

**Impact of market research externalities on induced technological
change and timing of pollution abatement**

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Abstract

The present study aims at identifying the impact of misspecification of the business-as-usual with respect to market research externalities (crowding out, duplication and inter-firm spillovers) on the timing of abatement. We were motivated by the inconsistencies in the literature regarding the conditions defining the baseline scenario when attempting to model climate change policies. As mentioned by a few authors, the proper baseline scenario must reflect reality, and assume that all market research externalities are considered external by the representative agent in the business-as-usual. For our purpose, we adapted the ENTICE-inspired top-down general equilibrium model elaborated by Shiell & Lyssenko (2014) by altering the conditions defining the business-as-usual. For instance, we formulated a variety of scenarios that each differ in their treatment of research market externalities, in particular duplication, crowding out and inter-firm spillovers. By comparing the results of simulations for each scenario, we were then able to single out the individual impact of market research externalities on abatement levels and the level of induced technological change. Results show that internalizing market research externalities in the business-as-usual alters the relevance of induced technological change and accelerates abatement following the implementation of first-best policy. In other words, the internalization of research market externalities in the business-as-usual underestimates, in some scenarios, the role of induced technological change in emissions mitigations, a result that was presented by Goulder & Mathai (2000) that specified their baseline scenario assuming that all research market externalities were internalized.

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Introduction

In a world where climate change and its consequences are of growing importance, many have tackled the task to prescribe the best policy to tame the looming menace of global warming. In response, modeling practices and techniques applied by experts in multiple fields have come a long way in being able to estimate more accurately the optimal policies to enforce. Economists also took part in the challenge in developing complex economic models, developing theories, and estimating empirically parameters defining our society in the hopes of bringing a renewed outlook on the issue. They included costs, structural constraints present in the economy, behaviors of agents, and many more misunderstood economic processes in their framework to yield more realistic and adaptable results to our current actuality. This contribution by economists to the body of research surrounding climate change policies has further pushed the boundaries of the knowledge frontier further into the unknown as economists are developing new techniques, knowledge and skills in the field of climate change modeling.

The most important factor in a path towards a clean environment is without a doubt technological change. In this era of mass consumption, production, pursuit of profit, and rent exploitation, the simple reduction of production and consumption to reduce emissions is not sufficient. Amongst other possibilities, abatement efforts need to stem from the introduction of innovative processes in the industrial world, which can only be achieved through continuous technological progress.

Also, given our constrained economy with a limited amount of resources, there is an important tradeoff between resources allocated towards abatement, investments in future low-emitting technologies and other economic processes. The challenge of economists and other researchers alike is to find that a good balance between abatement, consumption, and investments, which can only be achieved through the means of complex and elaborated multi-disciplinary models. Over time, such models have successfully incorporated new concepts, techniques, theories, and structures to reflect the changing economic system. Given the importance of technological change in the abatement process and its role towards a greener economy, an endogenous representation of technological change was quickly a necessity in nearly any model that attempts to address the issue of climate change. Part of our study aims at highlighting the importance of technological change in climate change policies to produce results more adaptable to our economic reality.

In addition, another important aspect of our world that is often misunderstood and is of uttermost importance in the role of climate change policy is the role of externalities. Externalities, in simple terms, are costs that are not entirely incurred by the agent in question. When present, externalities imply that society as a whole suffers the consequences of the actions of perhaps a few agents polluting the atmosphere that don't incur the full cost of their actions. Therefore, externalities are a question of perception and calculation by the agents concerned. For instance, it is very likely that a representative agent can miscalculate or not properly perceive the cost of his actions, resulting in a deadweight loss from a social planner's standpoint. The presence of externalities and the miscalculation of agents across the globe have an important part to play in the global warming problem that we are witnessing nowadays.

However, externalities are not only limited to the environmental impacts, but they are also present in many other markets in the economy. Research markets, that generate innovation through the means of investments and resulting technological change, are no exception, where technological change is often below or above the socially optimal level due to the presence of externalities. For example, the misperception of an agent of its return on research spending may induce him to spend less or more than the optimal level due to the presence of externalities. In our case, our primary focus will be on the presence of the duplication externality, inter-firm spillovers and crowding out.

Regardless of the market where externalities are present, the social planner can restore the economy to the social optimum or reduce deadweight loss with the help of the proper implementation of targeted policies. In the context of climate change policies, such policies can manifest themselves in the form of a carbon tax to compensate for environmental policies or subsidies to energy-related investments such that research and development (R&D) expenditures reach a socially optimal level.

Therefore, when modeling the economy, it is of crucial importance to consider the presence of externalities to implement adequate policies geared towards the amelioration of our environmental quality. As we will further discuss later, an important issue that arises when economists develop climate change models is the omission of highly relevant sectors or the misconception of reality. Naturally, a model that fails to reflect the reality will yield inaccurate and inefficient policies, hence the importance to properly account for the presence of externalities. Given the highly intricate and complex factors defining our society, it is up

to the economist's judgment to decide which factors are relevant to include and the ones that can be omitted for simplicity and lack of relevance.

The present study has the objective to identify how initial assumptions regarding research market externalities affect the impact of induced technological change and the timing of abatement. Through various simulations with altered formulations of technological change, the results show that not properly accounting for crowding out, duplication or inter-firm spillovers lead to misleading policy implication with respect to abatement levels over time. For example, the omission of crowding out due to R&D spending in energy-related human capital in the framework lead to an under-estimation of optimal abatement levels and delay of abatement efforts towards the future. Also, the internalization of research market externalities, such as duplication and crowding out, by the representative agent lead to opposite results. Inversely, when the representative agent internalizes inter-firm spillovers abatement levels decrease. For instance, Goulder and Mathai's (2000) model includes full internalization of research market externalities by the representative agent. The authors then conclude that induced technological change leads to a delay in abatement. By adapting Shiell and Lyssenko's (2014) model to reflect various initial assumptions defining the business-as-usual with respect to research market externalities, we've noticed that Goulder and Mathai's (2000) specification of the representative agent's problem leads to misleading results regarding the impact of induced technological change and the timing of mitigation efforts. First, we will review the literature on the issue of timing of abatement and induced technological change in the context of climate change policy. We will then present both models elaborated by Goulder and Mathai (2000) and Shiell and Lyssenko (2014) and the modifications made to the former model to show the impact of market research externalities. The modifications to Shiell and Lyssenko's model will be presented in the form of scenarios that vary on the basis of initial assumptions concerning research market externalities. Finally, we will present the results of the simulations, highlighting the impact of research market externalities on the timing of abatement and role of induced technological change through a comparison between scenarios.

Literature Review

The literature on climate change policy has been incredibly dynamic in the past few decades. A debate that has sparked a lot of interest and passion from researchers from a wide array of disciplines is the question of the timing of abatement efforts. With

technological change being a meaningful answer to global warming, policies directed at technological change have also been the subject of many research efforts. In this comprehensive review of the literature, we will first highlight the progress of the literature on technological change, with a focus on the timing of abatement. Second, we will address the gaps in the literature regarding endogenous technological change, induced technological change, research market externalities, and specification of the business-as-usual scenario.

As the consequences of climate change and its exposure on the global political scene became more apparent, many researchers attempted to tackle the challenge of prescribing policies that will address the threat of global warming. Amongst them, the IPCC Working Group III (1995) presented a series of emissions time path options to reach safe and environmentally-friendly stabilization emissions levels using a complex simulation model. Their results suggested a decline of emissions well below the current levels and also entail drastic early abatement to reach any of the given concentration stabilization levels. Inversely, Wigley et al. (1996) questioned the plausibility of their results, criticizing the sharp departure from the business-as-usual and near-impossible dramatic increase in abatement in the near term to reach the concentration targets. Maintaining the assumptions used in the Working Group's study, Wigley et al. formulated a similar framework but included the additional constraints that emission levels initially track a business-as-usual level. Using the central baseline scenario presented by IPCC, the authors fitted a smooth curve to the stabilization levels and dates using the same approximate method and by specifying technological change statically (i.e. costs of technologies don't change given current levels of emissions). Results of the study show a slow, gradual departure from the baseline time path and increased mitigation efforts in the long-run in comparison to the results presented by IPCC.

The models presented above all bear a common similarity – a simplistic representation of technological change. The computational and technical limitations of endogenous technological change scared away early researchers including them in their climate change models. Now that endogenous technological change plays an important part in growth theory and has gained credibility amongst economist along with the importance of innovation in warding off climate change, it has nearly become a prerequisite to include it in our models (Grübler et al. 1999). The models where technological change is presented exogenously, as an extension of the present not only fail to duplicate accurately historical data, but they are also inefficient and erroneous for models with a longer time horizon. The

extrapolation of historical data to the future also faces a multitude of shortcomings when attempting to model radical technological changes or just yield results that are inconsistent with reality.

For example, Grübler & Messner (1998) demonstrated the importance of endogenous technological change by the means of their coupled carbon-cycle and energy systems engineering model that aimed at determining the optimal time path of emissions given an atmospheric CO₂ concentration target of 550 parts per million by 2100. They also developed a model with an exogenous technological change that imitates the trends presented by Wigley et al. (1996). The comparison between the two models shows that endogenizing technological change leads to a lower initial level of emissions. They also show that delay in abatement is primarily due to the exogenous representation of technological change and that by endogenizing technological change, models yield results that are in favor of an early departure from the business-as-usual. However, it is important to note that this departure is not necessarily aggressive and is primarily directed at enhanced R&D investments in technological change. As noted by the authors, incorporating the assumptions that technological change is dependent on the condition within an economic system implies that new technologies don't "fall from heaven": they are the product of research efforts that go beyond the simple extension of the past.

The progress in computational general equilibrium, endogenous technological growth theory and knowledge in adapting complex integrated assessment models has allowed the emergence of climate change models with endogenous technological change. These models assume that technological change is cultivable, such that without investments in the present, innovation will not occur in the future. Many authors have stressed the importance of this creative process, and through time models have reached new lengths and are now more complex than ever before and yield results that are now much more realistic. In this section, we will review a few studies that have contributed to the literature of climate change models with endogenous technological change.

Endogenous technological change model can be divided into two categories. The first is bottom-up models which apply learning curves to technological change in energy sectors. They assume that cost reductions for renewable energy technologies are much greater than their high-emitting counterparts. The results of the simulations favor an accelerated abatement schedule in the short-term to stimulate the cost-reductions. These micro-scale models are useful for the analysis of smaller markets but fail to capture the

important macro-scale effect of the global economic system. Inversely, top-down models are usually general equilibrium models with simpler formulations of technological change and apply to larger scale scenarios. For our purpose, we will most importantly focus on top-down models.

In most top-down models, endogenous technological change manifests itself in two formulations. The first, learning-by-doing, follows the principle that costs of a given technology are a decreasing function of usage of that technology. More formally, the development of new technology comes hand in hand with cost reductions, which entails direct economies-of-scale effects. The other category is knowledge investment, which includes explicit costly investment in research and development (R&D) and other related activities that aim at improving current technologies or introducing new ones. The primary distinction between the two forms of endogenous technological change is that while learning-by-doing entails that usage improves the knowledge stock, knowledge investment requires costly investment to attain the same goal. The use of one formulation over another can dramatically affect the results in regards to the timing of abatement (Grübler et al. 1999).

As endogenous technological change became more familiar in climate change studies, so did the notion of induced technological change. The concept, first introduced by Hicks in 1932, is defined as “the change in relative prices of the factors of production is itself a spur to the invention of a particular kind directed to economizing the use of a factor that has become relatively expensive”(Hicks 1932). In the context of climate change policy, induced technological change is the change in research efforts because of climate change policies (i.e. tax on fuel). Grubb et al. (2002) define it as a “component of technological change that’s influenced by energy market conditions and expectations; [...] , induced technical change is technological development induced by circumstances on the demand side of the economy- principally, prices and markets, and perceptions of these, in response to varied factors including government policies.” Sue Wing (2003) defines induced technical change as “the change in the set of substitution possibilities that is brought about by the inventive response to changes in input prices”. Popp et al. (2010) define the concept as profit-driven investment that responds to changes in relative price, such that the direction of innovation points to the sector that has the increased relative price. In the context of climate change policies, an environmental policy implicitly or directly alters the price of inputs, which in turn affects the direction of technological change.

As pointed out by Grubb et al. (1995), if induced technological change is present, then abatement efforts also have an impact on the direction and significance of the technological change, economies of scale and learning that in turn have an impact on abatement costs. Inversely, autonomous technological change ignores this complex relationship between policies, technological change, and abatement costs. Therefore, abatement costs change irrespective of policies, which is inconsistent with reality. Furthermore, their aggregated top-down model aims at identifying how inertia and adaptability have an impact on the attractiveness of optimal abatement policies. The results of their simulations highlighted the importance of abatement efforts and adaptability of technological change. In contrast to previous studies, abatement does not only crowd out possibilities to investments, but it also plays an important role in stimulating technological advancement in low-emitting technologies. As a result, a delay in abatement would lead to decreased pressure on research efforts, slower technological progress, and limit reductions in abatement costs.

Goulder & Schneider (1999) centered their study on how induced technological change affects the attractiveness of climate change policies. The authors point out the importance of induced technological change for both the costs and benefits of emissions mitigation. The top-down formulated modeled induced technological change as a parameter that is equal to zero in the business-as-usual and equal to one when induced technological change is present. This formulation implies that in the baseline scenario, technological change is static. Results of their numerical model support that the presence of induced technological change makes carbon policies more attractive. Also, the authors show that the presence of a carbon tax tends to stimulate R&D expenditure in energy-related sectors but at the expense of other non-energy-related sectors. Finally, the results show that the presence of induced technological change leads to an increase in the net benefit of a carbon tax even though the gross costs of the carbon tax are raised as well.

On the other hand, Goulder & Mathai (2000) elaborated two macro-scale models of endogenous technological change, each with a different specification of technological change and evaluated under two policy criteria. The authors chose the R&D and learning-by-doing knowledge accumulation formulations of endogenous technological change. Rasmussen (2001) also followed a similar methodology for their paper but using only a learning-by-doing representation of knowledge accumulation in their top-down multi-sectoral model. The main structural difference between the two studies is that technological

change is embodied in different vintages of capital in Rasmussen (2001) whereas it is disembodied under Goulder & Mathai (2000). Results from both studies suggest that the inclusion of induced technological change leads to a delay in abatement, which opposes the widespread belief that when technological change is an increasing function of abatement, the optimal abatement time path will entail larger near-term abatement levels (Grubb 1997; Grubler et al. 1999). This surprising result is due to a multitude of intertwined relationships between abatement costs and technological change, but most particularly the fact that as technological change progresses over time, so does the reduction in abatement costs and entails slightly delayed mitigation efforts when induced technological change is present.

Nordhaus (2002) was a major player in the arena of induced technological change and climate change models with his R&DICE model, based on the previous DICE model, where carbon intensity modifications are due to induced innovation instead of substitution. He models induced technological change with a fixed-proportion production function to mimic the costly substitution of inputs. He notes two types of technological change, economy-wide and carbon-energy saving; the former is exogenous to focus on the latter. Induced technological change manifests itself when there is a rise in the price of carbon energy, which will induce firms to invest in technological change in sectors whose products rely less on carbon-based inputs than existing products. He then studies the impact of induced technological change by comparing the results to the business-as-usual scenario that is computed such that carbon intensity is endogenous. The results demonstrate that induced technological change does not lead to a lesser initial abatement level but possibly may have a greater positive impact on cumulative abatement, in the long run, highlighting the low relevance of induced technological change in the near term.

Popp (2004) builds his ENTICE model based on Nordhaus' DICE model. By analyzing empirical data, Popp comments on the assumptions of previous authors such as Buonanno et al. (2003) or Nordhaus (2002) and suggests that an increase in energy R&D will lead to a decrease in non-energy R&D due to a partial crowding-out effect. Those preliminary findings motivate Popp to employ a production function that allows for both endogenous technological change and factor substitution. His policy simulations are based on the imposition of a carbon policy where he compares exogenous and endogenous technological change under the implementation of climate change policy to isolate the impact of induced technological change. To simulate exogenous technological change, Popp restricts R&D spending to the base-case level found in the no policy simulation. He then proceeds with the

calculation of the ratio of change in abatement when adding endogenous technological change to highlight the value of induced technological change. The main findings of the study highlight the importance of including induced technological change as a way to reduce compliance costs of climate change policies and the importance of including potential innovation market failures to present more realistic results. Another significant result of the study is the consideration of partial crowding out effects of new energy research on other sectors, which reduces the potential welfare gains from induced innovation. On the other hand, as noted by Gerlagh (2008), the results of Popp's analysis are for the limited impact of induced technological change regarding emissions abatement in relation to factor substitution of a given technology, a conclusion also shared by Goulder & Schneider (1999) and Nordhaus (2002).

Gerlagh (2008) also aimed at estimating the implications of induced technological change by elaborating an endogenous growth model with three sectors and differentiated technological change formulations for each sector. The model is solved under business-as-usual, which assumes the absence of tax rates on emissions, and policy scenarios defined by the imposition of tax rates on emissions by the social planner, whose goal is the stabilization of CO₂ concentration levels at 450 ppm. Knowledge accumulation is research-based, and a leakage externality is included such that the marginal social benefit of research differs from the private social benefit of research. The results of Gerlagh's simulations support an advancement of abatement efforts, which is primarily motivated by the presence of induced technological change. As demonstrated in his paper, the increase in near-term abatement is due to the increase in research efforts due to the carbon tax and the partial crowding out effect. By comparing two scenarios, the author notices that only when full crowding out of research efforts is present that the introduction of a carbon tax will lead to a delay in abatement, a result consistent with Grübler & Messner (1998) and Goulder & Mathai (2000). Also, Gerlagh's findings first highlight the importance of induced technological change in decreasing costs of abatement and increasing the elasticity of emissions in terms of the carbon tax and cost reduction of abatement. Second they also show that induced technological change will lead to an increase in the importance of carbon-energy savings technologies in the long run to reach the CO₂ stabilization targets.

Furthermore, Hart (2008) contributes to the literature on induced technological change by assessing the impact of induced technological change on the optimal time path of a carbon tax in comparison to the Pigovian level when research market externalities are

present. The study makes significant contributions to the literature by correcting for the misspecification of research market externalities, analytical results and investment in production technologies as seen in previous studies also addressing the impact of induced technological change (Popp 2004; Gerlagh 2008; Goulder & Mathai 2000). Hart employed an AK-type model with marginal cost pricing in order to yield analytical and numerical results on the role of induced technological change on abatement and optimal carbon tax levels. He shapes technological change using two formulations: investment in emissions-savings and emissions-efficient technologies and where the difference between private and shadow price of an investment is due to research market externalities. The analysis yields an important result that due to research market imperfection, the optimal tax rate is set to a level greater than the Pigovian level and that the level will gradually gravitate towards the Pigovian level as the economy approaches the balanced growth path. In contrast to previous studies (Goulder & Schneider 1999; Popp 2004; Nordhaus 2002; Goulder & Mathai 2000), the dynamic between tax rate, research market externalities, and technological change will lead to an excessive amount of abatement in the short term (i.e. abatement in excess of the Pigovian level). Besides, an additional important conclusion of the paper states that the presence of inter-firm spillovers between firms specializing in emissions-saving technologies is not a good reason to justify an increase in carbon taxes above the shadow price of the additional carbon stock due to the fact that all sectors are equally undersupplied such that a change in the relative input prices is not necessary. Finally, setting the tax rate above its Pigovian level leads to excessive abatement efforts in addition to inducing investment, leading to a second-best solution. Therefore, a first-best policy option will require the use of other policy instruments, such as tailored research subsidies that prove to be difficult to assess due to the lack of technical knowledge and administrative complexity, a perspective also shared by Gerlagh et al. (2009).

Finally, Shiell & Lyssenko's (2014) study was motivated by the gaps in the literature of top-down models of induced technological change. They corrected for the lack of research-market externalities and improper BAU modeling with their single knowledge stock general equilibrium model based mainly on Popp (2004). But unlike previous authors, Shiell and Lyssenko's results demonstrate a greater optimism towards the contribution of induced technological change at increasing welfare in light of the first and second-best policies, in contrast to previous authors that are slightly more pessimistic towards the impact of induced technological change (Popp 2004; Nordhaus 2002). The authors pay particular

attention to the elasticity of substitution between energy services and other factors of production, the opportunity cost of R&D and its implications for crowding out, the initial level of R&D expenditures, the extent of duplication externality, the direction of inter-temporal research externalities, and the difference between the first-best and second-best policy. The results of their simulations don't focus primarily on the timing of abatement but does show that the contribution of induced technological change is highly dependent on the elasticity of substitution between inputs to production, opportunity cost, and assumptions regarding research market externalities.

Amongst the studies mentioned above addressing the role of induced technological change in the context of climate change policies, a few drawbacks have occurred in the literature that are worth mentioning. The first is the inclusion of research market externalities and the second is the specification of the business-as-usual.

First, as noted by Hart (2008) is the proper inclusion of market research externalities. The lack of inter-firm spillovers, inter-temporal spillovers, crowding out, and duplication externality lead to miscalculated policies. For instance, internalizing externalities in the business-as-usual leads to a tax rate different from its Pigovian level. Also, Gillingham et al. (2008) further comment that the omission of externalities in the model leads to a lack of appropriability problem in the model as agents assume that they capture all resulting benefits due to their research efforts. Greaker & Pade (2009) highlight the importance of the inclusion of innovation market imperfections by relaxing the assumption of internalizing externalities, which show that contrary to Goulder & Mathai (2000), it will lead to a higher carbon tax today when change is specified by R&D accumulation.

Another shortcoming in the literature on induced technological change is the misspecification of the business-as-usual. For example, in Goulder & Mathai (2000), the business-as-usual is modeled with autonomous technological change such that the policy scenario will lead to a more optimistic time path of falling abatement costs (Kverndokk & Rosendahl 2007; Gerlagh et al. 2009). Besides, when attempting to measure the impact of induced technological change, the misspecification of the business-as-usual scenario leads to significant distortions in the results (Shiell & Lyssenko 2014; Shiell & Lyssenko 2008; Rezai 2011). Shiell and Lyssenko (2014) suggested in their study that to identify the impacts of induced technological change, all research-market imperfections should be external to the agent in the baseline scenario (i.e. all forms of spillovers, duplication externality,

environmental externality) and endogenous technological change should not be omitted. Hart (2008), for example, models his business-as-usual scenario by setting his emission tax to zero and leaving all distortions internalized, an approach referred to by Rezai (2011) as constrained optimal baseline. As for Gerlagh (2008), he treats some distortions as internalized and some as externalized under business-as-usual. The lack of consistency among studies and their treatment of the baseline scenarios not only leads to questionable results but also makes the comparison between them nearly impossible.

The present study will attempt to highlight those drawbacks, in particular, the misspecification of the business-as-usual scenario and its assumptions regarding research market externalities. As noted, the internalization of externalities by the representative agent will effectively overestimate a part of the contribution of induced technological change on the results.

Methodology

The objective of our analysis is to identify the importance of initial assumptions in regards to research market externalities when trying to assess the impact of induced technological change on the timing of abatement. Our concern is that not properly accounting for market research externalities in the form of either duplication, crowding out, inter-temporal spillovers or inter-firm leakages will lead to misleading results when trying to assess how the introduction of induced technological change in our analysis impacts the timing of abatement. For that purpose, we will present a model by Shiell & Lyssenko (2014) which will be used as our reference point. Then, we will adapt the model in order to reflect different initial assumptions regarding research market externalities, as presented by a variety of scenarios, presented in table 1. The comparison of various scenarios will allow us to identify the importance of research market externalities in the framework and will be presented in the following section.

In their paper, Shiell & Lyssenko (2014) present a single-knowledge-stock model of R&D growth and climate change. Their model includes Nordhaus & Boyer's (2000) global climate system that accounts for externalities due to greenhouse gas emissions. The model is inspired mainly by Popp's (2004) ENTICE model, which is based on Nordhaus's (1994) DICE (Dynamic Integrated Climate-Economy) model, a computer-based model which attempts to integrate carbon cycle, climate science and economics. This global climate system is elaborated such that emissions accumulate in the atmosphere inducing a lag to

higher temperatures. Our model consists of 15 periods of 10 years. It includes structural equations for production, physical capital accumulation, supply of energy services, energy-related human capital, damage and price of fuel. The representative agent's preferences are represented by an instantaneous utility function taking the form of a logarithmic function dependent on per capita consumption and labor. Global welfare is measured by a population-weighted discounted utilitarian function, which is maximized in both the business-as-usual (no policy) and the social planner's problem. Finally, the model is closed by the inclusion of a budget constraint such that the net output is equal to the sum of consumption, investment in physical capital, R&D expenditures and a one-parameter adjustment cost function¹.

The choice of structural equations when solving the model differ depending on whether we are solving the social planner's or the representative agent's problem. In the first case, the social planner maximizes social welfare subject to the structural equations given that all externalities are internalized. In the later case, the representative agent maximizes his utility given the structural equations given that no externalities are internalized in the business-as-usual. As a result, the structural equations defining the return on energy-related human capital investment and the budget constraints differ.

First, the representative agent's perceived return (business-as-usual) and the social return (planner's problem), where h_t represents the change in energy-related human capital, which is assumed to be non-negative, H_t is the energy-related human capital, R_t is the energy-related research spending and where Δ represents the period duration of 10 years. Research market externalities are defined as follows: b is the parameter that stands for the duplication externality in research or "stepping on toes" as described in the prior section, ϕ stands for inter-temporal spillovers and l is the parameter for inter-firm leakages, such that the firm investing in R&D can only appropriate $(1 - l)$ of the benefits. The representative agent's perceived return to R&D is given by

$$h_t = (1 - l)v_t R_t \tag{1}$$

¹ More extensive details of the model are provided in Sheill and Lyssenko (2014)

where $v_t = \Delta a R_t^{b-1} H_t^\varphi$ is the average product of research expenditure, which is considered exogenous by the representative agent. On the other hand, the social return to energy-related human capital investment is

$$h_t = H_{t+1} - H_t = \Delta a R_t^b H_t^\varphi \quad (1')$$

We assume that the duplication externality, inter-temporal spillovers, and inter-firm spillovers are external to an individual firm's decision-making. The intuition stems from the assumption that an individual firm expects to receive the benefits of investment in R&D regardless of whether or not the product of their research is duplicated. Similarly, inter-firm spillovers (or leakages) is based on the assumption that agents undertaking R&D expenditures can only appropriate a portion of the returns. In addition, the motivation for assuming that inter-temporal spillovers are not internalized is based on the supposition that returns of current investment decisions on future research will only be appropriated by different firms in the future. Representative firms, therefore, expect a constant return to investment, as embodied by the average product of research efforts in equation (1).

In contrast, the social planner internalizes externalities by perceiving decreasing returns to investments, justified by the replacement of the average product of research in the representative agent's problem by the marginal return to research investment as represented by equation (1'). Following Shiell and Lyssenko's model, we also make an adjustment for unaccounted opportunity cost following the crowding out of R&D spending in other non-energy and un-modeled research sectors. Following the economic principle that firms will invest in knowledge capital until the perceived returns are equal to the perceived returns in the physical capital sector, it follows that the presence of externalities in the form of unaccounted opportunity cost will, therefore, lead to a non-optimal level of investment. The social planner's problem accounts for the possibility of crowding out of R&D expenditures in un-modeled sectors by R&D spending in energy-related sectors. Accounting for such effects leads to an adjusted budget constraint:

$$Y_t = C_t + I_t + (1 - \text{crowdout})R_t + \text{crowdout} \cdot R_t \cdot \psi + \left(\frac{\eta}{2}\right) \frac{I_t^2}{K_t} \quad (2)$$

where Y_t is production, C_t is consumption, I_t is investment in physical capital, $\left(\frac{\eta}{2}\right) \frac{I_t^2}{K_t}$ is the one-parameter adjustment cost factor of physical capital, $(1 - \text{crowdout})R_t$ stands for energy R&D expenditure that competes with C_t and I_t , $\text{crowdout} \cdot R_t \cdot \psi$ represents energy R&D spending which compete with R&D expenditure in un-modeled energy sectors and ψ stands for the social marginal product of R_t in terms of the investment numéraire K_t . As

opposed to the social planner, the representative agent doesn't account for crowding out nor the social marginal product of R_t , such that the budget constraint is as follows:

$$Y_t = C_t + I_t + R_t + \left(\frac{\eta}{2}\right) \frac{I_t^2}{K_t} \quad (2')$$

Our model is then solved in both the business-as-usual (BAU) and first-best policy options. In the case of the business-as-usual, the optimizing problem consists of a representative agent to maximize the welfare function with respect to flow and stock variables subject to the net production function, accumulation of physical capital, energy service supply, the adjusted energy-related human capital research function (the representative agent's perceived research function (1)), damage function, cost of fuel, and closed with the unadjusted budget constraint (2').

On the other hand, the first-best scenario consists of a social planner maximizing welfare with respect to flow and stock variables and subject to production constraints, energy-related human and physical capital accumulation equation, net output, damage function, global climate system and the adjusted budget constraint (2).

It's of importance to note the difference in solving the business-as-usual in contrast to the first-best scenario. What distinguishes the two scenarios is entirely conditional on perception. For example, the representative agent, unlike the social planner, perceives damages from CO₂ accumulation as external to their decision making process. The two scenarios also differ on the perceived returns to R&D investments. The representative agent perceives a constant return to investment employing the average product of research effort in the adjusted research function (1'), while the social planner's decision-making process applies the unadjusted research function (1). The closing budget constraint for each scenario is also different where the social planner adjusts the budget constraint of the representative agent by accounting for crowdout and the social marginal product of R&D expenditure in terms of the investment numéraire. To summarize, although both the business-as-usual representative agent and the first-best social planner follow the same structural set of equations, some aspects of the reality are omitted in the in the business-as-usual scenario.

We will limit ourselves to solving only the business-as-usual and the first-best scenario, which consists of a carbon tax and a research subsidy set by the social planner, in order to assess the optimal abatement levels. In each case, the solution is found by solving the appropriate combination of structural equations and first-order conditions (analogous to behavioral equations) for both the representative agent in the business-as-usual and the

social planner in the first best. In each scenario, we compute the business-as-usual and the first-best policy scenario using $b=0.7$, representing low duplication externality. The choice of focusing exclusively on the case of low duplication is motivated by the little relevance of results when duplication is high as shown by Shiell and Lyssenko (2014). For the sake of simplicity, we set aside the issue of intertemporal research spillovers and focus exclusively on the case of $\phi=0$. Table 1 displays each scenario and how they each differ in terms of initial assumptions in regards to research market externalities (i.e. inter-firm research spillovers and duplication) and crowding out. We then will calculate the change in emissions from implementing first-best policy and estimate the share of change in emissions attributable to induced technological change using the following metric inspired by Shiell and Lyssenko (2014):

$$\Delta^2 F = \Delta(\Delta F) = \left[\frac{(F_{end,op} - F_{BAU})}{(F_{exo,op} - F_{BAU})} - 1 \right] \times 100 \quad (3)$$

where F_{BAU} represents emissions levels in the business-as-usual, $F_{end,op}$ stands for emissions levels under first-best policy scenario given endogenous R&D and $F_{exo,op}$ represents emissions levels under first-best policy scenario given R&D levels set exogenously to their level depicted in the BAU. Such that the numerator and denominator of the fraction in equation (3) shows abatement levels following the implementation of first-best policy given either endogenous or exogenous R&D levels, respectively.

For our purpose, we'll elaborate ten distinct scenarios that differ in terms of initial assumptions in regards to research market externalities. Each scenario differs in terms of assumptions regarding research market externalities and how they are specified in both the business-as-usual scenario and the first-best scenario. The first scenario consists of duplicating the model presented in Shiell and Lyssenko (2014). Inversely, every subsequent scenario present in Table 1 considers slightly altered assumptions concerning the internalization of research market externalities in the business-as-usual. As a result, the choice of structural equations will depend on these assumptions and the model will be modified accordingly.

Table 1: Assumptions for scenarios – business-as-usual

Externality	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5

Table 1
(cont.):
Assumptions for
scenarios –
business-as-usual

Duplication (b)	N	Y	Y	Y	Y
Spillovers (l)	N	Y	Y	N	N
Crowdouts=0.5	N	N	Y	N	Y
Note: N= effect is not internalized in the BAU, Y= effect is internalized in the BAU, N/A = not applicable					

Externality	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
Duplication (b)	N	N	N	N	Y
Spillovers (l)	Y	N	Y	N	Y
Crowdouts=0.5	Y	Y	N	N/A	N/A
Note: N= effect is not internalized in the BAU, Y= effect is internalized in the BAU, N/A = not applicable					

Scenario 1

This scenario acts as our reference scenario and is identical to the simulations presented in Shiell and Lyssenko (2014). In the business-as-usual, the representative agent is not internalizing research market externalities (i.e. inter-firm spillovers and duplication) and does not account for crowding out. Therefore, the agent maximizes welfare with respect to the linear research function (1) and the unadjusted budget constraint (2'), such that the agent's private return to R&D investment is defined by the average product of research expenditure. In the first-best, the social planner is maximizing welfare, choosing an optimal level of the carbon tax and the research subsidy, subject to the research function (1') and the adjusted budget constraint (2), such that research market externalities are internalized, and crowding out is accounted for in the maximization problem.

Scenario 2

The second scenario assumes that the representative agent internalizes the duplication externality and inter-firm spillovers in the business-as-usual, while crowding out is considered external. Therefore, the representative agent's optimization problem is partly defined by the marginal research function (1') and the unadjusted budget constraint (2').

Scenario 3

The third scenario is almost identical to Scenario 2, with the exception that the representative agent now internalizes crowding out and is maximizing welfare subject to the adjusted budget constraint (2). In this case, both the representative agent and the social planner again internalizes inter-firm spillovers, duplication externality and crowding out.

Scenario 4

The fourth scenario is derived following Scenario 2, with the exception that the representative agent in the business-as-usual internalizes neither inter-firm spillovers nor is crowding out. Therefore, the representative agent internalizes only duplication externality. Again, we'll maintain the assumptions concerning the social planner presented in scenario 2.

Scenario 5

This scenario is nearly identical to scenario 4, apart from the assumption that we now assume that the representative agent in the business-as-usual now internalizes the possibility of crowding out, while maintaining that the duplication externality is internalized and inter-firm spillovers are not. The assumptions in regards to the social planner are identical to the ones presented in scenario 2.

Scenario 6

The sixth scenario follows from scenario 3 described above, with the only exception that the representative agent does not internalize the duplication externality in the business-as-usual. In this case, crowding out and inter-firm spillovers are considered internal to the representative agent and again the social planner internalizes all externalities in the first-best scenario.

Scenario 7

This scenario considers the possibility that the representative agent only internalizes crowding out in the business-as-usual. Again, the social planner is internalizing all externalities in the first-best scenario, maximizing welfare with respect to the adjusted budget constraint (2) and research function (1'). Now internalizing crowding out, the

representative agent considers duplication externalities and inter-firm spillovers external in the business-as-usual.

Scenario 8

The scenario assumes that the representative agent only internalizes leakages in the business-as-usual, while considering crowdouts and duplication as external. Therefore, we'll notice that the research function now incorporates a linear component but omits the crowding out and inter-firm spillovers parameters as per our assumptions.

Scenario 9

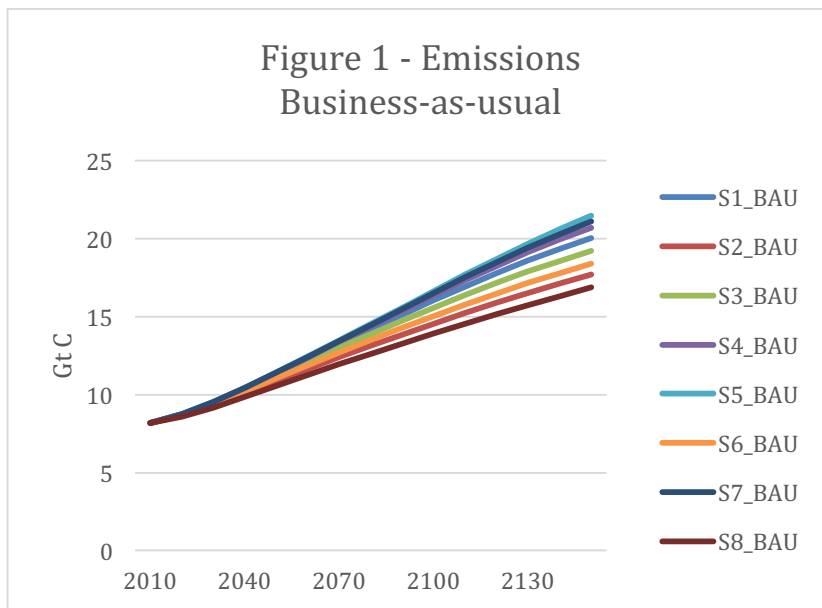
This scenario is analogous to scenario 1 with the only exception that we assume that crowdouts are completely omitted from the framework. Thus, none of the market research externalities are internalized in the business-as-usual and crowding out is set to zero throughout the analysis. This implies that both the representative agent and the social planner are subject to the unadjusted budget constraint (2')

Scenario 10

The last scenario considers the extreme case, where both inter-firm spillovers and duplication externalities are internalized in the business-as-usual. In addition, in this scenario we assume that crowdouts are entirely absent from the framework in order to reflect the assumptions found in studies like Goulder and Mathai (2000). In this case, the representative agent is maximizing welfare subject to the unadjusted research function as specified in equation (1') and the unadjusted budget constraint (2').

Results

The results of our simulations will be presented in two parts. First, we will present the findings of the simulations for the first eight scenarios and the impact of research market externalities on the time path of emissions, abatement and induced technological change. Second, we will focus primarily on scenarios 9 and 10 to highlight the impact of the



omission of crowding out from the framework on emissions level both in the business-as-usual and first-best scenario as well as abatement levels and induced technological change.

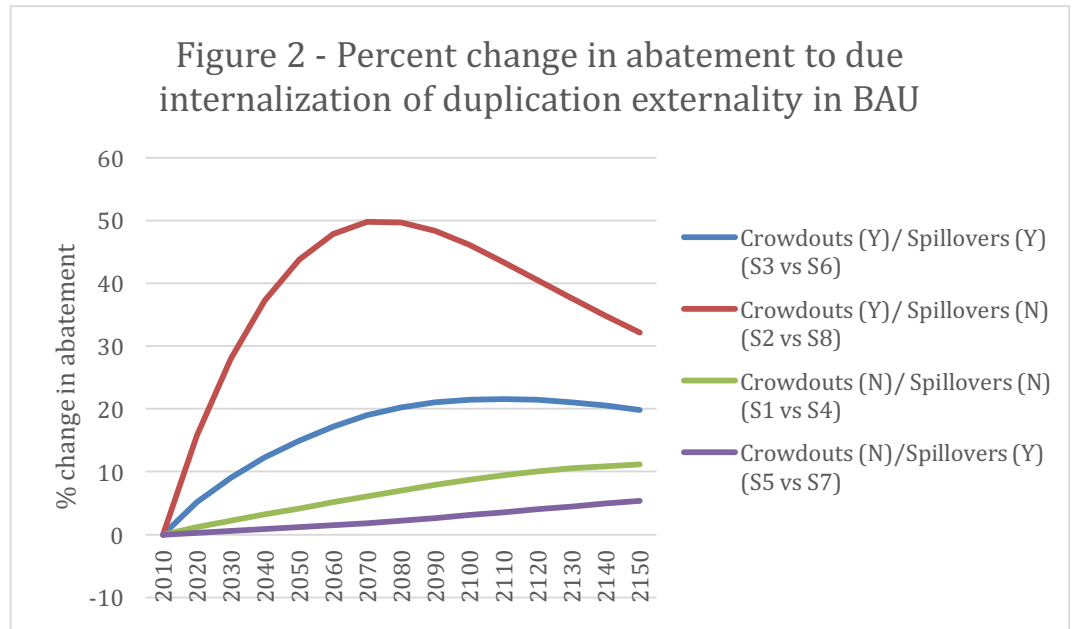
As a starting point, Figure 1 demonstrates the time path of emissions in the BAU for all eight scenarios that consider the presence of crowding out.

To identify the individual impact of internalizing research

externalities on the level and timing of abatement, we've proceeded with a comparison of each pair of scenarios that only differ in terms of the internalization of a given research externality. Figure 2 illustrates the impact on abatement of internalizing the duplication externality in the business-as-usual for each pair of scenarios that only differ in terms of internalization of the externality. The exercise was then repeated for crowding out and inter-firm spillovers and are shown in Figure 3 and 4, respectively. Results show that the percent change in abatement level following the internalization of any externality is significant and depends on initial assumptions concerning the other externalities. In addition, in each figure, the impact due to internalization of an externality leads either to a constant and gradual increase in abatement or a sharp increase in the near-term before reaching a peak and declining towards the end of the horizon.

As seen in Figure 2, the internalization of duplication in BAU leads to an increase in measured abatement in the optimal scenario, all else being equal. The graph shows that the increase in abatement is more important when crowding out is internalized and inter-firm spillovers are externalized by the representative agent, such that the internalization of duplication lead to a sharp increase in abatement level, up to 50% in the medium term

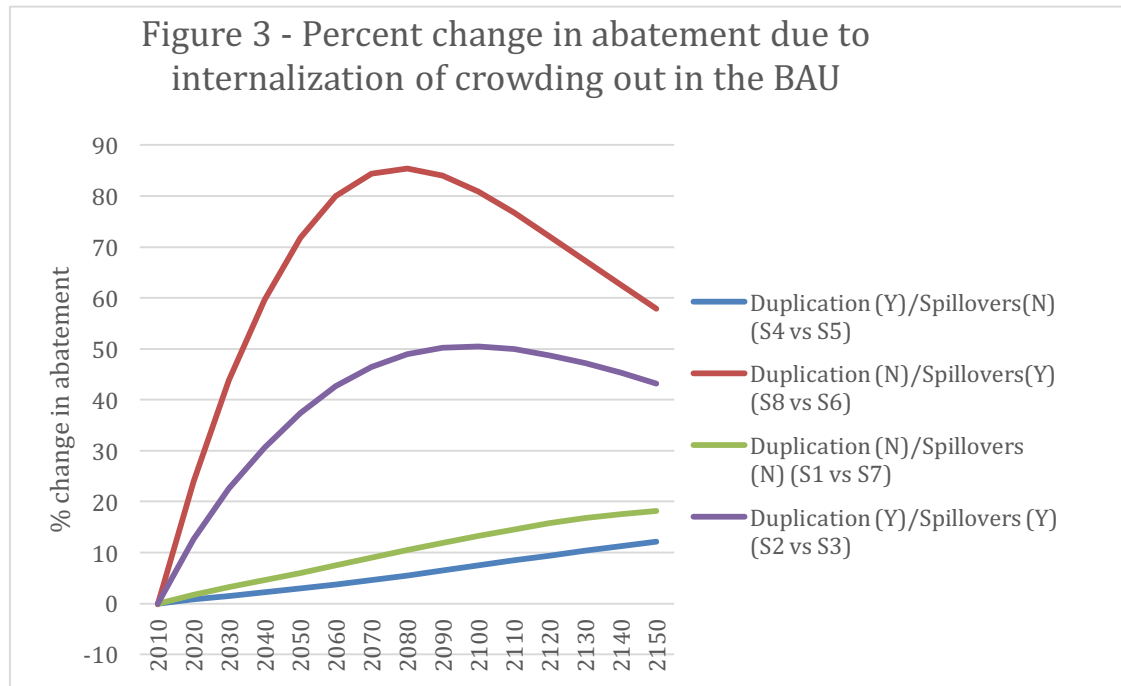
before stabilizing at approximately 30% towards the end of the horizon. On the other hand, the increase in abatement due to the internalization of the duplication externality is attenuated when



inter-firm spillovers are internalized and crowding out is externalized, as seen when comparing scenario 7 and scenario 5, such that abatement levels are increased by a maximum of 6%. In addition, we also notice that when crowdouts are not internalized in the BAU, the internalization of duplication induces a slow, constant and gradual increase in abatement levels. Inversely, when crowdouts are internalized in the BAU, the internalization of duplication leads to a sharper increase in abatement levels, reaching a peak before declining.

The results of the same exercise applied to the crowding out externality is shown in Figure 3. Results show that when the duplication externality is considered external and spillovers are internalized by the representative agent, the internalization of crowding out leads to an increase in abatement levels up to 85% around 2080 before decreasing to around 68% at the end of our horizon. Also, when the duplication externality is internalized

and spillovers are considered external, the increase of abatement levels due to internalization of crowding out is less significant, increasing gradually up to approximately 13% at the end of



the horizon. In addition, we notice that only when spillovers are internalized in the BAU, the internalization of crowding out lead to an increase in abatement that reaches a peak before declining. On the other hand, the inverse shows that the internalization of duplication lead to a constant, non-declining increase in abatement throughout the horizon given. Therefore, the gains in abatement following the internalization of crowding out are amplified when inter-firm spillovers are internalized by the representative agent, and the opposite applies when the duplication externality is internalized by the representative agent. In this case, the fact that the representative agent considers the duplication externality in his decision-making process absorbs a part of the increase in abatement following the internalization of the crowding out externality.

Finally, Figure 4 illustrates the percent change in abatement following the internalization of inter-firm spillovers in the BAU. In this case, the internalization of the externality leads to a decrease in abatement levels, regardless of initial assumptions concerning other externalities in the BAU. Although, we notice that the negative impact on abatement levels due to internalization of spillovers is most important when crowding out and duplication externalities are externalized by the representative agent. In contrast, when both duplication and interfirm spillovers are internalized, the negative impact on mitigation of emissions due to internalization of inter-firm spillovers is attenuated. With respect to the timing of abatement, the internalization of inter-firm spillovers leads to a consistent decrease in abatement levels, which is most significant when the other two externalities are

considered external, reaching up to 60% decrease at approximately 2090 before stabilizing at approximately 52% towards the end of the time span studied.

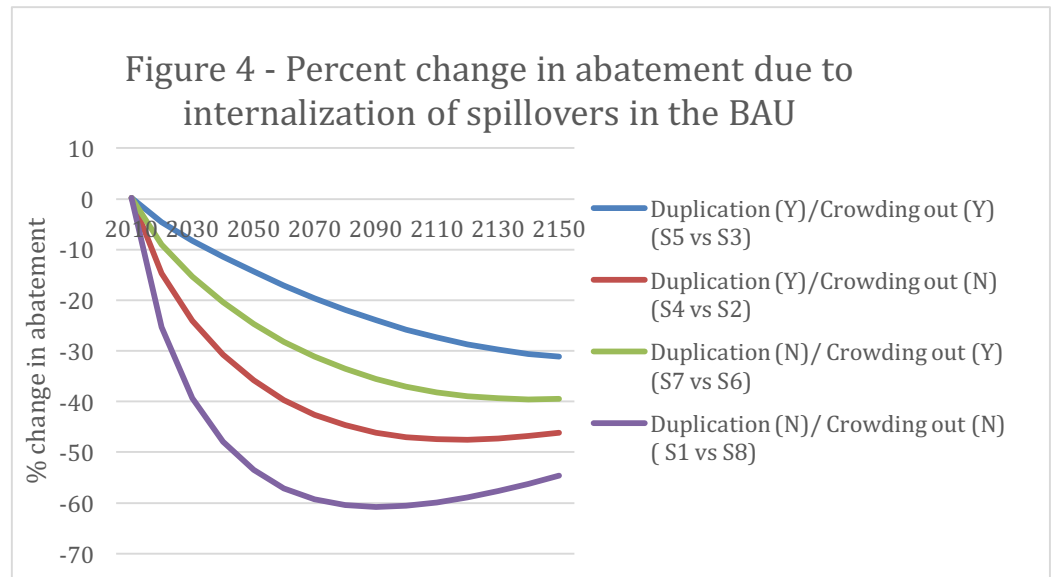
In order to understand the relationships that link emissions level and internalization of a given research externality, we highlight the role of each externality successively in the representative agent’s decision-making process and attempt to explain intuitively why the assumptions with respect to a given research market externality have such an impact on emissions levels, abatement and induced technological change. A representative agent that doesn’t internalize duplication expects to receive a constant return to R&D investment regardless of whether or not its efforts have been duplicated, leading to a level of R&D investments that’s higher than it would be if duplication externalities were internalized. On the other hand, when internalizing the duplication externality the agent reduces its research efforts and R&D expenditures, and emissions

increase as a result in the business-as-usual, as seen in Figure 1.

This clear correlation between the role of the duplication externality and emissions level is also supported by the results in Figure 5, which depicts the time path of R&D

expenditures by the representative agent².

On the other hand, our results support a similar relationship between the internalization of crowding and emissions levels. When crowding out is considered external, the representative agent’s marginal cost of new research spending does not reflect the social opportunity cost and the level of R&D spending is above what it would be if



² One should note that scenario 1 and scenario 9 have near identical levels of R&D expenditures due to the specification of crowding out in the business-as-usual scenario, such that the time path in Figure 5. The same is applicable to scenario 2 and scenario 10.

crowding out were internalized. In contrast, when the representative agent internalizes crowding out which is shown by adjusting his budget constraint, he now considers the true social opportunity cost of energy-related research in his decision-making process. As a result, internalization of crowding out brings a decreased level of R&D in BAU. Given the inverse relationship between energy-related R&D expenditures and emissions levels, the internalization of crowding out thus leads to an increased level of emissions in the business-as-usual, as depicted in Figure 1.

Finally, in the business-as-usual, an atomistic firm assumes that the representative agent engaging in R&D can only appropriate a portion of the benefits, which translates into the presence of a leakage parameter in the agent’s research function. Inversely, the internalization of inter-firm spillovers implies that the leakage parameter is equal to 0 in equation (6), the research function of the representative agent. Therefore, it’s easy to understand that when the agent internalizes inter-firm spillovers, it leads to an increase in R&D expenditures and a decrease in emissions level, as seen in the figures above.

Given the explanations above, it’s now a little more intuitive that scenario 5, which assumes that all externalities but inter-firm spillovers are internalized, would result in the lowest level of R&D and therefore yield the steepest time path and highest cumulative level of emissions in the business-as-usual as illustrated in Figure 1. In contrast, scenario 8 that

supposes that only inter-firm spillovers are internalized would yield the highest level of R&D and therefore the flattest time path and lowest cumulative level of emissions. The other six scenarios would lie between those two bounds.

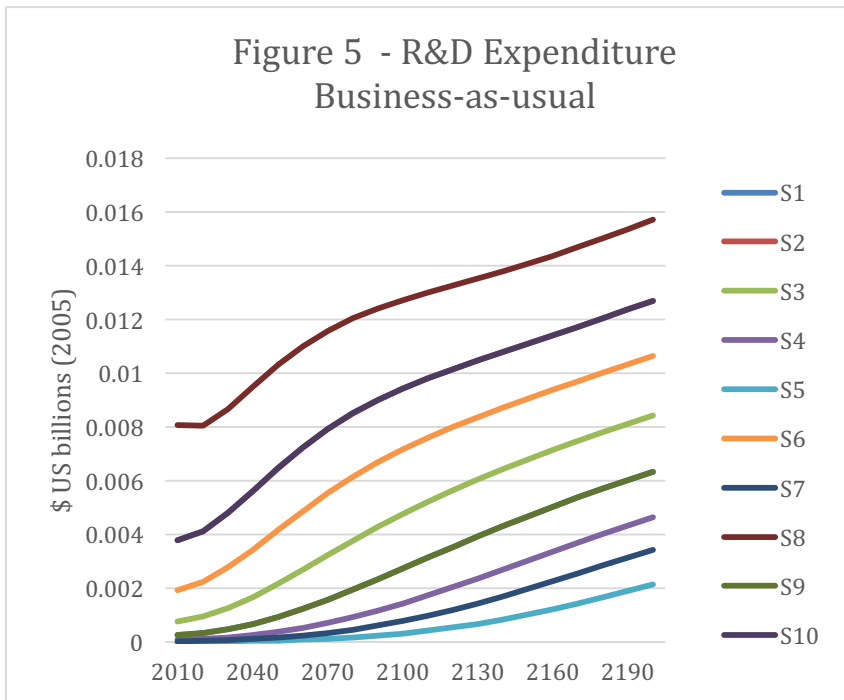
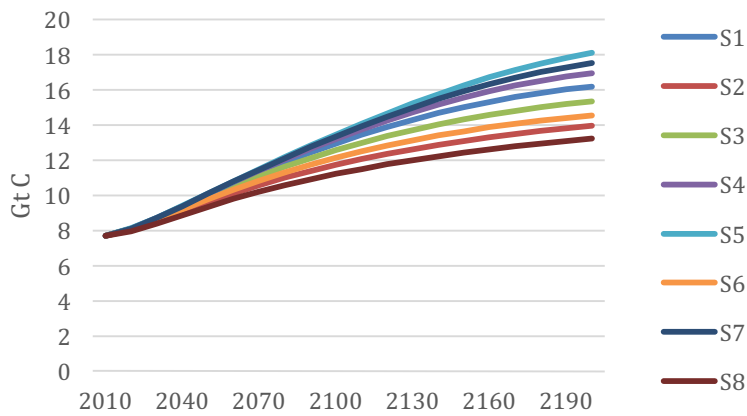


Figure 6 - Emissions
Exogenous R&D



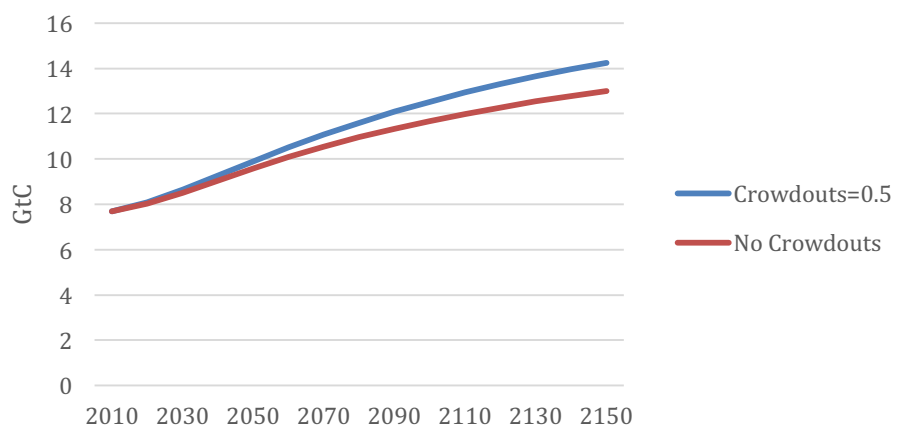
Also, the identical initial level of emissions and similarity in shape of time paths seen in Figure 1 implies that research market externalities have little to no impact on the level of emissions in the short run and on the trend in emissions of the representative agent. In other words, the internalization of an externality will accelerate or decelerate the rate at which emissions increase (depending on which externality is

internalized) but in no case would the emissions time path decrease following different specification of the representative agent’s perception regarding market research externalities.

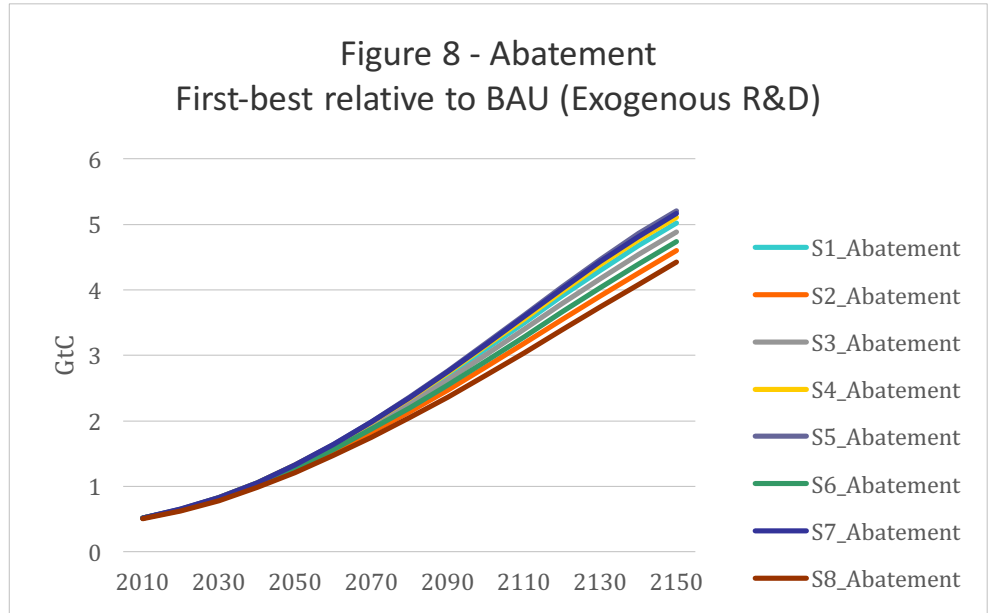
Computing the value of induced R&D in the first-best scenario requires running a version of the scenario with R&D set exogenously to the level obtained in the corresponding business-as-usual scenario. Such a version of the first-best scenario is shown in Figure 6 for each of the eight BAU scenarios.. Naturally, it’s quite obvious that the overall level of emissions is reduced for all scenarios relative to their baseline levels and that there’s an overall decrease in the slope of all time path as the social planner maximizes welfare. We also notice a slight decrease in the impact of internalizing any given externality as the difference between all scenarios at the end of the horizon in Figure 6 is reduced in comparison to the baseline level.

On the other hand, Figure 7 shows the time path of emissions in the first-best with endogenous R&D, both when crowdouts are present and equal to 0.5 and when crowdouts are omitted. For scenario 1

Figure 7 - Emissions
First-best policy criterion

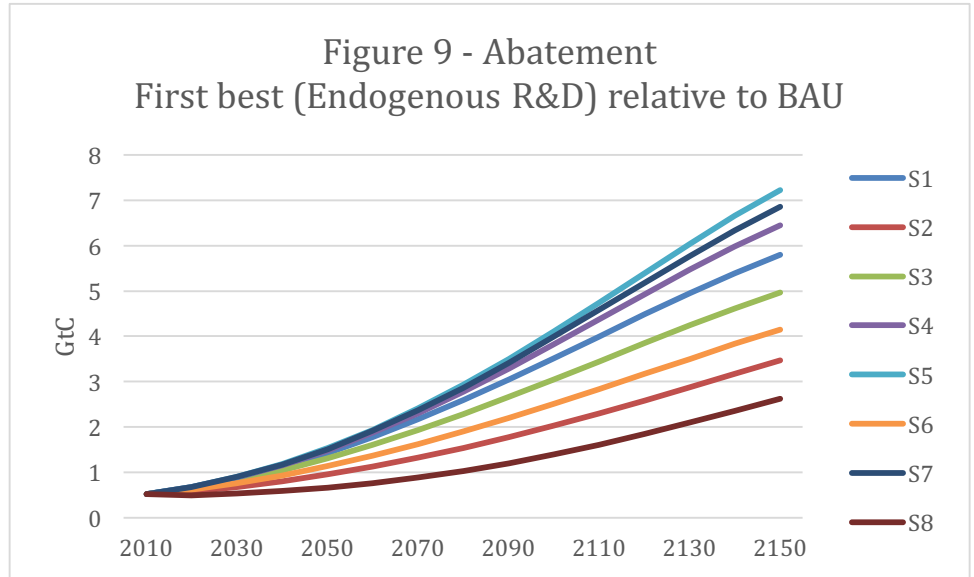


through 8, the level of emissions in the first-best policy scenario is represented by the time path that assumes that crowdouts are present and equal to 0.5. This commonality between the eight scenarios is due to the identical first-best policy assumptions.

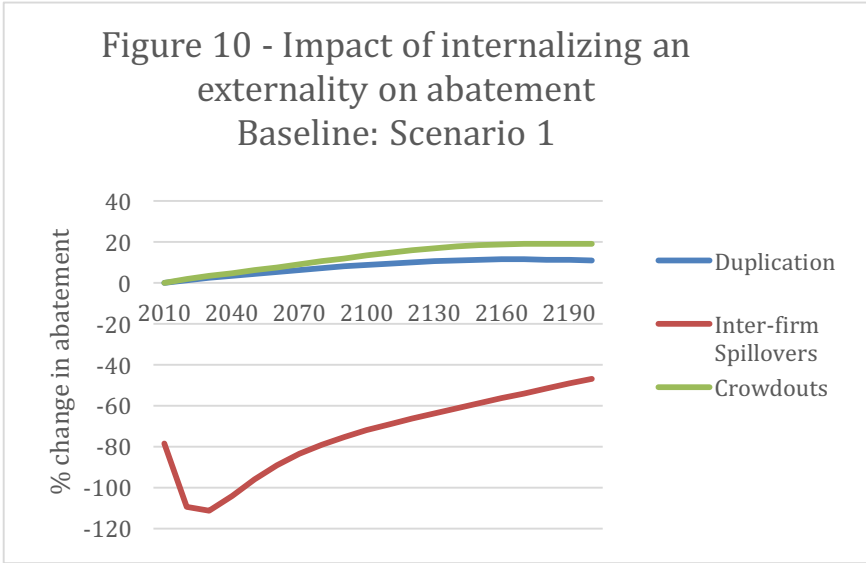


Having presented the time paths of emissions, we will now present abatement levels. The abatement time path is calculated simply by computing the difference between the emissions level in the first-best scenario and the BAU. First, Figure 8 illustrates the level of abatement when implementing the first-best scenario with exogenous R&D as indicated in Figure 6. As expected, abatement levels are very similar across the eight scenarios given that R&D levels are considered exogenous in the first-best scenario. We first note that the scenarios preserve the order presented in Figure 1, where scenario 5 and scenario 8 act as upper and lower bounds respectively. Also, we notice reduced relevance of initial assumptions on externalities in the business-as-usual as little difference distinguishes each scenario. Also, the scenarios that internalize duplication and crowding out tend to yield time paths of abatement with increased slope with decreasing marginal increase whereas scenarios that internalize inter-firm spillovers (scenario 8, for example) lead to time paths of abatement that are slightly more linear.

On the other hand, the time path of abatement for the first eight scenarios shown in Figure 9 is defined by the difference in the level of emissions under first-best scenario (with endogenous R&D expenditures), presented in Figure 7, and the respective level of



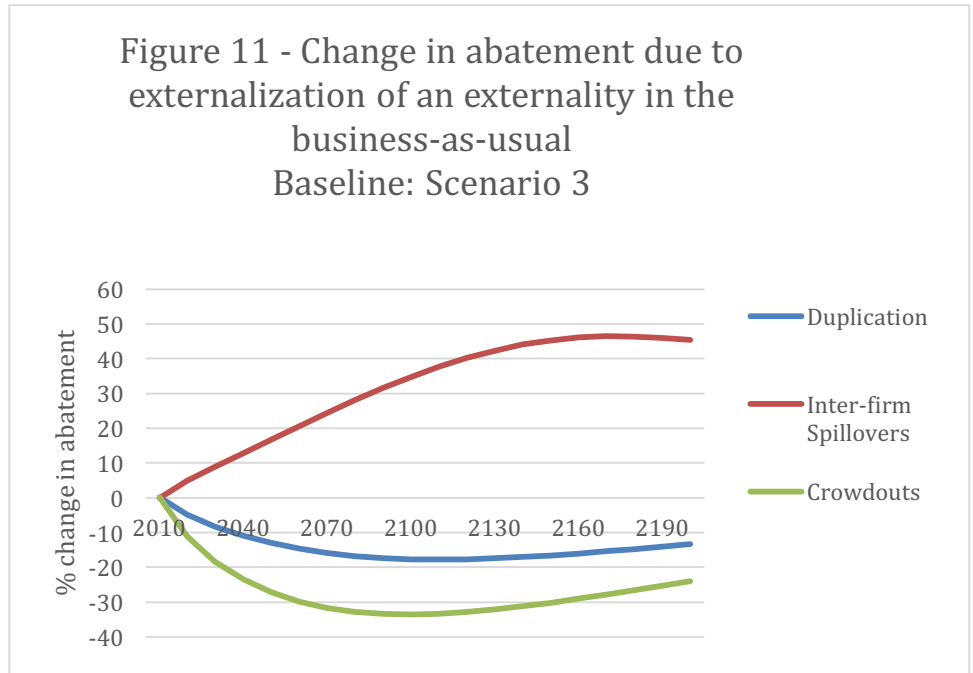
emissions in the business-as-usual in Figure 1. Given that the level of emissions in the first-best scenario is identical and below the baseline level for scenarios 1 to 8, it's understandable that the time paths of abatement would be relative to the results shown in Figure 1. More specifically, the time path associated with scenario 5, which considers that all externalities but inter-firm spillovers are internalized in the business-as-usual, has the steepest slope out of all first eight scenarios and the highest cumulative abatement. In contrast, scenario 8, which assumes that the representative agent internalizes only inter-firm spillovers generates an abatement time path with the flattest slope and, therefore, the lowest cumulative abatement. As for the time path of emissions in the business-as-usual, the time path of abatement of other scenarios lie somewhere between the specified upper and



lower bounds and all bear similar shapes. Comparing Figure 8 and Figure 9, we notice that baseline assumptions regarding research market externalities have much greater importance when R&D expenditures are considered endogenous in the first-best scenario. In this case, the abatement levels are also significantly greater, especially

when the representative agent internalizes duplication and crowding out, as seen by comparing abatement levels for scenario 5, 7, 4 and 1 in Figure 8 and 9.

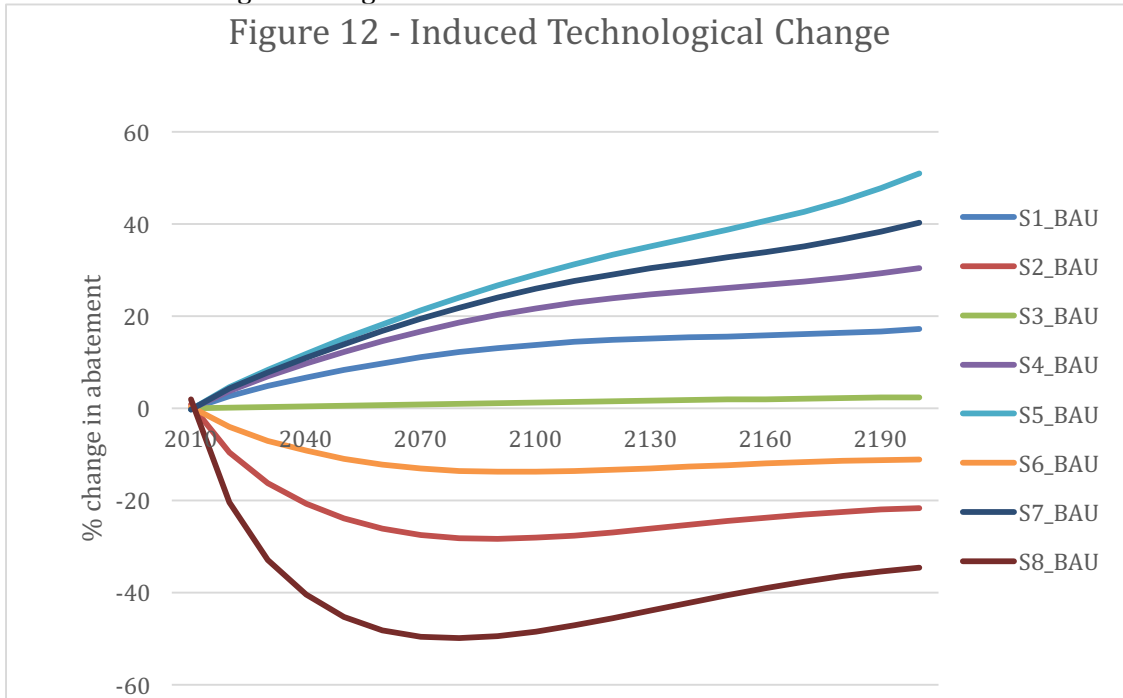
In order to explore the impact of assumptions concerning research market externalities by the representative agent in BAU on the measure of abatement in the first-best, we have computed the percentage change in abatement following the internalization of an externality, using scenario 1 as a baseline (recall that scenario 1 assumes that none of the externalities are internalized by the



representative agent), illustrated in Figure 10. We notice that internalizing crowding out leads to an increase in abatement, up to 20%. Internalizing duplication leads to similar results such that internalizing the externality increases abatement by up to 11%. Finally, the internalization of inter-firm spillovers results in a decrease in abatement that is considerably more important in the short-term, up to a -111% before decreasing to -47% in the long run. Thus, internalizing inter-firm spillovers has the greatest impact (in absolute terms) on abatement levels.

Similarly, the opposite exercise intends at highlighting the change in abatement following the externalization of an externality, given that all other externalities are internalized in the business as usual. The results by calculating the percentage change in abatement following the externalization of a given research market externality while using scenario 3 as a baseline and shown in Figure 11 suggest analogous conclusions. For instance, assuming that inter-firm spillovers are external to the representative agent causes abatement levels to increase up to about 46%. In contrast, if either crowding out or duplication is external to the representative agent implies that abatement level will decrease by a maximum of about 33% or 17% respectively.

Finally, the time path of the value of induced technological change for all eight scenarios is calculated using equation (8) above and is presented in Figure 12. In contrast to emissions and abatement levels, the value of induced technological change takes on negative values for the few scenarios that assume that inter-firm spillovers are internalized in the business-as-usual (scenario 2, 6 and 8). Note that a negative time path of induced technological change implies that the presence of endogenous technological change pressures abatement levels downwards in the first-best. For example, scenario 2, 6 and 8 yield too much R&D in the BAU and therefore the R&D level is reduced following the implementation of the optimal policy, which suggests increased emissions level. Another interesting result is the reduced significance of induced technological change when we assume that the representative agent internalizes all externalities (scenario 3), such that induced technological change has little relevance in abatement levels.



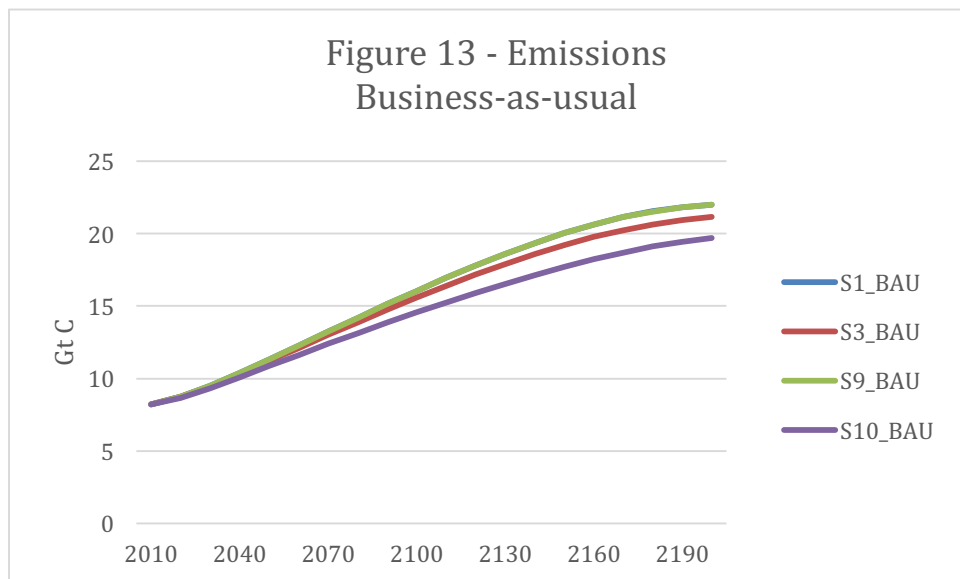
IMPORTANCE OF CROWDING OUT

Now having presented the results for the first eight scenarios and how the internalization of market research externalities by the representative agent plays a role in the level of baseline emissions, abatement and induced technological, it's now time to turn our attention to the impact of crowding out in our framework. As previously mentioned, scenarios 9 and 10 are analogous to scenarios 1 and 3 respectively but differ regarding the inclusion of crowding out, assuming that crowdouts are omitted and equal to zero in the framework.

First, Figure 13 illustrates the level of baseline emissions associated with scenarios 9, 10 and their respective counterparts that assume positive values for crowding out throughout the framework (i.e. scenarios 1 and 3). Results show that the omission of crowding out leads to significantly lower levels of emissions when crowding out is internalized by the representative agent (scenarios 3) and leave the emissions level nearly unchanged when crowding out is not internalized in the business-as-usual (scenario 1). Because scenario 1 assumes that crowding out is external to the representative agent, we can deduce that its omission would only affect the levels of emissions through its presence only in the structural equations, as it is absent from the agent’s behavioral first-order condition.

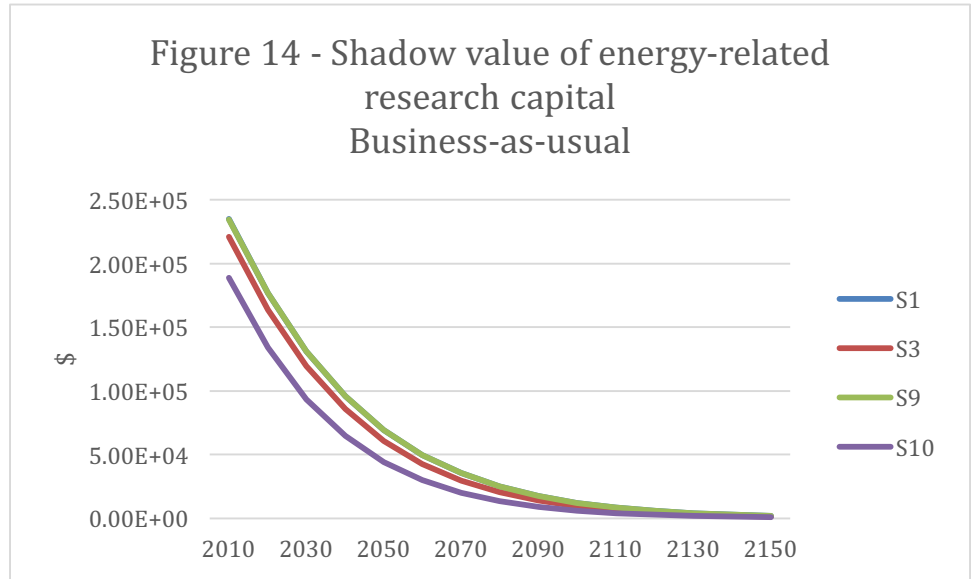
To further understand the relationship between assumptions concerning crowding out and levels of emissions in the business-as-usual, it’s interesting to consider the results shown in Figure 14, showing the shadow value of energy-related research human capital. First note that scenario 1 and scenario 9 have nearly identical levels of shadow value due to similarities in the conditions defining their baseline scenario. Assuming that crowding out is equal to 0 and absent (scenarios 9 and 10) further amplifies the reduction in the shadow price, thus explaining the lower level of emissions compared to other scenarios in Figure 10. The results are also supported by Figure 5 that illustrates the time path of R&D investments under each

scenario, such that scenarios with the lesser shadow price of energy-related research will also have the

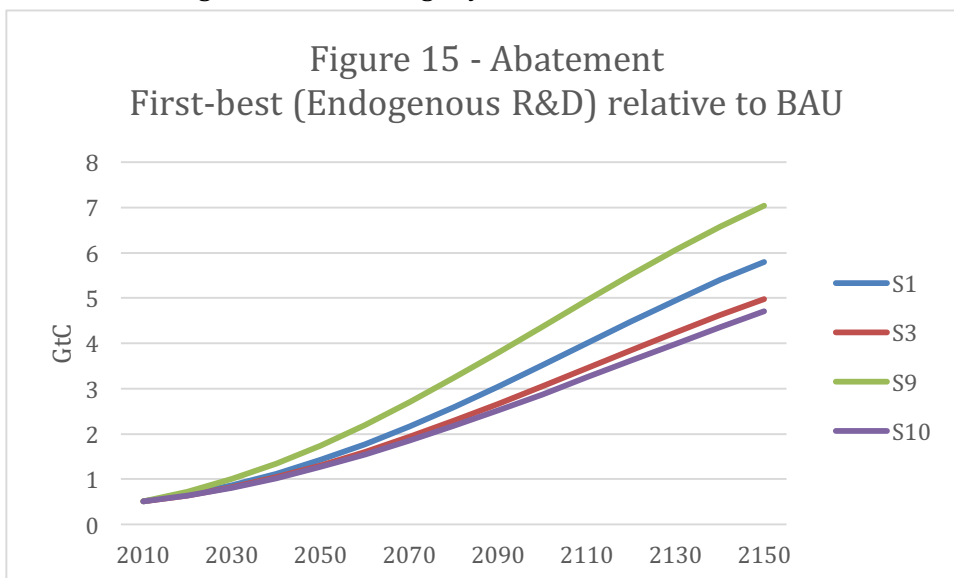


greater levels of research investment and, therefore, lower levels of emissions in the business-as-usual.

As previously mentioned, Figure 9 illustrates the level of emissions as prescribed by the social planner in the first-best scenario with



endogenous R&D both when crowding out is equal to zero and when it is positive. It was shown in Figure 13 that the omission of crowding out implies a decrease in emissions by the representative agent when externalities are internalized and left nearly unchanged when externalities are considered external. Figure 15 illustrates the time path of abatement under scenario 1, 3, 9 and 10, which is calculated by computing the difference between the first-best scenario with endogenous technological change and the level of emissions in the business-as-usual. As expected, the omission of crowding out leads to a considerably accelerated increase in abatement level with stabilization of levels towards the end of the horizon when research market externalities are external in the business-as-usual. On the other hand, when externalities are internalized by the representative agent, the omission of crowding out leads to a slightly lesser rate of increase of abatement levels and a later



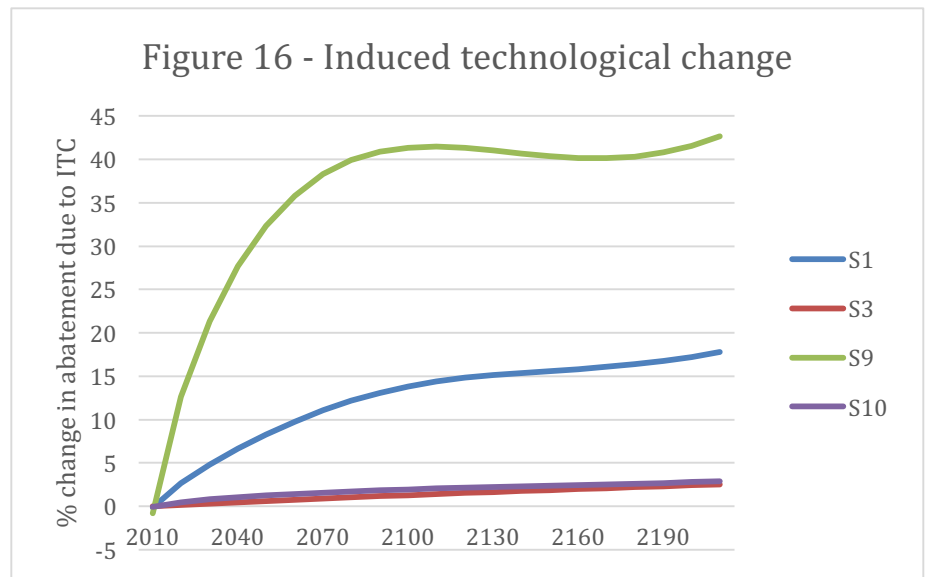
stabilization period relative to when crowdouts are included in the framework. This is justified by the fact that by omitting the possibility of crowding out in our framework

inevitably leads to a lower opportunity cost, such that 1\$ spent on R&D is equal to 1\$ in opportunity costs. Therefore, a decreased opportunity cost implies a greater amount of R&D spending, which translates into reduced level of emissions, all else being equal. An extended horizon would most likely provide us some more information on how the scenarios compare to one another with respect to the time path of abatement as it stabilizes in the long term.

Finally, Figure 16 shows the value of induced technological change for scenarios 1 and 3 and their counterparts with omitted crowding out. Results show that when externalities are not internalized in the business-as-usual (scenario 1) the omission of crowding out leads to a considerable increase in the share of abatement attributable to technological change and suggests that endogenizing technological change leads to an increase in abatement, especially in the short run given the steep slope of the curve (scenario 9). On the other hand, when externalities are internalized by the representative agent (scenario 3), the omission of crowding out leads to only a slight increase in the value of induced technological change. Therefore, the figure shows that the omission of crowding out has a minimal impact on the value of induced technological change when externalities are internalized in the business-as-usual, and the inverse applies when externalities are considered external to the representative agent.

Although Goulder and Mathai’s results were in favor of a delay in abatement once introducing induced technological change, our results only suggest a decrease in abatement when inter-firm spillovers are internalized, as presented in Figure 12. Although, the figure also shows that when internalizing all externalities in the business-as-usual (scenario 3),

the role of induced technological change is underestimated. On the other hand, when crowding out is omitted and all research externalities are internalized (scenario 10), the results support similar conclusions where abatement levels are decreased in the near-term.



Conclusion

To conclude, the present study aimed at highlighting the importance of research market externalities for the value of induced technological change in the context of climate change policies. By adapting Shiell & Lyssenko's (2014) general equilibrium model with endogenous technological change, we elaborated several scenarios that differ in terms of the assumptions defining the business-as-usual. Such assumptions include the internalization of research market externalities by the representative agent, including duplication, inter-firm spillovers and crowding out. By comparing the scenarios, we were then able to highlight the individual impact of internalizing a given research externality by the representative agent. Results of our simulations and analysis include the consistency of the impact of internalizing research externalities and augmented rate of increase of abatement when internalizing duplication and crowding out externalities in the business-as-usual. In contrast, the internalization of inter-firm spillovers lead to a deceleration of abatement, a negative value of induced technological change and lower emissions level. Finally, the results presented highlight the importance of research market externalities and their significance on the results, demonstrated by the difference in abatement, level of emissions and induced technological change between each elaborated scenario.

The process that surrounded the elaboration of this present study has also highlighted potential areas of improvement and direction of future studies in the field of endogenous and induced technological change. For instance, repeating our exercise using a second-best policy option or including inter-temporal spillovers could also further enlighten the importance of proper BAU specification on abatement level and induced technological change. On the other hand, the inclusion of uncertainty, backstop technologies, differentiated capital stocks framework as seen in the study by Jaccard & Rivers (2007) and applying the specifications of the business-as-usual recommended by a few authors (Shiell & Lyssenko 2008; Shiell & Lyssenko 2014; Rezai 2011) into a general equilibrium model could yield different result and policy implications for the role of induced technological change and the timing of abatement.

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