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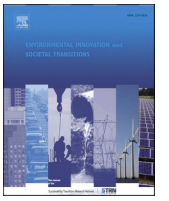

Legitimising technologies for a circular economy: Contested discourses on innovation for plastics recycling in Europe

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ABSTRACT

The European Commission aims to increase the recycling of plastic packaging to 60% by 2025, requiring fundamental changes towards a more circular economy. Pathways for this transition require policy support that largely depends on their legitimacy in the public discourse. These normative aspects remain poorly understood for 'in-between' technologies, i.e., technologies that are no longer novel but struggle to move to the growth phase within the technological innovation system. Therefore, we ask: How do discourses shape technology legitimacy for in-between technologies? Drawing on the empirical example of chemical recycling, the analysis renders two principal findings. First, legitimising and delegitimising storylines present contesting views on in-between technologies regarding their technological aspects, environmental and social impacts, and economic and policy implications. Second, how discourses contribute to technology legitimacy depends on the actors and interests that drive the prevalent storylines in particular contexts.

1. Introduction

Global plastic waste is an increasingly pressing environmental and public health challenge (Ellen MacArthur Foundation, 2022). Plastic pollution primarily results from inadequate disposal of plastics as well as leakage of microplastics, for instance, from synthetic textiles (OECD, 2023). Nearly 26 million tonnes of plastic waste are generated in the EU annually, of which only 30% are collected for recycling (European Commission, 2018). The EU Plastics Strategy aims for all plastic packaging to be either reused or recycled by 2030, in line with circular economy principles (Blum et al., 2020; Henry et al., 2021). This goal necessitates technological innovation and fundamental sociotechnical change along the entire plastics value chain. Linear production, consumption, and disposal patterns are insufficient to achieve these targets (Bening et al., 2021; Johansen et al., 2022; Tura et al., 2019).

Technologies and pathways for a circular economy require policy support that, in turn, requires legitimacy. Sociotechnical transitions to a circular economy are complex, involving technological innovation alongside changing institutional contexts (Kern et al., 2020; Prieto-Sandoval et al., 2018; Ritzén and Sandström, 2017). Accordingly, technologies require policy support, such as regulation and financial incentives (Köhler et al., 2019). Acquiring policy support necessitates legitimacy: "alignment (or misalignment) of the focal technology with elements in its wider context".

Legitimacy is often contested in the public discourse. Essentially, actors construct storylines to legitimise their preferred

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technologies or delegitimise the least favoured technologies. Legitimacy is essential for technologies at all phases of the technological innovation system (TIS) (Bergek et al., 2008; Markard, 2020). However, these normative aspects remain poorly understood for 'in-between' technologies that remain stuck in the 'formative' phase within the TIS, having acquired elements of the 'growth' phase but not fully entered it. These technologies are not novel, as both specialised and large international companies are developing and producing them. However, there are significant barriers to deploying them at scale, resulting in low sales, a relatively low number of relevant players, and a high degree of uncertainty, also regarding technical specifications (Markard, 2020).

Therefore, we ask: How do discourses shape technology legitimacy for in-between technologies? We answer the question by drawing on the chemical recycling (CR) example, an umbrella term for contested in-between technologies to advance the circular economy for plastics (Ragaert et al., 2017; Rahimi and García, 2017; Solis and Silveira, 2020). Chemical recycling technologies convert waste plastic molecules to different structures, some of which can be potentially used to produce new plastics materials (Plastics Recyclers Europe, 2022). According to proponents chemical recycling technologies could potentially tackle waste streams that are currently incinerated or landfilled and deliver higher-quality output (Plastics Europe, 2022). At the same time, uncertainties remain regarding the advantages of the technology, also in terms of environmental impact and economics (Systemiq, 2022).

We rely on evidence from eight countries with comparatively the most intensive debate on chemical recycling in Europe, narrowing it down to three case study countries for in-depth analysis – the UK, Germany, and Italy. The analysis proceeds in two steps: First, we rely on qualitative content analysis to identify the legitimising and delegitimising storylines and contested points on chemical recycling. Second, we analyse how these storylines form discourses in the case study countries and assess their implications on increasing institutional complementarity and technology legitimacy for the in-between technology.

This paper is structured as follows: Section 2 introduces the theoretical framework, Section 3 introduces the case background. Section 4 outlines the research design and methodology. Section 5 outlines and analyzes the findings, Section 6 discusses their implications and concludes the analysis.

2. Theoretical framework

2.1. Legitimacy for 'in-between' technologies

Different pathways and technologies can advance the transition to a circular economy, but they require policy support. Transforming sociotechnical systems entails changing technologies and institutions, including regulation, markets, and behaviours (Geels, 2002; Geels et al., 2017). The sustainability transitions scholarship, based on systems thinking, provides the foundation to explore multidimensional processes for fundamental change (Köhler et al., 2019). The TIS approach is particularly helpful in untangling the "set of networks of actors and institutions that jointly interact in a specific technological field" (Markard, 2020, p. 2). Transitions are inherently political, as transition targets, technologies, and policies are uncertain, normative, and contested (Avelino and Wittmayer, 2016; Fuenfschilling and Truffer, 2014; Meadowcroft, 2009, 2011). In this context, public policies drive purposive transitions of TIS towards specific goals.

Legitimacy shapes public policies and defines which technologies and transition pathways prevail (Scott, 2013). Legitimacy refers to "perceived consonance of an entity with its institutional environment, i.e. a socially constructed set of norms, values, beliefs and practices in its context". Essentially, technology necessitates a certain degree of legitimacy to mobilise policy support (Binz et al., 2020; Kishna et al., 2017; Murphy, 2015; Rosenbloom et al., 2016). Technology has a higher degree of legitimacy if it is complementary to the existing institutional context (Markard and Hoffmann, 2016). This creates a chicken-and-egg situation: technology requires legitimacy to increase its institutional congruence (complementarity) in the sociotechnical system, but a level of institutional congruence is required to claim legitimacy in the first place (Bergek et al., 2008; Bergek et al., 2008; Hekkert et al., 2007). Accordingly, missing complementarity components, such as industry standards, can hamper technology emergence (Johnson et al., 2006; Markard and Hoffmann, 2016; Wirth et al., 2013). Essentially, "complementary interaction of technical and non-technical components is vital" (Markard and Hoffmann, 2016, p. 63).

Typically, legitimacy building and the search for complementarities occur in the early phases of technological development. This paper relies on the life cycle of TIS approach to structure technologies at various stages of development: formation, growth, maturity, and decline. Certain technologies remain stuck 'in-between' the formation and growth TIS phases. Examples of such technologies include chemical recycling technologies (as analysed in the paper) and hydrogen. In-between technologies are not fully novel technologies: there is already a range of actors developing and producing chemical recycling technologies. Nevertheless, the technology struggles to move to the growth phase. Essentially, the in-between technologies have most characteristics of the formative TIS phase, such as a small number of actors, low sales, unclear institutional structuration and technology performance parameters, but they are not novel technologies. At the same time, these technologies struggle to grow, improve performance, and formalize technology-specific institutions (Markard, 2020).

We lack a detailed understanding of legitimacy formation for such in-between technologies. Scholars have primarily studied the legitimacy formation of novel technologies overall, such as solar electricity (Bergek, Jacobsson, and Sandén, 2008; Binz et al., 2020). Research has also looked at legitimacy dynamics for established technologies, such as agricultural biogas and nuclear power (Dai, 2019; Geels and Verhees, 2011), and also for phasing-out technologies, such as coal (Isoaho and Markard, 2020; Rosenbloom, 2018). However, we require a detailed understanding of the legitimacy of in-between technologies. Such technologies are highly affected by wider developments in their context that can ultimately define whether or they can grow and live up to its potential, rendering the study of such technologies particularly interesting (Turnheim and Geels, 2013).

2.2. Legitimacy through discourses

Technology legitimacy is formed through the public discourse, "a central arena in which struggles over legitimacy unfold" (Markard et al., 2021, p. 317). Discourse refers to the "ensemble of ideas, concepts and categorizations through which meaning is allocated to social and physical phenomena" (Hajer and Ultermark, 2008, p. 7). Discursive approaches highlight how problems and solutions are socially constructed by actors through collective sense-making processes (Hajer, 2005, 2006; Hajer and Versteeg, 2005; Rosenbloom et al., 2016). The conceptual framework adopted in this paper is outlined in Fig. 1.

First, competing storylines highlight the argumentative struggles and points of contestation and shape the discourse on the in-between technology in a given context (Point 1 in Fig. 1) (Bauer, 2018; Garud et al., 2010; Sengers et al., 2010). Essentially, "actors select certain aspects of the discourse while excluding others, thereby reducing the complexity of policy issues" (Markard et al., 2021, p. 317). Actors can shape the discourse with the aim of advancing particular solutions and interests, such as reinforcing an incumbent technology (Fuenfschilling and Truffer, 2016; Rosenbloom, 2018). The existing discourse, in turns, affects how actors frame specific issues in the first place (e.g., they can respond to present storylines) (Geels and Verhees, 2011; Harris, 2021).

Second, the discourse reflects and also shapes the institutional complementarity to the technology and with that – technology legitimacy in the sociotechnical system (Point 2 in Fig. 1) (Markard and Hoffmann, 2016). Institutional complementarites occur when "specific institutional structures positively affect the focal technology" (Markard and Hoffmann, 2016, 66). Namely, discourse reflects the norms, values, and beliefs regarding the in-between technology in the given sociotechnical context. The prevalence of legitimizing discourses can advance institutional complementarity in terms of policy decisions, regulations, and standards – furthering technology legitimacy (Ohlendorf et al., 2023). Formation of the complementarity between the in-between technology and its institutional context, in turn, requires overcoming certain challenges, such as mobilizing actors, aligning interests, and overcoming resistance of incumbent actors (Markard and Hoffmann, 2016).

Overall, discourse can trigger meaningful changes in the policy decisions, framing part of broader sociotechnical system change (that remains beyond the scope of this paper). The particular institutional environment of relevance here are institutions and policies pertaining to plastics and waste recycling systems, but broader aspects are considered, if relevant. Note that external influences, such as external pressure for change from EU strategies, can affect discourses and their legitimising effects.

3. Case background

3.1. Reducing plastic waste

To date, 23 % or 8 million tonnes of plastic waste is recycled in Europe through mechanical recycling technology (European Commission, 2018; Packaging Europe, 2022). Most plastic waste is either not collected for recycling or is lost during the sorting stage and is eventually incinerated or landfilled. Mechanical recycling, however, has shortcomings (Ribul et al., 2021). Plastic waste has to be washed and separated by colour and polymer type. Moreover, the quality of output decreases with each recycling cycle. The more contaminated waste streams cannot be recycled, and the output of mechanical recycling cannot be used in many applications, such as for food-grade packaging (Geueke et al., 2018; Ho et al., 2021; Matthews et al., 2021).

Chemical recycling has the potential to address the shortcomings of the status quo mechanical recycling technologies. Chemical recycling converts plastic waste into its constituent parts (Davidson et al., 2021; Lee and Liew, 2021; Sethi, 2016; Vogel et al., 2020). According to the industry chemical recycling could potentially transform a wider scope of waste than with the current system of mechanical recycling and produce recyclate with virgin plastic properties (Plastics Europe, 2022). The term chemical recycling denotes various technologies for decomposing and depolymerising plastic waste into its constituent parts. In essence, ISO defines

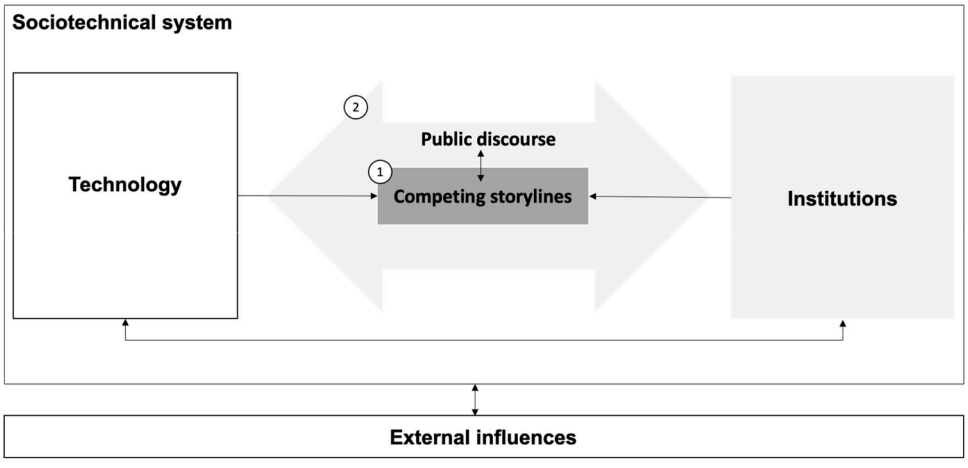

Fig. 1. Framework for analysis: legitimacy through public discourse.

chemical recycling as "conversion to monomer or production of new raw materials by changing the chemical structure of plastics waste through cracking, gasification or depolymerization, excluding energy recovery and incineration" (ISO, 2008). A challenge is that currently some actors call technologies that are used to convert plastics into fuel 'chemical recycling'. This, however, is not in line with the EU Waste Framework Directive, according to which recycling does not refer to "energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" (Directive 2008/98/EC, Art 3(17)) (European Commission, 2018).

3.2. Chemical recycling as 'in-between' technologies

Chemical recycling technologies remain 'in-between' technologies that struggle to move from the formation into the growth phase. On the one hand, there is proof of concept given the number of projects and companies on the market (see Section 5.1). The EU supports research and innovation in chemical recycling technologies, for instance, funding projects 'MMAtwo' (2018-2022) and 'PUREsmart' (2019-2022), in the future also through Horizon Europe. The EU Taxonomy Regulation Climate Change Act considers plastics in primary form manufactured by chemical recycling as a substantial contribution to climate change mitigation in situations where mechanical recycling is not technically feasible or economically viable, and where life-cycle GHG emissions (excluding any calculated credits from the production of fuels) are lower than the life-cycle GHG emissions of the equivalent primary plastic manufactured from fossil fuel feedstock (European Commission, 2021).

On the other hand, the share of chemical recycling in the EU is low. Although the EU Plastics Strategy (adopted in 2018) sets ambitious objectives to recycle 60 % of plastic packaging by 2025, it has not incorporated chemical recycling explicitly into the plastics and waste strategy. Currently, the EU Waste Framework Directive is technology-neutral, and chemical recycling is not included in mandated recycling targets. The new Packaging Directive is expected to approve chemically recycled PET by 2025 and other plastics products by 2030 (Moussu, 2022; Packaging Europe, 2022). Accordingly, to date, chemical recycling technologies struggle to grow and do not have substantial institutional support.

4. Research design and methodology

To analyse how discourses shape legitimacy for in-between technologies, we first identify the storylines and contested points on chemical recycling and second analyse how they unfold in three case studies shaping technology legitimacy (Table 1). Together, these two steps cover the two conceptual aspects depicted in Fig. 1.

4.1. Identifying storylines

The goal of this analysis step is to identify the storylines and the main contested points on chemical recycling in eight European countries, as well as identify case study countries for further research. The list of eight countries selected for analysis have the highest count of evidence on storylines in the public discourse on chemical recycling (based on the article count in Factiva for European countries).

First, to identify the storylines on chemical recycling and to choose the three case study countries, we gathered data using the search tool Factiva for the eight countrines in Europe with the highest number of articles for the initial set of search hits. These countries are the UK, Germany, Italy, Norway, France, Denmark, the Netherlands and Austria. Note that the UK is no longer part of the EU strategies but was in the past and is now still influenced by these due to the proximity of the markets. We picked the search terms iteratively, starting with a selection based on concepts that we picked up during the literature review on the topic, and then expanded the selection if we found further relevant terms during our search (details on search parameters for each country in Table A1 in the Appendix). We checked articles in all news sources available on Factiva, including specialised magazines on recycling and waste. Out of all search hits, 485 unique and relevant articles were found on chemical recycling in the eight countries combined, out of which 257 articles were in the countries with the highest article count – the UK, Germany, and Italy. These countries were chosen as case studies for further deep-dive analysis. For a detailed article count per country, please consult Table A3 in the Appendix. The period of analysis for this paper is January 2017 (a year in advance of the EU Plastics strategy) until May 2021. When referencing the newspaper articles from the Factiva analysis, we refer to their code number to facilitate the readability of the text. The actual reference is stored in Table A4 in the Appendix.

We used these insights to systematically classify the storylines for all countries analysed into four topics: technology, environmental and social impact, economics, and policy (acknowledging that some storylines can have dimensions of multiple categories). This list of topics emerged based on the prevalent storylines in the public discourse, where the unit of analysis is one storyline, namely, one

Table 1
Research design.

Analysis step	Data source	Goal	Output
Identifying storylines (4.1)	Factiva search	Identify storylines on chemical recycling grouped by topic	Storylines (5.2) based on 8 countries
Analyzing how discourses shape technology legitimacy (4.2)	Factiva search, press search, interviews	Analyze the discourses on chemical recycling and implications for technology legitimacy in the case study countries	Discourses and legitimacy implications (5.3) for three case study countries (UK, Germany, Italy)

meaningful statement about an aspect of chemical recycling. We considered the meaning and assumptions behind the storylines (instead of analysing detailed textual features) (Fairclough, 2005; Preuss and Dawson, 2009). We then classified these storylines into 'legitimising' and 'delegitimising'. Legitimising storylines support (or at least do not oppose) chemical recycling technologies, for instance, by addressing potential benefits. Delegitimising storylines oppose the technology and point to pitfalls. We then also gathered information on all the arguments and contested points that shape these storylines. The findings are summarised in section 5.2.

4.2. Analysing how discourses shape technology legitimacy

We also analysed the legitimacy implications of the discourse in the selected case country contexts of Germany, Italy and the UK, exploring institutional complementarity as discussed in Chapter 2.2.

First, we revisited the storylines in the three case study countries to identify the prevalent discourse on institutional complementarity in terms of norms, values, and expectations for chemical recycling technology. We identified the main legitimizing and delegitimizing narratives in each country. Note that ~10 % of the articles in the case study countries were in general newspapers, reflecting that the debate is still not very present in the general public, but rather unfolds among the stakeholders involved (see the list of the selected newspapers in Table A2 in the Appendix).

In a next step, to assess how public discourse reflects in institutional complementarity in terms of policy decisions, regulations, support programs, we researched policy and regulatory developments concerning chemical recycling in the UK, Germany, and Italy. We analysed policy documents, legal texts, government websites, press releases, and statements by politicians in the press. Given that chemical recycling is a comparatively novel topic in policy and regulatory debates, the scope of changes during the current and previous governments was feasible to trace. Namely, we searched the websites of the relevant ministries and institutions for files that are relevant to chemical recycling. Note that only a small part of these documents explicitly referred to chemical recycling.

Finally, we conducted semi-structured interviews to learn more detailed insights about how discourses shape institutional complementarity and legitimacy in case study countries. The interviews helped us confirm the most frequently encountered storylines and arguments and gain a better understanding of the actors that are most present in the public discourse and their motivations. We interviewed representatives from the most frequently quoted actors in the public debate in the respective countries, namely, private sector stakeholders from companies that have an interest in chemical recycling technologies. Given that chemical recycling technologies are highly capital-intensive, talking to the representatives of the companies also enables us to gain more detailed know-how and understanding of chemical recycling beyond what is available in the public debate. The list of interviewees is presented in Appendix Table A5 and the interview questions in Table A6.

The paper analyses qualitative data collected primarily through content analysis. Qualitative methods are particularly helpful when analysing aspects that are highly context-sensitive that cannot be quantified in a meaningful way. Nevertheless, qualitative research has shortcomings, such as the limited generalisability of findings, which makes comparisons across case studies difficult (Mahoney, 2010). To increase the validity of findings and further triangulate insights on this emerging topic, we engaged in public events relevant to chemical recycling at the time of writing and conducted follow-up desk research, looking at reports, academic publications, and social media (LinkedIn, Twitter). In total, we attended eight public events organized by various stakeholders, including international organizations, private sector companies, and research institutions.

5. Findings

5.1. Overall

According to our findings, the attention to chemical recycling has steadily increased in the public discourse in the countries researched, especially since 2019 (Fig. 2). This trend is in line with increasing business and policy activity on chemical recycling. In total, we counted nearly 70 announced projects (as of December 2021) in the set of eight countries, out of which 32 are in Germany, Italy, and the UK, mostly pilot or small industrial and commercial plants (full list of projects in Appendix Table A7).

Overall, we find that within the EU policy and regulatory umbrella, various discourses help legitimise or delegitimise chemical recycling technologies in Europe. Section 5.2 summarises the identified storylines on chemical recycling by topic. Section 5.3 analyzes the discourse patterns in the case study countries and discusses their legitimacy implications in their respective country contexts.

5.2. Storylines

We identified legitimising and delegitimising storylines on technology, environmental and social impact, economics, and policy of chemical recycling in the UK, Germany, and Italy. This analysis corresponds to point (1) in the conceptual framework (Fig. 1), the storylines are summarised in Table 2.

5.2.1. Technology

Two storylines emerge regarding chemical recycling technologies: on the one hand, chemical recycling has performance benefits compared to status quo technologies (legitimising). On the other hand – chemical recycling is not a 'silver bullet' to solve the plastics recycling issue (delegitimising). These storylines mainly touch upon two contested points, namely, the effectiveness of chemical recycling technologies and what should be defined as chemical recycling in the first place.

The two storylines contest whether chemical recycling technologies offer performance improvements compared to mechanical

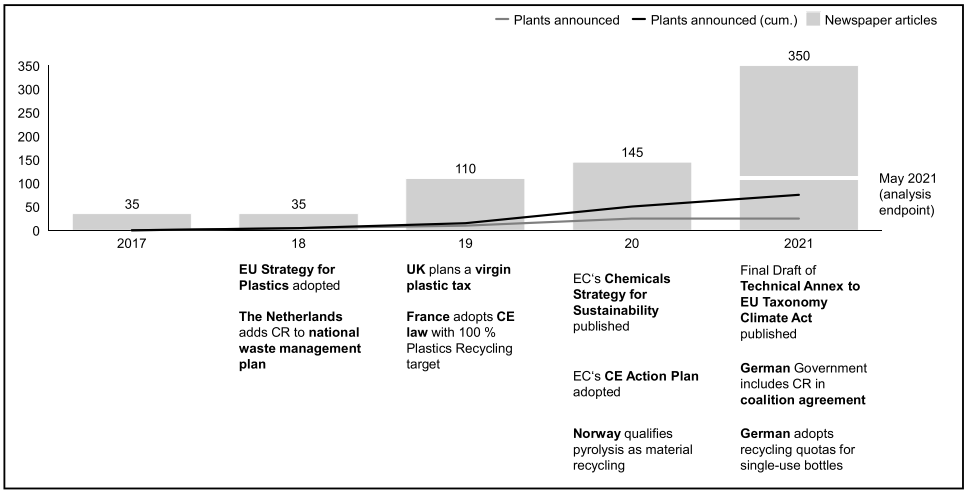

Fig. 2. Chemical recycling in the public press; technology and policy developments.[1]

recycling. According to the legitimising storyline, chemical recycling technologies offer potential effectiveness gains, especially the capability to produce virgin quality material for food-grade packaging (DE9, 22-25, 34, 45, 51, 54, 55) and to recycle mixed plastic waste that cannot be mechanically recycled (DE1, 2, 16,18,19). On the contrary, the other storyline argues that chemical recycling is not a 'silver bullet' and the effectiveness gains depend on many factors, such as the quality of the waste streams (UK53). According to some EU-wide NGOs, pyrolysis and gasification have low-efficiency rates, and depolymerisation requires clean and homogenous waste streams to generate high yields (Hann and Connock, 2020). We identified delegitimising storylines with various degrees of severity, from more radical to close-to-neutral, arguing that there is not one 'chemical recycling' and the effectiveness is highly technology-dependent.

In line with that, both legitimising and delegitimising storylines call for a consolidated EU chemical recycling definition that clearly excludes plastics-to-fuel technologies – however, based on different arguments. The storyline that chemical recycling has higher effectiveness contains arguments for clearer definitions in regulation with the aim of facilitating chemical recycling development. The storyline that chemical recycling is not a 'silver bullet', however, includes arguments to limit chemical recycling as an unsustainable activity. According to the Ellen MacArthur Foundation: "A lot of projects and facilities claim they do chemical recycling, but if you look at what they do with the output — the final oil-based product that comes out — it is sold as a fuel, it is not recycling" (UK17).

5.2.2. Environmental and social impact

We found the legitimising storyline that chemical recycling has environmental and social benefits to be in stark contrast to the delegitimising storyline that chemical recycling has no sustainability benefits. These storylines are mostly shaped around three points of contestation: the carbon footprint of chemical recycling technologies, the credibility of assessment processes, and social impact, including the 'not in my back yard' (NIMBY) effect.

First, the two storylines contest whether chemical recycling technologies enable a lower carbon footprint than the status quo. The arguments in the legitimising storyline claim that chemically recycled products have lower GHG emissions compared to conventional products (e.g., UKO23, DE10, 22, 25, 31, 49, NL10, 42). The arguments in the delegitimising storyline, however, contest that chemical recycling technologies are carbon-intensive, consuming excessive amounts of energy, water, and chemical resources. These arguments are also advanced by international NGOs (Hann and Connock, 2020).

Second, the storylines contest the technology assessment process, especially life cycle assessments (LCAs). We repeatedly found the delegitimising storyline to be developed around the arguments that current LCAs are insufficient to make credible claims about the technology (Tabrizi et al., 2020). While most legitimising storylines use the existing LCA insights for evidence, in some legitimising storylines, the LCAs can be further improved to avoid 'greenwashing', for instance, by international NGOs such as Planet Tracker (UK22).

Finally, primarily the delegitimising storylines are shaped around arguments on the social impacts of chemical recycling. These arguments point to the negative health and social benefits of the chemical recycling industry, mostly to the local communities, such as increased heavy goods vehicle traffic, disruption of sites, and health-impairing factory fumes (the NIMBY effect). Interestingly, in the UK, we also identified an argument that supporting chemical recycling means perpetuating the support for plastics value chains, which has inherent negative social consequences in terms of human environments and health (UK53). In the legitimising narratives, we identified the argument that chemical recycling could create regional employment, especially in sustainable industries in the UK, and

[1] The paper focuses on the timeline Jan 2017 – May 2021, but we conducted follow-up search for year 2021 to be able to compare article count with the previous years (the white line for 2021 rougly indicates the cut-off point of 78 articles up until May 2021)

Table 2
Contested storylines on chemical recycling.

Topics	Contested points		Legitimising storylines (emphasise complementarity)	Delegitimising storylines (emphasize lack of complementarity)
Technology			**CR technology has higher effectiveness**	**CR technology is not a 'silver bullet'**
	Effectiveness	Competitive advantage of CR technology	CR is flexible and can be used as feedstock in different applications CR potential depends on the technology	CR technology is not a 'silver bullet' for reducing plastic waste CR technologies have low efficiency and recovery rates High yields of CR only possible with clean and homogenous waste streams
	Definition	Plastics-to-fuel technologies	Plastics-to-fuel should be excluded from CR definition to promote CR and avoid 'greenwashing'	Plastic-to-fuel CR is deceptively called 'recycling', CR is a cover name for 'greenwashing'
Environmental and social impact			**CR technology has environmental and social benefits**	**CR technology has no sustainability benefits**
	Environmental impact	Carbon footprint of CR technology	CR has a lower carbon footprint than incineration	CR technologies are carbon-intensive and polluting CR technologies are not compliant with the 1.5°C target
	Evaluation processes	Credibility of LCAs	Existing LCAs are credible LCAs would benefit from additional guidelines	CR sustainability benefits are unverified (LCAs not credible) There is no robust methodology for calculating the climate impact
	Social impact	NIMBY effect	CR plants are safe against local environmental impacts	CR can have a negative local environmental impact
		Local impacts	CR can create regional employment in a sustainable industry	CR can have a negative health impact Demand for CR will be low, given the increasing hostility to plastics
Economics			**CR technology can be economically viable**	**CR technology cannot be economically viable**
	Feasibility	Feedstock availability	CR can have sufficient feedstock if adequately collected and sorted	Feedstock availability is a problem, given the low collection and sorting rates CR can cannibalise the waste streams that are currently used in MR Feedstock quality thresholds for CR are unclear CR requires clean and homogenous waste streams
	Profitability	Profitability at scale	CR can be profitable CR profitability potential lies in decentralised processes, not in large-scale applications	CR cannot be profitable with currently cheap virgin plastic prices Some CR is profitable in niche markets, but profitability is difficult at scale Low profitability potential due to sizable industry obstacles (e.g., lack of product standardisation, volatile demand)
	Supply chain	Inter-sectoral synergies	CR requires cooperation along the supply chain (e.g., through uptake-supply agreements)	-
Policy			**CR should be plastics policy priority/ necessitates policy changes**	**CR derails attention from the 'real problem'**
	Role of CR in plastics policy	Contribution to recycling goals	CR is indispensable to achieving recycling goals, reducing plastics product environmental footprint, and achieving a low-carbon economy Countries have no alternative plan to achieve recycling targets CR can fill the gaps that other recycling technologies cannot: recycle poor quality plastic waste, and produce virgin quality feedstock, including food-grade output	CR derails the policy efforts from the actual problem and perpetuates the overproduction of plastics CR kills innovation upstream, e.g., on packaging design Advancing CR risks high-carbon lock-ins
	Role of CR in waste hierarchy	Position vis a vis mechanical recycling	CR is an alternative to incineration to close the loop 'up the waste hierarchy' CR is complementary to MR for contaminated waste streams and producing food-grade packaging	CR creates undesirable competition for MR CR technologies should be below MR in the waste hierarchy CR technology is not yet mature to determine its place in the waste hierarchy

(*continued on next page*)

Table 2 (*continued*)

Topics	Contested points		Legitimising storylines (emphasise complementarity)	Delegitimising storylines (emphasize lack of complementarity)
				CR should be the last resort in the waste hierarchy
	Preferred policy towards CR	Policy priorities	Clarify CR definition at the EU level Clarify the legal status of CR in the waste hierarchy	Prioritise MR in policy before lowering the ambitions to less sustainable CR Clarify the legal status of CR in the waste hierarchy: depolymerisation as 'recycling', pyrolysis and gasification as 'recovery'
		Financial support	Explore options, e.g., public funding, distinctive green premium	Limit support for processes with a lower carbon footprint than virgin plastics
		Regulatory support	Include CR materials in recycling quotas Establish a measuring standard for recycled content, e.g., regulate the mass balance approach Employ indirect support mechanisms, e.g., virgin plastics penalties, recycled content targets, reduced plastic exports, EPR schemes	Limit CR feedstock to contaminated and degraded durable plastics only Evaluate impacts at the industrial level

boost existing chemical industries in Italy (IT17).

5.2.3. Economics

We identified contested storylines on whether or not chemical recycling can be economically viable, mostly contested around supply chain implications, profitability, and inter-sectoral synergies.

Storylines are based on contested arguments about whether there is sufficient plastic waste collection and sorting to fuel chemical recycling technologies and make it economically viable. The delegitimising storyline stresses the low collection and sorting rates in the EU (except for PET bottles) and lacking investment in infrastructure: "the challenges for recycling plastics remain chiefly at the start of the supply chain, with collection and sorting" (UKO53). The delegitimising storyline is also based on the argument that chemical recycling technologies will cannibalise waste streams used for mechanical recycling. Interestingly, also the legitimising storyline talks about feedstock availability but rather advocates for the need to improve that to help advance the technology, for instance, a chemical company stating that "waste management is a challenge" (UK52, 64) or a plastic reprocessor fearing "stiff competition for post-consumer material" (UK56).

Moreover, we identified arguments that directly challenge the profitability potential of chemical recycling technologies in the current market. The storyline that chemical recycling cannot be economically viable is often backed by the argument that it cannot be profitable with cheap virgin plastic prices (UK56). For instance, McKinsey & Company estimates that without a green premium, oil prices above 65 dollars per barrel are required to justify investments in chemical recycling (UK17, 23). Essentially, "it comes down to how much they [buyers] want to pay to be more sustainable with their material choices" (UK56). Such an argument is reinforced by some international NGOs, such as Zero Waste Europe (Tabrizi, 2021). Further obstacles to profitability can include demand volatility for recycled feedstock. The legitimising storyline, however, is optimistic that technology development will reduce costs and increase demand for chemical recycling, making it economically viable.

Finally, the legitimising storyline also claims that chemical recycling technologies can be successful and is also supported by the argument calling for potential benefits from inter-sectoral synergies, decentralised processes, and cooperation across the value chain. Cooperation can take numerous forms, from specific research collaboration to uptake agreements, providing security for investors (DE22-25). The storyline that chemical recycling technologies can be economically viable is comparatively stronger in the Nordic countries, particularly Norway and Denmark. To illustrate, private (e.g., Meglerhuset, DNB Markets) and public financial institutions provide funding for chemical recycling technologies development, and these events are widely presented as legitimising examples in the public debate (DK2, 7, 18, NO2, 9, 12, 16, 22, 23).

5.2.4. Policy

We identified that the legitimising storyline on policy claims that chemical recycling should be a priority and requires policy changes, while the delegitimising storyline claims that chemical recycling derails the attention away from the 'real' plastics problem. These storylines contest whether or not chemical recycling is instrumental in achieving the recycling targets, the positioning of chemical recycling technologies in the waste hierarchy, and the required policy support for chemical recycling.

We found that these storylines contest the contribution of chemical recycling to the recycling target goals. The legitimising storyline calls for policy support for chemical recycling, highlighting its helpful and perhaps even indispensable role in reducing the environmental footprint of plastics products and shaping the low-carbon economy (UK14). On the contrary, in the delegitimising storyline, chemical recycling derails attention from solving the plastics problem at the risk of high-carbon lock-ins and reducing innovation upstream, for instance, improving plastics packaging design (AT11). Some environmental NGOs also view chemical recycling as a counterproductive "distraction from the root of the problem: overproduction of packaging" (UK23) (Kelly, 2022).

The storylines also contest the positioning of chemical recycling technologies in the waste hierarchy, especially compared to the

status quo mechanical recycling. The most frequently encountered arguments in the legitimising discourses position chemical recycling as complementary to mechanical recycling and as an alternative to incineration (AT12, NL23, 36-38, UK5). According to the delegitimising storyline, however, chemical recycling creates undesirable competition for mechanical recycling and should be positioned as technologies of last resort to avoid cannibalising waste streams. According to some international NGOs and consultancies, the technology is too novel to make a clear judgment on its positioning: "the technical, economic and environmental performance [..] just isn't proven at scale yet" (UK17, 23). In fact, "each of the currently available processes is applicable for specific plastic waste streams. Thus, only a combination of different technologies can address the plastic waste problem" (Vollmer et al., 2020).

Accordingly, the storylines also contest the intensity of policy actions towards chemical recycling. The legitimising storyline contains a call for accelerating policy support, such as clarifying the legal status of chemical recycling (at the EU level), introducing regulatory measures such as a mass balance approach (for determining chemically recycling feedstock in a product), and providing financial support, for instance, the green premium in the UK (UK17, 23, 52, 64). Some international NGOs also call for more transparency by developing standards for recycled content and traceable labels for consumers. The government in the Netherlands added chemical recycling to the waste management plan as early as 2018, triggering media resonance (NL41). Another example is Denmark, where the Danish Environmental Agency classifies chemically recycling materials as 'recycling' and arguments for policy support have been advanced in relation to Quantafuel's Danish Skive plant (FR29, 32, 33). The delegitimising storyline contains fairly similar arguments across countries, calling on policy to prioritise mechanical recycling, limit financial support for processes with a lower carbon footprint than virgin plastics, and, with that, ultimately limit the scope of chemical recycling.

5.3. Discourses and legitimacy implications

We find that the public discourses in the UK, Germany, and Italy emphasize various aspets of norms, values, and expectations regarding chemical recycling technologies. Accordingly, the storylines reinforce or reduce insititutional complementarity in terms of policy decisions, technology-specific support programs, regulations, and standards, shaping legitimacy of the in-between technologies (point 2 in Fig. 1). These patterns are defined by the actors and interests that mobilize the storylines in the case study countries.

5.3.1. UK

The public discourse in the UK strongly highlights the institutional complementarity of chemical recycling technologies with the policy efforts to reduce plastics pollution to achieve sustainability goals. Interestingly, delegitimising storylines in the UK present chemical recycling as insufficient to achieve these goals, pointing to limited benefits from the technology. Storylines on chemical recycling in the UK have appeared relatively recently, mainly in expert forums and specialised press: "[the topic] is not on the radar for the man in the street" (Int5). Certain daily newspapers are increasingly engaging with the topic, particularly the Guardian.

The institutional complementarity in the public discourse in the UK is carried forward in policy proposals to transform the plastics value chain to enable chemical recycling technologies (Partridge and Medda, 2019). The UK Resources and Waste Strategy (2018) features policies to reduce plastic waste, and the upcoming policy updates are expected to boost chemical recycling (UK15, 16, Int5, 6) (L. Smith, 2022). Chemical recycling is also likely to be recognised as recycling content for the UK recycling tax (UK3, Int5,6). The public-private UK Plastics Pact (a roadmap for 2025 planning an additional recycling capacity of 500'000 tonnes per year and over GBP 150mn investment in the UK recycling infrastructure) actively calls for non-mechanical recycling for food-grade packaging (WRAP, 2022). We also identified incentives for research and innovation in chemical recycling. The government is "happy to put money behind this" (Int5) (Doherty, 2022). Overall, the UK "is a good space for chemical recycling companies" (Int6) with increasing technology-institution complementarity.

Nevertheless, policy challenges remain, especially regarding sorting infrastructure to separate highly recyclable materials such as PP (that ends up as mixed plastic) which is relevant for chemical recycling (Burgess et al., 2021). Currently, 44 % out of 2.4 million tons of plastic packaging waste (70 % of all plastic waste is plastic packaging waste) is recovered or mechanically recycled (mostly natural and coloured HDPE) (DEFRA, 2022; WRAP, 2022). The UK imports rPET feedstock to meet the demand (Baynham, 2022). To achieve the 2030 targets for 60 % reuse and recycling of municipal waste (as per DEFRA), the UK necessitates improvements in sorting infrastructure, especially as the British Plastics Federation expects rapid growth for 'non-mechanical recycling' in the UK, constituting the end-of-life route for 7 % of plastics in 2030 (British Plastics Federation, 2022).

Overall, the presence of leading industry actors in the public discourse, especially Recycling Technologies and Unilever, but also large NGOs that are repeatedly quoted in the public press, balances the discourse in favour of legitimising chemical recycling in the UK. A key example is Recycling Technologies, a company that actively runs collaborations with public and private sector actors, such as the retailer Tesco (UK7, 63), chemical companies Ineos and Trinseo (UK17, 51, 65), as well as various research and innovation institutions, including the Universities of Birmingham, Surrey, and Cranfield, and Innovate UK (government institution) (UK9, 17, 21, 51, 52, 64). The discourse is also upheld by consumer goods companies that need to live up to their recycling commitments, such as Unilever. Consumer goods companies can strongly affect the overall discourse: "NGOs and universities have opinions, and they are, of course, valid, but if a consumer goods company sets targets, there will be a large change in the value chain quickly" (Int6). NGOs, such as the Ellen MacArthur Foundation, caution about the broader risks inherent in the plastics value chain, especially packaging overproduction.

5.3.2. Germany

The public discourse in Germany is more conflicted about institutional complementarity of chemical recycling technologies, based on contested storylines. The discourse is primarily focused on technology aspects, particularly arguing that chemical recycling has

efficiency gains, such as tackling dirtier waste streams and producing higher-quality outputs (Int8, 9). Further storylines indicate that chemical recycling technologies can be economically profitable in these markets based on collaboration within the value chain. At the same time, we identified the comparatively highest prevalence of delegitimising storylines in Germany, primarily arguing that chemical recycling technologies are not a 'silver bullet' and has no sustainability benefits, questioning the credibility of the underlying LCA assessments (DE22-25). We also identified the delegitimising storyline that chemical recycling increases the risk of high-carbon lock-ins and reduces innovation upstream, for instance, by improving plastic packaging design (AT11). In other words, chemical recycling technologies are not complementary to the existing institutions, a notion also perpetuated by such public orgaisations as Grüner Punkt (AT1, DE38).

In this context, the institutional complementarity for chemical recycling in terms of regulatory and policy support has significant unrealized potential. On the one hand, policy attention to developing recycling and sorting infrastructure in Germany has been notable, with 46 % of plastic waste recycled annually (plastic packaging waste constitutes 30 % of all plastic waste), with the share of recyclate from post-consumer waste in new plastics products at 5.6 % (BMU, 2019). Moreover, all packaging is subject to an extended producer responsibility (EPR) scheme requiring those who bring packaging onto the market to take it back after use and recycle it (BGBL, 1991) (based on the Packaging Ordinance). This is ensured through a private 'dual system' (alongside the municipal waste system) whereby plastic packaging (and metals and liquid packaging boards) are collected separately (BMJ, 2017).

On the other hand, policy advances specifically tailored to chemical recycling in Germany are lagging behind technology development. The status quo actors recognize Germany as "the hardest market for anything that mechanical recycling players think is competition for them" (Int10). While policy support and recognition for chemical recycling were negated in the past, the coalition agreement of the government since 2021 is the first to state that chemical recycling will be included as a recycling option in the VerpackG (successor of the Packaging Ordinance, the main vehicle for reaching the recycling objectives in Germany) (Voss et al., 2021). This is in line with broader plastics policy, such as increasing the recycling quota (DE30, 37) (BMJ, 2017). Following up on the policy developments and whether/how the recycling industry will lobby against this can render interesting insights for future research.

The main actors in the conflicting public discourse in Germany are large chemical companies. Companies like BASF are interested in offering technological innovation in the existing markets and to benefit from inter-sectoral synergies and actively perpetuate legitimizing storylines. At the same time, for instance, Werner and Mertz, produces specialised delegitimizing content (e.g., videos) for social media, primarily LinkedIn, as we identified when triangulating the data. Further voices in the discourse include technology companies (e.g., Quantafuel, Remonids, Trinseo), packaging companies (e.g., Sudpack), consumer goods companies (e.g., Henkel), and research centres (e.g., University of Heidelberg) (DE4, 30, 35, 40, 43). Note that the storylines on policy and economics are less frequently perpetuated by consumer goods companies in Germany than in the UK, according to an interview: "[these companies] care that the content is recycled but do not necessarily care how" (Int10). Even more so than in the UK, the storylines on chemical recycling in Germany are mostly found in specialised media and rarely appear in daily newspapers such as Süddeutsche Zeitung or Frankfurter Allgemeine: the topic is "not yet ripe" for the broader public (Int7). The debate on chemical recycling in Germany is also active on social media and forums organised by large chemical companies, especially BASF (DE1-2).

5.3.3. Italy

The public discourse in Italy depicts strong complementarity between chemical recycling not only as a solution to address the plastic waste problem but also as part of a broader industry ecosystem and, ultimately, an economic development opportunity (cf. Paletta et al., 2019). The coverage of chemical recycling in the Italian press is comparatively higher than in the UK and Germany, likely as it is embedded in the broader economic narrative. However, Italy also scores comparatively lower on media freedom (Int1-3). Therefore, we verified the findings in follow-up interviews. We identified various kinds of legitimising arguments in Italy, highlighting environmental and social benefits as well as the economic viability of chemical recycling. However, instead of solely arguing for how this particular technology fits the efforts to solve the plastics problem, the storylines are embedded in a broader discourse on rewiring the economy towards industrial growth, specifically also the chemicals industry. Interestingly, we identified arguments in the storylines supportive of the chemical recycling industry that creates employment in Italy but not supportive of importing chemically recycled content from abroad (Int1-3, IT6-8).

In response to the shift to advance the industry in Italy, we also identified delegitimising storylines arguing that chemical recycling has no environmental benefits and, in fact, has negative consequences for society. Specifically, we found a strong NIMBY effect depicted in the storylines, driven by local citizen initiatives protesting the adverse environmental and health impacts of pyrolysis plants in Retorbido (IT65) and Lazio regions (IT10). Some of the delegitimising storylines also question the technology and whether chemical recycling plants produce plastics-to-fuel in disguise (IT17). As the word 'chemical' can have negative wording implications in this context, advocates of the technology often use different terms, such as 'super recycling' or refer to particular chemical recycling technology types directly, such as depolymerisation (Int4).

In this context, the institutional complementarity in terms of regulatory and policy support for the technology has been increasing, but the support is not equivocal. The current government, especially the Minister for Ecological Transition, is backing the plastics industry, chemical industry, and new technologies that solve inherent value chain problems (Int1-3). For instance, the plastic tax is expected to come into force in 2023 (exempting recycled and compostable products) (Scuderi, 2021). Advancing project authorisation at the regional and local levels is required to attract investment (Int4). Moreover, Italy has supporting policies for sorting infrastructure development, as plastics constitute an important value chain in Italy (Bologna is a 'packaging valley' with strong expertise in packaging automation) (Int4). Out of 3.9 million tons of plastic waste annually, 25 % are recycled, leveraging 132 plastics recycling plants and 32 sorting centres (ENF Recycling, 2022). However, certain regions have waste management challenges, and municipalities are funded for separate packaging collection (Conai, 2017). Italy imports 7.4 million tons of virgin plastics per year (Wit et al., 2019).

The technology legitimacy of chemical recycling technologies is driven by industry federations, especially Federchimica (federation of chemical industry) and, increasingly Confindustria (the main association for manufacturing and service companies in Italy). With this shift 'up the institutional hierarchy', one implication is that chemical recycling is depicted as one among many options to address the questions of plastic pollution and economic growth (Int1-3). Similar arguments are perpetuated by the non-profit consortiums that seek viable alternatives to incineration and landfill, particularly Corepla (consortium for the entire plastic packaging lifecycle), Conai (packaging waste), and Coripet (PET bottles) (Int4). Corepla is "among the most open-minded recycling associations in Europe", working closely with municipalities and chemical recycling companies such as Versalis, and open to various technologies (e.g., as opposed to Grüner Punkt in Germany) (Int2). Similarly, the bioplastics industry can offer another solution to the same problem (and is not compatible with chemical recycling as bioplastics use separate waste streams (Int4)). Italy has a strong bioplastics industry (e.g., Italy is the only country that has introduced an exemption for the Directive on Single-Use Plastics for bioplastics (Lettig, 2021; Molyneux and Mele, 2022)), and the Italian association for bioplastics (Assobioplastiche) does not overtly support chemical recycling but also does not oppose it (Int1-3).

6. Discussion and conclusion

Global plastic waste poses an increasingly pressing challenge, necessitating a transition to a circular economy. Technologies and pathways for a circular economy require policy support, and for that, they need legitimacy. Legitimacy is contested, especially through discourses in the public discourse. Legitimacy is important for technologies in all TIS phases. However, we lack insights into the legitimacy of in-between technologies, such as chemical recycling, that struggle to move from the formative to the growth phase within TIS, characterized by system expansion and technology diffusion. We asked: How do discourses shape technology legitimacy for in-between technologies?

First, similar storylines on technology, environmental impact, economics, and policy, can shape various discourses on in-between technology, depending on who advances them and the underlying interests. To illustrate, in the UK, legitimizing storylines are driven by specialised chemical recycling companies (e.g., Recycling Technologies) and consumer goods companies striving for recycling content (e.g., Unilever). These companies advocate for more support for chemical recycling in line with the existing policy goals to reduce plastic waste. The storylines in Germany are frequently built around specific advantages or disadvantages of the technology, highly contested by large chemical companies with diverging product portfolios. In Italy, the storylines are embedded in the broader discourse on the government's strategy to revive the chemical industry and industrial growth. Chemical recycling technologies emerge as one of technological options for industry institutions with broader agendas, depending on the environmental and social benefits and economic viability of the technologies.

Accordingly, the institutional complementarity reflected in and reinforced by the public discourse shapes the technology legitimacy in these countries. In the UK, the mostly legitimizing discourse on chemical recycling paves way for supportive policy proposals in line with the ambition to transform the plastics value chain. In Germany, direct policy support for the in-between technology is lagging behind, influenced by contested legitimacy of chemical recycling in the public disourse. In Italy, chemical recycling is part of a broader discourse on industrial development, on the one hand increasing institutional complementarity but also enabling other technologies to compete for the same goals. Essentially, these findings illustrate that the presence of actors with inherent interest in the technology development in the public discourse is key for its increasing legitimacy.

This paper renders two main findings on discourses legitimising the in-between technologies. First, legitimising and delegitimising storylines present contesting views on in-between technologies regarding their technological aspects, environmental and social impacts, and economic and policy implications. Second, how discourses contribute to institutional complementarity and increased technology legitimacy depends on the actors and interests that drive the prevalent storylines in particular contexts. Accordingly, even within one EU policy framework, the prevailing discourse and technology legitmimacy can unfold very differently across countries.

These findings have wider implications for the scholarly discussion on legitimacy in sustainability transitions. On the one hand, the in-between technologies require a number of actors advocating for the technology. Clarifying institutional structures and technology performance parameters for technology legitimacy can help move in-between technologies into the growth phase and enable at-scale deployment. On the other hand, the study also hints that it matters whether actors are well connected within a broader actor network. Essentially, actors form communities through shared interests and eventually also business and policy action, perpetuating the legitimizing discourse. Ultimately, the progress of the technology depends on the dominant actor network in a particular context.

This paper paves the way for further research on technology legitimacy for in-between technologies. First, it would be helpful to dig a level deeper into the actors behind the storylines and arguments, exploring discourse coalitions for in-between technologies and whether and how they differ from coalitions that form around a novel or established technologies. It would also be helpful to comprehensively explore actor networks, considering various relationships between actors (e.g., shared business or investment projects, research projects) and their impact on technology legitimacy. Second, it can be useful to consider the role of international actors, particularly NGOs and international organizations, in providing credibility for in-between technologies. As such technologies already have a proof of concept, international actors can encourage and contribute to evidence generation and add weight to the findings. Finally, we suggest systematically exploring the role of social media in legitimising in-between (and also other) technologies. Various data science-enabled research methods can be helpful in making sense of how storylines and arguments unfold, especially as increasingly many stakeholders talk about it.

CRediT authorship contribution statement

Inese Zepa: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Vivian Z. Grudde:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Catharina R. Bening:** Conceptualization, Methodology, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Table A1
Search terms used in Factiva analysis.

Country	Search terms
Austria	chemical recycling OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "chemisches Recycling" OR "Pyrolyse" OR "Depolymerisierung" OR "Monomerisierung" OR "Plasmavergasung" OR "Kunststoff (recycling) mit geschlossenem Kreislauf"
Denmark	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "kemisk genanvendelse" OR "pyrolyse" OR "depolymerisering" OR "monomerisering" OR "plasmaforgasning" OR "lukket sløjfe plast (genbrug)"
France	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "recyclage chimique" OR "pyrolyse" OR "dépolymérisation" OR "monomérisation" OR "gazéification du plasma" OR "gazéification au plasma" OR "recyclage en circuit fermé" OR "recyclage en boucle fermée"
Germany	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "chemisches Recycling" OR "Pyrolyse" OR "Depolymerisierung" OR "Monomerisierung" OR "Plasmavergasung" OR "Kunststoff(recycling) mit geschlossenem Kreislauf"
Italy	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "riciclaggio chimico" OR "depolimerizzazione" OR "monomerizzazione" OR "pirolisi" OR "gassificazione al plasma" OR "plastica a ciclo chiuso (riciclaggio)"
Netherlands	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "chemische recycling" OR "pyrolyse" OR "depolymerisatie" OR "monomerisatie" OR "plasma vergassing" OR "gesloten lus kunststof (recycling)"
Norway	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)" OR "kjemisk resirkulering" OR "pyrolyse" OR "depolymerisering" OR "monomerisering" OR "plasmaforgasning" OR "lukket sløyfe plast (gjenvinning)"
UK	"chemical recycling" OR "chemcycling" OR "pyrolysis" OR "depolymerization" OR "depolymerisation" OR "monomerization" OR "monomerisation" OR "(plasma) gasification" OR "closed loop plastic (recycling)"

Table A2
List of public newspapers considered as 'general' newspapers.

Country	Main daily / weekly newspapers
Austria	der Standard | die Presse
Denmark	Politiken | Berlingske | The Copenhagen Post
France	Le Monde | Figaro
Germany	Süddeutsche Zeitung | Frankfurter Allgemeine | die Welt
Italy	Il Sole 24 Ore | Corriere della Sera | La Stampa
Netherlands	de Telegraf | Algemeen Dagblad
Norway	Dagens Næringsliv | Aftenposten
UK	the Guardian | Financial Times | Economist

Table A3
Count of articles used in Factiva analysis (note: some articles correspond to multiple search terms).

Country	Relevant & unique articles	Pyrolysis	Chemical recycling	Chemcycling	Depolymerisation
Austria	33	8	27	0	0
Denmark	22	0	16	6	0

(*continued on next page*)

Table A3 (*continued*)

Country	Relevant & unique articles	Pyrolysis	Chemical recycling	Chemcycling	Depolymerisation
France	61	13	35	0	21
Germany	67	23	40	17	10
Italy	112	83	27	3	8
Netherlands	45	4	41	0	0
Norway	67	25	47	4	0
UK	78	15	60	0	8

Table A4
Most relevant list of sources from Factiva analysis.

Source code	Newspaper	Title	Year
UK			
UK3	Guardian	Recycling revealed: what happens to packaging in ist afterlife?	2019
UK5	PR Newswire	StePac Launches Sustainable Packaging Strategy; StePac reveals its innovative four-pillared strategy for greener packaging	2019
UK7	Guardian	'Plastic recycling is a myth': what really happens to your rubbish?	2019
UK9	Guardian	Recycling revealed: what happens to packaging in its afterlife?	2019
UK14	PR Newswire	SCS Members Trinseo and Ineos Styrolution Plan Commercial Scale Polystyrene Chemical Recycling Plant with Agilyx in Europe	2019
UK15	Regulatory News Service	Curzon Energy PLC Results for the Year Ended 31 December 2020	2021
UK17	Financial Times	Plastics-to-oil recyclers face a double struggle	2021
UK18	Packaging News Online	First European polystyrene recycling plants announced	2021
UK19	Guardian	How green are your leggings? Recycled polyester is not a silver bullet (yet)	2021
UK21	Swindon Advertiser	Swindon firm kicks off 1.2 million project to develop new material made out of recycled plastic	2021
UK22	Investment Week	Breaking the plastics chain: How can financial institutions be part of the pollution solution?	2021
UK23	Financial Times	Plastic makers bet on new waste recovery technologies	2021
UK40	ICIS News	INEOS Styrolution's ResolVE project concludes viability of R-PS through depolymerisation	2020
UK51	ICIS News	Chem recycler seeks to install units in waste centres	2020
UK52	ICIS News	Market intelligence: INEOS Styrolution advances chemical recycling of polystyrene	2020
UK53	ICIS Chemical Business	Chemical recycling faces big hurdles	2020
UK56	ICIS News	Market outlook: Market pushes recycled styrenics	2019
UK63	Mail Online	British company pioneers machine that could revolutionise recycling by super-heating plastic until it turns to wax	2019
UK64	ICIS News	INEOS Styrolution aims to produce recycled PS via depolymerisation	2019
UK65	European Plastics News	UK borough studies "all plastics" recycling facility.	2019
Germany			
DE1	Plastverarbeiter.de	BASF, Quantafuel und Remondis; Zusammen Kunststoffabfälle chemisch recyceln	2021
DE2	Dow Jones Newswires Germany	BASF prüft Ausbau des chemischen Kunststoffrecyclings	2021
DE4	Plastverarbeiter.de	PS und SSBR aus Kreislauf-Styrol; BASF liefert Styrol aus erneuerbaren oder recyclierten Rohstoffen an Trinseo	2021
DE10	Company Reports	bp and SABIC to develop circular products made from used plastic-based feedstock.	2021
DE11	Plastverarbeiter.de	Recycling-Initiative von Südpack, Recenso und Count; Öl aus Folienabfällen - Rohstoff für die Polymerindustrie	2021
DE16	Plastverarbeiter.de	KIT und Audi arbeiten zusammen	2020
DE18	ICIS News	Germany's Audi, tech institute launch project to recycle automotive plastics	2020
DE19	Plastverarbeiter.de	Chemisches Recycling technischer Kunststoffe; KIT und Audi arbeiten zusammen	2020
DE22	Company Reports	BASF investing in Pyrum Innovations for pyrolysis oil from waste tyres.	2020
DE23	Company Reports	BASF invests into Pyrum as part of its ChemCycling project: pyrolysis oil from waste tyres as additional raw material source next to oil from mixed plastic waste.	2020
DE24	Company Reports	BASF invests EUR 16 M in Pyrum to support pyrolysis of waste tyres.	2020
DE25	Plastverarbeiter.de	BASF investiert in Pyrum Innovations; Kapazitäten für Pyrolyseöl aus Altreifen erweitern	2020
DE30	Company Reports	Sudpack driving advances in chemical recycling.	2020
DE31	Company Reports	Chemical recycling for used mattresses: BASF pilot tests are up and running.	2020
DE35	Plastverarbeiter.de	Kreislaufwirtschaft; Chemisches Recycling bei Mehrschichtbeuteln	2020
DE37	Müll und Abfall	Chemisches Recycling von Kunststoffabfällen – eine Alternative zur werkstofflichen Verwertung? Chemical recycling of plastic waste – an alternative to material recovery?	2020
DE38	Müll und Abfall	Ansätze zur rohstofflichen Kunststoffverwertung; Approaches to chemical recycling of plastics	2020
DE43	Plastverarbeiter.de	Kreislaufwirtschaft; Remondis und Neste wollen chemisches Kunststoff-Recycling entwickeln	2019
DE45	Plastverarbeiter.de	Roh- und Zusatzstoffe; Aus Kunststoffabfall wird Cracker-Feedstock	2019
DE49	Company Reports	INEOS discloses results of ResolVe project that addresses polystyrene recycling.	2019
DE51	Company Reports	K 2019 - New products from plastic waste: BASF customers showcase prototypes made from chemically recycled material.	2019
DE54	Company Reports	BASF makes its first step in chemical recycling.	2019
DE55	Plastverarbeiter.de	Wertstoff wiederverwenden; Geflechtbauteile aus rezyklierten Carbonfasergarnen	2019
Netherlands			
NL6	Uzbekistan National News Agency	SABIC, Plastic Energy to construct commercial chemical recycling unit in the Netherlands	2021
NL7	Plastics Today News	Chemical recycling is no silver bullet for eliminating plastic waste.	2021

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Table A4 (*continued*)

Source code	Newspaper	Title	Year
NL8	Vanguard Nigeria	Sabic and Plastic Energy Start Construction of Circular Polymers Plant	2021
NLO2re2	Chimie Pharma Hebdo	Total Corbion PLA inaugurates its PLA unit in Thailand. Total Corbion PLA inaugure son unite de PLA en Thailande.	2019
NL23	WRBM Global Food	Cheaper plastic set to test market's 'true commitment to sustainability', warns report	2019
NL32	ENP Newswire	ING-What it takes to be a plastic hero	2019
NL36	European Plastics News	Sabic, UK firm to build chemical recycling plant.	2018
NL37	ICIS Chemical Business	SABIC plans waste plastic unit	2018
NL38	ICIS News	Price and market trends: SABIC plans demo plant to convert plastics waste into cracker feedstock	2018
NL41	Trade Arabia	Construction of facility to turn plastic into fuel starts at Port of Amsterdam	2018
NL42	PR Newswire Europe	LyondellBasell begint met de commerciële productie van polymeren met behulp van grondstoffen die afkomstig zijn van plastic afval	2021
France			
FR29	Chimie Pharma Hebdo	(EdIT): towards a plastic comeback? (Edito): vers un come back du plastique?	2020
FR32	Chemical Industry Digest	Carbios and TechnipFMC to Build Demonstration Plant for Depolymerization of Waste PET Plastics to Monomers	2020
FR33	Business Wire	Carbios et TechnipFMC annoncent la construction d'une usine de démonstration pour la dépolymérisation des déchets plastiques PET en monomères	2020
FR34	Industrie & Technologies	Recyclage; Total et Citeo misent sur la pyrolyse	2020
FR43	Emballagesmagazine.com	Le recyclage chimique des plastiques a un Ami	2019
Norway			
NO3	Esmerk Norwegian News	Norway/Italy: NextChem sign agreement with Agilyx for chemical recycling plants	2021
NO4	Contify Energy News	Maire Tecnimont Group's Nextchem and Agilyx sign an agreement for the global deployment of chemical recycling projects based on pyrolysis	2021
NO5	TDN Nyhetsbyrå	AGLX: AVTALE MED NEXTCHEM OM KJEMISK RESIRKULERING BASERT PÅ PYROLYSE	2021
NO6	TDN Nyhetsbyrå	QFUEL: MOTTATT MILJØSERTIFIKAT, SENDT FØRSTE KOMMERSIELLE PRODUKT TIL BASF	2021
NO10	TDN Nyhetsbyrå	KOMMENTAR: OSLO BØRS VENTES Å ÅPNE NED TIRSDAG	2021
NO11	Down Jones Institutional News	Press Release: Saga Pure ASA: Invests NOK 30 million in the chemical recycling company Pryme	2021
NO18	Resources News	Agilyx As Announces Intention To List On Merkur Market	2020
NO23	Dow Jones International News	Quantafuel: Quantafuel Asa | Second Quarter Results 2020	2020
NO49	PR Newswire Asia	Saga Pure: First quarter 2021 financial results	2021
Denmark			
DK7	Dow Jones International News	Lego Looks to Plants as Building Blocks for Bricks	2017
DK18	ENP Newswire	DTU: Independent Research Fund Denmark supports 23 projects	2020
DK26	Morgenavisen Jyllands-Posten	Watch medier	2021
Austria			
AT1	Müll und Abfall	Abfallwirtschaft im Zeichen von K. u. K.	2021
AT11	Austria Presse Agentur	Neuer Report deckt auf wie die Plastikindustrie seit Jahrzehnten strengere Regulierungen verhindert und die Plastikkrise verschärft	2020
AT12	Pressetext	BONUS Holsystem - Erstmals Klimaneutralität in der Abfallwirtschaft; Unternehmen unterstützt die Aufforstung zur Erhaltung der Artenvielfalt	2020
Italy			
IT6	ENP Newswire	Eni - Versalis, new certified product range for sustainability	2021
IT7	Alliance News	Versalis di Eni presenta gamma prodotti certificati per sostenibilità	2021
IT8	Adnkronos	Versalis: nuova gamma di prodotti certificati per la sostenibilità	2021
IT10	Il Messaggero	Rifiuti a Vazia, la Regione dice no	2020
IT17	Il Messaggero	Al Nucleo è previsto un impianto per il trattamento anual della plastica	2020
IT65	La Provincia Pavese	No del Tar, pietra tombale sulla pirolisi; Il Tribunale amministrativo ha respinto o giudicato inammissibili i ricorsi di Iet e Confindustria per il progetto di Retorbido	2018

Table A5
List of interviewees (anonymised).

Code	Country	Organisation	Role
Int1	Italy	Multinational chemical company A	Sustainability Community Manager
Int2	Italy	Multinational chemical company A	Commercial Manager
Int3	Italy	Multinational chemical company A	Head of Communications
Int4	Italy	National consortium	R&D Director
Int5	UK	Multinational chemical company B	Senior Sustainability Manager
Int6	UK	Multinational chemical company B	Sustainability Director
Int7	Germany	Multinational chemical company C	Director
Int8	Germany	Multinational chemical company C	Head of Advocacy
Int9	Germany	Multinational chemical company C	Senior Specialist
Int10	Germany	Multinational chemical company D	Head of Innovation

Table A6
llustrative interview guidelines.

Illustrative interview guidelines	
Plastics strategy	What is your strategy to fill the 2025 recycling targets? What strategy should the EU follow to close the plastics loop?**What are the critical missing pieces in the current approach?
Actor (stakeholder) landscape	Which stakeholders have an opinion on and interest in chemical recycling (in your country)? Which stakeholders oppose chemical recycling, and why?
Narratives	What are the main arguments why stakeholders support or oppose chemical recycling? Who are the stakeholders driving the key narratives? To what extent are the narratives backed by facts?
Probing for insights on specific narratives	Technology: What do you think are they key benefits of chemical recycling technology? What are the key drawbacks and risks? Environmental impact: How would you assess the energy balance for chemical recycling? Economics: How would you assess the potential to scale chemical recycling technology? Policy: Where in the recycling loop do you see place for chemical recycling technology? *These general questions were followed by probing for insights on specific storylines. Storylines from Table 2 were presented as a statement, to see if the interviewee agrees or not, and why.*

Table A7
List of chemical recycling projects identified in Europe.

Country	Company	Technology	Year announced
Austria	OMV	ReOil Pyrolysis (P2F)	2018
Denmark	Quantafuel	Pyrolysis	2019
Denmark	Quantafuel	Pyrolysis + integrated sorting	2021
EU	SCS, Agilyx, INEOS Styrolution, Trinseo	PS CR	2019
EU	NextChem & Agilyx	Pyrolysis	2021
France	Carbios	Depolymerisation PET	2020
France	Ineos Styrolution & Trinseo	Depolymerisation PS	2020
France	Orrion Chemicals Orgaform	PU-Foam recycling	2020
France	Plastic Energy & TOTAL	Pyrolysis	2020
France	Plastic Energy & Exxon Mobile	Pyrolysis	2021
France	VOW	Plastic to electricity	
Germany	APK	Solvolysis/Newcycling	2017
Germany	BASF	ChemCycling (uses pyrolysis oil)	2018
Germany	Leistritz & Rittec Umwelttechnik	Depolymerisation/RevolPET	2020
Germany	Audi & KIT	Pyrolysis/CR of plastics from the automobile sector	2020
Germany	Covestro	PU-Foam recycling	2021
Germany	Recenso, Südpack & Count	Carboliq	2021
Germany	Sabic & BP	Pyrolysis	2021
Germany	Recenso & Technip Energies	Combination of Carboliq with purification technology	2021
Germany	RenEW ELP & Licella	HydroPRS & CatHTR	2021
Italy	Re-Cord	Pyrolysis	2018
Italy	Garbo	ChemPet	2018
Italy	LyondellBasell	MoReTec	2019
Italy	Garbo	ChemPet	2019
Italy	INEOS		2019
Italy	Versalis	Pyrolysis	2020
Italy	Eni	Gasification	2020
Italy	Eni & Maire Tecnimont	Gasification	2020
Italy	marGnet	Low-temperature pyrolysis	2020
Netherlands	Green Energy Solutions	Pyrolysis (P2F)	2018
Netherlands	Sabic & Plastic Energy	Pyrolysis/Tacoil	2018
Netherlands	Sabic & Plastic Energy	Production of new polymer by TACOIL	2019
Netherlands	Fuenix & Dow	Pyrolysis + production of new polymers	2019
Netherlands	Quantafuel & Vitol	Pyrolysis	2020
Netherlands	Bluecycle	Pyrolysis	2020
Netherlands	Recycling Technologies	Pyrolysis	2020
Netherlands	Quantafuel & Vitol	Pyrolsis	2020
Netherlands	PRYME	Pyrolysis	2021
Netherlands	RetourMatras & H&S Anlagentechnik	Chemical recycling of PU (technology unclear)	2021
Netherlands	Neste & Ravago	Liquefaction	2021
Netherlands	Dow & Haldor Topsoe	Pyrolysis	2021
Netherlands	Shell & BlueAlp	Pyrolysis	2021
Norway	Quantafuel	Pyrolysis (P2L) + mechanical recycling +sorting	2020
Norway	VOW & Lindum	Plastic to electricity	
UK	Recycling Technologies	Pyrolysis/advanced plastics recycling facility	2019
UK	Recycling Technologies	Pyrolysis	2020
UK	ReVentas	PE & PP recycling (technology unclear)	2020
UK	Plastic Energy	Pyrolysis	2020

(*continued on next page*)

Table A7 (*continued*)

Country	Company	Technology	Year announced
UK	Poseidon Plastics	Glycolysis process of PET	2020
UK	Poseidon Plastics	Glycolysis process of PET	2020
UK	Worn Again Technologies	Dissolution process	2020
UK	Low Sulphur Fuels	Fast Electrical Process	2020
UK	Wastefront	Pyrolysis	2020
UK	Enval	Pyrolysis	2020
UK	Quantafuel	Pyrolysis	2021
UK	RENEW ELP	CAT-HTR	2021
UK	Mura Technology	HydroPRS	2021
UK	Enval	Pyrolysis	2021
EU	Ineos Styrolution & Müller	PS recycling	2019
EU	Remondis & Neste	CR capacity	2019
EU	Michelin & Enviro Systems	Pyrolysis	2020
EU	Ineos & Plastic Energy	Pyrolyis multilayer LDPE, LLDPE, HDPE, PP, PS	2020
EU	Lucite & Agilyx	CR of PMMa	2020
EU	INEOS & Pyrowave & Revital Polymers	CR of single-serve PS packaging	2020
EU	Technip Energies & Synova	Platform to jointly commercialise Synova's platform with Technip's steam cracking expertise	2021
EU	Powerhouse Energy Group PLC	Gasification/DMG	2021
EU	Plastic Energy	Pyrolysis	2021
EU	Recycling Technologies, INEOS & TRINSEO	Depolymerisation of PS	2021

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