Summary of Research

Radboud Honors Academy – Project Impact – Navigating Sustainability Transitions Team

In Partnership with the Institute for Sustainable Process Technology

Our Team:

Dennis Colin: Master's student of Biology with a specialization in Conservation and Restoration Ecology, with a background in ecological and socio-economic aspects of sustainability. dennis.colin@ru.nl

Enrico Fontein: Master's student of Economics with a specialization in Accounting and Control, with a background in (business) economics. enrico.fontein@ru.nl

Karolis Gritenas: Master's student of Biology with a specialization in Conservation and Restoration Ecology, with a background in data analysis and ecological fieldwork. karolis.gritenas@ru.nl

Maureen Poppelaars: Premaster's student in Communication Science (in preparation for the News and Information Master), with a background in international economics and business. maureen.poppelaars@ru.nl

Melissa Roncken Cossio: Master's student of the Adaptive Organisms program, with a specialization in Microbiology and Evolution, with a background in working with sustainable biomaterials. melissa.ronckencossio@ru.nl

Paige Kemper: Master's student in the Research Master for Social and Cultural Science, Comparative Politics track, with a background in public policy, renewable energy, and computer science. paige.kemper@ru.nl

Roberta Amalia Voiculescu: Premaster's student in Economics with a specialization in International Political Economy, and a background in international relations. roberta.voiculescu@ru.nl

Shane Aweeka: Premaster's student in the Global Political Economy and Science for Sustainability program with a background in politics, economics, and sustainable development. shane.aweeka@ru.nl

Vedansh Patel: Master's student in System Dynamics, with a background in software engineering. vedansh.patel@ru.nl

Introduction

In the past few decades, the use of waste as a resource has been explored more extensively. Transitioning the waste value chain towards circularity and improving carbon recycling, is ideal for industry and society as both a more sustainable and resource-secure alternative for materials. The transition towards material circularity is led by the adoption of recycling, including traditional mechanical recycling methods as well as newer chemical recycling methods. Gasification of waste is a type of chemical recycling that is increasingly explored as an alternative to landfilling and waste incineration. However, challenges in establishing a business case and coordinating this value-chain intervention inhibit momentum in industry adoption.

Instituting change across the waste value chain is an incredibly complex and challenging task. It requires consideration of technological readiness, financial feasibility, and coordinated interest across business stakeholders, government officials, financers, off-takers, logistic managers, as well as the resulting externalities in waste production, management, and evolving alternative technologies. To help understand and address these complexities, our Navigating Sustainability Transitions team from the Radboud Honors Academy has researched, interviewed stakeholders, and organized a summit event with leaders across the waste value chain in the Netherlands, to investigate the business case of waste gasification. Through this, we sought to map the systemic complexity of the value chain and position the business case with key bottlenecks and opportunities in the context of the sustainability transition. In this document, we offer a brief review of our approach to waste value chain research, as well as the key business case findings, bottlenecks, opportunities and potential next steps for transforming the waste value chain. We hope this document can act as a roadmap for understanding the complexity of the waste value transition and provide direction for industry leaders to push forward the effort.

Methodology

This research project emerged from a collaboration between the Radboud Honours Academy and the Institute for Sustainable Process Technology (ISPT), culminating in **Project Impact: Navigating Sustainability Transitions**. Over the course of eight months, our research group employed a variety of methodological approaches to examine the topic of gasification in the context of sustainability transitions.

First, we conducted extensive literature and market research to review the technologies, policies, and markets facilitating waste management and recycling. Our research focused on waste gasification as a promising technology for chemical recycling, aimed at retaining value within the existing waste value chain and reducing reliance on fossil-based hydrocarbon extraction for material and fuel production. This literature and market review was key for establishing a thorough and up-to-date understanding of gasification technologies and their implications.

Then, as the project advanced, we conducted 24 semi-structured interviews with stakeholders across the waste value chain and leading researchers, representing the different industry perspectives, technology information and interests as well as providing comprehensive insights and key insights into this sector. We also participated in stakeholder summit meetings organized by our industry partner, ISPT, and conducted targeted industry research in London to deepen our understanding of market dynamics and policy frameworks governing waste value chain interventions within and beyond the European Union.

Lastly, once we got a good perspective on every part of the value chain, we organized an industry-wide event. This event had as purpose to facilitate the dissemination of our findings, promote knowledge exchange between stakeholders, and obtain final additional insights and perspectives into the efficacy of gasification as a waste-value-chain intervention. Through this event, named “Industry Talks: Carbon Recycling through Waste

Gasification", we brought together 16 participants from diverse segments of the waste value chain, fostering meaningful discussions on the business case, bottlenecks, opportunities and next steps for adopting waste gasification technologies in industry. Notably, it marked the first occasion on which such a broad range of stakeholders convened to engage collectively on this topic. The stakeholders present during the Radboud Honours Gasification event, are: Blue Circle, DOPS, DOW, Enerkem, Gidara, ISPT, Nobian, NVRD, PreZero, Remondis, Renewi, Shell, Synprodo and TNO.

Value Chain Overview

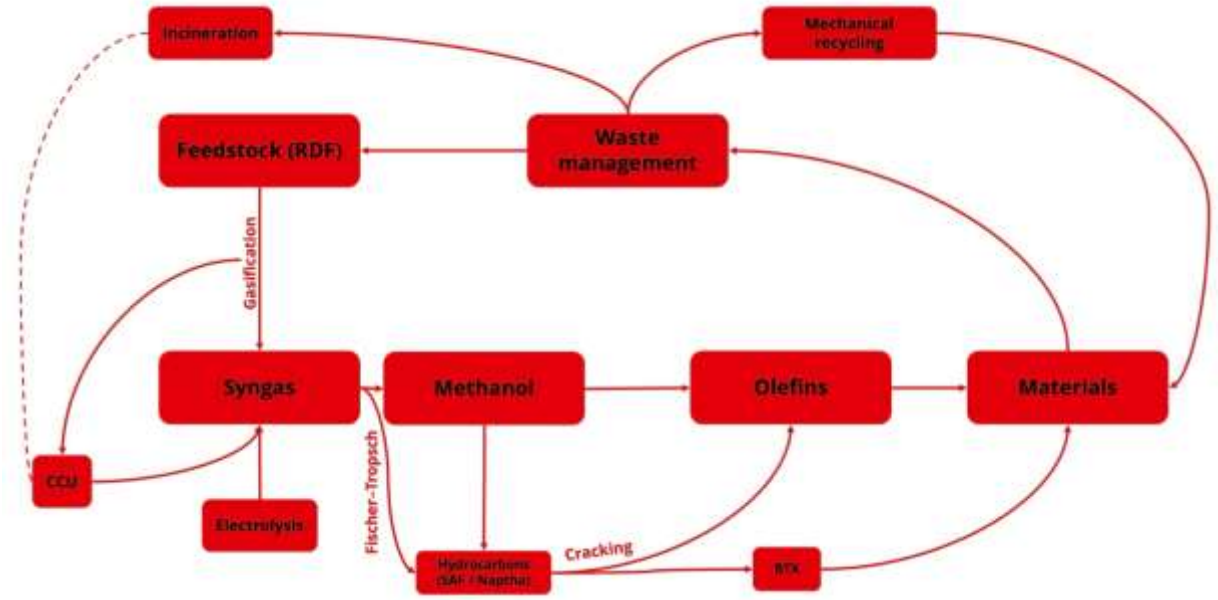

Figure 1. Visualization of the Gasification Waste Value Chain. This is a simplified scheme depicting important steps for the conversion of waste to materials (i.e. plastics) through gasification. The scheme additionally includes external processes such as mechanical recycling, incineration, CCU, hydrogen addition through electrolysis and SAF production.

Sorting

Purified waste streams will allow for increased feedstock inputs to ensure the certainty of gasification's proof of concept and ability to scale. Strategies highlighted by industry executives emphasized the need for better waste sorting. This could be achieved through encouragement of pre-sorting behaviors, such as waste material buy-back programs and financial incentive/penalty mechanisms. Additionally, promoting sorting process

synchronicity across various municipalities, which currently implement differing methods, is key to improving both opportunity for mechanical recycling as well as the potential for and reliability of waste-feedstock that could be used in gasifiers. Ideally, most, if not all, waste should be directed to mechanical recycling. However, current sorting technologies and the quality of available waste streams do not yet meet this expectation, particularly due to contamination that renders some materials unsuitable for mechanical recycling. As a result, there is always some unsorted waste left that will be either incinerated or landfilled. The gasification business case relies on this type of waste, as gasification would be implemented as a more sustainable way to deal with this carbon-containing waste, while also recovering materials in the waste.

Feedstock

Residual derived fuel (RDF), typically comprised of a combination of biowaste and residual waste, has been demonstrated to be a reliable, industrially favorable feedstock for gasification. RDF for feedstock increases the standardization for gasifier inputs, and therefore the regularity of the syngas outputs. This will further secure process predictability and improve the business case security, particularly important considering a secure business case requires security of supply of feedstock to assure syngas production.

Gasification

Despite its proven efficacy, gasification technology has encountered issues in scaling capacity due to low investment and permitting issues; the former of which can be correlated to the lack of a proof of concept. Even though gasification has been applied before for biomass conversion, its efficacy and viability as a carbon-containing waste recycling method needs to be proven. Chemicals such as methanol, ammonia, hydrogen, and diesel are viable products that can be synthesized from gasification-derived syngas,

making the technology potentially valuable for various industrial applications. However, the high capital expenditure (Capex) required to scale such projects remains a major barrier. For example, the estimated cost for offtake infrastructure alone can reach up to €800 million, and even in more optimized scenarios, it might only be reduced to around €400 million. In contrast, current available grants—often around €30 million—are insufficient to significantly offset these upfront costs. As a result, securing adequate financing remains a persistent challenge. Investment, permitting and off-takers present additional hurdles, further exacerbated by a lack of consumer confidence in the previous two chain-links.

Methanol to Olefins

Users of olefins have found it cost-effective to purchase fossil-derived methanol from outside the European Union for the production of olefins. Establishing a business case for a domestic-circular olefin market is critical to scaling gasification technology and ensuring proper investment in the practice. Circumventing the process can be done as well through the adoption of the Fischer-Tropsch method, which, through the production of Naphta can develop expanded polypropylene for the material outputs. Furthermore, by cracking Naphta and developing BTX (Benzene, Toluene, Xylenes), olefin production can be increased which will further strengthen the business case necessary for the implementation of gasification technology.

End User

Despite interest from developers in syngas-derived polypropylene and polyethylene, the cost-effectiveness of virgin plastic continues to be more effective, further weakening the business case. Appeal for the circular olefin marker has increased; however, stakeholders have indicated that the assurance of market demand is contingent upon the

implementation of legislation that would limit the purchasing of virgin plastic and enable greater flexibility in the classification of off-taken material products.

Outcomes

Business Case

The difficulty in establishing a business case arises from both the challenge of coordinating and addressing information gaps across stakeholders. Building a business case requires establishing a clear demand, but is also supported by regulation, financing, and technology.

Considering the large CAPEX and OPEX costs of a gasification plant, the availability of financing presents another consideration and hurdle to implementation. This is amplified by technical considerations rooting from technology readiness levels (TRL) for waste gasification, and variable conversion efficiencies dependent on feedstock homogeneity.

As a method for understanding and quantifying the financial business case for the waste gasification to materials pathway, we developed a business case calculator (accessible at https://gasification.pages.dev/). The calculator is initialized with literature derived values but then allows manipulating the different conversion efficiencies and parameters of the gasification plant. Using methanol is primary commodity, a final break-even price and financial gap are determined. While the parameters are determined from an academic source, the real-world values differ significantly depending on market context and technology. This is an indicative of the asymmetric information available to stakeholders: Individual organizations are unable to independently determine a business case across the entire value chain.

Bottlenecks and opportunities

Through our research and engagement with stakeholders, we identified several critical bottlenecks currently slowing progress in scaling innovative waste-to-energy solutions, particularly gasification technologies. A major challenge is the high capital cost associated with building new infrastructure, which often exceeds what customers or partners are willing to pay. This is compounded by uncertainty in estimating costs and choosing the right approach, making investment decisions difficult. Additionally, process changes such as introducing sorting facilities or rerouting waste streams add further logistical complexity, increasing the risk of inefficiencies and delays. Even when pilot projects show promise, many fail to scale due to lack of funding and cash flow constraints, emphasizing the need for more robust financial planning and support mechanisms. A further barrier is the limited understanding among policymakers of gasification's full potential, which has resulted in weak or misaligned policy support—highlighting the need for greater advocacy and education.

Despite these challenges, there are promising opportunities to move the sector forward. A key strategy is to minimize risk and cost by leveraging existing infrastructure—particularly by adapting current gasification units with reactors tailored to specific feedstocks and desired outputs. Additionally, for the gasification plant to become economically viable it needs to be large-scale, therefore, developing a centralized facility co-funded by multiple companies could improve capital efficiency, especially if supported by securing multiple input sources and guaranteed end-users to reduce market volatility. There is also a strong opportunity to learn from past attempts, especially those that failed not because of technical flaws, but due to financial and operational issues—lessons that can inform more resilient scaling strategies. Perhaps most critically, the sector would benefit from building a stronger industry consensus to collaboratively engage with policymakers, clarify misconceptions about gasification, and promote enabling regulatory frameworks.

Next Steps

Moving forward, the focus should be on facilitating strategic partnerships, fostering shared investment in infrastructure, and supporting knowledge-sharing about both successes and setbacks. At the same time, strengthening advocacy efforts, ensuring that decision-makers are better informed and more effectively aligned with the potential and requirements of emerging waste-to-energy technologies are key. By tackling these barriers collaboratively and capitalizing on shared opportunities, you can accelerate the development of scalable, financially viable, and environmentally sustainable solutions.

Without legislative support, the adoption of the gasification practice from all necessary stakeholders will require several arrangements from opposite ends of the value chain. First, stakeholders within the initial half of the value chain (disposal, sorting, feedstock and gasification) will need to develop working partnerships that disclose procedural methods and therefore alleviate uncertainty and asymmetric information that hinders adoption. When unanimous adherence is garnered, the system will operate appropriately, stakeholders routinely highlighted the uncertainty pertaining to sorting reliability, feedstock supply and classification of products. Second, securing the appropriate business case for the later half of the chain will be require adherence to the business case arraignments above. Adoption on the practice is contingent upon how and when the methanol, olefin and product output portion of the chain can be effectively.

Lastly, gaining clarity on the business case output remains especially important, as the expanded polypropylene necessary for material outputs has encountered scaling issues. Alternatively, through the utility of the Fischer-Tropsch method (1)Naphta>>(2)(cracking) BTX) one will be able to increase 1) olefin and 2)EPP supply, which will ensure greater robusticity of the material business case market; further cementing and clarifying the bottlenecks outlined in our studies.

Conclusion

Waste management practices can be more circular. Although it has been seen that it would be better to intervene in phases before the recycling stage, gasification stands as a potential intervention to improve circularity practices and secure resources for the future. This needs to happen on a large scale in order to be economically viable. However, this step would require some economical and legislative support to take off, as relevant stakeholders seem insecure about the logistical pathway this gasification implementation would take. Besides, the viability of implementation of gasification is compromised by how well stakeholders can communicate with each other. All in all, the business case for the implementation of gasification as a recycling technique is strong. It still has some bottlenecks, such as the high capital cost and asymmetrical information between the stakeholders. These bottlenecks can be resolved by implementing clearer communication streams between stakeholders and investors and engaging policymakers to get the required economical and legislative support. To unlock the full potential of gasification, stakeholders must come together to build trust, align objectives, and advocate for the policy frameworks and financial tools that will enable large-scale deployment. The time to act is now—transforming waste into value is not only possible, but essential for a more sustainable and circular future.

Appendix 1: Takeaways from 19 June Meeting:

Building on RHA Team Findings, additional findings from the "Industry Talks: Carbon Recycling through Waste Gasification" event include:

1.1.1 Business Case:

- Core Process Considerations
  - Efficiency gains in mechanical recycling changes feedstock
  - Pre-treatment
  - In methanol to fuel path: Proof of biogenic – mass balancing limitation in NL
  - Fischer–Tropsch process / NAPHTA
    - (Syngas → FT → NAPHTA → Cracker (shell/DOW) → BTX → Materials)
- Core Industry/Market Integration Considerations
  - Feedstock/Gasifier adaptation → lengthens waste chain
  - Market demand / pull forces integral, missing from dashboard
- Where Stakeholder Influence Could Improve Business Case
  - Stakeholders influence legislation key for building market / (green methane) economy
  - Mass balancing (biogenic C-14) in Netherlands – need clarity on the regulatory environment needed.
- Incineration decline (but prolonged by CC)
- Product price elasticity (improved by premium customers)
- Economies of scale + feedstock flexibility improve business case
- Pursue various paths for syngas

1.1.2 Bottlenecks:

- Funding:
  - Need to get more investment from IB or greenbanks, grants not enough – however, currently risk aversion by industry and investment
  - Funding for early plant → too much criteria. Scaling to TRL-9 financially difficult, and changing the industry – particularly with high CapEx a newer concept to lenders – is difficult
- Grant Criteria: Demonstrating that syngas/gasification product at least X% biogenic forces developers into feedstock requirements that are hard to meet – can actually be a barrier to achieving technology because applications for grants have unrealistic standards inhibiting middle stage scaling
- Fossil fuel demand competes with market for green methane
- geopolitical uncertainty
- new techniques/technologies → could change business case
- economies of scale – gap to be filled in scaling up solutions
- Offtakers want to see other offtakers + competition!
- Overcoming perceptions of gasification + hesitation around new technology – is *more* circular, key towards circularity even if not fully circular yet.
- Proportion of biogenic products demanded unrealistic
- Need clarity on NL C-14 mass-balancing regulations

1.1.3 Opportunities:

- Waste as value
- building and leaning (iteration)
- penalties (legislation)
- guaranteed off-take
- clear definition, goal for legislation
- narrative building for sustainable chemical industry and gasification as a pillar for that
- Boost offtaker security
- Middlemen/Brandowners must be a part of changing the system – have a lot of potential power as offtakers (pull-force)

- Contact the right people, partner with industry stakeholders to scale: potentially collaborate on project, get more actors investment and mutual interest in seeing successes
- More guarantees for feedstock suppliers

1.1.4 Potential Next Steps:

- Make space between recycling and recovery qualifications in EU standards:
    - Gasification/syngas could scale if fuel case also enabled – even though it isn't fully green, it is part of the process and is a better alternative.
    - EU Waste Regulation – partially green products still count as waste,
    - Changing legislation to make space for more green fuels/waste handling, which still prolongs and extracts value, ideal (even if not completely recycling, it is a step up, and should be incentivized compared to incineration)
- Explore markets for materials filtered out of feedstock and syngas: market for Green Chlorine, for Copper or carbon char, etc. that could get filtered out: boosts material security.
- Recruit more green-methanol offtakers (to pull business case)

Appendix 2: Takeaways from ISPT Meetings

From insightful conversations, discussions, and presentations organized by ISPT, we distilled the following findings.

1.1.5 February Meeting:

- **Topics of Discussion**:
  - 1) Achieving Carbon Circularity (dependent on biomass, ex. waste from farmers), and
  - 2) Scaling gasification from business standpoint (a means for circular carbon).
    - For both, a feasible business case hinges on secure (affordable) infrastructure as well as front end and back-end customers. Unclear which to start with.
- **Consensus On**:
  - Adoption: For solution to be adopted, need proof of concept of the adoption, function and scaling of gasification. Need solution to be 1) affordable, 2) scalable, 3) sustainable, and 4) secure to supply.
  - Messaging: Need clear, concise messaging and positioning on gasification of waste to quickly bring in stakeholders key to its adoption
  - Bottlenecks: Initial Capex of Projects, designing reactor for the waste stream available and syngas buyer's needs, coordinating logistics of waste stream transition for gasification, policy environment conducive for gasification, persuading industry of technology viability/covalorization, and permitting (recycling v waste plant influences business case, easier permitting if with pre-existing chemical plant too)
  - Opportunities to overcome bottlenecks: use existing infrastructure/existing chemical plants, coordinate shared investments by industry and/or secure funding from subsidy or PE/VC/alternative source, secure front- and back-end customers for acquiring waste and selling syngas, improve sorting capacities, develop a small scale proof of concept, collective industry support for educating + policy reform to support gasification and to regulate waste production.
  - Gasification can have modular or volume based ways to scale – however, coordinating space, logistics (buyers, sellers, and transportation) and finances is unclear.
- **Proposed Next Steps Include:**
  - Develop/Learn from Proofs of Concepts (compile findings)
  - Map system of logistics for waste management, policy environment, and funding opportunities
  - Map the front- (provide waste) and back- (buying syngas (need to know use)) end customers and their cost tolerances,
  - Clarify storyline and stakeholders/ processes needed for transition to gasification
- **Important to Consider**:
  - Achieve Internal Consensus within industry on risks and standpoints.
  - Develop good storyline (for why gasification, why good for you, and for society).
  - Inform ministry, boards, localities, households of the accurate and up-to-date information.
  - Look into policy initiatives coming from the EU: how get to non-voluntary market in NL? How to scale gasification? How to insource? What are benefits? And how might costs be absorbed in the value chain?
- **Remaining Questions:**
  - What is the capacity of gasifiers/will they be able to handle different waste streams?
  - Who is paying for the transition to gasification?
  - How is cost absorbed by the value chain?
  - Rerouting and sorting waste a bottleneck (for municipal solid waste): how does this happen (and who pays)?
  - With policy initiatives often coming from the EU, how get to non-voluntary market in NL?

- To what extent is sorting necessary for gasification to have viable business case / at what price point are customers willing to buy what quality of syngas?

1.1.6 May Meeting

- Some waste-gasification projects already underway (Gidara's AMA, Perpetual Next projects (Delfzijl)), others down the pipeline (Shell/Port of Rotterdam):
- Industry use cases are on the way to being proven: dilemma is building a scaled/commercial-level facility → cost for materials and process intervention and capital expenditure (which is > operational expenditure) very risky, and environment in NL/EU hesitant to take risk.
  - ex. 800Mil Eur for offtake, *maybe* as low as 400mil – but 30mil grants don't touch this, and getting financing is an issue.
  - Improve the risk by increasing the profit margins > grants/financing →
- Industry wide interest in government/legislative interventions to boost market environment for gasification projects (not subsidies – just clarifying + valuing products of gasification to be competitive with other material sources)
  - Notable Stakeholder interest in ministry supporting a select few projects, so that they can succeed as proof of concepts and pave way for wider industry adoption
  - **Need**: Ministries + national level government officials to understand the opportunities for circular materials, greater security of resources, and longterm cost improvements that gasification of waste / biomass / plastics offer
- While some gasification technologies have different approaches (ex. torrification prior to gasification, etc) – goal is as consistent input/output streams of gasifiers as possible
- **Potential Next Steps**: Goal to write white paper to bounce off of NGOs, messaging space – relay barriers undermining business case + tangible projects in pipeline and coming up that are looking to materialize, with the hope for XX needs.
  - Ideal: Clear narrative + white paper illustrating needs / advocating for market environment interventions
  - Question: what needs to be included in this? What NGO's should approve/back this in order for ministries to listen? what are ministries most persuaded by? what financing instruments are possible by ministry in the next 5 years?
  - For this, need shared information about industry proof of concepts / successes / failures (particularly if failure a money problem, not a technology problem)

Appendix 3: Preliminary Research Findings

This section reviews our preliminary findings, summarizing research findings from our London trip, literature and market research, and stakeholder interviews.

I. Takeaways from London Trip:

- Materials: Prioritize circular carbon, producing syngas (composition can be adjusted) – uses of syngas determine permitting of gasification plant (if recycling)*
- Process: Business developers drowning in policy/legislation changes (dictates margins)
- Key Ingredients: Market intervention (by policy) essential for Commercial Adoption, Funding (EU Innovation Fund, IPCEI), North America ideal for going demo -> commercial
- Need Narrative that balances tech + industry + societal value add of gasification
- Syngas purchase agreements for 5-10 years (more than 1 year)
- Questions: Who are the buyers? Why is there a policy/market gap in sustainable chemicals?

II. Preliminary Research Findings

Challenges with Gasification and Chemical Recycling Adoption (Or Opportunities for Intervention).

Pre-Treatment: The **mixed composition of waste streams** is a major challenge. Different plastics and biomass materials come with their own impurities, which can complicate the gasification process and affect the quality of the output. Achieving a consistent yield and purity of recycled materials is key for gasification and chemical recycling – and pre-treatments like sorting and decontaminating can help, but add to the cost and complexity.

Post-treatment: Then there's the matter of post-treatment, where reaching the purity and yield we aim for in products like syngas or hydrogen can be quite difficult. The **main outputs**, such as syngas, often **need further purification** to be usable, and the byproducts, like char and tars, have varying potential for reuse.

Repurposing Bi-products: Many in the industry are trying to repurpose these biproducts, but adoption is sometimes limited by a lack of supporting infrastructure and regulatory incentives.

Scaling: Many of the technologies are still maturing, so **moving from pilot to full-scale is also a challenge**, especially in terms of cost and process reliability.

Cost is another constraint since chemical recycling tends to be more expensive than conventional methods due to energy needs and pre-treatment requirements.

Energy Demands and Outputs: Both processes (gasification and chemical recycling) seem to require significant energy inputs, typically in the form of heat, which can impact their carbon footprint unless renewable sources are used. There currently seems to be an industry misunderstanding that the energy and cost for gasification is significantly more than for incineration: stakeholders we talked with have argued that in fact, the costs are relatively comparable (this needs further research). Further, if the biproducts can be re-purposed and/or exported, there is greater opportunity for profit.

Organized Waste Collection and Processing: Additionally, stakeholders often point out that scaling up gasification and chemical recycling really hinges on organizational infrastructure – such as waste collection, sorting, distribution (for export). Policies that support this infrastructure development will be key to moving forward.

Policies like **carbon pricing and recycling quotas** have a big influence on adoption. In areas with strict recycling mandates, for example, there's a clear push toward chemical recycling. **Extended Producer Responsibility (EPR)** is also coming into play, encouraging companies to rethink waste management from the outset.

On the market side, while there's rising demand for recycled content, especially with regulatory and consumer pressure, many customers of syngas are still unwilling to pay a premium for it. This reluctance affects the commercial viability of gasification. **Recycled content mandates** could help shift this trend by ensuring a market that values the environmental benefits. The aviation sector already has initial mandates for Sustainable Aviation Fuel (SAF), which could help accelerate the adoption of gasification and similar technologies for specific use cases.

ETS and ETSII are likely to already have a significant impact on consumer behavior, which could impact waste stream quantities (ref Belgian case, this needs further research though).

Alternatively, could be worth it to investigate government financing mechanisms (in addition to policies) such as **Pre-market commitments** and **special loan programs** to guarantee below market rates. Also private funding – **Shell partnership** to finance scaling with internal benefit or **VC funds** could be another direction for solving cost-to-scale problem.

III. Preliminary Interview Findings

The Navigating Sustainable Transitions team has vigorously sought perspectives and opinions from an array of industry leaders and companies involved in various aspects of the waste value chain. Members of the scientific community touted the efficacy of gasification and pyrolysis as an incineration alternative that would allow for the transformation of the waste value chain. However, despite their positive view of the practice, each interviewee identified barriers to its implementation and/or suggested that the waste value chain would better transform through alternative methods.

Our preliminary research identified three areas of focus within the waste value chain:

1) Design Problem: Waste prevention
    a. Preventing waste by ensuring proper and maximized utility of previously processed and recycled goods is an ideal intervention early in the waste value chain. The design of what becomes waste by the monopolies generating it needs to change to become more circular. The repurposing of waste also has potential for improvement. We believe the value of recycled waste is improperly utilized and are eager to find solutions to this deficit in circularity.
2) Behavioral Problem: Pre-Sorting (and Post-Sorting)
    b. From households to post-sorting initiatives, there are opportunities for intervention in sorting behavior to reduce cross contamination and improve overall waste value chain circularity. We see greatest potential for impact with waste sorting interventions, with feasible adoption in the short term (1-3 years), and this improved consistency in the waste value chain in turn will inspire greater confidence in gasification, pyrolysis and depolymerization technologies.
3) Circularity for non-Recyclable Waste Problem: Post-sorting and Chemical Recycling
    a. Shifting from incineration to more circular waste-processing technology is ideal for extracting greater value out of waste. Capital investment costs without clear profit predictions limits the interest in adopting these technologies.

1.1.7 Better Waste Design Will Improve Waste Reduction and Recycling

Waste is designed to be particularly (and strategically) difficult to recycle. In talking with a representative at NVRD, which organizes waste management for municipalities in the Netherlands, we learned that a significant barrier to more circular waste includes the physical design of it. Plastics, tennis balls, blended fabrics – many materials used in day-to-day life are designed for convenience of use instead of ease of recycling.

Further echoed by industry experts in circular plastics and carbon, the adhesives, layering, and complex designs of materials complicates their paths for circularity. Depolymerizing a 17-layer complex plastic isn't currently viable.

Additionally, the design of waste in day-to-day life reinforces a cultural disregard of waste. From the rise of single-use plastics and packaging materials with increased online shopping and materialism, to the mixed-material furniture that incorporates the required threshold of recycled material at the cost of in turn being more difficult to recycle, waste is growing in quantity and complexity.

Regulation of the design of waste to only be present when necessary, and to be easier to recycle when it is, is essential. Regulating the production of plastics, clothes, toys, furniture, etc. to use more easily recyclable materials would be ideal to address waste complexity. This comes with some uncertainties for how waste would be designed to avoid regulation, though. Additionally, regulating the presence of waste – the extent of single-use plastic use in grocery stores, in to-go containers, etc. - would be ideal to further reduce quantity of waste.

1.1.8 Increased Pre-Sorting Behavior Supports Recycling and Case for Gasification

With numerous waste streams and opportunities for recycling, increased education and incentives for households to pre-sort waste could both improve the amount of waste actually able to be recycled (avoiding cross-contamination rendering it to be residual waste) and provide greater reliability for what gasification feedstocks would be. Ways to change pre-sorting behavior could look similar to glass-bottle buy-back programs. It could also look like disincentives for incorrect disposal, such as municipalities fining households for incorrect sorting. Consistency of adoption for incentivizing pre-sorting behavior is essential though, requiring coordination across Dutch municipalities.

1.1.9 The Decline of Incineration

Incineration is not ideal for many reasons. A large reason it remains, however, is that the existing infrastructure and waste value chain paths are cheaper than adopting alternative approaches.

To adopt technologies that are better for circularity, which do a better job repurposing materials and energy from waste, the waste value chain must be reformed. Most of the chemical recycling, pyrolysis, and gasification technologies depend on clean waste streams. Increased organization, sorting capacity, and waste stream management will enable more reliable feedstock into these new technologies. This in turn will reinforce the reliability of their business case.

1.1.10 Views on Gasification

Pros:

- Gasification is a good solution when there are a lot of materials with relatively low quality. It is particularly effective with high carbon waste, such as contaminated plastics that couldn't otherwise be recycled.
- Ideal as a solution for dealing with waste in a more circular way.
    - Argument that biofuels ideal, and fuel from waste is better than from fossil fuels. A biproduct of gasification is better energy recycling than incineration.
    - This should not be mistaken for assuming efficiency: there are many more efficient forms to generate energy. *
        - There is a rise of demand for biogas/syngas (particularly for airlines)
- It is a robust technology that is not new or novel; proven to work

Cons:

- Business Case centered on value creation – with varying perspectives on how to interpret the business case. Limited predictability of waste streams quantity and quality makes it hard to justify such investment
    - Installation is capital intensive
    - Circular feedstocks for gasification are more expensive than incineration
    - Feedstock is more sensitive than for incineration.
- Argument that feedstock/waste stream designated for gasification in the next 5 years will shrink over the following 20 years with improvements in recycling and waste design reform.
- Limitations: space, permitting, capital investment, unguaranteed profits
- Gasification is used to extract increased energy from waste. Other processes that are even more optimal for distilling energy, such as carbon capture and electrolysis, are even more expensive. This in part is caused by the congestion and limitations of existing energy infrastructure, exacerbated by the energy crisis since the Ukraine war.

1.1.11 Additional Feedback

Solutions most likely to be a combination of regulation and incentive by government intervention. It is essential to take a systems-thinking approach to intervention though, and consider the numerous perspectives and changes in process influencing waste reform. Different angles on transforming the waste value chain we have already come across include (but are not limited to) the economic perspective that advocates for most affordable and scalable solutions, the circular technology researcher and startup perspective that looks for new ways to improve recycling and ways to scale new solutions, the existing waste management perspective that prioritizes longevity and low risk profit protection, and the municipal perspective balances meeting households' needs with grassroots education campaigns and lobbying against monopolies' waste designs.

Additionally, to consider a more global perspective, the expert we interviewed from SusBDe emphasized the need for the Netherlands to handle its waste domestically rather than exporting it. Exporting waste shifts environmental burdens to countries like Indonesia and Ghana, which already face significant waste challenges. They advocated for local recycling solutions and suggested that Europe focus on scaling impactful projects within or just outside the EU, such as in the Balkans, to retain regional influence and responsibility.