Promote justice, peace, and effective institutions			Improved energy efficiency leads to energy security by being independent of external energy supply and promoting low-carbon energy systems (Fankhauser and Jotzo, 2018).

3.6.5 Policy Approaches and Strategies

To implement the mitigation strategies a mix of appropriate policy instruments is required (e.g. recycling policy). The policies have to be innovative and definitive about GHG emissions reduction to justify the profound investment in making changes in production processes, use and recycling.

Even though material efficiency and circular economy have significant potential, they were neglected for a long time in low GHG industry roadmaps (Calisto Friant et al., 2021; Polverini, 2021). Material efficiency is also not properly addressed in product design, civil and architectural engineering, building codes and urban planning (Braun et al., 2018; Orr et al., 2019). Currently, policymakers are becoming more interested in circular economy strategies, which results in the establishment of new regulations for repair, reuse and recycling. Implementation of new initiatives is always slowed by specific barriers of different material loops (ex. lack of technologies for recycling plastics).

The investment in Research, Development and Innovation (RDI) for low-GHG process emissions is not reasonable without a convincing climate policy. Innovative business models cannot be implemented if they are not focused on the entire value chain with a focus on circularity and material efficiency (Vogl et al., 2018).

Policymakers can establish laws which will require industries to follow standards for product performance or have a limit on emissions therefore encouraging the use of low-GHG materials. This will lead to the situation that companies have to use production methods with a focus on material and energy efficiency.

Overall, the concept of durable products and materials by repairing, reusing and recycling is gaining interest now by policymakers. As an example, The EU Eco-design Directive forces industries to make additional parts for household appliances available for 7-10 years, therefore making it possible to extend product life and ensure repairability (Talens Peiró et al., 2020; Calisto Friant et al., 2021; Nikolaou and Tsagarakis, 2021). European Commission is extending the resource efficiency standards to cover not only energy-related products but also textile and furniture products (Domenech and Bahn-Walkowiak, 2019; Llorente-González and Vence 2019; European Commission, 2020; Polverini 2021). Extender producer responsibility is a policy proposed by policymakers that obligates the manufacturers to cover the cost of product treatment at the end of life (recycling) or manage the problematic waste (Kaza et al., 2018).

Of course, the economic value of discarded materials varies from one to another, therefore the cost of recycling is justified by such materials as steel, paper and aluminum, where the current rates are 85%, 60% and 43% respectively (Graedel et al., 2011; Cullen and Allwood, 2013). However, for some materials, re-circularity value remains low, as most of the plastics are disposed into landfills, while about 10% are recycled, and 12% are incinerated globally (Geyer et al., 2017; UNEP 2018). Therefore, extended producer responsibility systems have to be further strengthened to achieve the reduction of the use of virgin materials.

The effective implementation of circular economy policies relies on the implementation of R-strategies, which initially included Reduce, Reuse, Recycle and then further extended to Refuse, Reduce, Resell/Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover (energy), Re-mine and more (Reike et al., 2018). Even though the range of R-strategies is relatively wide, Recover and Recycling remain the most dominant ones. Policies should guarantee that circular economy products align with quality performance standards and that environmental cost is included in the market price. The policies can be implemented at different levels including micro (company), meso (industrial parks), and macro (cities) (Geng et al., 2019). The creation of eco-industrial parks is effective in terms of waste management as the waste from one facility can be further used as a feedstock for the other one (Tian et al., 2014; Winans et al., 2017). There is still a further need for proper data collection and a lack of indicators measuring the impact of circular economy practices. A broader application of circular economy principles may boost GDP and lead to the creation of new job positions.

3.7 Cross-sectoral Perspectives– IPCC AR6 Chapter 12

According to the keyword analyses carried out with the code in Chapter 2–Methodology, the distribution of keywords occurrences in IPCC AR6 Chapter 11: “circular economy”–30, “recycling”–17, “renewable energy”–37, “reuse”–4, “sharing”–3, “waste”–130, “sustainability”–72, “life cycle assessment (LCA)”–12, “efficiency”–70.

3.7.1 Introduction and Cross-sectoral Perspectives

The main focus of this chapter is to go beyond the individual sectors and provide the systematic review of cross-sectoral topics like carbon dioxide removal (CDR), food and land systems. The chapter covers important cross-sectoral linkages and discusses the potential associated with mitigation options deployment. Table 3.7.1a highlights the main aspects discussed in Chapter 12 and description how the same are addressed in other chapters.

Table 3.7.1a. Overview of cross-sectoral perspectives (IPCC, 2022).

Issues addressed in Ch.12	**Ch.5**	**Ch.6**	**Ch.8**	**Ch.9**	**Ch.10**	**Ch.11**
Potentials	Demand change	Renewable energy, CCS, CCU	Urban planning	Electrification	Electric vehicles, Fuel, Decoupling	Biomass CCS, CCU
CDR		BECCS		Carbon storage inside buildings		
Food systems	Food demand	Energy demand	Controlled-environment agriculture		Food transport	Food processing and packaging
Land use		Bioenergy, solar energy		Biomass supply	Biomass supply	Biomass supply
Cross-Sectoral perspectives	Electrification, Digitalization, Circularity					

IPCC Sixth Assessment Report estimates the higher mitigation potential compared to earlier reports, especially in energy, transport and industry sectors. In the energy sector, improvements in understanding on how to integrate the higher shares of solar, wind and other renewable energy sources into power systems contribute to this potential. For industry, materials efficiency and recycling are significant for emission reduction. The transport sector's shift to electrification and biofuels support decarbonization. The potential for buildings is lower than the one in AR4 (IPCC, 2007), since current retrofitting rates and nearly zero-energy building developments are insufficient for full sector decarbonization for the next 10-15 years, only in long-term perspective.

It is important to summarize mitigation options at specific sectors and to what extent they can be beneficial to achieve zero-GHG emissions, therefore several options are gathered in Table 3.7.1b.

Table 3.7.1b. Mitigation options for specific sectors (IPCC, 2022).

Sector	**Mitigation option**	**Possibility of zero-GHG**
Energy	Increase in electrification	Zero CO_2 is possible
Buildings	Sufficiency, efficient HVAC system, efficient appliances, renewable energy use	Nearly net zero CO_2 is possible in case grid electricity is decarbonized
Transport	Electrification, use of biofuels	Mostly possible if the electricity sector is decarbonized
Industry	Increased material efficiency and recycling, full Decarbonization, CCS, CCU	Net zero is possible with retrofitting, 85% reduction is possible

3.7.3 Carbon Dioxide Removal and Food systems

Carbon Dioxide Removal is referred to the set of technologies that remove carbon dioxide and sequester it from the atmosphere and preserve products, geological, ocean, terrestrial reservoirs (Smith et al., 2017). CDR methods are important to create carbon sinks as a form of climate change mitigation (Honegger et al., 2021). CDR includes methods like afforestation/reforestation (A/R), soil carbon sequestration (SCS), bioenergy with carbon capture and storage (BECCS), biochar, and wetland restoration. Enhanced weathering is a technique for carbon capture which involves mining rocks, which contain minerals absorbing carbon dioxide. As well as minerals, construction waste and mining waste can be used as source material.

GHG emissions from the food industry are associated with production, processing, distribution, consumption and managing residuals. In 2018, the number of emissions were estimated to be 17 $GtCO_2$-eq yr^{-1}, which was 31% of total anthropogenic GHG emissions (Solazzo et al., 2020). Considering energy emissions in food, 43% is coming from refrigeration being energy intensive. Waste from the food industry, including food, packaging and wastewater types, accounted for 1.7 $GtCO_2$-eq yr^{-1} of total food emissions in 2018. 55% of that came from domestic and commercial wastewater, 36%- solid waste; 8%- industrial wastewater, 1%- incineration of waste.

Moving to the land implications, demand for croplands can be lowered by use of food waste and crop residues to provide human-edible food (Van Hal et al., 2019). Shifting from animal protein to vegetable ones can facilitate pressure reduction of land resources, therefore lead to increase of natural ecosystems, reforestation for carbon sequencing, increase of wood supply for bio-based product production for fossil fuel substitution (Hayek et al., 2021).

3.7.4 Mitigation Opportunities

Mitigation strategies in food systems require significant changes in related production, processing and consumption chain. Several proposed technologies are not yet mature and require further development, some can be mature but not widely implemented on a large scale. Table 3.7.4 presents the main characteristics of mitigation strategies of food systems and their effect on GHG emissions.

Table 3.7.4. Mitigation opportunities for food systems (IPCC, 2022).

Mitigation options		**Effects on GHG mitigation and co-benefits**	**References**
Agriculture, aquaculture, fisheries	Agroecology	↓ GHG/area ↓ Energy Circular approaches regarding food losses Circular resource use	Wezel et al., 2009; Van Zanten et al., 2018; Van Zanten et al., 2019; van Hal et al., 2019.
Controlled environment agriculture	Soilless agriculture	↓ food losses: harvest on demand Controlled loops or resource use	Beacham et al., 2019; Benke and Tomkins, 2017; Gómez and Gennaro Izzo, 2018.
Food processing and packaging	Valorization of by-products, food waste management	Substitution of bio-based materials ↓ of food losses	Göbel et al., 2015; Caldeira et al., 2020.
	Food conservation	↓ Food waste	Silva and Sanjuán, 2019; FAO, 2019a.
	Smart packaging	↓ Food waste ↑Material-efficiency	Molina-Besch et al., 2019; Poyatos-Racionero et al., 2018; Müller and Schmid, 2019.
	Energy efficiency	↓ Energy	Niles et al., 2018.
Storage and distribution	Reduction of food waste in retail and catering	↓ Food waste ↓ Downstream energy demand ↓ Downstream material demand	Buisman et al., 2019; Albizzati et al., 2019; Liu et al., 2016.

Table 3.7.4. Mitigation opportunities for food systems (Continued).

	Energy efficiency	↓ Energy in refrigeration, lightening	Chaomuang et al., 2017; Lemma et al., 2014.

Controlled-environment agriculture includes the use of cultivation systems as hydroponic and aquaponic. Aquaponic system combines hydroponics with aquaculture, where fish waste is used as fertilizer for plants, while hydroponics nutrient-rich water solution is used. One of the main benefits of these systems is minimization of water and nutrient losses, as water is recycled in closed a system (Rufʜ-Salʜs et al., 2020). However, controlled-environmental agriculture is very energy-intensive. The energy consumption can be reduced by improved efficiency of cooling and lightning, as well as employment of low-carbon energy sources (Benke and Tomkins, 2017).

Mitigation options in food processing focus mainly on reduction of fossil energy and food waste. Reduction of food waste leads to savings in emissions by reduction of primary inputs wastage. One more option is the implementation of circular bioeconomy frameworks by food by-products valorization via the recovery of energy and nutrients. Reduction of food waste can be partially achieved by optimization of food packaging as well, therefore extending the shelf life of a product.

New strategies concerning food packaging include the use of more sustainable materials and shift to reusable options (Coelho et al., 2020). Intelligent packaging has indicators to access fresh information, as well as data carriers which store information about conditions (Poyatos-Racionero et al., 2018). Active packaging regulates conditions inside the packaging like oxygen level, moisture and etc, therefore extending the shelf life of a product (Emanuel and Sandhu, 2019).

LCA can be used in order to assess the benefits and drawbacks of packaging types (Silva and Sanjuan, 2019). Materials containing glass, aluminum and steel are considered to be energy intensive, hence significant energy savings can be achieved via recycling (Camaratta et al., 2020). In addition, these materials are inert on landfill. In comparison, other packaging materials like paper or biodegradable packaging require lower energy during the manufacturing process but might release methane when reaching anaerobic landfill. Another important mitigation option includes energy efficiency by using low-carbon energy sources for heat and electricity generation.

Different legislation measures concerning food waste already exist. In France, the food reaching its best-before date should be donated to charity organizations and banned to be wasted (Global Alliance for the Future of Food, 2020). In Japan, Food Recycling Law establish recycling target for restaurants at 50%, food manufacturers at 95% (Liu et al., 2016).

The synergy between food systems and reduced GHG emissions can be enhanced by cross-sectoral governance. However, various challenges may exist like those associated with water-energy-food nexus framework. Overall, framework for cross-sectoral governance was not integrated into policy (Urbinatti et al., 2020).

3.7.5 Land-related Impacts Associated with Mitigation Options

Several mitigation pathways face the issue of being land-intensive including bioelectricity with CCS, coal with CCS, hydropower and concentrated solar power. They exceed the use of land for wind farms and PV plants by about five times.

Several options exist which are decoupled from intensive energy use. Organic consumer waste, processing by-products and harvest residuals can be used in the production of bio-based products, therefore lowering the pressure on land use and providing waste management solutions. 90% of renewable heat that is used for industrial applications is generated from bioenergy. Industries generating waste such as paper and pulp, food can reuse it as a fuel (IEA, 2020c). The additional amount of heat and electricity produced but not needed can be redirected to district heating systems. Extra waste and residues can be used to produce biofuels or as raw material for other industries (Haus et al., 2020). Electrification can facilitate the increased process efficiency and share of biomass used for production of bio products (Silva et al., 2021). Integrating floating solar PV panels over canals or dams can reduce the land use for generation of renewable energy as well (Haas et al., 2020).

Bio-based systems and afforestation/reforestation (A/R) can facilitate land treatment via restoration and rehabilitation. Land rehabilitation restores land for biomass production for biochar, bioenergy/bioenergy with carbon capture and storage (BECCS), while restoration focuses on biodiversity benefits, therefore leading to key trade-off between production and biodiversity (Cowie et al., 2018).

Biorefineries are utilized to convert biomass into feed, food, biomaterials, bioenergy (Schmidt et al., 2019). They are beneficial for minimization of waste production, high resource use efficiency and multi-product use (Schmidt et al., 2019). Pyrolysis can be used to produce combustible gas and biochar by conversion of organic wastes (food waste, agricultural residuals, sludge) (Schmidt et al., 2021). Increase of wood usage for buildings can reduce the emissions associated with cement and steel production (Churkina et al., 2020). In cases where these materials are hard to substitute, biomass can be used instead of fossil fuels. Biofuels can lead to significant reduction of emission in transport and industry. Use of bio-based packaging and plastics can be increased, while resource-use efficiency can be achieved with the help of biorefineries for converting biomass into food, fuels, bio-based products (Schmidt et al., 2019).

Circular bioeconomy focuses on two cycles, which are the biological one, concerning regeneration in biosphere and technical one, prioritizing recycling, refurbishment and reuse to maximize material recovery (Mayer et al., 2019a). It emphasizes the return of biomass to the biosphere after completion of the technical cycle. Circular economy principles are important for both biomass and non-renewable resources due to their scarcity. Resource use can be minimized with recycling of materials, reuse of products and management of waste, while preserving material value. However, considering the use of biofuel for transport, the losses to the environment are unavoidable and reuse and recycling cannot be applied. Biomass resources should be managed from the perspective of preserving value inside the carbon cycle.

3.7.6 Other Cross-sectoral Implications of Mitigation

Some mitigation measures can be beneficial to apply in more than one sector. As for renewable energy technologies (wind, solar), they can be used for grid electricity supply, energy supply for agriculture and for implementation into building sector (Shahsavari, 2018). CCS and CCU can be applied to different industrial sectors including steel, iron, cement, paper and pulp, petrochemicals) (Garcia and Berghout, 2019). CCS combined with biomass result in carbon sink. Reduction of demand leads to improvements in energy and material efficiency. Some mitigation measures can have cross sectoral integrations. Electric vehicles can lead to Decarbonization of electricity grid, while plug-in hybrids running on biofuel result in reduction of emissions (Lutsey, 2015). The excess of energy from building sector can be redirected to electric and hybrid vehicles (Zhou et al., 2019). The optimization of industrial processes can reduce material inputs and energy demand, therefore resulting in reduced resource extraction. Recycling as well can contribute to decrease of primary resource extraction. Use of renewable power instead of coal-fired power will lead to reduction of coal mining and therefore lower emissions. Renewable energy can be generated via anaerobic digestion of organic waste, along with that waste can be recycled to avoid methane generation while landfilling. The nutrients can be recovered to be reused in fertilizers (Creutzig et al., 2015).

Demand-side mitigations also have cross-sectional implications. For instance, electrifying residential areas can reduce emissions from heating and lighting, while electrifying the industrial sector could lead to a shift away from fossil fuels. However, the effectiveness of electrification largely depends on the energy source used—specifically, whether low-carbon or fossil fuel-based energy is utilized. A potential downside of demand-side mitigations is that reducing electricity demand in certain sectors may limit the scalability of carbon capture and storage (CCS) and renewable energy technologies.

Circular economy takes into account the entire value chain, implementing eco-design, keeping materials in use and regenerating natural systems (Ellen MacArthur Foundation, 2013; CIRAIG, 2015). One of the circular economy principles is to rethink how products can be delivered in order to minimize impact on environment and resource use as well as maximize benefits for society. Circular economy can have cross-sectional applications. According to scientific literature, circular economy has the highest potential in energy and industry sectors, while mid-range in building and waste management (Cantzler et al., 2020). Circular economy approaches have a significant importance for building low-carbon infrastructure by optimizing the use of resources, lowering environmental harm caused by extraction, manufacturing and decommissioning of infrastructure (Jensen et al., 2020; Mignacca et al., 2020). Circular carbon economy approach is the combination of circular economy and carbon technologies including CCU, CCS and CDR.

Chapter 4 –Results and Discussion

4.1 Quantitative analysis

It is essential to understand the distribution of key concepts across the selected chapters in order to identify the role of circular economy and related principles in different sectors. By analyzing the occurrences, the section provides insights into how frequently and in what context CE-related terms appear within the IPCC AR6.

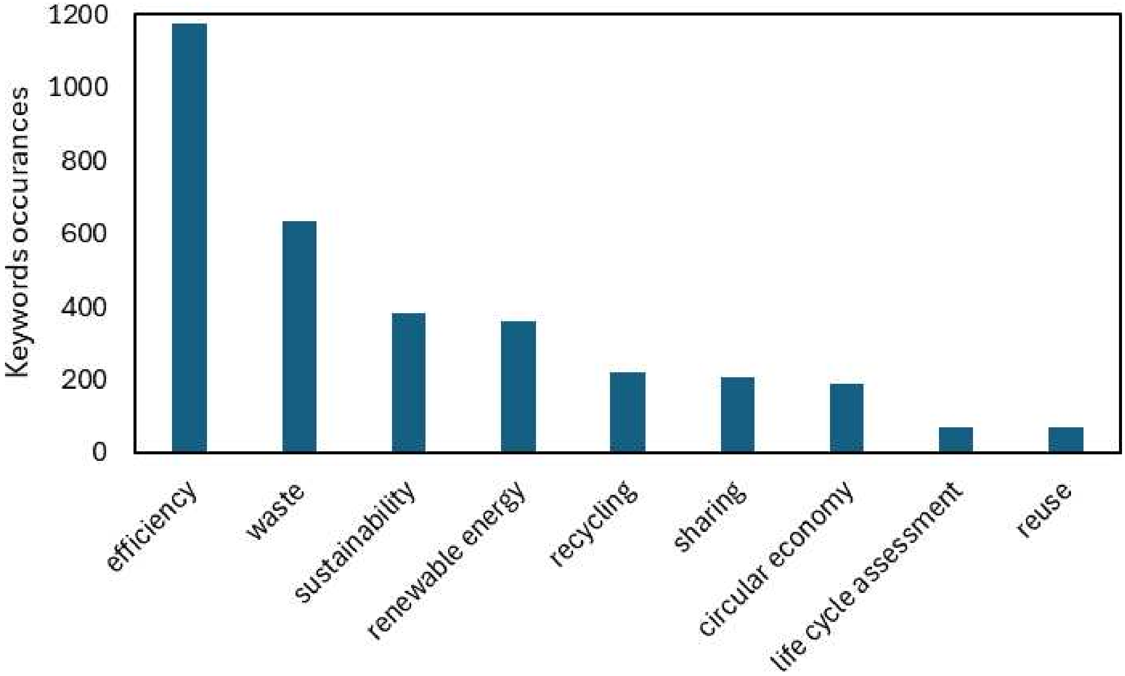

Figure 4.1. Total number of keywords occurrences across selected chapters.

Fig. 4.1 presents the total number of keyword occurrences across analyzed chapters. The concept of “efficiency” is the most frequently mentioned with over 1,000 occurrences, highlighting its significant role in the discussions related to material, energy and resource efficiency. The second most common word is “waste”, emphasizing the waste management strategies including prevention, reduction, recycling and waste-to-energy approaches. “Sustainability” ranks third, mostly mentioned in association with the Sustainable Development Goals’ framework. The following keywords are “renewable energy” and “recycling” as they are mostly important in terms of energy transition and resource recovery in a circular economy context. The keywords mentioned less often are “sharing”, “circular economy”, “life cycle assessment (LCA)” and “reuse”. The terms highlight the emerging strategies like sharing economy, circular models and extended product lifespan.

An additional comparison of keyword frequency is shown in the form of a heatmap in the following Table 4.1. The color grading for heatmap was applied across the rows, where the lowest frequency is indicated with red color and the highest one with dark green. This visualization reveals which sectors approach CE more extensively and where any gaps may exist.

Table 4.1. Heatmap of keywords distributions across selected chapters.

Keywords	Chapter 5	Chapter 6	Chapter 8	Chapter 9	Chapter 10	Chapter 11	Chapter 12
circular economy	45	2	16	14	12	70	30
recycling	35	21	22	6	13	104	17
renewable energy	31	126	46	81	19	20	37
reuse	19	6	6	3	2	28	4
sharing	128	6	12	22	24	10	3
waste	79	89	155	20	11	149	130
sustainability	111	36	64	30	41	28	72
life cycle assessment	3	11	3	1	34	6	12
efficiency	144	122	43	373	169	253	70

On the whole, the following statements can be drawn:

- “Circular economy” is mostly referenced in Chapter 11 (Industry), highlighting the importance for industrial applications with the moderate present in Chapter 5 (Demand, Service, and Social Aspects of Mitigation) and Chapter 12 (Cross-sectoral Perspective).
- “Recycling” and “Reuse” expectedly appear in Chapter 11 (Industry).
- “Renewable energy” is concentrated in Chapter 6 (Energy) and Chapter 9 (Buildings) stating the direct relevance in energy discussions. “Sharing” is found in Chapter 5 (Demand, Service, and Social Aspects of Mitigation) supporting the relevance of the sharing economy concept in the context of the chapter.

- "Waste"- related discussions are the most frequent for Chapter 8 (Urban Systems and Other Settlements), Chapter 11 (Industry), and Chapter 12 (Cross-sectoral Perspective).
- "Sustainability" is the most prominent in Chapter 5 (Demand, Service, and Social Aspects of Mitigation), followed by Chapter 8 (Urban Systems and Other Settlements) indicating strong connection to Sustainable Development Goals and urban planning aspects.
- "Life cycle assessment (LCA)" is mostly mentioned in Chapter 10 (Transport), hence supporting its importance in transport impact evaluation.
- "Efficiency" is extensively highlighted in Chapter 9 (Buildings) and Chapter 11 (Industry).

4.2 Qualitative analysis

4.2.1 Separate chapters analysis with concept maps

The review of the chapters of interest revealed a rich variety of CE-related concepts to be addressed including the one stated as initial keywords and additional ones. These concepts are deeply interconnected and form the foundation of suitable mitigation strategies across sectors like energy systems, urban planning, buildings, transport and industry. The complexity of relationships between concepts can make it challenging to understand how individual strategies contribute to broader goals of decarbonization. To address this challenge, concept maps were prepared for each chapter, as visual instruments to illustrate relationships between key themes, strategies and sectors. Circular Economy, as a key linking framework, is highlighted by green color, arrows indicate the interconnection between different concepts.

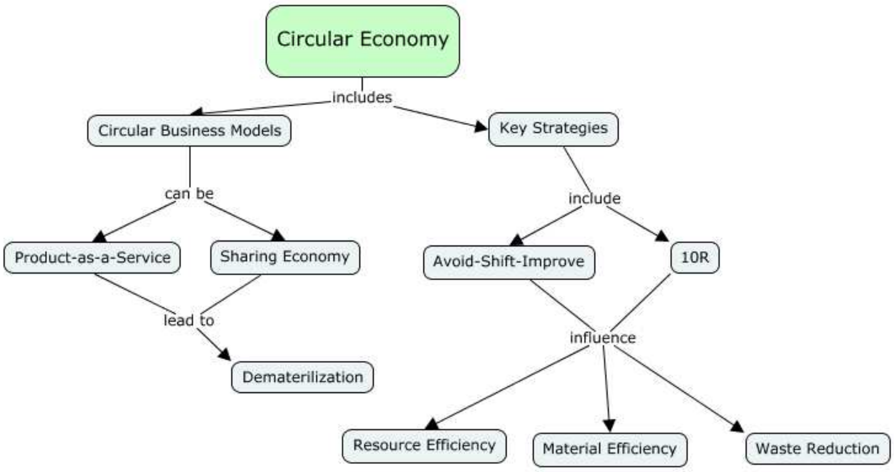

Figure 4.2a. Conceptual framework of Chapter 5 (Demand, Service, and Social Aspects of Mitigation)

Fig.4.2a summarizes the key ideas addressed in Chapter 5 (Demand, Service, and Social Aspects of Mitigation), focusing on Circular Economy Business Models (Product-as-a-Service and Sharing Economy) as well as key strategies (e.g., Avoid-Shift-Improve, 10R framework) and their outcomes as waste reduction, material efficiency, resource efficiency and dematerialization. The map shows how demand-side actions can affect the environmental impact.

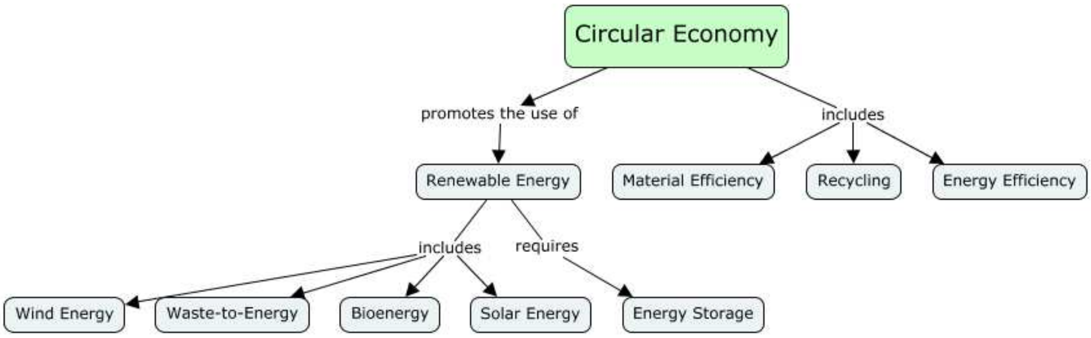

Figure 4.2b. Conceptual framework of Chapter 6 (Energy)

Fig.4.2b refers to Chapter 6 (Energy) and highlights the concepts supported by circular economy as material efficiency, energy efficiency, recycling, while showing the interconnection between CE and renewable energy (solar, wind, waste-to-energy, bioenergy) and presenting the necessity of energy storage for renewables.

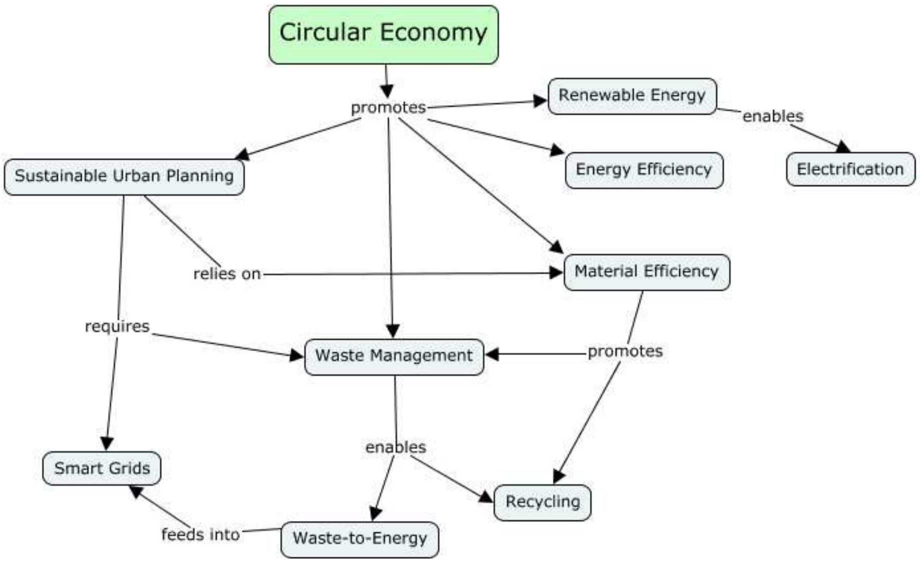

Figure 4.2c. Conceptual framework of Chapter 8 (Urban Systems and Other Settlements)

Fig.4.2c represents Chapter 8 (Urban Systems and Other Settlements), showing the importance of circular economy in sustainable urban planning, emphasizing the concepts of waste management, smart grids and waste-to-energy, thus showing how different elements can work together to optimize the use of resources, reduce waste and improve urban sustainability.

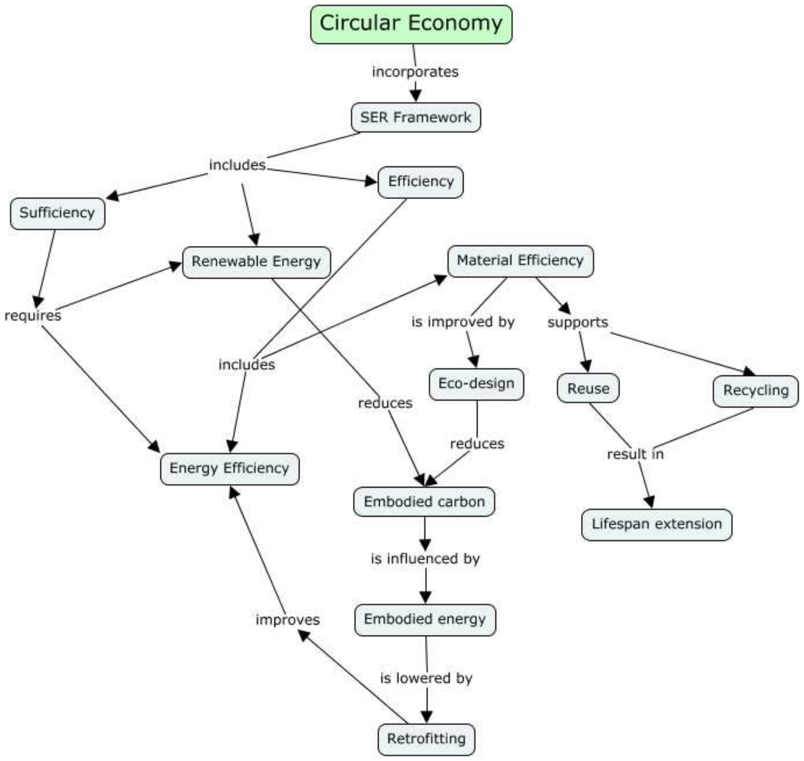

Figure 4.2d. Conceptual framework of Chapter 9 (Buildings)

Fig.4.2d. visualizes Chapter 9 (Buildings), illustrating the relationship between circular economy and sustainability strategy as SER framework, which includes sufficiency, efficiency (material, energy) and renewable energy. Material efficiency is enhanced by eco-design which as well as renewables reduces the embodied energy and embodied carbon. Additional concepts of reuse and recycling support material efficiency and extend the lifespan of product/material, while retrofitting is important for energy efficiency. Overall, the map presents how CE principles lead to lower footprint and product/material lifespan extension.

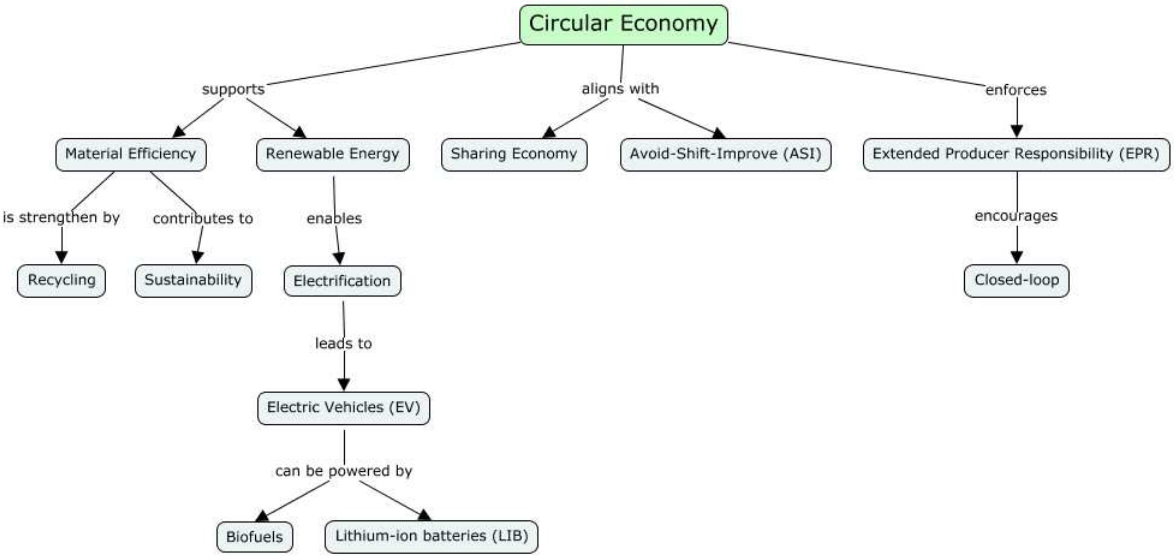

Figure 4.2e. Conceptual framework of Chapter 10 (Transport)

The concept map (Fig.4.2e) shows how in Chapter 10 (Transport) circular economy connects with various sustainability frameworks and strategies. One of the main branches is renewable energy, which supports the electrification of transportation through the adoption of electric vehicles (EVs), which can also use biofuel as a power source and lithium-ion batteries for energy storage. Circular economy enforces the EPR which facilitates the establishment of closed-loop systems. The concept of sharing economy is aligned with the circular economy through reduced consumption.

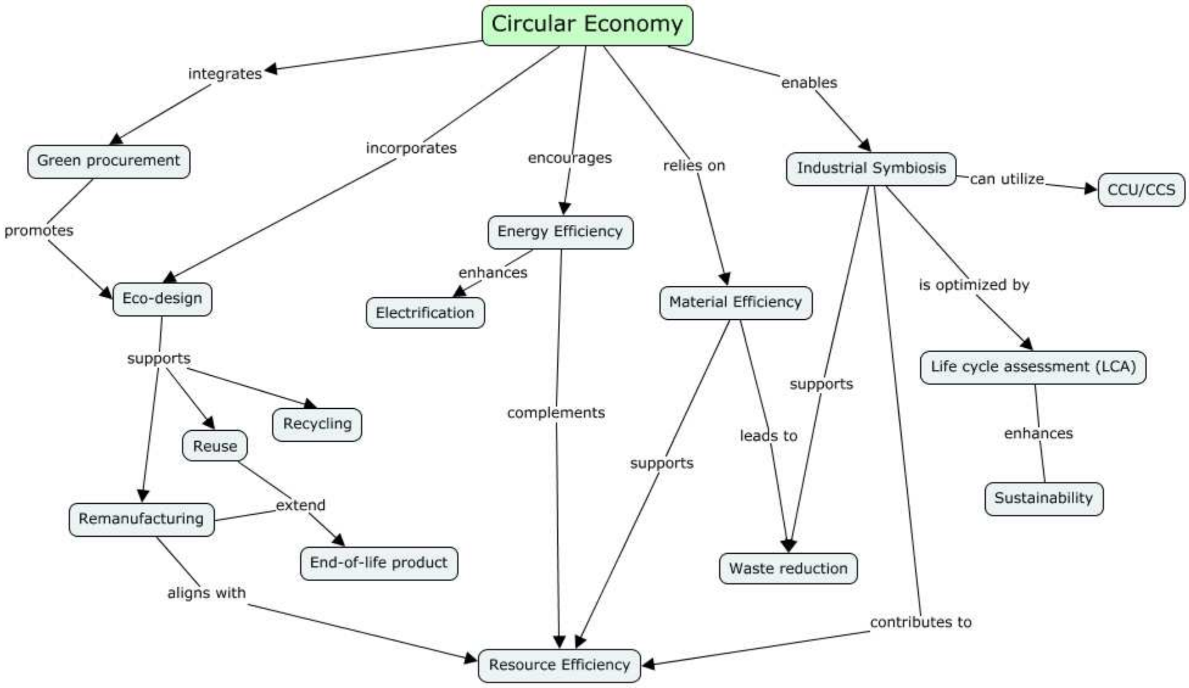

Figure 4.2f. Conceptual framework of Chapter 11 (Industry)

Concept map (Fig.4.2f) refers to Chapter 11 (Industry) and shows how circular economy incorporates eco-design, which promotes reuse, recycling and remanufacturing, thus leading to extension of product lifespan. Energy efficiency enhances electrification, while material efficiency supports waste reduction and both contribute to resource efficiency. Industrial symbiosis enables sharing of resources and can utilize CCU/CCS for emission reduction. Life cycle assessment optimizes sustainability by evaluating environmental impacts. Together all the concepts contribute to a sustainable circular system.

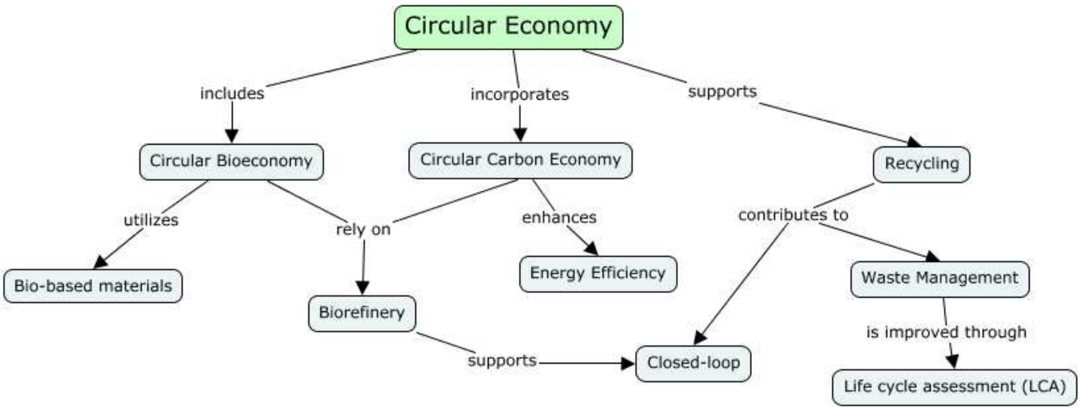

Figure 4.2g. Conceptual framework of Chapter 12 (Cross-sectoral Perspective)

Concept map (Fig.4.2g) shows how circular economy is interconnected with concepts of circular bioeconomy and circular carbon economy. They both integrate the use of biorefineries, and circular bioeconomy utilizes bio-based materials. Moreover, recycling contributes to closed-loop systems and waste management, which can be improved by LCA.

4.2.2. Summary of interconnections between circular economy and CE-related concepts across sectors

Table 4.2. Keywords distribution across selected chapters and relation to their context.

Keyword	**5. Demand, Services, and Social Aspects of Mitigation**	**6. Energy**	**8. Urban Systems and Other Settlements**	**9. Buildings**	**10. Transport**	**11. Industry**	**12. Cross-sectoral Perspectives**
Circular Economy	ASI approach, concept of 10R	Demand-side actions	Urban design, closed-loop systems	Embodied carbon reduction	Extended Producer Responsibility	Industrial symbiosis, product design	Circular bioeconomy, biorefineries
Reuse	Product-as-a-service model; extension of product lifetime through change of consumer behavior	Secondary material use	Materials recovering from dismantled buildings, reuse of timber	Repurposing, retrofitting of existing buildings	Battery reuse, remanufacturing	Component reuse	Reuse of industrial by-products
Recycling	Waste hierarchy	Battery recycling; recycling in solar and wind systems	Recycling PV panels, batteries, wastewater recycling	Recycling concrete and masonry	Recycling of battery systems, vehicle materials	Chemical recycling, secondary raw materials	Battery recycling, biorefineries, food systems
Renewable Energy	Electrification, decentralized energy	Solar energy, wind energy, bioenergy	Electrification, integration to urban energy systems	SER framework, cooling and heating systems	Electric vehicles, biofuels	Electrification	Cross-sectoral integration of renewables

Table 4.2. Keywords distribution across selected chapters and relation to their context (Continued).

Sharing	Shared use of assets (shared mobility, accommodation)	Sharing of product and services as demand-side action	Shared infrastructure (smart grids)	Sufficiency measures, ReSOLVE framework	Shared mobility	Industrial symbiosis	Industrial energy sharing
Waste	Reduction of food waste; waste minimization strategies (industrial symbiosis)	Waste-to-Energy, handling of e-waste	Waste management, waste hierarchy, Waste-to-energy	End-of life waste management	Waste reduction through dematerialization	Waste management, waste-to-energy	Food waste management
Sustainability	Patterns of sustainable consumption	Connection to SDG, low-carbon grids	Connection to SDG, sustainable urban planning	Connection to SDG, sustainable building materials	Connection to SDG, sustainable transport infrastructure	Connection to SDG	Connection to SDG, sustainable policy frameworks
LCA	Life cycle thinking in service model	Environmental impact evaluation for solar PV	Applied in urban planning to access environmental impact	Applied to estimate embodied energy and carbon footprint	Applied in battery production, used for assessment of biofuels	LCA in industrial processes	Applied for packaging materials, biofuel, building materials
Efficiency	Resourse efficiency, energy efficiency, material efficiency	Energy efficiency, material efficiency	Energy efficiency	Energy efficiency, material efficiency, HVAC efficiency	Energy efficiency, material efficiency, lightweight materials	Energy efficiency, material efficiency	Systematic efficiency improvement

Table 4.2 summarizes to what extend the circular economy and related concepts as reuse, recycling, renewable energy, sharing, waste management, sustainability, life cycle assessment (LCA) and efficiency are utilized and interconnected in demand-side actions, energy systems, urban systems, buildings, transport, industry and cross-sectoral perspectives. By having this analysis, the environmentally and economically beneficial synergies can be identified.

Circular economy is introduced as unifying concepts across all the sectors. In demand-side actions (Chapter 5) it is addressed through 10R principles and Avoid-Shift-Improve (ASI) framework, where the main goals are focused on social perspective as demand reduction, shift to low-carbon alternatives and improve efficiency. For instance, "Avoid" exploits the reduction of food waste through the behavior changes; "Shift" proposes the preference to shared mobility rather than owning a private car; "Impove" suggests the enhancing of energy efficiency in systems. In industry, circular economy implemented through industrial symbiosis and eco-design can lead to the use of waste as a resource for another process, therefore creating a closed-loop system. For example, steel manufacturers can use recycled scrap to produce new steel hence reduce the need for virgin materials.

Reuse and recycling are important strategies to reduce the embodied carbon and extend the lifetime of materials. In buildings (Chapter 9), the reuse of timber and repurposing and retrofitting of existing buildings can significantly reduce the GHG emission in comparison with new construction. The old warehouse can be repurposed to be used in residential buildings, therefore preserving the embodied carbon, while concrete from demolished buildings can be recycled and aggregates to be reused in new constructions, therefore reducing the amount of waste and new materials. In transport (Chapter 10), batteries reuse, and remanufacturing is essential for minimizing the environmental impact of electric vehicles (EV), batteries can be potentially used in buildings or energy systems as energy storage. Recycling of batteries should be implemented to reduce the pressure on extraction of such critical raw materials as lithium and cobalt. Meanwhile in industries (Chapter 11), chemical recycling and use of secondary raw materials help to close the loop for metals and plastic. Plastic can be broken down into chemical components to be used to produce new products or recycled aluminum can be used in manufacturing which is less energy intensive compared to virgin material. However, certain challenges remain as large energy requirements for specific recycling options, therefore according to Ellen MacArthur Foundation glossary, "recycling is the last resort action".

Renewable energy is a mitigation strategy that goes across all sectors. In the energy sector (Chapter 6), renewable energy is represented through solar, wind and bioenergy that are suitable replacements for fossil fuels and now supported by advancements in energy storage (mainly lithium batteries). The Sufficiency-Efficiency-Renewables (SER) framework promotes the integration of renewables in buildings (Chapter 9) such as installation of solar panels on the rooftops of residential and commercial buildings and using this energy for heating and cooling. Moreover, renewable energy enables the electrification of transport and industry: charging of EV with electricity from solar and wind farms, powering the industrial processes. Considering the urban systems (Chapter 8) as the whole, renewable energy can be managed using a smart grid context and coupled with district heating systems, therefore reducing the overall carbon footprint as smart grid exploits digital technologies to balance demand and supply. Even though solar and wind energy are the types of more prioritized renewables, bioenergy should be as well taken into account. For instance, as highlighted in Cross-sectoral perspective (Chapter 12), agricultural waste can be converted into biogas that can be applied for heating and electricity in buildings (Chapter 9), industry (Chapter 11) and used as a biofuel for transport (Chapter 10).

Sharing economy is essentially important for demand reduction and optimization of resource use. In transport (Chapter 10), the shared economy helps to decrease GHG emissions by switching from private vehicle ownership to shared mobility (car-, bike-sharing, e-scooters). In urban systems (Chapter 8), the shared infrastructure such as smart grids and district heating systems may facilitate energy efficiency. As an example, households can share the excess of renewable energy between each other, or multiple buildings can share heat from centralized renewable energy sources. In buildings (Chapter 9), shared principles can be applied through the ReSOLVE framework which promotes shared living spaces and utilities, hence highlighting the sufficiency measures to reduce energy and materials consumption.

Waste is mostly addressed through waste management, which is one of the main concepts enabling transition from linear to circular economy. Demand-side mitigations (Chapter 5) and industry (Chapter 11) highlight the importance of food waste reduction and industrial symbiosis for waste minimization. In industry (Chapter 11), industrial symbiosis is explained as an approach where waste is shared between companies to be used as a valuable resource, therefore leading to waste reduction and the need for virgin materials. Cross sectoral perspective (Chapter 12) and demand-side mitigations (Chapter 5) address the food waste reduction from different perspectives including changing human behavioral patterns (implementing meal planning), turning waste into valuable products (turning organic waste into nutrients) or recovering energy. In energy systems (Chapter 6), waste is converted into renewable energy through the use of waste-to-energy systems like incineration or anaerobic digestion. In urban systems (Chapter 8), waste hierarchy strategies prioritize reduction, reuse and recycling.

Life cycle assessment (LCA) is a critical tool to evaluate environmental impact of materials and processes across sectors. Thus, in energy systems (Chapter 6), LCA is used to assess the environmental footprint of solar PV and wind systems, while in buildings (Chapter 9), this is used to estimate the amount of embodied carbon in construction materials. Finally in industry (Chapter 11), LCA evaluates energy intensity and emissions of recycling processes.

As this analysis shows (Fig. 4.1), efficiency is an important concept which stands out across all the sectors in forms of resource, material of energy efficiency. In industry (Chapter 11) material efficiency is achieved by optimizing material use, while energy efficiency can be improved through the best available technologies (BAT). In buildings (Chapter 9), material efficiency (e.g. substitution), energy efficiency (improvements in insulation) and HVAC efficiency strategies lower GHG emissions. In transport (Chapter 10), fuel efficiency and lightweight materials enhance the performance of EVs and reduce emissions. Energy efficiency can be improved through smart grids and energy storage systems (Chapter 6) as well as efficient urban planning (Chapter 8).

When considering finally the general concept of Sustainability, this is mainly addressed through Sustainable Development Goals. A dedicated section is devoted to the discussion of this topic (See following 4.2.3).

4.2.3 Circular Economy and Sustainable Development Goals

This section focuses on the interconnection between circular economy and sustainable development goals. Schroeder et al., (2019) studied 17 SDGs and 169 targets, where the author distinguished the strongest relationships and synergies between circular economy strategies and SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), SDG12 (Responsible Consumption and Production) and SDG 15 (Life on Land). Below, a comparison is made between these SDGs and the IPCC AR6 to show how the latter addresses the former, according to the perspective of this thesis as well.

SDG 2 (Zero Hunger)

Literature	IPCC 6th Assessment Report
Sustainable Development Goal 2 focuses on ending hunger, increasing food security and improved nutrition. Applying the Rethinking concept of circular economy through the entire value chain of agriculture can facilitate the reduction of food and waste losses. The food waste and losses can be generated at the starts of the chain as caused by consumers at the end. The circular food system should be regenerative. Nutrient loop can lead to rehabilitation of degraded land, so minimize the need for fertilizers. Agricultural residues and organic waste can be reduced, recycled or reused through biogas technologies (Holland Circular Hotspot, 2020).	The IPCC 6th AR does not directly highlight the connection between circular economy and SDG 2, however similar ideas are stated in Chapter 12 (Cross-Sectoral Perspective). It highlights the mitigation options in food systems including agriculture, food processing and packaging, storage and distribution and potential benefits of them, thus aligning with SDG 2.

SDG 6 (Clean Water and Sanitation)

Literature	IPCC 6th Assessment Report
Circular economy can help achieve universal access to clean drinking water through the implementation of several technologies like wastewater treatment to reduce its discharge to drinking water (International Water Association, 2016). The recycling and reuse of water can lead to a reduction of pollution and elimination of hazardous chemicals, therefore resulting in enhanced water quality (sub-target 6.3). In industry and agriculture circular economy practices mostly applied to the reuse of	Within the scope of IPCC 6th AR, SDG 6 is discussed within industry context (Chapter 11) mainly with connection to material efficiency which highlights the reduction of water by recycling of material as virgin materials require more water input, and reuse of water at different stages of production. In urban systems (Chapter 8), the value of wastewater recycling is highlighted, saying that recycling can reduce the load on wastewater treatment plants, therefore reduce the cost of plant maintenance. From the perspective of renewable energy (Chapter 6),

wastewater and reduce the withdrawal of fresh water.	water pumping technologies can exploit solar energy and as well benefit SDG 6.

SDG 7 (Affordable and Clean Energy)

Literature	IPCC 6th Assessment Report
According to the Ellen Macarthur Foundation (2019), circular economy-related strategies help to tackle climate change and focus on transition towards renewable energy with a combination of energy efficiency. Circular economy can lead to the reduction of emissions by changing the way the products are made and used.	In transport (Chapter 10) and buildings (Chapter 9), SDG 7 can be achieved by utilizing renewable energy, increasing energy efficiency and ensuring closed loop carbon cycle. Energy sector (Chapter 6) addresses the importance of renewable energy as well. In industry (Chapter 11), industrial waste can be used for production of fuel and therefore energy generation.

SDG 8 (Decent Work)

Literature	IPCC 6th Assessment Report
Compared with linear economy, circular economy creates more jobs which are also local and meaningful. The UK Waste and Resources Action plan (WRAP) estimates that creation of 3 million extra job places within EU by 2030 by expanding the circular economy. The current employment in the circular economy sector (waste, recycling, repair, leasing, rental) is about 3.4 million people. The recycling sector is labor-intensive, therefore there is a chance for increased productivity (Schroeder et al., 2019).	In the transport sector (Chapter 10), resource efficiency can lead to positive economic growth, which is one of the goals of SDG 8. In industry (Chapter 11), the application of material efficiency, energy efficiency and industrial symbiosis leads to the creation of new business models, thus requiring new job positions and leading to sustainable economic growth. The application of mitigation strategies in buildings (Chapter 9) contributes to macroeconomic well-being.

SDG 12 (Responsible Consumption and Production)

Literature	IPCC 6th Assessment Report
A lot of circular economy practices are relevant for SDG including waste/water management, sustainable supply chain, sustainable products and services. CE enables the decoupling of economic growth from the use of natural resources therefore insuring sustainable development. Moreover, the use of raw materials cannot be considered without energy. Energy use in raw materials is an important part of energy management, where the circular economy has significant potential (Holland Circular Hotspot, 2020).	In industry (Chapter 11) achievement of SDG 12 can be done through material efficiency, which supports the reduction of virgin material and waste and improvement of processes along the lifecycle of product. In transport, SDG 12 is addressed through reduced consumption of material during the production of vehicles. Considering the energy sector (Chapter 6), improved energy efficiency and energy conservation can lead to more sustainable consumption of electricity. Improved resource management in buildings (Chapter 9) supports SDG 12.

Several SDGs have indirect but still important interconnections to be addressed including SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action).

SDG 9 (Industry, Innovation and Infrastructure)

Literature	IPCC 6th Assessment Report
Circular economy practices are crucial for sustainable industrialization, especially remanufacturing, industrial symbiosis and closed-loop supply chains. Special attention is put on industrial symbiosis as it creates a network, where materials and energy continuously cycle without waste (Holland Circular Hotspot, 2020).	SDG 9 can be achieved through decarbonized public transport (Chapter 10), material efficiency strategies (reuse, recycling, remanufacture) in industry (Chapter 11).

SDG 11 (Sustainable Cities and Communities)

Literature	IPCC 6th Assessment Report
The concept of circular cities represents the relationship between circular economy and urban systems, where key circularity elements are embedded into infrastructure. In circular cities the value of resources is preserved as long as possible through sharing, reuse, repair, remanufacturing and recycling (Holland Circular Hotspot, 2020).	In urban systems (Chapter 8) sustainable urban planning leads to greater sustainability. In buildings (Chapter 9) the embodied energy of the building can be reduced by the use of sustainable materials, therefore supporting sustainable urban development.

SDG 13 (Climate Action)

Literature	IPCC 6th Assessment Report
According to Ellen Macarthur Foundation (2019), circular economy is a systematic and cost-effective approach for climate change mitigation. The application of circular economy strategies to just four industrial materials (steel, cement, plastics, aluminum) can facilitate the reduction of emissions by 40% in 2050, therefore gradually leading towards net-zero emission targets.	The report mostly addresses circular economy benefits for SDG 13 through improvements in transportation (Chapter 10) such as reduction of GHG emissions along the value chain and sustainable transport. In the industrial sector (Chapter 11), the effect of material efficiency on mitigation of climate change should still be better researched. Mitigation actions in buildings (Chapter 9) claim to significantly reduce emissions.

Chapter 5 – Conclusion and Future Work

The main focus of the work was to identify to what extent the concept of circular economy and circular economy related concepts are addressed in the IPCC 6th Assessment Report.

The main purpose of the IPCC 6th Assessment Report is to provide the latest scientific research outcomes regarding climate change. According to code analysis conducted in the Chapter 2 of AR6 –Methodology, Climate Change 2022: Mitigation of Climate Change report (Working Group III's contribution) was chosen as a focus of extensive discussion. The report assesses global efforts for reduction of GHG emissions, evaluates mitigation strategies and explores the ways to tackle climate change. The range of CE concepts were tracked across the different chapters of the report including Demand, Service, and Social Aspects of Mitigation (Chapter 5), Energy (Chapter 6), Urban Systems and Other Settlements (Chapter 8), Buildings (Chapter 9), Transport (Chapter 10), Industry (Chapter 11), Cross-Sectoral Perspective (Chapter 12).

According to the complex analysis conducted in Chapter 3 (Circular Economy and related concepts across selected chapters) and Chapter 4 (Results and Discussion), it has been distinguished that circular economy in the IPCC 6th Assessment Report is one of the many approaches for broader climate mitigation, however it is not the main theme of the report. Circular economy is acknowledged particularly in sector-specific chapters; however, it is mostly discussed through the circular economy-related concepts rather than concept of CE itself.

The scope of this work included the analysis of only selected chapters (sectoral chapters) of the Climate Change 2022: Mitigation of Climate Change report due to the word count limitations. As a part of future work, it is important to assess the rest of the global chapters including Chapter 13 (National and Sub-national Policies and Institutions), Chapter 14 (International Cooperation), Chapter 15 (Investment and Finance), Chapter 16 (Innovation, Technology Development and Transfer), Chapter 17 (Accelerating the Transition in the Context of Sustainable Development).

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