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Review

Enhancing Climate Neutrality and Resilience through Coordinated Climate Action: Review of the Synergies between Mitigation and Adaptation Actions

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Abstract: Recently, reported long-term climate change consequences, such as rising temperatures and melting glaciers, have emphasized mitigation and adaptation actions. While moderating the severity of climate changes, precautionary human actions can also protect the natural environment and human societies. Furthermore, public and private collaboration can leverage resources and expertise, resulting in more impactful mitigation and adaptation actions for effective climate change responses. A coordinated and strategic approach is necessary in order to prioritize these actions across different scales, enabling us to maximize the benefits of climate action and ensure a coordinated response to this global challenge. This study examines the interplay between climate mitigation and adaptation actions in Greece and the European Union (EU). We conducted a literature search using relevant keywords. The search results were systematically approached in alignment with two pairs of thematic homologous entities, enabling the review of these literature findings to be organized and holistically investigated. In this respect, the three fields of agriculture, energy, and multi-parametric determinants of climate neutrality have emerged and been discussed. Our analysis also focused on the key implemented and planned mitigation and adaptation climate actions. Through this review, we identified the most important motives and challenges related to joint adaptation and mitigation actions. Our findings underscore the need for a comprehensive approach to climate action planning that incorporates both adaptation and mitigation measures.

Keywords: climate change impacts; adaptation actions; mitigation actions; climate neutrality; zero emissions

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1. Introduction

1.1. Theoretical Background on Climate Change in an International Context

During the last four decades of analysis, climate change (CC) is one of the most contentious issue and pressing threats of humanity. Therefore, understanding societal viewpoints of climate change and its risks is crucial for the successful implementation of measures aimed at reducing and adjusting to its impact. In the relevant literature, there is a plethora of studies that have been focused on climate-related disasters on a regional scale of analysis, in order to propose management actions to better control the climatic uncertainties. In parallel, these studies can advance the measures and policies of environmental sensitivity among the local communities that are affected by such natural calamities [1–3], pointing out the significance of human contribution towards global-leveled climate changes (CCs) [4,5]. The recognition of CCs can be followed by adaption to this phenomenon. Climate mitigation is related to selected anthropocentric interventions in reducing sources or enhancing the sinks of greenhouse gases, while actual or expected climatic stimuli initiate the climate adaptation of human systems in order to moderate harmful effects or to seize beneficial opportunities [6].

Effective climate adaptation necessitates evaluating the degree and range of comprehension surrounding the matter, identifying the motivations for taking action, and assessing the capacity to execute measures across diverse scales, from worldwide to national and from regional to local levels. Many studies examine the opinions and perceptions of key stakeholders with an interest in and/or responsibility for adaptation, with the aim of influencing their engagement to CC [7–17].

Fadeyi and Maresova [7] examined the priorities of CC actors, who are defined as proponents, specialists, campaigners, government officials, climate change human rights organizations, non-governmental organizations, and interested individuals, in three developing countries of west Africa, and concluded that there is a need for continuous work by governments and local authorities to better harness their opinions for climate action. Simonsson et al. [8,9] assessed the perceptions of stakeholders in Sweden's two largest cities concerning climate risks and constraints to adaptation and concluded that the main obstacle to effective adaptation is considered to be response capacity; in particular, primary adaptation measures are directly affected by challenges in coordination, conflicting interests, and lack of stakeholders' willingness to get involved (in such adaptation measures). Russel et al. [10] indicated that increasing the CC impact awareness of stakeholders in administrative sectors could improve the coordination of CC actions without strong hierarchical steering. Government and non-governmental sectors are also reported in the relevant climate change references [11–14]. Stakeholder engagement is an important step of the decision-making process. Potential future risks are reduced through the implementation of stakeholder engagement, as key groups have the chance to express their opinion while also contributing to the improvement of the effectiveness of a measures/actions. Piwowarczyk et al. [15] assessed the awareness of institutional stakeholders in eight Baltic Sea riparian countries on climate change impacts on coastal areas, while Dincă et al. [16] examined stakeholder perspectives on the effects of climate change on tourist activities at destinations greatly dependent on climate resources and variability. Dilling and Bergren [17] described the need for consultation between stakeholders and providers of climate information with the aim of improving the usefulness of the information and covering the needs of stakeholders.

1.2. Theoretical Background on Climate Change in Greece

The interrelated problem of CC impacts and global warming undoubtedly needs to be confronted with government regulations and policies that instill citizens with environmental awareness and place them in favor of protecting the environment. However, costly governmental policies should rely on public interest and approval to support government spending towards environmental protection, in an institutionally fair, non-corrupting, and effective manner [18]. Climate change policies encompass initiatives and strategies aimed at regulating greenhouse gas emissions and reducing carbon output to alleviate the effects of climate change, while also establishing essential conditions that enable individuals to adapt to climate-related risks and fluctuations [19].

In the relevant literature, a thematic search was undertaken utilizing the Scopus database in the year 2022, using relevant keywords that link the notion of CC in Greece in terms of awareness, values, perceptions, policies, and adaptation. The collected studies are detailed in Tables 1–3. The chronological coverage dates back to the beginning of 2010, and all studies have been placed in reverse chronological order, and with entries in the same year in alphabetical order in relation to the last name of the first authors.

Table 1. Overview of the joint keyword results from the Scopus database: "Climate change", "Greece", "awareness", "values".

Ref. #	Key Aspects and Issues Addressed
[1]	This research explored the connection between human perceptions of disasters, climate change risk, and sustainability of natural sources, utilizing the New Ecological Paradigm (NEP) framework. A survey was conducted in Greece that served as a representative example of the multi-hazard region in the eastern Mediterranean. There is a positive association between direct disaster experience, individual beliefs regarding the causes of recent catastrophes in the country, environmental awareness, and climate change risk perception. These factors implied that extreme events in shaping perceptions of climate change are associated with opinions on the impacts of climate change.
[2]	Freshwater ecosystems in the Mediterranean region face challenges of ecosystem service disruptions from the combined effects of multiple stressors. Obstacles in addressing climate change projections include quantifying uncertainties, the limited knowledge or comprehension of local (river) catchment management practices and disciplines by modelers, and insights into the intricate interactions between the biosphere, human activities, and socio-economic and environmental factors. Innovative interdisciplinary approaches can help to refine climate change scenarios at the level of river basins, while concentrating on the formulation of specific climate change scenarios, such as the Local Stakeholder participative workshop in the Evrotas river basin. This workshop offers insights into anticipated changes in water demand under various alternative scenarios.
[20]	The "SKYROS Project" is a collaborative effort between the Port Authority of Skyros, an island in Greece, and the University of the Aegean's Department of the Environment, which has been active since 2015. The project primarily focuses on environmental initiatives that promote climate change awareness among local residents and visitors. The "SKYROS Project" gathers data through the Tourist Observatory and the Maritime Observatory established at Skyros Port. Specifically, a guest book compiles visitor comments, creating a comprehensive view of the environmental and tourism outcomes of effective practices reported annually. To enhance the understanding of environmental awareness, the concept of an environmental camp for children emerged. This idea supports the launch of the "SKYROS Project" as an educational tool of national campaigns based on climate change awareness through children's camps in remote geographical contexts.
[21]	The significant threats of climate change on certain Mediterranean wetlands have prompted European and national authorities to prioritize their protection and express serious concern. Among these initiatives is a collaborative project between Spain and Greece, focusing on the Aiguamolls de l'Empordà (northeast Catalonia, Spain) and Kotychi-Strofylia wetland (Western Greece) coastal wetlands, which warrant safeguarding by both European and national authorities. The examination of stakeholders' perceptions on local climate change reveals contrasting viewpoints, using relevant meteorological data from the Estartit station (near Aiguamolls de l'Empordà, Spain) and Andravida station (near Kotychi-Strofylia, Greece). In this context, semi-structured interviews among coastal wetlands' stakeholders disclosed interesting insights on the perceptions and challenges encountered by various social, political, environmental, and economic actors in the regions studied. Over the past two decades, the impacts of climate change, including rising air temperatures, alterations in precipitation patterns, prolonged periods of drought, and shifting seasonal cycles, have been increasingly noticeable. These effects have had a significant impact on wetland ecosystems and the neighboring regions. Despite stakeholders from Spain showing a greater understanding of sustainability issues in comparison to those from Greece, approximately two-thirds of all stakeholders interviewed in both regions believed that their coastal wetlands were not sustainable. In contrast, Greek stakeholders exhibited a stronger commitment to remaining in their territory than their Spanish counterparts. Furthermore, around half of the stakeholders expressed a positive inclination towards natural-based methods of adaptation relying on technical solutions, such as establishing sandy dune systems and shoreline barriers.

Table 2. Overview of the joint keyword results from the Scopus database: "Climate change", "Greece", "perceptions", "policies".

Ref. #	Key Aspects and Issues Addressed
[22]	Climate change has various consequences on agricultural production, which calls for a reorganization of agricultural practices in countries with significant agricultural sectors, such as Greece. These climate change effects have a direct impact on the economic and social aspects of farms in rural regions. The socioeconomic repercussions of climate change in the Central Macedonia region of Greece were assessed using a multi-criteria model that simulates these impacts while calculating seven social and economic indicators. This model was applied, taking into account the primary crops grown in the local farming areas. The multi-criteria model indicated that adjustments in the average farm's crop plan for the region are required due to the emergence of climate change. The scenarios demonstrated a detrimental influence of climate change on all social and economic indicators, with persistent effects over time. Through such case studies, policymakers can better understand the socio-economic impacts of climate change and subsequently design targeted planning and policy implementation.
[23]	Existing human-induced pressures from agricultural irrigation, industrial infrastructure, urbanization, and tourism activities are impacted by climate change, making it essential to estimate future changes in the hydrological dynamics of coastal-, surface-, and deltaic-water systems in a Mediterranean environment. The modeling parameters included river hydrology, storm surges, coastal flooding, water scarcity, and heat stress effects on irrigated agriculture being coupled with atmospheric data to evaluate climate change effects on the Nestos river delta in Greece. An Integrated Deltaic Risk Index (IDRI) was introduced as a means of assessing vulnerability to determine the impact of climate change on the study area, showing that heightened deltaic vulnerability is present under specific scenarios, particularly for the future time horizon. The projected IDRI underscored the necessity for comprehensive water resource management in contrast to individual water process risk indexing in environmentally sensitive areas.
[3]	The aim of this study was to identify distinct groups of citizens and their characteristics to develop effective climate change communication strategies. The research was conducted from January 2014 to June 2015, collecting and analyzing a total of 1536 questionnaires using α-Cronbach's coefficient and outlining the descriptive statistics and jointly conducting the analyses of Friedman's non-parametric criterion, factor analysis, and cluster analysis. It was also revealed that Greek citizens (organizations, scientists, locals) were motivated and initialized to take action against climate change. Two groups of citizens were identified: (a) Primarily composed of public servants or unemployed individuals who were satisfied with government activities related to municipal projects concerning adaptation, energy conservation, and lifelong learning. (b) Mainly consisting of young to middle-aged, unmarried citizens working in both public and private sectors. This group expressed satisfaction with both the efforts of non-governmental concerned parties and government activities related to adaptation to extreme environmental events, mitigation, and waste management.
[24]	Taking into account the indications of climate change (CC) having negative effects on the tourism economies of Greece, Spain, and Turkey, an empirical model was employed by leveraging a distinct dataset. This model provided a useful interpretation of temperature measurements and facilitated the estimation of the economic consequences of CC on various economic structures, revealing a detrimental and widespread impact of CC on the economies of Greece, Spain, and Turkey. It is recommended that these three nations participate in robust international collaboration to counteract the unfavorable consequences of CC.
[25]	Over the past decade, there has been an increasing agreement among researchers that social factors and local community engagement play a crucial role in shaping public decision-making processes in coastal areas. Social capital has emerged as a vital aspect that has garnered significant interest, considering local communities' capability to climate change consequences. An investigation was conducted to assess citizens' perceptions of three coastal zone management policies, namely "hold the line", "managed realignment", and "no active intervention", along with the effect of social capital on the degree of social acceptability for these suggested policy alternatives. The significance of social capital's role was evaluated through an ordinal regression analysis, revealing that institutional and social trust can positively impact citizens' support for the managed realignment policy. Moreover, people who hold the belief of reciprocity within their community are more likely to endorse proactive intervention strategies.

Table 2. *Cont.*

Ref. #	Key Aspects and Issues Addressed
[26]	Given the strong evidence that climate change is a global environmental issue with various economic repercussions, this study aimed to examine the measurement of economic consequences resulting from climate change. The study specifically looked at the environmental changes in Greece, manifested through economic losses caused by damages to rural production and subsequent insurance compensations. Data provided by the Greek Agricultural Insurance Organization (GAIO) were utilized, based on the assumption that climate change is real, and these alterations significantly impacted GAIO's operations as the primary institution for insuring rural production in Greece. Statistical analysis and appropriate non-parametric tests were employed, indicating a growing shift in the occurrence frequency of extreme events related to atmospheric precipitation, primarily rain and hail. Additionally, an increase in windstorms was observed across most regions.
[27]	The primary aim of this study was to examine the perceptions of Greek and British citizens regarding environmental protection and their efforts to address climate change. The influence of key determinants of environmental behavior was investigated using Eurobarometer data and logistic regression analysis. Factors significantly impacting environmental perceptions and behavior in both countries were identified. The findings revealed that perceptions of EU climate change policy and education play a substantial role in shaping the environmental perceptions of both Greek and British citizens. Such a perception is determined by easy access to information, age, gender, occupation, and purchasing power.
[28]	A compelling research objective involves connecting climate change to the carbon footprint in electricity production. In the early 2010s, the carbon footprint of the Greek electricity sector and related damages were estimated. This connection can be better understood by quantifying the external costs associated with climate change airborne emissions (mainly CO_2) produced during all phases of the power plants' lifecycle in Greece. In this regard, the EcoSenseLE tool was utilized in combination with the fundamental principles of the Life Cycle Assessment (LCA) approach. The external cost determination was carried out using seven types of power plants. It is worth noting that hydro and wind power plants exhibited exceptional performance, followed by the performance of PV and biomass-fired power plants. Natural gas-fired power plants demonstrated good performance, while oil-fired power plants showed poor performance. Lignite displayed the worst performance among the evaluated plants, impacting the average external cost of the sector, as lignite-based electricity plants are the predominant energy source for electricity production in Greece.

Table 3. Overview of the joint keyword results from the Scopus database: "Climate change", "Greece", "adaptation".

Ref. #	Key Aspects and Issues Addressed
[12]	National governments in Greece have historically played a crucial role in addressing climate change mitigation and adaptation issues. In this context, the key indicators used are the national commitments to reduce or limit greenhouse gas (GHG) emissions, which are derived from the Kyoto Protocol (KP), the Doha amendment of the KP, and European legislation related to the Europe 2020 targets on energy and climate change. Subsequently, the time-series of the country's GHG emissions were analyzed, at both regional-spatial and sectoral levels. Using Greece's official GHG inventory, the achievement level of the national commitment under the KP and the anticipated surplus of GHG emission allowances were estimated. By considering relevant projection scenarios, an assessment of national progress in achieving the emission reduction targets for the period 2013–2020 was undertaken, and sectors not included in the Emission Trading System in the European Union were also evaluated. The key findings of this study include the identification of major sector-specific strategies and action plans on climate change adaptation issues, primarily incorporated in National Strategies, National Action Plans, and Rural Development Programs (RDP) 2007–2013

Table 3. *Cont.*

Ref. #	Key Aspects and Issues Addressed
[29]	This study's methodological framework provides a comprehensive evaluation of existing climate change mitigation and adaptation strategies. Mitigation measures aim to reduce CO_2 and other greenhouse gas emissions to slow the increase in global temperature. In contrast, adaptation strategies relate to the capacity of natural or human systems to manage the impacts of climate change, aiming to minimize negative consequences and capitalize on any potential benefits. In terms of methodology, specific parameters were considered to determine the most effective set of alternatives available in Greece. The selection of the optimal-ranked alternative within a defined strategy is a complex process that can be facilitated through a multi-criteria decision-making approach. A tailored questionnaire was developed, and climate change experts provided their input during face-to-face interviews. The ELECTRE III multi-criteria decision analysis was employed for comparative evaluation, as it is well-suited for addressing complex environmental issues. The use of renewable energy sources, energy efficiency increases, and the improvement of forest management (primary determined by tree planting and rational water management) are all promising measures of realistic climate change mitigation planning. Utilizing multi-criteria analysis offers an innovative way to determine the optimal combination of strategies, focusing on specific parameters that result in the most effective set of measures for Greece. This approach lays the foundation for strategic governance and policy modeling in the area under study.
[30]	Taking into account the ecological, social, and economic aspects of climate change impacts, it is essential for all nations to prioritize and implement mitigation and adaptation measures. In this context, the contingent valuation method (CVM) was employed to estimate the monetary value of national mitigation and adaptation costs related to climate change in Greece. CVM can be applied to Greek climate change experts, as they primarily represent the most informed members of Greek society concerning the technical and economic aspects of climate change. This study focused specifically on the opinions of national experts, who do not represent the general (non-specialized) population. The monetary estimation includes the experts' willingness-to-pay (WTP) for mitigation and adaptation measures, as well as their preferences for the proportion of the national GDP allocated to fund such measures in both the present and the future. Questions regarding political and institutional climate change settings also contribute to a more comprehensive socioeconomic analysis in short-term and long-term climate change evaluations.

Based on the aforementioned literature review on CC in the Greek context, it can be denoted that there is a steadily developed and multifaceted literature production that has been interestingly developed within the last decade of reference [31–34] linking carbon emission effects on CC, including air pollution, global warming, risk of climate change, and restoring of carbon cycle management. In this context, the following dimensions of consideration can also be revealed:

(1) The effect of regulation and governmental policies on CC can play a vital role in climate mitigation, such as in codifying varied mandatory standards to the national contexts of environmental planning, while highlighting the importance of institutions to effectively implement governmental policies of environmental protection [18].

(2) The effect of renewable energy on CC; indeed, CC and RES exploitation are strongly interrelated with one another. The available literature on climate change (CC) mitigation policies in EE examines strategies aimed at households and addresses energy poverty. The research indicates that renewable energy can have a positive impact on mitigating the effects of climate change [34].

(3) The impact of economic growth on climate change (CC) is a complex issue. While economic growth can enhance the adaptive capacity of individuals and communities, the

level of such adaptive capacity is largely dependent on a country's economic status, with developing nations being more vulnerable to the adverse effects of climate change than developed nations with higher adaptive capacity. Additionally, countries experiencing high levels of economic growth tend to be less susceptible to climate risks, suggesting that growth can mitigate the negative impacts of CC. In addition to improving access to finance and investment to enhance skills, various growth policies can help decrease vulnerability to climate change. Among the Greek national policies and measures that have been conducted regarding CC impacts in the short term, the cost/benefit analysis (CBA) has been proven especially fitting regarding environmental footprints, considering that the investigation of CBA is affected by the cost of CO_2 abatement, being also associated with approaches of various external cost estimation [28].

The primary scope of this review study is to determine the research gap between the climate change consequences to the natural environment and the human actions undertaken to manage these climatic calamities and, secondly, to examine the potential synergies developed between climate mitigation actions and climate adaptation measures in those domains directly affected by climate change. The analysis considers the current preconditions of policy landscape, barriers, and opportunities, as well as the collaboration priorities among stakeholders. To this end, this review study also aimes to disclose plans and policies towards materializing the mitigation and adaptation efforts on achieving climate mitigation objectives that can enhance resilience to climate change impacts. It is also noteworthy to identify those collaborative opportunities and coordinating actions to address the challenges of climate change by drawing and implementing suitable climatic planning and strategies. The collected literature information can supplement the discussion of extensively differentiated issues concerning climate change in an integrated manner, such as synergies between mitigation and adaptation actions, collaboration between the public and private sectors, prioritization across different spatial scales and administrative levels, and climate neutrality, as well as the association of the above actions with land uses, transportation, green infrastructure, and energy.

2. Methodology and Analysis

2.1. Methodological Background

A prolific literature production on climate neutrality has been reported in the fields of geographical determinant, mainly Europe [35–37], forestry management [38], and ethical concerns and considerations [39], as well as integrated approaches of climate neutrality and sustainable development [40].

Ambitious climate change initiatives for businesses, governments, and other entities have been executed by Spanish firms reporting to the Carbon Disclosure Project [41]. The main areas requiring enhancement are devising action plans, computing, and compensating. Top scores were observed in the energy, finance, and other services sectors. However, present commitments are insufficient for achieving long-term international climate neutrality objectives, and businesses should continue striving for them. A supportive regulatory framework could facilitate aligning private and public efforts in the climate neutrality domain [41].

EU public funds efficiency literature on climate neutrality demonstrates varying degrees of efficiency among EU countries [42]. Growth in public funds allocated to environmental protection did not consistently correspond to advancements in climate neutrality objectives. Activities connected to building renewable energy sources had the most considerable positive influence on achieving climate neutrality goals. There was no observed correlation between expenditures on transport infrastructure and climate neutrality, indicating that public funds designated for construction did not affect climate neutrality [42].

Between 2005 and 2019, it was noted that decisions regarding public fund allocation were not based on the expected reduction amount relative to the volume of expenditure [42]. Projects demonstrating the highest economic efficiency should be selected, irrespective of political or geographic factors [42]. This phenomenon should be used by decision-makers to create reference methodologies and best practices for the successful implementation of climate objectives and the Energy Performance of Buildings Directive (EPBD) [42].

In general, the literature presents local interest case studies [43,44], concentrating on various aspects, such as evaluating the ideal energy system arrangement, seasonal protocols, and energy composition and corresponding technology capacities [45–47], as well as exploring key influential determinants of accomplishing climate neutrality targets in the manufacturing sector [48].

A critical issue in agriculture, forestry, and other land use (AFOLU) sectors is how global emission budgets compatible with climate stabilization can be downscaled to national targets [49]. The consequences of different downscaling rules for national food production and climate neutrality objectives are not well known. To downscale global methane budgets into national policy targets in an equitable and globally acceptable manner, the interconnected priorities of food security and carbon offsetting must be considered simultaneously [50].

Moreover, energy communities and climate city contracts are seen as essential interventions for achieving citizen-focused and climate-neutral cities [51,52]. Research has provided advanced insights into EU energy community strategies and potential contractual agreements that can ensure commitment between parties and enable active citizen involvement in the energy sector [51]. Realizing climate-neutral cities by 2050 and working by and for citizens necessitates decisive actions, particularly considering that cities are responsible for 65% of energy consumption and 70% of CO_2 emissions [51].

2.2. Analytical Background

The analytical part of this study contains the search outcome from the Scopus database using the keyword expression of "climate neutrality" and the subtopic of "zero emission". In the relevant literature, yield is the outcome of this thematic search, which was undertaken at the first trimester of the year 2023. The collected studies have been organized into the four domains, being paired in entity-couples: "year of publication" and "country/territory", Table 4, as well as "keywords" and "subject areas", Table 5. The groups of domains supported relevancy and coherence to each of the pairs developed, while the way of outcomes' presentation in both Tables 4 and 5 is based primary on those entries that are commonly reported at each one of the two main fields of allocation, being termed as "Climate neutrality and Zero emission" and "Climate Mitigation Adaptation in Europe". Secondly, the other entries have been presented in relation to the descending order of results reported, accordingly.

Table 4. Literature overview in the joint fields of "climate neutrality" and "zero emission" in Europe. Domains of analysis: "Year of publication" and "Country/Territory".

Climate-Related Field / Domain of Literature Search	Climate Neutrality and Zero Emission	Climate Mitigation Adaptation in Europe	Climate-Related Field / Domain of Literature Search	Climate Neutrality and Zero Emission	Climate Mitigation Adaptation in Europe
Year of Publication	**Number of Published Studies**		**Country/Territory**	**Number of Published Studies**	
2023 (first trimester)	3	0	United Kingdom	2	4
2022	18	1	France	2	3
2021	10	0	Germany	4	1
2020	2	1	Spain	2	3
2019	1	0	Austria	2	2
2018	1	1	Poland	7	0
2017	1	2	Greece	6	0
2016	1	0	Denmark	0	3

Table 4. *Cont.*

Climate-Related Field / **Domain of Literature Search**	**Climate Neutrality and Zero Emission**	**Climate Mitigation Adaptation in Europe**	**Climate-Related Field** / **Domain of Literature Search**	**Climate Neutrality and Zero Emission**	**Climate Mitigation Adaptation in Europe**
Year of Publication	**Number of Published Studies**		**Country/Territory**	**Number of Published Studies**	
2007–2015	0	4	Finland	0	3
Subtotal	**37**	**9**	Italy	0	3
			Latvia	3	0
			Belgium	2	0
			Esthonia	0	2
			Ireland	2	0
			Netherlands	0	2
			Subtotal	**32**	**26**

Table 5. Literature overview in the joint fields of "climate neutrality" and "zero emission" in Europe. Domains of analysis: "Keywords" and "Subject Area".

Climate-Related Field / **Domain of Literature Search**	**Climate Neutrality and Zero Emission**	**Climate Mitigation Adaptation in Europe**	**Climate-Related Field** / **Domain of Literature Search**	**Climate Neutrality and Zero Emission**	**Climate Mitigation Adaptation in Europe**
Keywords:	**Number of Published Studies**		**Subject Area**	**Number of Published Studies**	
Greenhouse Gas (10)—Greenhouse Gases (12)	22	2	Energy	18	2
Climate Change	9	7	Environmental Science	13	5
Carbon Dioxide	7	2	Social Sciences	5	4
Climate Neutrality	13	0	Agricultural and Biological Sciences	4	2
Carbon (4)—Carbon Emission (5)	9	0	Economics, Econometrics, and Finance	3	1
Gas Emissions	9	0	Business, Management, and Accounting	2	1
Emission Control	8	0	Engineering	12	0
Decarbonization	6	0	Mathematics	9	0
Investments	6	0	Chemical Engineering	2	0
Greenhouse Gas Emissions	5	0	Computer Science	2	0
Adaptation	0	4	Biochemistry, Genetics and Molecular Biology	0	1
Action Plan	0	2	Earth and Planetary Sciences	0	1
Environmental Policy	0	2	**Subtotal**	**70**	**17**
Europe	0	2			
Nature-based Solutions	0	2			
Temperature	0	2			
Urban Planning	0	2			
Subtotal	**94**	**27**			

Based on Table 4, it is noteworthy that the research focus on climate neutrality and zero emissions has a leading role over the relevant literature production on climate mitigation and adaptation measures and policies in Europe, especially during the last two decades of analysis. The relevant ratios are:

- Last 3 years of publication/Last 20 years of publication = 0.89 (based on publications at climate neutrality and zero emission),
- Last 3 years of publication/Last 20 years of publication = 0.22 (based on publications at climate mitigation and adaptation),
- Overall publications on climate neutrality and zero emission/Overall publications on climate mitigation and adaptation = 4.11,
- Top-15 countries on climate neutrality and zero emission/Top-15 countries on climate mitigation and adaptation = 1.23.

According to the search results of Table 4, it can also be inferred that there has been a noticeable increase in the literature production of climate-centered studies within the last five years of publication, which could be attributed to the pressing measures that have to be undertaken nationally and globally to adopt a net zero GHGs emissions policy by 2050, while also abiding to the Paris Climate Accord's goals of reducing warming of the atmosphere to less than 1.5 to 2 °C based on pre-industrial levels.

Based on Table 5, it is observed that the common-reported keywords (out of the top-17 keywords) of both "climate neutrality and zero emission" and "climate mitigation and adaptation" measures and policies in Europe, are those of "Greenhouse Gas—Greenhouse Gases", "Climate Change", "Carbon Dioxide", which account for 40% for both fields of analysis: "climate neutrality and zero emission" and "climate mitigation and adaptation". Similarly, it is shown that the common-reported subject areas (out of the top-12 subject areas) of both "climate neutrality and zero emission" and "climate mitigation and adaptation" measures and policies in Europe are those of "Energy", "Environmental Science", "Social Sciences", "Agricultural and Biological Sciences", "Economics, Econometrics, and Finance", "Business, Management, and Accounting", which account for 64% of the field of "climate neutrality and zero emission" and 88% for the field of "climate mitigation and adaptation". Therefore, it can be inferred that the climate mitigation and adaptation actions are prioritized in light of the environmental, socio-economic, and agro-biological domains of analysis.

2.3. Agriculture and Climate Neutrality

According to research [53], agricultural activities are a significant source of greenhouse gas (GHG) emissions. While exporting agricultural products can potentially reduce carbon dioxide (CO_2) emissions, it may lead to an increase in emissions of nitrous oxide (N_2O) and methane. On the other hand, importing agricultural products can be positively associated with all GHG emissions. However, the impact of agricultural trade on GHG emissions varies significantly and is dependent on the type of emission [53]. Additionally, while the Environmental Kuznets Curve (EKC) framework is valid for CO_2 and N_2O emissions, it is not applicable to methane emissions. High GHG emitters should transition from traditional to sustainable agricultural practices and adopt green trade policies to achieve climate neutrality targets [53].

A related study investigated the global interest in minimizing the environmental impacts of farming by reusing agricultural waste and decreasing agricultural GHG emissions [54]. This study examined the potential of Mediterranean viticulture for GHG emissions mitigation and Carbon (C) storage in biomass and soil, determining the C balance at the vineyard level and concluding that conventional viticulture could be transformed into zero-emissions by reducing nitrogen (N) fertilizers, decreasing tillage frequency, using less fuel, and maintaining field margin vegetation at the farm level [54]. This approach could be used for the design of eco-schemes related to C farming under the new Common Agricultural Policy (CAP) [54], a policy that has been also and extensively investigated in similar studies [55–60].

Dairy cattle production, especially in developed and highly industrialized countries such as the US is another critical domain of climate neutrality in the agricultural sector [61,62]. The US dairy industry has made a commitment to implementing a net-zero greenhouse gas (GHG) emissions policy by 2050. By lowering farm-level absolute emissions by 23% from present-day levels, the industry could attain climate neutrality in the coming decades [61].

A study that linked climate neutrality with agriculture and GHG emission reduction reported that one of the primary sources of GHG emissions in agriculture is the treatment of soils using nitrogen fertilizers for crops, especially grain crops [63]. The study suggested cost-effective measures for the future, such as zero-emissions on-farm machinery and equipment, low or no-tillage, potential alternatives to grain production, and N-inhibitors on pasture [63].

According to research [64], forest mitigation projects can generate positive impacts on local livelihoods and enhance adaptive capacity. These projects can augment the provision of local ecosystem services, create diversified income and economic activities, foster the development of infrastructure or social services, and fortify local institutions. Forests also provide adaptation possibilities, such as improving the resilience of habitats due to enhanced coastal zone conservation and enhancing heat resilience [64]. Agroforestry systems are frequently cited as offering synergies for both mitigation and adaptation, given their capacity to boost soil fertility under temperature rising conditions, curb soil erosion, and confer other environmental and climate advantages [65].

However, trade-offs exist, including the possibility of resource conflicts and the risks posed by monoculture production [65]. Additionally, the use of biofuels and solid bioenergy involves certain trade-offs. For instance, some trade-offs are related to species that may be effective in sequestering carbon but may have lower economic value or be less resilient to the impacts of climate change [65]. It can also be indicated that growing forests commonly support better carbon sequestration performance compared to mature forests, although this argument remains controversial [65].

2.4. Energy and Climate Neutrality

In the realm of long-term policy decisions for sustainable energy transitions, models sometimes struggle to account for environmental impacts and restrictions beyond direct greenhouse gas (GHG) emissions and land use. This can lead to a partial or potentially misleading understanding of the genuine sustainability challenges linked to different transition pathways. While decision-makers seek access to a more comprehensive array of environmental, material, and socio-economic indicators, only a limited number of tools currently fill this void. To address this, Martin et al. [66] devised the ENBIOS framework, which integrates a wider range of indicators into energy modeling and policymaking practices. Utilizing the Calliope energy system optimization model, the ENBIOS framework analyzed various energy pathways for the European energy system. By 2030 and 2050, overall emissions are expected to decrease considerably, but there could be significant increases in land, labor, and critical raw material demands. These projections align with negative trends in key metabolic indicators during this period, including a 25.6% decline in energy metabolic rate, a four-fold increase in land requirements for energy, and a 74.2% rise in the critical raw material supply risk-to-energy ratio. Biomass heat and wind and solar-generated electricity are anticipated to influence future developments across the majority of indicator categories [66].

Alongside the ENBIOS framework, another tool, called ENE-CO2Calc, has been developed to determine current ecological and economic footprints through the calculation of final energy demand in different sectors within municipalities [67]. This municipality-focused energy modeling tool employs consistent statistical datasets to create meaningful scenarios up to 2050, taking into account climate policy objectives and renewable energy source potentials, as well as incorporating the mobility emission forecast tool "PROVEM". A case study of ENECO2Calc applied to an Austrian municipality found that a combination of decentralized renewable energy technologies, central co-generation units in the heat sector, solar PV and co-generation units in the electricity sector, and synthetic biofuels with a higher degree of electrification in the fuel sector were among the most promising options for the region. As a result, this model offers valuable support for pursuing climate neutrality, allowing municipalities to design and implement effective economic and ecological footprint strategies [67]. A crucial factor to consider is the deployment of innovative technologies to expedite climate neutrality initiatives in energy-intensive sectors, such as industry and its various subsectors. Commonly studied frontline technologies include the transition from fossil fuel feedstocks to non-fossil gases such as hydrogen, carbon capture usage and storage, increased electrification, and the expanded use of secondary raw materials. By examining each industrial subsector's specific conditions, appropriate technology groups can be introduced through a sector-specific approach to bridge the ambitious net-zero emission gaps [68].

Although there is a general consensus on the relationship between energy and climate neutrality, the pace and motivations for energy transitions vary across different European geographical contexts. The European Union's commitment to achieving climate neutrality by 2050 necessitates a deeper understanding of the energy transition across diverse contexts and scales, which could enhance collaboration among stakeholders. By coupling policy document analysis with stakeholder engagement activities at national (Greece), regional (Nordic Region), and continental (EU) scales, researchers have identified critical issues and challenges in the European energy transition as well as variations in stakeholder perceptions across geographical contexts [69]. As stakeholder perspectives are influenced by contextual factors, there is a need for context-sensitive policies that address the distinct issues and challenges in Europe. By examining existing policies and addressing persistent challenges, researchers can gain a more comprehensive understanding of cross-country collaboration to foster European energy transitions.

In addition to energy transitions, the transportation sector plays a crucial role in achieving climate neutrality. One of the main challenges for achieving climate neutrality by 2050 is the transition of the road transport sector, particularly through the replacement of internal combustion vehicles with zero-emission technologies [70]. The widespread adoption of electric technologies in this sector, which involves both businesses and households, hinges on technological progress and the abiding emission regulations of zero-emission vehicles or other new vehicles entering the market. A study focusing on Poland under a climate neutrality scenario projected that, by 2050, approximately 30% of vehicles in both passenger and freight transport would still use fossil fuels [70]. However, this shift in fleet composition could result in an 80% reduction in CO_2 emissions and an increased demand for electricity and hydrogen [70]. In a comparable study conducted in Poland, the developed scenarios and implemented policy options revealed a notable anticipated impact on agricultural output and prices (primarily livestock production). Additionally, there were shifts in the production structure towards crops and alterations in farm income during the specific timeframe examined [71].

Another study estimated the expenses associated with electric vehicle (EV) recharging infrastructure in the EU and identified factors influencing investments in this area by 2030 and 2050 [72]. This study utilized an energy-demand methodology that incorporated assumptions on charging needs, fleet structure, and the probability of recharger survival, as well as learning rates. The researchers performed regression analysis and found a strong correlation between fast chargers and investment costs, which is especially relevant during the period from 2021 to 2030. During this time, a fast-charging network is crucial for reducing charging times and promoting the adoption of EVs. The second most significant factor affecting costs was the energy output per charging point, while other factors, although important, had a negligible impact on system costs [72].

Furthermore, achieving climate neutrality necessitates suitable policies that ensure regulatory coherence and proper market design to address the needs of various actors across sectors, including farmers, technology investors, distributors, and end-users [73]. Market and policy coordination is required to unlock energy sources, such as bioenergy's contribution to decarbonization, and support the attainment of EU climate goals by 2050.

Bioenergy can play diverse roles in reducing GHG emissions in the EU by mid-century. Alternative climate change pathways based on different emission reduction targets and energy-planning options, such as electrification, behavioral changes, and synthetic fuels, can help in assessing the challenges and opportunities associated with developing a large-scale bioenergy supply system in the EU. Some studies report that bioenergy can provide between 14% and 17% of final energy consumption and 7–9% of electricity generation [74].

2.5. Multi-Parametric Determinants of Climate Neutrality

The significant role of aviation in achieving climate neutrality by 2050 has recently sparked societal discussions to ensure the sector becomes responsible and widely advantageous. A scientific approach developed a model outlining the path for aviation to reduce CO_2 emissions by 90% by 2050, bringing it down to a level where residual emissions can be removed from the atmosphere without competing with other sectors that also require negative emissions. At a timescale of 40 years, investment funding of a total budget of USD 3.3 trillion is directed to implement high-quality carbon removal projects that can further benefit biodiversity and society [75].

In related research, two empirical methods were integrated into a theoretical approach that included multiple linear regression and a non-causal analysis as a robustness method. This was aimed at addressing the multifaceted influence of economic growth, digitalization, eco-innovation, energy consumption, and patents on environmental technologies on GHG emissions in European countries between 2010 and 2018. The findings revealed that digitalization, measured by individual internet users and patents on environmental technologies, determined the volume of GHGs in Europe. Economic growth also had a significant impact on emission levels, as did renewable energy consumption. Economic growth, digitalization, eco-innovation, and renewable energy all had direct or indirect effects on GHG emissions in many European countries. The impact of economic growth on climate neutrality is contingent on its sustainability. Additionally, patents have a conditional effect that depends on the extent to which they translate into environmentally efficient technologies. Such research offers a more comprehensive understanding of how the European digitalization process can be positioned within macroeconomic policies and long-term planning designs in relation to GHG emissions [76].

Considering that the EU and China have committed to achieving net-zero emissions by 2050 and 2060, respectively, legal frameworks can be conceptualized to support these goals, taking into account the stringency of objectives and the adaptiveness of relevant legal frameworks. The legal nature of achieving net-zero emissions by 2050 and 2060 involves bindingness, scope, prescriptiveness, and precision of obligations, as well as compliance mechanisms. Moreover, the adaptability of pertinent legal frameworks is determined by the interplay between the dynamism of mitigation policies and the legal institutions and processes that facilitate decarbonization. According to some experts, the objective of achieving climate neutrality is deeply ingrained in the European Union's climate law framework, which features a high degree of overall rigor. Conversely, China largely pursues administrative measures without formal regulations and robust enforcement mechanisms. In this context, carbon neutrality is subjected to regulatory integrated legal reforms, showing that China explores a distinctive approach to meeting its research objectives [77].

3. Results and Discussion

Over the past two decades, climate change literature has significantly expanded, involving a wide range of decision-makers across various spatial and temporal scales, particularly in Europe [78–86]. The UNFCCC, its subsidiary bodies, and Member Parties have traditionally focused on mitigation efforts. However, a surge of grassroots interest in recent times has led to an increase in local mitigation initiatives. In contrast, adaptation decisions are made by both the public and private sectors, with some involving large-scale construction projects overseen by public-sector decision-makers, and others being localized and involving numerous private-sector agents [87].

The interplay between adaptation and mitigation involves different stakeholders, each with their respective roles to play. Stakeholders can be characterized based on their organizational structure (public or private), decision-making level (policy, strategic planning, or operational implementation), spatial scale, timeframe of concern, and different functions within a network, such as single actor, stakeholder regime, or multi-level institution). Decisions may be centered on adaptation only, mitigation only, or a combination of both. Moreover, a small number of public or corporate decision-makers bear direct responsibility for both adaptation and mitigation [87]. For instance, while adaptation efforts could be overseen at a central governmental level, such as the Ministry of the Environment, local authorities; land-use planners; or the Trade, Energy, or Economic Ministry can often address adaptation and mitigation issues [87]. In this context, adaptation measures are typically implemented on the scale of an impacted system, which is regional at best but primarily local. However, some adaptation efforts may lead to spillovers across national boundaries, such as by impacting international commodity prices in agricultural or forest-product markets [87].

Mitigation and adaptation strategies and action plans are not exclusive to climate change, but are also applied to other potential hazards, such as industrial safety [88,89]. These strategies aim to reduce risk and increase resilience to potential hazards. By implementing these strategies and developing action plans, organizations can proactively manage risks and reduce the negative impacts of potential hazards. Overall, mitigation and adaptation strategies provide a framework for developing effective action plans for a range of potential hazards, including those related to industrial safety [90].

Mitigation efforts seek to reduce both the positive and negative impacts of climate change, thereby lessening the overall burden of adaptation. Conversely, adaptation is selective in nature and can capitalize on positive impacts while minimizing negative ones [87]. While mitigation and adaptation share the common goal of addressing climate change, they differ in their objectives. Mitigation aims to tackle the root causes of climate change (the accumulation of greenhouse gases in the atmosphere), whereas adaptation seeks to manage the impacts of climate change. Both approaches are crucial, as even with robust mitigation efforts the climate will continue to evolve in the coming years, necessitating adaptation. However, adaptation alone cannot entirely mitigate all negative impacts, underscoring the significance of mitigation efforts in curbing changes in the climate system [64].

In this regard, the spatial scales of adaptation and mitigation efforts differ, with adaptation benefits being primarily local, while mitigation benefits are global, despite climate change being an international issue. Additionally, adaptation and mitigation vary in terms of temporal scales and involved economic sectors [64]. Prior studies have emphasized the importance of identifying synergies and trade-offs in land use, biomass, and ecological systems, rather than technical, economic, and social systems. It is critical to evaluate these synergies and trade-offs across spatial and temporal scales and account for the virtual impacts of imported goods (such as virtual water contents). Moreover, it is crucial to recognize the lock-in effects of investments in technological systems that must be resilient to changes in framework conditions over their lifetime [65].

Despite the most stringent mitigation efforts, climate change will continue to impact natural and human systems over the next few decades, necessitating adaptation measures (Working Group I Fourth Assessment Report, Working Group III Fourth Assessment Report). However, without adequate mitigation, the scale of climate change may reach a point where adaptation becomes impossible for some natural systems and incurs high social and economic costs for most human systems [87]. Mitigation and adaptation strategies encompass technological, institutional, and behavioral options, as well as the implementation of economic and policy instruments to promote their use. Research and development efforts are also critical in reducing uncertainty and enhancing the effectiveness and efficiency of these options. There are opportunities to integrate adaptation and mitigation efforts into broader development policies and strategies [87], e.g., The Working Group III

Fifth Assessment Report: Climate Change 2014: Mitigation of Climate Change evaluated the scientific, technological, environmental, economic, and social aspects of mitigation, including greenhouse gas emission trends, mitigation policies, and long-term mitigation pathways across various sectors, including energy supply, transport, buildings, industry, agriculture (particularly land use), and human settlements [88].

Effective mitigation efforts require the involvement of major greenhouse gas emitters worldwide, while adaptation measures are primarily implemented at local and national levels. Mitigation efforts sustain global benefits, while the costs and ancillary benefits are primarily local. In contrast, both the costs and benefits of adaptation are generally experienced at local and national levels. As a result, mitigation is primarily driven by international agreements and subsequent national policies, potentially supplemented by unilateral and voluntary actions. On the other hand, adaptation typically involves private actions by affected entities, public arrangements for impacted communities, and national policies [87].

In addressing the impacts of climate change in cities, it is essential to give equal importance to both adaptation and mitigation. In this context, it is critical to adopt measures that promote co-benefits, ensuring that limited resources will be utilized effectively and managed efficiently [91]. There is a growing body of research on joint benefits and synergies between adaptation and mitigation, but this is still relatively limited compared to the significance of these synergies in cities. These areas are expected to experience most of the future urban growth and are more vulnerable to climate change impacts. Despite increasing awareness of the importance of addressing both adaptation and mitigation measures, there is still a disconnect between rhetoric and reality. Some cities prioritize only one of these measures due to challenges in coordinating activities across diverse departments with inconsistent priorities or concerns regarding feasibility in simultaneously considering both adaptation and mitigation. Thus, investigating mitigation–adaptation interactions in sparsely examined regions, such as those in global south cities, is worth further exploration [91]. In Figure 1, the transformability dimensions toward mitigation–adaptation synergies for climate change are illustrated.

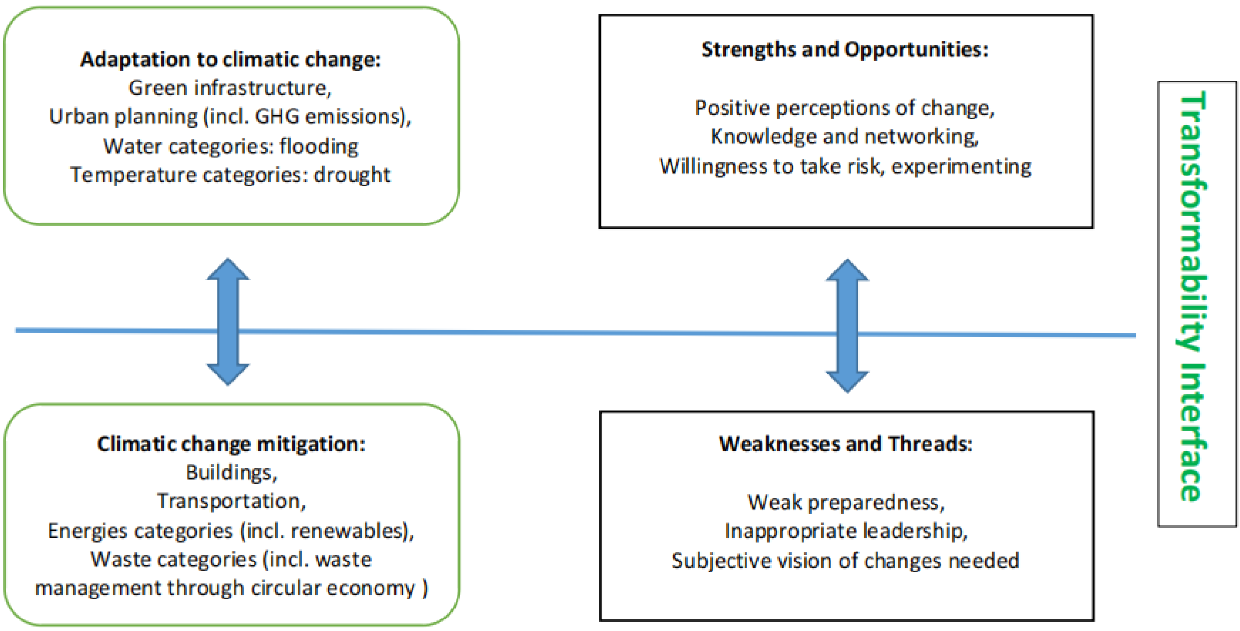

Figure 1. Transformability dimensions towards mitigation–adaptation synergies for climate change. Source: Enhanced by [91,92].

Based on Figure 1, it can be observed that enhancing adaptation to climate impacts such as flooding, extreme temperature events, and droughts are all determining green infrastructure, GHG emissions reduction, urban planning, and water categories. On the other hand, measures relevant to building, transportation, energy, and waste categories primarily pertain to climate change mitigation, due to the substantial energy-saving benefits achievable through efficiency improvements in these sectors. Nevertheless, these measures also offer adaptation co-benefits, highlighting the potential for synergies between adaptation and mitigation in urban climate action [91].

It should be noted that decisions made in macro-economic policy, agricultural policy, development bank lending, energy security, and forest conservation can have a significant impact on reducing emissions, even though they are not directly considered as part of climate policy. Conversely, policies not related to climate can also affect adaptive capacity and vulnerability [92]. It is essential that the ultimate goals of sustainability and "green growth" promotion are accomplished through harnessing the benefits of mitigation–adaptation synergies in the energy, forestry, and agricultural sectors. This is especially crucial for indigenous and local communities being heavy linked on their local natural environments; thus, it is implied that indigenous social-ecological systems can be decisive in developing multifaceted mitigation–adaptation synergies [92].

It is also critical to mention that research differences reported between adaptation and mitigation, as well as the integrated model of assessment 'bottom-up' studies, can be confusing and inconsistent with one another. Such differences and inconsistencies are considered as emerging artifacts of the research approaches on the inter-relationships developed between adaptation and mitigation. In the long term, synergy aspects involved at national developmental frameworks could be mainstreamed across funds where it is not already implicit in the funding criteria. Furthermore, both content and processes between mitigation and adaptation can be better defined and guided by climate funds on how to address synergy aspects [65]. Climate funds and climate action plans are concentrated on either adaptation or mitigation. Geographically, mitigation has been deemed a priority for cities in the global north, whereas adaptation has been the focus for the global south [91]. global north cities historically produce emissions and adversely affect the mitigation, as well as bearing increasing responsibility due to their larger emissions contribution. Conversely, adaptation is seen as especially crucial in developing countries that historically generate lower GHG emissions (resulting in lower mitigation potentials), though being more susceptible to climate impacts [91].

Although the primary emphasis was on mitigation, the significance of adaptation is gaining more recognition, fueled by the increasing realization that specific levels of climate change are unavoidable due to past emissions. Furthermore, the uncertainties surrounding the success of mitigation strategies highlight the need to enhance adaptation capabilities [91]. An integrated mitigation–adaptation grid of climate change it is presented in Figure 2.

Figure 2 demonstrates that the connections between adaptation and mitigation might uncover methods for effectively implementing both adaptation and mitigation measures collectively [87]. The 'act, learn, then act again' framework can be employed here exclusively for outlining the components of the decision problem, rather than as a substitute for the numerous analytical approaches discussed in this review study. In fact, this framework can be utilized to categorize different approaches descriptively, such as deterministic versus probabilistic methods and cost-effectiveness analysis versus cost-benefit analysis. Consequently, as per Figure 1, the concept of cost encompasses not only economic or financial aspects but also an extended understanding that includes non-monetary/intangible values. Decision analysis has been more commonly associated with the inter-relationships between adaptation and mitigation than with adaptation alone; however, a robust decision framework is appropriate for examining future climate change vulnerabilities [87]. In this regard, these synergies offer no assurance that resources will be used most efficiently when trying to reduce climate change risks [87], highlighting which actions offer increased co-benefits and synergies, and as a result, merit additional examination by planners and policymakers, often involving strategies that address both mitigation and adaptation synergies [91]. Opportunities for such synergies are more plentiful in specific sectors (agrarian management, forestry, built environment) but are restricted in others (marine systems, energy, health). Assessment complications are also induced by lacking data of theory and practice that directly tackles the potential of both adaptation and mitigation synergies in climate policy [87].

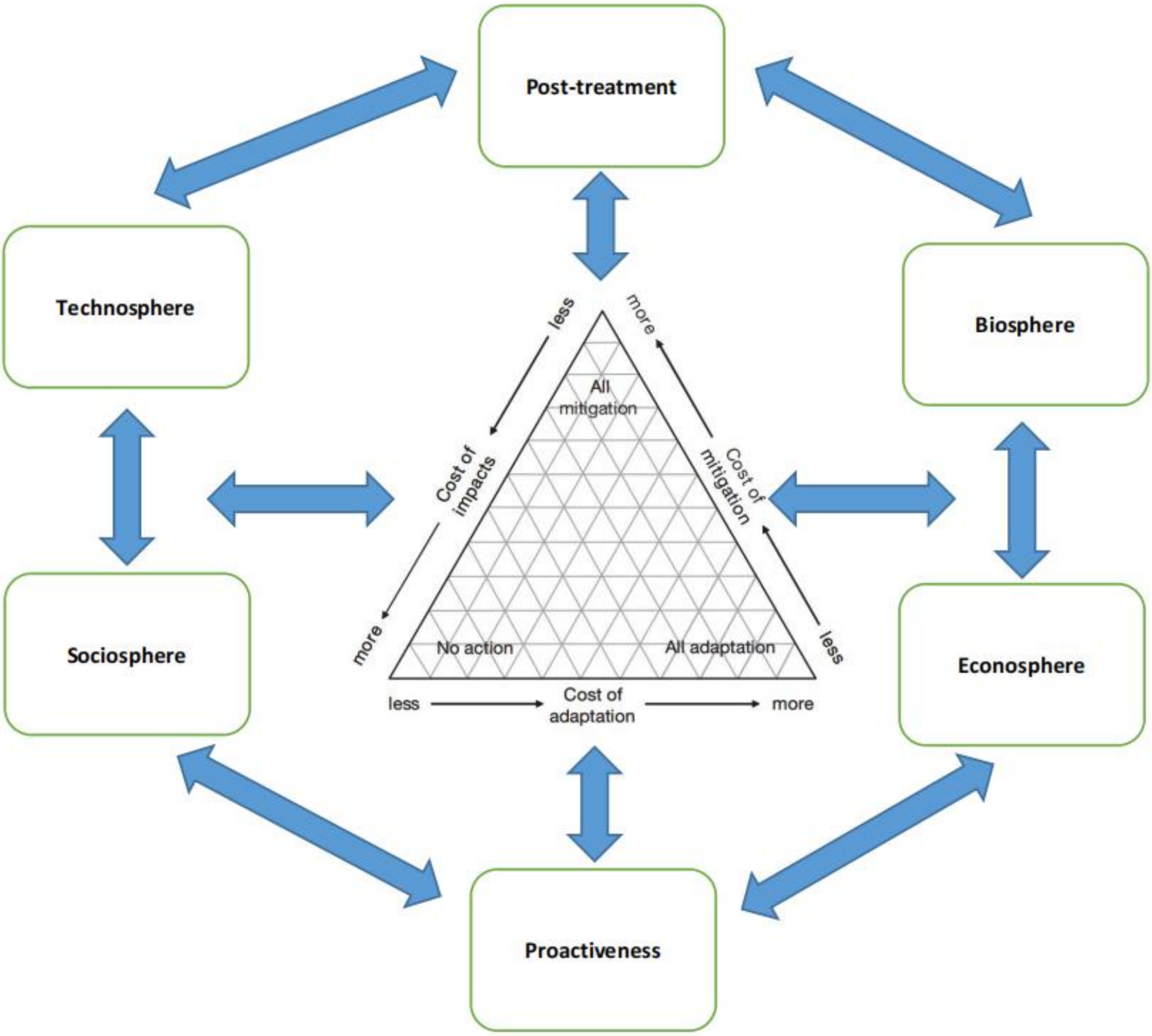

Figure 2. The mitigation–adaptation grid of climate change. Overview of inter-linkages developed on the natural and anthropocentric environment. Source: Enhanced from [87], p. 748.

As indicated by Figure 2, considering the current state of the energy sector, transformations are more likely to transpire through a series of decisions over time rather than occurring instantaneously. Adaptation decisions have begun addressing present climate risks (e.g., drought early-warning systems) and adopting forward-looking or proactive measures (e.g., land-use management). As climate change worsens, autonomous or reactive actions (e.g., purchasing air-conditioning during or after a heatwave) are anticipated to increase. Buying decisions such as those being driven by rapid technological shifts from one technological level to another pathway (e.g., linked to leapfrog technologies developed in the communication sector) can also disrupt trends and accelerate transitions signaled by substantial shifts [87]. Consequently, based on Figure 2, integrated assessment modeling can be informed by examining the factors and processes that determine whether and when adaptation and mitigation can function synergistically in climate policy. Owing to its emergence as a research field, the body of literature is limited but is quickly growing. At the same time, the literature is quite diverse, as there is no consensus on the feasibility or even desirability of exploiting interrelationships between adaptation and mitigation. Some researchers [87] perceive the potential for creating synergies between adaptation and mitigation, while others remain more doubtful regarding the benefits of considering them together. The disparities in approaches between adaptation and mitigation research and between integrated assessment modeling and 'bottom-up' studies can create confusion when published results in the literature appear to contradict each other.

Acknowledging the economic trade-offs between the immediate local advantages of adaptation and the long-term global benefits of mitigation requires information about the costs and benefits of these actions over time. Integrated assessment models supply rough estimates of relative costs and benefits at highly aggregated levels, but only a few models account for feedback from impacts. The intricacies of the relationships between adaptation and mitigation become clear at more detailed analytical and implementation levels [87]. These intricacies, which include specific adaptation and mitigation options operating on different spatial, temporal, and institutional scales, and involving various actors with diverse interests, beliefs, value systems, and property rights, pose a challenge to the design and implementation of decisions based on economic trade-offs beyond the local scale. Specifically, making the concept of an 'optimal mix' of adaptation and mitigation operational is challenging, as it requires harmonizing welfare impacts on individuals living in different locations and at different times into a single global measure of well-being [87].

The analysis above suggests that, due to the primarily local or regional effects of adaptation, adaptation benefits will be valued differently based on the social, economic, and political contexts in which they occur [87]. Mitigation benefits enacted today will manifest in several decades because of the long atmospheric residence time of greenhouse gases (near-term ancillary benefits such as reduced air pollution are possible), whereas many adaptation measures would take effect immediately and produce benefits by decreasing vulnerability to climate variability [87]. As climate change advances, the benefits of adaptation (i.e., damage prevention) will increase over time. As a result, there is a delay between incurring mitigation expenses and realizing the benefits from reduced climate change impacts, while the timeframe between adaptation investments and returns is generally shorter. Furthermore, adaptation actions have been historically driven by the self-interest of affected private actors and communities, rather than international agreements and subsequent national public policies [87].

It can also be contended that it is highly probable that global climate change mitigation progress will be insufficient to avert relatively high levels of regional and sectoral impacts, and that such conditions would present growing challenges to the capacity of adaptation to prevent significant disruptions to development processes. If this were to become a reality later in this century, one response could be an urgent move toward geo-engineering solutions. In anticipation of such a scenario, and perhaps as an additional method to emphasize the importance of progress with mitigation in determining sustainable development prospects in various contexts, there is an urgent need for research on geo-engineering costs, benefits, risks, a broad range of potential impacts, and fair and equitable frameworks for global policy and decision-making [93]. The critical point here is climate-resilient pathways for sustainable development to avert such an unfavorable outcome, considering that climate change mitigation, climate change adaptation, and sustainable development should be integrated and mutually supportive [93]. In Table 6, an integrated overview of mitigation and adaptation initiatives regarding climate actions is outlined.

Table 6. The main dimensions and drivers of mitigation and adaptation initiatives. Source: Enhanced by [65].

Dimensions	Capacity Development	Drivers	Framework of Action	Goals and Goods
Water	Understanding	Globalization	Governance	Energy and Food security
Land		Urbanization	Economy and Technology	Land productivity
Energy	Managing	Climate change	Ecosystems	Climate mitigation and adaptation Biodiversity
Capital	Innovating	Socio-economic development	Society	Socio-economic systems in national-level of analysis

Based on Table 6, the favorable effects of synergies encompass goals and goods can be attained through the synergistic efforts, as follows [65]:

- Land uses and climate actions;
- Transportation and climate actions;
- Green infrastructure and climate actions;
- Energy and climate actions.

Each one of these key-aspects of climate actions is succinctly presented below.

3.1. Land Uses and Climate Actions

Several co-benefits of adaptation have been observed in compact urban development that emphasizes enhanced accessibility, connectivity, and mixed land use. In contrast to urban sprawl, compact urban development lowers land demand, allowing for the avoidance of risk-prone areas. This not only reduces exposure to hazards such as flooding and wildfire [91], but also helps protect valuable ecosystems such as forests and wetlands. These natural assets offer essential ecosystem services for adapting to flood risk and heat events [91].

Although "ecosystem-based adaptation" (EbA) focuses on climate-affected ecosystems (such as mangroves shielding coastal areas, forestry management, agrarian management, natural water sources), it is fundamentally a human-centered approach to adaptation. EbA aims to reduce human vulnerability by providing ecosystem services. It is becoming increasingly recognized that well-managed ecosystems can support societies in adapting to current climate hazards and future climate change by delivering various ecosystem services. For EbA, understanding the intertwined vulnerabilities of people and ecosystems and examining ecosystems in their broader context is crucial [64].

A wide range of agricultural actions involve the use of land, water, resources, and energy. When designed appropriately, these actions can provide both mitigation and adaptation benefits. Measures in the agricultural sector include soil conservation, drought and climate-resilient plants and crops, composting, mulching, enhanced irrigation, and other sustainable farming techniques, often collectively referred to as "climate-smart agriculture" [65]. Mitigation opportunities target various aspects of agricultural production, such as grazing land management, pasture improvement, organic soil management, restoration of degraded lands, livestock and manure management, and using agricultural residues for bioenergy [65]. Actions within these areas include carbon sequestration in soils, plants, and biogenic products, nutrient and fertilizer management, modified grazing practices and intensity, drainage avoidance, and the implementation of low- or no-tillage techniques. In terms of livestock, actions involve improving feeding practices and breeding low-emission animal breeds [65].

Numerous options are available for adapting crop and livestock production systems to climate change, including advanced actions such as utilizing Information and Communication Technology (ICT) to provide weather data to farmers for managing risks related to temperature and rainfall variability, as well as implementing weather index-linked insurance schemes [65]. Mitigation and adaptation measures can both provide economic and social advantages as a result of new and enhanced farming opportunities, especially for small-scale farmers with limited access to irrigation and artificial fertilization as methods of adapting to climate changes. Furthermore, these measures may help preserve and strengthen biodiversity and essential ecosystem services, such as pollination [65].

3.2. Transportation and Climate Actions

Public transportation can indirectly cope with communities, being indirectly associated with increased resilience against negative health impacts, supporting the improvement of public health and environmental quality, while simultaneously reducing household healthcare costs and transportation costs. Additional indirect economic resilience benefits can be achieved if public health and time-saving advantages result in reduced productivity loss in the workplace through well designed public transportation schedules and nurturing economic activities around pedestrian-friendly transport stations [91].

In addition to public transportation measures, other noteworthy transportation-related actions that contribute to meeting mitigation goals while also boosting adaptation capacities include improving vehicle efficiency standards, electrifying urban transportation, and encouraging car-sharing services. These strategies lead to economic resilience through cost savings and strengthen resilience to energy shocks with energy-saving capacities [91].

3.3. Green Infrastructure and Climate Actions

Green Infrastructure (GI) measures have gained considerable interest across various categories. While the primary focus has been on adaptation benefits, ample evidence exists regarding mitigation co-benefits related to carbon sequestration and cooling effects towards reducing energy consumption. Such carbon-sink devices that have a long lifetime and advanced insulation properties include green roofs and facades. It is also noteworthy that a longer lifespan is essential for mitigation, considering the significant emissions embodied in construction materials. Moreover, additional lifecycle emission savings can be achieved through green roofs' insulation properties, which decrease heat transfer and boost building energy efficiency. Further emission savings can be derived from cooling effects that indirectly lower energy consumption [91].

In the relevant literature, numerous adaptation co-benefits have been reported in urban agriculture, being considered as a GI measure of mitigation–adaptation co-benefits and multiple ecosystem services [91]. The main benefits of GI include enhanced thermal comfort, stormwater management, food security, improved microclimatic conditions, enhanced soil carbon sequestration, economic resilience, and social resilience. Food security is also supported as urban food production can meet some communities' food needs and reduce reliance on food transportation, which might be disrupted during significant disasters [91]. Food production can also serve as an income source for certain groups, thereby improving their economic resilience. Furthermore, involvement in urban farming programs can boost social resilience by nurturing social capital. This is attainable through opportunities for individuals from various income groups and cultural backgrounds to interact and collaborate, as exemplified in Munich, Germany [91].

Urban areas are characterized by their use of ecosystems for local food, biofuels, water supply and reserves, recreational spaces, biodiversity, and related job and income opportunities. Assessing synergies and trade-offs in urban areas requires understanding the impacts of urbanization, which involve increased pressure on local ecosystem services and resources [65]. Several measures and green structures, such as parks, grass grids, and green building surfaces and roofs, are alternatives to hard surfaces; all of them can provide benefits of reduced energy use and enhanced climate resilience. These green structures can improve stormwater management, decrease the urban heat island effect, and enhance local air quality [65]. Specifically, the potential of green building programs that promote the integration of energy-efficient systems and passive design techniques has been emphasized to reduce energy loss and consumption, and to decrease human-induced CO_2 emissions. Building retrofit programs can further enhance the energy efficiency of existing building stock while considering the water–energy nexus, especially in regions facing water stress [91]. Because urban mitigation actions typically involve energy and water efficiency and increasing green spaces, trade-offs are less evident [65]. Therefore, a smart climate solution to jointly address mitigation and adaptation in an interconnected energy, water, and land-use systems offers greater opportunities for identifying synergies:

- Water intensity of biofuels and hydropower;
- Energy intensity of desalination and water transportation;
- Competition for local/competitive land uses areas for biofuel production, food production, recreational spaces, urbanization/domestication sites, infrastructure [65].

Generally, the social costs of carbon estimates are considered to be low-confidence due to numerous gaps in impact and valuation study coverage, uncertainties in projected climate change, decision framework choices, and the applied discount rate [87]. Marginal abatement cost estimates range from −2% to +8% of GDP, while estimates of avoided marginal damages cover three orders of magnitude [87]. The marginal cost of adaptation has not been calculated, though some estimates assume a reduction in impacts due to adaptation [87]. Integrating the marginal abatement cost, avoided marginal damages, and the marginal cost of adaptation into an optimal strategy for climate response all involve significant uncertainty, which is unlikely to be effectively reduced in the near term [87].

3.4. Energy and Climate Actions

Energy and air pollution co-benefits mainly involve decentralized and distributed energy supply systems—wind, solar, and hydropower—that promote cleaner and more efficient energy supplies, while addressing efficiency loss that can occur in conventional centralized plants during transmission and distribution phases [91]. Renewable-based decentralized systems can both support mitigation benefits and improve adaptation capacities, thus alleviating pressure on water-stressed regions [91]. Decentralizing and diversifying energy supply systems also minimizes risk and ensures that the failure of some components does not result in total system failure [91]. Centralized systems, conversely, may experience significant power loss, as in the cases of severe storm events and high temperatures, where there are peak power needs [91].

Incorporating a shadow price for climate change externalities in large infrastructure projects may lead to shifts in adaptation portfolios. Assessments of actual shifts in energy demand and emission reduction methods are desirable. While most integrated assessments focus on regional or global scales, local dialogues have begun exploring synergies [87]. Synergies and trade-offs in the energy sector typically involve increased use of renewable energy sources and improvements in energy efficiency from end-users to transmission and conversion. A lifecycle perspective can be adopted when considering the marginal effects of using biogenic resources to reduce CO_2 emissions, such as through Indirect Land Use Change (ILUC) [94]. This includes accounting for indirect effects such as emissions from ILUC and potential leakage impacts. To avoid trade-offs, the possibilities of replacing first-generation biofuels with second- or third-generation alternatives should be assessed [65].

Adaptation perspectives in the energy sector include reduced sensitivity to oil price fluctuations and decreased dependence on fuel imports. Micro-generation and other means of improving electricity access can enhance energy efficiency in households and reduce negative health impacts from using open fires for cooking, as well as improve studying conditions through better lighting [65]. The energy sector emphasizes potential trade-offs related to the agriculture and forestry sectors. A shift to bio-based economies may increase pressure on biogenic resources in both sectors, affecting land use decisions on micro-, meso-, and macro-scales, potentially leading to increased GHG emissions. Inter-annual and seasonal precipitation variations, along with projected changes in precipitation, may challenge long-term resilience of water-intensive energy systems [65].

4. Conclusions, Challenges and Future Research Prospects

Climate change adaptation and mitigation can be integrated into sustainable risk management and enable a full understanding of those decision-making processes at various levels. The mitigation and adaptation costs and benefits are intensively differentiated; mitigation benefits are more global, while adaptation benefits are typically more localized. Furthermore, research and policy discussions by decision-makers are differentiated, because mitigation often involves influential industrial stakeholders from the energy sector at higher decision-making levels, while adaptation involves more dispersed stakeholders at the local level across various sectors [93]. To significantly reduce global emissions, mitigation decisions must be made by major emitters or groups of countries. In contrast, adaptation usually falls to local practitioners, although it often relies on national and global support [93].

Integration choices for adaptation and mitigation will vary depending on each country and locality's circumstances [93]. In highly vulnerable countries, adaptation may be a higher priority due to the immediate benefits gained from reducing vulnerabilities to current and future climate changes. In developed countries, adaptation initiatives are often seen as a lower priority because of the perception of abundant adaptive capacity [93]. However, substantial losses and damages related to climatic variability in some industrialized countries challenge this view. Mitigation may be viewed as a more pressing political issue in countries that contribute a significant proportion of GHG emissions and may be seen as an investment opportunity for the domestic private sector. Designing "win-win" and "triple-win" interventions and strategies can achieve an appropriate balance of mitigation and adaptation within the context of sustainable development [93].

Several factors should be considered when evaluating combined adaptation and mitigation policy designs, including avoiding trade-offs, identifying synergies, enhancing response capacity, developing institutional links, and mainstreaming adaptation and mitigation considerations into broader sustainable development policies [93]. Sustainable development is heavily influenced by climate change extremes, necessitating transformative shifts in human and environmental systems. Key research considerations include fostering synergies between climate change adaptation and mitigation actions, embracing the concept of "additionality", and establishing criteria for financially supporting climate adaptation that emphasize the significance of co-benefits for development. This research can also explore the distinctions between adaptation and development, enabling the allocation of financial resources to support adaptation initiatives [93].

From a central government perspective, primary climate actions should include implementing national policies that mandate national authorities to approve mitigation projects only if they take adaptation into account [64]. Additionally, international policies should address climate adaptation and mitigation collectively, as some countries have proposed that "adaptation measures" be developed with consideration for adaptation and mitigation synergies, with REDD+ options being especially relevant [64]. One potential standard to adopt is the Climate Community Biodiversity Standards, which assess the impacts of land-based mitigation projects while explicitly incorporating diverse adaptation criteria [64].

Further research opportunities for effective and practical climate actions should investigate the potential of technological and institutional innovations to achieve sustainable development in the face of climate change impacts and responses. The central question revolves around how climate change responses might offer opportunities for innovative development paths or how technological advancements can strategically contribute to development through climate change integration [93]. These research approaches could strengthen institutional development and enhance our understanding of how social institutions influence resource use, how decision-making related to risk occurs under uncertain conditions, and what best practices enable institutions to effectively integrate climate change responses with sustainable development features such as participation, equity, and accountability [93].

Implementing these strategies is not only precautionary but also supports adaptive management and risk reduction for development. Research in this area aims to refine and better understand the roles and interactions between autonomous response behaviors and policy initiatives while expanding the body of empirical evidence on implementing desirable changes, such as adaptive management and governance capacity. These strategies can also enrich our understanding of the differences between retrofitting older infrastructure (a challenge in many industrialized countries) and designing new infrastructure (a challenge in many rapidly developing countries) [93].

Future research can incorporate social inclusiveness into the integration of development and climate change responses. It is crucial to address issues of social values, climate justice, equity, and participation, and how they relate to the implementation of mitigation and adaptation interventions and sustainable development policies in various regional and sociopolitical contexts, being the "best practices" identified and implemented [93]. These distinct regional and sociopolitical settings inevitably encourage and shape purposeful ethical, equitable, and sustainable transformations [93]. Enhancing society's response capacity can also promote both adaptation and mitigation by effectively and jointly facilitating both options into sectoral planning and development. If climate policy and sustainable development are to be pursued jointly, it is essential not only to assess specific policy options that might achieve both objectives but also to investigate the determinants of response capacity that underpin those options in alignment with the underlying socioeconomic and technological paths, especially of positive environmental sign [87,95].

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