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Governance frictions at work? Explaining socio-technical transformation in waste-to-energy

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ABSTRACT

Sectors such as waste management can be understood as highly interconnected socio-technical, political, and economic systems characterized by ongoing tensions between stability and change. But what triggers socio-technical sector change and transformation? We state, there are governance frictions at work. This paper contributes to research on socio-technical transformation by examining how different governance regimes interact and generate governance frictions over time. Based on the cross-governance regime friction approach, we conceptualise transformation as a consequence of friction between competing and interacting governance regimes. Governance regimes stand for a specific set of configurations of institutional setting, regulatory framework, and actor orientation and decision-making. Taking the case of waste-to-energy, we identified three existing governance regimes. The reference governance regime of waste management is accompanied by two competing regimes, that are the circular economy and the climate and pollution governance regimes. The governance friction analysis reveals the following: waste management governance requires the continued provision of reliable disposal capacity and operational continuity, circular economy governance seeks to reduce waste flows and progressively limit the role of incineration, while climate and pollution governance increasingly subjects waste-to-energy to decarbonisation imperatives, carbon pricing and technological mitigation requirements. As a result, transformative pressures accumulate within infrastructures, investment cycles, operational routines, and business models. In our view, this conceptual and empirical research is a new approach to tackle the important field of analysing and explaining socio-technical transformation, and deliver fruitful insights on governance strategies and practices to cope with large-scale problems and grand challenges.

1. Introduction

Socio-technical transformations emerge through complex interactions between self-organization and political steering, in which clear cause-and-effect relations are often difficult to identify. Transformation processes are therefore not purely self-evolving or emergent, but unfold under varying degrees of strong or weak government hierarchy [1–3]. As the complexity and interdependence of socio-technical systems deepen, the need for governance approaches capable of anticipating and managing change over extended time horizons gain importance [4]. Traditional policy cycles, shaped by short-term political mandates, electoral incentives, and immediate economic pressures, struggle to address persistent and multi-generational challenges such as climate change, biodiversity loss, or the transition towards circular economies. Long-Term Governance has emerged as a conceptual framework [5] to address these tensions between self-organisation and target-oriented steering approaches. It embraces broad policy orientation that embeds foresight, institutional resilience, and adaptive capacity in decision-making unfolding over extended time horizons, often under conditions of ambiguous problem framings and shifting normative commitments [5–7].

In infrastructure-intensive sectors such as energy, mobility, or waste management, multiple long-term governance regimes increasingly converge on the same socio-technical systems. Their interaction generates overlapping governance configurations in which different normative visions, institutional logics, and policy instruments co-exist and interact. Governance frictions emerge [8,9] where these regimes impose partially incompatible demands on the same infrastructures and practices. To analyse these dynamics, this paper develops and applies the concept of cross-governance regime frictions, approaching socio-technical transformation as emerging through frictions between competing and interacting long-term governance regimes [8].

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Governance regimes are understood as institutionalized arrangements composed of actors, rules, policy instruments, and shared problem framings. They are typically oriented towards long-term normative objectives (e.g. sustainability, decarbonization, public health) embedded in specific temporal horizons (e.g. 2030 or 2050 targets), and operationalized through distinctive sets of policy tools.

These governance challenges become particularly visible in waste management and waste-to-energy (WtE). Waste governance represents a paradigmatic "wicked problem" [10,11], characterized by complex trade-offs, fragmented authority, and competing environmental, social, and technological priorities [10–12]. As one of the main pillars of residual waste treatment in the European Union (EU), WtE infrastructures provide an illustrative case for analysing socio-technical transformation processes, societal pressures, and contested future reconfigurations. In the 1980s, particularly in Western Europe, WtE technologies were promoted as responses to growing landfill dependency, combining waste volume reduction with energy recovery [13,14]. Over time, these infrastructures became progressively institutionalized, embedded in regulatory regimes, locked-in by capital-intensive investments, and coupled with energy grids and markets [15].

Against this background, the paper asks which governance regimes coexist around shared WtE infrastructures and what governance frictions emerge when these governance regimes converge, leading to transformative change over time. In the case of WtE, three long-term governance regimes intersect: waste management, circular economy, and climate mitigation and pollution control. Within the *waste management regime*, WtE has been institutionalized as a reliable and hygienic infrastructure for the safe treatment of residual waste. This regime stabilizes the industry by framing it as a necessary safeguard against environmentally inferior disposal options and as a backbone of municipal waste systems. The *circular economy regime* has progressively reframed waste as a "resource" [16], challenging the legitimacy of WtE by prioritizing material recovery, waste prevention, and closed-loop systems [17]. From this perspective, incineration is normatively repositioned as a residual and shrinking option, legitimate only as long as it does not undermine higher-value circular practices. At the same time, climate mitigation and pollution control has intensified scrutiny of incineration-related emissions [18], reconstituting WtE as a regulated emitter within decarbonization pathways. This regime questions WtE's climate compatibility while simultaneously promoting technological responses. This institutional triangulation makes WtE an exemplary site for analysing how overlapping governance configurations emerge in practice, how actors navigate and manage regime frictions, and how infrastructures could evolve – ultimately shedding light on the dynamics of socio-technical transformation. We empirically examine these dynamics through the qualitative case study of WtE infrastructures in Europe and its implementation at the national level in Germany. Germany here serves as an illustrative empirical context to make the research tangible, though it stands for comparable cases in the EU.

The paper proceeds as follows: Section 2 develops the conceptual framework of cross-governance regime frictions, introduces the case of waste management, and identifies the research gap. Section 3 outlines the empirical methods employed. Section 4 presents the empirical findings across the three governance regimes, while Section 5 synthesizes the results and discusses the implications of governance frictions. Section 6 concludes with reflections on overlapping governance configurations, policy implications, and directions for future research.

2. Theoretical background

2.1. Conceptual framework of cross-governance regime frictions

Sectors such as waste management can be understood as highly interconnected socio-technical, political, and economic systems characterized by ongoing tensions between stability and change. Stability is reproduced through established infrastructures, routinized practices, institutional arrangements, and accumulated investments, while change is driven by innovation, external pressures, and shifting political and societal expectations. In this paper, we focus on long-term transformation processes emerging from governance frictions across co-existing governance regimes. To conceptualise these dynamics, we develop the approach of cross-governance regime frictions and relate it to debates on governance, regime interaction, and socio-technical transformation.

In the following, we deduce from the literature the key dimensions of the cross-governance regime frictions approach, namely the 'governing', the 'cross-regimes', and the 'frictions'.

First, 'governing' socio-technical transitions requires institutional arrangements capable of sustaining coordination, shared visions, and legitimacy over extended time horizons, under conditions of uncertainty, path dependence, and normative contestation [19,20]. The notion of governance captures this governing environment by encompassing, according to Mayntz [21], both "a system of rules" – that is, a regulatory structure – and the modes through which these rules are enacted and implemented. Adopting an institutionalist perspective, regulatory structures are understood as institutional frameworks within which actors operating in each field align their activities. As an analytical framework, governance theory directs attention to the specific characteristics of these regulatory structures in a social field of action – regardless of how they emerge – and to their effects on the behaviour and strategies of the actors subject to them [21]. The literature on long-term governance extends this perspective by explicitly incorporating time and temporality, emphasizing foresight, resilience, and adaptive capacity [5,6,22,23], while also diagnosing the limitations of short-term policy cycles in addressing long-term transformation challenges [24,25].

Taking long-term timelines and transformation processes into account, we consider governance regimes as specific configurations of institutional settings, regulatory frameworks, actor orientations, and decision-making logics. This perspective invites analytical attention, on the one hand, to actors' interests and goals, the strategies they deploy to pursue them, and the resources at their disposal; and, on the other hand, to the modes and mechanisms through which interactions unfold, including patterns of coordination, conflict, and mutual adjustment. From this standpoint, industries are not governed by a single coherent regime. Rather, multiple governance regimes coexist and interact, thereby shaping long-term transformation processes [8,26].

Second, scholarship on regime interaction and governance complexity has shown how cross-regimes overlap and produce both synergies and conflicts [27–30]. In parallel, work on institutional layering [31,32,33,34] and governance assemblages [35] has traced how new policy layers accrete onto existing institutional architectures, creating overlapping arrangements through processes of gradual adaptation, bricolage, and recombination. Related debates on policy coherence and policy multiplicity further underline how overlapping regimes may generate institutional misfit, tension, and incoherence [36–40]. Drawing on these strands and on socio-technical transitions research on regimes, lock-in, and field dynamics [41,42], we conceptualise *overlapping long-term governance regimes* as governance arenas where structurally divergent institutional orders cohabit and interact around the same socio-technical systems. These interactions unfold not only discursively [43], but also materially and organisationally through shared infrastructures, investment cycles, and operational routines. Rather than forming integrated policy systems, overlapping governance regimes often produce fragmented, dynamic, and partially contradictory configurations of institutions, actors, and norms [44].

Third, the co-existence of regimes within such overlapping governance configurations foregrounds governance 'frictions' – that is, cross-regime frictions – as a constitutive dynamic rather than a governance failure [45–47]. By governance friction, we refer to patterned tensions and contradictions that arise when overlapping and interacting governance regimes advance competing expectations regarding goals, time horizons, and policy instruments. In the context of long-term governance, we distinguish three recurrent forms of cross-regime friction. First, normative contradictions and policy dissonance occur when regimes promote incompatible visions of “good” governance [48] and when policy instruments originating from different regimes interact in ways that produce conflicting incentives or unintended cross-effects [49], for example between greenhouse-gas reduction targets, material recovery objectives, and the continued legitimisation of WtE through energy recovery. Second, role ambiguity [8,50] arises when actors face inconsistent mandates across regimes, as when waste utilities are framed as hygienic service providers and regulated emitters. Third, frictions generate transformative pressures that may become generative [51,52]. While they can amplify inertia, investment risk, and operational uncertainty, they may also open space for reinterpretation, adaptive learning, and institutional innovation [39,40,53]. This generative dimension aligns with scholarship on tensions as productive governance mechanisms and on institutional improvisation in complex governance settings [54]. Frictions may therefore catalyse experimentation and strategic ambiguity, enabling actors to renegotiate priorities and reposition themselves within evolving governance configurations [55].

Cross-governance regime frictions can, therefore, be defined as the co-existence of several regimes each of which comprises a framework of rules, processes, behaviours and self-understanding, and institutions used to direct, control, and hold the system accountable. It defines how power is exercised, decisions are made, and stakeholders are involved in managing affairs. The parallelism of regimes causes frictions between them that induce transformational pressure through adaptation and change processes.

To operationalize these dynamics analytically, we distinguish three interrelated dimensions of cross-regime friction. First, normative frames and policies capture how each governance regime defines desirable futures and legitimate transformation pathways. Second, actors' roles and modes of action focus on how responsibilities, obligations, and expectations are distributed across industries, public authorities, and other stakeholders. Third, transformative pressures refer to the economic, technological, organisational, and infrastructural changes demanded of the sector. Within this framework, governance regimes are not treated as functionally equivalent. Instead, one regime may stabilise existing infrastructures and operational logics, while additional regimes introduce pressures for reorientation, radical redefinition, or adaptive integration. The intensity of these pressures may also vary, as governance regimes differ in their regulatory strength, economic implications, and capacity to impose transformative demands on socio-technical systems. Although the cross-governance regime friction approach stands within the broader tradition of transition studies, it directs analytical attention towards the consequences of overlapping long-term governance regimes.

The cross-governance regime friction approach relates to several alternative concepts and approaches within socio-technical transformation research. In the field of transition studies, scholars have explored medium- and long-term transformation processes from a socio-technical systems perspective, combining narrative analyses with more practical guidelines [26,27]. A key perspective of this research area is on understanding, analysing and encouraging processes and cause-impact chains of socio-technical change. Within this field, several popular approaches have been developed, for instance, strategic niche management [28,29], transition management [30–32], and the multi-level perspective (MLP) approach [27,33,34]. The latter conceptualizes transitions as an interplay of dynamics between the landscape (macro-level), regime (meso-level), and niches (micro-level). MLP thereby functions as a heuristic device, or middle-range theory, meant to direct “the analyst's attention to relevant questions and problems” concerning transitions [35]. In contrast, transition management aims to support decision-makers and other actors in making a transition, which is a long term, cross-domain, cross-scale, multi-actor, and multi-domain process. As a result, transition studies research the process of change and propose tools for understanding and managing – that is governing – complex socio-technical system transformations. Another approach is the concept of Sociotechnical Imaginaries [56] from the field of Science and Technology Studies. Central to this approach is the structural significance of the human capacity for imagination as a constitutive, formative element of future developments. The cultural factor of collective imagination thus becomes a significant factor in shaping not only possible but also probable futures inducing transformational pressure. Promises, visions, and expectations are embedded in scientific practices and the organization of science; its actors thus shape future trajectories in the fields of research and innovation. In doing so, societies exhibit parallel, partly complementary, and partly competing imaginations [8].

2.2. *The case of waste management and waste-to-energy*

Waste from human activities and its management has a long tradition tracing back to very early human history, with handling of waste evolving alongside social organization, production systems, and material practices [57,58]. In modern consumer-oriented societies, however, waste governance faces growing challenges related to increasing waste volumes, complex material flows, and the need for coordinated policy responses across multiple governance levels and sectors [58,59].

Within the European context, waste policy has long been grounded in public health protection and regulatory harmonization, aiming to prevent environmental disparities across Member States. The Waste Framework Directive (75/442/EEC) defined waste broadly as any substance or object discarded, intended to be discarded, or required to be discarded by its holder [60]. By the 1980s and 1990s, the policy rationale increasingly shifted towards environmental protection and pollution control [14], laying the groundwork for stricter landfill regulation. The Landfill Directive (1999/31/EC, amended by Directive 2018/850/EU) promoted waste diversion and the reduction of biodegradable municipal waste sent to landfill [61]. Although it never explicitly promoted incineration, its diversion targets created strong pressures for alternative treatment routes.

The Directive 2000/76/EC on the incineration of waste represents the first EU legislation dedicated exclusively to waste incineration. Its regulatory focus lies on waste incineration and co-incineration plants, without reference to WtE as a political or sectoral concept [62]. The notion of incineration with energy recovery was formalized later through the Waste Framework Directive (2008/98/EC), which introduced the *waste hierarchy* - often depicted as an inverted pyramid with prevention, reuse, recycling, recovering at the top, and disposal as the last-resort option. Within this framework, a clear distinction is made between disposal operations (D10: incineration without energy recovery) and recovery operations (R1: use principally as a fuel or other means to generate energy) [63]. From this point onwards, EU legislation systematically refers to incineration of waste *with* energy recovery.

The term “waste-to-energy” itself, however, does not originate in primary EU legislation. Instead, it emerged in technical literature, European Environment Agency (EEA) reports, and European Commission policy documents following the 2008 Directive. This shift in terminology reflects a broader political and discursive repositioning: whereas incineration had previously been framed predominantly as a pollution-intensive activity requiring strict regulation (see Directive 2000/76/EC), it was subsequently recast as a recovery operation contributing to the circular economy for non-recyclable waste. The label “waste-to-energy” thereby conferred sectoral legitimacy by emphasizing the role of incineration as energy infrastructure producing electricity and heat, rather than merely as an end-of-pipe waste treatment option. In our case-study, we focus specifically on these recovery operations, with a particular attention to WtE.

A key goal of EU waste policy is to reduce the amount of waste sent to landfill, aiming to limit landfilling to 10% of municipal waste by 2035 [64]. In 2021, several Member States, including Finland, Belgium, Sweden, Denmark, the Netherlands, and Germany, have achieved low landfill rates partly through extensive incineration capacity [65].

However, while incineration contributes to energy recovery, it does not necessarily lead to higher recycling rates. For instance, Norway, with similar policy frameworks to the EU, experienced a substantial increase in waste incineration over the past decade, with only marginal improvements in recycling performance [66]. Similar tensions can be observed in cities such as Madrid, where incineration contributes to landfill reduction while simultaneously increasing the carbon footprint of waste management systems [67]. In Germany, the situation is similar to that in the Scandinavian countries, where there is an highly regulated system, a high incineration capacity, and landfills that are being phased out [68]; besides that, the waste-based energy contributes approximately 3.7% of Germany's final energy demand [69]. In contrast, Eastern European countries have historically relied on landfills and are heavily dependent on European funds to finance their waste management systems, in countries such as Romania and Bulgaria more than 50% of waste is disposed of in "unspecified landfills" [68].

Circular economy policies aim to minimize waste generation and optimize resource use, which in turn influences incineration practices by promoting recycling and reuse. However, higher recycling rates can reduce the availability of combustible materials for incineration, potentially making it less economically viable [67]. On one hand, the generation of electricity and heat through incineration can prevent greater environmental damage from landfill sites. On the other hand, it may also hinder the long-term transition to a circular economy by encouraging waste production, as incinerators require large volumes of waste. Existing policies often fail to account for the inherent complexity of waste management systems [66]. The transformational change process in the WtE case sets the boundary of our leading research question, the study's novelty, and the methodological approach as laid out in the next section.

2.3. Research gap, research question, and research novelty

Within transition studies, there remains a need to better analyse how transformation processes unfold in infrastructure-intensive sectors characterized by highly interconnected socio-technical, political, and economic systems. Taking WtE as an empirical case, the analysis focuses on the simultaneous influence of three governance regimes, i.e. *waste management*, *circular economy*, and *climate and pollution*, which advance distinct normative frames and policies, actors' role expectations, and transformation demands towards WtE infrastructures and practices.

Thus, our leading research question reads as follows: *Which leading governance regimes coexist, and what governance frictions emerge when these regimes converge on shared waste-to-energy infrastructures?* Long-term transformation through governance frictions, thus, will be analysed by the case of waste management and WtE.

Building on the waste management long-term transformation perspective, the research makes three novelty contributions. First, it shifts the unit of analysis from single governance regimes to overlapping long-term governance configurations anchored in shared socio-technical infrastructures, where multiple regimes operate in parallel and impose partly incompatible expectations. Second, it advances cross-governance frictions as an analytical lens examining how the co-existence of governance regimes translates into organisational, economic, and infrastructural consequences. Third, it operationalises cross-governance frictions through three analytically distinct dimensions (i.e. normative frame and its policies, actors' roles and actions, transformative pressures), which structure the empirical analysis of WtE at the intersection of the climate and pollution, circular economy, and waste management regimes.

Conceptually, the article contributes to scholarship on long-term governance [5] by theorising overlapping long-term governance configurations as dynamic and structurally incoherent arrangements rather than as coherent or sequential policy frameworks. Rather than assuming regime succession or replacement, the analysis highlights how multiple governance regimes remain simultaneously operative over extended time horizons. To structure and operationalize the empirical analysis, the governance regime approach is disaggregated into three analytical dimensions:

- *normative frames and policies*, capturing how each regime defines desirable futures and legitimate pathways for WtE materializing them into policies;
- *actors' roles and modes of action*, focusing on how regimes assign responsibilities and obligations to industry, public authorities, and other stakeholders;
- and *transformative pressures*, referring to the economic, technological, and organisational changes demanded of the sector.

Together, these dimensions provide the basis for identifying and comparing cross-regime frictions across the three governance regimes analysed. The conceptual framework is summarized in Fig. 1.

3. Methods

This study employs a qualitative, case-oriented research design to investigate how developments across different governance regimes affect the socio-technical system centred on WtE. The empirical focus is on the European WtE governance system, shaped by the interaction of circular economy, climate and pollution, and waste management policy regimes. While the analysis primarily addresses governance dynamics at the European level, Germany serves as an empirical context to examine how these dynamics are interpreted and implemented in practice, given its early landfill diversion, extensive WtE infrastructure, and strong exposure to European policy developments.

The empirical analysis combines policy document analysis with semi-structured interviews to examine the evolution of waste management pathways as they relate to WtE, with particular attention to socio-technical narratives and values, conflicts between strategic orientations, and the governance mechanisms through which transformation is pursued.

The research proceeded in two stages. The first stage was exploratory, a review of publicly available sources was conducted, including legislative texts, policy documents, reports, academic literature, and press material. The search process relied on targeted searches of institutional websites and EU policy databases, as well as references within relevant documents. A corpus of 27 key policy and regulations (Appendix A) were selected through a purposive and iterative approach based on their relevance to WtE governance and their connection to the three governance regimes. These documents were analysed, classified according to the three governance regimes, and triangulated with the interview data. This phase also informed the identification of key actors and organizations within the field.

In the second stage, semi-structured expert interviews were conducted with representatives of organizations involved in WtE governance at the EU and German levels. Interviewees were selected through a combination of purposive [70] and snowball sampling [71]. Initial participants were identified through a stakeholder analysis aimed at mapping key actors across policy, industry, and civil society domains [72]. Additional interviewees were recruited through recommendations, allowing the sample to expand towards knowledgeable actors within the field.

Expert interviews are a permanent feature in the toolbox used in empirical social research. The fieldwork consisted of 13 semi-structured expert interviews conducted between December 2024 and April 2025, each lasting approximately 45 min. The sample included public authorities, industrial associations, WtE operators, and non-governmental organizations. Although limited in size, the sample targets actors directly involved in shaping, implementing, or contesting WtE governance, allowing for in-depth insights into cross-regime dynamics. Expert interviews have the advantage that a small number is often sufficient, since their expert knowledge can be specifically tapped into to provide

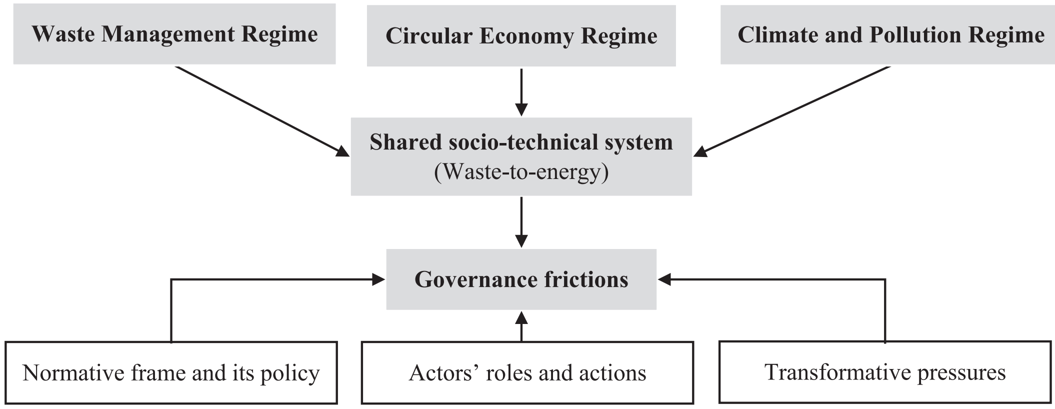

Fig. 1. Analytical representation of the cross-regime frictions applied to the waste-to-energy case. Source: own elaboration.

enough empirical data for exploring a topic. Data collection continued until information saturation was reached regarding the core analytical dimensions of the study, i.e. normative frames, actors' roles, and perceived transformative pressures. Table 1 summarizes the composition of the interview sample.

The interviews explored how stakeholders perceive ongoing transformations in European waste governance and its implementation in Germany and the European contexts, with particular attention to the evolving role of WtE. The interview guide was set in five thematic blocks: (I) the evolution of waste governance narratives, (II) the role and positioning of WtE within circular economy and climate and pollution governances, (III) policy impacts and industry/municipal adaptation, (IV) governance tensions across actors and levels, and (V) future outlooks and transition pathway. While core themes remained consistent, questions were adapted to reflect the interviewees' institutional roles and expertise. All interviews were recorded, transcribed, and coded using MAXQDA.

The identification of *governance regimes* was informed by the initial document analysis and existing literature, which highlighted distinct but overlapping policy logics related to circular economy, climate and pollution, and waste management. These regime distinctions were subsequently explored and refined through the interviews. The analysis followed a comparative and iterative approach, combining policy document analysis and interview material. This triangulation enabled the identification of *governance frictions* across governance regimes and supported the examination of how actors interpret and respond to potentially conflicting long-term policy demands. Coding focused on inconsistencies and tensions across regimes in terms of normative orientations, actors' role expectations, and transformation demands directed at WtE. The analysis combined deductive categories derived from the conceptual framework with inductive insights emerging from the empirical material. Coding was conducted independently by two researchers and subsequently compared and refined through iterative discussion, enhancing the robustness of the analytical process.

Several measures were adopted to enhance the reliability and validity of the analysis. First, triangulation was ensured by combining multiple data sources and perspectives across governance levels and stakeholder groups. Second, the use of semi-structured interview guides helped ensure consistency across interviews while allowing flexibility to explore interviewees' expertise. Third, the iterative coding and cross-checking process contributed to analytical robustness. While the study focuses on a specific empirical configuration, it aims at analytical generalization. By elucidating how multiple governance regimes interact around shared infrastructures, the findings contribute to theory-building on cross-regime frictions and are potentially transferable to other infrastructure-intensive sectors subject to overlapping long-term policy agendas.

Table 1
Overview of interviewees.

Vertical governance level	Stakeholder type	Number of interviews (codes)
European	– Environmental NGO – Industrial association – Public organization	– 1 (*i01*) – 4 (*i02, i06, i07, i12*) – 1 (*i04*)
National (Germany)	– Industrial association – Public organization – Waste-to-energy operators	– 2 (*i05, i09*) – 2 (*i03, i08*) – 3 (*i10, i11, i13*)

Source: own elaboration.

4. Findings: Cross-governance waste management regime comparison

Based on the analysis of policy documents and stakeholders' interviews, we identified three governance regimes that are particularly relevant for the WtE sector. These regimes do not operate sequentially but simultaneously shape WtE infrastructures, practices, and expectations. First, *waste management* constitutes a *reference point* governance regime structured around established waste treatment hierarchies and infrastructures, within which WtE plays a key role in the treatment of residual waste [73]. Second, the *circular economy* emerges as an *emerging* governance regime that prioritizes closed loop cycles for reuse, repair, refurbishment, remanufacturing, and recycling, and explicitly aims to minimize residual waste volumes, thereby redefining the legitimacy and scope of waste-to-energy. Third, the *climate and pollution* governance operates as a *cross-cutting* regime that increasingly imposes climate mitigation and pollution control requirements on waste management practices, including WtE [59].

4.1. "Waste management" governance regime

4.1.1. The normative frame and its policies

Incineration with energy recovery, commonly referred to as WtE [74], has been implemented in several Member States, including Germany, Denmark, the Netherlands and Belgium, since the 1970s, and emerged as a residual treatment option adopted at the EU level in later decades, [13,14,75]. The normative and regulatory foundations crystallized a WtE regime centred on the safe, reliable, and economically viable treatment of residual waste with heat and power benefits that serves as an attractive and practical option away from landfilling, what can be called the **landfill-diversion imperative frame**. Anchored in the waste hierarchy, the regime legitimizes WtE as a recovery operation, positioned above landfill but below prevention, reuse, and recycling [13]. As one respondent summarized, WtE plants remain "a public service" with a duty to "treat [waste] in a reliable and environmentally safe

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way" (*i12*). In practice, however, the hierarchy is not applied uniformly across the EU, with significant variations often shaped by existing infrastructure, political preferences, and institutional capacity [76]. The WtE regime's landfill-diversion imperative is not merely aspirational but risk-oriented: interviewees recounted Germany's 2005 ban on landfilling untreated municipal solid waste as a decisive measure that other EU states still have not matched, with landfill remaining above 40% in parts of Europe and a 10% target for 2035 still distant (*i06*) [77,78]. Several respondents linked landfill diversion not only to hygiene but also to climate, stressing the long "methane tail" of landfills – limited gas capture early on, decades of post-closure emissions, and the impossibility of flaring dilute methane (*i11*).

Another core rationale can be called the **double benefit waste and energy frame** covering the win-win of environmental responsible waste treatment and energy provision. On one hand, waste flow control aims at preventing environmentally inferior practices such as cross-border shipments to weaker environmental standards jurisdictions. This objective is articulated in Regulation (EU) 2024/1157, which underscores the need to regulate shipments of waste to ensure that they are managed in a way that protects human health and the environment [79]. As one interviewee explained: "If it's not regulated, it goes off in not sustainable ways, because you don't pay to have to buy a good, you pay to get rid of it", hence "good regulation is important for the waste sector" (*i02*). In addition, the WtE regime is normatively expected to adapt to evolving waste streams. Stakeholders stressed that some residual fractions are permanent: hazardous, degraded, or composite materials "for which there is no solution for recycling" (*i05*). And from that end, incineration of waste delivers the surplus benefit of energy provision: "Waste-to-energy was developed with a lot of investment in abatement or pollution techniques or dealing with sanitary issues, and avoid emergency. Then we also increased the energy recovery in order to have a win-win: you avoid waste around, you avoid pollution, and you also get energy: bingo" (*i12*). In this sense, incineration is not cast as competing with recycling but as a complement – guaranteeing controlled treatment for unavoidable residues while delivering co-benefits such as district heating or post-incineration metal recovery. Interviewees noted that technological pathways (e.g., chemical recycling for mixed municipal streams) have not yet materialised at industrial scale, reinforcing the role of WtE as a proven safeguard within a system that must balance regulatory ideals with material and infrastructural realities (*i03, i06*).

4.1.2. *The actors' roles and actions*

The regulatory framework of waste management is defined by its **layered governance** along different levels from EU's supra national over national federal state towards the regional/local levels. Building on these normative principles, the waste hierarchy has been operationalized through a layered mix of regulatory, economic, and informational instruments. The Waste Framework Directive (2008/98/EC) provides definitions, mandates waste management plans, and created registers to monitor and collect waste flows, and sets recycling targets [63]. However, while European legislation sets the overarching principles, implementation is devolved to national and subnational authorities. In Germany, for example, "waste management is made at the state or municipal level only […] within the frame of legislation" (*i5*). Federal states (Länder) and municipalities (Kommunen) develop Waste Management Plans (Abfallwirtschaftspläne) that combine disposal capacity planning with everyday responsibilities such as maintaining cleanliness and organising separation systems. This decentralisation ensures local responsiveness but also creates interdependencies: operators remain bound by upper-level rules on permitting, investment approvals, and compliance.

In the WtE regime, actors' roles are defined by the day-to-day imperatives of ensuring capacity, environmental safety, and economic viability of the WtE business. EU waste legislation often assigns roles indirectly, **shaping responsibilities** without naming actors explicitly as anchored within the layered governance approach. The multi-level structure is particularly evident in Germany, where state and regional authorities define the permitting and planning frameworks while municipalities operate or procure collection and sorting services. This layered governance creates interdependencies: local operators may seek operational improvements but remain highly dependent on legislation at the upper administrative level for approvals and compliance (*i08*). While within EU directives local and regional authorities are frequently referred to only through Member State obligations, yet they are in practice responsible for implementing separate collection systems, prevention programs, and recycling infrastructure. However, persistent gaps – "lots of organic waste" still in residual bins, valuable materials lost "due to ignorance, lack of knowledge, or lack of interest" (*i08*) – translate directly into waste management system inefficiencies. Similarly, EU directive shape the citizens' role requiring separate collection "at source" making them responsible for sorting waste, while with the approach of Extended Producer Responsibility financial and organisational obligations are transferred onto producers.

As a result, the layered governance shapes responsibilities with operators and municipalities as key actors with role assignment as custodians of hygiene and infrastructure, **balancing service provision with affordability**. WtE operators retain a central role as providers of reliable and safe residual waste treatment, ensuring compliance with landfill diversion targets and environmental protection standards, and to operate economically (at least achieving cost coverage). They are consistently described as economic, environmental, and social gatekeepers with business model responsibility: in this role they serve for the destruction of hazardous substances that cannot be safely landfilled or recycled (*i03, i12*), fulfilling what many respondents termed a "hygienic task (…) to treat [waste] in a reliable and environmentally safe way" (*i02*). This responsibility extends to managing contaminated or degraded materials for which "there is no solution for recycling" (*i05*), as well as to treating hazardous fractions that arise from industrial, commercial, and household waste streams.

4.1.3. *The transformative pressures*

While waste management regime legitimizes WtE as a permanent safeguard against landfill and hazardous waste, it simultaneously exposes operators to mounting economic and operational pressures. These derive not from abstract visions (e.g., circularity), but from the material and financial realities of keeping large-scale facilities viable under shifting waste flows, regulatory expectations, and volatile markets. A central tension, thus, is WtE market economics dependence relying on high utilisation rates rationales. Respondents emphasised that even small drops in throughput rapidly translate into competitive pressure: when WtE plants run below 95% capacity "the plants try to buy more waste" (*i05*), seeking to secure additional waste inputs to maintain thermal stability and economic efficiency. In highly competitive markets (e.g., Germany), this may lead to lower or even negative gate fees, effectively incentivizing waste inflows to keep plants running close to full capacity. Such dynamics place operators in an **institutionalized market vs. policy paradox**: while policy increasingly promotes waste reduction and recycling, the financial stability of existing facilities relies on a steady or even growing supply of combustibles. Economic cycles exacerbate this fragility: "When the economy goes down, then the waste amount goes down, the prices go down and the waste management goes down too," as one practitioner put it, underscoring the vulnerability of WtE to broader market fluctuations (*i05*). The governance structures through which many plants are owned and operated further intensify these constraints. Facilities co-owned by multiple municipalities face strong political resistance to raising gate fees, even when upgrades or maintenance are required. In such contexts, operators are caught between the obligation to provide uninterrupted, safe disposal and public expectations that waste treatment remain low-cost. This tension reinforces reliance on securing stable waste streams through long-term contracts or inter-municipal agreements, but leaves little room for adaptive responses to changing waste composition.

Feedstock quality, composition, and dynamics represent another axis of transformative pressure. The expansion of source separation and mixed-waste sorting has not eliminated residual streams; rather, it often generates substantial volumes of rejects that require thermal treatment. Operators have observed that over 40% of the plastics collected for sorting ultimately end up being incinerated (*i05*), while mechanical-biological treatment plants only recover a small proportion of metals before sending most of their outputs to WtE facilities or landfills. Rising heating values in residual fractions increase operational complexity, forcing plants to adjust combustion conditions without reducing overall volumes. Far from being displaced by upstream innovations, WtE is therefore continually re-inscribed as the absorber of system inefficiencies. Cross-border dynamics exacerbate these vulnerabilities. Where landfill remains cheaper and less regulated, as in several EU Member States, waste exports undermine local utilisation rates and erode investment security. Respondents highlighted cases in which waste collected under the guise of recycling crosses borders, only to be incinerated or landfilled in less regulated Member States due to contamination or market constraints (*i03, i10*). In this way, uneven enforcement across Europe destabilises national and municipal planning, subjecting operators to uncertainties beyond their control (*i02*). These multiple pressures converge on the same contradiction: WtE is indispensable for waste management, but its business model is continuously destabilised by the very policies and market shifts that reaffirm its necessity.

4.2. "Circular economy" governance regime

4.2.1. Normative frame and its policies

The transition from a traditional waste management approach to a circular economy framework in the EU has been gradual, marked by increasing conceptual and regulatory overlap, with circular economy policies building upon established waste management principles. In this sense, the circular economy reframes a *cradle-to-grave* logic into a *cradle-to-cradle* rationale, while retaining the legal scaffolding of waste policy. This shift can be described as a **"grave-to-cradle" turn** within the circular economy regime. Interviewees articulated this transition in closely aligned normative terms. They described the circular economy regime as grounded in the idea that waste should be prevented, reduced, and continuously cycled back into productive use, with a fundamental shift in perspective whereby "waste is a resource" rather than a residual to be eliminated (*i02*). Several respondents further stressed that the circular economy is not simply a waste management policy but an economy-wide vision, "a state of the economy we are aiming at" (*i05*). Within this vision, prevention has clear primacy – "the best waste is the waste that is prevented in the first place" (*i01*) – while resource retention is linked to strategic autonomy: "since Europe is scarce in raw materials, we need to try to keep materials as much as possible in Europe" (*i02*). The 2015 Circular Economy Action Plan (COM(2015) 614) was the European Commission's first systematic attempt to codify this economy-wide turn, prioritizing material recovery and treating energy recovery as a lower-tier option under the waste hierarchy [80]. Interviewees captured the corresponding cultural and political resonance of this turn: where disposal once connoted modernity and efficiency, the emphasis now lies on minimising residual fractions, with only non-recyclable waste deemed suitable for incineration.

This aspirational horizon currently stands as breakthrough between "paper and practice". On one hand, it has strong political appeal since "politicians really bought into it (…) everybody wants to be part of the circular economy" (*i01*). On the other hand, however, some interviewees warned that the package was "a breakthrough" only on paper, and circular economy is more of a political narrative than an operational reality, unevenly implemented across Europe. In practice, recycling rates remained constrained by design and material quality, significant shares of waste continued to be incinerated or landfilled, and there was still no binding prevention targets for municipal waste (*i01*). Precisely because circular economy narrows the legitimate scope for end-of-pipe solutions, the Commission issued a communication detailing the role of WtE in the circular economy in order to clarify WtE's residual role [74]. This Communication explicitly states that WtE can support circular economy only if it does not hinder higher-level options like reuse and recycling, and should be guided strictly by the waste hierarchy. It also cautions against incineration, particularly in contexts where overcapacity could lead to stranded assets and lock-in effects, ultimately discouraging investment in recycling and other circular practices. Some interviewees echoed these concerns indirectly, pointing to the contradictions in the push for "high-quality recycling". While normatively attractive, these standard risks delegitimizing "normal" recycling and generating larger volumes of rejects, which then flow back into WtE. Moreover, closed-loop recycling is "not always possible, it's very expensive, and there is always the question of who is going to pay for that" (*i06*). Elsewhere, circular economy principles are more embedded but still face structural tensions between political aspiration and technical, economic, and material realities. As one respondent put it: "particularly in the countries where they have a low level of separate collection and a lot of landfilling, the focus is really on incineration – they start from the wrong end: they start building infrastructures just to get rid of waste, rather than building infrastructures keeping in mind the future. You know, you're not going to get very far by just burning stuff" (*i01).*

Directive (2018/851/EU) reinforced the waste hierarchy and advanced the transition towards a circular economy by promoting resource efficiency and sustainable material management. It also called on Member States to phase out subsidies inconsistent with the hierarchy [81]. Taken together, these normative shifts increasingly aligned waste policy with circular economy principles, **framing WtE as a residual option** within a broader transition towards material circularity. The 2020 Circular Economy Action Plan consolidated this trajectory by explicitly avoiding the promotion of WtE and instead prioritizing product reuse, recycling, and the development of secondary raw materials markets [82]. However, interviewees emphasised the material and political limits of this transition. Even if product design improves, "there are only so many cycles that you can recycle" before materials degrade or contaminants accumulate (*i09*). Hazardous fractions and composite products are also expected to persist, implying that some residual waste will inevitably require safe treatment (*i05, i09, i12*).

4.2.2. The actors' roles and actions

In the circular economy regime, the redistribution of roles reflects the normative primacy of prevention, reuse, and high-quality recycling over disposal. WtE operators, once seen as technical enablers of landfill diversion under the waste hierarchy, are now problematized in circular economy discourse: framed as locking in linear waste flows and destroying potentially recoverable materials, WtE infrastructures are increasingly treated as a problematic legacy that may conflict with the long-term goals of circularity. These actors are also seen as residual actors whose legitimacy depends on their ability to deal only with the fraction of waste that cannot be recycled to the required quality standards. As an interviewee stressed, incineration should be restricted to "what we cannot recycle in high quality" (*i05*), with respondents acknowledging that rejects from recycling remain unavoidable (*i02, i09, i13*). This positions WtE at the bottom of the circular hierarchy: still necessary in the short to medium term, but normatively expected to contract over time.

In this shifting landscape, the sector does not passively accept its "residualisation". Instead**, WtE operators actively reposition** themselves within circular economy narratives by foregrounding their contributions to resource management. These actors emphasise post-incineration recovery – extracting metals, reusing mineral fractions from bottom ash, and thus "replacing primary raw materials" (*i02*), particularly important in a European context with scarce resources.

They also stress that, “when you incinerate things, you produce something useful, which is the energy” (*i02, i05, i13*). Such claims seek to recast incineration as part of material and energy loops rather than a mere end-of-pipe solution. However, this discursive repositioning co-exists with persistent criticism that WtE “locks in” linear systems by destroying resources that could otherwise be retained, reinforcing the conditional and contested character of its role in a circular transition.

At the European level, **EU policymakers act as vision-setters**, embedding circular economy principles into legislation. The European Commission plays a central role in defining ambitious targets and promoting systemic redesign, while simultaneously navigating political compromises in the Parliament and Council – arenas in which industry lobbying has been shown to dilute reuse and prevention measures, as illustrated by debates on packaging regulation (*i01*). Member States are expected to implement separate collection systems and enforce prevention targets. Municipalities, in turn, are tasked with improving source separation and with making infrastructural decisions that influence residual waste flows, such as whether to integrate mixed-waste sorting facilities into waste management plans (*i01*). In practice, these roles are enacted unevenly. In some regions, local governments act as pioneers, introducing door-to-door collection systems and quickly increasing recycling rates. In others, progress remain limited, with persistently low levels of separate collection and continued reliance on landfilling or incineration (*i01*).

One of the main differences between the WtE regime and the circular economy regime is the shift in **responsibility towards designers and manufacturers**, who are increasingly expected to prevent waste generation through eco-design and product durability standards [82,83]. Yet, interviewees repeatedly stressed that design is the critical bottleneck: even diligent citizens cannot properly sort composite products, such as disposable vapes with integrated batteries and coils, which “nobody can afford to dismantle” and thus end up in residual waste (*i09*). More broadly, the absence of stringent design-for-recycling rules means that producers continue to prioritise branding, variety, and single-use convenience over recyclability (*i01*). As one respondent argued, systemic improvements could be achieved if packaging were standardised: “if all shampoo bottles looked the same, without fancy designs” – but “that's obviously not how the world works” (*i09*). Civil society organizations also gain a more strategic role, both in advocating for ambitious targets and in educating citizens to participate in circular practices. Citizens themselves are cast as pivotal actors in enabling circularity, primarily through proper source separation, reuse practices, and responsible consumption choices. Interviewees noted that the effectiveness of high-quality recycling systems hinges on citizen compliance, with poor sorting or contamination undermining material recovery. Citizens are also expected to embrace prevention-oriented habits (repairing, reusing, and avoiding unnecessary purchases), aligning individual behaviour with the systemic goals of the circular economy regime (*i11*).

4.2.3. The transformative pressures

There is contradictory pressure on WtE transformation. Within the circular economy regime, WtE operators face a persistent normative pressure to **reduce WtE's role and size** in the waste system. Circular economy policy and discourse assume that upstream measures – better product design, hazardous substance restrictions, improved labelling, and high-quality recycling standards – will progressively divert material away from incineration. The underlying ambition is that WtE capacity should decline over time, as more waste is captured for reuse or recycling. However, respondents pointed out that this shift is not straightforward in practice. Efforts to raise recycling standards have the unintended effect of increasing the share of material rejected from recycling processes, which then flows to WtE. Thus, higher recycling standards lead to higher residual waste. As one interviewee warned, limiting recycling “only to the high-quality material” risks producing “more rejects, that could not be treated in a specific way” (*i06*). In such cases, the pressure to improve recyclate quality paradoxically secures WtE's position as a necessary outlet. Economic conditions further complicate this picture. For certain waste streams – particularly plastics – recycling remains commercially fragile. As one respondent explained, “the only driver for using recycled material is the cost (…) and in certain markets (…) the price could not be lower than the virgin material” (*i06*). When treatment costs exceed the price of virgin feedstock, demand for secondary materials drops, and WtE continues to absorb significant volumes of residuals.

Alongside upstream diversion efforts, circular economy policy exerts a more **direct technological and operational pressure** on WtE: the expectation to increase post-incineration material recovery. These expectations require investment in additional treatment stages, changes in plant design, and a reframing of the sector's identity from energy provider to supplier of secondary raw materials. In addition, the symbolic politics of circular economy heighten the scrutiny of WtE. The regime's political appeal compels operators to publicly demonstrate their alignment with circularity, even as stakeholders continue to perceive their core activity as incompatible with long-term circular economy goals. This creates a double bind: WtE is expected to handle unavoidable residuals efficiently today, while simultaneously being urged to make itself redundant in the future.

4.3. Climate and pollution governance regime

4.3.1. Normative frame and its policies

The inclusion of WtE within the climate and pollution regime reflects a broader evolution of EU environmental policy, which has shifted from a narrow focus on disposal and public health to a regulation introduced strict controls on integrated governance of climate, resources, and emissions. This can be summarized as a **“pollution control baseline” frame.** Early policy pollutants like NO_x, SO_2, dioxins and heavy metals, embedded incineration in a public health and environmental protection agenda [62]. Although compliance increases operational costs, the ability to generate energy, combined with renewable energy incentives, still promotes WtE as a viable treatment route [13]. Respondents emphasised that even today the sector is subject to “the most stringent rules in EU legislation when it comes to pollutants other than CO_2” (*i07*), with emission limits periodically tightened through a further developing regulatory framework [84,85]. This continuity illustrates a regulatory layering process: climate mitigation is added to, rather than replacing, pre-existing obligations to protect air quality and public health (*i05*).

However, there is a reframing based on principles of universality when it comes to climate mitigation policy. Regulators increasingly stress that all sectors, including waste management, must contribute to the EU's overarching goal of climate neutrality. Stakeholders recognize the equity rationale: “you want to have a level playing field within the EU” in order to avoid “carbon leakage towards landfilling” or other less regulated outlets (*i09*). This equity principle seeks to prevent competitive distortions while ensuring that climate responsibilities are shared across all waste treatment options. Such arguments underpin the revision of Directive 2003/87/EC through Directive (EU) 2023/959, which mandates that by 2026 the Commission must assess the feasibility of including municipal waste incineration in the Emission Trading System (ETS), with possible entry into force by 2028.

The stated rationale is that emissions from waste incineration – long unpriced – should be fully accounted for in order to reinforce climate goals, avoid carbon leakage, and incentivize reuse and recycling in line with the circular economy and the waste hierarchy [86]. This **“climate mitigation integration” frame** encompasses economic, normative, and technological dimensions. A first turning point in this reframing is the introduction of the EU ETS, which institutionalized climate accountability for large CO_2 emitters. While the ETS initially applied only to installations burning fossil fuels, its underlying logic progressively expanded towards additional sectors.

During the 2010s, EU climate governance evolved into a more comprehensive low-carbon transition framework, integrating greenhouse gas reduction goals across policy domains, most notably through the European Green Deal (COM (2019) 640). This trajectory culminated in the European Climate Law (Regulation (EU) 2021/1119), which made the objective of climate neutrality by 2050 legally binding [87]. Within this evolving framework, infrastructures such as WtE are normatively reframed as sources of greenhouse gas emissions – particularly from fossil-based plastics – that must be addressed within climate neutrality pathways. As one respondent put it, "the waste sector is […] the downstream of everything" and therefore an integral part of both the climate problem and its solution (*i06).*

Second, normative tightening also operates beyond the ETS through sustainable finance governance. The Taxonomy Regulation (EU) 2020/852 excludes waste incineration (except for hazardous non-recyclable waste) from activities classified as environmentally sustainable, explicitly citing its misalignment with circular economy principles. This exclusion not only constraints access to green finance but also reinforces the normative expectation that WtE must progressively align with both climate mitigation and resource efficiency objectives [88].

And finally, both policy and practice converge on the expectation of technological innovation as key enabler of compliance. At the legislative level, Directive 2009/31/EC and subsequent EU initiatives place carbon capture and storage (CCS) within the decarbonization toolbox. Interviewees confirm that operators are now expected to adapt to evolving climate standards through measures that cut or capture CO_2 emissions, even though they highlight the structural limits of WtE compared to other sectors: while regulators insist on universal coverage, operators argue that the structural dependence on residual waste as input leaves them with limited options for decarbonization (*i06*).

4.3.2. The actors' roles and actions

The climate and pollution regime exerts **stabilising, strengthening, and extending role assignment and positioning** effects. It empathizes the role of WtE operators as primarily hygienic service providers, but extends and amplifies their role as regulated emitters embedded in the EU's climate governance architecture. Legally, this is laid down in the Waste Incineration Directive (2000/76/EC) and its successor, the Industrial Emissions Directive (2010/75/EU), which imposed the installation of filters, compliance with emission limit values, the application of the best available technology, and regular environmental reporting. Under the more recent ETS revision (Directive (EU) 2023/959) [86], operators are formally reclassified as regulated emitters, obliged to monitor, report and verify emissions under Regulation (EU) 2018/2066 and to surrender allowances corresponding to their verified CO_2 output. In this regulatory framework, operators are no longer positioned solely as end-of-pipe waste processors but as accountable actors in decarbonization pathways. Interviewees echoed this shift, noting that "we are aware of our fossil CO_2 emissions (…) and we want to do something about it" (*i02*). However, this reframing also opens the possibility of WtE becoming a carbon removal actor. Stakeholders stressed that "if you then store it, then it's (…) carbon removal (…); since you capture not only the fossil CO_2 [but] also biogenic [CO_2], you could achieve negative emissions" (*i02*). In this role, WtE becomes part of a wider industrial carbon management ecosystem, potentially supplying captured CO_2 for storage or utilisation and supporting mitigation in hard-to-abate sectors (*i04, i05*).

The climate regime also strengthens the **WtE's role as energy provider**, particularly where fossil fuels are phased out of district heating systems, as in Germany (*i05*). Several operators emphasised that WtE delivers stable, partly renewable, and locally sourced energy, "reducing the dependence from importing fossil fuels from sometimes difficult regions" (*i02*). Since the war in Ukraine, this contribution has been framed in terms of energy security and affordability (*i03*), with respondents stressing that "energy is precious" and that WtE heat supply can cover more than half of local demand in some regions at relatively low cost, since "the fuel is already there" (*i02*). In this reframing, WtE is not only a climate liability but also a contributor to energy resilience and social welfare.

Beyond plant operators, the climate and pollution regime also redefines the roles of other governance actors towards **more integrative and systemic roles**. The European Commission assumes a more direct integrative steering role, not only through the prospective ETS design but also via the Innovation Fund and the Industrial Carbon Management Forum, which connect WtE stakeholders with CO_2 storage providers, transport operators, and other industrial actors. While not explicitly mandate, Member States increasingly expected to reflect the role of WtE into National Energy and Climate Plans, ensuring coherence between waste policy, emissions targets, and energy system planning. National and regional competent authorities are tasked with issuing environmental permits, supervising compliance with best available technology and emission limit values, under the Industrial Emissions Directive, and approving monitoring plans under the ETS framework. Municipal authorities, especially where they own WtE assets, are reframed from being primarily service providers to regulated entities directly subject to climate compliance obligations, influencing contractual arrangements and long-term investment decisions. Industry and technology providers, in turn, take on an enabling role by developing Carbon Capture, Utilisation, and Storage (CCUS) infrastructure, CO_2 transport networks, and storage solutions.

4.3.3. The transformative pressures

The Climate and pollution regime exerts tangible economic, technological, and infrastructural pressures on the WtE sector. The most immediate concern relates to the financial impacts of EU ETS inclusion, that needs **economic business model adjustments**: "the EU ETS costs will probably rise and rise, because the CO_2 allowances will be more costly" (*i02*). Several respondents warned that in such cases "you will get sooner or later bankrupt, if you don't have a business case with carbon capture" (*i02*). Several respondents warned that if ETS costs apply to WtE but not to landfilling, "landfill might be cheaper… or in the worst case, [waste] would be exported somewhere [else, like] Malaysia, Tunisia" (ibid.), potentially triggering carbon leakage towards landfilling and undermining both climate and waste hierarchy goals (*i05*).

Technological innovation becomes another explicit expectation. Policymakers increasingly frame WtE facilities as testbeds for **advancing and innovating mitigation technologies**, whether through CCUS or through experimental processes such as pyrolysis and gasification (i13). This aligns waste treatment with industrial decarbonisation and negative-emissions strategies, but also expands the operator's role beyond waste destruction to active participation in technological transitions. Some respondents attempted to reframe this position more positively, stressing that when landfill diversion, energy, and material recovery are accounted for, "you're looking at a plant that is carbon negative (…) if you add carbon capture, then you're going to be carbon negative" (*i07*). Technological pressures are centred on the deployment of CCUS as a technological CO_2 treatment innovation. While some operators are "starting investing in this technology (…) to understand if it works, how it works, how much does it cost" (*i06*), the "huge cost" and "extremely energy consuming" nature of current solutions remains a barrier (ibid.). Infrastructure constraints – such as "issues about cross-border transport of CO_2 […] because CO_2 is considered as a waste" (*i04*) – add further uncertainty. Meanwhile, ongoing tightening of pollutant emission limits continue to drive capital-intensive retrofits: in Germany, for example, "two thirds [of the investment] is for flue gas cleaning, not for the incinerator" (*i05*). These compliance costs interact with climate-driven investments, creating planning insecurity and deterring new build capacity: "you don't have planning security […]. The legal framework is not there yet […], you cannot spend public money for a business case that 'might' pop up in the future" (*i02*). Taken together, these pressures indicate that the Climate and pollution regime is reshaping WtE's operational environment. Beyond altering its normative framing and institutional roles, the regime is constraining economic models, heightening exposure to competitive displacement, and imposing new technological and infrastructural imperatives under conditions of regulatory and market uncertainty.

5. Discussion: Cross–regime frictions and its mechanisms

The empirical results are summarized in Table 2. Building on Fig. 1, we find several governance frictions, which are sharpened through cross-regime comparison and illustrated in Fig. 2 while Appendix A provides temporal information on key policies according to the three governance regime.

First, at the level of *normative framing*, the comparison reveals sharply diverging leading principles. The waste management regime is oriented towards a landfill diversion imperative, within which WtE is stabilised as a reliable disposal infrastructure that delivers the dual benefits of hygienic waste treatment and energy provision. This framing privileges **incremental compliance** and continuous operational optimisation within existing infrastructures. In contrast, the circular economy regime promotes a "grave-to-cradle" approach that considerably challenges this stabilisation logic. By prioritizing waste prevention, reuse, and high-quality recycling, it reframes WtE as a necessary but residual option, whose role should diminish over time. This introduces an **aspirational normative frame**, as well as a contradiction: while waste management seeks to secure long-term disposal capacity, the circular economy aspires to render such capacity progressively redundant. The climate and pollution regime, on the other hand, builds on the long-standing rationale of pollution-control that has historically supported landfill diversion through incineration. However, with **climate mitigation integration**, this regime increasingly reframes WtE as a source of greenhouse gas emissions, generating considerable economic and technological challenges that further destabilize its role.

Friction mechanisms in the normative frame and its policies shape how the three regimes coexist and interact with one another around shared socio-technical infrastructures, generating differentiated yet cumulative transformative pressures over time. These interacting normative frames produce persistent governance frictions, whereby WtE is simultaneously secured in the present while being questioned in the future. Consequently, transformative pressure emerges as an ongoing tension between stability-oriented infrastructure, aspirational circularity goals, and escalating climate accountability within long-term governance processes.

Table 2
Key results of waste-to-energy, circular economy, and climate and pollution regime.

Waste management	Circular economy	Climate and pollution
Normative frame		
• "Landfill-diversion imperative" frame • "Double benefit waste/energy" frame	• "Turning grave to cradle" frame • "Waste-to-energy residual option redefinition" frame	• "Pollution control baseline" frame • "Climate mitigation integration" frame
Actors' role and actions		
• stable role assignment and actor network through layered governance shaping responsibilities • operators and municipalities act as custodians of hygiene and infrastructure, balancing service provision with affordability	• altering actor positioning with shifting and redistribution of roles • EU decision-makers act as vision-setters • designers and manufacturers to bear "waste" responsibility	• stabilising, strengthening, and extending role assignment and positioning • operators as hygienic service providers and regulated emitters • strengthening role as energy provider
Transformative pressure		
• WtE operators dealing with market vs. policy paradox • adjusting to feedstock quality, composition, and dynamics	• reduce waste-to-energy's role and size • higher recycling standards lead to higher waste residuals	• economic business model adjustments • advancing technological CO_2 treatment innovations (CCUS)

Source: own elaboration.

Second, the regime comparison also reveals marked differences in the *actors' roles and their modes of action* across the three governance regimes. Within the waste management regime, a multi-level, layered governance structure assigned stable and clearly defined responsibilities. Operators and municipalities are primarily responsible for implementing and monitoring waste management activities, acting as custodians of hygienic and environmentally sound waste treatment procedures. Their main task is to balance reliable service provision with affordability, a role that can be characterized as a form of **common good entrepreneurship**. In contrast, the circular economy regime promotes the redistribution and reconfiguration of responsibilities along the value chain. EU decision-makers act as vision-setters, while WtE operators emphasise their role as energy providers in an attempt to reposition themselves. The **common good vision** of the circular economy regime also includes new actors, such as producers and designers, as substantial players. The climate and pollution regime occupies an intermediate position between stabilisation and reconfiguration. Through its long-standing pollution control, it has historically played a stabilising role in shaping responsibilities and practices in the WtE sector. At the same time, the progressive integration of climate mitigation into regulatory and economic boundary conditions extends and reshapes role assignments within the sector. For example, this form of **common good integration** expands the role of WtE operators beyond that of hygienic service providers to include that of regulated emitters subjected to climate accountability. As a result, the development and deployment of mitigation technologies, such as CCS and/or CCUS, increasingly become a prerequisite for the sector's future viability.

Friction mechanism in actors' roles and actions have the consequence of simultaneously stabilising existing responsibilities and reconfiguring expectations around WtE. Within the waste management regime, clearly defined and layered role assignments establish municipalities and operators as custodians of hygienic, reliable, and affordable service provision, reinforcing operational stability and incremental optimisation. In contrast, the circular economy regime redistributes responsibilities along the value chain, problematising WtE as a residual and conditional actor, while expanding the roles of producers, designers, civil society, and citizens. This reallocation generates frictions as operators actively seek to reposition themselves within circular narratives, while municipalities are constrained by existing infrastructure and waste flows. The climate and pollution regime reshapes the configuration of actors further by extending the role of WtE operators from service providers to regulated emitters and prospective carbon management actors, embedding them within climate governance and technological innovation agendas. Taken together, these overlapping role assignments produce persistent frictions, whereby actors are tasked with both stabilising current systems and enabling transformative change, generating cumulative transformative pressure over time.

Third, comparing governance regimes highlights distinct forms of *transformative pressure* acting on WtE. Within the waste management regime, this socio-technical system is primarily exposed to pressures originating from its sectorial and market positioning. As an infrastructural service operating in competitive and regulated markets, operators face continuous "internal" transformative pressure to reconcile market dynamics and policy expectations. In particular, they must navigate a persistent market-policy paradox: while public policy increasingly promotes waste reduction and recycling, the financial viability of existing facilities depends on a stable, or even growing, supply of waste. At the same time, day-to-day operational pressures arise from the continuous change in the quality and composition of the feedstock under volatile market conditions. Taken together, these

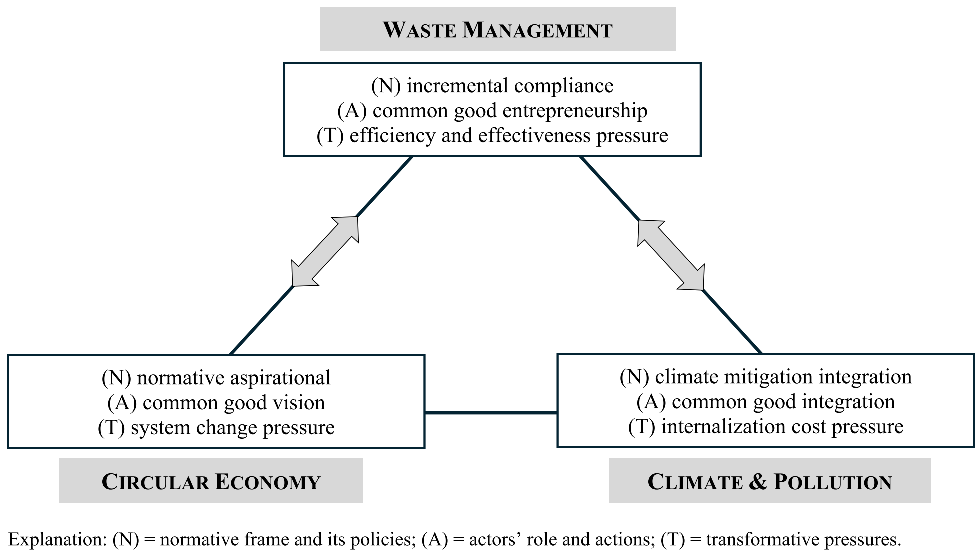

Fig. 2. Frictions from waste-to-energy governance regime comparison. Source: own elaboration.
Explanation: (N) = normative frame and its policies; (A) = actors' role and actions; (T) = transformative pressures.

dynamics translate into substantial "internal" pressures for incremental **efficiency and effectiveness improvements**. By contrast, the circular economy regime exerts transformative pressure by calling into question both the scale and the long-term role of WtE. However, this **system changes pressure** remains entangled in a vision-reality paradox. While the circular economy advances an ambitious vision of waste reduction and high-quality recycling, these aspirations often function more as political commitments than as operational outcomes. In practice, higher recycling standards can generate higher volumes of residual fractions, thereby reinforcing, rather than diminishing, the reliance on WtE operators to manage unavoidable waste streams. It seems that the transformative needs initiated by the climate and pollution regime are much stronger due to higher **internalization cost pressure**. The extension of the ETS on the waste sector heavily pressures towards economic business model adjustments and technological innovation for climate friendly CO_2 handling.

Our findings suggest that overlapping governance regimes do not exert equivalent pressures intensity on the WtE socio-technical system. *Friction mechanisms from transformative pressure* generate distinct, yet interacting, forces that act on WtE. Within the waste management regime, transformative pressure is primarily internal and operational, arising from market dynamics, utilisation rate dependencies, volatile waste flows, and cost-sensitive governance arrangements. While these pressures incentivize incremental efficiency improvements, they also reinforce a market–policy paradox, whereby financial viability depends on stable waste volumes despite policy-driven waste reduction goals. The circular economy regime translates transformative ambition into a persistent vision–reality paradox. While upstream diversion and high-quality recycling are encouraged, higher rejection rates and fragile recycling markets continue to ensure that WtE remains a necessary outlet for residual waste. Consequently, circular economy pressures tend to reconfigure**.** Expectations and performance standards without delivering a proportional reduction in WtE volumes. The climate and pollution regime introduces the strongest external transformative pressure by internalising climate costs and the tightening of regulatory and technological requirements. The prospective inclusion in the EU ETS, combined with expectations around CCUS deployment, subjects' operators to significant economic, technological, and infrastructural challenges under conditions of regulatory uncertainty. Overall, these produce cumulative and sometimes contradictory dynamics, whereby WtE becomes simultaneously indispensable yet also increasingly constrained, and pushing it towards technological and business model reconfiguration.

6. Conclusions

Research on socio-technical transformation and long-term governance has increasingly emphasised the importance of understanding how complex infrastructures evolve, and the extent to which they can be steered towards specific goals, such as sustainability. This paper contributes to this debate by examining how different governance regimes interact and generate governance frictions over time. Based on the cross-governance regime friction approach, the article conceptualizes transformation as a consequence of friction between competing and interacting governance regimes. Governance regimes stand for a specific set of configurations of institutional setting, regulatory framework, and actor orientation and decision-making.

In the case of WtE, the reference governance regime of waste management is accompanied by two competing ones: the circular economy and the climate and pollution governance regimes. Empirically, the regime comparison revealed commonalities and differences in terms of the normative frame and its embedding in policies, the role and actions of actors, and transformative pressure. The normative frame and its policies produce transformative forces resulting from frictions between incremental compliance, normative aspirations, and climate mitigation integration. Actors' roles and actions cause frictions between common good entrepreneurship, vision, and integration, while the transformative pressure focuses on frictions between efficiency and effectiveness pressure, system change pressure, and internalization cost pressure.

The case of WtE illustrates a governance configuration in which multiple governance regimes impose partly incompatible demands on the same socio-technical infrastructure. Waste management governance requires the continued provision of reliable disposal capacity and operational continuity, circular economy governance seeks to reduce waste flows and progressively limit the role of incineration, while climate and pollution governance increasingly subjects WtE to decarbonisation imperatives, carbon pricing and technological mitigation requirements. These demands cannot be prioritised or implemented sequentially without undermining one another. As a result, transformative pressures accumulate within infrastructures, investment cycles, operational routines, and business models. WtE capacity must be maintained to ensure reliable service provision, even though policy objectives aim to reduce waste volumes. Higher recycling standards increase residual fractions requiring treatment, while carbon pricing raises operational costs without eliminating dependence on incineration infrastructure. Policies intended to reduce the role of WtE therefore simultaneously reproduce its necessity, while intensifying the economic and technological pressures placed upon it. The findings suggest that governance frictions emerge not only from conflicting policy objectives, but also from the absence of governance mechanisms capable of reconciling competing demands once they converge operationally within an industry. Consequently, unresolved contradictions are displaced onto operational actors. WtE operators and municipalities become responsible not only for implementing policy objectives, but also for mediating the incompatibilities between them.

From a long-term governance perspective, the findings can be interpreted as conditionally transferable to different governance contexts. For example, in regions where European policy frameworks inform policy design, such as in Latin America, the identified governance frictions and overlapping configurations may serve as anticipatory markers of potential tensions during the establishment of WtE systems or other waste treatment strategies, such as landfill or recycling. Conversely, in highly consolidated systems characterized by mature and institutionalized policy regimes, such as those in Scandinavian countries, the results may provide insights into the side effects of WtE stabilisation, particularly in relation to tensions with the circular economy and emissions control systems. The cross-governance regime frictions approach may act as a diagnostic lens, revealing inconsistencies between policy objectives and highlighting critical points where adaptation, realignment and incremental change may be required to steer socio-technical systems over time. This is particularly relevant in infrastructure-intensive sectors, such as energy, waste, and water, where investments are long-lived and policy misalignments can have enduring consequences.

In our view, this conceptual and empirical research is a new approach to tackle the important field of analysing and explaining socio-technical transformation, and deliver fruitful insights on governance strategies and practices to cope with large-scale problems and grand challenges. However, what is certainly needed is to further develop the approach of cross-governance regime frictions and its operationalization for carrying out research, in order to gain further empirical evidence from, comparative case-studies, and tie back the conceptual and empirical regime comparison results to broader areas such as sustainability, long-term governance and transformation sciences.

CRediT authorship contribution statement

Danieli Braun Vargas: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Stefania Sardo:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Dirk Scheer:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no competing interest that could have influences the work reported in this paper.

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Appendix A. Corpus of EU policy documents analysed presented in chronological order and assigned to governance regime

Document	Year	Type	Governance Regime	Notes
First Waste Directive (75/442/EEC)	1975	Directive	Waste Management	General waste policy, first EU definition of “waste”, disposal-oriented
Landfill Directive (1999/31/EC)	1999	Directive	Waste Management	Limits biodegradable waste in landfills, promotes diversion
Waste Incineration Directive (2000/76/EC)	2000	Directive	Waste Management	Emission limits for incineration (dioxins, heavy metals, NOx, SOx)
EU ETS Directive (2003/87/EC)	2003	Directive	Climate & Pollution	Carbon pricing system for CO2 and GHGs, include WtE plants in scope
Taking sustainable use of resources forward - A Thematic Strategy on the prevention and recycling of waste (COM (2005) 666)	2005	Communication	Circular Economy	Early driver of circular principles, introduces waste prevention in EU agenda
Waste Framework Directive (2008/98/EC)	2008	Directive	Waste Management	Waste hierarchy, Extended Producer Responsibility
CCS Directive (2009/31/EC)	2009	Directive	Climate & Pollution	CO_2 storage framework, enables CCS use by WtE
Industrial Emissions Directive (2010/75/EU)	2010	Directive	Climate & Pollution	Best available techniques-based emission control for WtE and co-incineration
Towards a circular economy: A zero waste programme for Europe (COM(2014) 398)	2014	Communication	Circular Economy	First framework approach to CE
Closing the loop - An EU action plan for the Circular Economy (COM(2015) 614)	2015	Communication	Circular Economy	EU roadmap for circular economy
ETS Market Stability Reserve (2015/1814/EU)	2015	Decision	Climate & Pollution	Controls surplus of ETS allowances
The role of waste-to-energy in the circular economy (COM (2017) 34)	2017	Communication	Circular Economy	Guidelines on WtE's role in the circular economy
A European Strategy for Plastics in a Circular Economy (COM (2018) 28 final)	2018	Communication	Circular Economy	Lifecycle approach to plastics

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(*continued*)

Document	Year	Type	Governance Regime	Notes
Effort Sharing Regulation (2018/842/EU)	2018	Regulation	Climate & Pollution	Sets binding national targets for sectors outside ETS
Renewable Energy Directive (2018/2001/EU)	2018	Directive	Climate & Pollution	Promotes renewable energy including biogenic WtE
Landfill Directive (2018/850/EU)	2018	Directive	Waste Management	Revises Landfill Directive 1999/31/EC, sets target of max 10% municipal waste to landfill by 2035
E-waste, Batteries and ELVs Directive (2018/849/EU)	2018	Directive	Waste Management	Amends directives on e-waste, batteries and end-of-life vehicles, enhances selective collection and treatment of these wastes
Waste Framework Directive (2018/851/EU)	2018	Directive	Waste Management	Revises Waste Framework Directive (2008/98/EC), recommends phasing out subsidies for incineration of recyclable materials
Packaging and Packaging Waste Directive (2018/852/EU)	2018	Directive	Waste Management	Revises Packaging and Packaging Waste Directive (94/62/EC), limits packaging sent to incineration or landfill
Commission Implementing Decision on BAT (2019/2010/EU)	2019	Implementing Decision	Climate & Pollution	Establishing the best available techniques conclusions, under Directive 2010/75/EU
Second Circular Economy Action Plan (COM(2020) 98)	2020	Communication	Circular Economy	Deepens CE in priority sectors
Taxonomy Regulation (2020/852/EU)	2020	Regulation	Climate & Pollution	Classifies which economic activities qualify as environmentally sustainable
2030 Climate Target Plan (COM(2020) 562 final)	2020	Communication	Climate & Pollution	Emission reduction targets
European Climate Law (2021/1119/EU)	2021	Regulation	Climate & Pollution	Climate neutrality 2050
EU ETS Revision (2023/959/EU)	2023	Directive	Climate & Pollution	Expands ETS scope
Ecodesign requirements for sustainable products (2024/1781/EU)	2024	Regulation	Circular Economy	Product circularity requirements
Critical Raw Materials Act (2024/1252/EU)	2024	Regulation	Circular Economy	Resource recovery

Data availability

Data will be made available on request.

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