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ABBREVIATIONS

Abbreviation	Full name
AI	Artificial Intelligence
BLF	Behavioural Lever Framework
GDPR	General Data Protection Regulation
NAM	Norm Activation Model
SEM	Socio-Ecological Model
SDT	Self-Determination Theory
TPB	Theory of Planned behaviour
TTM	Transtheoretical Model
XAI	Explainable AI

1. Introduction

1.1 Overview of Climate Change Adaptation Needs

Climate change poses complex and multifaceted challenges that require both immediate and long-term adaptation strategies in order to increase the inherent resilience of social and environmental systems to its effects. As climate-related natural phenomena and disasters become more frequent and severe, there is an urgent need to develop adaptation solutions that protect ecosystems, infrastructure and vulnerable communities from the impacts of rising temperatures, extreme weather events and changing environmental conditions. The global community must respond to these challenges by increasing climate resilience through coordinated efforts in policy, science, technology and citizen engagement (Del Río Castro et al., 2021).

Key areas of concern in climate adaptation include water scarcity, food security, coastal and urban resilience, infrastructure capacity, and biodiversity protection. As natural systems are disrupted, resource management becomes more critical, requiring innovations in agriculture, energy use and urban planning to maintain sustainability. Vulnerable populations, especially in developing regions, will be disproportionately affected, highlighting the need for equitable and inclusive adaptation strategies (Balagun et al., 2020). To meet these diverse needs, climate adaptation must be both proactive and reactive, anticipating future risks while addressing immediate vulnerabilities.

Technological innovations, such as artificial intelligence (AI), offer significant potential for climate adaptation by providing predictive analytics, real-time monitoring and dynamic resource management (Rau et al., 2022). However, as adaptation needs are highly localised, there is a critical need for community-based and participatory approaches that engage stakeholders in decision-making processes and ensure that adaptation solutions are culturally appropriate and socially equitable (Cattino & Reckien, 2021), rendering adaptation to climate change not only a technical challenge, but also a behavioural and systemic one.

1.2 behavioural and Systemic Change for Climate Resilience

Achieving climate resilience requires fundamental changes in both individual behaviour and societal systems. More specifically, important and influential behavioural change theories such as the Theory of Planned Behaviour (TPB), the Norm Activation Model (NAM), and Self-Determination Theory (SDT) are instrumental in better understanding the drivers of pro-environmental behaviour (Ajzen, 1991; Deci & Ryan, 1985). These theories emphasise the need to promote intrinsic motivation, social norms and perceived control over environmental actions to encourage sustainable habits. For example, by increasing awareness of the consequences of one's actions, individuals are more likely to feel personally responsible for reducing their environmental impact (Rau et al., 2022).

In addition, systemic change involves transforming the larger structures and institutions that shape societal responses to climate risks. Ecological systems theory and the Behavioural Lever Framework (BLF) highlight the importance of multi-level interventions that engage actors across sectors, from individual households to global policy frameworks (Bronfenbrenner, 1979). Systemic change requires the coordination of policies, infrastructure and economic systems that are aligned with sustainability goals.

This includes policies that promote renewable energy, sustainable agriculture and climate-resilient urban planning.

behavioural and systemic changes are deeply interrelated and mutually reinforcing, forming a dynamic interplay that is critical for achieving long-term sustainability. On the one hand, shifts in social norms—such as growing public support for renewable energy or increased awareness of climate change—can significantly influence individual and collective behaviour. When sustainable practices become socially desirable or morally imperative, individuals are more likely to adopt environmentally responsible habits, such as reducing energy consumption, investing in solar panels, or supporting green businesses. These behavioural changes, when widely adopted, can create a ripple effect that signals to policymakers and institutions a demand for broader structural transformation.

Conversely, systemic changes—such as the implementation of government subsidies for clean energy, the establishment of carbon pricing mechanisms, or the redesign of urban infrastructure to support public transportation and cycling—can make sustainable choices more accessible, affordable, and appealing to the general population. These top-down interventions not only lower the barriers to individual action but also help institutionalise sustainability within the fabric of society. For instance, when renewable energy becomes more economically viable due to subsidies, individuals and businesses are more inclined to transition away from fossil fuels.

This reciprocal relationship suggests that fostering a culture of sustainability cannot rely solely on either individual behaviour change or systemic reform. Instead, it necessitates a coordinated approach that bridges grassroots engagement with strategic policy interventions. Community-driven initiatives, educational campaigns, and local activism play a crucial role in cultivating environmental awareness and motivating personal responsibility. At the same time, supportive legislation, financial incentives, and regulatory frameworks are essential for embedding sustainability into economic and social systems.

As El Kirat et al. (2024) emphasise, achieving meaningful progress toward sustainability requires the alignment of values, incentives, and institutional frameworks at all levels of society. Only by simultaneously addressing both behavioural and systemic dimensions can we create the conditions for a resilient, equitable, and environmentally sound future.

1.3 Role of NEUROCLIMA in Facilitating Change

The NEUROCLIMA project plays a pivotal role in addressing the dual need for behavioural and systemic change by leveraging innovative AI technologies and citizen engagement frameworks. The central goal of NEUROCLIMA is to create a 'nervous system' that connects policy makers, public institutions and citizens, enabling a bi-directional flow of information, feedback and decision making that supports climate resilience. By fostering trust between citizens and policy makers, NEUROCLIMA aims to increase participation in climate governance and build a more resilient society. The project uses a range of tools and approaches, including AI-driven decision support systems, participatory governance models, and educational frameworks designed to engage citizens in sustainability efforts through playful learning and creative arts (Cattino & Reckien, 2021; Tounsi & Temimi, 2023). In addition, NEUROCLIMA is actively developing monitoring mechanisms that track citizens' needs, pain points and expectations to ensure that climate adaptation strategies are responsive and inclusive. By aligning local actions with broader systemic goals, the project aims to foster a culture of climate resilience that integrates individual behaviour with institutional frameworks and AI-driven interventions. Through this holistic approach, NEUROCLIMA contributes to the EU Mission on Adaptation to Climate Change[1] and other global efforts to reduce climate vulnerability and promote sustainable development.

2. Literature Review

2.1. Introduction to the Literature Review Approach

This chapter draws on a narrative literature review enriched with scoping elements, aiming to identify and synthesise key theoretical models that account for individual and collective behavioural change in the context of climate adaptation. The combined approach was selected for both conceptual and methodological reasons. In particular, the scoping component was deemed appropriate for the objectives of the NEUROCLIMA project, which requires engagement with a wide range of disciplinary perspectives and evolving conceptual frameworks.

Scoping was chosen because it facilitates a broad, structured mapping of relevant theories across disciplines, offering the flexibility to explore complex and emergent fields where boundaries are still under negotiation (Kumar & Sharma, 2022). Unlike systematic reviews, which are defined by narrow research questions and strict inclusion criteria, the scoping approach is more suitable for NEUROCLIMA's interdisciplinary nature, which links behavioural change with systemic transformation and the integration of AI technologies in climate adaptation (Baileche et al., 2024).

To ensure transparency and methodological rigour, the review was guided by predefined selection criteria. Theoretical models were included if they (a) addressed behavioural change processes at the individual, group, or societal level; (b) had been applied or adapted in environmental or climate-related contexts; and (c) offered conceptual tools relevant to interventions or system design. Models were excluded if they lacked empirical grounding, were limited to narrow clinical applications, or did not extend beyond descriptive accounts. This process allowed for the inclusion of theories that are both well-established and those emerging from recent interdisciplinary research.

In addition, the narrative element supports a deeper interpretation of selected theories by enabling conceptual analysis and cross-disciplinary synthesis. This dimension is particularly valuable in examining how psychological models—such as the Theory of Planned Behaviour, Norm Activation Model, Transtheoretical Model, and Self-Determination Theory—can be meaningfully connected to AI-supported interventions in the field of climate adaptation (Li et al., 2024; Irby et al., 2023). To enhance methodological rigour, the integration of scoping and narrative techniques was operationalised through a two-phase process. First, the scoping component was used to identify a comprehensive set of relevant theoretical frameworks across disciplines, based on inclusion criteria such as applicability to climate-related behaviour, conceptual maturity, and interdisciplinary relevance. Second, the narrative approach was employed to interpret these frameworks in depth, with emphasis on their theoretical assumptions, mechanisms of change, and policy relevance. This combined methodology allowed the review not only to

[1] https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/adaptation-climate-change_en

present the theories themselves but also to evaluate their practical applicability in current intervention and policy settings (Podmetina et al., 2022).

By including scoping elements, the review also makes it possible to identify areas of convergence between theoretical models and technological tools, especially in the context of AI. This is a necessary step for designing integrated frameworks that can support behavioural and systemic change. Such mapping facilitates the recognition of synergies between motivational drivers and digital mechanisms, thus informing more effective and context-sensitive interventions (Parwez, 2022; Marradi & Mulder, 2022).

2.2 behavioural Change Theories

Behavioural change theories are critical to understanding and guiding the changes in individual and community behaviour needed to address climate change. These important theories provide a framework for designing interventions that encourage environmentally responsible behaviour and promote long-term change. In the context of climate change adaptation, Theory of Planned Behaviour (TPB), Norm Activation Model (NAM), Transtheoretical Model (TTM) and Self-Determination Theory (SDT) stand out as key theoretical models for understanding and influencing behaviour. These theories help to identify the factors that drive pro-environmental behaviour (PEB) and how these can be supported through interventions. We will focus on these theories in this deliverables considering their impact throughout the last decades on scientific research.

Rationale for Theory Selection

This study adopts the Theory of Planned behaviour (TPB), the Norm Activation Model (NAM), the Transtheoretical Model (TTM), and Self-Determination Theory (SDT) based on their strong empirical validation, theoretical coherence, and relevance to both individual and community-level environmental behaviour. These theories have consistently demonstrated explanatory value in environmental psychology, particularly in recent research on climate-related behaviours (Kumar & Sharma, 2022; Baileche et al., 2024).

The **Theory of Planned behaviour (TPB)** provides a well-documented structure for understanding how individual attitudes, perceived social pressure (subjective norms), and perceived control over behaviour influence intentions and environmental actions. Its relevance has been confirmed in a range of settings, with studies showing that TPB effectively predicts behaviours like energy-saving and sustainable mobility (Li et al., 2024; Irby et al., 2023; Podmetina et al., 2022).

The **Norm Activation Model (NAM)** addresses the ethical and moral dimensions of environmental behaviour. It highlights the importance of personal norms and a sense of moral obligation in driving pro-environmental choices, especially within community-based initiatives (Parwez, 2022). Current research suggests that when NAM integrates social norms, it enhances the impact of interventions aimed at strengthening community resilience to climate change (Marradi & Mulder, 2022).

The **Transtheoretical Model (TTM)** is useful for understanding the process of behavioural change, which is central to climate adaptation strategies. TTM conceptualises behaviour change as a progression through distinct stages—precontemplation, contemplation, preparation, action, and maintenance. Its stage-based approach has proven effective in supporting long-term behavioural shifts, including waste reduction and sustainable consumption (Wang et al., 2024; Walpita, 2023).

The **Self-Determination Theory (SDT)** adds a critical motivational perspective by focusing on internal psychological needs such as autonomy, competence, and relatedness. These elements are particularly important for encouraging sustained engagement in climate-related behaviours, especially in digital or AI-enhanced interventions (Marquam et al., 2020; Daddi et al., 2018). As technological tools become increasingly integrated into climate action, understanding intrinsic motivation is key to maintaining long-term participation.

These theories were selected based on their capacity to explain motivational and behavioural mechanisms underlying pro-environmental actions, their alignment with AI-enabled tools, and their prominence in recent climate adaptation literature. Alternative models, such as the Protection Motivation Theory or the Value-Belief-Norm Theory, were considered but excluded due to conceptual overlap with NAM or limited relevance to digital and AI-based contexts (Li et al., 2022).

In summary, the integration of TPB, NAM, TTM, and SDT provides a comprehensive psychological basis for the NEUROCLIMA framework. This theoretical foundation supports both scientific rigor and practical flexibility, particularly in addressing the evolving role of technology in climate adaptation.

2.2.1 Theory of Planned behaviour (TPB)

The Theory of Planned Behaviour (TPB), developed by Ajzen (1991), remains one of the most widely applied frameworks for predicting and explaining human behaviour. It posits that behavioural intention is the primary determinant of action, shaped by three key constructs: attitudes towards the behaviour, subjective norms, and perceived behavioural control. These components reflect, respectively, the individual's evaluation of the behaviour, perceived social expectations, and the perceived ease or difficulty of performing the behaviour (Ajzen, 1991).

Within climate adaptation research, the TPB has been used to model pro-environmental behaviours by examining how beliefs about environmental outcomes, social pressures, and self-efficacy influence decision-making. For example, individuals who view energy-saving behaviours positively, perceive social support for such actions, and believe they can effectively implement them are more likely to reduce energy consumption (Ajzen, 1991; Bamberg, 2013). However, while the TPB offers a structured and empirically supported framework, its applicability to climate adaptation is limited by its reliance on individual-level cognitive variables and its assumption of rational decision-making.

One significant limitation is the theory's difficulty in accounting for the 'intention–behaviour gap'—the discrepancy between stated intentions and actual behaviour. This gap is particularly pronounced in climate adaptation contexts, where structural, economic, or infrastructural barriers often prevent individuals from translating intention into action (Bamberg, 2013). Moreover, the TPB tends to underemphasise affective, habitual, or contextual influences that are critical in dynamic and uncertain environmental settings. While perceived behavioural control is included in the model, it may insufficiently capture the complexity of systemic constraints, such as institutional inertia or unequal access to resources.

To address these limitations, recent studies have explored how technological tools—such as AI-driven feedback systems—can enhance the model's predictive power by increasing users' perceived behavioural control and supporting real-time decision-making (Jain et al., 2023). However, these enhancements must be critically assessed for their ability to reduce structural inequities, rather than simply optimising individual-level compliance.

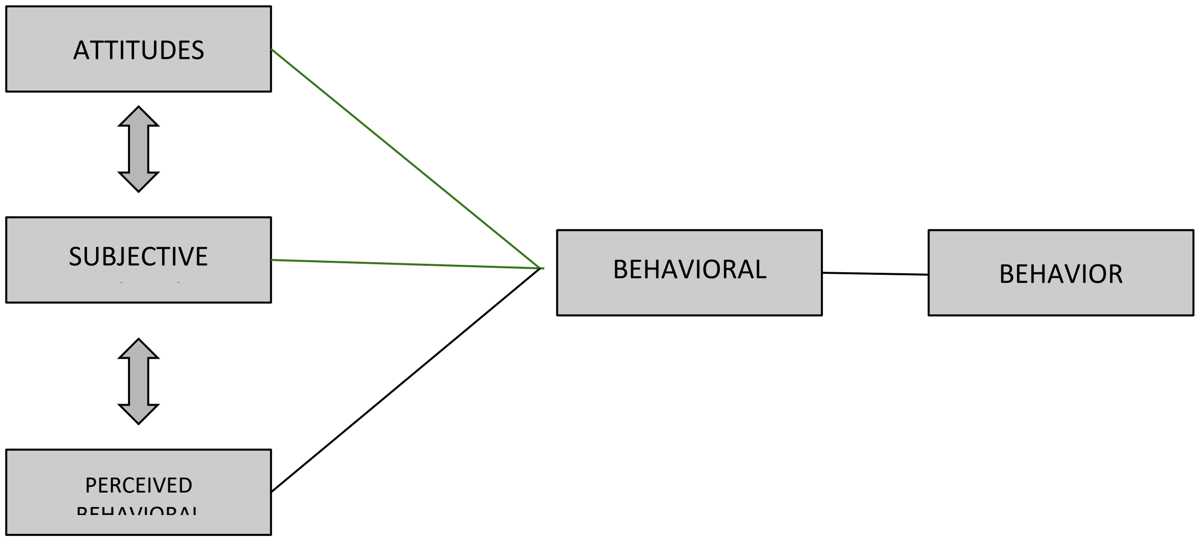

Figure 1. Theory of Planned behaviour (TPB) diagram

2.2.2 Norm Activation Model (NAM)

The Norm Activation Model (NAM), introduced by Schwartz (1977), explains prosocial behaviour as being primarily driven by personal norms and a sense of moral obligation. According to the model, individuals are more likely to act when they are aware of the negative consequences of inaction and when they feel personally responsible for addressing those consequences. This makes NAM particularly relevant to climate adaptation, where individual and collective actions can mitigate environmental risks (Schwartz, 1977).

In adaptation-related behaviours—such as reducing household emissions, conserving water, or supporting mitigation policies—NAM helps explain why some individuals adopt sustainable practices even in the absence of external incentives. The activation of personal norms is often triggered by increased awareness of environmental threats and a corresponding sense of personal accountability (Rau et al., 2022). Awareness-raising campaigns, public communication strategies, and targeted messaging have been shown to enhance this process by linking behavioural consequences with moral responsibility (Tounsi & Temimi, 2023).

However, the application of NAM in climate adaptation contexts faces certain limitations. First, the model assumes a relatively linear cognitive and moral process, potentially overlooking the role of structural, social, or emotional barriers that may inhibit behavioural change. For instance, even when individuals recognise the consequences of their behaviour and accept responsibility, they may be unable to act due to socioeconomic constraints or lack of enabling infrastructure. Second, NAM may overestimate the stability and universality of moral norms, which are often shaped by cultural, political, and situational factors. This is particularly important in diverse or polarised settings where climate responsibility is unevenly distributed or contested.

Recent developments in AI technologies offer potential enhancements to NAM's applicability by delivering personalised and context-sensitive feedback. For example, AI-supported tools can visualise environmental consequences in real time, thereby reinforcing individuals' perceived responsibility and activating personal norms more effectively. Moreover, large-scale AI-driven campaigns can reach varied demographic groups and tailor messages to local moral frames (Jain et al., 2023). Nevertheless, such tools must be deployed with caution, as algorithmic personalisation may reinforce existing biases or exclude vulnerable populations unless designed with equity and inclusivity in mind.

2.2.3 Transtheoretical Model (TTM)

The Transtheoretical Model (TTM), developed by Prochaska and DiClemente (1984), conceptualises behaviour change as a dynamic process occurring across five stages: pre-contemplation, contemplation, preparation, action, and maintenance. Individuals are seen as progressing through these stages over time, with interventions ideally tailored to their current position in the change continuum (Prochaska & DiClemente, 1984).

In the context of climate adaptation, TTM is relevant because sustainable behaviours—such as shifting to low-carbon transport or adopting household energy-saving practices—often emerge gradually rather than as sudden shifts. The model allows for differentiated engagement strategies: for instance, awareness-raising is suitable for those in the pre-contemplation stage, while action-oriented tools are better suited for those actively implementing change. Tailoring interventions to each stage can support more sustained and realistic behaviour change, particularly when climate actions require long-term commitment and adaptation to new routines (Rau et al., 2022).

Despite its practical utility, the TTM has limitations in addressing the structural and systemic factors that often condition climate-related behaviours. Its focus on individual progression may underemphasise external constraints such as policy environments, financial barriers, or social norms that can impede even the most motivated individuals. Additionally, stage progression in real-world contexts is not always linear; people may regress or cycle through stages repeatedly, especially in response to environmental uncertainty or crisis conditions. This non-linearity is not always well accounted for in standard applications of the model.

Moreover, the model's original design was developed in health-related contexts, and its adaptation to environmental behaviours requires careful attention to contextual and collective dimensions. In climate adaptation, many behaviours involve not only personal choices but also interactions with communal resources and institutional systems.

Emerging AI technologies can enhance TTM-based approaches by identifying users' behavioural stages through real-time data and delivering customised feedback or prompts accordingly. Such tools can help maintain engagement through personalised encouragement or barrier-specific solutions (Jain et al., 2023). However, the ethical implications of behavioural monitoring and the risk of oversimplifying complex motivations must be critically assessed, particularly in sensitive contexts where adaptation decisions intersect with social vulnerability.

Figure 2. Stage-Based Diagram of the Transtheoretical Model (TTM)

2.2.4 Self-Determination Theory (SDT)

Self-Determination Theory (SDT), developed by Deci and Ryan (1985), focuses on the distinction between intrinsic and extrinsic motivation in driving behaviour. According to SDT, individuals are more likely to engage in sustained behavioural change when three basic psychological needs are met: autonomy (a sense of volition and control), competence (a belief in one's effectiveness), and relatedness (a feeling of social connection and belonging) (Deci & Ryan, 1985). These needs provide a foundation for intrinsic motivation, which is generally more durable and self-sustaining than motivation driven by external rewards or pressures.

In the context of climate adaptation, SDT underscores the importance of engaging individuals through personal commitment, empowerment, and meaningful social participation. Interventions that prioritise community involvement, environmental education, and local agency—such as participatory resilience planning—are often aligned with the theory's principles. These approaches have been shown to foster a sense of ownership and capability among participants, encouraging the maintenance of adaptive and environmentally responsible behaviours (El Kirat et al., 2024).

However, the application of SDT to climate adaptation must also be critically examined. While the theory offers a robust psychological framework, it is primarily focused on individual-level motivation and may not fully account for broader systemic or structural constraints that shape environmental behaviour. For instance, fostering autonomy is limited when individuals lack access to resources, infrastructure, or decision-making processes. Similarly, promoting competence may be insufficient in contexts where climate action is perceived as ineffective due to institutional inertia or collective inaction. The emphasis on internal motivation, while valuable, risks obscuring the material and political conditions that enable or inhibit climate-relevant choices.

AI-based tools—such as behaviour tracking apps and personalised feedback systems—can enhance SDT-aligned interventions by supporting autonomy and competence through real-time data and goal-setting (Rau et al., 2022). However, such technologies must be designed carefully to avoid undermining intrinsic motivation through excessive monitoring or reliance on extrinsic prompts. Furthermore, the risk of excluding populations with limited digital access raises equity concerns that are often not addressed within SDT's original formulation.

2.3 Systemic Change Models

Systemic change models provide a framework for understanding the broader social, institutional and environmental changes needed to adapt to climate change. They recognise that individual behavioural changes must be integrated into broader systemic changes to address the multiple challenges posed by climate change. This section focuses on three key models: Ecological Systems Theory, the Behavioural Lever Framework (BLF) and the Socio-Ecological Model (SEM), each of which offers a comprehensive approach to understanding and promoting systemic change for climate adaptation. While these models offer valuable conceptual tools for designing multi-level interventions, they also have limitations in practical implementation. This section provides a critical perspective on their strengths and potential gaps when applied in real-world climate adaptation efforts.

2.3.1 Ecological Systems Theory

Bronfenbrenner's Ecological Systems Theory (1979) offers a multi-level understanding of human behaviour, positing that individuals are influenced by various interconnected environmental systems. These systems are organised in a nested hierarchy:

- **Microsystem**: The immediate environment, such as family, school and peers, where direct interactions occur. In the context of climate adaptation, this includes how local, everyday decisions, such as household energy use, directly influence individual climate-related behaviours (Bronfenbrenner, 1979; Xue, Liu, & Zhang, 2024).
- **Mesosystem**: The interactions between different microsystems. For example, the relationship between an individual's household and local environmental organisations can influence sustainable practices through shared knowledge and community activities (Xue et al., 2024).
- **Exosystem**: External environments that indirectly influence an individual's behaviour. This includes local or national climate adaptation policies that influence individual choices, such as government incentives to use renewable energy (Bronfenbrenner, 1979).
- **Macrosystem**: The broader cultural, economic and social context. This includes the global framework and socio-political structures that influence climate policies and societal norms (Xue et al., 2024).

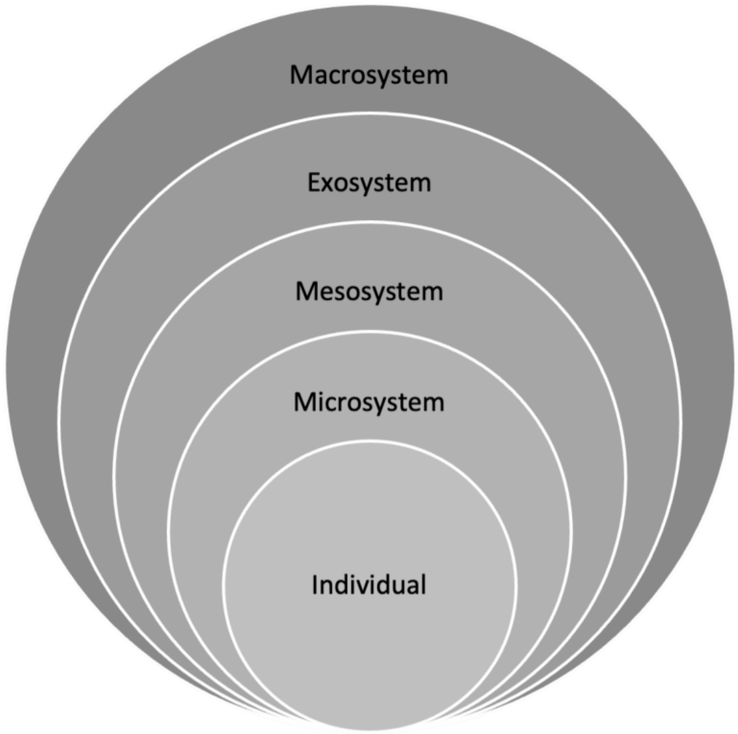

Figure 3. Ecological Systems Theory Layers

Bronfenbrenner's theory is particularly useful for understanding the multiple layers of influence on individual climate adaptation behaviour, showing how personal actions are shaped by broader societal systems. For climate adaptation to be effective, interventions need to work at multiple levels, ensuring that supportive structures are in place in households, communities and institutions (Bronfenbrenner, 1979).

However, the practical application of Ecological Systems Theory in climate adaptation faces several limitations. First, the theory assumes a level of coherence and interaction between system levels that may not exist in fragmented governance structures. Coordination between household, community, and policy levels is often lacking, especially in low-resource or politically unstable contexts. Additionally, the theory offers limited guidance on how to operationalise cross-level interventions or resolve conflicts between system demands—such as when national climate policies contradict local needs or values (Xue et al., 2024). Finally, its abstract structure may hinder direct translation into actionable programming unless complemented by more targeted behavioural tools.

2.3.2 behavioural Lever Framework (BLF)

The Behavioural Lever Framework (BLF) identifies strategic interventions to influence individual and collective behaviour to drive systemic change. The framework is structured around six key behavioural levers:

- **Material incentives**: Providing financial motivations, such as subsidies for renewable energy, encourages individuals to adopt sustainable practices (Bujold, Switzer, & Krupnik, 2020).
- **Regulation**: Establishing policies that require environmentally friendly practices, such as carbon emission caps or energy efficiency standards (Bujold et al., 2020).

- **Choice architecture:** Designing environments that make sustainable choices more accessible. For example, urban planning that encourages walking or cycling over car use (Bujold et al., 2020).
- **Social influences:** Using social norms and peer pressure to encourage pro-environmental behaviour. Public campaigns that emphasise shared responsibility for climate action can effectively shift societal norms (Rau, Williams, & Ruddell, 2022).
- **Emotional appeals:** The use of emotional messages to encourage behaviour change by appealing to values and ethical considerations. This can include framing climate action as a moral obligation to future generations (Jain, Sharma, & Sinha, 2023).
- **Information**: Providing individuals with data and insights about their environmental impact, such as real-time feedback on energy use, can encourage more sustainable behaviour (Bujold et al., 2020).

The BLF highlights the importance of designing interventions that not only motivate individual behaviour, but also change societal norms and institutional practices. In the context of climate adaptation, AI and digital technologies can enhance these efforts by personalising feedback and automating recommendations for energy-saving behaviour (Bujold et al., 2020; Jain et al., 2023). Despite its strategic utility, the BLF also presents limitations. The framework assumes that the levers function independently and universally, yet the effectiveness of each lever varies across cultural, socio-economic, and institutional contexts. For instance, material incentives may be effective in high-income contexts but less so where basic needs remain unmet. Moreover, emotional appeals and social influences can backfire if they trigger resistance, anxiety, or climate fatigue, especially among vulnerable populations (Rau et al., 2022). The BLF also pays limited attention to structural inequities, potentially reinforcing individual responsibility narratives without addressing systemic barriers. Integrating equity-based considerations remains an area requiring further development.

Table 1. behavioural Lever Framework (BLF) Table

Lever	Description
Material Incentives	Financial motivations like subsidies for renewable energy
Regulation	Policies that enforce eco-friendly practices
Choice Architecture	Structuring environments to promote sustainable choices
Social Influences	Using peer pressure and social norms to encourage behaviour
Emotional Appeals	Encouraging change through values and ethical considerations
Information	Providing data and insights to guide behaviour

2.3.3 Socio-Ecological Model (SEM)

The Socio-Ecological Model (SEM) builds on ecological systems theories by highlighting the dynamic interplay between individual behaviour and broader societal influences. The SEM operates at several levels:

- **The individual:** Knowledge, attitudes and skills related to climate adaptation. At this level, individuals' understanding of climate risks and ability to adopt sustainable practices are key (El Kirat, Smith, & Borrego, 2024).
- **Interpersonal:** Social relationships that support or hinder climate-smart behaviour. For example, family, friends and local leaders can significantly influence an individual's climate actions (El Kirat et al., 2024).
- **Community:** The role of local institutions, such as schools and municipalities, in providing resources and initiatives that encourage sustainable behaviour (Linardos et al., 2022).
- **Organisational:** Policies and practices within organisations that promote climate adaptation, such as businesses adopting green energy practices or local governments implementing climate education programs (Linardos et al., 2022).
- **Policy**: The national and international frameworks that set the stage for large-scale climate adaptation efforts. This level includes government policies such as carbon pricing or climate resilience strategies (El Kirat et al., 2024).

Figure 4. Socio-Ecological Model (SEM) Diagram

The SEM illustrates how climate adaptation requires coordinated efforts across multiple levels of society, from individual actions to global policy initiatives. AI technologies can enhance the effectiveness of the SEM by providing insights across these levels, enabling more comprehensive climate adaptation strategies. For example, AI can predict future climate risks and guide infrastructure investments at the policy level, while providing personalised advice on sustainable practices to individuals (Jain et al., 2023; Linardos et al., 2022). The SEM provides a comprehensive view of multi-level influences, but several challenges arise when applying it to climate adaptation in practice. One key limitation is the model's complexity, which can make it difficult to prioritise intervention levels or identify causal mechanisms. The broad scope may lead to diffuse strategies that lack focus or measurable impact. Additionally, the SEM often presumes the existence of enabling institutions and governance structures at each level. In many regions, particularly those facing governance deficits or resource scarcity, such structures may be weak or absent, undermining implementation. Moreover, the model does not sufficiently address how power asymmetries and political interests can shape or constrain climate adaptation efforts at institutional and policy levels (Linardos et al., 2022).

2.3.4 Sustainability Transitions

Sustainability transitions involve systemic changes in socio-technical systems that are necessary to achieve long-term environmental sustainability. These transitions involve changes in technologies, markets, policies, infrastructure and consumer behaviour, all aimed at reducing environmental impacts and increasing resilience to climate change (Geels, 2011). Sustainability transitions are intentional and require active collaboration between governments, business and civil society, in contrast to historical transitions driven by market forces alone (Smith et al., 2005).

Artificial intelligence (AI) has a critical role to play in facilitating the sustainability transition by improving decision-making, optimising resource use and increasing efficiency in key sectors. In energy, AI helps balance supply and demand in renewable energy grids, enabling better integration of solar and wind power and reducing reliance on fossil fuels (Haefner et al., 2021). In agriculture, AI-driven precision farming optimises the use of water, fertilisers and pesticides, reducing environmental damage while increasing productivity (Balogun et al., 2020). Similarly, AI applications in urban planning, such as smart city initiatives, improve traffic management, waste reduction, and energy efficiency, all of which contribute to more sustainable urban environments (Allam & Dhunny, 2019).

Enabling Sustainability Transitions: Aligning AI Innovation with Strong Governance and Policy Frameworks: Transition management, as described by Loorbach (2010), emphasises strategic planning, stakeholder engagement and iterative learning to steer socio-technical systems towards sustainability. Policies that promote sustainability, such as carbon pricing and renewable energy incentives, help to align market behaviour with environmental goals. However, these policies must also address social equity to ensure that the benefits of sustainability transitions are distributed equitably across society (Mikulewicz et al., 2023). AI can support policymakers by modelling the impacts of different scenarios, helping to improve decision making and policy design (Weyant, 2017).

Shaping Sustainability Transitions: How AI Not Only Optimises Systems but Also Influences Consumer Behaviour: AI-powered platforms provide personalised feedback on an individual's environmental impact, nudging them towards more sustainable choices. For example, AI tools track personal carbon footprints and suggest actions to reduce them, making sustainability more accessible to consumers (Ferreira et al., 2020). Platforms that promote sustainable consumption patterns, such as those that minimise food waste, use AI to efficiently match supply and demand, reducing waste and encouraging environmentally friendly behaviours (Cardoso et al., 2019).

Despite its potential, the use of AI in sustainability transitions poses challenges, particularly with regard to its environmental impact. AI systems, especially those involving data centres, consume significant amounts of energy and contribute to greenhouse gas emissions (Malmodin & Lundén, 2018). Therefore, it is crucial to ensure that the environmental benefits of AI outweigh its costs through the development of energy-efficient technologies. Furthermore, AI systems can reinforce social inequalities if they are not designed with inclusivity in mind, as algorithms trained on biased data can perpetuate inequalities (Crawford, 2021).

In conclusion, AI has enormous potential to drive sustainability transitions by optimising systems, influencing behaviour and informing policy decisions. However, its success depends on robust governance, equitable policies, and minimising its own environmental footprint. By aligning AI innovations with broader sustainability goals, societies can accelerate the transition to a more sustainable and climate-resilient future.

2.3.5 System Innovation and Socio-Technical Systems

System innovation plays a crucial role in addressing the challenges of climate change by integrating both technological advances and socio-cultural changes. The concept of system innovation refers to the transition from one socio-technical system to another, as defined by Geels (2005). In the context of climate adaptation, system transitions often occur through social tipping points (STPs), where a critical threshold is surpassed, leading to rapid and irreversible societal change. These tipping points are influenced by leverage points (LPs), which serve as intervention areas where small changes can lead to significant systemic shifts (NEUROCLIMA D2.1, 2024). Recognizing these points allows policymakers and communities to strategically design interventions that accelerate sustainable transformations. These transitions require significant changes not only in the technological framework, but also in the social, institutional and behavioural dimensions. Such changes are central to addressing sustainability challenges because they involve interactions between different elements such as technology, policy, markets and human behaviour. The interplay of these factors underlines the complexity of socio-technical systems and the need for comprehensive change to address environmental concerns.

Socio-technical systems are multifaceted configurations that include technological artefacts, regulatory frameworks, user practices and broader societal norms. These systems operate in a dynamic context where technology alone cannot drive sustainability transitions unless accompanied by cultural and behavioural changes (Geels, 2005; Vergragt & Jansen, 1993). This integration of technology with societal change is essential for promoting sustainable development, as clean technologies alone are not sufficient to mitigate environmental degradation without parallel changes in societal norms and practices.

The role of artificial intelligence (AI) in managing these complex socio-technical systems is increasingly recognised, especially in the area of climate adaptation. AI makes a significant contribution to real-time data analysis, which is essential for understanding and responding to climate challenges. For example, AI-driven systems can process vast amounts of environmental data and provide predictive insights that support decision-making at different levels, from local governance to global climate policy frameworks (Rolnick et al., 2023). These insights enable the integration of societal feedback into adaptation strategies, ensuring that responses to climate challenges are not only technically sound but also socially inclusive.

Furthermore, AI facilitates the coordination of diverse stakeholders, including policymakers, researchers and communities, by providing platforms that facilitate collaboration and data sharing (Haefner et al., 2021). Such platforms are essential for fostering the community-building processes that Geels (2011) identifies as critical for socio-technical transitions. By improving communication and providing tools for collective action, AI helps to bridge the gap between technological innovation and societal adoption.

In conclusion, system innovation in the context of socio-technical systems requires a comprehensive approach that integrates both technological advances and socio-cultural transformations. AI plays a central role in this process by enabling real-time data analysis, supporting decision-making and facilitating stakeholder collaboration, all of which are essential for effective climate adaptation and sustainability transitions.

2.4 Integration of AI in Climate Adaptation

While the preceding sections reviewed the theoretical foundations of behavioural and systemic change, this section explores how artificial intelligence (AI) operationalises and enhances these models within real-world climate adaptation strategies. The integration of artificial intelligence (AI) into climate adaptation is revolutionising the way we approach climate resilience, resource management and real-time adaptive systems. AI offers advanced tools to predict, manage and mitigate the effects of climate change, enabling more efficient and data-driven responses to environmental challenges. This section explores how AI is contributing to climate adaptation, focusing on three key areas: Predictive climate analysis, resource management and infrastructure planning, and real-time adaptation mechanisms.

2.4.1 AI in Predictive Climate Analytics

AI-driven predictive analytics has become an essential tool for forecasting climate risks and improving resilience. By analysing large datasets from sources such as satellite imagery, historical climate data and real-time environmental monitoring, AI algorithms can predict extreme weather events, rising sea levels and temperature fluctuations with increasing accuracy (Del Río Castro et al., 2021). This will allow governments and organisations to make informed decisions about how to protect vulnerable areas and populations.

For example, predictive models powered by AI can simulate future climate scenarios, allowing planners to anticipate the impact of natural disasters such as floods or droughts and take preventative action. Jain, Sharma, and Sinha (20-23) highlight the role of AI in identifying emerging climate threats early enough to mitigate their impact, which is critical for improving disaster preparedness and response strategies. AI tools can also help predict the spread of climate-sensitive diseases or agricultural disruptions, helping policymakers to allocate resources effectively (Hey et al., 2009).

A notable application of AI in predictive analytics is its use in early warning systems. These systems rely on machine learning models to predict the likelihood and intensity of natural disasters. For example, AI-powered systems have been used to provide early warnings of hurricanes and heat waves, significantly reducing the time needed to mobilise emergency responses (Tounsi & Temimi, 2023).

2.4.2 AI in Resource Management and Infrastructure Planning

AI has a transformative role to play in optimising the management of critical resources such as water, energy and agriculture - areas that are particularly vulnerable to climate change. AI systems help analyse and optimise resource use, ensuring that infrastructure is resilient and can adapt to changing environmental conditions.

In water management, AI can monitor and predict water availability, helping to allocate resources more efficiently during droughts or floods. Balagun et al. (2020) highlight the application of AI in urban centres for sustainable water management, where AI systems track water use patterns and recommend adjustments to prevent overconsumption during critical periods.

In the field of energy management, AI-driven systems are helping to optimise energy use and grids. Digital twins, which are AI-driven virtual models of real-world systems, are used to monitor and synchronise energy consumption in real time, improving energy efficiency and reducing carbon footprints (Onile et al., 2021). These AI systems not only predict energy demand, but also ensure that renewable energy sources such as solar and wind are effectively integrated into the grid, promoting sustainability.

In infrastructure planning, AI helps to design and maintain climate-resilient infrastructure. By analysing data from different sources, AI systems can simulate how infrastructure - such as bridges, roads and buildings - will perform under different climate scenarios. This allows city planners to make data-driven decisions that ensure long-term resilience to climate threats such as rising sea levels or increased storm frequency (Linardos, Papadopoulos, & Stylianides, 2022). AI also supports the development of green infrastructure, which can better absorb environmental shocks and reduce the overall carbon footprint of cities (World Economic Forum & PwC, 2021).

2.4.3 AI in Real-time Adaptation Mechanisms

AI's ability to facilitate real-time adaptation is critical to responding to the unpredictable nature of climate change. By integrating AI with the Internet of Things (IoT), real-time monitoring systems can dynamically adjust infrastructure operations, resource allocation, and disaster response protocols based on current conditions.

AI-based real-time adaptation mechanisms are particularly effective in managing energy grids, water systems and urban infrastructure. For example, AI-integrated smart grids can automatically adjust energy distribution to balance supply and demand, reducing strain on the grid during peak usage periods (Bujold et al., 2020). Similarly, AI-driven systems monitor urban water networks to detect leaks and optimise water distribution during periods of scarcity, ensuring efficient water use (Balagun et al., 2020).

In agriculture, AI is being used to dynamically adjust irrigation systems based on real-time soil moisture data, weather conditions and crop needs, improving water efficiency and crop yields (Rolnick et al., 2023). These systems not only help farmers adapt to changing climate conditions, but also promote sustainable agricultural practices by minimising resource waste.

In addition, AI plays a crucial role in disaster response by providing real-time data to emergency responders. Machine learning algorithms analyse data from sensors, drones and satellites to map disaster-affected areas and predict the movement of natural disasters such as floods or wildfires, enabling faster and more effective responses (Jain et al., 2023).

2.4.4 Challenges and Limitations of AI in Climate Adaptation

Despite the immense potential of artificial intelligence (AI) to support climate adaptation efforts, several challenges and limitations need to be addressed to ensure its effective and equitable implementation.

First, a key issue revolves around privacy concerns. AI systems often require large amounts of data, including both environmental and personal information, to function optimally. This poses significant privacy challenges, as the collection and processing of sensitive data, particularly in the context of individual behaviour and health, can lead to unintended privacy violations or misuse of information (Cowls et al., 2023). Ensuring that AI systems comply with strict data protection regulations, such as the General Data Protection Regulation (GDPR), is essential to maintain public trust and prevent the exploitation of personal information.

Second, another pressing challenge is the high energy consumption associated with AI technologies. AI models, especially those that require significant computational power such as deep learning and machine learning algorithms, contribute to a significant carbon footprint (Crawford, 2021). The paradox here is that while AI can help optimise systems for climate adaptation and reduce emissions, its own operational processes, particularly in data centres, can negate these environmental benefits. As noted by Malmodin and Lundén (2018), AI technologies accounted for 1.4% of global greenhouse gas emissions in 2015, a figure that is likely to increase as AI use grows. Addressing this issue will require innovations in energy-efficient computing and a move towards greener AI infrastructure, such as the use of renewable energy in data centres (Cowls et al., 2023).

Third, ethical considerations also play a central role in the limitations of AI for climate adaptation. Biases in AI algorithms can exacerbate existing inequalities and lead to decisions that marginalise vulnerable communities. For example, AI systems may inadvertently prioritise the needs of wealthier regions or communities with greater access to technology and data, further disadvantaging underserved populations (Dwivedi et al., 2022). This can perpetuate social and environmental inequities, which contradicts the goals of equitable climate adaptation. Ensuring fairness and transparency in AI decision-making processes is therefore crucial. Incorporating ethical AI frameworks and practices, such as Explainable AI (XAI), can help address these biases by making AI decisions more understandable and accountable to all stakeholders (Rolnick et al., 2023).

Beyond these discrete challenges, it is important to consider the broader trade-offs and unintended consequences that may arise from AI-driven climate adaptation. One such trade-off lies in the increasing reliance on automated systems and predictive models, which, while efficient, can lead to diminished human agency or a reduced role for community-led decision-making. Overreliance on algorithmic solutions may promote technocratic governance structures that prioritise computational efficiency over democratic participation, especially when decisions are made based on opaque models. Moreover, interventions optimised through AI may favour short-term, measurable gains—such as immediate efficiency improvements—while neglecting longer-term social or ecological impacts that are harder to quantify. Another unintended consequence concerns adaptive path dependency: once infrastructure and policy systems become deeply integrated with specific AI tools, it becomes difficult to revise or reorient these systems in response to emerging needs or social concerns. These trade-offs must be acknowledged and balanced through participatory governance, transparency, and continuous monitoring of AI impacts.

In conclusion, while AI offers promising solutions for climate adaptation, its deployment must overcome complex challenges related to data privacy, energy consumption, and ethical biases. Overcoming these limitations will require a multifaceted approach that includes stronger data governance, innovations in sustainable AI infrastructure, and ethical safeguards to ensure that AI contributes to an inclusive and sustainable future.

2.5. EU policy frameworks for adaptation to climate change and strategic communications

The European Union has adopted an increasingly integrated and strategic approach to adaptation to climate change, positioning it as a central component of its environmental and economic agenda. The updated EU Strategy on Adaptation to Climate Change[2], published in 2021, is one of the main pillars of the European Green Deal[3]. It sets a clear goal: to make all EU Member States climate resilient by 2050. This strategy promotes a smarter, faster, and more systemic method of adaptation. “Smarter” adaptation focuses on improving access to climate risk data and knowledge. Key platforms such as Climate-ADAPT[4] and the Risk Data Hub[5] provide reliable information to local authorities, helping them understand local vulnerabilities and plan tailored interventions. These tools are designed to support evidence-based decision-making and strengthen local capacity to act proactively.

The strategy also promotes “faster” adaptation, aiming to reduce delays in the implementation of tested solutions. Ensuring water security and reducing protection gaps are essential elements, given their importance to public health, economic activity, and biodiversity. Systemic adaptation means embedding resilience into wider EU policy domains, such as cohesion funds, biodiversity protection, and the Common Agricultural Policy[6]. By integrating adaptation into broader policy mechanisms, the EU ensures that responses to climate risks are not isolated but contribute to a cohesive, long-term development model. However, despite the sophistication of the strategy, significant disparities remain in how Member States report on their adaptation efforts. In many cases, national reporting lacks uniformity and does not use common indicators, making it difficult to assess collective progress or draw meaningful comparisons. This inconsistency reduces the transparency and accountability of adaptation actions. To address this, there is a need to standardise reporting methods and introduce stronger monitoring frameworks.

In parallel, the EU has launched the Mission on Adaptation to Climate Change under the Horizon Europe programme. This initiative seeks to support at least 150 European regions and communities in becoming climate resilient by 2030. Its approach begins with local participation and ends with systemic transformation. The Mission promotes co-creation, encouraging local authorities, researchers, and civil society to work together to design and test innovative pathways to resilience. These are not abstract concepts but actionable plans that can be tailored to local needs and challenges. The Mission’s structure also emphasises financial and technical support. With funding of approximately €1 billion from Horizon Europe and the potential to attract further public and private investments, the Mission provides essential resources to scale up local innovation. It does not simply aim to address immediate climate risks; it seeks to build lasting, adaptable systems that can withstand future challenges. The Mission is also closely aligned with the broader 2021 Adaptation Strategy, ensuring that actions at the regional and local levels feed into a coordinated EU-wide vision. In doing so, it recognises the importance of context-sensitive planning, local knowledge, and inclusive processes.

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[2] https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en

[3] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

[4] https://climate-adapt.eea.europa.eu/en

[5] https://drmkc.jrc.ec.europa.eu/risk-data-hub#/

[6] https://agriculture.ec.europa.eu/common-agricultural-policy_en#:~:text=The%20common%20agricultural%20policy%20(CAP,and%20keeps%20rural%20areas%20vibrant.

To ensure meaningful transformation, behavioural and systemic changes in policy implementation and reporting are also necessary. Although Regulation (EU) 2018/1999[7] requires Member States to report on their adaptation plans, most current submissions remain descriptive and lack measurable, comparable indicators. This limits the EU's ability to track adaptation outcomes and to refine strategies based on evidence. In addition to technical shortcomings, limited public awareness and weak engagement at the local level further slow progress. A 2023 survey of 400 municipalities revealed that many local governments are unaware of key EU adaptation tools, such as Climate-ADAPT or the Copernicus system. Many have not yet developed local adaptation plans. This reflects a broader challenge: adaptation is often seen as an abstract, top-down process. To change this, the EU promotes the use of citizen science, community-based monitoring, and participatory planning. Such approaches not only improve the relevance of adaptation actions but also help build public trust. Strengthening the links between national and local authorities is also essential. Clearer coordination structures and better alignment of resources can ensure that regional and local efforts support national priorities and that good practices can be shared more effectively. However, it is also important to acknowledge the growing societal and political resistance to certain aspects of EU green policy. Recent years have seen increased pushback from stakeholders concerned about economic burdens, social equity, and the pace of regulatory changes. This sentiment, particularly evident in debates over agricultural reforms and climate mandates, signals a need for more inclusive and context-sensitive communication. Public acceptance cannot be taken for granted, especially when digital tools and AI-driven interventions are perceived as top-down or opaque. Addressing this resistance directly—by involving communities early, improving transparency, and adapting strategies to local values—can help build trust and ensure the long-term success of adaptation initiatives.

Digitalisation and artificial intelligence (AI) play a growing role in these efforts. The EU uses digital platforms and AI tools to gather, analyse, and visualise climate data. These tools help policymakers anticipate climate risks, understand behavioural patterns, and adjust interventions in real time. Platforms like Climate-ADAPT serve as central hubs, connecting scientific insights with policy planning and public outreach. The integration of these technologies is not limited to data collection. AI is increasingly used to model complex climate scenarios, assess vulnerabilities, and explore adaptive options under different conditions. At the same time, digital tools offer new opportunities for public engagement. Interactive platforms, mobile applications, and virtual consultations enable citizens to contribute their views and experiences. This contributes to more democratic and inclusive adaptation planning.

However, gaps remain. Many climate policies do not fully address social inequalities. Vulnerable groups—such as people with disabilities, elderly populations, and economically marginalised communities—are often left out of decision-making processes. In some cases, adaptation policies can even reinforce existing disparities if not carefully designed. The European Commission recognises these risks and encourages the integration of social equity considerations into the design, funding, and monitoring of adaptation projects. This includes targeted outreach, disaggregated data collection, and the development of inclusive methodologies.

Overall, the EU's adaptation framework is evolving. It combines policy ambition, local action, financial tools, and digital innovation. The challenge now is to bridge the remaining implementation gaps, enhance collaboration across governance levels, and ensure that adaptation policies are effective, inclusive, and grounded in local realities. In this evolving landscape, strategic communication, citizen participation, and

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999

digital tools will continue to play an essential role. The EU's approach to adaptation is no longer simply about protection from climate risks. It is about transforming systems, empowering communities, and reshaping how resilience is built across regions and societies.

2.5.1 In the Framework of a Conceptual Model for Behavioural and Systemic Change for Climate Change Adaptation: **What We Have Learned So Far from European Projects**

Recent European projects have provided valuable insights into how behavioural and systemic change can support climate change adaptation. These experiences show that effective adaptation depends not only on technical capacity but also on how people, institutions, and systems interact.

The CLIMATEFIT project[8] identified key barriers in adaptation finance. Public authorities often struggle to access and manage diverse funding sources. Financial and investment entities remain hesitant due to unclear returns, limited data, and low awareness of nature-based solutions. The project found that readiness to invest increases when actors engage in structured dialogue, share information, and co-develop strategies. It also showed that behavioural factors—such as trust, perceived risk, and institutional complexity—play a central role in shaping financing decisions.

In the MountResilience project[9],systemic approaches were used to help regions create their own transformation paths. The project worked with mountain communities using participatory methods and a socio-technical-ecological framework. By including local councils and stakeholders from different sectors, it enabled each region to define practical actions suited to its needs. These actions were supported by scientific models, decision-making tools, and adaptation catalogues. The project confirmed that lasting change requires local ownership, strong coordination, and alignment between values, institutions, and technologies.

The PRO-CLIMATE project[10] developed a behavioural change framework using a combination of agent-based modelling, motivation–opportunity–ability theory, and institutional analysis. It showed that behavioural adaptation is influenced not only by access to information, but also by social norms, emotional drivers, and group dynamics. The project explored how change spreads through communities and institutions, especially when supported by aligned goals, shared values, and trust in the process. Behaviour is shaped by institutions, and institutional change, in turn, depends on people's willingness to engage.

Projects such as MountResilience and MIRACA[11] emphasised that nature-based solutions must be socially embedded. While many of these solutions—like afforestation, green infrastructure, and coastal protection—are technically effective, they only succeed when supported by public understanding and long-term governance. MIRACA, which focused on critical infrastructure, highlighted that most adaptation options are still designed for single hazards, with limited consideration of compound risks or cascading

[8] https://climatefit-heu.eu/
[9] https://mountresilience.eu/
[10] https://pro-climate.eu/
[11] https://miraca-project.eu/

effects. This points to the need for more integrated planning that links physical measures with behavioural and policy dimensions.

The PIISA project[12] analysed climate insurance systems in Europe and found significant gaps in protection, especially for vulnerable sectors and regions. Many people are either not covered or underinsured. Barriers include affordability, low trust, weak risk awareness, and complex administrative frameworks. Innovative models such as parametric insurance, insurance of ecosystem services, and public–private partnerships have potential but are not yet widely used. The project stressed the importance of behavioural insights in designing insurance schemes that are not only technically sound but also socially acceptable.

Across all these projects, a common message emerges. Effective adaptation depends on the interaction between systems and behaviours. It requires strategies that recognise the complexity of social, ecological, and institutional contexts. Interventions should be designed with the people they affect, using models and methods that reflect real-world conditions. Change is more likely to be sustained when it is co-created, locally relevant, and supported by policies that align short-term actions with long-term goals. European research has shown that building climate resilience is possible when adaptation is understood as both a behavioural and a systemic process.

2.6 Conclusion

This review has brought together theories, and frameworks insights to support a deeper understanding of behavioural and systemic change in climate adaptation. The integration of psychological models, institutional approaches, and digital technologies offers a solid foundation for designing strategies that are both people-centred and system-aware. Yet, beyond theoretical depth, the value of these models lies in their practical relevance.

One of the main conclusions is that change cannot be isolated at either the individual or structural level. Behavioural intentions need enabling environments. Equally, no policy or system reform can succeed without public engagement. Efforts to adapt must move between personal decisions, community action, institutional design, and broader governance structures. A model that connects these levels is more likely to generate realistic and lasting outcomes.

Artificial intelligence emerges as a promising tool for strengthening these links. It helps translate behavioural insights into adaptive systems, informs decision-makers with real-time data, and creates feedback loops that support learning and flexibility. However, the use of AI must be approached carefully. Its benefits depend on how it is governed, what values it reflects, and how accessible it is to all groups. Climate adaptation, to be fair and inclusive, must remain alert to inequalities that technology can reinforce if left unchecked.

A second important insight is the need for context-sensitive design. Models and strategies must be tailored to local realities. Behavioural drivers differ across communities. Institutional capacities vary. Climate risks take diverse forms. Projects like MountResilience and PIISA show that successful interventions start by listening to the people affected and aligning technical solutions with social priorities. Similarly, the EU's

[12] https://piisa-project.eu/

Funded by the European Union

Mission on Adaptation supports regions in building their own resilience pathways, grounded in local knowledge and supported by shared tools.

A third lesson concerns the value of cross-sector collaboration. Adaptation is not a task for environmental authorities alone. It involves education, health, urban planning, finance, civil protection, and culture. Behavioural and systemic change takes place across boundaries. This makes coordination essential. It also calls for clear and open communication. The language of adaptation must be understandable, inclusive, and focused on action.

As climate impacts become more frequent and severe, the challenge is not only to respond, but to shape change in ways that are just, meaningful, and sustainable. The NEUROCLIMA framework builds on this understanding.

3. Framework for behavioural and Systemic Change

3.1 Overview of Key Components

Integrating monitoring mechanisms, addressing citizens' needs and managing the dynamics of behaviour change are essential aspects of promoting citizen engagement in climate change adaptation. This section outlines the critical components of the conceptual framework to achieve effective and sustainable engagement.

3.1.1 Monitoring Mechanisms for Citizen Engagement

Monitoring mechanisms play a crucial role in evaluating the effectiveness of citizen engagement in climate change adaptation. Effective monitoring ensures that engagement strategies are responsive to citizens' needs and actions, and provides real-time feedback to improve outcomes. Several models emphasise different aspects of monitoring citizen engagement.

Arnstein's Ladder of Citizen Participation (1969) provides a basic model for assessing levels of participation, from tokenism to full citizen control (Cattino & Reckien, 2021). However, more adaptive and technologically integrated monitoring tools are needed to support dynamic citizen participation in climate change adaptation. AI-driven platforms are increasingly being used to monitor citizen engagement by analysing social media, public sentiment and participation in climate programmes. This monitoring provides data-driven insights that enable policymakers to adjust interventions in real time (Tounsi & Temimi, 2023).

Participatory mapping and citizen science are also effective mechanisms for engaging citizens in monitoring climate impacts. Projects such as Climate Watch enable citizens to collect and report data on environmental changes, which is then analysed and used to inform local adaptation planning (Irwin, 2021). This bottom-up approach not only promotes engagement, but also improves the accuracy of monitoring climate impacts (IFAD, 2009).

The incorporation of digital technologies, such as AI, enables more sophisticated data collection and monitoring mechanisms that provide personalised feedback to users, fostering sustained engagement. For example, real-time feedback mechanisms through AI-enabled platforms provide insights into energy use, water conservation and waste reduction (Rau et al., 2022). These tools allow users to track their environmental impact and receive recommendations for improvement, promoting ongoing engagement in climate adaptation efforts (Rolnick et al., 2023).

The monitoring mechanisms described here reflect key principles from the Theory of Planned Behaviour (TPB) and the Norm Activation Model (NAM). For instance, AI-enabled feedback loops support the TPB construct of ‘perceived behavioural control’ by enhancing individuals’ sense of agency through real-time data. Similarly, NAM is reflected in the use of participatory monitoring tools that raise awareness of environmental consequences and reinforce moral responsibility. When individuals see the environmental impact of their actions visualised, personal norms are more likely to be activated, supporting sustained engagement.

3.1.2 Pain Points, Needs, and Expectations of Citizens

Addressing citizens' pain points, needs and expectations is crucial to fostering meaningful engagement in climate adaptation. Research highlights the importance of understanding citizens' needs and removing barriers that may hinder participation. Findings from the NEUROCLIMA ethnographic review (D2.1, 2024) indicate that pain points in climate adaptation often stem from psychological (e.g., lack of perceived impact), economic (e.g., cost barriers), and institutional (e.g., policy inconsistencies) factors. These obstacles discourage behavioural shifts even when awareness is high. AI-driven monitoring and participatory governance can mitigate these issues by offering personalised feedback, targeted incentives, and increased transparency in decision-making.

One of the main pain points for citizens in climate adaptation is the complexity of information and lack of clarity in climate policies (Ferreira et al., 2020). Many citizens struggle to understand how their actions contribute to broader climate goals, leading to disengagement. Digital platforms powered by AI can help simplify and tailor policy information to individuals based on their location or specific concerns (Rolnick et al., 2023). This personalisation makes information more accessible and encourages citizens to take action by reducing the cognitive load required to engage with complex climate issues (Hey et al., 2009).

Self-Determination Theory (SDT) is particularly relevant in addressing citizens’ expectations for autonomy, competence, and relatedness. AI-powered platforms that provide personalised content and recognise individual contributions enhance perceived competence and autonomy, which are central to fostering intrinsic motivation. When citizens feel connected to broader adaptation efforts and see their input valued, their sense of relatedness is also strengthened. In this way, SDT helps explain why citizens remain engaged when their psychological needs are met through transparent and tailored engagement mechanisms.

In addition, citizens expect transparency and accountability in climate decision-making. Studies show that citizens are more likely to engage when they feel their input is valued and when decision-making processes are transparent (Hügel & Davies, 2020). AI technologies can facilitate more transparent decision-making by making data and analysis accessible to the public, allowing citizens to see how their input is being used (Dwivedi et al., 2022).

AI-driven citizen engagement platforms also offer opportunities to address the needs of marginalised communities, which are often underrepresented in climate adaptation efforts. These platforms can be designed to be inclusive, ensuring that all citizens have access to engagement tools, regardless of their socio-economic status or digital literacy levels (Cattino & Reckien, 2021). By addressing the diverse needs and expectations of citizens, engagement strategies can be more equitable and effective (Satterthwaite et al., 2024).

3.1.3 Scaling and Dynamics of behavioural Change

Scaling up and managing the dynamics of behaviour change is a critical component of climate adaptation strategies. Behavioural change does not happen in isolation; it requires scaling across different sectors of society, and the dynamics involved are complex and multifaceted.

The process of scaling social innovations to achieve systemic impact involves three types of scaling: scaling out, scaling up, and scaling deep (Moore, Riddell, & Vocisano, 2015). Scaling out involves replicating successful initiatives to impact larger numbers of people, while scaling up involves embedding changes in policy and legislation to ensure that innovative approaches are institutionalised. Scaling deep targets cultural change, emphasising the long-term changes in values, beliefs and practices required for systemic change. A combination of these three types of scaling is essential to address climate challenges comprehensively (Lam et al., 2020).

AI technologies have an important role to play in scaling behavioural change by providing real-time feedback and data-driven interventions that encourage sustainable practices. For example, AI can be used to scale community-based interventions by analysing participation trends and identifying effective strategies to increase engagement (Balagun et al., 2020). In addition, AI-driven tools can scale deeply by encouraging long-term behavioural change through personalised feedback and gamification techniques (Cellina et al., 2019).

The dynamics of behaviour change are influenced by multiple factors, including social norms, emotional appeals, and material incentives (Bujold et al., 2020). AI-driven interventions can improve these dynamics by providing tailored recommendations based on an individual's specific behaviours and motivations. For example, AI can analyse an individual's energy consumption patterns and suggest personalised tips to reduce energy use, reinforce positive behaviours, and help individuals maintain sustainable habits over time —although such interventions must also guard against automation bias and path dependence, where users may over-rely on AI recommendations or become locked into suboptimal behavioural routines (Jain et al., 2023).

The Transtheoretical Model (TTM) offers a valuable framework for understanding how AI tools can support individuals at different stages of behavioural change—from raising awareness in the pre-contemplation stage to reinforcing habits during maintenance. For example, AI-driven gamification can motivate individuals in the preparation or action stages by offering structured prompts. Additionally, SDT complements these efforts by ensuring that behavioural change is not only externally reinforced but also internally sustained through motivation aligned with personal values. Scaling deep—through cultural shifts in values and norms—is also informed by the NAM, which highlights the importance of moral commitment and perceived responsibility as drivers of long-term transformation.

In conclusion, scaling and managing behavioural change requires a multifaceted approach that incorporates technological innovation, policy support and cultural change. AI technologies offer powerful tools to enhance these processes and ensure that behaviour change is sustained and effectively scaled across different levels of society.

3.2 Framework for Empowering Citizens and Policymakers

Effective adaptation to climate change requires a framework that empowers both citizens and policymakers to collaborate, understand complex data and make informed decisions. By integrating inclusive practices, leveraging AI-driven decision support systems, and promoting transparent policymaking, this framework aims to support both individual action and systemic change.

3.2.1 Inclusion of Public Institutions

The involvement of public institutions in climate change adaptation is a critical element in promoting systemic change. Institutions, including government agencies and public organisations, provide the necessary infrastructure, funding and regulatory frameworks that can enable broad citizen participation.
Public institutions, such as local governments, play a key role in promoting climate adaptation through participatory governance models. For example, deliberative democracy and co-production models allow citizens to work directly with institutions to develop locally relevant climate strategies. According to Cattino and Reckien (2021), these participatory models promote dialogue and help to create an inclusive decision-making process in which citizens' views and local knowledge are integrated into public policies. Knowledge co-production is particularly effective when applied in the context of vulnerable communities, enabling collaboration between scientists, policy makers and local communities to produce more robust and contextually relevant adaptation strategies (Norström et al., 2020).

Involving public institutions can also help bridge the gap between top-down policy approaches and the needs of local communities. Arnstein's Ladder of Citizen Participation (1969) illustrates how public institutions can move from mere consultation to partnership and full citizen control over climate adaptation efforts. This framework shows how empowering citizens at different levels of decision-making can lead to more ambitious climate policies and actions. In addition, ensuring the active involvement of local institutions fosters a shared sense of ownership and responsibility for climate adaptation strategies.

The involvement of public institutions in climate governance aligns closely with Ecological Systems Theory (EST), which emphasises the interaction of individuals with nested environmental systems. Local governments, as part of the mesosystem and exosystem, play a critical mediating role between personal behaviours and broader policy environments. Their ability to embed climate adaptation within education, community services, and infrastructure planning reinforces multi-level engagement, a key tenet of EST. Additionally, the Socio-Ecological Model (SEM) highlights the role of organisational and policy-level influences, suggesting that institutional participation is essential for embedding adaptive behaviours across societal layers.

3.2.2 Inclusive Policy Making and Deliberative Practices

Empowering citizens in climate adaptation requires not only technological solutions but also structured engagement strategies. According to NEUROCLIMA's stakeholder engagement framework, multi-level governance is essential for ensuring that AI-driven adaptation models align with local needs. Social tipping points, as identified in recent policy impact assessments, suggest that integrating citizen feedback mechanisms can accelerate the adoption of systemic adaptation measures.

Inclusive policy-making ensures that all sectors of society, including marginalised and vulnerable groups, have a voice in climate adaptation efforts. This approach is essential for achieving equity and justice in addressing climate risks. Policymakers need to adopt deliberative practices that promote transparency, accountability and inclusiveness in decision-making processes.

Deliberative practices, such as town hall meetings and public consultations, can provide platforms for a wide range of stakeholders to contribute to policy discussions. Willis et al. (2021) highlight that deliberative democracy can foster deeper engagement by including diverse voices in structured dialogues on climate policy. Citizens' assemblies, for example, have been successful in bridging the gap between public opinion and climate policymaking, producing actionable recommendations that reflect the concerns of both experts and ordinary citizens.

Inclusive policy-making also benefits from the integration of different knowledge systems, including traditional and indigenous knowledge. This inclusiveness strengthens the legitimacy and effectiveness of climate adaptation strategies by ensuring that policies are tailored to the specific challenges faced by different communities (Norström et al., 2020). Policymakers need to ensure that participatory governance is not tokenistic, but truly collaborative, so that the public has real influence over the outcomes of climate adaptation efforts.

The application of inclusive, deliberative policymaking is strongly supported by the Behavioural Lever Framework (BLF), which identifies 'social influence', 'information', and 'emotional appeals' as strategic tools for shaping behaviour. Deliberative processes such as citizens' assemblies and town halls act as real-world mechanisms that activate these levers by fostering shared norms, collective responsibility, and transparency. Moreover, the SEM underlines that policy-level interventions must be aligned with community- and individual-level realities. In this light, inclusive policy-making ensures that adaptation strategies are not only scientifically sound but also socially embedded and context-specific.

3.2.3 Decision-Support Systems and AI

Artificial intelligence (AI) and digital tools offer powerful opportunities to assist both citizens and policymakers in adapting to climate change. AI-based decision support systems can process large datasets, provide real-time insights and improve decision-making by identifying optimal climate resilience strategies.

AI-based decision support systems allow for the integration of predictive analytics that can forecast climate risks and inform adaptation strategies. For example, AI can analyse environmental data, such as temperature changes and sea level rise, to predict future climate scenarios and guide policymakers in infrastructure planning (Jain et al., 2023). These predictive tools are essential for proactive adaptation, helping governments anticipate risks and implement measures to mitigate potential damage.

In addition to forecasting, AI enables personalised feedback mechanisms that can empower citizens to monitor and reduce their environmental impact. Tools such as smart meters and AI-powered apps provide real-time data on energy consumption and water use, and offer personalised tips for adopting sustainable practices (Rau et al., 2022). These tools not only encourage individual behaviour change, but also facilitate collective action by enabling citizens to contribute to broader climate goals through data sharing and collaboration.

In addition, AI increases transparency in policymaking by providing accessible data and visualisations that are easy for the public to understand. AI systems can aggregate and interpret complex climate data, helping both citizens and policymakers make informed decisions. For example, AI-powered platforms can present real-time environmental updates and recommendations to help communities prepare for natural disasters or respond to climate-related emergencies (Rolnick et al., 2023). These decision support tools ensure that both policymakers and citizens are equipped with the knowledge and resources necessary for effective climate adaptation.

Decision-support systems and AI-enabled tools also reflect principles from both the BLF and SEM. The BLF offers a practical guide for designing these tools through levers such as 'information', 'choice architecture', and 'material incentives', which are often embedded in AI interfaces (e.g., dashboards, gamified apps, personalised rewards). At the same time, the SEM emphasises the need for alignment between individual, organisational, and policy levels—a structure mirrored in integrated AI platforms that connect citizen behaviour with institutional decision-making. These technologies operationalise multi-level models by translating complex data into actionable insights across all layers of the system.

3.3 Designing and Evaluating Civic Participation Models

Designing and evaluating models for citizen participation is essential for effective adaptation to climate change. Civic participation not only empowers citizens to contribute to climate action, but also fosters collective ownership of climate policies. By focusing on the co-production of knowledge and stakeholder alignment, this section explores key aspects of enhancing citizen engagement in climate policy.

3.3.1 Enhanced Civic Participation and Co-Production of Knowledge

One of the most effective models for enhancing citizen participation is the co-production of knowledge. This approach involves collaborative efforts between scientists, policy-makers and the public to generate knowledge that is both scientifically sound and contextually relevant. Co-production ensures that different types of expertise and knowledge systems are integrated into the decision-making process, thereby increasing the legitimacy and effectiveness of climate adaptation strategies.

According to Norström et al. (2020), co-production processes are iterative and involve different actors working together to produce knowledge that is directly applicable to local contexts. This model is particularly important in the context of climate change adaptation, where vulnerable communities often possess valuable traditional and indigenous knowledge that can complement scientific evidence. Knowledge co-production not only builds public trust in climate policies, but also improves the overall quality of research and decision-making by integrating local knowledge into broader climate resilience strategies.

Co-production models have been implemented in several climate adaptation initiatives. For example, participatory mapping and citizen science initiatives allow local communities to contribute data and insights that are directly used in the planning and implementation of adaptation strategies (IFAD, 2009). These models empower citizens by involving them in monitoring and assessing climate impacts, thus creating a sense of ownership and responsibility for climate action.

Furthermore, co-production of knowledge can help address gaps in climate literacy and public engagement, two significant barriers to effective climate action. By involving citizens in the knowledge creation process, this model fosters a deeper understanding of climate risks and the need for adaptation, thereby increasing civic participation at both local and national levels (Satterthwaite et al., 2024).

3.3.2 Aligning Stakeholders in Climate Policy Communication

Effective climate policy communication requires aligning the interests and perspectives of multiple stakeholders, including governments, local communities and non-governmental organisations. This alignment ensures that climate policies are both relevant and actionable, addressing the specific needs of different groups while promoting collective action.

Stakeholder alignment can be achieved through participatory governance models, such as deliberative democracy, which involve diverse voices in the policy-making process. Deliberative models provide platforms for structured dialogue that enable citizens to engage in meaningful discussions on climate policy. For example, citizens' assemblies have been used in several countries to bridge the gap between public opinion and policy-making, resulting in more ambitious and implementable climate policies (Willis et al., 2021).

Effective stakeholder communication also requires the use of AI and digital platforms to increase transparency and inclusivity in climate decision-making. AI-powered tools can facilitate communication by providing real-time data and visualisations that help stakeholders understand complex climate information. These platforms can be used to disseminate policy updates, engage citizens in real-time feedback loops, and facilitate knowledge sharing across different sectors (Rolnick et al., 2023).

In addition, AI can help align stakeholder interests by analysing public sentiment and identifying key influencers who can drive climate-related behaviour change within their communities. This approach ensures that climate communication strategies are both targeted and inclusive, encouraging broader participation in climate adaptation efforts.

In conclusion, the design and evaluation of citizen participation models is critical to promoting effective climate adaptation strategies. Enhanced citizen participation through co-production of knowledge and stakeholder alignment in climate policy communication ensures that climate policies are not only scientifically sound, but also socially relevant and actionable.

3.4. Conclusion

The framework presented illustrates a shift in how climate adaptation should be approached. Instead of viewing citizens as passive recipients of policy, it positions them as active participants in both the design and implementation of adaptation strategies. This perspective requires rethinking institutional roles, engagement methods, and the integration of digital tools, particularly artificial intelligence.

One key insight from this framework is that engagement is not an end in itself. It must be designed as a dynamic and evolving process. Monitoring mechanisms are essential, not only to evaluate participation levels but to understand the quality of engagement and the barriers that citizens face. Technologies that provide real-time feedback and personalised insights can support this process, but only when used in ways that reflect human needs and social context.

Another important observation concerns the complexity of behavioural change. Encouraging sustainable practices requires more than disseminating information or offering incentives. Behaviour is shaped by norms, values, emotions, and institutional environments. Efforts to scale behavioural change must reflect this complexity. Approaches that combine technological innovation with community-based knowledge and culturally sensitive communication are more likely to foster long-term transformation.

The framework also highlights the importance of inclusion and equity. Many climate adaptation initiatives unintentionally exclude the very communities most affected by climate risks. Factors such as digital access, institutional trust, and cultural recognition shape the ability of citizens to engage meaningfully. Designing accessible participation models and addressing specific obstacles faced by marginalised groups should not be treated as additional considerations—they are fundamental requirements for effective and just adaptation.

The role of public institutions emerges as central. Institutions are not only facilitators of policy but also mediators of social change. Their capacity to act as bridges between data, decisions, and community knowledge is essential. However, this depends on their willingness to adopt deliberative approaches, support co-creation, and engage in two-way communication. Institutional transparency and responsiveness remain crucial for sustaining public trust and participation.

While machine learning as a computational method is technically neutral, artificial intelligence systems are not inherently neutral tools. Their outputs are shaped by the data they are trained on, the objectives they are optimised for, and the socio-technical choices embedded in their design and deployment. Its effectiveness in supporting adaptive governance depends entirely on how it is designed, implemented, and governed by human actors. AI systems can amplify citizen voices, provide real-time insights, and personalise climate communication. Yet they also raise questions about data governance, algorithmic fairness, and accountability. The challenge lies in aligning technological innovation with democratic values. Ensuring that AI systems are understandable, transparent, and inclusive will determine whether they enhance or undermine citizen empowerment.

Another key dimension of the framework is the strategic use of knowledge co-production. Collaborative processes between citizens, scientists, and policymakers enrich both the legitimacy and relevance of adaptation strategies. Co-production is not only about collecting diverse perspectives. It is about shifting the role of knowledge itself—from something delivered to communities to something developed with them. This approach builds stronger social foundations for collective action and increases the effectiveness of interventions.

Lastly, the alignment of multiple stakeholders remains a structural necessity. Climate adaptation involves different interests, levels of authority, and forms of knowledge. Aligning these requires shared tools, inclusive language, and decision-making processes that prioritise both evidence and lived experience. AI platforms can support this alignment by visualising complex systems, identifying points of convergence, and facilitating dialogue—but only when embedded in inclusive governance models.

Taken together, these insights show that effective climate adaptation requires more than technical solutions. It demands a reconfiguration of relationships—between citizens and institutions, between knowledge and policy, and between individual behaviour and collective responsibility. The framework supports this reconfiguration by combining behavioural understanding, systemic approaches, and digital tools in a coherent and flexible model.

Rather than offering fixed solutions, it proposes a way of thinking and acting—grounded in participation, guided by evidence, and responsive to local realities. This orientation is essential not only for addressing the practical challenges of climate risk, but for fostering a more inclusive, adaptive, and resilient public sphere.

4. Technological Integration in Climate Adaptation

4.1 AI-driven Personalization and Nudging in Climate Action

Before exploring how AI can support climate action, it's important to recognise that these technologies also raise serious concerns. While they offer useful tools for encouraging sustainable behaviour, they can also affect people's privacy, limit personal choice, or be used in ways that feel too controlling. Public trust is essential, and recent criticism of top-down digital solutions—especially in climate policy—reminds us that AI must be used carefully, with fairness and transparency in mind.

The integration of artificial intelligence (AI) into climate adaptation efforts is revolutionising the way individuals and societies address environmental challenges. AI's ability to personalise interventions and provide targeted nudges has emerged as one of the most significant advances in promoting climate-smart behaviour and systemic change. AI-driven personalisation and nudging combine data analytics, behavioural science and real-time feedback to promote sustainable climate action by helping individuals and communities adopt greener behaviours. This section explores the different ways in which AI is being used in personalisation and nudging for climate adaptation.

AI-Driven Personalisation

Personalisation is a key component of AI's contribution to climate action. AI systems use real-time data to tailor interventions based on individual behaviours, preferences and needs, creating tailored experiences that encourage long-term behaviour change. AI can analyse patterns in an individual's energy use, waste production, water consumption, and even transportation habits to recommend small, actionable steps to reduce an individual's carbon footprint (Rau et al., 2022). This personalisation ensures that interventions are not only relevant, but also practical and achievable for the individual, increasing the likelihood of sustained engagement in climate-friendly practices.

One of the most important elements of personalisation is the ability of AI to process large datasets, including demographic, behavioural and geographic information, to create a comprehensive profile for each user. These profiles are then used to make tailored suggestions. For example, AI can recommend more energy-efficient appliances based on a household's consumption patterns, or suggest eco-friendly commuting options based on an individual's daily travel habits (Jain et al., 2023). The personalised feedback provided by AI has a significant impact on changing habits by providing contextual advice that fits seamlessly into a person's daily routine. At the same time, this kind of personalisation should be used responsibly. If the technology becomes too invasive or hard to understand, people might feel pushed into decisions without fully realising it. This could reduce trust, so it's important to keep AI systems open and respectful of users' choices.

AI-Powered Nudging

Nudging is another powerful tool used in behavioural change strategies, and AI has greatly enhanced the effectiveness of this technique. A nudge is a subtle request or suggestion that encourages people to make better decisions without restricting their choices or significantly changing their incentives (Thaler & Sunstein, 2008). AI uses behavioural data to predict when and how to nudge users towards climate-friendly actions, increasing the effectiveness of these interventions (Tounsi & Temimi, 2023).

For example, an AI system could monitor a household's energy consumption and, if consumption spikes above normal levels, send a real-time notification suggesting ways to reduce consumption, such as turning off lights or adjusting thermostat settings. Similarly, AI can nudge users towards more sustainable purchases by analysing their shopping patterns and recommending eco-friendly alternatives during online transactions. This form of nudging is particularly powerful in addressing the 'intention-behaviour gap', where individuals have the intention to act sustainably but fail to follow through due to a lack of motivation, knowledge or reminders (Rau et al., 2022). However, these same nudges can become problematic if people don't realise they are being influenced. Without clear explanations or options to opt out, this might feel manipulative, raising important questions about fairness and personal freedom.The integration of artificial intelligence (AI) into climate adaptation efforts is revolutionising the way individuals and societies address environmental challenges.

However, it is important to acknowledge that algorithmic nudging remains ethically controversial. Concerns include issues of manipulation, opacity, and the potential erosion of individual autonomy. The NEUROCLIMA *Legal and Ethical Issues Manual* (D1.7) (Mizsei, Bogucki, & Fischer, 2024) outlines that nudging must adhere to principles of transparency, respect for individual choice, and fairness, particularly when AI systems personalise interventions based on behavioural profiles. Algorithmic nudges must therefore be carefully designed to avoid coercion and should be complemented by ethical safeguards that ensure users remain informed and in control of their choices.

Dynamic Interventions and Context-Aware Feedback

AI-driven nudging systems can deliver dynamic and adaptive interventions, adjusting their frequency and content based on observed behavioural patterns. For instance, if a user consistently demonstrates climate-positive behaviours, the system may reduce the intensity of nudging to respect user autonomy—an approach that, while potentially supportive of long-term behavioural reinforcement, must be implemented with caution given ongoing ethical and regulatory debates, particularly within the EU context. Conversely, when users show signs of disengagement, the system can increase the frequency of nudges or change the nature of the suggestions to re-engage them (Rolnick et al., 2023).

In addition, AI systems can use location-based data to provide contextual feedback. For example, if a particular city is experiencing a heatwave, AI systems could inform residents of ways to reduce their energy consumption, such as using fans instead of air conditioning. Similarly, if the area is at risk of drought, AI could recommend water conservation strategies that are both timely and regionally relevant (Del Río Castro et al., 2021). This adaptability ensures that AI interventions are not only personalised to the individual, but also responsive to the broader environmental context in which they live.

The Role of AI in Gamification for Climate Action

Gamification is a method of applying gaming design elements to non-gaming contexts, and AI has a critical role to play in enhancing this strategy for climate action. Gamified experiences, such as energy-saving apps that track and reward users for reducing their consumption, are becoming increasingly popular. AI systems can make these experiences even more engaging by offering personalised challenges and rewards based on the user's behaviour. For example, users can receive points for reducing their water or energy consumption, and AI can adjust the difficulty of these challenges based on the user's progress, keeping them motivated (Cellina et al., 2019).

In addition, AI enables social influence through leaderboards and community challenges, where users can compare their progress with others in their community or network. This adds a competitive element and encourages users to strive for better environmental performance by using social influence and peer pressure (Tounsi & Temimi, 2023). Gamification, combined with AI-driven personalisation, creates a fun and engaging way for individuals to stay engaged in climate action.

Ethical Considerations and Challenges

While AI-driven personalisation and nudging offer numerous benefits, there are ethical concerns that need to be addressed. One of the most important issues is privacy. AI systems require large amounts of personal data to provide accurate recommendations and nudges, raising concerns about how this data is collected, stored and used. There is also the risk of manipulation, where nudges could be used to steer individuals towards behaviours that benefit businesses or governments rather than the environment (Dwivedi et al., 2022).

Another challenge is to ensure that AI systems are inclusive and equitable. If AI-driven interventions rely on technology that is inaccessible to certain populations (e.g., those without smartphones or internet access), they may exacerbate existing inequalities in climate adaptation. It is therefore crucial to design AI systems that are accessible to all individuals, regardless of socioeconomic status or geographic location (Rolnick et al., 2023).

AI-driven personalisation and nudging have the potential to revolutionise climate adaptation strategies by providing tailored, dynamic and context-aware interventions that encourage individuals to adopt more sustainable behaviours. By leveraging real-time data and behavioural insights, AI can provide timely and relevant feedback that helps bridge the gap between intention and action. However, as outlined in the NEUROCLIMA Legal and Ethical Issues Manual (Mizsei, Bogucki, & Fischer, 2024), ethical considerations such as data privacy, inclusivity, and transparency must be carefully addressed to ensure that AI applications in climate adaptation serve the public good in an equitable and accountable manner.

4.2 Gamification and Playful Learning Experiences for Climate Engagement

The use of gamification and playful learning experiences in technological solutions in climate action has gained considerable attention for its ability to engage individuals emotionally, cognitively and behaviourally. This approach transforms abstract climate challenges into relatable and interactive experiences, making the learning process more enjoyable while fostering long-term commitment to environmental sustainability. Gamification combines game mechanics with real-world activities to motivate individuals to take climate-friendly actions, while playful learning experiences harness creativity to enhance emotional and cognitive engagement.

4.2.1 Gamified Approaches for Educational Interventions

Gamified tools supported by digital technologies can make climate education more effective and engaging. By adding elements such as points, challenges, progress tracking, or rewards into learning platforms, these tools help users better understand environmental issues and stay motivated.

Artificial intelligence strengthens this process by adapting the experience to each user. It can track progress, analyse behaviour, and offer feedback based on actual performance (Rau et al., 2022; Jain et al., 2023). When the content becomes too easy or too difficult, the system adjusts automatically. This supports learning that fits the user's pace and keeps interest high.

AI also helps simplify complex information. Visual dashboards or mobile applications show how daily actions—like saving water or reducing energy use—can have a real impact. When people see the results of their efforts in clear and direct ways, they are more likely to stay involved.

In addition, AI allows gamified platforms to include social features. These might include sharing achievements, comparing progress, or completing tasks together. Such interaction helps build a sense of community and reinforces learning through group support (Cellina et al., 2019). These tools can also connect with physical systems, like sensors in homes or schools, so users receive feedback based on their actual behaviour.

Gamified educational tools are more than just interactive games. When combined with adaptive technologies, they become flexible systems that support long-term behavioural change. They also provide useful data to policymakers and educators on what works best for different groups.

By focusing on user experience, feedback, and motivation, gamified systems supported by AI can help make climate learning more personal, inclusive, and scalable. This approach brings together behavioural insights and technological capacity, creating tools that support both education and action.

4.2.2 Emotional and Cognitive Engagement via the Creative Arts

The creative arts have proven to be a powerful medium for fostering emotional and cognitive engagement with climate action. Artistic expressions such as music, visual arts, theatre and multimedia installations can evoke deep emotional responses, making abstract climate issues more tangible and relatable. Creative arts not only raise awareness, but also inspire action by connecting people to climate issues on a personal, emotional level (Lustig et al., 2025).

Climate-related art projects often use storytelling to create narratives that humanise the consequences of climate change and help individuals visualise the future impacts of environmental degradation (Rau et al., 2022). Emotional engagement is crucial because it motivates individuals to act, especially if they feel a personal connection to the climate crisis. For example, community-driven art projects that depict local environmental challenges can resonate more deeply with participants, encouraging them to become advocates for change in their communities (Cattino & Reckien, 2021).

The creative arts also facilitate cognitive engagement by encouraging participants to explore complex climate concepts in an imaginative and accessible way. For example, educational theatre performances about climate resilience can help audiences understand scientific data by presenting it in a dramatic, narrative-driven format. Similarly, interactive exhibits that allow users to visualise the effects of global warming on their local ecosystems can make the data more relatable and easier to understand (Ferreira et al., 2020).

The creative arts can also be used to foster collaborative learning experiences. Projects that involve participants in creating art related to climate change often encourage dialogue and co-creation, deepening understanding through group reflection. Such collective artistic endeavours can also help bridge gaps in climate literacy by making information more accessible to diverse audiences, including those with lower levels of formal education (Rolnick et al., 2023). These approaches promote inclusivity and ensure that climate action messages reach a wide demographic, increasing the overall impact of climate education efforts.

In conclusion, the integration of gamification and the creative arts into climate action strategies provides an innovative way to engage individuals on both an emotional and cognitive level. By making climate education interactive, immersive and emotionally engaging, these approaches increase the likelihood of long-term behaviour change and foster a deeper commitment to environmental sustainability.

4.3 AI in Feedback and Monitoring Mechanisms

AI has emerged as a powerful tool for improving feedback and monitoring mechanisms in climate adaptation. By automating the collection, processing and analysis of vast amounts of data, AI technologies provide real-time feedback and personalised insights, enabling more efficient monitoring of individual and collective behaviours related to climate action. AI-driven feedback and monitoring mechanisms are particularly important for assessing the effectiveness of interventions and ensuring that climate adaptation strategies are responsive to changing environmental conditions and societal needs.

AI-Powered Feedback Mechanisms

One of the key contributions of AI to climate adaptation lies in its capacity to generate real-time, data-driven feedback loops that support both behavioural change and systemic policy adjustments. While earlier sections have discussed individual-level feedback, AI also facilitates broader insights by analysing aggregated behavioural patterns across communities and regions. These insights allow for adaptive governance: enabling policymakers to evaluate the responsiveness of different populations to climate interventions, identify disparities in engagement, and redirect resources more effectively (Del Río Castro et al., 2021).

Beyond monitoring and recommendations, AI-based feedback systems also play a role in reinforcing behavioural change over time. When designed transparently and ethically, such systems can support user autonomy and long-term motivation—provided that feedback remains actionable, context-sensitive, and free from manipulation (Mizsei, Bogucki, & Fischer, 2024). Importantly, these systems should be evaluated not only on their technical performance but also on their social outcomes, such as inclusivity and fairness in how different user groups are engaged (Rau et al., 2022).

Monitoring Mechanisms in Climate Adaptation

Monitoring mechanisms are crucial for tracking the progress of climate adaptation efforts and ensuring that strategies are effective at both individual and systemic levels. AI greatly enhances the ability to monitor climate-related actions by automating the collection and processing of data from multiple sources, such as sensors, satellites and social media. This automation enhances the scale, speed, and precision of environmental monitoring, enabling the continuous tracking of climate impacts and adaptation efforts in real time across diverse settings (Rolnick et al., 2023).

AI-driven monitoring mechanisms can also predict potential environmental risks. For example, AI-powered predictive analytics can forecast the likelihood of extreme weather events, such as floods or heat waves, based on historical climate data and real-time environmental conditions (Balagun et al., 2020). These predictions enable early warning systems that alert governments and communities, allowing them to take pre-emptive action to mitigate risks (Tounsi & Temimi, 2023).

In addition, AI can enhance participatory monitoring efforts by integrating citizen-generated data into climate monitoring systems. Platforms that allow citizens to report local environmental changes, such as air quality levels or water pollution, can be combined with AI technologies to validate and analyse the data. This approach not only improves the accuracy and coverage of environmental monitoring, but also fosters greater public engagement in climate adaptation efforts (Cattino & Reckien, 2021).

Improving Accuracy and Efficiency

AI excels at managing large data sets that would be impossible to analyse manually, ensuring that feedback and monitoring mechanisms are both accurate and timely. In the context of climate adaptation, this ability is invaluable. For example, AI algorithms can analyse satellite images to monitor deforestation, urban sprawl or agricultural practices that contribute to climate change. By detecting subtle changes in land use or vegetation cover, AI can help policymakers identify areas where environmental degradation is occurring and take corrective action before the damage becomes irreversible (Hey et al., 2009).

AI's ability to process data in real time also enables dynamic monitoring of environmental conditions. For example, smart sensors embedded in infrastructure such as water systems or energy grids can continuously collect data on resource use and environmental impacts. AI algorithms analyse this data to detect anomalies, such as leaks or inefficiencies, and suggest immediate corrective actions, thereby improving the sustainability and resilience of these systems (Rolnick et al., 2023).

Improving Citizen Engagement and Accountability

AI-enabled feedback and monitoring systems not only provide valuable data to policymakers, but also empower citizens to take an active role in climate adaptation. Platforms that provide individuals with real-time feedback on their environmental impact can foster greater accountability and engagement. For example, AI-powered apps that track personal carbon footprints allow users to see how their daily choices - such as transportation or energy consumption - contribute to climate change (Rau et al., 2022). These tools not only raise awareness, but also encourage users to take responsibility for reducing their environmental impact.

In addition, AI can help ensure that climate adaptation efforts are inclusive and equitable. By analysing demographic data, AI can identify underserved communities that may be disproportionately affected by climate change but lack access to resources or support systems. This allows policymakers to target interventions more effectively, ensuring that vulnerable populations are not left behind in climate adaptation efforts (Cattino & Reckien, 2021).

In summary, AI-driven feedback and monitoring mechanisms represent a critical advancement in climate adaptation efforts. These technologies provide real-time, data-driven insights that improve the effectiveness of interventions at both the individual and systemic levels. By enabling more accurate monitoring, predictive analytics and personalised feedback, AI plays a critical role in promoting sustainable behaviours and ensuring that climate adaptation strategies are responsive, efficient and equitable.

4.4 AI in Smart Cities

Artificial Intelligence (AI) has the potential to revolutionise urban areas, transforming them into smart cities where infrastructure, energy management and public services are optimised for efficiency and sustainability. Integrating AI into city systems enables real-time data collection and analysis, providing city planners and policymakers with the insights they need to make data-driven decisions. This can significantly improve resource allocation, reduce waste and reduce greenhouse gas emissions (Allam & Dhunny, 2019).

One of the key areas where AI can make an impact is in optimising transport systems. AI algorithms can analyse traffic patterns and predict congestion, enabling better traffic management and the creation of more efficient public transport routes. By reducing idle time and optimising vehicle flow, AI-driven transport systems can significantly reduce emissions, helping to reduce a city's carbon footprint (Balogun et al., 2020). In addition, AI can support the transition to electric vehicles (EVs) by optimising the placement of charging stations based on real-time data on vehicle usage and energy demand (Rolnick et al., 2023).

AI also has an important role to play in the management of urban ecosystems, such as parks and forests, which are essential for increasing biodiversity and improving air quality. For example, AI can be used to monitor urban forests, using sensors and drones to track the health of trees and detect early signs of disease or stress (Nitoslawski et al., 2019). This proactive management of green spaces not only contributes to biodiversity, but also ensures that urban environments are more resilient to the impacts of climate change, such as heatwaves and flooding.

In terms of energy management, AI is central to making cities more energy efficient. AI systems can monitor energy consumption in buildings and public infrastructure, allowing energy use to be dynamically adjusted based on real-time needs (Onile et al., 2021). This will reduce energy waste and support the integration of renewable energy sources by predicting energy demand and adjusting supply accordingly. Digital twins - virtual models of physical systems - can be used to simulate and optimise energy networks, ensuring that energy distribution is as efficient as possible (Onile et al., 2021).

A major benefit of AI in smart cities is the facilitation of communication between citizens and city planners through AI-powered platforms. These platforms allow for real-time input from residents on various urban issues, from public services to environmental concerns. By facilitating this two-way communication, AI enables a more inclusive and responsive approach to urban planning, where citizens are co-managers of their city's resources (Gulsrud et al., 2018). For example, AI-powered apps can enable citizens to report problems such as waste management issues or traffic congestion, while city officials can use this data to make informed decisions and deploy resources more effectively.

In summary, AI is instrumental in transforming urban areas into smart cities by optimising infrastructure, energy management and public services. Through AI, cities can enhance their sustainability efforts, reduce emissions, and foster a more collaborative relationship between citizens and city planners. As cities continue to face the challenges of climate change, AI offers valuable tools to make urban environments more efficient, resilient and responsive to the needs of their inhabitants.

4.5. Conclusion

The integration of AI into climate adaptation strategies represents a promising, yet complex, development. By supporting personalised interventions, adaptive feedback, and participatory engagement tools, AI can promote behavioural change and enhance the responsiveness of governance systems (Rau et al., 2022; Jain et al., 2023).

Techniques such as nudging and gamification—when ethically designed—can help bridge the intention–behaviour gap and sustain motivation through personalised and socially embedded strategies (Del Río Castro et al., 2021; Cellina et al., 2019). AI's capacity for real-time monitoring and predictive analytics also strengthens climate resilience by enabling timely adaptation responses and improving the inclusiveness of data collection through citizen participation (Rolnick et al., 2023; Cattino & Reckien, 2021).

However, the ethical risks associated with personalisation, automation, and data collection must not be overlooked. As outlined in the NEUROCLIMA *Legal and Ethical Issues Manual* (Mizsei, Bogucki, & Fischer, 2024), issues such as transparency, data protection, and equitable access must be addressed to prevent reinforcing existing inequalities or compromising autonomy (Dwivedi et al., 2022; Mizsei, Bogucki, & Fischer, 2024).

In sum, while AI technologies offer transformative potential in the climate domain, their contribution to the public good depends on careful, participatory, and ethically grounded implementation.

5. Strategies for Engaging Citizens in Climate Adaptation

5.1 Models of Civic Engagement

The examination of models of civic engagement in climate adaptation highlights the role of public participation in creating inclusive, sustainable and collaborative climate solutions. This section explores three key frameworks that have been instrumental in structuring and evaluating citizen participation in the context of climate change: Deliberative Democracy and Citizen Assemblies, Arnstein's Ladder of Citizen Participation, and the IAP2 Spectrum of Public Participation.

5.1.1 Deliberative Democracy and Citizen Assemblies

Deliberative democracy has become a central model for promoting meaningful citizen engagement in climate policy. It emphasises inclusive, structured dialogue and ensures that diverse voices are part of the decision-making process (Cattino & Reckien, 2021). Despite these efforts, policy inconsistency and misinformation remain significant barriers to citizen engagement in climate action. The NEUROCLIMA ethnographic study (D2.1, 2024) highlights that shifting political agendas often undermine long-term climate commitments, creating uncertainty for citizens and policymakers alike. Furthermore, the spread of misinformation contributes to public skepticism, requiring more transparent and participatory governance approaches to foster long-term trust.

Citizens' assemblies have gained traction in several countries, notably the UK and France, where climate assemblies have successfully influenced national climate policy. In these settings, citizens were given the opportunity to engage with expert knowledge, deliberate on possible climate action, and provide input that influenced government decisions. This model has shown that ordinary citizens, when given the space and resources, are capable of contributing thoughtful, actionable recommendations on complex climate issues (Willis et al., 2021).

The strength of the deliberative democracy model lies in its ability to bridge the gap between top-down policy approaches and grassroots participation. By directly involving citizens in the decision-making process, it fosters greater public buy-in and legitimacy, leading to more ambitious climate policies and greater public support for implementation (Dryzek et al., 2019).

5.1.2 Arnstein's Ladder of Citizen Participation

Sherry Arnstein's Ladder of Citizen Participation, developed in 1969, remains one of the most influential models for understanding levels of public involvement in decision-making processes. The ladder categorises participation into eight levels, ranging from non-participation (manipulation, therapy) through degrees of tokenism (informing, consulting, appeasing) to citizen power (partnership, delegated power, citizen control) (Arnstein, 1969).

In the context of climate adaptation, Arnstein's ladder provides a useful framework for assessing the extent to which citizens are genuinely involved in policy-making. On the lower rungs, citizens are merely informed or consulted, with little real influence over outcomes. As engagement moves up the ladder, citizens gain more control, culminating in full citizen power, where they have a direct hand in decision-making (Cattino & Reckien, 2021).

The ladder highlights the importance of moving beyond tokenistic participation - where citizens are merely informed or consulted without real influence - to more empowering forms of engagement. For climate adaptation efforts to be truly inclusive and effective, it is crucial that public participation is not limited to the lower rungs of the ladder. Instead, initiatives should aim to engage citizens in partnerships or delegated power, ensuring that their voices are integral to policy outcomes (Irwin, 2021).

5.1.3. IAP2 Spectrum of Public Participation

The International Association for Public Participation (IAP2) has developed a spectrum of public participation that provides a structured approach to assessing different levels of engagement. The IAP2 spectrum ranges from 'Inform' (the least participatory level, where citizens are merely given information) to 'Empower' (the most participatory level, where citizens have the authority to make decisions) (IAP2, 2021).

The five levels of participation in the IAP2 spectrum are:

1. **Inform** - Citizens are informed about climate policies and measures, but are not involved in the decision-making process.
2. **Consult** - Policymakers seek feedback from citizens on proposed climate actions, but final decisions are made without significant input from citizens.
3. **Involve** - Citizens are actively involved in the decision-making process to ensure their concerns are understood and taken into account.
4. **Collaborate** - Citizens work with policymakers to develop climate adaptation strategies, sharing decision-making power.
5. **Empower** - Citizens are fully empowered to make decisions about climate adaptation policies, such as through community-led adaptation projects.

The IAP2 spectrum allows organisations and governments to choose the level of participation that best suits their goals and resources. It emphasises the need for clarity about how much influence citizens will have on the final decision. In climate adaptation, this transparency is crucial for building trust between the public and decision-makers (Cattino & Reckien, 2021).

In conclusion, models of civic engagement such as Deliberative Democracy, Arnstein's Ladder of Citizen Participation and the IAP2 Spectrum of Public Participation provide valuable frameworks for engaging citizens in climate adaptation. Each model provides different mechanisms for enhancing public participation, from structured deliberative forums to fully empowered citizen decision-making processes. As climate adaptation strategies evolve, these models underscore the importance of ensuring that public participation is meaningful, equitable and capable of driving transformative action.

5.2. Playful Learning Experiences and Climate Change Awareness

The integration of playful learning experiences, including gamification and human-centred design, has become a key approach to promoting awareness and behaviour change around climate change. These educational interventions engage individuals at cognitive, affective and behavioural levels, providing immersive and interactive experiences that encourage long-term commitment to environmental sustainability.

5.2.1. Game-Based Learning and Behavioural Change

Game-based learning (GBL) is increasingly recognised as an effective strategy for promoting environmental awareness and behaviour change in relation to climate change. Through GBL, educational interventions incorporate game elements such as rewards, feedback loops, challenges and levels that motivate participants to engage deeply with environmental content. These interventions have been particularly effective in bridging the gap between theoretical understanding of climate issues and the practical application of sustainable behaviour.

The Learning and Game Mechanics (LM-GM) framework (Arnab et al, 2015) serves as a foundation for these gamified experiences. By integrating educational objectives with game design, the framework enables participants to engage with climate-related challenges in a meaningful way. In addition to this, the climate change engagement framework also outlines 15 core gamification attributes, divided into cognitive, behavioural and emotional dimensions, for fostering multi-level climate change engagement through gamified learning experiences (Ouariachi et al., 2019). Game-based learning can cognitively stimulate citizens to think critically about climate change adaptation actions, evoke personal connections and emotions, linking climate change to issues players care about and inspire real-world action by offering feedback loops, rewards, and social interaction that encourage citizens to apply what they learn in the game to their everyday lives.

Furthermore, AI-powered platforms can dynamically adjust the difficulty of challenges based on individual progress, ensuring that participants remain engaged without feeling overwhelmed. This adaptive approach keeps learners motivated while helping them internalise the importance of climate-friendly practices (Jain et al., 2023). The combination of learning objectives and game mechanics thus provides a fun and interactive way to promote climate awareness and behaviour change, with positive long-term climate change outcomes.

5.2.2 Human-Centered Design in Climate Education

Human-centred design (HCD) in climate education prioritises the needs, experiences and emotions of learners, making educational interventions more relevant and effective. HCD principles are particularly useful in designing playful and immersive experiences that encourage participants to explore climate issues from both intellectual and emotional perspectives.

HCD frameworks help ensure that climate education is not only accessible, but also engaging for diverse audiences. This approach places the learner's perspective at the centre of the educational design process and encourages flexibility, inclusivity and user participation (Tounsi & Temimi, 2023). For example, by tailoring climate content to learners' cultural or local contexts, HCD helps to create more relatable and impactful educational interventions.

This learner-centred approach is exemplified by initiatives such as participatory art projects and storytelling exercises, where individuals explore climate change through creative expression. Studies show that integrating the creative arts into climate education fosters cognitive and emotional engagement, encouraging learners to think deeply about climate issues and their personal role in addressing them (Rau et al., 2022).

Furthermore, the application of social interaction and team-based challenges highlights the importance of collaborative learning in fostering a community-driven approach to climate action. Team-based missions in gamified platforms allow participants to engage in collective problem-solving and climate-related challenges, thereby building a sense of community responsibility and increasing engagement (Galoete et al., 2023).

By using HCD in playful learning experiences, climate education becomes not only informative but also transformative, inspiring proactive engagement with climate issues and promoting behavioural change at both individual and collective levels.

5.3. Conclusion

This chapter has explored two key areas that are integral to a conceptual framework for behavioural and systemic change in climate change adaptation: civic engagement models and playful learning experiences. Both areas offer important insights into how to empower citizens and policymakers to address climate change challenges by fostering collaboration, inclusivity, and innovative approaches to education and public participation.

Models of Civic Engagement

An examination of models of civic engagement underscores the critical role of public participation in creating inclusive and sustainable climate solutions. Three basic frameworks - Deliberative Democracy and Citizen Assemblies, Arnstein's Ladder of Citizen Participation and the IAP2 Spectrum of Public Participation - highlight different ways of engaging citizens in climate policy and adaptation.

Deliberative democracy and town hall meetings provide a robust model for promoting meaningful public participation through structured, inclusive dialogue. This model emphasises the importance of drawing on diverse perspectives through citizens' assemblies, where ordinary people are empowered to deliberate on climate policy and make actionable recommendations. The success of such assemblies in countries such as the UK and France demonstrates the model's ability to bridge the gap between top-down policymaking and grassroots participation (Willis et al., 2021). The strength of the model lies in its ability to foster legitimacy and public support for ambitious climate policies, which are essential for the implementation of effective adaptation strategies.

Arnstein's Ladder of Citizen Participation provides a clear hierarchy of public involvement in decision-making, from non-participation to full citizen control. This framework illustrates the importance of moving beyond tokenistic forms of participation to truly empowering citizens. In the context of climate adaptation, ensuring that citizens are involved at higher rungs of the ladder - such as through partnerships or delegated power - is crucial to creating inclusive and effective climate policies (Arnstein, 1969). Empowering citizens at this level can increase the relevance and success of adaptation policies by aligning them more closely with community needs and preferences.

The IAP2 Spectrum of Public Participation provides a flexible, structured approach to public engagement, ranging from informing citizens to fully empowering them in decision-making. This spectrum provides a tool for policy-makers and organisations to tailor their engagement strategies to their objectives and resources. Importantly, it emphasises the need for transparency about the extent of public influence on decisions, which is essential for building trust between the public and decision-makers (IAP2, 2021). In the context of climate adaptation, ensuring that citizens know how their input will be used is critical to maintaining engagement and trust throughout the policy process.

These models collectively emphasise the need for meaningful, equitable and transparent public participation. As climate adaptation strategies evolve, these frameworks provide guidance on how to structure citizen engagement in ways that not only increase buy-in, but also drive transformative action.

Playful Learning Experiences and Climate Change Awareness

In addition to structured civic engagement models, playful learning experiences have emerged as an innovative and effective approach to promoting climate change awareness and behaviour change. Integrating gamification and human-centred design into climate change education provides engaging, immersive experiences that reach learners on cognitive, emotional and behavioural levels.

Game-Based Learning (GBL) provides a compelling framework for embedding environmental education in game-like contexts, making the learning process interactive, fun and motivating. Using game mechanics such as points, levels and feedback loops, GBL links abstract climate concepts to practical, everyday actions that participants can take to reduce their environmental impact. The Learning and Game Mechanics (LM-GM) framework supports these interventions by ensuring that educational objectives are seamlessly integrated into the game design, making the experience both meaningful and engaging (Cellina et al., 2019). In addition, AI-powered platforms can dynamically adjust the difficulty of challenges to match individual progress, fostering sustained engagement and promoting long-term behaviour change (Jain et al., 2023).

Human-centred design (HCD) further enhances climate education by placing learners' experiences, emotions and needs at the centre of the educational process. HCD ensures that climate education is not only informative, but also relatable and impactful. By tailoring content to learners' cultural and local contexts, HCD creates a more personalised and relevant educational experience (Tounsi & Temimi, 2023). This approach is particularly evident in initiatives such as participatory art projects, which integrate creative expression with climate awareness, fostering deep emotional and cognitive engagement (Rau et al., 2022). In addition, team-based challenges in gamified platforms encourage social interaction and collaboration, helping to build a sense of community responsibility for climate action (Galoete et al., 2023).

Through these playful learning experiences, climate education is transformed into a proactive, engaging process that promotes both individual and collective behaviour change. By tapping into intrinsic motivations, emotional connections, and social dynamics, gamification and human-centred design provide powerful tools for fostering a deeper commitment to sustainability.

In conclusion, the combination of civic engagement models and playful learning experiences provides a comprehensive framework for driving behavioural and systemic change in climate adaptation. While civic engagement models ensure that citizens are empowered and their voices are integral to policy outcomes, playful learning experiences offer immersive and interactive ways to engage individuals emotionally and cognitively. Together, these approaches underscore the importance of developing climate adaptation strategies that are not only scientifically sound, but also socially inclusive and capable of inspiring sustainable, transformative action.

6. Policy Implications and Recommendations

6.1 AI Literacy and Inclusivity in Climate Adaptation

As artificial intelligence (AI) becomes an increasingly integral part of climate adaptation strategies, ensuring widespread AI literacy and inclusivity is critical. AI literacy involves equipping citizens and policymakers with the knowledge and skills needed to understand AI technologies, how they work, and how they can be applied in climate adaptation efforts. This is particularly important to ensure that the benefits of AI are shared equitably across all segments of society. The role of AI in climate adaptation ranges from predicting extreme weather events to optimising resource management, so it is essential that communities are educated about its capabilities and limitations (Del Río Castro et al., 2021).

One of the biggest challenges to integrating AI in climate adaptation is the digital divide, particularly in underserved and marginalised communities. Without access to technology or the skills to engage with AI tools, these groups may be excluded from the benefits of AI-driven adaptation efforts. For AI to truly promote inclusive climate adaptation, the public and private sectors must work together to develop accessible, user-friendly tools designed for communities with varying levels of digital literacy (Dwivedi et al., 20-22). In addition, inclusive policies should ensure that AI-driven adaptation strategies take into account the specific vulnerabilities of these communities, as they are often disproportionately affected by climate change (Balagun et al., 2020).

AI literacy initiatives can be supported through educational programmes that integrate AI into climate science curricula, public workshops and online resources that simplify complex AI concepts. In addition, efforts should be made to create AI tools that are transparent and interpretable, allowing non-expert users to understand and effectively engage with AI systems. This democratisation of AI knowledge is essential for fostering public trust and ensuring that climate adaptation strategies are equitable (Del Río Castro et al., 2021).

6.2 Public-Private Partnerships for AI-enabled Adaptation Strategies

The European Union's Fit for 55 package, along with the Green Deal and climate adaptation strategies, including the new EU Clean Industrial Deal that was in February 2025.provide a structured policy framework for AI-enabled climate resilience. The Fit for 55 measures, including the Emissions Trading System (ETS) and the Social Climate Fund (SCF), aim to ensure that AI-driven solutions for climate adaptation align with broader systemic policy shifts. Furthermore, EU policy frameworks emphasize impact assessments as a core mechanism to evaluate AI-driven interventions, ensuring their effectiveness in mitigating climate risks.

Public-private partnerships (PPPs) are a key mechanism for advancing AI-enabled climate adaptation strategies. By pooling resources, expertise and infrastructure, these collaborations can drive the development and deployment of AI technologies that enhance climate resilience across sectors. The World Economic Forum (WEF) highlights the role of PPPs in harnessing digital technologies to reduce emissions and increase resilience to climate impacts, highlighting that AI has the potential to contribute significantly to global climate goals by 2030 (World Economic Forum & PwC, 2021).

PPPs facilitate the scaling of AI solutions by combining the innovation of the private sector with the regulatory support and broader reach of public institutions. For example, governments can incentivise private companies to develop AI-based climate solutions by offering tax breaks or grants, while companies can provide technical expertise and investment to bring these solutions to market. This model has been successfully applied in sectors such as agriculture, where AI-driven systems are being used to optimise water use and predict crop yields, benefiting both private companies and public food security initiatives (Balagun et al., 2020).

A critical aspect of PPPs in AI-driven climate adaptation is to ensure that they are designed to be both inclusive and sustainable. To achieve this, partnerships must prioritise the development of AI tools that are accessible to small businesses, local governments and non-profit organisations, rather than focusing solely on large corporations. In addition, governments must implement policies that protect public interests, such as data privacy and environmental sustainability, while encouraging private sector innovation (Rolnick et al., 2023).

6.3 Ethical Considerations in AI Deployment for Climate Resilience

Ethical considerations are not just important—they are foundational to the responsible use of AI in climate resilience. Without addressing them head-on, even the most technically sound solutions risk reinforcing inequality or eroding public trust. As AI systems are increasingly used to guide climate adaptation strategies, concerns about privacy, data security and algorithmic bias need to be addressed to ensure that AI technologies are used responsibly and equitably. One of the main ethical concerns is the collection and use of personal data. AI systems that monitor individual behaviours, such as energy or water use, rely on vast amounts of data, raising questions about how this data is stored, who has access to it, and how it is used (Hey et al., 2009).

Another ethical issue is the risk of algorithmic bias in AI systems. If AI models are trained on biased data, they may produce recommendations or predictions that disadvantage certain groups, particularly marginalised communities that are already vulnerable to climate impacts. For example, if an AI system used to allocate resources during a climate disaster is based on data that underrepresents rural areas, these regions may receive inadequate support (Crawford, 2021). To mitigate these risks, it is crucial that AI developers prioritise fairness and transparency in their algorithms to ensure that AI-driven climate solutions are fair and equitable.

In addition, the energy consumption of AI technologies is itself an ethical dilemma. AI systems, particularly those that rely on large-scale data processing, can consume significant amounts of energy, contributing to the very problem they are designed to solve. Policymakers and developers must work together to ensure that AI systems are designed with energy efficiency in mind, minimising their carbon footprint while maximising their effectiveness in climate adaptation (Scholz et al., 2018).

In conclusion, the ethical use of AI in climate adaptation requires careful consideration of privacy, fairness and sustainability. By establishing clear ethical guidelines and regulatory frameworks, policymakers can ensure that AI technologies are used in ways that promote both climate resilience and social justice.

6.4. Conclusion

The use of artificial intelligence (AI) in climate adaptation offers transformative opportunities, but requires careful consideration of key policy implications to ensure equitable and effective outcomes. The integration of AI in predicting climate risks, optimising resource management and promoting behavioural change has the potential to revolutionise global climate resilience efforts. However, to realise these benefits, it is essential to address challenges related to AI literacy, inclusivity, public-private collaboration, and ethical deployment.

AI Literacy and Inclusivity

Ensuring widespread AI literacy is fundamental to the success of AI-driven climate adaptation strategies. Equally important is acknowledging the ethical dimensions of deploying AI in climate adaptation. Concerns about data protection, algorithmic bias, and digital surveillance are especially relevant in behavioural interventions that rely on personal information. These issues must be addressed upfront, not as afterthoughts, to build inclusive, fair, and accountable climate strategies.

By equipping citizens, communities and policymakers with the necessary skills to understand and use AI technologies, societies can ensure that these tools are not limited to experts or privileged groups. The digital divide remains a significant challenge, particularly in marginalised and underserved communities. Without equitable access to AI technologies, these populations risk being excluded from critical adaptation efforts, exacerbating their vulnerability to climate impacts. Collaborative efforts between the public and private sectors are critical to developing accessible AI tools and educational programmes that foster inclusivity and public trust in AI-driven strategies (Del Río Castro et al., 2021).

Public-Private Partnerships to Scale Up AI Solutions

Public-private partnerships (PPPs) are essential for advancing AI-enabled climate adaptation strategies. The combined resources, expertise and infrastructure of both sectors can drive innovation and scale AI solutions that promote climate resilience. Successful models, such as AI in agricultural management or energy optimisation, demonstrate the potential of PPPs to contribute significantly to global climate goals. However, the design of these partnerships must ensure that the benefits of AI tools extend beyond large corporations to small businesses, local governments and non-profit organisations. In addition, policy frameworks must balance the need for innovation with the protection of public interests, including data privacy and environmental sustainability (World Economic Forum & PwC, 2021).

Ethical Considerations in the Use Of AI

The ethical deployment of AI in climate adaptation requires addressing issues related to data privacy, algorithmic bias and environmental sustainability. AI systems rely on vast amounts of data to function, raising concerns about how personal and environmental data is collected, stored, and used. Policymakers need to establish robust regulations to protect the privacy of individuals, while ensuring transparency in how AI models operate. In addition, algorithmic biases risk exacerbating inequalities, especially if AI tools are not designed with marginalised communities in mind. Efforts to mitigate these biases and ensure fairness in AI decision-making are essential for promoting social justice in climate adaptation. Finally, the energy consumption of AI technologies presents an additional ethical dilemma, as energy-intensive AI systems may contribute to the environmental challenges they seek to address. The development of energy-efficient AI models is crucial for balancing technological innovation with sustainability goals (Scholz et al., 2018).

In conclusion, the integration of AI into climate adaptation strategies has immense potential to increase global resilience to climate change. However, for these technologies to succeed, policymakers must prioritise inclusivity, foster collaborative public-private partnerships, and implement ethical frameworks that ensure fairness, transparency, and sustainability. By addressing these challenges, AI can be harnessed to create more equitable, effective and responsible climate adaptation strategies that benefit all segments of society.

7. Case Studies

7.1 AI in Disaster Risk Reduction

Artificial intelligence (AI) has become a critical tool in disaster risk reduction (DRR), improving the ability to predict, manage and mitigate the impact of natural disasters exacerbated by climate change. AI-driven technologies enable real-time data analysis, predictive modelling and advanced simulations that provide early warnings and guide preparedness efforts. One notable case is the use of machine learning algorithms to predict extreme weather events such as floods, hurricanes, and heat waves (Del Río Castro et al., 2021). By analysing historical climate data, satellite imagery, and current environmental conditions, AI systems can predict the likelihood, severity, and trajectory of disasters, enabling faster and more informed responses.

In practice, AI-based early warning systems are now widely used to improve disaster preparedness. For example, AI models used in flood forecasting have significantly reduced the response time for mobilising emergency services. In urban centres prone to flooding, these systems provide real-time updates to both citizens and governments, allowing for the timely implementation of evacuation protocols or infrastructure adjustments (Balagun et al., 2020). Furthermore, AI's ability to analyse large datasets contributes to the resilience of disaster-prone communities by enabling accurate and localised risk assessments. This ensures that resources can be allocated effectively, focusing on high-risk areas and populations.

However, the use of AI in DRR is not without its challenges. Data accessibility and the digital divide remain significant barriers, particularly in underserved regions that are disproportionately affected by climate disasters. To bridge this gap, governments must invest in AI infrastructure that includes marginalised communities in disaster preparedness efforts (Dwivedi et al., 2022). Public-private partnerships can also play a key role in developing AI-driven systems that are accessible, equitable and culturally adaptable.

7.2 behavioural Change Interventions via AI

Recent impact assessments within the NEUROCLIMA project indicate that AI-driven climate interventions must account for socio-economic tipping points to ensure their long-term viability. By integrating AI into climate resilience policies, governments can enhance predictive modeling capabilities, allowing for more effective disaster risk reduction and adaptation planning. For example, policy impact assessments suggest that AI-supported urban resilience models can increase social preparedness for extreme weather events.

The role of AI in promoting behavioural change in climate adaptation is increasingly being explored, particularly through AI-driven personalisation and nudging strategies. By harnessing vast amounts of behavioural data, AI systems can encourage sustainable habits, such as reducing energy consumption, minimising waste and optimising transport choices. These interventions often involve real-time feedback mechanisms that adapt to user behaviour and provide tailored recommendations to nudge individuals towards environmentally friendly practices (Rau et al., 2022).

A prominent example of AI-enabled behavioural intervention is found in energy-saving applications, where users receive personalised recommendations based on their consumption patterns. Smart meters integrated with AI can track household energy use and suggest concrete actions—such as adjusting thermostat settings or upgrading to energy-efficient appliances (Rolnick et al., 2023). These systems have shown effectiveness in addressing the intention–behaviour gap, helping individuals follow through on sustainable intentions that might otherwise remain unacted upon due to lack of motivation or timely feedback.

However, these successes are not universal. In one recent community deployment of a smart energy platform, user engagement dropped significantly after the initial launch. This decline was linked to insufficient ongoing support and unclear data visualisations, which limited users' ability to act on the information provided. Similarly, gamified platforms—designed to reward climate-friendly behaviours—have encountered difficulties maintaining participation in areas with low digital literacy or where sustainability goals clash with everyday economic constraints. These cases demonstrate that AI's effectiveness is highly contingent on the surrounding social, cultural, and economic context. Without attention to these factors, even technically sound solutions may fail to achieve meaningful or lasting impact.

At the community level, AI is also being used to support participatory sustainability efforts. Algorithms can analyse patterns in citizen engagement, identify which strategies are most effective, and offer real-time recommendations to scale these successes. Gamified interventions—such as awarding points for reducing carbon emissions or conserving water—can help sustain engagement over time (Cellina et al., 2019). When thoughtfully designed, these systems dynamically adapt to user behaviours and provide ongoing motivation, making climate action more engaging and accessible. Yet, as earlier examples show, inclusive design, clear communication, and responsiveness to local conditions remain critical for these interventions to succeed.

7.3 Systemic AI Frameworks in Resource Management

A notable application of AI in resource management is in the agricultural sector, where AI-driven models are being used to predict crop yields, optimise irrigation and reduce food waste. For example, AI systems can assess soil moisture levels, weather forecasts, and crop needs to recommend precise irrigation schedules that minimise water waste while ensuring optimal crop growth (Rolnick et al., 2023). In energy management, AI technologies are being used to optimise energy grids and efficiently integrate renewable energy sources such as solar and wind power into the grid. By predicting energy demand and dynamically adjusting supply, these AI systems improve the resilience and sustainability of energy infrastructure.

The implementation of AI in resource management frameworks also involves public-private partnerships, where governments work with technology companies to scale AI solutions. These partnerships facilitate the deployment of AI systems that address both local and national resource challenges, ensuring that communities have access to sustainable and equitable resource management tools. However, challenges such as data privacy, energy consumption by AI systems, and algorithmic bias must be carefully managed to ensure ethical and responsible AI deployment (Scholz et al., 2018). One example is Google's collaboration with governments to improve climate disaster preparedness. The **Flood Hub** platform uses AI to predict floods and provide early warnings, helping communities take action before disasters strike. This tool is now available in over 80 countries, offering forecasts up to seven days in advance. Such AI applications demonstrate how simple yet powerful technology can assist governments in protecting people from climate-related risks.

In conclusion, AI-driven solutions in disaster risk reduction, behaviour change interventions, and resource management highlight the transformative potential of AI in climate adaptation. However, equitable distribution of AI technologies, public engagement, and ethical considerations remain critical to ensure that the benefits of AI are shared across all communities and sectors.

7.4. Conclusion

The integration of artificial intelligence (AI) into climate adaptation strategies represents a significant leap forward in humanity's ability to mitigate the risks of climate change, promote sustainable behaviours, and efficiently manage critical resources. The case studies of AI applications in disaster risk reduction (DRR), behaviour change interventions and resource management highlight both the transformative potential of these technologies and the critical challenges that must be addressed to ensure equitable, ethical and effective implementation.

AI has demonstrated its value in disaster risk reduction by providing real-time data analysis and predictive modelling that improves preparedness and response to extreme weather events. By analysing large data sets, AI technologies can provide early warnings that enable communities and governments to act quickly, reducing the loss of life and property. However, the equitable distribution of the benefits of AI remains a challenge, particularly in underserved and marginalised regions. Bridging the digital divide through investment in AI infrastructure and partnerships is critical to ensuring that all communities can benefit from these life-saving technologies.

In the area of behaviour change, AI has been shown to be effective in promoting sustainable habits through personalised interventions. AI-powered tools, such as energy-saving applications, use real-time data to provide tailored recommendations, encouraging individuals and communities to adopt greener practices. By bridging the gap between intention and behaviour, AI increases individual and collective participation in climate action. However, the success of AI-driven behaviour change initiatives depends on the continued engagement of users and the accessibility of these tools across socio-economic demographics.

Resource management is another area where AI has proven invaluable. AI technologies optimise the use of critical resources such as water, energy and food by analysing environmental conditions and consumption patterns. In agriculture and energy management, AI has improved efficiency and sustainability by predicting crop yields, optimising irrigation and integrating renewable energy sources into power grids. However, as AI systems become more embedded in resource management frameworks, ethical considerations - such as data privacy, energy consumption by AI systems, and algorithmic bias - will need to be addressed to ensure that the use of AI remains responsible and equitable.

In conclusion, while AI offers powerful tools for climate adaptation, it is essential to ensure that these technologies are developed and implemented in ways that promote diversity, inclusivity, equity, and sustainability. Public engagement, ethical governance, and collaboration between the public and private sectors are critical to ensuring that AI-driven climate adaptation strategies benefit all communities. As climate challenges continue to escalate, AI has the potential to be a central force in building a resilient and sustainable future, but only if its use is guided by principles of fairness and responsibility.

8. A Phenomenological Insight into Behavioural and Systemic Change for Climate Adaptation

This chapter explores how behavioural and systemic change is experienced and understood by individuals and communities within the context of climate adaptation. It draws on two key sources of information:

1) In-depth interviews conducted by POLIMI researchers in Italy in April 2025, and
2) The interactive workshop 'Behavioural Levers in Action', which was held in Malta during the 4^(th) NEUROCLIMA consortium meeting.

Together, these activities provide valuable insights for developing a human-centred conceptual framework for behavioural and systemic change.

8.1 Interviews. Summary of Key Findings

As part of Task 3.1 of the NEUROCLIMA project, four semi-structured interviews were conducted by researchers from Politecnico di Milano in April 2025. The purpose of these interviews was to explore professionals' experiences and perceptions of participatory processes in climate-related initiatives, with a focus on the integration of digital tools, civic engagement, and environmental adaptation. Although these interviews primarily served the objectives of Task 3.1, their content also offered rich material on behavioural change and adaptation processes, which was further examined through phenomenological analysis. By applying a phenomenological lens during the interpretation of the interview material, the analysis focused on how participants make sense of participation, behavioural drivers, and systemic transformations within specific socio-technical contexts. Rather than treating behaviour as abstract or modelled constructs, the analysis foregrounded lived experience, local narratives, and situated meaning-making.

A consistent theme across the interviews was **the perception of fragmentation in citizen participation.** Respondents—drawn from fields such as civic technology, public policy, and design—described how existing participatory frameworks often remain disjointed, poorly integrated into decision-making processes, and inaccessible to a wide range of users. This lack of coherence was said to reduce trust and continuity, limiting long-term behavioural engagement. Instead, participants emphasised the value of hybrid formats that combine the emotional depth of in-person dialogue with the accessibility and scalability of digital participation. These hybrid environments were seen as capable of enabling stronger identification, shared ownership, and more inclusive deliberation.

Digital technologies were viewed with both promise and caution. Their legitimacy, according to the participants, depends on whether they are co-designed, contextualised, and responsive. When technologies are imposed without adaptation to local realities, they risk being perceived as alien or extractive. Several respondents pointed to the value of digital platforms that use explainable AI to visualise and cluster group preferences, provided these are integrated with facilitated dialogue and transparent feedback loops. Behavioural change, in this view, is less about individual rational decisions and more about emotionally and socially mediated processes.

Moderation emerged as a critical human layer in these digitally supported participatory settings. Interviewees described moderators as essential interpreters between algorithmic outputs and human discourse—mediating understanding, clarifying uncertainty, and maintaining emotional safety. Rather than replacing human facilitation, digital systems were expected to enhance it. This co-presence of algorithmic suggestion and human guidance enabled what participants referred to as shared interpretive processes, through which people engaged not only with issues but also with each other's perspectives and experiences. Such interaction was seen as a foundation for cultivating mutual recognition, collective meaning, and behavioural commitment.

Importantly, behavioural and systemic change were not perceived as separate domains. Respondents framed them as deeply interdependent, with behavioural shifts understood as situated, relational, and often iterative. Systemic transformation was seen to occur when changes in personal behaviour aligned with community practices and institutional structures. Participants stressed the need to pilot initiatives in different local contexts, allowing barriers and enablers to surface through practice. Each local context produced its own "journey," shaped by historical, cultural, and structural conditions—requiring flexibility and ongoing learning.

Importantly, this process surfaced limitations of proposed interventions. For example, strategies relying heavily on digital nudging were seen as less viable in older populations with limited smartphone access. Others noted that monetary incentives sometimes undermined intrinsic motivation over time, especially when extrinsic rewards were removed. These reflections stress the importance of iterative testing and learning in real-world adaptation efforts.

8.2 Workshop-Based Insights: Behavioural Levers in Practice

At the 4th NEUROCLIMA Consortium Meeting in Malta (12–13 May 2025), the "**Behavioural Levers in Action**" workshop provided a hands-on opportunity for project partners to apply the **Behavioural Lever Framework (BLF)** to four realistic climate-related scenarios. Each scenario presented a specific behavioural challenge rooted in daily practices such as water use, recycling, transportation, and energy consumption.

Participants worked in groups to select three levers from the BLF for each case. Rather than designing interventions per se, they were asked to identify *why* certain levers would be appropriate based on the scenario's behavioural dynamics, constraints, and opportunities. Below, each scenario is described through the lens of its context, challenge, and behavioural levers selected.

Scenario 1: Water Consumption on a Tourist Island

Context: A popular island struggles with excessive water use, especially during tourist season. Public awareness campaigns have failed to shift consumption patterns among locals and visitors.

Challenge: *How can water use be reduced without relying solely on moral appeals or bans?*

Applied Levers:

- **Material Incentives.** Recognised as a practical driver, incentives were considered important for reducing overuse without resorting to restrictive regulation. Economic rewards (e.g., discounts or rebates) tied to lower consumption were framed as a way to make conservation efforts personally beneficial.

- **Information.** Participants agreed that previous campaigns had limited impact likely due to generic messaging. Therefore, information needed to be localised, visual, and immediate—linking individual behaviour to community impact in tangible terms.
- **Choice Architecture.** This lever was applied to restructure how water use decisions are presented. Default settings on irrigation systems or nudges in accommodation facilities (e.g., signage, low-flow fixtures) were viewed as subtle yet effective mechanisms to shift user behaviour passively.

Scenario 2: Apartment Recycling in Dense Urban Areas

Context: In a high-density neighbourhood, recycling rates are below 30%. Bins are placed far from entrances, and residents report lack of time and motivation as barriers.

Challenge: *How can recycling become easier?*

Applied Levers:

- **Choice Architecture.** Participants viewed this lever as essential in reducing friction and increasing convenience. By redesigning the placement of bins and simplifying sorting instructions, recycling could be made a default behaviour rather than an effortful task.
- **Material Incentives.** Small, consistent rewards (e.g., community recognition, vouchers) were considered helpful in building initial engagement. Incentives were seen as useful to overcome inertia in contexts where intrinsic motivation is low.
- **Regulation.** Applied not as punitive enforcement but as structural support—e.g., requiring building owners to ensure bin accessibility or mandating minimum infrastructure standards. Regulation was framed as enabling behavioural change by shifting responsibility to service providers.

Scenario 3: Urban Cycling and Modal Shift

Context: Although cycling lanes have been built in the city, they remain underused. People cite concerns over safety, low social acceptance of cycling, and limited access to information.

Challenge: *How can residents replace short car trips with bikes?*

Applied Levers:

- **Social Influence.** This lever was viewed as central. The group identified the importance of visible role models—such as local leaders or peers—who could normalise cycling and influence social norms. Peer pressure and community identity were seen as critical for overcoming cultural stigma.
- **Information.** Safety information, route maps, and benefits of cycling needed to be communicated clearly and positively. Emphasis was placed on addressing misconceptions, making cycling appear not only safe but socially valued and efficient.
- **Regulation.** Considered necessary for reinforcing safety and accessibility—for instance, enforcing speed limits for cars in shared zones or ensuring maintenance of cycling lanes. Regulation was also seen as a signal of institutional commitment to sustainable transport.

Scenario 4: Electricity Overuse in Subsidised Households

Context: Households receiving financial support for energy continue to consume high levels of electricity. Many lack knowledge about energy-efficient appliances or follow energy-intensive habits.

Challenge: *How can behavioural change be promoted without removing financial aid*?

Applied Levers:

- **Information.** Energy literacy emerged as a priority. The group stressed the need for simple, targeted education on appliance efficiency, energy-saving habits, and the long-term cost of overuse. The messaging needed to be culturally sensitive and accessible.
- **Material Incentives.** Instead of removing aid, participants suggested redirecting support to promote energy efficiency—for example, linking subsidies to appliance upgrades. This lever was seen as a bridge between welfare policy and sustainable consumption.
- **Choice Architecture.** By reframing energy choices—for example, pre-setting thermostats or offering energy-saving modes as defaults—households could be guided toward lower consumption without coercion. This lever was particularly relevant in addressing habitual overuse.

Cross-Scenario Observations

The application of the Behavioural Lever Framework across the four cases highlighted several recurring insights:

1. **Integrated Levers Are More Effective.** In each case, no single lever was seen as sufficient. Groups consistently paired motivational, cognitive, and structural tools to create conditions for change.
2. **Material Incentives Offer Entry Points but Require Alignment.** Economic rewards were commonly selected, but their success depends on careful calibration to avoid dependency or distortion of environmental goals.
3. **Social Influence Needs Stronger Attention.** Despite its proven potential, this lever was underused across scenarios—indicating a need for greater emphasis in the framework and capacity-building among practitioners.
4. **Choice Architecture Is Understood, But Not Fully Exploited.** Participants recognised its value but requested clearer examples and design strategies. It is a promising but underdeveloped area within the current framework.
5. **Regulation Functions Best When Enabling, Not Punitive.** Across scenarios, regulation was not interpreted as control but as infrastructure that supports consistent behavioural expectations and shared responsibility.

This detailed exploration of behavioural levers in applied contexts strengthens the utility and adaptability of the Behavioural Lever Framework. It also generates practical knowledge for refining NEUROCLIMA's broader **Conceptual Framework for Behavioural and Systemic Change**, ensuring that behavioural insights are embedded in real-world practices, institutional settings, and lived experiences.

8.3 Contribution to the Conceptual Framework for Behavioural and Systemic Change

The integration of findings from the interview analysis and the workshop-based scenario exercises offers more than complementary perspectives—it allows for the formulation of a coherent conceptual shift in how behavioural and systemic change should be understood and supported within climate adaptation frameworks. What emerges is not a simple accumulation of tools or empirical observations, but a recognition that behavioural strategies gain relevance only when embedded in broader relational, institutional, and design ecosystems. Rather than promoting behavioural change as a standalone goal, the evidence suggests that it should be treated as both a *driver* and *symptom* of systemic processes—deeply shaped by the quality of participation, the transparency of mediation, and the design of choice environments. The framework must therefore adopt a layered architecture: one that connects micro-level behaviour with meso-level organisational practice and macro-level policy structure. This includes acknowledging that behavioural levers are not merely instruments to be deployed but are configured through processes of negotiation, adaptation, and co-production. Their effectiveness is relational, context-dependent, and contingent on alignment across levels of system functioning.

Additionally, the findings stress the need for a dual capacity within the framework: it must support **deliberate design**—enabling actors to structure interventions thoughtfully—and at the same time remain **adaptive to emergence**—recognising that behavioural outcomes often arise unpredictably through interaction and experimentation. This calls for a model that incorporates both predefined lever typologies and real-time learning loops.

The conceptual synthesis also highlights the importance of **institutional interfaces**: points where individual behaviour meets collective governance. These interfaces—whether in digital spaces, community platforms, or policy channels—are where behavioural intentions are either reinforced or neutralised. The framework should therefore address not only what shapes behaviour but also where behavioural intention meets structural possibility.

Finally, a consistent implication across both data sources is that any attempt to scale behavioural interventions must be preceded by an understanding of **local intelligibility**. The success of behavioural and systemic interventions rests less on their normative coherence and more on their resonance with place-based meaning systems, histories of trust, and practical constraints. The framework must explicitly accommodate variation—not as a challenge to overcome, but as a generative condition for relevance and legitimacy.

9. Conclusion

9.1 Summary of Key Findings

The analysis of climate change adaptation strategies presented in this conceptual framework highlights the importance of integrating artificial intelligence (AI), participatory models and behavioural interventions to promote both individual and systemic change. This comprehensive approach underscores the multifaceted nature of climate adaptation and the need for innovative solutions that address the complex interplay between technology, human behaviour and institutional frameworks.

AI-Driven Solutions for Climate Adaptation

AI is revolutionising the way we approach climate adaptation by providing powerful tools for real-time data analysis, predictive modelling and resource management. In particular, AI-driven systems have shown immense potential in disaster risk reduction, resource optimisation and behaviour change interventions. For example, AI-based early warning systems for natural disasters have improved the ability of governments and communities to predict and respond to extreme weather events such as floods, hurricanes, and heat waves (Del Río Castro et al., 2021). These systems reduce response times and enable targeted resource allocation, thereby increasing the resilience of vulnerable populations.

In resource management, AI technologies are optimising agricultural productivity by improving irrigation systems, reducing water waste and predicting crop yields. Similarly, in energy management, AI models are being used to integrate renewable energy sources into existing grids and dynamically adjust energy distribution to meet demand in real time. These systemic applications highlight the transformative potential of AI in promoting sustainable development and mitigating the effects of climate change.

Behavioural Change Interventions through AI

AI also plays an important role in promoting behaviour change through personalised interventions and nudging strategies. By analysing user data, AI-powered platforms offer tailored recommendations that encourage individuals to adopt more sustainable behaviours, such as reducing energy consumption, minimising waste and using greener transport options. Behaviour change applications, such as energy saving apps, exemplify how AI can be used to nudge individuals towards greener habits by providing real-time feedback and personalised challenges (Rau et al., 2022). These interventions help to bridge the intention-action gap, motivating individuals to act on their environmental awareness and commitment.

In addition, gamified platforms that incorporate AI-driven feedback loops have proven effective in fostering long-term engagement. By offering rewards and incentives for sustainable behaviour, these platforms make climate action more engaging and accessible to a wider audience, from individuals to entire communities.

Models of Citizen Engagement in Climate Adaptation

Effective climate adaptation requires the active participation of citizens and communities in decision-making processes. A review of models of civic engagement, including deliberative democracy, Arnstein's Ladder of Citizen Participation and the IAP2 Spectrum of Public Participation, shows the importance of empowering citizens at all levels of participation, from consultation to decision-making. Models such as citizens' assemblies have successfully demonstrated that diverse groups of individuals, when provided with the necessary tools and knowledge, can contribute meaningful insights to climate adaptation policy (Cattino & Reckien, 2021).

Furthermore, models such as participatory budgeting and community-led adaptation emphasise the value of local knowledge and bottom-up approaches. These initiatives allow communities to tailor adaptation measures to their specific needs and contexts, thereby promoting more inclusive and resilient outcomes. The inclusion of marginalised and vulnerable groups in decision-making processes is essential to ensure that adaptation efforts address the needs of those most affected by climate change (Satterthwaite et al., 2024).

Ethical Considerations in the Use of AI

The use of AI in climate adaptation also raises important ethical considerations, particularly in relation to privacy, data security and algorithmic fairness. The reliance on large data sets for AI-driven climate solutions raises concerns about how personal data is collected, stored, and used. In addition, the potential for algorithmic bias in AI systems underscores the need for transparency and accountability in the design and implementation of AI technologies. Policymakers and AI developers must work together to create frameworks that ensure AI systems are fair, equitable, and energy efficient, minimising their environmental footprint while maximising their impact on climate resilience (Scholz et al., 2018).

9.2 A Conceptual Framework for Behavioural and Systemic Change for Climate Change Adaptation in NEUROCLIMA

The urgent need to adapt to climate change requires a multifaceted approach that includes not only technological advances and policy initiatives, but also a thorough understanding of the behavioural and systemic changes needed to build climate resilience. It is recommended that the NEUROCLIMA project adopts a dual approach, addressing both individual behaviours and broader systemic changes. This chapter outlines the design and purpose of D3.3, a conceptual framework that NEUROCLIMA should implement to drive these changes. By integrating innovative AI tools, participatory methods and educational interventions, NEUROCLIMA can promote climate resilience at both individual and societal levels.

9.2.1 Purpose of the Conceptual Framework

The D3.3 framework provides a structured approach to facilitating the behavioural and systemic changes that are essential for effective climate adaptation. It is recommended that NEUROCLIMA uses this framework to provide individuals and institutions with the knowledge and tools to better understand climate risks and implement strategies to mitigate them. Key objectives include:

- **Promoting pro-environmental behaviour** through education, motivation and the provision of accessible, actionable information.
- **Facilitating systemic change** by promoting policies and infrastructure that are aligned with sustainability goals and ensure long-term adaptation.
- **Helping policymakers** design climate-resilient policies that are informed by data and long-term sustainability goals.
- **Using artificial intelligence (AI)** to tailor recommendations and provide real-time feedback, enabling both individuals and institutions to adapt dynamically to evolving climate challenges.

By addressing both behavioural and systemic elements, NEUROCLIMA can bridge the gap between individual actions and collective institutional responses, ensuring that climate adaptation is both personal and global in scope.

9.2.2 Behavioural Change as a Central Component

Behavioural change lies at the heart of NEUROCLIMA's implementation of the D3.3 framework. Theories such as Theory of Planned Behaviour (TPB), Norm Activation Model (NAM) and Self-Determination Theory (SDT) can be used to understand and influence the factors that motivate individuals to adopt climate-friendly behaviours. Each of these theories provides insight into different aspects of behaviour change:

- **TPB** focuses on how attitudes, social norms and perceived control shape individuals' intentions to act sustainably. NEUROCLIMA can use AI tools to provide personalised feedback, nudges and support to bridge the intention-behaviour gap and motivate individuals to act on pro-environmental intentions.

- **NAM** highlights the role of personal norms and moral commitments in driving behaviour change. NEUROCLIMA's AI systems could deliver targeted messages that emphasise the consequences of inaction and individual responsibility in climate adaptation.
- **SDT** emphasises intrinsic motivation and autonomy in adopting sustainable practices. Through the use of AI-based decision support systems, NEUROCLIMA can enhance individuals' sense of agency by providing tailored recommendations and real-time feedback to support sustainable choices.

It is recommended that NEUROCLIMA integrates AI tools to provide personalised, contextualised feedback that encourages sustainable actions. These AI-enabled interventions would help overcome barriers such as lack of motivation or support, ensuring that individuals feel empowered to contribute to climate adaptation efforts.

9.2.3 Systemic Change: A Holistic Approach

While individual behavioural change is essential, systemic change is equally important, if not more so, given its potential impact. It is recommended that NEUROCLIMA emphasises the transformation of institutions, infrastructure and policies to support long-term climate adaptation and change all the helixes in the Quintuple helix model (Carayannis, Barth, & Campbell, 2012). **Ecological Systems Theory and the Behavioural Lever Framework (BLF)** should be used to examine how changes at the macro level can influence individual and collective behaviour:

- **Ecological Systems Theory** emphasises the interconnectedness of individuals and their environment. NEUROCLIMA could apply this theory by ensuring that policy interventions, community programmes and institutional frameworks are aligned to create environments that naturally support sustainable behaviour.
- The **Behavioural Lever Framework (BLF)** identifies six key levers - material incentives, regulations, choice architecture, social influences, emotional appeals and information - that can be used to change societal norms and institutional practices. NEUROCLIMA could operationalise these levers by embedding AI in decision-making systems to ensure that sustainability is integrated into public policies and institutional frameworks.

For example, NEUROCLIMA can use **AI-enabled predictive tools** to inform governments about climate vulnerabilities and infrastructure risks, helping to align policy frameworks with climate goals. Multi-level interventions - from local to international - are essential to ensure that systemic change is scalable and sustainable, and to increase the accessibility and normalisation of climate-smart practices.

9.2.4 AI-Driven Decision Support and Citizen Engagement

One of the outstanding innovations that NEUROCLIMA should incorporate into the D3.3 framework is the integration of AI technologies to drive both behavioural and systemic change. AI tools would provide:

- **Predictive analytics**, which would help policymakers forecast climate risks and identify potential vulnerabilities in the regions and/or geographies of their jurisdiction, enabling proactive urban and other planning and intervention.
- **Real-time monitoring** that would provide individuals with actionable insights into their environmental impact - whether through energy use, transport choices or waste management - and suggest immediate steps to reduce their carbon footprint.
- **Participatory governance models**, where AI-powered platforms facilitate citizen engagement in climate policy. These platforms would allow citizens to monitor progress, provide feedback, and work with institutions to design adaptation strategies.

9.2.5 Empowering Citizens and Policymakers

The D3.3 framework should emphasise the empowerment of both citizens and policy makers:

- For **citizens**, NEUROCLIMA should promote participatory tools such as **town hall meetings** and **deliberative democracy models**. Through these tools, individuals can collaborate with policymakers to co-create solutions tailored to their local climate risks and provide guidance for climate change adaptation processes. AI systems would further empower citizens by providing accessible data and personalised insights, helping them to understand their role in climate adaptation.
- For **policymakers**, NEUROCLIMA should provide **AI-driven decision support tools** that analyse large datasets - from climate models to resource management indicators. These tools would enable policymakers to make informed decisions and design adaptation strategies that are both **proactive** (anticipating future risks) and **reactive**(addressing immediate climate challenges). AI systems would streamline policy evaluation by providing real-time insights into the effectiveness of adaptation measures.

This dual empowerment would ensure that both top-down and bottom-up approaches to climate adaptation are integrated, promoting greater trust, accountability and efficiency in addressing climate risks.

9.2.6 Conclusion

It is recommended that NEUROCLIMA as a project adopts the D3.3 conceptual framework as a comprehensive strategy and guidance document to drive both the behavioural and systemic changes needed for climate adaptation. By leveraging AI tools, fostering citizen engagement, and promoting inclusive governance models, NEUROCLIMA can support the transformation needed to build a climate-resilient society. The integration of data-driven insights, participatory models, and systemic interventions would ensure that adaptation strategies are equitable, sustainable, and responsive to both individual and collective needs. Through these collaborative efforts, NEUROCLIMA could pave the way for a more resilient future where climate adaptation is both proactive and inclusive.

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ANNEX I - Glossary of Key Terms and Concepts

behavioural Models

1. **Theory of Planned behaviour (TPB)**: A psychological theory that suggests an individual's behaviour is driven by their intentions, which are influenced by their attitudes toward the behaviour, perceived social norms, and perceived control over the behaviour. In the context of climate adaptation, TPB helps explain why individuals engage (or fail to engage) in pro-environmental actions based on these factors.
2. **Norm Activation Model (NAM)**: A theory that focuses on how personal norms, moral obligations, and awareness of the consequences of one's actions influence pro-social and pro-environmental behaviours. NAM is particularly relevant to encouraging individuals to act on climate change when they feel a moral responsibility.
3. **Transtheoretical Model (TTM)**: A stage-based model of behaviour change that identifies five stages through which individuals progress: pre-contemplation, contemplation, preparation, action, and maintenance. TTM is useful in climate adaptation for designing interventions that support individuals at different stages of readiness to change.
4. **Self-Determination Theory (SDT)**: A theory of motivation that emphasizes the role of intrinsic motivation—acting out of personal satisfaction or internal values—over extrinsic rewards. In climate adaptation, SDT suggests that individuals are more likely to engage in sustainable behaviour when they feel autonomous, competent, and connected to others working toward the same goals.

Systemic Models

5. **Ecological Systems Theory**: Developed by Urie Bronfenbrenner, this model explains human development as influenced by different environmental systems. It is composed of four interconnected layers: the microsystem (individuals and their immediate environments), mesosystem (interactions between microsystems), exosystem (external systems that indirectly influence behaviour), and macrosystem (broader cultural, social, and economic environments). In climate adaptation, this model highlights how individual behaviours are shaped by broader systemic influences.
6. **behavioural Lever Framework (BLF)**: A model that identifies strategic levers to influence behaviour at individual and societal levels. These include material incentives, regulation, choice architecture, social influence, emotional appeals, and information. The BLF is critical for designing policies and interventions that drive systemic change for climate resilience.
7. **Socio-Ecological Model (SEM)**: A framework that outlines the complex interplay between individual behaviour and broader societal factors across different levels—individual, interpersonal, community, organisational, and policy. SEM emphasizes the need for multi-level interventions to address climate adaptation, as it integrates individual actions with larger institutional and policy frameworks.

Technological Integration in Climate Adaptation

8. **Artificial Intelligence (AI)**: The use of machine learning, data analytics, and other advanced technologies to optimise decision-making processes. In climate adaptation, AI is used for

predictive analytics, resource management, real-time monitoring, and personalised interventions to improve adaptation strategies and resilience.

9. **Predictive Climate Analytics**: AI-driven models that analyze vast datasets, including satellite imagery and historical climate data, to forecast climate risks such as extreme weather events, sea level rise, and temperature fluctuations. These analytics inform proactive adaptation strategies to mitigate potential impacts.
10. **Gamification**: The use of game design elements (e.g., points, rewards, challenges) in non-game contexts to motivate participation and behaviour change. In climate adaptation, gamification is used to engage citizens in sustainable practices through playful, competitive, and rewarding experiences.

Citizen Engagement Models

11. **Deliberative Democracy**: A form of participatory democracy where citizens are actively involved in policy discussions and decision-making. Citizen assemblies, which involve diverse groups deliberating on climate issues, are a key component of this model in climate adaptation strategies.
12. **Arnstein's Ladder of Citizen Participation**: A model that ranks levels of citizen engagement in decision-making from non-participation (manipulation) to full citizen control. In climate adaptation, it highlights the importance of moving beyond tokenistic involvement to true citizen empowerment.
13. **IAP2 Spectrum of Public Participation**: A framework for assessing the level of public engagement in decision-making, ranging from "inform" (providing information) to "empower" (citizens have full decision-making power). It is used to structure how citizens are involved in climate adaptation processes.