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The cost and climate impact of myopic investment decisions in the chemical industry

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ABSTRACT

Rapid demand growth would double GHG emissions of fossil-based chemicals and plastics production by 2050. In contrast, recycling, biomass utilization, and electrification enable pathways to net-zero GHG emissions. Such pathways often compare the costs of fossil and renewable technologies based on the next 30 years. However, this assumption contrasts the timeframes of legislative periods and investors desiring fast returns, leading to myopic (i.e., short-term) investment decisions. Therefore, this study compares pathways based on long-term with myopic decision-making. While a 20-year foresight still achieves net zero by 2050, a 10-year foresight fails the net-zero target and increases cumulated GHG emission by 43%. Moreover, the chemical industry would invest +307 bn-USD (+3.2%) in additional fossil and, thus, potentially stranded assets. Therefore, industry and investors should account for the environmental and economic impacts of myopic decision-making and practice long-term decision-making to mitigate carbon lock-ins, stranded assets, and financial risks for investors.

1. Introduction

Today's chemicals and plastics production is primarily based on oil and other fossil resources (International Energy Agency, 2017). These fossil resources are either used as carbon feedstock (58%) or combusted for process energy (42%), and thus contribute to global greenhouse gas (GHG) emissions. If production remains fossil-based, the chemical industry is predicted to use 15% of the estimated carbon budget to keep global warming below 1.5 °C by 2050 (Ellen Mac Arthur Foundation, 2016). For GHG mitigation, the chemical industry can replace fossil energy with renewables and substitute fossil feedstock using low-emission technologies based on biomass (Lee et al., 2019; Ögmundarson et al., 2020), CO2 (Carus et al., 2020; Hepburn et al., 2019; Kätelhön et al., 2019), or plastic waste (Geyer et al., 2017; Zheng and Suh, 2019). However, most low-emission technologies require higher investment and operating costs (International Energy Agency, 2013, 2018a; Material Economics, 2019). To level the playing field, governments introduce carbon-pricing policies, e.g., emission trading schemes and carbon tax., which may boost the future deployment of low-emission technologies in line with climate goals.

Whether the introduced carbon pricing, in fact, is sufficient to achieve set climate goals can be assessed via transition pathways based on optimization models. Previous research on transition pathways of the chemical industry (Geres et al., 2019; Zibunas et al., 2022) and the energy sector (Goldstein et al., 2016; Primes, 2018) commonly considers the entire time horizon, e.g., till 2050, in a single optimization, often referred to as perfect foresight and implying long-term decision-making. (Goldstein et al., 2016; Primes, 2018)

However, in reality, investors often have a short-term perspective since they demand low risk and a fast return on investment. Moreover, legislative periods and, thereby, policy-making often do not match the long-term perspective implied by the optimization models (Fuso Nerini et al., 2017; Heuberger et al., 2018; Keppo and Strubegger, 2010). As a result, investor preferences and policies could drive the chemical industry towards so-called myopic decision-making (Fuso Nerini et al., 2017). Myopic decision-making maximizes short-term profits and thus considers only a shorter timeframe for the decision process (Heuberger et al., 2018). Consequently, myopic decisions will differ from decisions modeled with a

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Abbreviations: BAU, Business-as-Usual Scenario; Bio, biomass; BCA, border carbon adjustment; CBAM, carbon border adjustment mechanism; CCfD, carbon contracts for difference; CCU, carbon capture and utilization; Elect, electrification; ETF, exchange-traded funds; GHG, greenhouse gas; Rec, recycling; SDS, Sustainable Development Scenario; USD, United States Dollar; WACC, weighted average costs of capital.

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long-term perspective. As myopic decision-making is closer to real-world decisions, a comparison to long-term decision-making can provide valuable insights for policy design (Babrowski et al., 2014; Dagoumas and Koltsaklis, 2019; Fuso Nerini et al., 2017; Gils et al., 2018; Heuberger et al., 2018; Poncelet et al., 2016).

Previous research incorporates myopic decisions using limited foresight combined with a rolling horizon approach. The rolling horizon approach originally aims to reduce computation time by dividing the single optimization into smaller subproblems (Babrowski et al., 2014; Marquant et al., 2015; Silvente et al., 2015). Further studies use the rolling horizon to derive more realistic transition pathways (Chen and Ma, 2014), to calculate the impact of sudden technological advances (Heuberger et al., 2018), and to investigate the risk of stranded assets (Johnson et al., 2015) and carbon lock-ins (Keppo and Strubegger, 2010).

Most research on myopic decision-making focuses on the energy sector, indicating higher costs and less GHG mitigation (Fuso Nerini et al., 2017; Goldstein et al., 2016; Heuberger et al., 2018; Primes, 2018). In contrast, a transition pathway of the chemical industry towards 2050′s climate goal under myopic decision-making is missing. Thus, the impact of myopic decision-making on the chemical industry’s low-carbon transition has not been quantified, and policies regarding this transition might not be tailored accordingly.

Here, we analyze the impact of myopic investment decisions on costs and GHG mitigation of the chemical industry. For this purpose, we use a techno-economic bottom-up model (Meys et al., 2021; Zibunas et al., 2022) of the chemical industry covering the production of 18 large-volume base chemicals and 14 large-volume plastics, accounting for over 75% of the chemical industry’s GHG emissions (International Energy Agency, 2013). We extend the time-resolved version (Zibunas et al., 2022) of the Technology Choice Model (Kätelhön et al., 2016) by a rolling horizon method with limited foresight to incorporate myopic investment decisions. Based on the myopic extension, we derive transition pathways for varying foresights.

Our results show that myopic decision-making with a 10-year foresight increases GHG emissions between 2020 and 2050 and cumulated costs by 43% and 1.4%, respectively. Accordingly, myopic decision-making would fail to realize the expected GHG mitigation. Thus, policymakers should promote long-term investment behavior of industry, institutions, and society to ensure achieving mid-century climate goals.

2. Deriving transition pathways with long-term and myopic decision-making

2.1. Goal and scope of the study

The goal of this study is to assess the impact of myopic decision-making on the costs and GHG emissions of the global chemical industry. For this purpose, we compare several limited foresights for transition pathways of the chemical industry to net-zero GHG emissions. The transition pathways concern the years 2020 to 2050 and comprise scenarios from our previous study (Zibunas et al., 2022), including fossil-based production, biomass utilization, carbon capture and storage (CCU), and plastic waste recycling. Furthermore, the pathways are based on a bottom-up model covering 18 large-volume base chemicals, 14 large-volume plastics, and corresponding plastic waste (Meys et al., 2021). In the following, we describe the study’s scope in more detail, defining the functional unit, data sources, and the methodological framework to calculate transition pathways with myopic decision-making.

2.2. Functional unit

The functional unit quantifies the function of the investigated product system. In this study, the system’s function is the global production of 18 large-volume base chemicals, 14 large-volume plastics, and the treatment of corresponding plastic waste between 2020 and 2050. In the Supplementary Information, Tables S1 and S2 show annual production and waste volumes as well as growth rates.

2.3. System boundaries

We use a cradle-to-grave system boundary, including the production of chemicals and plastics, the corresponding upstream supply chain, utilities, and disposal at the end of life. Explicitly modeling the use-phase of chemicals and plastics is not possible due to a lack of data. Furthermore, the use phase would not differ between transition pathways since the products of all assessed low-emission technologies are chemically identical to the fossil-based pathway. Thus, a detailed assessment of the use phase is out of the scope of this study. However, we still implicitly account for the use-phase of chemicals by modeling the end-of-life of chemicals as combustion of the chemical’s carbon content. For plastics, we model the end-of-life according to literature data (Geyer et al., 2017): Landfilling rates are assumed to decrease from 49% in 2020 to 6% in 2050, while recycling and energy recovery rates in 2020 are 23% and 28%, respectively. The recycling and energy recovery rates from 2020 until 2050 are determined by cost optimization.

The upstream supply chain of chemicals and plastics includes several intermediates such as monomers, solvents, or other reactants. The production of intermediates is modeled as unit processes, forming the foreground system of the bottom-up model. The background system comprises the remaining processes, e.g., biomass cultivation, using aggregated datasets from the LCA database ecoinvent. More information on all intermediates and the source of aggregated datasets can be found in chapter 1 of the SI. Moreover, unit processes in the foreground system do not account for environmental impacts from infrastructure and transportation due to a lack of data. However, the aggregated datasets do account for environmental impacts of infrastructure and transportation from other industrial sectors, e.g., biomass cultivation.

2.4. Modeling transition pathways

We define general assumptions valid for all calculations to derive transition pathways of the chemical industry. The assumptions are equal to our previous study in order to achieve consistent assessments. In the following, we describe the difference in modeling between perfect and limited foresight with the rolling horizon approach, the status quo of deployed technologies at the beginning of the transition pathway, and the modeling of investment decisions. Finally, we introduce scenarios to cover a broad range of potential pathways.

2.4.1. Perfect & limited foresight with the rolling horizon approach

This study assesses a broad range of limited foresights instead of commonly used perfect foresight to analyze the impact of myopic investment decisions on costs and greenhouse gas mitigation of the chemical industry. Fig. 1 illustrates the concept of the rolling horizon to model limited foresight versus perfect foresight. In perfect foresight optimization, all investment decisions are made in a single optimization covering the entire investigated period, e.g., 2020 to 2050. Thus, all investment decisions are perfectly aligned and consider all information, e.g., resource and carbon prices or constraints for technology deployment.

However, with limited foresight, each investment decision is only based upon information for the years within the decision makers’ foresight, e.g., the decision makers plan only 10 years ahead. Here, limited foresight is modeled as an iterative rolling horizon to derive a transition pathway over the entire investigated period, which is 2020 to 2050 in this study (in line with literature on the energy sector). In each iteration i of the rolling horizon, investment decisions are made within the decision makers’ foresight n, e.g., 10 years (Fig. 1). After an iteration i, the investment decisions for the first m years of this iteration are fixed from the next iteration $i + 1$ on, while the remaining decision can be re-

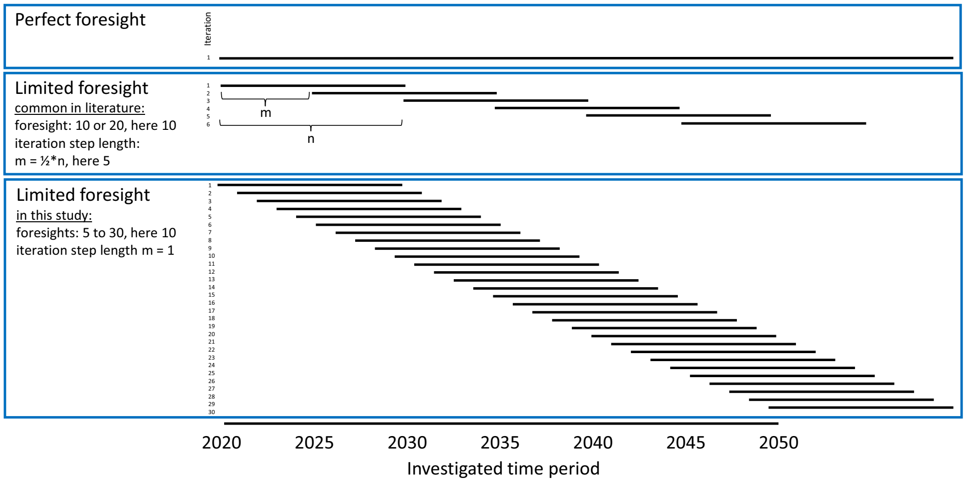

Fig. 1. Illustration of perfect foresight optimization and limited foresight combined with the rolling horizon approach.
For the rolling horizon approach, we illustrate a foresight of 10 years and an iteration step length of 1 year. Perfect foresight, in practice, usually extends the optimization period (as depicted here) or assumes salvage values at the end of the investigated period to avoid artificial short-term decisions.

evaluated. The parameter *m* is referred to as the iteration step length. In previous studies, foresights and iteration step length vary depending on the studies' goals. Often, the iteration step is half the length of the foresight but at least 5 years; in order to reduce the necessary iterations and corresponding computation time (Babrowski et al., 2014; Marquant et al., 2015; Silvente et al., 2015). In this study, per scenario of transition pathways (see further down), we consider one fixed foresight. Across all scenarios, we assess foresights between 5 and 30 years to assess the impact of myopic investments over a broad range of foresights (details on the scope of foresight in SI). In the context of this study, foresights below 30 years are referred to as myopic decision-making, since excluding some of the chemical plants' lifetime. For all scenarios of transition pathways, we enable investment decisions in every year and choose an iteration step length *m* of 1 year to prevent overestimating the impact of myopic decision- making (details in chapter 2.1 of the SI). As a reference to myopic decision-making, we use long-term decision-making represented by a 30-year foresight. We choose the 30-years foresight as it complies with the maximum lifetime of plants and thus allows considering all costs of an investment. Furthermore, we discuss differences between the rolling horizon with a 30-year foresight and a single perfect foresight optimization in the SI.

2.4.2. *Existing production capacity in 2020*

The fossil-based plants already existing in 2020 are represented by the best available fossil-based technologies, i.e., the industrialized technologies with the lowest overall costs. The age distribution of the existing plants is assumed to be uniform regarding the production volume, i.e., for a specific chemical, each year, the same amount of plants in terms of production volume reaches a specific age. Thereby, the uniform age distribution implies that each year the same amount of production capacity will reach the maximal lifetime and retire. Based on the literature, we assume a lifetime of 30 years (Seto et al., 2016). The uniform age distribution and the maximum lifetime of 30 years cause 1/30 (= 3.3%) of the production volume already existing in 2020 to expire each year. However, chemical plants could actually exceed the maximum lifetime of 30 years but would require significant refurbishments. Assuming a strict age limit equates the potential refurbishment with investing in a new plant. Thereby, we implicitly considered a potential lifetime extension in a conservative manner.

2.4.3. *Investment decisions*

In this study, we consider investments decisions in three cases: (1) A plant needs to be replaced due to expiring its lifetime; (2) A plant is replaced before the end of its lifetime since keeping the existing plant is more expensive than investing in a new plant using an alternative technology. Case 2 is particularly relevant for existing fossil plants facing carbon pricing while competing with potential new low-carbon plants. (3) Increasing demand requires additional plants. Cases 1 and 3 account for 3.3% and 3.1% of new investments compared to the starting capacity in 2020, totaling about 6% each year. Investments according to case 2 cannot be predetermined since resulting from the cost-optimal timing to discard depreciated fossil plants.

Investment decisions aim to minimize the overall costs to represent a chemical industry that follows cost-driven decision-making. Costs comprise capital and operational expenditures. Operational expenditures include feedstock and energy costs, salaries, regular maintenance, and carbon pricing. The overall costs are calculated utilizing the net-present-value method, which is common practice for deriving transition pathways (Goldstein et al., 2016; Primes, 2018). As an interest rate for the net present value, we use the weighted average costs of capital (WACC) (Goldstein et al., 2016; International Energy Agency, 2017; Primes, 2018). In line with the literature, we assume a WACC of 8% for investments in the chemical industry (Geres et al., 2019; International Energy Agency, 2017, 2018b).

Except for myopic decision-making, we assume perfect investor behavior. In reality, imperfect decisions may also result from a lack of information or company-specific goals. However, we exclude such imperfections from this study to isolate the effect of myopic decision-making.

2.4.4. *Scenarios for transition pathways with myopic decision-making*

This study assesses 105 scenarios: A Business as Usual Scenario and four net-zero pathways, i.e., pathways achieving net-zero GHG emissions by 2050. The net-zero pathways differ in available technologies, thus also referred to as technology pathways. The pathways are the same as in our previous study (Zibunas et al., 2022) to ensure consistent assessments. In our previous study, we derived net-zero pathways by applying perfect foresight and adjusting carbon pricing to incentivize a cost-optimal transition to net-zero by 2050. For each of the four net-zero pathways, we assess foresights between 5 and 30 years, creating 104 (=4 × 26) individual scenarios. Thereby, we derive a wide range of scenarios for a comprehensive assessment.

In the Business as Usual Scenario, the chemical industry remains fossil-based and maintains the recycling rate from 2020 (23%),(Geyer et al., 2017) i.e., investment decisions are constrained to fossil-based technologies and the recycling rate. Thus, investments only occur to replace fossil plants that expire or to meet growing demands. Thereby, the Business as Usual Scenario sets the GHG mitigation of the net-zero pathways into perspective.

The four net-zero pathways comprise cost-optimal transitions from fossil to low-emission technologies. Resource costs are predominantly based on the Sustainable Development scenario (SDS) from the International Energy Agency (International Energy Agency, 2018b). In contrast to the SDS's grid mix, we assess a chemical industry having access to renewable electricity at 36 USD/MWh and 20 $g_{CO2\text{-}eq}$/kWh by 2030, which was found to be essential for electrifying the chemical industry. The literature emphasizes the importance of renewable electricity for the chemical industry regarding economic (Hepburn et al., 2019) and environmental (Meys et al., 2021) competitiveness and absolute environmental sustainability (Bachmann et al., 2023). Implications of this assumption for electricity are discussed in the SI.

For biomass, we assume a price of 200 USD/$t_{dry,}$ representing a conservative literature estimate (details in chapter 2.3 of the SI) (Alonso et al., 2017; Geres et al., 2019; Lewandowski et al., 2000; Sanchez et al., 2015). In line with the SDS, carbon prices start at 25 USD/$t_{CO2\text{-}eq}$ in 2020. The further carbon pricing trajectory is adjusted to incentivize net-zero GHG emissions by 2050 when following cost-optimal investment decisions. Thus, the carbon prices depend on the low-emission technologies available to each pathway. Each of the four net-zero pathways represents a different combination of low-emission technologies: (1) electrification and recycling (Elect + Rec), (2) electrification and biomass (Elect + Bio), (3) biomass and recycling (Bio + Rec), and (4) a combination of biomass, electrification, and recycling (All) (details in chapter 2.4 of the SI).

In this study, we focus on the pathway combining all low-emission technologies (All) and corresponding variations of foresight to assess the impact of myopic decision-making independent of technology restrictions. Still, the other three pathways and the corresponding variations of foresight serve as a sensitivity analysis. Please find chapters 3.1 and 3.2 in the SI for the descriptions of the other pathways and details on the sensitivity analysis. Neither of the pathways should be seen as advocacy for specific low-emission technologies but should determine the effect of myopic decision-making compared to long-term decision-making.

3. Myopic decision-making delays GHG mitigation

The Business as Usual scenario (BAU, Fig. 2a) yields a fossil-based chemical industry, which would emit about 5.5 Gt in 2050 due to increasing production volumes (on average 3.3%/a). Thereby, the BAU scenario emphasizes the need for GHG mitigation and sets the GHG mitigation of the following pathways into perspective.

Long-term decision-making with a foresight of 30-years serves as a reference to pathways with less foresight since the results are practically identical to perfect foresight (details in chapter 3.4 of the SI). With a 30-year foresight, a cost-driven chemical industry would transition to net-zero GHG emissions by 2050 if carbon prices linearly increase from 25 USD/t_{CO2eq} in 2020 to 190 USD/t_{CO2eq} in 2050 (purple line, Fig. 2a).

The pathway for long-term decision-making (purple line, Fig. 2a) has step changes in annual GHG emissions, where circular technologies can cost-efficiently substitute depreciated fossil plants. The deployed low-emission technologies comprise a combination of plastic waste recycling, biomass utilization and electrification and achieves net-zero GHG emissions by mid-century (details in *Low-emission technology deployment and stranded assets*).

Myopic decision-making, on the other hand, can delay GHG mitigation by several years up to postponing net zero past 2050 (see Fig. 2a). The delay can increase cumulated GHG emissions between 2020 and 2050 by up to 114% compared to long-term decision-making, i.e., a 30-year foresight (see Fig. 2b).

Since, for long-term decision-making, the foresight matches the assumed 30-year lifetime of plants, all future operational and carbon pricing costs of a new plant are included in an investment decision. In contrast, a 20-year foresight excludes some of a new plant's future operational and carbon pricing costs from the investment decision. Still, the pathway with a 20-year foresight reaches net zero in 2050 (blue line, Fig. 2a). Reducing the foresight even further neglects even more of the future costs. In particular, neglecting future carbon pricing reduces the costs of the incumbent fossil technologies, making them more cost-competitive compared to their circular alternatives. Therefore, myopic decision-making can delay the deployment of circular technologies and corresponding GHG mitigation. For instance, GHG mitigation is visibly delayed for a 10-year foresight (bright green line, Fig. 2a). Due to the delay, the chemical industry would not achieve net zero by 2050,

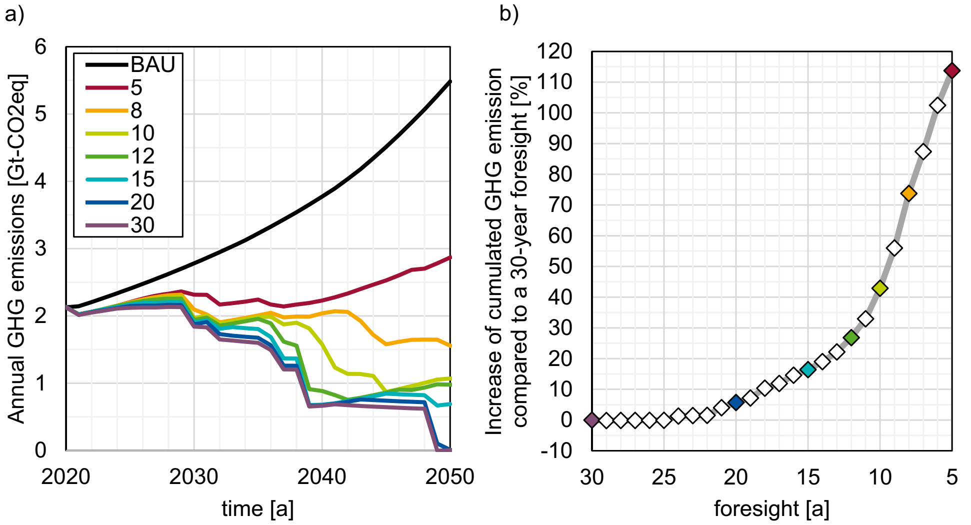

Fig. 2. The impact of myopic decision-making on GHG emissions of the chemical industry.
a) Annual GHG emissions of the global chemical industry between 2020 and 2050 for a fossil-based supply-chain (BAU) and cost-optimal supply-chains under carbon pricing, where all low-emission technologies are available (scenario All) when considering a foresight for investment decisions of either 5, 8-, 10-, 12-, 15-,20- or 30-years. **b)** Increase of cumulated GHG emissions of the global chemical industry between 2020 and 2050 depending on the foresight for investment decisions compared to long-term decision making, represented by a 30-year foresight. Colored markers correspond to the transition pathways in a), and white markers represent additional transition pathways not shown in a).

contrary to long-term decision-making with the same carbon pricing incentivizes. Therefore, policies designed with long-term decision-making in mind would fail if the chemical industry, in reality, plans with less than 20 years of foresight. Thus, such policies should be accompanied by promoting long-term decision-making to foster GHG mitigation. For instance, Kunreuther and Weber (Kunreuther and Weber, 2014) suggest smart problem framing, using choice defaults and establishing social norms to promote long-term decision-making with regard to low-carbon investments.

Delayed GHG mitigation due to myopic decision-making becomes even more evident when comparing cumulated GHG emissions between 2020 and 2050 instead of annual emissions in 2050 (Fig. 2b). For instance, annual GHG emissions for myopic decision-making with a 15-year foresight (turquoise line, Fig. 2a) differ by less than 0.21 Gt/a from long-term decision-making (purple line, Fig. 2a), except for 2049 and 2050. However, corresponding cumulated GHG emissions increase by 15% (turquoise marker, Fig. 2b). Therefore, cumulated GHG emissions should be evaluated to assess the impact of myopic decision-making. Cumulated GHG emissions increase exponentially when reducing the foresight, up to + 43% for a 10-year foresight or even + 114% for a 5-year foresight (bright green & red marker, Fig. 2b). The increase in cumulated GHG emissions gets increasingly steep for two reasons: (1) The delay increases disproportionately as foresight diminishes. (2) Shorter foresights postpone GHG mitigation to later years. The postponement becomes more problematic as the years progress, given the rising intensity of GHG emissions due to the increase in chemical production volume and its associated fossil emissions.

The impact of myopic decision-making on GHG mitigation is similar for the three further technology pathways (details in chapter 3.2 of the SI): (1)biomass utilization and recycling, (2) biomass utilization and electrification, and (3) electrification and recycling. These pathways have fewer technology choices than the pathway with all circular technologies (All). To also incentivize net zero by 2050, carbon prices increase steeper. The pathways also show exponentially increasing cumulated GHG emissions when the foresight is reduced. For 2 out of the 3 alternative pathways, cumulated GHG emissions also increase by about 40% at a 10-year foresight and surpass 100% of additional cumulated GHG emissions at a 5-year foresight (+101 to 169%). Only the pathway limited to electrification and recycling is impacted less owing to late GHG mitigation even with long-term decision-making (+25% at a 10-year foresight) (details in chapter 3.2 of the SI).

In summary, myopic decision-making would compromise GHG mitigation efforts over different technology pathways. In contrast, long-term decision-making will help reduce annual GHG emissions by 2050 but also minimize cumulated emissions along the transition pathways. Thus, policymakers should promote long-term decision-making to support GHG mitigation and comply with mid-century emission targets.

4. Myopic decision-making increases overall costs

Myopic decision-making influences not only GHG mitigation but also the underlying investment decisions and corresponding costs. The cumulated future costs of the chemical industry's investments between 2020 and 2050 increase by up to 1.4% for a 10-year foresight and 7.5% for a 5-year foresight, respectively (Fig. 3) (details in chapter 3.3 of the SI).

As already observed for GHG emissions, the impact of myopia on the three further technology pathways is similar also in terms of costs (details in chapter 3.1 of the SI): Costs increase exponentially with reduced foresight, ranging between +0.7–1.4% and +7.4–9.0% for 10 and 5 years of foresight, respectively. Thus, independent of the availability of technologies or corresponding resources, myopic decision-making consistently increases the costs of the chemical industry. This increase would add to the original cost increase of 4% for transitioning from the current fossil to a net-zero chemical industry based on long-term decision-making (Zibunas et al., 2022).

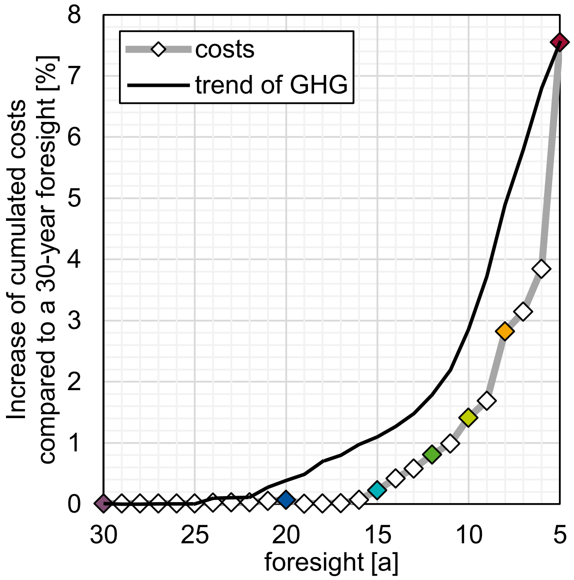

Fig. 3. The impact of myopic decision-making on cumulated costs of the chemical industry.
Cumulated costs of the chemical industry for all investments made between 2020 and 2050 (details in chapter 3.3 of the SI), including the depreciation of capital costs for plant construction and future operational costs (including feedstocks, salaries, and carbon taxes) for varying foresight in comparison to long-term decision making, represented by a 30-year foresight. The costs correspond to Fig. 2, thus showing cost-optimal supply chains under carbon pricing, where all low-emission technologies are available (scenario ALL). Colored markers correspond to the transition pathways in Fig. 2a), and white markers represent additional transition pathways not shown in Fig. 2a). The black line is based on the increase of cumulated GHG emissions between 2020 and 2050 from Fig. 2b). The GHG emissions are rescaled in a manner that highlights whether GHG emissions or costs are more sensitive to decreasing foresights relative to their maximum increase (at a 5-year foresight). For this purpose, the cumulated GHG emissions from Fig. 2b), for each foresight, are divided by the cumulated GHG emission for a 5-year foresight and multiplied by the cumulated costs for a 5-year foresight.

Accordingly, focusing on short-term profits in the presence of long-term climate goals will make the transition to net-zero cost even more. Therefore, investors and decision-makers should adopt a long-term perspective to identify the cost advantages of low-emission technologies in time. Avoiding myopic decision-making could also attract more investors, fueling the chemical industry's transition towards net zero. For example, long-term investment gained popularity among private investors with the rise of Exchange-Traded Funds (ETFs), a finance product that in general incorporates a long-term strategy: (BlackRock, 2023; Reeves, 2023). The global volume of ETFs increased from 1,3 trillion-USD in 2010 to 10 trillion-USD in 2021, which is similar to the capital required for a transition to a net-zero chemical industry (Statista: Deutsche Bank et al., 2022). Thereby, long-term investments of the required magnitude can be observed. However, further extensive investigation is needed to foresee if current global trends might result in sufficient capital acquisition for long-term investments across all industries (see discussion).

Although the impact of myopia on costs is non-negligible, GHG emissions are more sensitive to myopia: GHG emissions already increase with foresights of around 20 years (black line, Fig. 3). In contrast, costs display lower sensitivity, becoming significantly influenced only when foresights reach 15 years and below (Fig. 3). The lower sensitivity results since only foresights of 15 years and below significantly delay the transition pathways between 2040 and 2050. Between 2040 and 2050, carbon prices are high enough to render prolonging some fossil production markedly cost-intensive. In contrast, the difference in GHG emissions between fossil and circular technologies remains constant over time. Consequently, delays commencing as early as a 20-year foresight promptly affect GHG emissions. Overall, the results stress the importance of promoting long-term decision-making, particularly to achieve climate targets and but also to keep costs at a minimum.

In summary, myopia would increase the overall long-term costs of the chemical industry due to suboptimal technology deployment, i.e., high costs due to carbon pricing or more stranded assets (see next section and discussion).

5. Low-emission technology deployment and stranded assets

Myopic decision-making delays GHG mitigation and increases costs (Figs. 2 & 3) by altering the underlying deployment of low-emission technologies.

When applying myopic decision-making, the chemical industry deploys the same low-emission technologies as with long-term decision-making. No changes in the general technology selection are also observed for the other technology pathways (detail in SI) and have been indicated from research on power generation (Heuberger et al., 2018; Poncelet et al., 2016). The pathway combining all circular technologies with 30 years of foresight (All) deploys the following technologies: Mechanical and chemical (via pyrolysis) recycling of plastic waste, bio-based ethanol and methanol, their subsequent conversion to ethylene and propylene, as well as electrical steam production, and the production of ammonia via hydrogen from electrolysis. In particular, mechanical and chemical recycling are key enablers for low costs (Zibunas et al., 2022), GHG mitigation (Meys et al., 2021), and overall environmental sustainability since recycling keeps costs and environmental impacts of virgin production at a minimum (Bachmann et al., 2023).

Despite no technology changes, myopia delays the deployment of these low-emission technologies, which is also in line with the literature on power generation (Heuberger et al., 2018). For instance, with long-term decision-making, the chemical industry fully deploys bio-based propylene by 2050. In contrast, fossil-based propylene makes up 50% of 2050′s propylene production with a 10-year foresight. For each low-emission technology, the delay depends on capital and operational costs in comparison to its corresponding fossil technology. The delay is more significant if the mitigation costs are higher since neglecting some future carbon pricing drastically decreases the low-emissions technology's cost-competitiveness.

Furthermore, delaying the deployment of low-emission technologies increases the risk of stranded assets compared to long-term decision-making: For instance, with a 20-year foresight, the chemical industry invests 63 bn-USD more into fossil plants, which will become stranded assets by 2050 (Fig. 4). These assets are discarded since even myopic decision-making realizes the suboptimality at some point and tries to cut the losses. Reducing the foresight to 10 years results in even more fossil investments between 2020 and 2050 (+307 bn-USD). These assets are not stranded by 2050 yet as myopia does not allow for realizing their suboptimality yet. However, these assets will ultimately be stranded if carbon prices increase further or policy measures oblige the chemical industry to mitigate emissions (Johnson et al., 2015). A 10-year foresight increases investments in potentially stranded assets by 3.2% compared to the overall capital expenditures with a 30-year foresight. Similar trends are observed for the three alternative technology pathways (1.6%, 2.7%, and 3.2%; see SI).

In summary, myopia increases the risk of stranded assets, which already exists in the pathway with long-term decision-making. This increased risk results from postponing the cost break-even between fossil and circular technologies: (1) At a first break-even point, carbon costs have increased such that a low-emission technology and the corresponding incumbent fossil technology have the same net present value when building a new plant. Until this first break-even point, the chemical industry continues to invest in refurbishments and new plants using fossil technology. Corresponding investments, on average, concern about 6% of the chemical industry's current assets each year (details in methods). Myopic decision-making neglects future carbon pricing costs and thus overestimates the cost-competitiveness of fossil technologies, resulting in more fossil investments and, ultimately, stranded assets. (2) At a second break-even point, carbon prices burden fossil production so much that even replacing fully depreciated fossil plants is cost-optimal. Postponing this second break-even point does not lead to an additional build-up of fossil assets since, after the first break even point, the chemical industry already invests in the low-emission alternative. However, postponing the second break-even point prolongs the operation of the remaining emission-intensive plants, increasing the cumulated GHG emissions between 2020 and 2050.

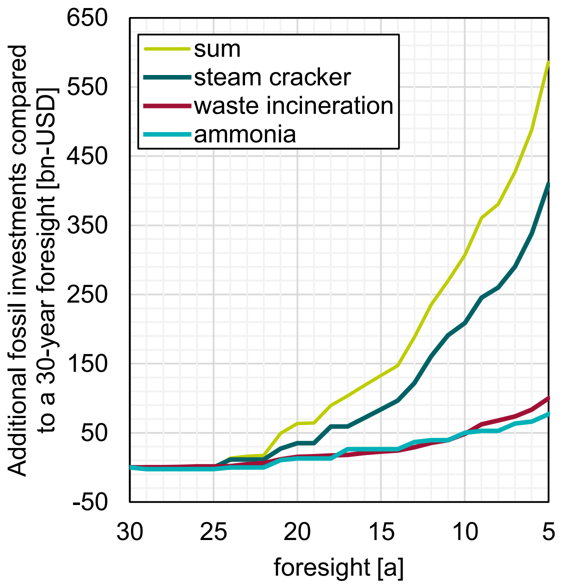

Fig. 4. The impact of myopic decision-making on generating additional stranded assets in the chemical industry.
Additional stranded assets are measured by the difference in fossil-based investments between varying foresights and long-term decision-making, represented by a 30-year foresight. The figure depicts the additional steam cracker, plastic waste incineration, fossil ammonia plants, and the sum of all three, which are the biggest contributors to fossil investments. Note that not all of the additional fossil-based investments are already stranded assets by 2050, as the scenarios cost-optimally respond to carbon pricing, and no exogenous GHG emission limit is considered. However, these additional fossil-based investments will either prolong GHG emissions of the chemical industry or become stranded assets at some point. For foresights of 20 years and higher, all additionally built fossil assets are stranded by 2050. In contrast, for shorter foresights, none of the additionally built fossil assets will be stranded by 2050 since the additional assets are less than the remaining fossil production caused by the shorter foresight. This figure shows the technology pathway combining all low-emission technologies (All), thus corresponding to Figs. 2 & 3.

In conclusion, long-term decision-making is a key to minimizing the risk of stranded assets, which could destabilize the long-term profitability of investments in the chemical industry. Furthermore, the literature indicates that the global industry, in general, will end up with stranded assets if it does not start to cut its links to fossil resources (Carbon Tracker Initative, 2022). Thus, the chemical industry should practice long-term decision-making and start deploying low-emission technologies to avoid stranded assets.

6. Discussion

6.1. Key assumptions

This study determines the impact of myopic decision-making on the chemical industry's overall costs and GHG emissions by combining a bottom-up model (Meys et al., 2021) and transition pathways to net-zero GHG emissions (Zibunas et al., 2022) with a rolling horizon approach. Key assumptions for the assessment concern the carbon pricing trajectories from the transition pathways, assessed in detail in our previous study (Zibunas et al., 2022), and the length of foresight, on whose sensitivity we focus this study.

6.2. Summary of results: the impact of myopic decision-making

Our results show that myopic decision-making would consistently compromise GHG mitigation efforts of net-zero pathways over different technology scenarios. Suboptimal technology deployment due to myopic decision-making would increase the long-term costs of the chemical industry and the risk of stranded assets. For example, a 10-year foresight can increase the chemical industry's GHG emissions by 43% and overall costs by 1.4% compared to a transition with 30-year foresight. Meanwhile, the chemical industry would invest an additional 307 bn-USD in fossil assets that might become stranded in the future.

6.3. Myopia's impact could be even higher

In fact, the impact of myopic decision-making can be even higher considering the self-reinforcing mechanisms of lock-ins (Unruh, 2000), which have not been included in this study. Self-reinforcing mechanisms comprise efficiency and cost improvements of technologies in operation. The incumbent fossil technologies would befit from such improvements, making future deployment more cost-competitive and thus more likely. Indeed, incumbent fossil technologies are expected to have little to no cost reductions. However, low-emission technologies are expected to improve significantly, particularly if deployed early on (Kalkuhl et al., 2012). For instance, hydrogen production is expected to reduce its capital costs (Detz et al., 2018), while corresponding renewable electricity production also continuously improves. Photovoltaics has achieved significant cost reductions, which are strongly linked to deploying the technology and the corresponding increase in the experience of local engineers (Neij et al., 2017). Thus, missing out on efficiency and cost improvements due to delayed implementation would undoubtedly intensify the impact of myopic decision-making (Grubb et al., 2021). Therefore, future research should account for missing out on efficiency improvements from myopia. In particular, the possibility for cost improvements by early deployment highlights the urgency for action.

6.4. The risk of a carbon investment bubble

Focusing on long-term profits and supporting low-carbon investments reduces investors' risk due to the so-called carbon bubble (Carbon Tracker Initative, 2015, 2022; Fuso Nerini et al., 2017; Rorke, 2022). The carbon bubble can be summarized as the overvaluation of fossil-based companies. Previous literature suggests that current evaluations do not incorporate the mismatch between potential revenues based on fossil reserves and the carbon budget defined by the Paris Agreement (Carbon Tracker Initative, 2022) (an extensive discussion on the carbon bubble can be found in the literature (Carbon Tracker Initative, 2015; Meyer and Brinker, 2014)). Such a bubble is expected to burst and result in stranded assets once policies oblige the industry to commit to the carbon budget. Policies might call for more low-carbon instead of fossil products such that demand for virgin fossil products decreases and previously deployed carbon-intensive investments are unable to make the expected return (Carbon Tracker Initative, 2022). For instance, EU legislation is already planning a quota for minimum recycled content in new plastic products (European Commission, 2022). Therefore, also in the chemical industry, carbon-intensive investments bear the risk of stranded assets and insufficient future returns. Without the expected returns, stock prices of fossil industries could crash. Overall, continuing carbon-intensive investments risks compromising long-term profitability, the stability of financial institutions, and, thus, the overall economic sustainability. Increasing awareness for financial risks resulting from myopia might convince investors of long-term low-carbon investments. Debates on transition-related financial risks have already shifted their focus to stranded fossil assets and thus away from former discussions on the risk of rising low-carbon industries (Semieniuk et al., 2021). Still, aggressive environmental policies could also bear risks, which again calls for long-term planning.

6.5. Climate-based risk for finance

By postponing GHG mitigation, myopic decision-making intensifies another risk to long-term profitability, which are climate impacts themselves. Climate impacts are expected to reduce the financial performance of companies both indirectly, e.g., less efficient workforce due to heat stress from global warming, and directly, e.g., demolition of production sites due to extreme weather events. Previous literature suggests that climate change impacts increase the expected value at risk of global financial assets by 50% (Dietz et al., 2016). However, to make climate-based risks a real driver for investment decisions, appropriate calculation methods have to be integrated into state-of-the-art decision-making practices.

6.6. Myopic decision-making compromises environmental and economic sustainability

In summary, myopic decision-making intensifies multiple elements that compromise economic and environmental sustainability, including stranded assets, lock-ins, financial risks for investors, reduced long-term profitability, and climate impacts. Thus, investors and policymakers should be aware of the risks and environmental impacts and help to overcome challenges hindering sustainable long-term decisions.

6.7. Enhancing long-term decision making

One major challenge to long-term decision-making is the uncertainty surrounding long-term price forecasts. In particular, uncertainties of carbon price forecasts are challenging since a low-carbon investment's cost competitiveness often relies on pricing the corresponding carbon-intensive investment. Policies could address such uncertainty from carbon pricing by providing financial safety nets, e.g., carbon contracts for difference (CCfD). In the case of a CCfD, a company that adopts a low-carbon technology is paid the cost increase compared to the corresponding incumbent fossil production, including carbon prices. Thus, CCfDs ensure that low-carbon production does not cost more than corresponding fossil production, even when carbon prices are lower than expected. Consequently, decision-makers can rely on a fixed contract instead of uncertain price predictions.

Furthermore, international differences in carbon pricing introduce uncertainty regarding the cost competitiveness of low-carbon production within a global market. Low carbon prices elsewhere will allow cheaper carbon-intensive production, making a low-carbon investment less competitive. Similar to CCfD, a carbon board adjustment mechanism (CBAM) (see also border carbon adjustment, BCA), as planned by the EU (European Commission, 2021; European Parliament, 2022) and proposed in the USA (Rorke, 2022), would ensure the cost competitiveness of low-carbon production internationally. The CBAM taxes incoming carbon-intensive products to level the playing field in a global market. Additionally, CBAM reduces the risk of carbon leakage, where fossil production transfers to regions with less carbon pricing, eventually leading to higher overall emissions. Both the EU and the USA include chemicals in the recent discussion around CBAM. (European Commission, 2021; European Parliament, 2022; Rorke, 2022) On the downside, CBAM taxes initially paid by an importing company could increase consumer prices in the importing country. (Grubb et al., 2022) High-income countries, such as the USA or in the EU, are arguably more likely to accept higher consumer prices. Therefore, it might be questionable if low-income countries could follow and implement CBAM taxes.

In summary, policies need to address market uncertainties and create reliable incentives to support long-term and low-carbon investment decisions.

6.8. A shift in the behavior of institutions and private investors

Another lever to encourage long-term decision-making in the industry is patient long-term financing (Mazzucato, 2022). Corresponding capital could come from public development banks or already long-term-oriented pension funds. In particular, pension funds additionally advocate for global GHG mitigation to decrease climate-related financial risks (Dietz et al., 2016). For instance, some EU pension funds have started to shift towards low-carbon investments (Egli et al., 2022). However, across all OECD countries, most pension funds are still predominantly focused on fossil-based assets (Rempel and Gupta, 2020). Shifting pension funds globally towards sustainable sectors could foster long-term decision-making and accelerate the transition to net zero. Previous research found that pension funds incorporating sustainability via ESG principles showed resilience in volatile markets and often even outperformed their non-ESG counterparts (Ikwue et al., 2023). However, pension funds have arguably tended to be conservative in the past, which might slow an area-wide transition of pension funds to sustainable investments. On the other hand, there are customers demanding more sustainability in pension fund portfolios, supporting a transition (Bauer et al., 2021). Globally, further institutions have already started to divest their assets from fossil fuels (Institute for Energy Economics and Financial Analysis, 2021), e.g., universities driven by student activism. However, meeting climate goals will ultimately also require mobilizing private capital at scale (Bhattacharya et al., 2020).

6.9. Conclusion

In summary, policies, institutions, and private investors will play their role in reshaping the financial system towards more long-term and low-carbon investments (Bhattacharya et al., 2020). Fostering such trends and corresponding investments will allow the chemical industry to focus on long-term decision-making and achieving net zero GHG emissions. Emphasizing the long-term consequences of chasing short-term profits and highlighting financial opportunities will be key factors in attracting sufficient capital. Although carbon-intensive investment performed well in the past, a long-term trend emerges: The ongoing shift towards achieving net-zero GHG emissions will reduce the demand for carbon-intensive products (Carbon Tracker Initative, 2022). This decrease entails significant value loss for those who invested in companies that did not show adequate foresight in their corporate strategy to transition away from fossil production. Overall, long-term and low-carbon investments can help to mitigate economic risks and foster GHG mitigation.

CRediT authorship contribution statement

Christian Zibunas: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Raoul Meys:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Arne Kätelhön:** Writing – review & editing, Methodology, Conceptualization. **André Bardow:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

André Bardow reports a relationship with Carbon Minds GmbH that includes: board membership and equity or stocks. André Bardow reports a relationship with Exxonmobil that includes: consulting or advisory. André Bardow reports a relationship with TotalEnergies SE that includes: consulting or advisory and funding grants. Raoul Meys reports a relationship with Carbon Minds GmbH that includes: board membership and equity or stocks. Arne Kätelhön reports a relationship with Carbon Minds GmbH that includes: board membership and equity or stocks. If there are other authors, they 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

All data are publicly available. However, some cases require a user license from IHS Markit to access the underlying data. To gain access, IHS Markit can be contacted via the following website: https://ihsmarkit.com/products/chemical-technology-pep-index.html.

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Supplementary materials

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