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► **To cite this version:**

Briera Thibault, Julien Lefèvre. Credible climate policy commitments are needed for keeping long-term climate goals within reach. 2024. halshs-04619188

HAL Id: halshs-04619188

<https://shs.hal.science/halshs-04619188>

Preprint submitted on 20 Jun 2024

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Credible climate policy commitments are needed for keeping long-term climate goals within reach

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June 20, 2024

Abstract

Credible climate policy commitments are crucial for aligning decision-makers' expectations with policy objectives, thereby catalyzing timely low-carbon investments. However, Integrated Assessment Models (IAMs), the primary numerical tools for evaluating solution spaces, policy timing, and investment dynamics in mitigation scenarios, have largely neglected this critical issue. Here, we introduce a framework for addressing credible climate policy commitments with IAMs and conduct a quantitative assessment of their significance for global climate policy effectiveness in achieving long-term goals. We clarify the shortcomings of existing narratives and analytical approaches, proposing a method to integrate a more sophisticated representation of policy credibility in an IAM. Our findings demonstrate that failing to get expectations right can increase cumulative CO₂ emissions by 11.1% compared to scenarios with perfect policy foresight. By 2035, the emissions gap can be as high as 45% in the power sector with regard to the perfect foresight case, under low credibility and limited foresight on policy implementation, highlighting the adverse interplay between capital inertia and low policy credibility. These results underscore the urgent need to explicitly incorporate the credibility of policy commitments into the tools used for climate policy-making.

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In the Paris Agreement adopted in 2015, countries agreed to hold the global mean temperature rise "well below 2°C" and to pursue efforts to limit it to 1.5°C [1]. To reach this ambitious climate target, an increasing number of countries are announcing their intention to achieve carbon neutrality [2]. To meet these long-term goals, countries submit Nationally Determined Contributions (NDCs) that detail concrete short-term policies. Current binding pledges are insufficient to meet the Paris Agreement's targets, necessitating accelerated climate action by mid-century to achieve long-term stabilization goals [3]. It is far from guaranteed that future governments will keep promises made in the past and will convert pledges for the future into concrete climate policies all over the world [4].

In this context of weak near-term action and ambitious long-term targets, credible climate policy commitments yet are essential to maintain the pace of massive low-carbon investments needed to decarbonize the economy [5]. The profitability of these long-lived infrastructures depends largely on expectations about the existence and stringency of future climate policies. Consequently, climate mitigation policies create significant uncertainties for private investors [6], [7], [8], potentially leading to postponed investment decisions until more information is available [9], [10]. This misalignment between agents' expectations and policy objectives risks carbon lock-in [11] and stranded assets [12], especially if stringent climate policies are delayed [13], [14]. To avoid a disorderly transition and achieve ambitious climate mitigation goals, credible climate policy commitments are needed to offset the lack of immediate incentives to invest in low-carbon technologies. However, evidence suggests that economic agents' expectations currently do not fully align with global climate pledges [15].

In this paper, we argue that, despite its central importance in the fight against climate change, the issue of the credibility of climate commitments has been largely overlooked by Integrated Assessment Models (IAMs), a family of complex numerical tools used to inform climate policy-making. Notably, the words "credible" and "credibility" appear only once each in Chapter 3, dedicated to long-term mitigation pathways, in the latest IPCC WG3 report [16]. One reason for this apparent disinterest lies in the core assumptions of the models. Indeed, many IAMs are not designed to address the issue of credibility. The dominant family of IAMs is intertemporal optimization models, which assume a single, all-knowing decision-maker plans under perfect knowledge of future outcomes and

consequences of its actions [17]. These core assumptions leave little room for uncertainty regarding the conduct of climate change mitigation policies. Ignoring the problem of credible commitments in IAMs can lead to overestimating the speed at which economic agents respond to changing policy signals and underestimating the inertia of socio-technical systems [18]. This provides a biased view of the effectiveness of climate policies and proves to be misleading for climate policy-making. Some studies and models that deviate from the intertemporal optimization framework explore situations of misaligned expectations and policy objectives. Yet, these studies rarely focus on the issue of credibility, instead making implicit assumptions about how agents anticipate (or do not anticipate) future climate policies. To the best of our knowledge, there is no structured literature on the role of credible commitments in achieving deep decarbonization goals. Only a few studies have explicitly incorporated credible climate policy commitments within IAMs in the past two decades [19].

This study contributes to global efforts to enhance the realism of climate policy models and provide more accurate and relevant information to policy-makers [20]. First, we show that existing IAM studies already describe situations of misaligned expectations and policy objectives through modeling assumptions and scenario designs. For these studies, we identify the underlying narratives in terms of credibility and foresight on future climate policies. Following these insights, we demonstrate how credibility can be explicitly and comprehensively integrated into an IAM framework. Our approach goes beyond the standard dichotomy between intertemporal optimization models describing credible forward-looking policy signals and simulation models representing myopic agents [21]. This article represents both cases of myopic and perfect foresight on climate policies and introduces an intermediate scenario of low credibility of long-term targets and limited foresight on policy implementation, which reveals credible commitments as a policy lever to accelerate climate change mitigation. Using the Integrated Assessment Model IMACLIM-R [22], we find that credible climate policy commitments are instrumental in aligning CO₂ emission pathways with ambitious mitigation goals in sectors with long-lived capital, such as the power and transportation sectors.

1 Credible commitments in Integrated Assessment Models

From the perspective of decision-makers, the issue of credible climate policy commitments centers on the ability (or inability) to predict future climate policies with certainty, often referred to as climate policy uncertainty [23]. We do not aim to determine whether policymakers will keep their promises but focus on how the lack of reliable information about future climate policies affects investment patterns and delays the adoption of low-carbon technologies.

We define "credible commitments" as policy announcements that combine detailed implementation plans with confidence that policymakers will adhere to the plan. Credible commitments acknowledge that decision-makers need foresight on concrete policy developments to assess a policy package's credibility. These two dimensions cannot be addressed separately, as policy credibility depends on the plan's characteristics [24]. For this study, we differentiate between foresight on future concrete policies and the likelihood of pursuing a long-term target. Economic agents face *ambition uncertainty*¹ when they cannot know with certainty the long-term mitigation goal targeted by policymakers. The Paris Agreement sets a unique, globally shared target, but disagreements over interpreting "well below 2°C" remain, causing significant uncertainty due to discrepancies in CO2 emission pathways and the socio-economic transformations compatible with this objective [27]. Net zero pledges address only part of this problem, as many CO2 pathways can lead to carbon neutrality. Additionally, commitment to the announced long-term target is never fully guaranteed [28], [29], [30], and there is a real risk of countries abandoning their pledges, especially if the low-carbon transition costs are perceived as too high [31]. To deal with ambition uncertainty, it is assumed that agents rely on scenarios to describe plausible future states corresponding to different levels of ambition for climate change mitigation [32]. Agents then assign subjective probabilities based on their beliefs about the likelihood of each scenario materializing.

Even without ambition uncertainty, economic agents may face implementation uncertainty due to a lack of foresight on future policy developments. Detailed implementation plans for long-term targets are often still in development or lacking, creating an

¹Sometimes referred to as transition scenario uncertainty [25] or climate target uncertainty [26]

”implementation gap” between policy announcements and actual implementation [33]. Policymakers face a tradeoff between making reliable long-term commitments and announcing short-term policies, maintaining flexibility to adjust to new information [34]. Additionally, some policy instruments, like cap-and-trade systems, generate implementation uncertainty by design. For target-driven instruments, the carbon price is determined by the demand and supply of carbon allowances, which depend on past innovation and investment in low-carbon technologies. Therefore, it becomes difficult for private actors to predict the future carbon price when climate policies are target-driven. To summarize, credible commitments combine low ambition and implementation uncertainty by providing a clear, detailed plan to reach a long-term target and a high level of confidence that the plan will be implemented.

We found a set of studies that explore the impact of ambition uncertainty in scenarios of delayed climate action, providing an initial body of work addressing credibility using IAMs. Most of these studies share a common narrative of a binary switch in beliefs about the long-term policy target, referred to as ”Delayed Transition” scenarios [14] (Figure 1). Agents initially ignore the possibility of climate policy tightening until a certain date, typically 2030. Then, they align their expectations with the long-term target once they observe more stringent climate policies being implemented. This narrative of switching beliefs and immediate alignment of agents’ expectations is largely driven by model constraints. Most models in these studies are intertemporal optimization models, requiring perfect foresight on policy trajectories to solve the optimization problem. To induce a temporary misalignment between agents’ expectations and policy objectives, the models force agents to invest as in the business-as-usual scenario until a certain date, then implement the long-term target in the next period ². This explains why these studies address credible commitments only in delayed policy scenarios. Exceptions to the narrow ”Delayed Transition” narrative include studies using the stochastic version of the intertemporal optimization model WITCH [35]. These studies tell a more nuanced story of agents facing ambition uncertainty and assigning equal probabilities to each possible long-term target until the real long-term target is disclosed [26], [36]. However, these pioneering

²See footnote 3 of [13]

studies still assume perfect foresight on policy implementation³. Therefore, they address credible commitment only through ambition uncertainty, not implementation uncertainty. To capture implementation uncertainty, intertemporal optimization models need to release the perfect foresight assumption and use rolling time horizons [37]. Rolling horizons reduce the future information required to solve the optimization problem, mimicking myopia about future variables, including policy developments. To date, models with rolling horizons have been developed for energy system modeling only [38],[39]. Policy credibility and foresight beyond the myopic investment horizon is thus contained in the value attributed to the capital at the end of this horizon, known as salvage value [40]. Developing myopic intertemporal optimization IAMs is a promising avenue to address credible commitments in IAMs, but it is costly and time-consuming for such complex tools.

Some simulation models, a category of Integrated Assessment Models that do not rely on optimization techniques, provide an alternative starting point for capturing credible commitments in IAMs. Recursive-dynamic models like IMACLIM-R [22], GCAM [41], and IMAGE [42] assume "myopic foresight," meaning agents have no information about future developments in a scenario, including prices, demand, available technologies, and policies [43]. Agents extrapolate the future from the present and the past but ignore forward-looking policy signals, which reflects deep implementation uncertainty, as the agents are blind to future policy developments. Because myopic foresight is part of the modeling assumption, studies do not explicitly refer to credibility, instead justifying the myopic foresight assumption by citing a general state of future uncertainty, incentivizing agents to rely on past and present information [44]. The myopic assumption is relevant for economic and technological variables like future prices, demand, and available technology, but less convincing for policy variables

In practice, recursive-dynamic models like IMACLIM-R often model investment decisions, such as choices between electricity generation technologies, types of cars, or heating systems, based on comparing the life-cycle costs of different options. They typically use Net Present Value (NPV) and derivatives like the Levelized Cost of Electricity in the

³"Because agents have perfect foresight, the hedging behavior factors in the expectation over future possible scenarios. Current decisions are taken knowing the variable values that will be faced in each branch and knowing the probability of realization of each branch" in De Cian and Tavoni 2012.

power sector to rank available options and derive corresponding market shares using logit-like choice functions [45]. In these frameworks, myopia to future policy development is only one of many modeling assumptions. Forward-looking policy signals can be incorporated into NPV and expected profit calculations to relax the myopia assumption. A toy model of investment based on NPV calculations formally illustrates this in the Online Supplementary Materials.

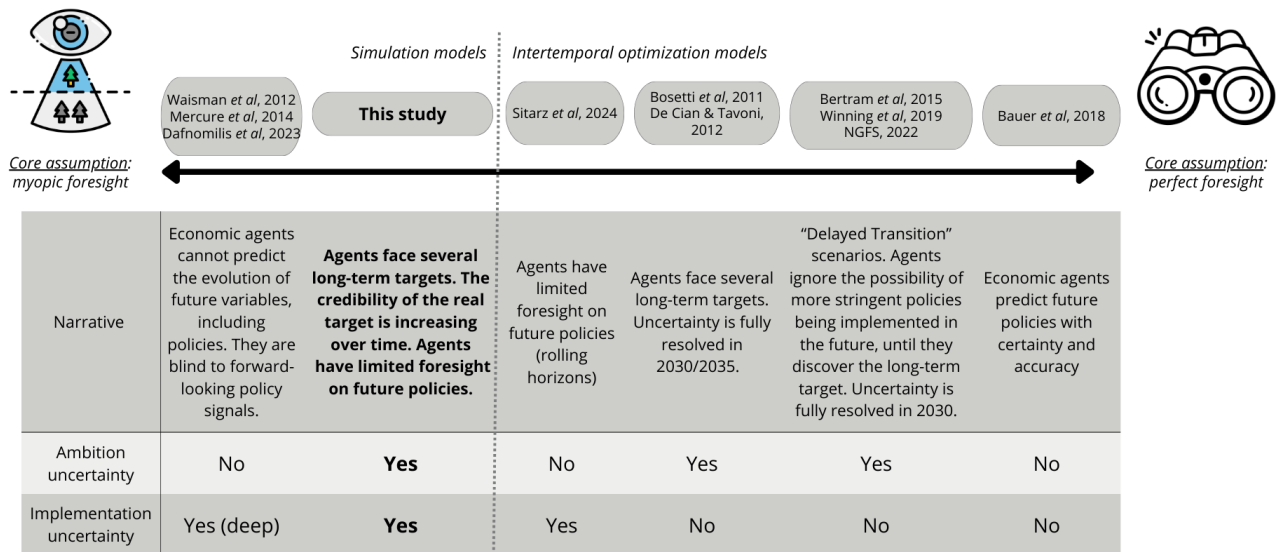


Figure 1: Reviewing the IAM literature through the lens of credible commitment: underlying narratives and illustrations with IAM studies.

2 Assessing the importance of credible commitments to achieve ambitious climate change mitigation goals

Starting with a formerly myopic model, IMACLIM-R, we introduce expectations of future climate policies to address both ambition uncertainty and implementation uncertainty (see Methods for details on the model and the implementation of credibility features). The effectiveness of climate policies is assessed under varying levels of credibility and foresight on future policies. The scenario design combines a policy pathway with assumptions about the credibility of policy commitments (Table 1).

Policy-makers target Net Zero by 2060⁴ using a global carbon tax. Net Zero targets are preferred over carbon budgets for three main reasons. First, Net Zero targets align

⁴2060 represents a compromise between current early Net Zero pledges (e.g. the EU), late targets e.g. 2070 for India and countries without carbon neutral targets

with the current architecture of pledges under the Paris Agreement. Second, Net Zero targets emphasize credibility along the policy pathway rather than focusing solely on the long-term goal [46]. Additionally, carbon-neutral scenarios limit temperature overshoot and reduce reliance on negative emission technologies [47]. In the *Early* policy scenario, stringent climate policies are implemented starting in 2020, ensuring a linear reduction of CO₂ emissions to reach carbon neutrality in 2060. Nationally Determined Contributions (NDCs) are implemented first until 2030 in the *Delayed* policy scenario. Three cases explore different assumptions about the credibility and foresight of future policies. The *Myopic* case assumes agents ignore forward-looking policy signals, following the standard recursive-dynamic model assumption like IMACLIM-R. The *FullCred* case assumes perfect foresight on future policies, a relatively unexplored scenario in simulation IAMs. The *LowCred* case illustrates low credibility of the long-term target and limited foresight on future policy implementation. Initially, economic agents assign a 20% probability to the Net Zero target and 80% to the business-as-usual (*NDC*) scenario. This probability increases to 100% within five years once stringent climate policies are implemented: in 2020 for the *Early* scenario and 2030 for the *Delayed* scenario. Additionally, agents face implementation uncertainty, with foresight on future policies reduced to five years.

Figure 2) shows global fossil CO₂ emissions from energy use. Emissions decrease in all policy scenarios after plateauing in 2025. In the *NDC* scenario, CO₂ emissions reach 17 GTCO₂ by 2050, consistent with recent estimates using updated NDC pledges [48]. Regardless of policy delay or credibility, CO₂ emission pathways converge to Net Zero by 2060 in both the *Early* and *Delayed* scenarios. By mid-century, the carbon tax incentives are sufficient to trigger low-carbon investment and phase out fossil fuels. Technical inertia, not misaligned policy targets and expectations, hinders faster decarbonization. However, in the short and medium term, CO₂ emission pathways diverge significantly. The primary factor for short-term discrepancies is the delay in policy implementation. By 2030, CO₂ emissions range from 22 to 25 GTCO₂ in the *Early* scenario compared to 29 to 33 GTCO₂ in the *Delayed* scenario. Accelerating climate action through early implementation of stringent policies is crucial for quickly reducing CO₂ emissions and achieving ambitious climate goals.

		Policy target		
		NDC	Net Zero (NZ) 2060	
			Early	Delayed
Credibility of policy commitments	Description	NDC-compliant policies	NZ 2060 targeted as of 2020	NDC policies until 2030, NZ after 2030
No	Agents ignore forward-looking policy signals	NDC_{Myopic}	$Early_{Myopic}$	$Delayed_{Myopic}$
Full	Agents have perfect foresight on future policies	$NDC_{FullCred}$	$Early_{FullCred}$	$Delayed_{FullCred}$
Low	Low credibility of NZ target (20%), increases over time 5y foresight on policy implementation	Not implemented for NDC	$Early_{LowCred}$	$Delayed_{LowCred}$

Table 1: Resume of the scenario design: interplay between levels of credibility and policy delay

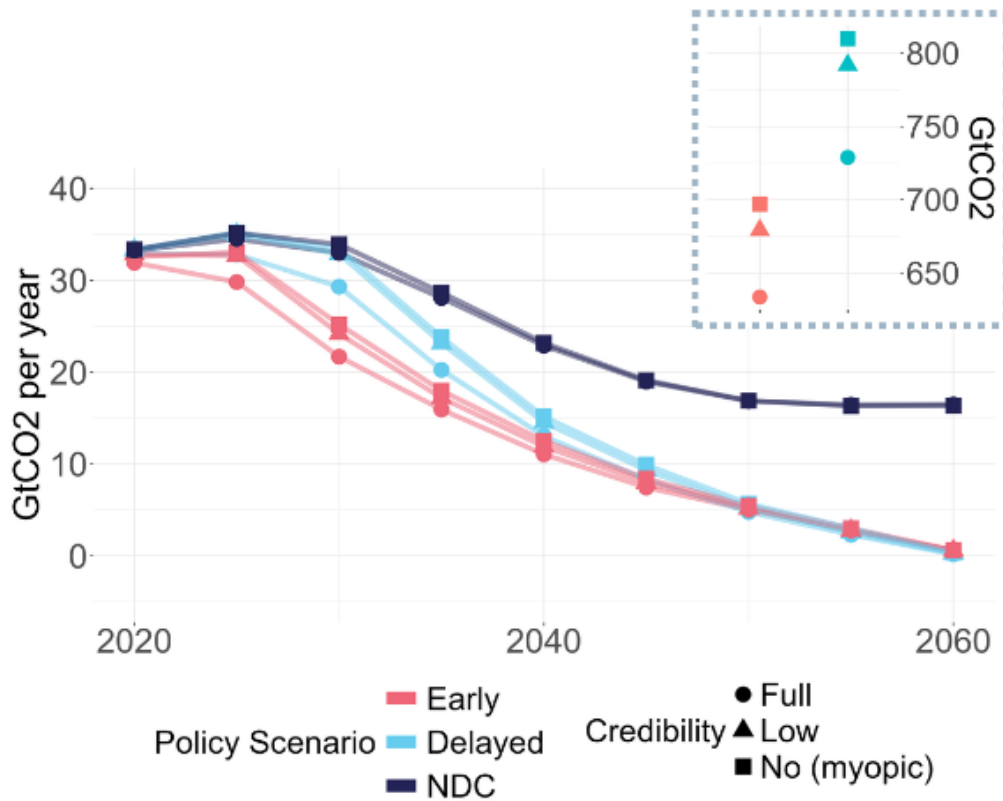


Figure 2: CO2 emissions pathways from fossil fuel combustion for energy uses and Net Zero Cumulative CO2 emissions 2020-2060 (including from Industrial Processes).

When controlling for the delay in policy implementation, the importance of credible commitments becomes clear. Cumulative CO₂ emissions increase by 10% in the *Early* scenario and by 11.1% in the *Delayed* scenario if agents are blind to forward-looking policy signals compared to the *FullCred* case. The delay in implementation heightens the need to align expectations with policy objectives to achieve CO₂ reductions, but credible commitments remain central to achieving climate goals in early policy scenarios. Comparing the *FullCred* and *Myopic* cases highlights the importance of forward-looking signals for the effectiveness of carbon pricing policies.

The *Myopic* assumptions capture an extreme situation of agents' total blindness to forward-looking policy signals, which has little empirical support. The *Delayed_{LowCred}* case provides a more nuanced story of combined delayed action and strengthening credibility of the long-term target, with limited foresight on policy implementation. This scenario appears to be more in line with the current state of pledges and implementation plans. *Delayed_{LowCred}* also results in significantly higher cumulative CO₂ emissions compared to the *Delayed_{FullCred}* case. The emission gap between the *Delayed_{LowCred}* and *Delayed_{FullCred}* cases is largest in 2030 (+3.6 GtCO₂). This gap remains large by 2035, the date at which ambition uncertainty is resolved (+2.9 GtCO₂), and remains significant in 2040 (+1.5 GtCO₂). These results underscore the importance of aligning expectations with policy objectives to reduce CO₂ emissions in the short term, especially given the presence of long-lived infrastructure and capital inertia.

3 Interplay between capital inertia and credible commitments

Figure 3 compares global CO₂ emission pathways for two sectors of the economy: the power sector (*Supply|Electricity*) and personal car transportation (*Transportation|Passenger|LDV*). The focus on these two sectors is motivated by their long-lived capital and the degree of technological detail in the IMACLIM-R model (see Online Supplementary Materials for sectorial details). The CO₂ emission gap between scenarios of policy credibility is wider in these sectors since other sectors of the economy are less (or not) sensitive to forward-looking policy signals in IMACLIM-R. In these sectors, the risk of carbon lock-

in is high if credible climate policy commitments are not provided. In both cases, the *Delayed_{FullCred}* scenario outperforms at least the *Early_{LowCred}* scenario in terms of CO₂ emissions, meaning that getting expectations right can compensate for a ten-year delay in the implementation of climate policies. In the *Delayed* policy scenarios, the lack of credible commitments leads to a significant increase in CO₂ emissions that lasts until 2050. By 2035, CO₂ emissions from the power sector are 45% higher in the *Delayed_{LowCred}* scenario compared to the *Delayed_{FullCred}* scenario, respectively 15% for the personal car transportation sector. The emissions gap is more pronounced in the electricity sector due to the higher capital inertia of the power sector compared to the transportation sector. In IMACLIM-R, the complete rotation of the car fleet takes years, while the lifetime of power plants varies from 20 (oil peakers) to 80 years (hydropower). Therefore, investment decisions are more sensitive to forward-looking policy signals in the power sector than in the transportation sector. The use of sector-specific discount rates exacerbates the importance of credible commitments in the power sector since the discount rates used by firms in the power sector are lower than the discount rate used by households for car purchases.

The delayed phase-out of fossil fuels in the power sector is further visible in capacity additions and in the energy mix, expressed as deviations from the *FullCred* case in each Net Zero policy scenario. In both *Early* and *Delayed* policy scenarios, the *LowCred* and *Myopic* cases lead to lower investments in variable renewable energy sources in the 2020s compared to the *FullCred* (Figure 4). Credible climate policy commitment successfully incentivizes the deployment of wind and solar power in the short run, while the lack of credible commitments delays the deployment of low-carbon technologies. As a consequence of slower renewable energy deployment, existing fossil fuel capacity is more extensively used to generate electricity in the *LowCred* and *Myopic* cases, leading to higher Primary Energy use of Coal and Gas (Figure 5). Overall, by 2035 in the *Delayed* policy scenario, the use of fossil fuels (without CCS) increases by more than 46EJ in the *Myopic* case compared to the *FullCred* case (38 EJ in the *LowCred*). In the *Delayed_{FullCred}* scenario, these unabated fossil fuels are substituted by a mix of low-carbon technologies, mostly wind and solar power ⁵.

⁵By convention, a conversion efficiency of 100% for wind and solar is used, hence the apparent total

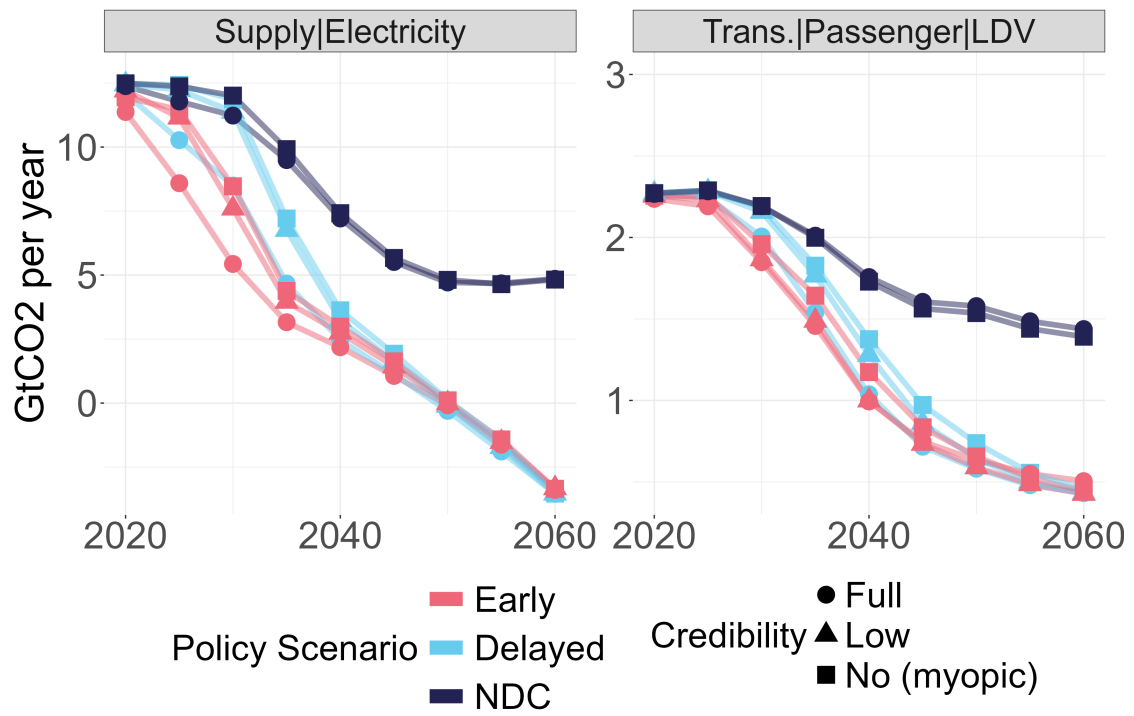


Figure 3: CO2 emissions pathways from the power sector and from personal car transportation

primary energy use gap on Figure 5. See Figure 9 in Online Supplementary Materials A.1.

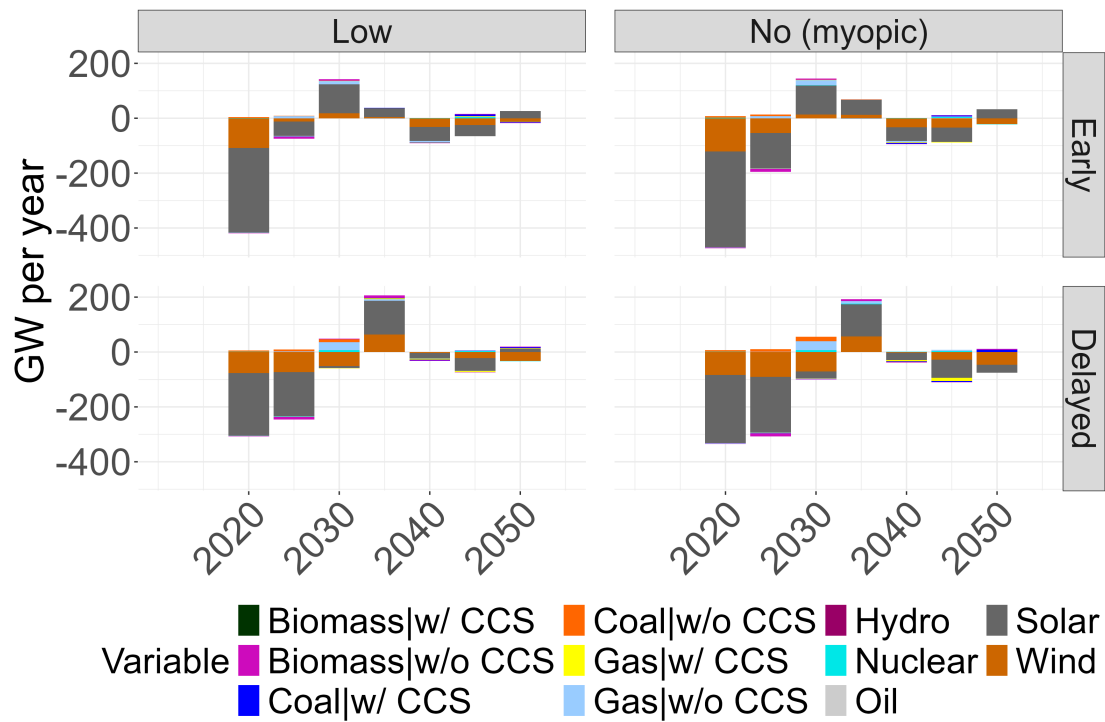


Figure 4: Capacity additions in the power sector, deviation from the *FullCred* case, with a focus the transition period (2020-2050)

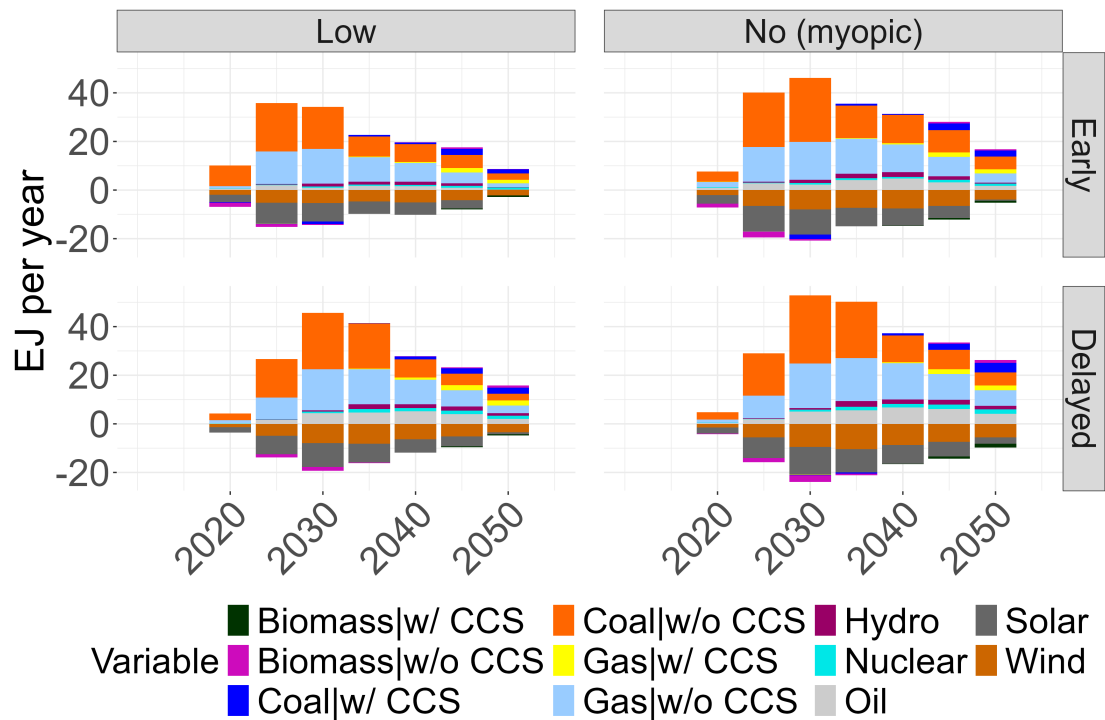


Figure 5: Primary Energy, deviation from the *FullCred* case, with a focus the transition period (2020-2050)

4 Discussion

In this article, we move beyond the typical dichotomy of myopic versus perfect foresight to explore more nuanced scenarios involving low policy credibility and limited foresight within an Integrated Assessment Model (IAM). Policy credibility is introduced as a parameter of the model, allowing us to assess how credible commitments can impact the achievement of ambitious climate change mitigation goals. Our findings underscore the critical role of credible climate policy commitments in swiftly reducing CO₂ emissions, particularly in sectors with significant capital inertia, such as the power sector. This analysis constitutes a first step towards a more comprehensive integration of the role of credible commitments in IAMs. The methodology developed in this study is transparent and can be easily replicated in other Integrated Assessment Models that share a similar structure to IMACLIM-R. This effort contributes to integrating political economy insights into Integrated Assessment Models to enhance their policy relevance [49].

Recognizing the influence of credibility on investment patterns paves the way for a broader analysis of policy instruments beyond the global carbon price [20]. Under imperfect markets fraught with informational issues, second-best policies can consist of a mix of different instruments, including subsidies or bans that provide different types of incentives to economic agents [50]. If current governments cannot tie the hands of future governments, the optimal policy package includes additional policy instruments such as R&D subsidies [51]. The lack of credibility of implemented policies provides an alternative explanation for the "policy outcome gap," i.e., the apparent ineffectiveness of implemented policies [52]. Indeed, implemented policies can be less effective than expected if economic agents anticipate a future reversal.

On this point, our study does not delve into mechanisms that could enhance the credibility of climate policy commitments and ensure their persistence. Policy credibility hinges on the government's reputation, built through consistent adherence to past commitments. When reputation is weak, credibility can be bolstered through legal and institutional mechanisms that restrict future governments, known as "commitment devices" [28]. The main route taken by governments to strengthen the credibility of climate policy commitments combines legislation and delegation [53]. Legally binding pledges in-

crease the cost of policy reversal for future governments, hence fostering policy credibility [54], while delegation seeks at insulating climate policy design and implementation from day-to-day politics [55].

Finally, in this paper, we assume that the degree of policy credibility and foresight on future policies do not modify the financing conditions of investments. In practice, it is very likely that investors' expectations also depend on policy credibility and foresight on future climate policies. If policy credibility is low, investors may not reallocate capital into low-carbon technologies and require higher returns on investment to compensate for the additional risk. Higher financing costs would further diminish the profitability of low-carbon investments in the absence of credible policy commitments. The integration of the financial system into the model would connect private investment decisions from firms and households with financial markets' expectations [56]. Such integration would capture feedback loops between investment decisions, decarbonization pathways, and investor expectations. Understanding these links and representing them in climate policy models offer promising directions for future research [57].

5 Online Methods

The IMACLIM-R Model

The IMACLIM-R model is a recursive, dynamic, multi-region and multi-sector model of the world economy used to project. It combines a comprehensive CGE macroeconomic core with a bottom-up representation of the energy and transportation sectors. IMACLIM-R models CO₂ emissions from Energy and Industrial Processes⁶ and allow for Carbon Dioxide Removal through Bioenergy with Carbon Capture and Storage (BECCS) for electricity generation only.

Each year, agents produce and consume goods and services under a set of inherited constraints (input-output coefficients, labor productivity, population) that constitutes a fixed frontier of production. Prices adjust to clear markets in a standard Computable General Equilibrium fashion. Prices and quantities become signals for investment deci-

⁶CO₂ emissions from Industrial Processes are exogenous to the model, so they are not included in Figures 2 and 6

sions happening in the bottom-up modules, which update the set of constraints for the next period and move the frontier of production. In sectors with long-lived capital, agents form investment decisions based on life-cycle costs (LCC) calculations, like the Levelized Cost of Energy in the energy sector or the Total Cost of Ownership for private cars (see Supplementary Materials for further details). LCC is computed as the sum of the annualized capital expenditures ($CAPEX_{ann}$), operation and maintenance ($OPEX$), and fuel costs ($FUEL$). When relevant, the LCC are divided by the energy output (*e.g.* electricity generation) over the technical lifetime of each technology T . CAPEX are annualized using Capital Recovery Factors (CRF) that converts an initial investment into a stream of annual payments over the lifetime of the asset. Projected variables in the LCC calculation are expected variables due to the endogenous nature of prices and demands in market economies (and as represented by the CGE macroeconomic core of IMACLIM), but also due to climate policies. In particular, expected fuels costs depend both on the expected carbon tax development and fossil fuel prices. Following the rationale of recursive-dynamic IAM, current fossil fuel prices are taken as the best proxy for future prices. Only the carbon tax expectations are forward-looking and depend on the level of credibility and foresight on future climate policies.

For carbon-intensive technologies, fuel costs depend on the expected carbon tax development and the carbon intensity of the fuel. A period t , the expected carbon tax for the future period $t + r$ is denoted $E_{t,r}(\tau_{t+r})$

$$LCC_t = \frac{\sum_{r=0}^{T-1} CAPEX_{ann}(t, T, i) + OPEX_{t+r} + FUEL_{t+r}(E_{t,r}(\tau_{t+r}))}{\sum_{r=0}^{T-1} E_{t+r}} \quad (1)$$

$$CAPEX_{ann}(t, T, i) = CAPEX_t \times CRF(i, T) \quad (2)$$

$$CRF(i, T) = \frac{i(1+i)^T}{(1+i)^T - 1} \quad (3)$$

with i the discount rate and T the technical lifetime of the asset. Technology and regionally-specific discount rates are used in the power sector, while uniform rates are applied in the other sectors.

5.1 Long-term targets and policies

The CO₂ tax pathways $\tau_{t,s}$ are determined by the social planner to reach the three levels of ambition or policy scenarios s : Nationally Determined Contributions (NDC), Early Net Zero (*Early*) by 2060, NDC then Net Zero target by 2060 (*Delayed*). In all policy scenarios, $\tau_{t,s}$ is set to reach the target under perfect foresight on future climate policies, *i.e.* in the *FullCred* cases. The level of ambition is chosen *ex ante* by policymakers, which do not deviate from their initial target, meaning that the policy scenario is set prior to the start of the simulation. In the *FullCred* case, decision-makers anticipate perfectly the carbon tax policy from 2020 to the model’s horizon ($T_{end} = 2100$). In the NDC case, the carbon tax reproduces short-term CO₂ pathways based on updated NDC-compliant pathways [48], leading to a global 7% reduction in CO₂ emissions in 2030 from 2019 levels. The ”continuation of efforts” post-2030 is modeled by keeping the CO₂ price constants, while several alternative definitions coexist [58], [59]. Due to the high degree of technical inertia in IMACLIM-R, this conservative definition of the ”continuation of efforts” still delivers significant CO₂ emission reductions in the long run. The implementation of climate policies starts in 2020, with no explicit policy announcement before this date, meaning that all scenarios share the same trajectories until 2020. For the *Delayed* policy scenario, we assume that the carbon tax reaches *Early* levels by 2050.

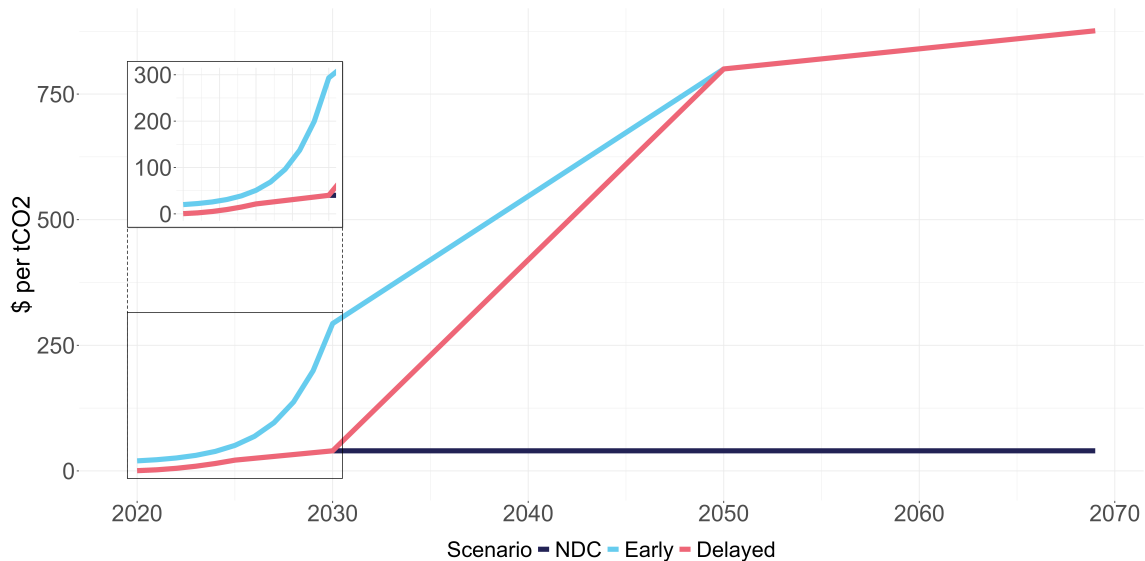


Figure 6: CO₂ price pathways in the *NDC*, *Early* and *Delayed* policy scenarios.

5.2 Credible commitments in IMACLIM-R

The forward-looking policy signal given by $\tau_{t,s}$ is unequally integrated into decision-makers' investment decisions depending on the assumption the level of credibility and foresight on policies. In the *Myopic* case, agents ignore forward-looking policy signals and only react to current prices. The expected carbon tax pathways at period are independent from the scenario s and are given by:

$$\forall s \in S, E_{t,r} = \tau_{t,s} \quad (4)$$

In the *FullCred* case, agents have perfect foresight on future policies and use the real carbon price in their investment decisions. They can anticipate the long-term target (*i.e.* which scenario s is going to materialize) and the corresponding carbon tax pathways.

$$\forall s \in S, E_{t,r} = \tau_{t+r,s} \quad (5)$$

The *LowCred* case captures a situation of low credibility and limited foresight on future policies: agents face both ambition uncertainty and implementation uncertainty. Starting with implementation uncertainty, the foresight on future policies is limited to five years ($H = 5$)⁷. $E_{s,t,r}$ denote the expectations formulated at time t for the future level of carbon tax at period $t + r$, conditional on the scenario s materializing:

$$\begin{aligned} \forall s \in S, \forall r \leq H, E_{s,t,r}(\tau_{t+r,s}) &= \tau_{t+r,s} \\ \forall r > H, E_{s,t,r}(\tau_{t+r,s}) &= \tau_{t+H,s} \end{aligned} \quad (6)$$

Because of ambition uncertainty agents do not know the real long-term target, the expected carbon tax is an average of the carbon taxes for each scenario, weighted by the probability of each policy scenario to materialize. This applies only to Net Zero scenarios, as we do not explore the *Lowcred* case for the NDC scenario.

$$E_{t,r}(\tau_{t+r,s}) = \sum_{s \in S} \pi_{s,t} \times E_{s,t,r}(\tau_{t+r,s}) \quad (7)$$

⁷The 5-year timeframe reflects typically forecast length for market-based instruments like the EU ETS ([60]).

$\pi_{s,t}$ are fixed according to the following assumptions. In 2020, the initial subjective probability of being in the *NDC* scenario, $\pi_{NDC,t}$ is set to 80%. If agents observe stringent climate policies being implemented as of 2020 (*Early* scenario), $\pi_{Early,t}$ is set 20% and $\pi_{Delayed,t}$ to 0% (*Delayed* scenario). The credibility of the Net Zero target increases linearly to 100% within 5 years, to mimic the progressive alignment of expectations with policy objectives.

If policy commitments correspond to the *NDC* policy pathways in 2020 (*Delayed*), $\pi_{Delayed,t}$ is set 20%, and the beliefs remain identical until 2030. When more stringent policies than NDC are implemented in the *Delayed* policy scenario, $\pi_{Delayed,t}$ increases to 100% within 5 years as in the *Early* scenario.

6 Acknowledgements

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No. 101081604 (PRISMA)

7 Author Contributions

T.B. formulated the research question with help from J.L. for conceptualization. T.B. and J.L. jointly conceived the scenario design. T.B. conducted scenario runs and created visualizations. T.B. and J.L. interpreted the results. T.B. wrote the first draft of the paper. All authors provided critical feedback and contributed to the final manuscript.

References

1. UNFCCC. The Paris Agreement, 24–45 (2015).
2. Hale, T. *et al.* Assessing the rapidly-emerging landscape of net zero targets. *Climate Policy* **22**, 18–29 (2022).
3. Roelfsema, M. *et al.* Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications* **11**, 1–12 (2020).
4. Galley, S. C. *et al.* Credibility gap in net-zero targets leaves world at high climate risk. **xxx**, 2–4 (2023).
5. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* **3**, 589–599 (2018).
6. Dorsey, J. *Waiting for the Courts: Effects of Policy Uncertainty on Pollution and Investment* **4**, 1453–1496 (Springer Netherlands, 2019).
7. Fried, S., Novan, K. & Peterman, W. B. Climate policy transition risk and the macroeconomy. *European Economic Review* **147**, 104174 (2022).
8. Lin, B. & Zhao, H. Tracking policy uncertainty under climate change. *Resources Policy* **83**, 103699 (2023).
9. Pindyck, R. Irreversibility, Uncertainty, and Investment. *Journal of Economic Literature* (1991).
10. Blyth, W. *et al.* Investment risks under uncertain climate change policy. *Energy Policy* **35**, 5766–5773 (2007).
11. Bauer, N., McGlade, C., Hilaire, J. & Ekins, P. Divestment prevails over the green paradox when anticipating strong future climate policies. *Nature Climate Change* **8**, 130–134 (2018).
12. Van der Ploeg, F. & Rezai, A. The risk of policy tipping and stranded carbon assets. *Journal of Environmental Economics and Management* **100** (2020).
13. Bertram, C. *et al.* Carbon lock-in through capital stock inertia associated with weak near-term climate policies. *Technological Forecasting and Social Change* **90**, 62–72 (2015).

14. NGFS. NGFS Scenarios for central banks and supervisors, 1–48 (2022).
15. Victor, D. G., Lumkowsky, M. & Dannenberg, A. Determining the credibility of commitments in international climate policy. *Nature Climate Change* **12** (2022).
16. Riahi, K. *et al.* 2022: Mitigation pathways compatible with long-term goals. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Cambridge, 295–408 (2023).
17. Usher, W., Barnes, T., Moksnes, N. & Niet, T. Global sensitivity analysis to enhance the transparency and rigour of energy system optimisation modelling. *Open Research Europe* **3** (2023).
18. Ha-Duong, M., Grubb, M. J. & Hourcade, J.-C. Influence of socioeconomic inertia and uncertainty on optimal CO₂-emission abatement. *Nature* **390** (1997).
19. Bosetti, V. & Victor, D. G. Politics and economics of second-best regulation of greenhouse gases: The importance of regulatory credibility. *Energy Journal* **32**, 1–24 (2011).
20. Barbrook-Johnson, P. *et al.* Economic modelling fit for the demands of energy decision makers. *Nature Energy*, 1–6 (2024).
21. Stiglitz, J. E. *et al.* Report of the High-Level Commission on Carbon Prices. *International Bank for Reconstruction and Development and International Development Association/The World Bank* (2019).
22. Waisman, H., Guivarch, C., Grazi, F. & Hourcade, J. C. The Imacim-R model: Infrastructures, technical inertia and the costs of low carbon futures under imperfect foresight. *Climatic Change* **114**, 101–120 (2012).
23. Berestycki, C., Carattini, S., Dechezleprêtre, A. & Kruse, T. Measuring and assessing the effects of climate policy uncertainty. *Working paper* (2022).
24. Rogge, K. S. & Dütschke, E. What makes them believe in the low-carbon energy transition? Exploring corporate perceptions of the credibility of climate policy mixes. *Environmental Science and Policy* **87**, 74–84 (2018).

25. Le Guenedal, T. & Tankov, P. Corporate Debt Value under Transition Scenario Uncertainty, 1–29 (2022).
26. Bosetti, V., Carraro, C., Sgobbi, A. & Tavoni, M. Delayed action and uncertain stabilisation targets. How much will the delay cost? *Climatic Change* **96**, 299–312 (2009).
27. Pathak, M. *et al.* 2022: *Technical Summary* Climate Ch, 51–148 (2022).
28. Kydland, F. & Prescott, E. RULES RATHER THAN DISCRETION - INCONSISTENCY OF OPTIMAL PLANS. *JOURNAL OF POLITICAL ECONOMY* **85**, 473–491 (1977).
29. Helm, D., Hepburn, C. & Mash, R. Credible carbon policy. *Oxford Review of Economic Policy* **19**, 438–450 (2003).
30. Chiappinelli, O. & May, N. Too good to be true? Time-inconsistent renewable energy policies. *Energy Economics* **112**, 106102 (2022).
31. Campiglio, E., Lamperti, F. & Terranova, R. Believe me when I say green! Heterogeneous expectations and climate policy uncertainty. **Forthcomin** (2022).
32. Flora, M. & Tankov, P. Green investment and asset stranding under transition scenario uncertainty. *SSRN Electronic Journal*, 1–21 (2022).
33. United Nations Environment Programme. *Gap Emissions Gap Report 2022: 2: The Closing Window — Climate crisis calls for rapid transformation of societies*. 1–102 (2022).
34. Nemet, G. F., Jakob, M., Steckel, J. C. & Edenhofer, O. Addressing policy credibility problems for low-carbon investment. *Global Environmental Change* **42**, 47–57 (2017).
35. Bosetti, V., Carraro, C., Galeotti, M., Massetti, E. & Tavoni, M. WITCH A World Induced Technical Change Hybrid Model. *The Energy Journal* **27**, 13–37 (2006).
36. De Cian, E. & Massimo, T. Mitigation Portfolio and Policy Instruments When Hedging Against Climate Policy and Technology Uncertainty. *Environmental Modeling and Assessment* **17**, 123–136 (2012).
37. Quemin, S. & Trotignon, R. Emissions trading with rolling horizons. *Journal of Economic Dynamics and Control* **125**, 104099 (2021).

38. Keppo, I. & Strubegger, M. Short term decisions for long term problems - The effect of foresight on model based energy systems analysis. *Energy* **35**, 2033–2042 (2010).
39. Heuberger, C. F., Staffell, I., Shah, N. & Mac Dowell, N. Impact of myopic decision-making and disruptive events in power systems planning. *Nature Energy* **3**, 634–640 (2018).
40. Sitarz, J., Pahle, M., Osorio, S. & Pietzcker, R. EU carbon prices signal high policy credibility and farsighted actors (2023).
41. Thomson, A. M. *et al.* RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Climatic Change* **109**, 77–94 (2011).
42. Stehfest, E. *et al.* *Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications* 30 (The Hague: PBL Netherlands Environmental Assessment Agency, 2014).
43. Lefèvre, J. Hybridization challenges in energy-economy integrated models and representation of the low carbon transition (2016).
44. Bibas, R. *et al.* IMPact Assessment of CLIMate policies with IMACLIM-R World: Model documentation Version 1.1. *Cired* (2016).
45. De Boer, H. S. H. S. & van Vuuren, D. D. P. Representation of variable renewable energy sources in TIMER, an aggregated energy system simulation model. *Energy Economics* **64**, 600–611 (2017).
46. Dolphin, G., Pahle, M., Burtraw, D. & Kosch, M. A net-zero target compels a backward induction approach to climate policy. *Nature Climate Change* **13**, 1033–1041 (2023).
47. Riahi, K. *et al.* Cost and attainability of meeting stringent climate targets without overshoot. *Nature Climate Change* **11**, 1063–1069 (2021).
48. Van de Ven, D. J. *et al.* A multimodel analysis of post-Glasgow climate targets and feasibility challenges. *Nature Climate Change* **13** (2023).
49. Peng, W. *et al.* Climate policy models need to get real about people - here's how. *Nature* **594**, 174–176 (2021).

50. Grubb, M., Poncia, A., Drummond, P., Neuhoff, K. & Hourcade, J.-c. Policy complementarity and the paradox of carbon pricing, 711–730 (2023).
51. Ulph, A. & Ulph, D. Optimal Climate Change Policies When Governments Cannot Commit. *Environmental and Resource Economics* **56**, 161–176 (2013).
52. Fransen, T. *et al.* Taking stock of the implementation gap in climate policy. *Nature Climate Change* **13**, 752–755 (2023).
53. Lockwood, M. Routes to credible climate commitment: the UK and Denmark compared. *Climate Policy* **21**, 1234–1247 (2021).
54. Brunner, S., Flachsland, C. & Marschinski, R. Credible commitment in carbon policy. *Climate Policy* **12**, 255–271 (2012).
55. Grosjean, G., Acworth, W., Flachsland, C. & Marschinski, R. After monetary policy, climate policy: is delegation the key to EU ETS reform? *Climate Policy* **16**, 1–25 (2016).
56. Battiston, S., Monasterolo, I., Riahi, K. & Ruijven, B. J. V. Accounting for finance is key for climate mitigation pathways. **3877**, 1–5 (2021).
57. Sanders, M., Serebriakova, A., Fragkos, P., Polzin, F. & Egli, F. Representation of financial markets in macro-economic transition models — a review and suggestions for extensions OPEN ACCESS Representation of financial markets in macro-economic transition models — a review and suggestions for extensions (2022).
58. Dafnomilis, I., den Elzen, M. & van Vuuren, D. P. Achieving net-zero emissions targets: An analysis of long-term scenarios using an integrated assessment model. *Annals of the New York Academy of Sciences*, 98–108 (2023).
59. Van Soest, H. L. *et al.* Global roll-out of comprehensive policy measures may aid in bridging emissions gap. *Nature Communications* **12**, 1–10 (2021).
60. Edenhofer, O. *et al.* Decarbonization and EU ETS Reform: Introducing a price floor to drive low-carbon investments (2017).

A Online Supplementary Materials

A.1 Additional results

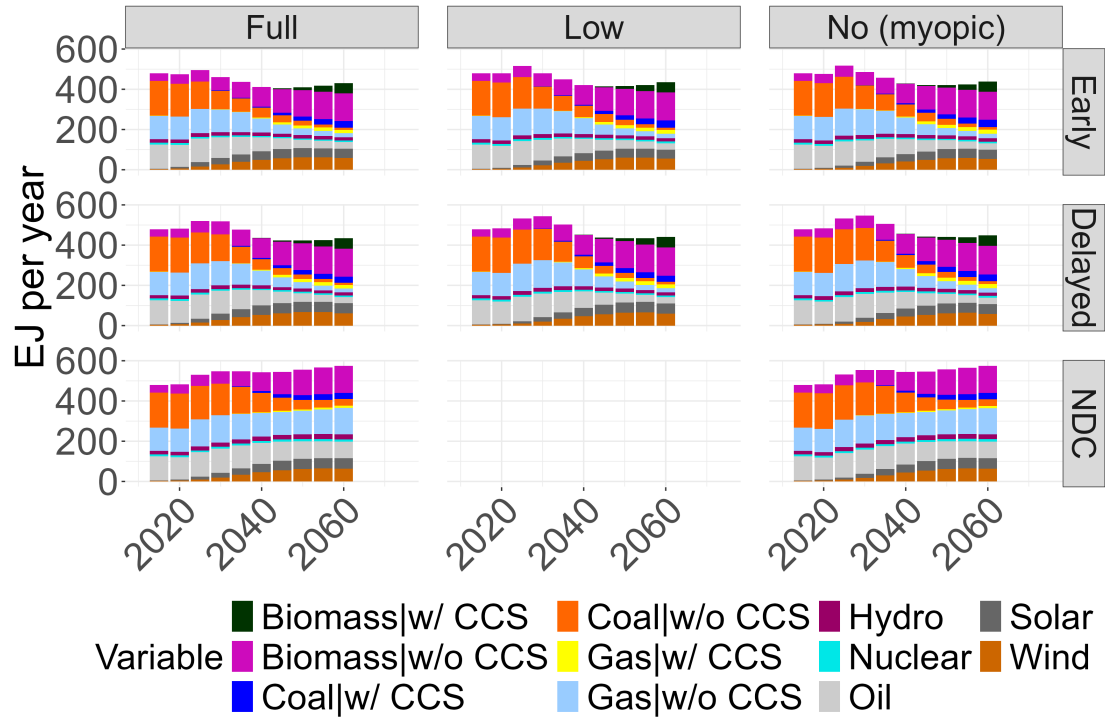


Figure 7: Primary energy mix, 2020-270

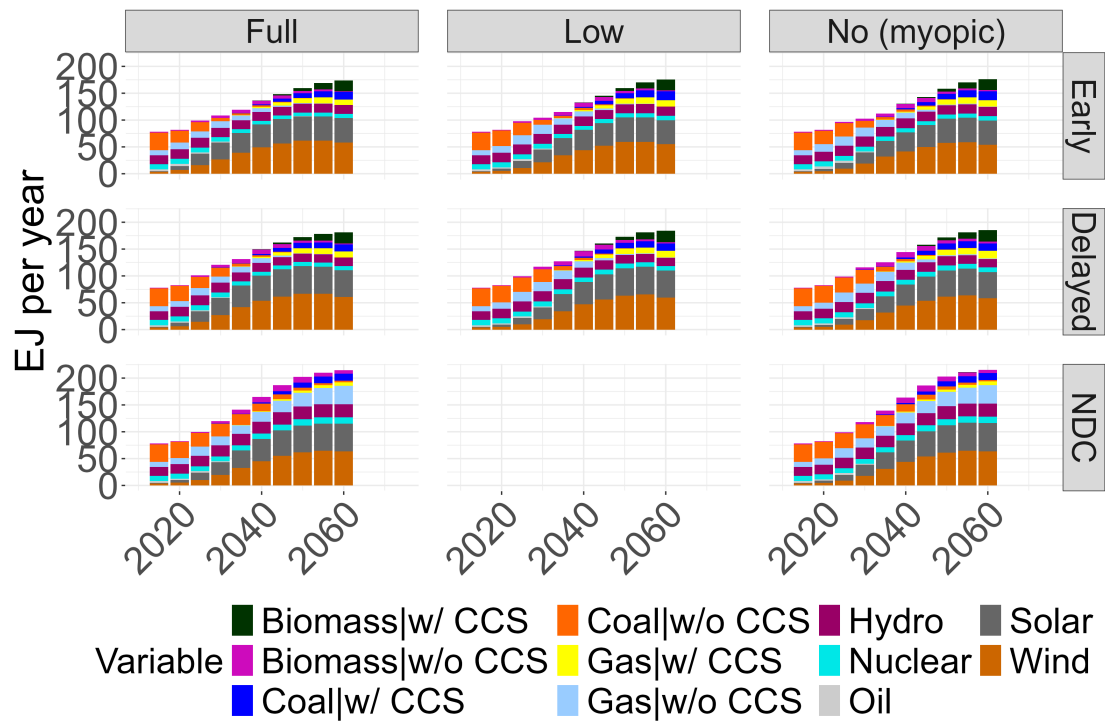


Figure 8: Electricity mix (Secondary Energy), 2020-270

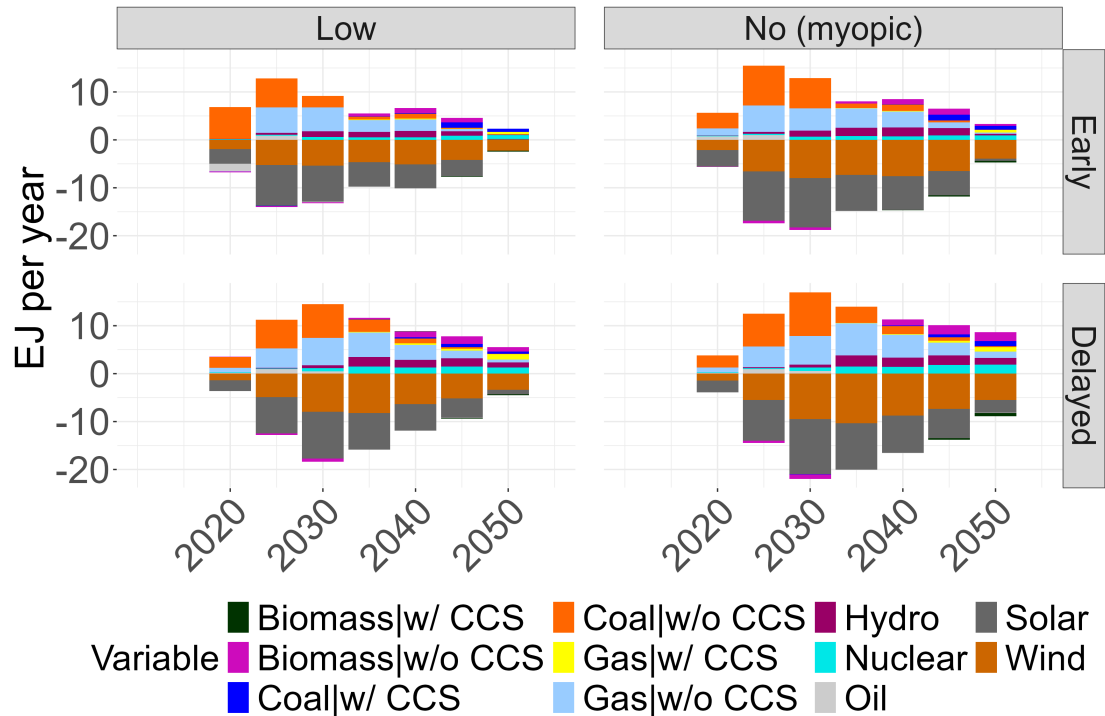


Figure 9: Electricity mix, deviation from the FullCred case (Secondary Energy), 2020-2070

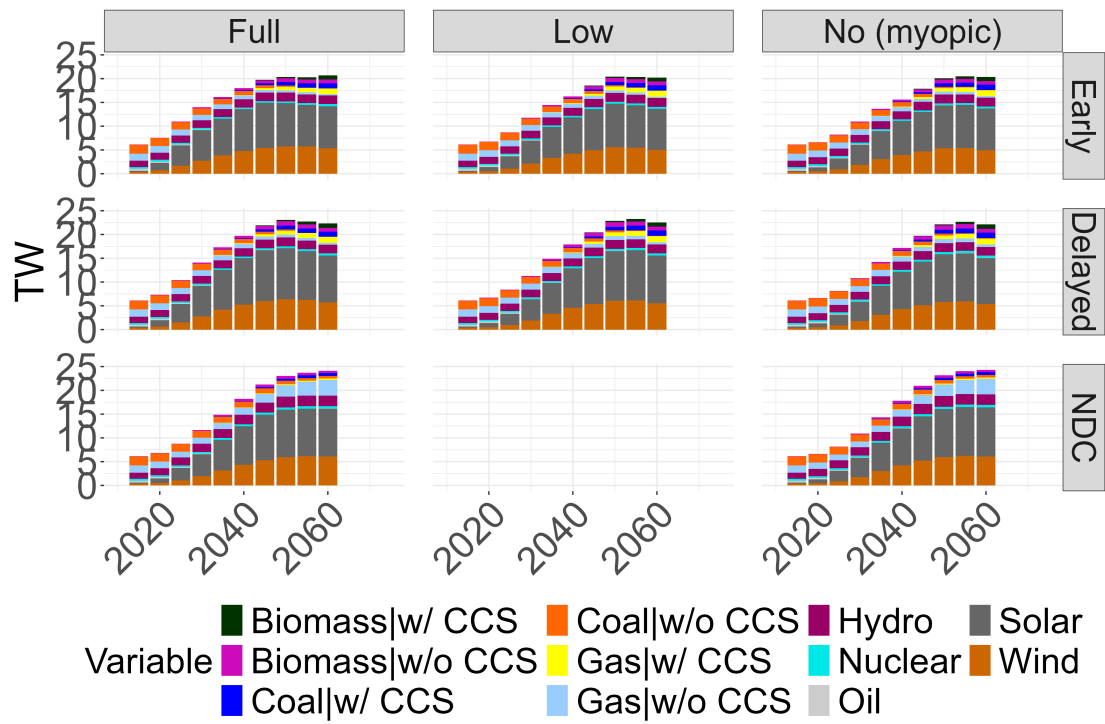


Figure 10: Power sector capacity, 2020-2070

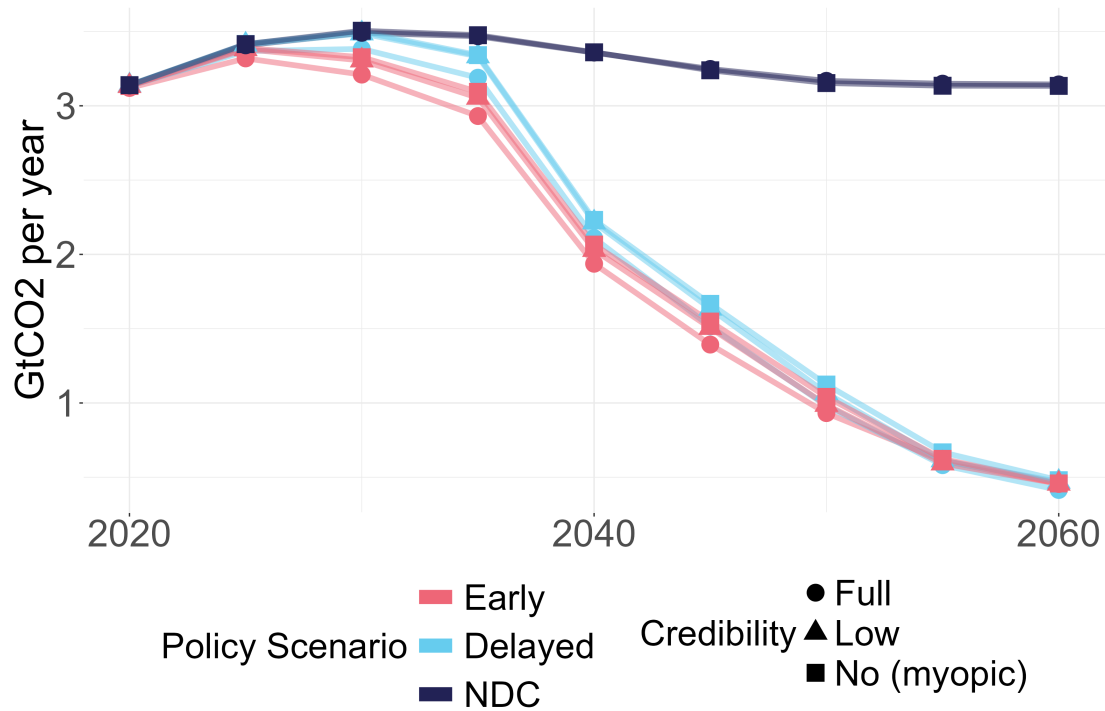


Figure 11: CO2 emissions from the residential sector, 2020-2070. The little discrepancy between the policy credibility and foresight scenarios is due to the fact investment decisions in this sector are only partially driven by forward-looking NPV calculations (see Online Supplementary Materials - Section A.3: Sectoral investment decision in IMACLIM-R).

A.2 Credible climate policy commitments in a toy model of investment

To illustrate the effect of credible policy commitments on investments in IMACLIM-R, we present a simple rule of investment based on a Net Present Value (NPV) with climate policy uncertainty that mimics the mechanisms of IMACLIM-R. By doing so, we show that any IAM representing investment decisions as a comparison of NPVs - typically LCOE in the power sector for recursive-dynamic models - can replicate our methodology.

We start from an irreversible investment model in which a representative risk-neutral producer decides whether to invest in a low-carbon (L) or a high-carbon technology (H), in the absence of climate policy uncertainty.

The producer invests in technology L or H in period 0. The low-carbon technology is more capital-intensive than the high-carbon alternative: $I_L > I_H$, with I_i the CAPEX of technology i . Both technologies produce a normalized unit of output in each of the next T periods that yield a periodical and constant revenue $R_t = R$, but technology H emits

CO2 in the process ($Emi_L = 0, Emi_H > 0$). The producer has to pay a carbon tax τ_t for each unit of CO2 emitted at period t . The producer discounts future cash flows at a private discount factor γ_t^p . The discount rate describes how agents value the future over the present and encapsulates ethical parameters (pure time preference). Its value is not directly related to climate policy-making, even though de-risking policies can lower the cost of capital and affect the discount rate [1]

We assume that the social planner wants to decarbonize the economy and favors carbon-free technology. He seeks the lower tax level that incentivizes low-carbon investments to minimize market distortions.

The private welfare associated with investment in technology i is given by the Net Present Value of cash flows:

$$U_i^p = -I_i + \sum_{t=1}^T \gamma_t^p (R - \tau_t Emi_i) \quad (8)$$

We further simplify the model to find closed-form solutions. We first assume that there are only two operation periods, *i.e.* $T = 2$. Second, we assume that the external cost of CO2 grows at rate β , *i.e.* $E_{t+1} = E_t * (1 + \beta)$ to capture the non-linearity of climate change impacts. In return, we also constrain the social planner's carbon policy. The social planner commits a period zero to an initial tax level τ_1 and a rate of increase for the next period α such that $\tau_2 = \tau_1 * (1 + \alpha)$.

These additional assumptions imply that the welfare of the private investor is given by:

$$U_i^p = -I_i + \gamma_1 (R - \tau_1 Emi_i) + \gamma_2 (R - \tau_1 (1 + \alpha) Emi_i) \quad (9)$$

Let's refer to this base model as model 1. We use the break-even carbon tax that makes the producer indifferent between the two technologies, *i.e.* that equalizes U_L^p and U_H^p , as an indicator for the effectiveness of climate policy commitments. Higher break-even taxes signal poor effectiveness of forward-looking incentives and low credibility of commitments. The break-even tax of model 1 is given by Equation 10:

$$\tau_1^{M1} = \frac{I_L - I_H}{(\gamma_1 + \gamma_2(1 + \alpha))Emi_H} \quad (10)$$

Under our assumptions, τ_1^{M1} is positive since the low-carbon technology is more capital-intensive than the high-carbon alternative. In addition to those already stated, our base model includes a supplementary underlying assumption: the investor has perfect foresight on the carbon policy. To put in in other words, there is no climate policy uncertainty. We first introduce ambition uncertainty into our base model. Ambition uncertainty has an ambiguous effect on investment strategies. On one hand, as underlined by the literature on real options, uncertainty can lead to a wait-and-see behavior, as agents postpone investment decisions until the uncertainty (about the long-term target) is resolved ([2]). On the other hand, the possibility of stringent climate policies being introduced in the future creates incentives for hedging behavior through early adoption of low-carbon technologies ([3]). Ultimately, the impact of ambition uncertainty on investment decisions depends on the range of possible futures (the set of scenarios) and the associated subjective probabilities [4], which can differ among economic agents [5].

We build model 2 by adding the following assumptions to model 1. Agents face two possible scenarios corresponding to different policy objectives: a climate mitigation scenario (*CLIM*) whose initial tax is ($\tau_1 = 1$) and a business-as-usual (*BAU*) scenario, in which no carbon tax is implemented ($\tau_1 = 0$). Agents estimate that the likelihood of the *BAU* scenario to materialize is $\pi^{BAU} = p$. The private welfare of the agent is given by Equation 11:

$$U_i^p = -I_i + p[\gamma_1 R + \gamma_2 R] + (1 - p)[\gamma_1(R - \tau_1 Emi_i) + \gamma_2(R - \tau_1(1 + \alpha)Emi_i)] \quad (11)$$

The break-even tax for the private producer is:

$$\tau_1^{M2} = \frac{I_L - I_H}{(1 - p)(\gamma_1 + \gamma_2(1 + \alpha))Emi_H} \quad (12)$$

Under our set of assumptions, scenario uncertainty favors a "wait-and-see" behavior since $\tau_1^{M2} > \tau_1^{M1}$. The private producer is less likely to invest in the low-carbon technology

in model 2 than in model 1. This result is contingent upon the set of scenarios considered by the producer and the probability assigned to each of them. For illustration purposes, we stick to very simplistic designs in our toy model. For instance, this general framework can be populated with more diverse scenarios, dynamic probabilities that evolve with new information ([4]) or even heterogeneous beliefs among the population of decision-makers ([5]).

Implementation uncertainty is then added to model 1 to form model 3. In our framework, implementation uncertainty does not involve subjective probabilities for the possible long-term targets, but rather uncertainty regarding the concrete policies (both instrument and their stringency) associated with each target. We assume that the decision-maker possesses reliable information about the tax introduced in period 1, but not in period 2. We capture this by introducing an expected rate of growth of the carbon tax $\tilde{\alpha}$. In our illustration with the IMACLIM-R model, $\tilde{\alpha}$ is set to zero, meaning that τ_1 is taken as the best estimate for τ_2 . Keeping the $\tilde{\alpha}$ notation, the private welfare of the agent in model 3 is given by Equation 13:

$$U_i^p = -I_i + [\gamma_1(R - \tau_1 Emi_i) + \gamma_2(R - \tau_1(1 + \tilde{\alpha})Emi_i)] \quad (13)$$

The break-even tax for the private producer is:

$$\tau_1^{M3} = \frac{I_L - I_H}{(\gamma_1 + \gamma_2(1 + \tilde{\alpha}))Emi_H} \quad (14)$$

τ_1^{M3} is higher than τ_1^{M1} at the condition that $\tilde{\alpha} < \alpha$, meaning that the implemented carbon tax in period 2 is higher than what agents expect. If agents underestimate the stringency of future climate policies (mostly because they lack of reliable information to anticipate future policy developments based on current commitments), then stronger short-term incentives are needed.

Table 2 resumes the assumptions and break-even taxes of the three models. Under the set of assumptions made, both implementation uncertainty and ambition uncertainty decrease the effectiveness of forward-looking signals given by prices. The break-even tax is lower in model 1 than in models 2 and 3. The relationship between policy credibility

Model number	Addition assumption to model 1	Break-even tax
1		$\tau_1^{M1} = \frac{I_L - I_H}{(\gamma_1 + \gamma_2(1 + \bar{\alpha}))Emi_H}$
2	2 long-term targets: BAU with probability p, climate with probability 1-p	$\tau_1^{M2} = \frac{I_L - I_H}{(1-p)(\gamma_1 + \gamma_2(1 + \bar{\alpha}))Emi_H}$
3	Unknown policy implementation are period 2	$\tau_1^{M3} = \frac{I_L - I_H}{(\gamma_1 + \gamma_2(1 + \bar{\alpha}))Emi_H}$

Table 2: Resume of the break-even tax for the private producer in the toy model.

and the discount rate is visible in the break-even taxes. In both three cases, increasing the discount factors γ_1 and γ_2 raises the break-even tax: if decision-makers focus on the near terms, the long-term incentives provided by future carbon taxes become less effective.

A.3 Sectoral investment decision in IMACLIM-R

The 5 energy and transportation sectors of IMACLIM-R benefit from a bottom-up description of investment decisions. The following sectors (or sub-sectors) model investment decisions with a comparison of NPV: the electricity generation sector, the residential (building) sector, private cars sector. The extractive sectors (coal, gas and oil) are not ruled by NPV calculations in the current version of IMACLIM-R. They are thus myopic to forward-looking policy signals.

For the residential sector, only the construction and renovation decisions are determined by NPV calculations. Evolutions of energy use within a type of building are not sensitive to forward-looking policy signals. Discount rates in the electricity sector are technology and regionally-specific, and calibrated using the dataset from [7]. For car purchases, the discount factor is 23% [8]. A 10% uniform discount rate is used for construction and renovation decisions.

A.4 Backstop technology availability

Carbon Dioxide Removal (CDR) technologies play a pivotal role in deep decarbonization pathways. The delay in climate policy implementation can be offset by the deployment

Type of investment (sector) and coverage	Options	Criteria	Ambition uncertainty	Implementation uncertainty
Power plant (electricity): full market shares in t+10	25 electricity generation technologies [6]	LCOE (per load band)	X	X
Construction/renovation (buildings)	3 types of buildings: BAU, SLE, VLE	Life-cycle cost	X	X
Private cars (transportation): market shares of new sales	2 types of cars: ICE, EV	Life-cycle cost	X	X

Table 3: Sectoral investment decisions and climate policy uncertainty in IMACLIM-R. ICE: internal combustion engine. EV: electric vehicles (including hybrid cars). SLE: standard low energy, VLE: very low energy.

of negative emission technologies if carbon prices are sufficiently high [9]. However, their technical and economic potential as well as their rate of deployment are subject to deep uncertainties. The absolute potential for CDR from BECCS is set to 5 GtCO₂/yr, following similar exercises [10] and potential estimates [11]. Moreover, the deployment of BECCS is constrained by an S curve that characterizes the diffusion of new technologies, with technology availability starting in 2040.

References

1. Ameli, N. *et al.* Higher cost of finance exacerbates a climate investment trap in developing economies. *Nature Communications* **12**, 1–12 (2021).
2. Blyth, W. *et al.* Investment risks under uncertain climate change policy. *Energy Policy* **35**, 5766–5773 (2007).
3. De Cian, E. & Massimo, T. Mitigation Portfolio and Policy Instruments When Hedging Against Climate Policy and Technology Uncertainty. *Environmental Modeling and Assessment* **17**, 123–136 (2012).

4. Flora, M. & Tankov, P. Green investment and asset stranding under transition scenario uncertainty. *SSRN Electronic Journal*, 1–21 (2022).
5. Campiglio, E., Lamperti, F. & Terranova, R. Believe me when I say green! Heterogeneous expectations and climate policy uncertainty. **Forthcomin** (2022).
6. Briera, T. Capturing physical, technical and economic constraints on electricity generation: a description of the IMACLIM-R electricity module. *Les cahiers de la Chaire* (2023).
7. Calcaterra, M. *et al.* Reducing cost of capital to finance the energy transition in developing countries: a multi-model analysis. *Nature Energy* **Accepted** (2024).
8. Ramea, K., Bunch, D. S., Yang, C., Yeh, S. & Ogden, J. M. Integration of behavioral effects from vehicle choice models into long-term energy systems optimization models. *Energy Economics* **74**, 663–676 (2018).
9. Strefler, J. *et al.* Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters* **13** (2018).
10. NGFS. Climate Scenarios Technical Documentation (2023).
11. Fuss, S. *et al.* Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters* **13**, 2016–2050 (2018).