Essays on the Transition to Sustainable Economies

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Introduction

More than ever before do today's societies face the challenge to transition to environmentally friendly modes of production. The latest report of the intergovernmental panel on climate change (IPCC, 2022) emphasizes the urgency to reduce greenhouse gas emissions to ensure the preservation of the human habitat. Current modes of production and consumption are incompatible with the continuity of natural conditions essential for a safe human existence.

The necessity to diminish our environmental footprint is not up for debate. What remains to be understood, though, is how to best transition to *green* economies in our complex world. This dissertation is an attempt, first, to shed light on societal (Chapter 1), economic (Chapter 2), and political (Chapter 3) challenges that exacerbate a transition and, second, to propose policies facilitating the transition. The following elaborates in more detail the three self-contained chapters of this essay.

Chapter 1: Labor Income Taxes and Social Responsibility in an Unequal Economy. The first chapter points to income inequality as a factor complicating an economic transition. The chapter investigates a societal change as the origin of a transition. It starts from three observations: first, consumers have a choice between sustainable and unsustainable products. Second, the willingness to pay a premium in order to avoid negative externalities, i.e., *social responsibility*, has been rising recently. Third, I document for the US in 2018 that even though economies as a whole are rich enough to consume sustainable and more expensive goods, the distribution of income is such that low-income households cannot subsist on sustainable goods alone. Consequently, a rise in social responsibility is less effective in reducing an externality on the aggregate simply because sustainable consumption is too costly for some households. Instead, a rise in social responsibility intensifies perceived inequality as poor households cannot consume according to their desire for sustainability while satisfying basic consumption needs.

The chapter builds a quantitative model featuring the key ingredients discussed above: income inequality, basic needs, and a choice between a sustainable and an unsustainable good where the latter exerts an externality. In line with the literature on consumer preferences, the externality comprises environmental externalities, questionable working conditions, and the maltreatment of livestock (Vermeir and Verbeke, 2006). In this setting, a benevolent government seeks to maximize social welfare. To this end, the government can use corrective and labor income taxes. What is the optimal mix between corrective and labor income taxes as households become more socially responsible in their consumption choice?

I find that the optimal policy is always a mix of corrective and labor income taxes. The reason is income inequality. As opposed to corrective taxes, using a labor income tax to reduce overall production by diminishing labor supply is less costly in terms of inequality. Furthermore, as social responsibility increases, the optimal policy shifts away from corrective taxes toward labor income taxes in order to redistribute more. The reason is that perceived inequality aggravates as the poor cannot consume in line with their desire for sustainable goods. In this case, redistribution becomes the preferred policy instrument to target the externality. Redistribution affects the aggregate externality because households differ in how much a fraction of an additional unit of income is spent on the unsustainable good due to the necessity to satisfy basic needs.

Chapter 2: Meeting Climate Targets: The Optimal Fiscal Policy Mix. The second chapter focuses on firms' economic incentives as a challenge to mitigating the costs of transitioning to a low-emission economy. Recent empirical research documents the importance of non-green knowledge for green innovation (Barbieri, Marzucchi, and Rizzo, 2021). A prominent example are electric vehicles which are a combination of batteries and cars, that is, of non-green technologies. However, depending on the structure of patents, firms do not internalize the societal benefits of innovation in their research decision.

Taking this challenge into account, the chapter studies the optimal policy to satisfy emission targets in line with climate goals agreed upon in the Paris Agreement. In contrast to the first chapter, it is government intervention which initiates the transition to a low-emission economy and not households. Again, the government can use carbon and labor income taxes to implement emission targets. More precisely, the question asked is: "What is the optimal mix between carbon and labor income taxes to meet emission targets?"

To answer the question, the chapter develops a model economy which uses green and fossil energy sources as inputs to production. The former is defined as not emitting any CO_2. Technologies are either compatible with the green or non-green sectors of the economy meaning that fossil-based technologies cannot be used to produce green energy. This model feature combined with the observation that the fossil sector is technologically more advanced makes a transition to green energy sources costly. To produce as much output in a green economy as in a fossil economy necessitates research on green technologies.

The generation of technology advances, i.e., innovation, is modeled in great detail. Two key aspects shape the productivity of researchers in the model. First, knowledge generated in a sector today inspires innovation within the same sector tomorrow. These *within-sector knowledge spillovers* imply that researchers in the fossil sector are especially productive. Therefore, allocating less researchers to the fossil sector means a reduction in the productivity of researchers overall. Second, knowledge spills from one sector to another. Such *cross-sectoral knowledge spillovers* render research on fossil technologies valuable in a future where only green technologies can be employed.

How do the considered fiscal tax instruments operate in this economy? A carbon tax lowers the use of fossil energy and, thus, emissions. This reduction, however, entails a decline in the returns to research on non-green technologies so that fossil-based research efforts shrink. This constitutes a conundrum for the government: reducing the use of fossil fuels while maintaining research activity on fossil technologies.

A labor income tax may help mitigate the conflict of objectives. Labor income taxes diminish emissions by lowering labor supply and, thus, overall production. At first glance, this appears excessively costly given that it is only a certain sector of the economy which exerts an externality and green alternatives are available. Nevertheless, labor income taxes qualify as a complement to carbon taxes since they leave returns to fossil research high relative to returns to green research.

The optimal fiscal policy mix depends on the stringency of the emission limit which has to be satisfied: until 2050 some positive net emissions are feasible. From 2050 onward, net emissions have to be zero (IPCC, 2022). This bisection makes two distinct regimes optimal. In the run-up to the net-zero emission limit, the government chooses a low tax on carbon which on its own would violate the emission limit. Therefore, the government taxes labor to curb overall production and, thus, emissions. This policy mix achieves a higher share of fossil research activity. Under the stricter net-zero emission limit, however, using a labor income tax to lower emissions becomes too costly. The optimal policy then consists of an excessive carbon tax. The aggressive carbon tax has the advantage to direct more researchers to the green sector. More green research spurs green innovation in the future through within-sector knowledge spillovers. As a byproduct, the share of fossil energy in output declines so that a higher level of economic activity becomes feasible within the bounds of the emission limit. The labor income tax, therefore, turns into a subsidy to raise the level of production.

Chapter 3: Green Consumer Preferences, Innovation, and Lobbying. The final chapter—a joint project with Olimpia Cutinelli Rendina and Antoine Mayerowitz—combines the main themes of the previous two chapters: social responsibility and innovation. Similar to the first chapter, it is consumers' concerns about the environment from which impulses for a change in production emerge. Innovation is one margin of adjustment via which firms may respond to greener demand. In this chapter, the hindrance to a quick transition to green technologies is political: next to cleaner innovation, firms may choose lobbying to decelerate policymakers' efforts to protect the environment. More precisely, we empirically study the question how automobile producers respond to a shift in consumer preferences: do they innovate cleaner technologies or do they increase lobbying expenditures on environmental issues?

We find that the average firm responds in both dimensions: research shifts to clean technologies away from dirty ones as firms are confronted with greener demand. At the same time, the average firm's lobbying expenditures on environmental policy making increases. We argue that the results are best understood as a demand-driven mechanism: when households lower demand for dirty goods due to environmental concerns, investment in clean R&D becomes especially important. This could be the case because a minimum investment on research is necessary to reach a critical level of clean technologies to produce, for example, a car. As a result, firms' eagerness to protect profits in order to finance more clean research increases. To sum up, we conjecture that environmental lobbying helps firms finance the transition to cleaner production.

While firms seem to engage in lobbying to finance cleaner innovation—as presumably intended by consumers when demanding cleaner goods—a potential slow down in environmental regulation conflicts with a required timely transition to green economies. Our results, therefore, call for investigating additional policies to accelerate the transition to clean innovation and production such as research subsidies.

References

Barbieri, Nicolò, Alberto Marzucchi, and Ugo Rizzo. 2021. "Green technologies, complementarities, and policy." Working paper ISSN 2057-6668. Science Policy Research Unit. [2]

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* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926." [1, 3]

Vermeir, Iris, and Wim Verbeke. 2006. "Sustainable food consumption: Exploring the consumer "attitude - Behavioral intention" gap." *Journal of Agricultural and Environmental Ethics* 19 (2): 169–94. [2]

Chapter 1

Labor Income Taxes and Social Responsibility in an Unequal Economy

1.1 Introduction

Recent research demonstrates the existence of *social responsibility* in markets (Bartling, Weber, and Yao, 2015), that is, households' utility from consumption depends on the externalities associated with the production of the goods consumed. And the share willing to pay a premium for sustainable products is rising.[1] Such a change in preferences suggests a transition to sustainable production and fewer externalities on aggregate. But income inequality renders sustainable goods unaffordable to poor households, posing an obstacle to a demand-led transition. As a result, (i) redistribution affects the externality, and (ii) consumption inequality aggravates as social responsibility rises. In the light of changing social responsibility and high income inequality, I ask: What is the optimal policy as social responsibility increases?

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1. In 2015, 66% of households were willing to pay a premium for sustainable brands, compared to 50% in 2013 in a sample of 60 countries (The Nielsen Company, 2015). Indeed, the market share of sustainable consumer packaged goods in the US rose from 14.3% in 2013 to 16.6% in 2018 (Kronthal-Sacco, Van Holt, Atz, and Whelan, 2020) despite a price premium generally charged for sustainable goods (The Conference Board, 2020). In a multi-country survey, Simon-Kucher & Partners (2021) document an accepted price premium of 25% on average.

The answer to this question depends on how counteracting effects of social responsibility relate quantitatively: the government faces a trade-off between the provision of a public good and equity, as both the corrective tax and the distortionary income tax lower labor supply. On the one hand, the rise in social responsibility implies a demand-driven reduction in the externality.[2] Ceteris paribus, less government intervention to reduce the externality is necessary. More resources become available for redistribution. On the other hand, a rise in social responsibility exacerbates consumption inequality since poor households cannot consume the desired bundle without violating a consumption minimum. Accelerated government intention to reduce inequality conflicts with the mitigation of the externality.

Macroeconomic research has primarily focused on the supply side to study corrective policies in representative agent models. This paper, in contrast, scrutinizes the optimal policy in a model with a demand-determined economic structure and income inequality. I find that, first, for all levels of social responsibility labor income taxes are part of the optimal corrective policy. Second, a surge in social responsibility induces an optimal shift from corrective taxation to redistribution. The worsening of consumption inequality urges the government to focus on equity. Since redistribution attains a better balance between providing the public good and equity when social responsibility is high, it becomes the essential part of the optimal corrective policy. However, with this policy, the government relinquishes an efficient reduction in the externality.

In more detail, I suggest a model economy that consists of a sustainable and an unsustainable, polluting production sector. Households choose between these two goods by trading off their desire to consume sustainably against a requirement to satisfy basic consumption needs. There are two household types which differ solely in the effective labor productivity they provide. This gives rise to income heterogeneity. Income inequality and the externality motivate government intervention. Having a distortionary labor income tax and a corrective tax at her disposal, a Ramsey planner maximizes social welfare. Yet, both instruments distort households' labor supply decisions so that a trade-off between equity and public good provision arises and the first-best allocation is not attainable.

In the model, social responsibility shapes the utility a household derives from consuming the sustainable over the unsustainable good. There is no heterogeneity in social responsibility across income groups, which I provide evidence for in the empirical section of the paper. Instead, all household-specific variation in the composition of consumption bundles results from income inequality. I obtain

2. I abstract from information frictions to focus the paper on the role of inequality. I assume throughout that households perfectly observe the externalities arising from the consumption of a good. In reality, a misrepresentation of externalities through sustainability claims is most likely important.

this behavior by introducing utility costs which rise whenever a household's consumption is close to or below basic needs. As a result, low-income households' consumption tilts towards the cheaper alternative and does not reflect their desire to consume socially responsibly.

Contrary to an elaborate household side, the production side is simple. The research question is studied in a partial-equilibrium set-up to focus on the most basic ambiguous effects which a change in social responsibility generates for the optimal policy. Both production sectors are perfectly competitive, prices are flexible, and firms produce with a constant returns to scale technology.

Before describing the results, I use the following two paragraphs to highlight some important aspects of the calibration. I calibrate the model to the US in 2018. The comparison of micro data on disposable income to the price of a sustainable basic-needs bundle determines the share of poor and rich households in the model: the poor cannot afford to subsist on sustainable goods alone. One can think of the sustainable bundle as being in line with social and ecological concerns, containing, for example, organic food, fair trade products, and energy from renewable sources.[3] To proxy the relative price of the sustainable basic-needs bundle, I use a time series on organic and conventional food prices provided by the US Department of Agriculture. Prices are then aggregated according to the food bundle suggested by the EAT-Lancet Commission (2019) - a bundle designed to respect planetary and health boundaries. I find that in 2018, 44.96% of US households were not in the financial position to satisfy their basic needs with sustainable goods alone.

To zoom in on the role of inequality, I refer to an objective measure of needs which I take from the IWPR (2018). In contrast to observed subjective needs, this measure is less prone to habits or a keeping-up-with-the-Joneses motive of consumption levels, for instance. Therefore, in the model, households may lower their consumption beyond previous consumption levels as they become more socially responsible as long as basic needs are sufficiently covered.

I conduct several quantitative experiments to study the optimal policy response to growing social responsibility. The main exercise consists in exogenously changing the degree of social responsibility shared by households.[4] To differentiate the role of basic needs from the general effects of social

3. Vermeir and Verbeke (2006) describe *sustainable products*, inter alia, as resulting from production processes that are environmentally friendly, entail fair working conditions, and avoid maltreatment of livestock. I follow this notion of sustainability.

4. Changing preferences bears the risk of making a potentially invalid welfare comparison as the value measure changes. It is, for instance, questionable whether the world is indeed a better place from suddenly liking a previously disliked situation, while the situation as such remained the same. Nevertheless, observing a change in preferences is a legitimate motivation to think about adequate policy changes. Therefore, the analysis focuses solely on policy discussions and how the economy is shaped by the change in preferences.

responsibility, I run the experiment in both the *baseline* model sketched above and a *standard* model which does not account for basic needs.

In the standard model, by construction, income inequality does not affect the aggregate production ratio. Nevertheless, labor income taxes are chosen higher for all levels of social responsibility to target the externality. In the standard model, labor income taxes only affect the externality by lowering labor supply. Therefore, in an unequal economy, the optimal environmental policy[5] is a combination of both compositional and reductive policies—in the model represented by the corrective and the income tax, respectively. The reason is that solely relying on the corrective tax would be too costly in terms of equity.

The exercise uncovers that, absent basic needs, the optimal policy can set a lower corrective tax while converging to the efficient level of the externality due to the behavioral change in demand. An accompanying rise in labor income taxes is optimal to compensate for the decline in transfers when the corrective tax and its tax base decrease. There is no movement in the corrective policy towards labor income taxes as social responsibility strengthens.

In contrast, when basic needs are added to the analysis, the optimal policy shifts away from corrective taxation to redistribution so that transfers increase as social responsibility grows. In the following two paragraphs, I discuss the underlying mechanisms and the optimal policy in turn.

The enhancement in social responsibility exacerbates inequality in two ways. First, for the same distribution of income, consumption inequality aggravates with social responsibility. A stronger taste for the more expensive good raises the cost of the *desired* bundle—the bundle which would be chosen absent basic needs and which is in line with social responsibility. Poor households, however, who are more concerned with satisfying their basic needs, consume a higher share of the cheaper good. The discrepancy between the composition of the actual and the desired bundle increases with social responsibility. This compositional effect lowers composite consumption of the poor. Second, as the preference for the more expensive bundle becomes very strong, the poor eventually reduce the sum consumed accepting to suffer from too low consumption. Both effects urge the government to spend more resources to mitigate poverty and to relinquish a further decline in the externality closer to the efficient level.

Since the policy focus turns to equity, the Ramsey planner optimally relies on redistribution as a corrective policy instrument. Lump-sum redistribution affects the externality because basic needs render the marginal propensity to consume

5. I use the terms *environmental* and *corrective* to refer to the policy targeted at the externality interchangeably. The externality arising from unsustainable consumption can broadly be thought of as an environmental externality. Environmental concerns have been found to be the main driver of sustainable demand (The Conference Board, 2020) and are of major political importance.

unsustainable goods income dependent. Whenever this marginal propensity of a rich household is higher than that of a poor household, one more unit of lump-sum redistribution to the poor raises sustainable demand on aggregate. The mechanism emerges as poor households recompose their budget share towards the more expensive good once their basic needs are sufficiently met.

I quantify the importance of either tax instrument on the externality by assuming a sequential introduction of jointly determined optimal taxes: first, the corrective tax is implemented; second, the labor income tax follows. When social responsibility is weak, the contribution of the labor income tax to lowering the externality works through reducing labor supply. The corrective tax is the most important environmental policy tool. The importance of instruments is reversed at high levels of social responsibility: redistribution accounts for a reduction of the externality by up to 40%, because the unsustainable good is inferior to poor households. The corrective tax, in contrast, becomes relatively unimportant lowering the externality by only 12% at the highest level of social responsibility considered.

Finally, I show that the planner chooses a higher labor income tax than in a counterfactual model without externality when social responsibility is high. This finding is in sharp contrast to Bovenberg and De Mooij (1994) who argue that corrective tax revenues are optimally used to lower distortionary labor income taxes when the government has to generate funds: the so-called *weak* double-dividend hypothesis. The reason is that recycling corrective revenues as transfers intensifies the efficiency costs of labor income taxation when the uncompensated wage elasticity of labor supply is positive. The findings in my standard model are in line with the weak double-dividend hypothesis: corrective tax revenues are optimally used to lower distortionary labor income taxes, and the labor income tax is always below its optimal level absent an externality. Intuitively, the corrective tax intensifies the efficiency costs of distortionary income taxes. The introduction of basic needs into the model changes this result. Then, there may be environmental improvements associated with redistribution. The environmental gains add to the benefits of labor income taxation outweighing accelerated efficiency costs when social responsibility is high. As a result, the optimal labor income tax in the model with externality and corrective tax exceeds its counterpart in a world without externality.

Literature. The present paper is one of the first to relate social responsibility and inequality in a macroeconomic framework. Social responsibility has been studied in the behavioral economics literature. Bénabou and Tirole (2010) discuss the phenomenon and rationalize its existence, for example, by a (perceived) lack of government action. Bartling, Weber, and Yao (2015) provide experimental evidence that social responsibility shapes market interactions. The recent work by Aghion, Bénabou, Martin, and Roulet (2022) is one rare example to study social responsibility from a macroeconomic perspective. The authors study its interactions with competition and innovation, while the present paper keeps the supply side simple yet introduces inequality and basic needs.

The paper is broadly related to the literature on optimal environmental policy. This strand of literature generally focuses on a representative household and corrective taxation (compare Golosov, Hassler, Krusell, and Tsyvinski, 2014; Acemoglu, Akcigit, Hanley, and Kerr, 2016). While a supply-side perspective dominates in these papers, my paper shifts the focus to the demand side. Furthermore, I emphasize the role of labor income taxes in the optimal corrective policy which has been given less importance.

Therefore, more specifically, the paper adds to the discussion of the optimal environmental policy in a distortionary fiscal setting which has mainly focused on representative agent settings and exogenous governmental revenue constraints. As already alluded to, Bovenberg and De Mooij (1994) discuss the advantage of recycling environmental tax revenues to lower distortionary income taxes instead of increasing transfers. Since then, a vast literature has examined the weak double-dividend hypothesis (e.g., Goulder, 1995; Bovenberg and Goulder, 2002). Building on this literature, Barrage (2020) studies optimal corrective taxation in a distortionary fiscal setting with carbon cycle and representative agent in a quantitative model.

Similar to the model presented here, Jacobs and van der Ploeg (2019) add inequality and non-linear Engel curves to the setting in Bovenberg and De Mooij (1994) and abstract from an exogenous funding condition. They show that distortionary labor income taxes are used to target the externality when the corrective tax does not completely internalize the social costs of the externality. While the paper by Jacobs and van der Ploeg (2019) nests the present model as a special case, this paper here studies the effect of distinct intensities of the non-linearity due to varying degrees of social responsibility. Vona and Patriarca (2011) discuss the role of redistribution on externalities when household income determines the share of clean consumption. However, they abstract from the impact of social responsibility on inequality which is found to be the main driver of the optimal policy mix in my model.

Finally, in the sense that demand initiates the transition to sustainability, the project contributes to the literature on structural transformation (for an overview, see Herrendorf, Rogerson, and Valentinyi, 2014). Introducing a penalty term to capture the importance of basic needs when income is low allows inequality and redistribution to matter for the economic structure. That is not the case under the frequently used Stone-Geary preferences because marginal propensities to consume either good are independent of income. In this regard, the model relates to the articles by Matsuyama (2002), Foellmi and Zweimüller (2008), and Boppart (2014) who employ hierarchical consumption preferences. Yet, in contrast, the present paper's model does not assume a fixed hierarchy of goods a priori. This seems a better fit for the distinction of goods along the dimension of sustainability.

Outline. In Section 1.2, I empirically motivate the paper. Section 1.3 presents the model. The calibration follows in Section 1.4. In Section 1.5, I show and discuss results and sensitivity analyses. Section 1.6 concludes.

1.2 Empirical motivation

This section serves to motivate the paper's exercise using US data: first, we observe a rise in households' willingness to pay for the avoidance of negative externalities, but, second, the distribution of income is such that poor households cannot afford sustainable goods.

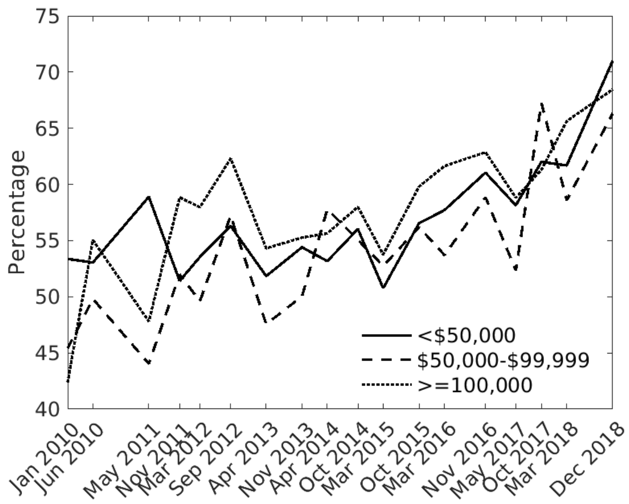
1.2.1 Rising social responsibility

A rationale for the rise in socially responsible consumption behavior is, for instance, a rising awareness of climate change (Bénabou and Tirole, 2010), and environmental concerns are the most important motive to purchase sustainable goods (The Conference Board, 2020). I use a representative survey for the US population from the *Climate Change in the American Mind* project conducted by Howe, P., Mildenberger, M., Marlon, J., & Leiserowitz, A. (2015) to show that the awareness of climate change has accelerated. Panel (a) in Figure 1.2.1 depicts the percentage by income group which indicated being worried about climate change. These shares have been rising steadily from early 2010 to end-2018 for all income groups.[6] Notice that not only have they been growing but also does the solicitude about climate change seem to converge over time across income groups. I take this evidence to model attitudes towards sustainability homogeneously across income groups.[7]

6. The question asked reads "*How worried are you about global warming?*". Appendix 1.A provides more details and shows related graphs in figure 1.A.1.

7. On this modeling choice compare also Panels (c) and (d) in Figure 1.A.1: The evolution of the share of strongly and weakly worried households moves similarly over income groups.

(a) Solicitude about climate change



(b) Support of coal emission regulation

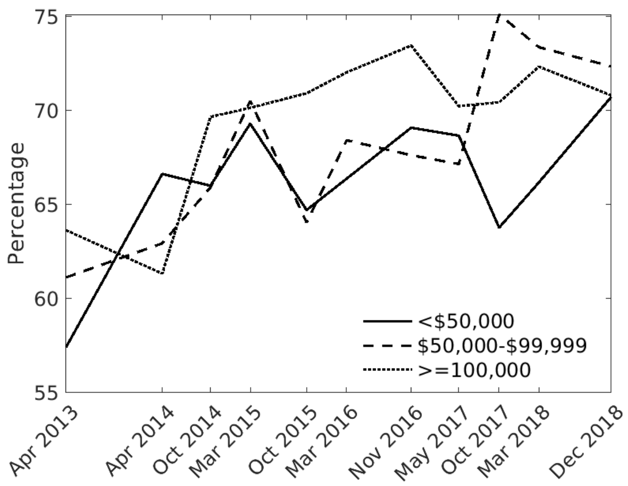


Figure 1.2.1. Household environmental concerns

Notes: The data comes from the *Climate Change in the American Mind* project (Howe, P., Mildenberger, M., Marlon, J., & Leiserowitz, A., 2015), a representative survey for the US population. The plots are based on the following questions: "*How worried are you about global warming?*" for Panel (a) and "*How much do you support or oppose the following policy? Set strict carbon dioxide emission limits on existing coal-fired power plants [...] The cost of electricity [...] would likely increase.*" for Panel (b). Panels (a) and (b) show the share of *weakly* and *strongly* supporting/worried participants relative to the complete weighted sample.

In line with concerns, the support for potentially costly policy interventions—which I take as a proxy of demand for sustainable goods[8]—has also been increasing. Consider Panel (b) in Figure 1.2.1, which shows the percentage by income group who expresses support for a regulation of coal emissions despite a possible increase in electricity costs. The support for such a policy displays some variation across income groups. In line with the narrative developed here, for almost all time periods the plot suggests that the richer a household the more likely it is to support costly policy interventions.[9]

1.2.2 Basic needs and inequality

Assume the rise in social responsibility continues, how should the optimal policy react? This thought experiment is at the heart of the paper. When all households are rich enough to sufficiently satisfy their basic needs with the sustainable good, the exercise seems trivial: the behavioral change in demand directs production to the sustainable sector making less government intervention necessary. A smaller corrective tax is required, thereby reducing overall efficiency costs. Furthermore, there are no costs in terms of inequality associated with a rise in social responsibility.

However, the necessity of government action remains if the income distribution is such that low-income households cannot satisfy their basic needs with the sustainable good alone. Then, these households face a trade-off between sustainable consumption and the satisfaction of basic needs. As a result, first, demand does not lower the externality as intensely. Second, consumption inequality aggravates, since the poor want to consume a higher share of sustainable goods which conflicts with meeting basic needs.

Figure 1.2.2 highlights that inequality, indeed, constitutes a hindrance to a demand-led externality reduction. In the plot, I compare the estimated distribution of per-capita disposable income in 2018 in the US to the costs of a sustainable and an unsustainable consumption bundle. I use income data from the Panel Survey of Income Dynamics (PSID) and calculate disposable income using the NBER's TAXSIM tool[10]; basic needs are taken from the IWPR (2018).[11]

In 2018, 44.96% of US households did not have the financial means to purchase basic needs in a sustainable quality alone; consider the solid orange line.

8. Demand, too, can be perceived as having a political dimension given the choice between sustainable and unsustainable products. On aggregate, individual consumption decisions implement the degree of sustainable production in the economy. This exhibits some parallels to a vote on the degree of sustainable production.

9. Panels (g) and (h) in Figure1.A.1 show the evolution of support for a potentially costly regulation of the energy sector. The patterns are similar to the ones discussed for coal emission regulations.

10. Accessed here https://users.nber.org/~taxsim/taxsim32/.

11. Appendix 1.A describes the data presented in Figure 1.2.2 in more detail.

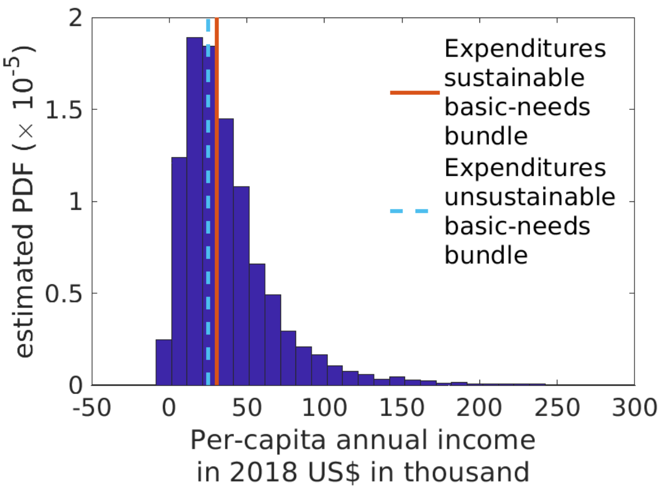


Figure 1.2.2. Basic needs and income inequality

Notes: The information on income comes from the Panel Survey of Income Dynamics (PSID). Disposable income is derived using the NBER's TAXSIM tool. As an objective measure of basic needs I refer to the consumption bundle calculated by the Institute for Women's Policy Research (IWPR). Price information on organic and conventional food from the US Department of Agriculture (USDA) proxies the price premium for sustainable goods. I apply the relative price to expenditure categories for which a sustainable alternative reasonably exists. For a single-adult household, annual expenses to cover basic needs amount to US$25,128 in unsustainable and to US$30,752 in sustainable quality.

Even if social responsibility is low and households only want to consume a small budget share of the sustainable good, inequality in the US prevents corresponding consumption: in 2018, a fraction of 36% was incapable of covering basic needs only with the unsustainable good; see the dashed blue line.

1.3 Model

I build a static partial equilibrium model of structural transformation. There are three types of agents in the model which will be described in turn: households, firms, and the government.

Households. The economy is populated by a unit mass of households. A share λ is characterized by a high effective labor productivity, z_h, and I refer to them as *rich*. The share of *poor* households, $1-\lambda$, is less productive with $z_l < z_h$. Households are identical in all other aspects.

A generic household chooses labor supply, unsustainable, and sustainable consumption to maximize lifetime utility according to[12]:

$$
\begin{aligned}
&\max_{\{c_{st}\}_{t=0}^{\infty},\{c_{nt}\}_{t=0}^{\infty},\{l_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t U(c_t, l_t; H_{nt}) \\
&s.t.\;\; p_{st}c_{st} + c_{nt} \;\leq\; w_t(1-\tau_{lt})zl_t + T_t, \\
&\qquad l_t \;\leq\; L, \\
&\qquad c_t \;=\; \begin{cases} \left(\omega^{\frac{1}{\sigma}} c_{st}^{\frac{\sigma-1}{\sigma}} + (1-\omega)^{\frac{1}{\sigma}} c_{nt}^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} & \text{if } \sigma \neq 1, \\ c_{st}^{\omega} c_{nt}^{1-\omega} & \text{if } \sigma = 1. \end{cases}
\end{aligned} \tag{1.3.1}
$$

Each period, the household receives income from lump-sum transfers, T_t, and effective labor supply, $w_t z l_t$, of which a fraction τ_{lt} has to be paid as taxes. The choice of a linear labor income tax is not innocent as a fully non-linear tax allows to correct for distributional effects of the environmental tax (Kaplow, 2012). I follow Jacobs and van der Ploeg (2019) who argue that a linear labor income tax constitutes a good benchmark for the piece-wise linear tax schemes observed in reality which are not able to fully compensate for distributional effects of the corrective tax. The real wage, w_t, and the sustainable good's price, p_{st}, are given in units of the unsustainable good, c_{nt}. A household's economic time endowment is denoted by L. The household problem reduces to a static one as the model abstracts from capital, saving technologies, and carbon cycles. Therefore, in what follows, time indices are dropped for simplicity.

Social responsibility. The consumption goods, c_s and c_n, provide the same utility in terms of quantities consumed but differ with respect to the externalities occurring in the production process. The weight on sustainable consumption, ω, in the constant elasticity of substitution aggregator, eq. (1.3.1), governs the willingness to pay for sustainable goods. As this parameter rises, households are willing to give up more units of the unsustainable good for an additional unit of the sustainable one. Therefore, I refer to ω as social responsibility. Goods are aggregated as imperfect substitutes in the composite consumption bundle

12. I drop the indicator of the household type for readability.

stressing their different degree of sustainability.[13]

The period utility function is given by

$$U(c,l;H_n) \;=\; u(c,l) - \rho(\hat{c};\bar{c}) + g(H_n).$$

The felicity function u is strictly increasing and strictly concave in composite consumption, c, and leisure, $L-l$.

Penalty term. The penalty term, $\rho(\hat{c}_t;\bar{c})$, drives a wedge between social responsibility and actual consumption. The wedge depends on the gap between the sum of goods consumed and basic needs. Individual consumption goods enter as perfect substitutes: $\hat{c} = c_n + c_s$. This assumption captures that goods are equal according to the consumption service they provide to cover basic needs. It holds that $\rho(\hat{c}) \geq 0 \;\forall \hat{c}$. The function is strictly decreasing in $\hat{c}$ and approaches zero as $\hat{c} \to \infty$. The period utility function is calibrated such that the penalty term reduces utility quickly when quantities consumed fall below basic needs, $\bar{c}$. This urges affected households to place more emphasis on maximizing the sum consumed instead of consuming in line with their taste for sustainability. Throughout the paper, I refer to this model as *baseline* model and to a model without penalty term, i.e., $\rho(\hat{c};\bar{c}) = 0 \forall \hat{c}$, as *standard* model.

The advantage of this utility specification above the common Stone-Geary preferences in the context of the paper is threefold. First, in contrast to Stone-Geary preferences, employing a penalty term generates not only heterogeneity in the *average* propensity to consume but also in the *marginal* propensity to consume either good. This effect is essential for redistribution to matter for the economic structure. Second, the preferences suggested here induce households to reshuffle their budget share through cutting consumption of the previously necessary good. Since goods are perfect substitutes as regards basic consumption services, reducing consumption of one in favor of the other is sensible. Thirdly, the preferences I suggest allow to observe consumption below the basic-needs threshold. In contrast to common consumption minima, basic needs are a soft threshold in the sense that consuming below is a possibility. Given that income levels below this threshold are observed in the data, this alternative approach seems a better fit.

13. The modeling choice of social responsibility assumes that households act responsibly irrespective of whether they perceive their action to have an impact on the externality or not. Alternatively, one could model households to internalize a fraction of the externality. Both approaches capture distinct motives for sustainable consumption. The alternative model only captures perceived effectiveness of demand to lower the externality as the motive for sustainable consumption. In contrast, the version considered here is agnostic on the motives behind sustainable consumption. Social responsibility can also be driven by image concerns, social pressure, or warm glow.

To gain some intuition on how the penalty term affects households' consumption decisions, eq. (1.3.2) below shows how consumption of the two goods relates for a utility-maximizing household:[14]

$$c_n^{\frac{1}{\sigma}} = p_s \left(\frac{1-\omega}{\omega}\right)^{\frac{1}{\sigma}} c_s^{\frac{1}{\sigma}} - (p_s - 1)\frac{\partial \rho(\hat{c};\bar{c})}{\partial c_n} \frac{c^{\frac{\sigma-1}{\sigma}} c_n^{\frac{1}{\sigma}} c_s^{\frac{1}{\sigma}}}{\omega^{\frac{1}{\sigma}}}. \tag{1.3.2}$$

When the penalty term is set to zero, eq. (1.3.2) coincides with the result in the standard model and unsustainable consumption is a constant fraction of income. Note that $\frac{\partial \rho(\hat{c};\bar{c})}{\partial c_n}$ is negative which implies that whenever the sustainable good is more expensive, that is, $p_s > 1$, unsustainable consumption is higher than in the standard model. Although sustainability might be valuable to these households, their unsustainable demand remains high.[15]

As income rises, the penalty term vanishes and households start to recompose their budget to eventually consume at the *desired* ratio, i.e., the ratio which is in line with social responsibility as it maximizes the composite consumption good given prices. Hence, the cheaper good is inferior at some income levels. Once the desired budget share is reached, a marginal increase in income does not cause a reallocation of budget shares and demand numerically coincides with the one in the standard model. Vice versa, when the unsustainable good is more expensive, unsustainable consumption is below its standard counterpart. Appendix 1.E depicts Engel curves for different degrees of social responsibility and relative prices to illustrate this feature of the model.

These preferences capture two mechanisms through which income and the environmental footprint have been shown to relate empirically. For the US, Sager (2019) finds that the consumption of emissions is increasing and concave over the income distribution. In the model, first, poor households consume a higher budget share of polluting goods. Second, rich households' consumption has a negative effect on the environment through high levels of composite consumption.

Externality. Households suffer from the size of the unsustainable sector represented by the strictly decreasing, convex function $g(H_n)$, which they take as given. To motivate this specification, think of households which understand the connection between unsustainable production and an environmental externality. The size of the unsustainable sector, captured by its labor input, H_n, may be associated with a higher risk of climate catastrophes lowering utility. As regards

14. The equation follows from the first order conditions with respect to the unsustainable and the sustainable consumption good.

15. I perceive social responsibility as a desire to consume sustainably, as a willingness to pay independent of the necessity to cover basic needs. There, hence, exist socially responsible households in the model whose consumption basket does not reflect that they are socially responsible. Instead, these households suffer from low sustainable consumption.

the other aspects of sustainability, the disutility could arise from empathy with workers and livestock which seems again well captured by the quantity of inputs used for production.

Production. Individual consumption goods are produced by a sustainable and an unsustainable sector according to the following production function

$$Y_j = A_j H_j, \text{ for } j \in \{s, n\}.$$

The variable A_j denotes total factor productivity in sector j which is exogenous and constant. While the sustainable sector does not cause negative externalities, the unsustainable one does. Profits of the sustainable and the unsustainable sector are given by

$$\pi_s = p_s Y_s - w H_s,$$
$$\pi_n = p_n Y_n - w(1 + \tau_n) H_n.$$

The government levies ad-valorem excise taxes, τ_n, on unsustainable production costs. This choice is motivated by the definition of sustainability adopted in this paper: next to corrective externalities, the externality arises from the treatment of workers and livestock. Consider an example of two sectors A and B which produce at the same degree of sustainability, but, sector A has a higher productivity. Then, the maltreatment of animals and workers should result in the same level of externality. Similarly, I assume that environmental degradation does not rise with productivity, thus, technology is emission saving in this model (such technology is, for instance, discussed in Acemoglu, Aghion, Bursztyn, and Hemous, 2012, (p.145)).[16]

Both sectors are assumed to be perfectly competitive. This, on the one hand, impedes to study interactions of social responsibility and monopolistic competition, yet, on the other hand, it allows to focus on mechanisms solely arising from the demand side. Profit-maximization of firms and choosing the unsustainable good

16. Some algebra reveals that the ad-valorem excise tax is equivalent to an ad-valorem sales tax levied on unsustainable output. The unsustainable firm's problem under a sales tax, $\hat{\tau}_n$, becomes: $(1-\hat{\tau}_n)Y_n - wH_n$, and equilibrium prices are $\hat{w} = A_n(1-\hat{\tau}_n)$ and $\hat{p}_s = \frac{A_n}{A_s}(1-\hat{\tau}_n)$. Since the corrective tax in both versions only affects prices directly, it follows that the equilibrium allocation is the same if $\tau_n = \frac{1}{1-\hat{\tau}_n} - 1$. Results for a model with a corrective tax on unsustainable consumption are qualitatively and quantitatively similar to the ones from the baseline model. While a consumption tax leaves prices constant, the labor market distortion results from the complementarity of unsustainable consumption and leisure (compare Jacobs and van der Ploeg, 2019).

as numeraire imply the following equilibrium conditions:

$$\begin{aligned} p_n &= 1, \\ w &= \frac{A_n}{1+\tau_n}, \\ p_s &= \frac{1}{1+\tau_n}\frac{A_n}{A_s}. \end{aligned}$$

Relative prices are only a function of productivities and the environmental tax.

Government. The government maximizes a Utilitarian social welfare function by the use of a corrective tax, τ_n and a distortionary labor income tax, τ_l. It redistributes revenues to households as lump-sum transfers, T, and runs a balanced budget:

$$T = \tau_l wH + \tau_n wH_n,$$

where $H = \lambda z_h l_r + (1-\lambda) z_l l_p$ is total labor supply. The government is assumed to act as a Ramsey planner: the optimal allocation is defined as maximizing the social welfare function subject to feasibility and the behavior of firms and households. [17]

Market clearance. To close the model, I require that goods and labor markets clear in equilibrium:

$$\begin{aligned} \lambda c_{sr} + (1-\lambda) c_{sp} &= Y_s, \\ \lambda c_{nr} + (1-\lambda) c_{np} &= Y_n, \\ \lambda z_h l_r + (1-\lambda) z_l l_p &= H_s + H_n. \end{aligned}$$

Appendix 1.C defines the competitive and social-planner equilibrium and provides an overview of all equations characterizing a competitive equilibrium.

17. I solve the Ramsey problem using a primal approach (Lucas and Stokey, 1983). Here, prices and policy instruments are replaced by optimality conditions describing a competitive equilibrium. Prices, taxes and transfers are then chosen to implement the optimal allocation. Appendix 1.D spells out the Ramsey problem.

1.4 Calibration

To calibrate the model, I assume the following functional forms

$$
\begin{aligned}
u(c,l) &= \log(c) - \chi \frac{l^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}}, \\
\rho(\hat{c};\bar{c}) &= \frac{1}{\phi}\exp(-\phi(c_n + c_s - \bar{c})), \\
g(H_n) &= -\psi H_n^{\eta}.
\end{aligned}
$$

The model depends on five sets of parameters. Those that govern consumption, $\phi, \bar{c}, \sigma, \omega$, labor supply, L, χ, θ, inequality, z_h, z_l, λ, production, A_n, A_s, and the externality η, ψ. In its initial steady state, the model is calibrated to the US economy in 2018; one period equals a year. Table 1.4.1 provides an overview of all parameters, their target, and the calibrated values.

The parameters governing inequality and basic needs, $\bar{c}$, are calibrated by comparing micro data on disposable household income to expenses required to satisfy basic needs. Income data comes from the PSID using tax estimates from the NBER's TAXSIM tool. The income measure also includes food stamps. Other transfers in kind, such as health care or education are accounted for in the basic-needs measure. Basic needs are taken from the IWPR (2018) (IWPR) as discussed in Appendix 1.A and Section 1.2. A share of $\lambda = 0.56$ of US households is found to be able to fully cover basic needs with sustainable goods and is therefore considered *rich*. I define households which are not able to rely on sustainable goods alone as *basic needs-constrained* or *poor*, since their income does not accommodate the satisfaction of basic needs to any arbitrary level of social responsibility. Output and income measures are expressed in terms of the basic-needs bundle, equal to 25,128$, which is normalized to $\bar{c} = 1$. The unsustainable good is the numeraire. Thus, $Y_n = 1$ equals one annual basic-needs bundle of unsustainable goods, and one unit of output in the sustainable sector, $Y_s = 1$, equals one annual basic-needs bundle of the sustainable good.

The parameter which governs the importance of basic needs, ϕ, is set to 12. This value allows to solve the model for relatively low income levels and not too big differences in hours worked, while, at the same time, ensuring a decent importance of the penalty term when income is low. Given this value of ϕ, I next deduce a value for σ, the parameter which approximately corresponds to the price elasticity of substitution (PES) of households which are unconstrained by basic needs. I use information from a micro study of the organic and conventional milk market (Chen, Saghaian, and Zheng, 2018). The parameter σ is chosen to rationalize behavior of the average household in Chen, Saghaian, and Zheng (2018). The resulting value is $\sigma = 1.71$.[18] The calibrated value is reasonable in that σ determines the elasticity of substitution between the unsustainable and the sustainable good in the composite consumption function which captures how the way a good is produced matters for utility. Hence, as regards the externality households perceive goods not as close substitutes but as having distinct characteristics. The goods are no complements either: it would be counterintuitive if utility from sustainable consumption can only be derived if there is unsustainable consumption, too.

Next, I calibrate the parameter determining social responsibility, ω. It is chosen to reconcile model equations with the market share of sustainable consumer packaged goods in 2018, which is taken from Kronthal-Sacco et al. (2020). This approach leads to a value of $\omega = 0.24$. Therefore, on average, households derive a higher utility from unsustainable consumption. This seems questionable since the unsustainable good is equivalent in consumption services but is disadvantageous in satisfying social responsibility. How can such a good be preferred by consumers? Note that the model explicitly accounts for income and price differentials only to explain the attitudes-behavior gap. That is, a gap between attitudes towards sustainability and actual consumption behavior (Vermeir and Verbeke, 2006). Therefore, the parameter ω captures not only environmental and social attitudes but also factors other than income and prices which decouple attitudes from actual consumption behavior. For example, the utility derived from unsustainable consumption can be higher as these goods are more easily available or in line with habits. As I vary the parameter in the quantitative exercise, one can think of these other factors losing in importance.

Furthermore, I separately match the following variables to values taken from the literature. The total time endowment on household level in the model matches 14.5 hours per day (following Jones, Manuelli, and Rossi, 1993) and is normalized to $L = 1$. The Frisch elasticity, θ, is set to 0.75 as suggested by Chetty, Guren, Manoli, and Weber (2011) who search to reconcile micro and macro estimates. The labor income tax rate is set to the value reported in Barrage (2020) for the US, $\tau_l = 0.24$. The tax on unsustainable labor input is set to $\tau_n = 0$.

With the values for ϕ, θ, ω, λ, $\bar{c}$, L, τ_l, and τ_n at hand, I jointly calibrate the parameters, A_n, A_s, χ, z_h, z_l, by targeting the following values while equilibrium conditions hold. First, effective labor productivity of the poor, z_l, is chosen to match average income of the poor in 2018 in terms of unsustainable basic needs: 0.68. Second, I ensure consistency with total per-capita output in \$US. Third, consequently, total income of the rich matches the difference between GDP and total income of the poor amounting to 4.00 basic need bundles. As a result, average income of a rich household in the model overestimates after-tax income

18. Appendix 1.B expounds the derivation of the price elasticity of substitution.

in the data. I take this approach nevertheless, since my focus rests on the financial capacity of low income households. Aggregate output is equally important as it determines the economy's ability to satisfy basic needs. Fourth, I require that total labor supply matches the average hours worked per worker in 2018 in the US provided by the OECD (2021) which is 0.34. This equation pins down χ. Fifth, the relative price observed for the food bundle in 2018, $p_s = 1.56$, is used to inform the productivity gap between the sustainable and unsustainable sector. Appendix 1.B.2 displays the target equations.

This approach results in $z_l = 0.03$, $z_h = 2.13$, and $A_n = 8.62$. In a sensitivity analysis in Section 1.5.3, I find that the low productivity of the poor relative to the rich does not drive the results. Here, I recalibrate the model so that the poor are 30% richer which also reduces income of the rich so that $z_l = 0.14$ and $z_h = 2.03$. The resulting disutility of labor is $\chi = 23.51$. Since the shadow value of income of the poor is relatively high due to the penalty term, they supply more labor. The household-specific hours worked per week in the baseline calibration are 24.4 and 46.4 for rich and poor households, respectively. The qualitative difference in hours worked seems implausible in the light of the results in Bick, Fuchs-Schündeln, and Lagakos (2018) who find that hours worked are indeed negatively correlated with the wage rate for poorer countries but positive in the US.

The unsustainable sector produces 56% more output per unit of labor input in the baseline calibration. I use the price difference of $p_s = 1.56$ which results from comparing organic and conventional food bundles, instead of the one resulting from the relative price of the sustainable versus unsustainable needs bundle. The reason is that the expenditure categories in the basic-needs bundle are rather broad and do not allow to decide on a more granular level whether a sustainable counterpart exists. This most likely reduces the relative price of the sustainable bundle which is found to equal 1.22. This approach is subject to caveats. For instance, it only relies on price differentials in selected food markets, and market imperfections such as monopolistic power and price stickiness are abstracted from. Furthermore, the productivity gap in other sectors might well differ from the one in the food sector. Since the production gap is a crucial parameter in the model, Section 1.5.3 discusses results for a lower productivity gap.

Finally, I choose the parameters governing the externality to make a rich household willing to give up 2% of its annual unsustainable consumption for a 1% reduction in unsustainable labor input in 2018. It is also ensured that the function is convex.

Table 1.4.1. Calibration

Parameter	Target/Source	Value
Utility		
ϕ	-	12
σ	Price elasticity in milk market (Chen, Saghaian, and Zheng, 2018)	1.71
ω	market share of consumer packaged goods with sustainability claim in base year (Kronthal-Sacco et al., 2020)	0.24
$\bar{c}$	expenses for annual basic needs from IWPR (2018) for single-adult household excluding taxes and savings in base year: 25,128$	1
Labor supply		
L	time endowment per day: 14.5 (Jones, Manuelli, and Rossi, 1993)	1
χ	average hours worked per worker: 0.34 (OECD, 2021)	23.51
θ	Chetty et al. (2011)	0.75
Externality		
η	percentage of composite consumption a rich household is willing to give up for a 1% reduction in H_n: 2%	1.34
ψ		9.98
Inequality		
z_l	average disposable income poor in terms of basic needs: 0.68	0.03
z_h	average disposable income rich in terms of basic needs; as difference between income poor and GDP: 4.00	2.13
λ	share able to purchase basic needs sustainably	0.56
Production		
A_n	GDP per capita in terms of $\bar{c}$: 2.5	8.62
A_s	relative price of sustainable food bundle: 1.56	5.52
Baseline policy		
τ_l	Barrage (2020)	0.24
τ_n	carbon tax on national level in base year	0

1.5 Results

In this section, I present and discuss the results. Section 1.5.1 shows the main results, which are subsequently discussed in Section 1.5.2. Section 1.5.3 addresses how results change when crucial assumptions are altered.

1.5.1 Main results

We are now equipped to run the main experiment: exogenously changing the degree of social responsibility shared by households. As a benchmark, I present the efficient allocation a social planner chooses in Section 1.5.1.1. Section 1.5.1.2 depicts the optimal policy and allocation.

1.5.1.1 Social planner allocation

(a) Unsustainable output **(b)** Sustainable output **(c)** Composite consumption rich/poor

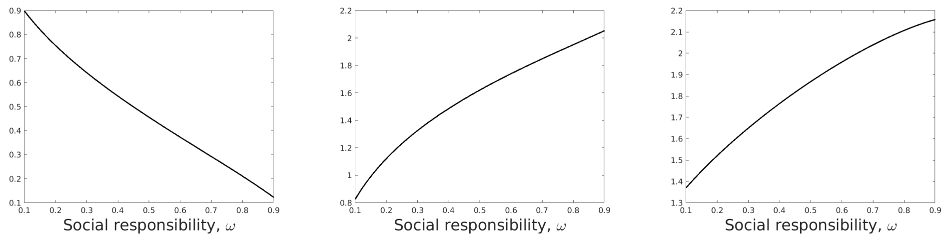


Figure 1.5.1. Efficient allocation

The social planner maximizes the Utilitarian social welfare function subject to resource constraints as formally laid out in Appendix 1.C. Figure 1.5.1 represents the results. One trade-off the social planner faces is to reduce the externality while increasing utility from consumption. The trade-off loses in tension as households begin to prefer the sustainable good. The social planner reduces unsustainable output, Panel (a), and increases the sustainable one, Panel (b), as social responsibility rises. As a result, both composite consumption, Panel (c), and the externality declines. In contrast, when social responsibility is low, the social planner prevents too high levels of consumption in order to curb the externality.

A second trade-off arises from the utility of consumption, on the one hand, and the disutility from labor, on the other hand. A shift in preferences towards a more expensive bundle—in the sense that more labor is needed to produce the same level of composite consumption—exacerbates this trade-off. Indeed, absent the externality, more expensive preferences imply a reduction in composite consumption. Yet, the presence of the externality makes it efficient to choose a lower labor input and output level, especially when tastes are inclined to the polluting good. In sum, composite consumption increases as preferences become more environmentally friendly. More expensive preferences explain the slow down of the reduction in unsustainable output as social responsibility increases.

The social planner allocation attains perfect consumption equity—due to the separability of labor and consumption in the utility function—and a steady reduction in unsustainable production as social responsibility advances. However, this allocation is not feasible under the Ramsey planner: both tax instruments lower labor supply which creates a trade-off between the provision of the environmental good and equity. The following section presents the results under the Ramsey planner.

1.5.1.2 Optimal policy and allocation

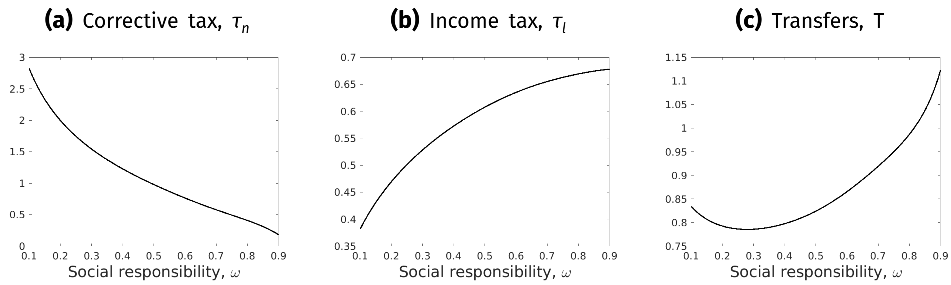


Figure 1.5.2. Optimal policy

Figure 1.5.2 shows how optimal taxes and transfers vary with social responsibility. It stands out that the optimal policy mix shifts towards redistribution as social responsibility rises. This is the first main result. When social responsibility is relatively low, such as in the baseline calibration with $\omega = 0.24$[19], a high corrective tax of $\tau_n = 1.78$ characterizes the optimal policy; that is, unsustainable producers' tax burden amounts to 178% of their production costs. The optimal labor income tax for the baseline calibration is $\tau_l = 0.50$; the government charges roughly half of a household's labor income. Transfers equal 79% of the basic-needs bundle in unsustainable goods.

As social responsibility rises to the highest value considered, $\omega = 0.9$, that is, an accepted price premium of $\frac{p_s - p_n}{p_n} = 0.32$ in equilibrium, the corrective tax steadily reduces to 18%, and the labor income tax increases to 68%. Transfers reach their peak with 1.12 units of the unsustainable basic-needs bundle.

Figure 1.5.3 depicts some key variables under the optimal policy as a function of social responsibility. The solid line reflects the variable; the dotted vertical line indicates when the sustainable good becomes more expensive than the unsustainable one.

19. In equilibrium, this corresponds to an accepted price premium of $\frac{p_s - p_n}{p_n} = -0.44$.

First, unsustainable output, that is, the externality, falls by more than 50% from 0.71 at $\omega = 0.24$ to 0.29 at $\omega = 0.9$. Sustainable output rises with social responsibility from 0.72 to 1.02 basic-needs bundles; observe Panel (a). This is driven not only by the shift in demand towards sustainable goods but also by policy interventions.[20] The output of both sectors displays some delay in the rise/drop as social responsibility increases (roughly at $\omega = 0.55$). As the corrective tax reduces, the price premium for sustainable goods rises which slows down the demand-driven rise in sustainable output and the drop in unsustainable output through consumption by the rich. For the price premium and other additional variables see Figure 1.F.1 in Appendix 1.F.

The rise in aggregate output, Panel (b), from roughly above 1.1 units of the unsustainable bundle to 1.62 is explained by two forces: first, a lower environmental tax implies a higher wage rate which boosts labor supply. Second, a reduction in the environmental tax implies a decline in distortions of labor allocations.[21]

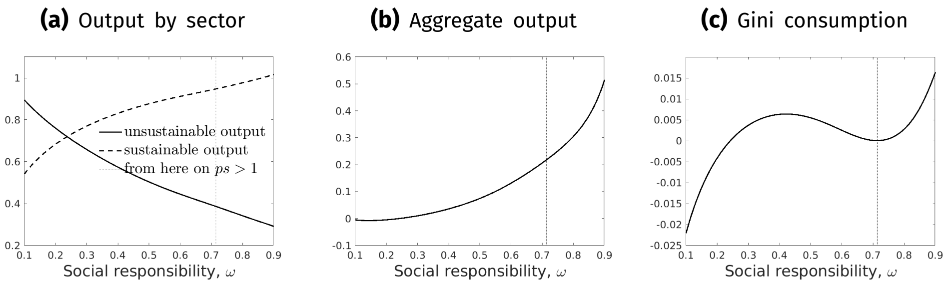


Figure 1.5.3. Optimal allocation

The Gini coefficient of composite consumption, Plot (c), rises with social responsibility but not monotonically so: there is a downward sloping part starting from a value of social responsibility of approximately $\omega = 0.4$ to $\omega = 0.71$. This reduction in the Gini of consumption results from a convergence of prices under the optimal policy. Generally, when prices of the two goods differ, the poor cannot consume the bundle which maximizes composite consumption, the *desired* bundle.

20. Figure 1.F.2 in the Appendix compares the allocations in the laissez-faire economy to the one under the optimal policy to differentiate the effect of a behavioral change from policy interventions.

21. With a non-zero environmental tax, labor is not allocated to maximize the composite consumption good given technologies but diverges because of the environmental policy. This effect is present also in a representative agent model absent basic needs. In this model, market clearance, utility-, and profit maximization imply

$$\frac{h_s}{h_n} = (1 + \tau_n)\frac{\omega}{1 - \omega}.$$

The environmental tax renders the sustainable sector relatively more productive in the eyes of the agents. But it is not, and aggregate output reduces with environmental taxation.

Instead, the poor have to take into account the quantities of individual goods they can purchase to satisfy their basic needs. This trade-off becomes more intense the bigger the price difference. At higher levels of social responsibility, the Gini is minimized when prices are equal, and the trade-off faced by the poor between the quantity and the quality of consumption vanishes. I refer to this as the *compositional* effect of equity: the composition of consumption bundles affects inequality. Panel (c) in Figure 1.F.1 shows how the actual consumption ratio of the poor relates to the desired bundle.

At lower levels of social responsibility, the increase in inequality follows from a divergence of income levels. As the environmental tax drops—implying a rise in the wage rate—the rich profit more from a higher labor income and the poor suffer from lower transfers. At very high levels of social responsibility a rise in the price of the desired bundle explains the rise in inequality. Indeed, composite consumption of the rich also reduces as they want to consume a more and more expensive bundle, however, the drop in composite consumption by the poor is more extreme: the additional compositional effect reduces composite consumption by the poor even more.

1.5.2 Discussion

What explains the optimal policy mix as social responsibility rises? I argue in the following that the policy focus turns to equity as social responsibility grows, and poor households suffer from not consuming according to their social preferences (sections 1.5.2.1 and 1.5.2.2). As a result, the government chooses a lower environmental tax to handle inequality thereby forfeiting an efficient reduction in the externality (section 1.5.2.3). To compensate for the lower environmental tax, the government sets a higher labor income tax to target the externality (section 1.5.2.4), and redistribution becomes the essential tool to handle the externality (section 1.5.2.5).

1.5.2.1 Optimal policy without basic needs

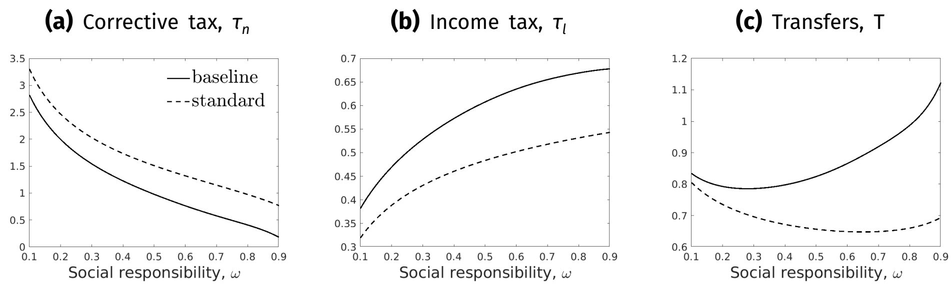


Figure 1.5.4. Optimal policy with and without basic needs

I now compare the optimal policy in the baseline model to the optimal policy in the standard model to study the role of basic needs in Figure 1.5.4. In the standard model, depicted by the dashed graphs, a shift from environmental taxation to higher labor income taxes is also visible. However, there is no rise in transfers. In contrast, transfers even diminish with social responsibility. The intuition for this result is as follows: as social responsibility reduces, government intervention for environmental reasons is less necessary. A lower corrective tax becomes optimal. The lower tax rate and a lower environmental tax base—due to the shift in demand away from the unsustainable good in the laissez-faire economy—reduce government revenues. To keep transfers from falling too much, a higher labor income tax becomes optimal.[22] The finding is in line with Bovenberg and De Mooij (1994) who show that environmental tax revenues are optimally used to lower the distortionary labor income tax.

Thus, there is no shift to redistribution absent basic needs. Hence, taking into account basic needs explains the shift away from corrective taxes to redistribution. However, whether it is explained by equity or environmental concerns is not obvious. To shed light on the rationale behind this policy change, the next section quantifies the effect of government intervention.

1.5.2.2 Policy focus

Figure 1.5.5 shows the effect of government intervention measured as the percentage change in the optimal allocation relative to the laissez-faire allocation for unsustainable production, aggregate output, and the Gini of consumption. In the baseline model, the policy focus shifts to equity, while a reduction of the externality loses in importance; see Panels (a) and (c). The externality and output are reduced by around 62.5% and 56% when social responsibility is low. In contrast, the impact reduces to around 51% and 35% when social responsibility is high, respectively. The Gini of consumption, Panel (c), however, is reduced almost similarly for all levels of social responsibility by between 66% and 60%.

I conclude from this observation that the increase in inequality makes it optimal for the government to intervene less for environmental purposes, since aggregate output and redistribution are more valuable when social responsibility is high.

22. This interpretation is supported by the impact of government intervention in the standard model, shown by Panels (a) to (c) in Figure 1.F.3 in Appendix 1.F.2. The government reduces the externality by roughly the same for all levels of social responsibility. The strong reduction in inequality when the environmental tax is high follows from the reduced labor income of the rich. It is a byproduct of the environmental policy.

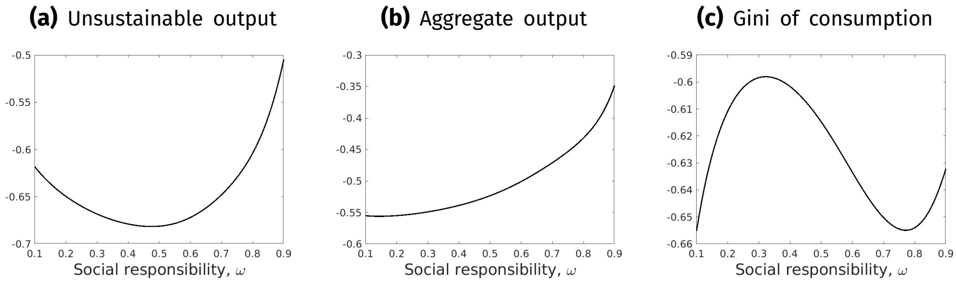


Figure 1.5.5. Effect of government intervention

Notes: The figure shows the percentage change under the optimal policy relative to the laissez-faire allocation in the baseline model.

1.5.2.3 Comparison to the efficient allocation

Figure 1.5.6 compares the optimal allocation to the efficient one. As a result of the more pronounced importance of inequality, the optimal ratio of unsustainable to sustainable production does not converge to the efficient ratio as social responsibility rises, consider Panel (a) in Figure 1.5.6. Panel (b) of the same Figure depicts how the gap between unsustainable production in the optimal and the efficient allocation widens with social responsibility. This reflects that the optimal policy is more concerned with equity. Hence, the Ramsey planner relinquishes a more efficient reduction in the externality in favor of equity.[23] Panel (c) contrasts the efficient and optimal output ratio in the standard model absent basic needs. In this model, the behavioral change in consumption helps attain an output ratio close to the efficient one despite a lower environmental tax. As households become more socially responsible, the government is able to implement a more efficient level of the externality despite the second motive of government intervention: inequality.

1.5.2.4 Reliance on labor income tax as corrective policy instrument

How much of the rise in labor taxes is explained by equity and how much by the externality motive of government intervention? I argue in this section that the turn in the policy focus to equity does not fully explain the rise in redistribution. In fact, once the corrective tax is set lower to better cope with the higher degree of inequality, the government finds it advantageous to exploit the redistribution channel of environmental policy by setting an even higher labor income tax than

23. I run an additional experiment, where I implement the optimal policy from the standard model into the baseline model. This policy features a higher environmental tax. Figure 1.F.4 in the Appendix shows the results. They reassure that the environmental tax would indeed attain a lower externality level very close to the efficient one. The reliance on redistribution, thus, is not rationalized by the environmental tax being less effective in lowering the externality.

(a) Output ratio, y_n/y_s, baseline model **(b)** Unsustainable output, y_n, baseline model **(c)** Output ratio, y_n/y_s, standard model

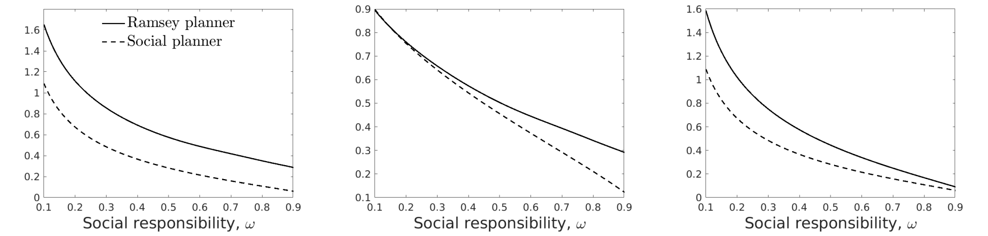


Figure 1.5.6. Comparison optimal and efficient allocation

absent an externality. More generally, the following section shows that in an unequal world labor income taxes are used as a corrective policy tool even absent basic needs.

To show that the labor income tax is higher in the model with externality for environmental reasons requires to compare the optimal labor income tax in the full model to the optimal tax resulting in a model without externality but the environmental tax is fixed at its optimal level. The reason is that the corrective tax affects both efficiency costs of income taxation and inequality which alter the optimal income tax independent of the externality. In the counterfactual experiment proposed here, efficiency costs and equity benefits of labor income taxation are equivalent to the full model. Comparing the optimal labor income tax resulting in this setting when the externality is switched off to the full model, captures solely the impact of the externality on the optimal labor income tax.

(a) Income tax, τ_l, baseline model **(b)** Income tax, τ_l, standard model **(c)** Decomposition policy effect on unsustainable output

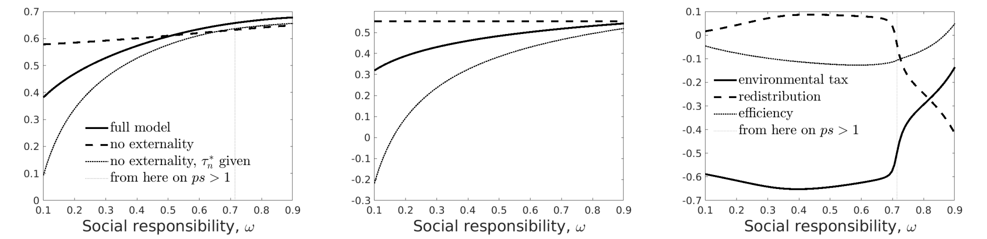


Figure 1.5.7. Labor income tax as environmental policy instrument

Notes: Panels (a) and (b): the solid graph represents the optimal policy in the full model. The dashed graph results in a model when the unsustainable sector does not produce any externality. Finally, the thin dotted line depicts the optimal labor income tax in a model where the optimal environmental tax is fed into the model as a parameter but there is no externality. Panel (c) shows the additional change in unsustainable output implemented by the respective policy relative to the laissez-faire level, where, first, the environmental tax is implemented, followed by lump-sum redistribution, the redistribution channel, and finally labor is allowed to adjust, the efficiency channel. Panel (c) refers to the baseline model.

In Panel (a) in Figure 1.5.7, the dashed graph shows the optimal policy when the externality is set to zero so that the government only cares about inequality. The solid graph represents the optimal policy in the full baseline model. The thin dotted line shows the optimal policy when the optimal environmental tax resulting in the full model is fed into the Ramsey model as a parameter but the externality is kept at zero. It stands out that at all levels of social responsibility, labor income taxation is used as a corrective policy measure; consider the solid and dotted graphs. When social responsibility is low, the labor income tax is up to 30 percentage points higher to reduce the externality. At these levels of social responsibility, labor income taxation contributes to lowering the externality through lowering labor supply, the *efficiency channel* (which I further discuss in Section 1.5.2.5 below).

The use of labor income taxes as environmental policy element is robust to whether basic needs are considered in the analysis or not; observe the equivalent graph for the standard model in Panel (b). In a representative agent calibration of the economy, however, the labor income tax is optimally set to zero; see Appendix 1.F.4. Hence, inequality makes it optimal to set lower environmental taxes complemented with distortionary labor income taxes to target the externality; the finding is in contrast to Jacobs and van der Ploeg (2019).

Consider again Panel (a) in Figure 1.5.7. The reliance on labor income taxation as environmental policy vanishes with social responsibility, but not completely; instead, the labor income tax is constantly around 0.5 percentage points higher in the setting with externality. The role of labor income taxes as a environmental policy instrument pushes them above optimal levels absent externality; compare the solid and dashed graphs. This finding is in stark contrast to Bovenberg and De Mooij (1994) who argue that environmental tax revenues are optimally used to lower the distortionary labor income tax. In this model, instead, the additional environmental benefits through redistribution exploiting heterogeneous marginal propensities to consume sustainable goods—the *redistribution channel* of environmental policy—outweigh the increased efficiency costs.[24]

1.5.2.5 Effectiveness of policy instruments

Having established that the optimal policy shifts to redistribution for equity reasons, it remains an open question how important individual tax instruments are to lower the externality. Given that the impact of taxes on allocations is interdependent, further assumptions are necessary to tell apart the effect of

24. In the standard model, the optimal labor income tax in the specification with externality never exceeds the level in the world without externality, in line with the weak double-dividend result. When the environmental tax can almost implement the efficient level of the externality, labor income taxation is almost only used for equity purposes; compare Panel (b) in Figure 1.5.7.

distinct policy channels. I make the following assumption: the government chooses the optimal tax system jointly to maximize the social welfare function but implements taxes sequentially. First, the optimal corrective tax is implemented (step 1). Second, the optimal labor income tax is enforced. The effect of the income tax is split into the redistribution channel (step 2) by keeping labor supply fixed but raising the labor income tax to the optimal level, and the efficiency channel (step 3), where labor supply is allowed to react to the optimal labor income tax.

Panel (c) in figure 1.5.7 depicts the contribution of each channel on unsustainable output as a percentage of the laissez-faire level: the effect of the corrective tax (the thick solid line), the redistribution channel (the dashed graph), and the efficiency channel (the thin dashed-dotted graph).[25]

To summarize the main finding of this exercise: redistribution raises the externality for levels of social responsibility below $\omega = 0.71$, that is, when the sustainable good is cheaper. For all levels of social responsibility above $\omega = 0.71$—now the sustainable good is more expensive—redistribution adds to the reduction of the externality. Its importance increases with social responsibility eventually accounting for approximately 90% of the total policy effect on the externality by implying a cut of up to 40%. Simultaneously, the impact of the corrective tax reduces to -12%, thereby only accounting for 20% of the total policy intervention. The reason is that demand of poor households is less responsive to changes in relative prices as long as the order of prices persists. The efficiency channel of labor income taxation contributes to lowering the externality until social responsibility is very high at around $\omega = 0.85$. At the highest levels of social responsibility, the efficiency channel causes an increase in the externality of approximately 6%. The positive effect is explained by a lower income of poor households due to the reduction in output. Consequently, the poor raise their share of unsustainable consumption. I provide an in depth analysis on each instrument's mechanism in Appendix 1.F.5, where I also present additional variables in Figure 1.F.6.

1.5.3 Sensitivity

While social responsibility is changed exogenously, it is assumed that all other features of the economy remain unchanged. This seems questionable since variations in social responsibility most likely take time. This section, therefore, discusses results with (i) a lower productivity gap and (ii) changes in the distribution of income.

25. For any variable X, percentage changes are calculated as $\frac{X^2-X^1}{X^0} = \frac{X^2-X^0}{X^0} - \frac{X^1-X^0}{X^0}$ =% *change due to step 2 in addition to the effect of step 1*. Where the superscript indicates the step in the experiment, and zero indicates the laissez-faire economy.

1.5.3.1 Lower productivity gap

Comparison of the optimal policy at a lower productivity gap of $A_n/A_s = 1.22$ to the baseline calibration[26] resembles the comparison to the standard model. As shown by Figure 1.5.8, there is no shift to redistribution when productivity in the sustainable sector is higher. The corrective tax is so high so that the sustainable good is the cheaper alternative for all values of social responsibility. As a result, redistribution increases the externality throughout. Indeed, the optimal labor income tax never exceeds the optimal tax absent an externality, compare Panel (c).

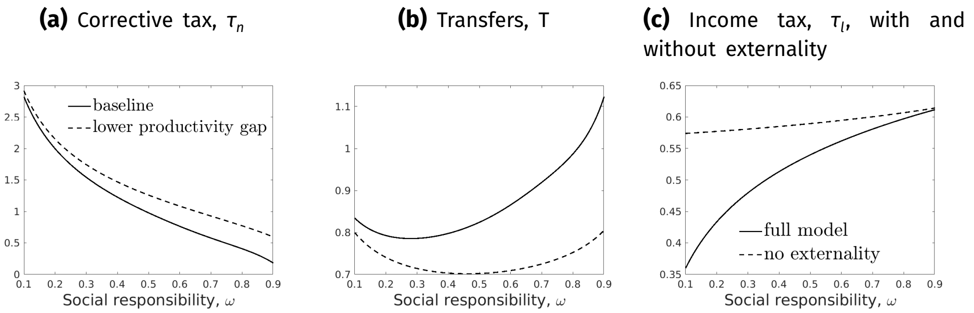


Figure 1.5.8. Optimal policy with lower productivity gap

1.5.3.2 Less inequality

Income of the poor plays a crucial role; as argued, the severity of inequality makes the shift to redistribution optimal when social responsibility is very high. Furthermore, the distribution of income determines the direction of the effect of redistribution on the externality.

Increasing income of the poor by 30% so that they can consume 90% of an unsustainable basic-needs bundle in the baseline calibration[27] results in a reduced shift to redistribution as depicted by Figure 1.5.9. When social responsibility is low, the corrective tax is lower and the labor income tax is slightly higher than in the baseline calibration. When poor households are richer and their consumption bundle is less determined by basic needs, their demand is more responsive to the corrective tax through small changes in the relative price. Furthermore, unsustainable demand is lower in the laissez-faire allocation explaining a lower environmental tax. The labor income tax is higher at these values of social responsibility to counter the smaller revenues through corrective taxation.

26. This calibration results in $A_s = 7.04$ instead of $A_s = 5.52$ in the baseline calibration. Except for the disutility of labor which raises slightly, $\chi = 23.55$, and a lower degree of social responsibility, $\omega = 0.21$, all other parameters remain unchanged.

27. In this counterfactual calibration, $z_h = 2.03$ and $z_l = 0.14$ in contrast to $z_h = 2.13$ and $z_l = 0.03$ in the baseline calibration. All other parameters remain unchanged.

For high levels of social responsibility, the corrective tax is higher than in the baseline calibration, and the labor income tax is smaller. As inequality is less intense, a more aggressive corrective tax can be implemented. Additionally, the elasticity of demand by the poor to the corrective tax is higher. These two observations raise the effectiveness of the corrective tax on the externality compared to the baseline model; see Panel (c) in Figure 1.5.9. Albeit redistributing less, the redistribution channel of corrective policy remains important a corrective policy instrument. A smaller increase in income of the poor suffices to raise their sustainable budget share similarly to the baseline calibration.

(a) Corrective tax, τ_n **(b)** Income tax, τ_l **(c)** Decomposition policy effect on y_n

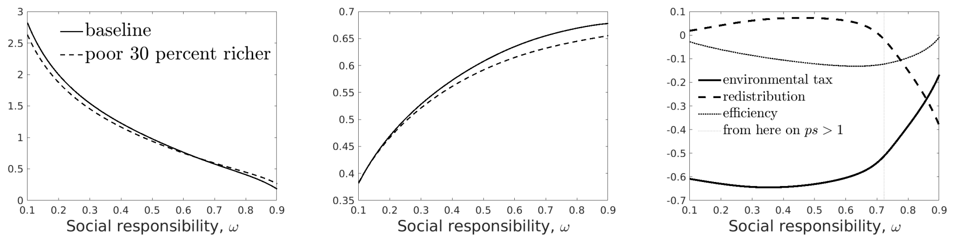


Figure 1.5.9. Optimal policy with poor 30% richer

1.6 Conclusion

This chapter shows that growing social responsibility causes a shift in the optimal policy mix away from corrective taxation towards redistribution. Redistribution becomes the preferred environmental policy tool above corrective taxes when social responsibility is high. The reason is that rising social responsibility induces a detrimental increase in consumption inequality, as more sustainable consumption conflicts with the satisfaction of a minimum consumption level by the poor. Then, redistribution achieves a better balance between equity and the provision of the public good, however, this policy choice comes at the cost of an inefficiently high externality.

More generally, I find that, in an unequal economy, labor income taxes form part of the optimal environmental policy. They complement corrective taxation in lowering the externality through redistribution or a reduction of aggregate production. While the former channel relies on the non-linearity of Engel curves and depends on the level of social responsibility, the latter mechanism persists in a model with linear Engel curves and is independent of social responsibility.

The results constitute a warning against policy ambitions to foster consumers' willingness to pay for sustainable consumption goods at today's high income inequality. One might expect that a behavioral shift in demand allows for a lower externality at smaller efficiency costs, since less government intervention is required. However, the rise in social responsibility increases inequality so that the need for government intervention remains high. Eventually, the aggravation of inequality prevents the government to attain the efficient level of the externality.

To finish, I briefly point out directions for further research. First, the paper focuses on the role of inequality abstracting from dynamics in other dimensions. For example, in parallel to changing preferences, technological progress could ameliorate the increase in consumption inequality by narrowing the productivity gap between sectors. Second, basic needs are calibrated to an objective measure. This is informative on what would happen if we were willing to reduce consumption to a minimum. In reality, however, basic needs are most likely subjective. A calibration from observed consumption shares would allow to take the subjectivity of consumption minima into account.

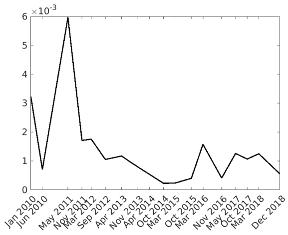
Appendix 1.A Attitudes, basic needs, and inequality

Attitudes. Figure 1.2.1 in the main text draws from the *Climate Change in the American Mind* project (Howe, P., Mildenberger, M., Marlon, J., & Leiserowitz, A., 2015). A participant is categorized as concerned about climate change or supporting a coal emission regulation if he/she chooses category 3 or 4 out of 4 categories in response to the question "*How worried are you about global warming?*" or "*How much do you support or oppose the following policy? Set strict carbon dioxide emission limits on existing coal-fired power plants to reduce global warming and improve public health. Power plants would have to reduce their emissions and/or invest in renewable energy and energy efficiency. The cost of electricity to consumers and companies would likely increase*". The highest category 4 was labeled *a great deal* or *strongly support* and category 1 *not at all* or *strongly oppose*. Participants who refused to answer whether they are worried made up 2.3% of the whole weighted sample population at maximum. As regards the support for coal emissions, roughly 3.7% of the weighted sample did not answer at maximum.

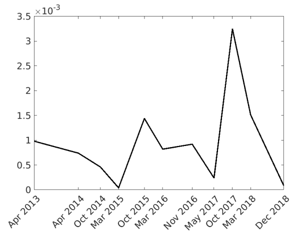
Panel (a) and (b) in Figure 1.A.1 show the variances of the two measures discussed above across income groups: being worried and support for the regulation of coal emissions. While concerns about climate change seem to converge across income groups, the support for coal emissions, if anything, diverges. Panel (c) and (d) show the strongly and the weakly worried share of households across income groups. The similar shares are shown by Panels (e) and (f) for the support of coal emissions. In line with this chapter's approach, the increase in strong support for the policy stems from medium to high-income households. The rise in the weakly supporting share is driven by the lowest income group; compare Panels (e) and (f). As regards attitudes towards climate change, the strong and the weak share behave similarly across income groups; see Panels

(c) and (d) in the same figure. Finally, Panel (g) highlights how the support for another potentially costly energy policy evolved over time; that is, the answer to the question: "*How much do you support or oppose the following policies? Require electric utilities to produce at least 20% of their electricity from wind, solar, or other renewable energy sources, even if it costs the average household an extra \$100 a year.*" Panel (h) differentiates total support for energy regulation into weak and strong support and compares it to the evolution of concerns. Panels (g) and (h) support the evidence of the plots on coal emission regulation.

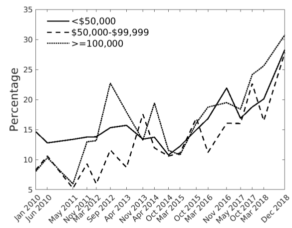
(a) Variance: Concerns



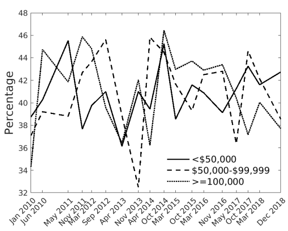
(b) Variance: Coal emission regulation



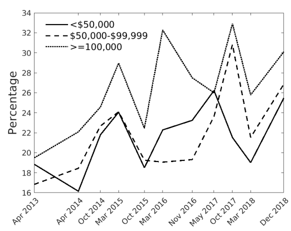
(c) Strongly worried



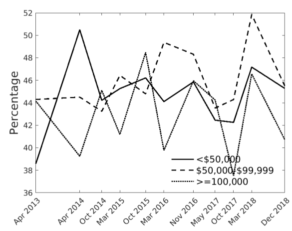
(d) Weakly worried



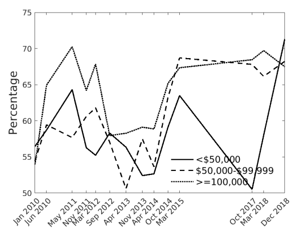
(e) Strong support coal emissions by income group



(f) Weak support coal emissions by income group



(g) Support for utility regulation



(h) Weak and strong support: Utility regulation

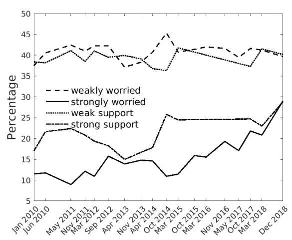


Figure 1.A.1. Attitudes towards climate change

Basic needs. Basic needs for a single-adult working household are taken from the *Basic Economic Security Tables* provided by the IWPR (2018).[28] The basic-needs bundle is more objective in that it does not (solely)[29] rely on observed consumption and expenses which most likely do not reflect needs but are affected by financial constraints or habits. For example, rents and utilities are taken from the US Department of Housing and Urban Development Fair Market Rents which are rents at the 40th or 50th percentiles of US rents. Food is taken from the USDA Center for Nutrition Policy and Promotion's low-cost food plan. Which is the third lowest out of four consumption food plans. The USDA includes a bit more than a minimal standard of nutrition but does only allow for self-prepared food. For more information on the methodology see McMahon, Horning, and Suh (2018).

Table 1.A.1 shows for each consumption category expenses for an unsustainable, column (1), and sustainable quality, column (2). Throughout the calculations, I make conservative choices so that the resulting expenses can be interpreted as a lower bound of basic needs. Therefore, basic needs for a single adult without child but with employer benefits are considered reducing expenses for childcare and health. Furthermore, savings for emergencies and retirement are also abstracted from.

In the next three paragraphs, I explain in more detail how I derive estimates of the sustainable basic-needs expenses. I assume that the expenses provided by the IWPR (2018) are given in terms of unsustainable goods which make up the biggest market share and are generally cheaper, more in line with a basic-needs bundle. To proxy expenses for sustainable counterparts, I use the relative price resulting from a food basket constructed by the EAT-Lancet Commission (2019), represented by Table 1.A.2,[30] and prices of the USDA (2021) for organic and conventional goods.

Prices are provided on a weekly basis from the beginning of 2015 to the end of 2020 as a national weighted average for a variety of items such as *yogurt* or *mushrooms*. I classify these granular product categories into the product categories used by the EAT-Lancet Commission (2019). I have price data available for seven out of 14 items; compare column (2) of Table 1.A.2. Weeks for which prices are not available are imputed using the average of 4 adjacent weeks. In Figure 1.A.2, I plot the weekly expenses for the resulting food bundle in organic and conventional

28. For the US, a variety of basic-needs measures exists. For an overview see Gordon M. Fisher (2012). The one calculated by the IWPR has been chosen as it provides a nation-wide measure and necessary expenses by consumption category so that the overall price of a sustainable bundle can be calculated at less aggregate level.

29. The *Health care* and *Personal and Household items* are based on observed expenditures.

30. The EAT-Lancet Commission (2019) constructed dietary plans which respect both health and planetary boundaries. The advantage of this consumption basket is that it contains detailed information on quantities and product types and therefore allows to calculate a sustainable price which is not the case for the more granular food category in the IWPR's basic-needs bundle. At the same time, it is designed to meet basic needs.

prices. To smooth short run fluctuations, I take the mean over the full time span over the weekly relative expenses of the organic relative to the conventional basket. The price for the organic bundle is on average 56% higher than its unsustainable counterpart. The result is taken to approximate the relative sustainable price in 2018.

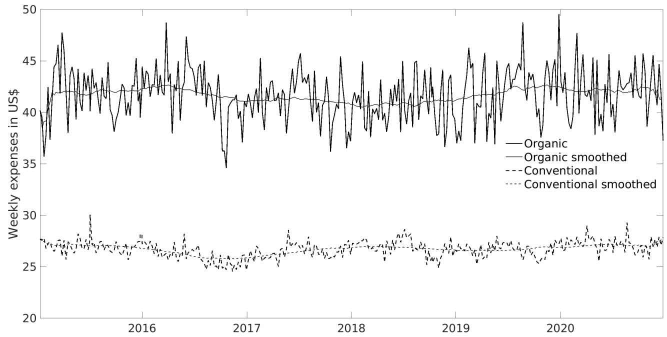


Figure 1.A.2. Weekly expenses for organic and conventional food bundles

Notes: Expenses for a food consumption bundle as suggested by the EAT-Lancet Commission (2019) for which organic and conventional prices are available. The thick lines refer to weekly expenses, while the thin lines show smoothed expenses as the floating average over one year.

I apply the relative price to those categories in the IWPR (2018) basic-needs bundle which plausibly have a sustainable counterpart, as indicated by column (3) in Table 1.A.1. Again, since categories are fairly broad, I only apply the price difference to categories which broadly allow for a sustainable choice. For instance, since rents make up the biggest part of the *Housing & Utilities* category, I do not multiply this item despite energy expenses falling into this category, too. Summing over all consumption categories gives expenses for a sustainable and an unsustainable bundle.

Table 1.A.1. Monthly basic expenses for a US single working adult in 2018 US$

Category	(1) Unsustainable	(2) Sustainable	(3) Sustainable exists
Housing & Utilities	785	785	false
Food	267	417.23	true
Transportation	476	476	false
Personal & Household items	389	607.88	true
Healthcare	177	276.59	true
Monthly basic needs (sum)	2,094	2,562.70	
Annual basic needs	25,128	30,752.38	

Income inequality. Expenses for the single-adult sustainable basic-needs bundle are compared to households' per-capita disposable income to judge whether a household has too few resources to consume according to an arbitrary level of social responsibility.

Table 1.A.2. Requierd nutrient intake

Product	(1) Intake in grams per day	(2) Price available
Rice, wheat, corn	232	-
Potatoes	50	✓
Vegetables	300	✓
Fruits	200	✓
Whole milk, equivalents	250	✓
Beef, lamb, pork	14	✓
Chicken, other poultry	29	✓
Eggs	13	✓
Fish	28	-
Legumes	75	-
Nuts	50	-
Unsaturated oils	40	-
Saturated oils	11.8	-
Sugars	31	-

Annual income data comes from the PSID (2020). The total family income measure encompasses pre-tax income from all sources including transfers, social security income, and food stamps. I derive households' disposable incomes using the NBER's TAXSIM tool.[31] The *old* OECD equivalence scale[32] is applied to derive the respective per-capita income a household has at its disposal.

The unsustainable basic-needs expenses are almost twice as big as the official poverty threshold provided by the Bureau of Labor Statistics in 2018 which on average across the US amounts to US$12,784 for a single adult. The official poverty measure is an inflation-corrected measure of a poverty level defined in 1963. The measure is three times the expenses for a minimum diet in 1963.[33] It, hence, does not account for changes in living costs such as medical care or transportation costs.[34]

31. Provided here https://users.nber.org/~taxsim/taxsim32/.

32. I use the *old* OECD equivalence scale which applies a higher weight on the second adult and children than the modified version. I follow Bradshaw, Middleton, Davis, Oldfi, Smith, et al. (2008) who show for the UK that the modified scale underestimates the needs of families.

33. The factor of three equals the relation of food expenses to total after-tax money income of the average US family in 1955.

34. For more details on how the census bureau's poverty threshold is derived see https://www.census.gov/topics/income-poverty/poverty/guidance/poverty-measures.html.

Appendix 1.B Calibration

1.B.1 Price elasticity of substitution

The price elasticity of substitution between sustainable and unsustainable produce, defined as

$$PES = \frac{\frac{d\left(\frac{c_n}{c_s}\right)}{\frac{c_n}{c_s}}}{\frac{d\left(\frac{p_s}{p_n}\right)}{\frac{p_s}{p_n}}},$$

is matched with the price elasticity of substitution between organic and conventional milk purchases derived from estimates found by Chen, Saghaian, and Zheng (2018). The study uses Nielsen scanner data for 2013 in the US with a final sample of 24,861 households who purchased milk regularly. The milk market seems to be a good proxy for the market for sustainability as no close substitutes are available.

In the model, the unsustainable price is held fixed with the unsustainable good being the numeraire. This is not the case in the data and both conventional and organic prices vary. I, therefore, derive an adequate measure of price elasticity for the model under the assumption that the unsustainable price is constant in the data. As a result, the 1 percentage change in the relative price is solely driven by a change in the sustainable price.

$$\frac{d\left(\frac{p_s}{p_n}\right)}{\frac{p_s}{p_n}} = \frac{dp_s}{p_s} - \frac{dp_n}{p_n} = \frac{dp_s}{p_s}.$$

and the price elasticity of substitution becomes

$$PES = \frac{\frac{d\left(\frac{c_n}{c_s}\right)}{\frac{c_n}{c_s}}}{\frac{dp_s}{p_s}} = \frac{\frac{dc_n}{c_n}}{\frac{dp_s}{p_s}} - \frac{\frac{dc_s}{c_s}}{\frac{dp_s}{p_s}}.$$

In the data, cross and own price elasticities of three milk categories are documented: *organic, conventional brand,* and *conventional private label*. The organic category is treated as the sustainable counterpart in the data. The conventional subcategories are added to match unsustainable consumption. Hence,

$$c_n = c_{cpl} + c_{cb},$$

where *cpl* and *cb* indicate *conventional private label* and *brand*, respectively. The elasticity of unsustainable consumption with respect to sustainable prices is then given by

$$\frac{\frac{dc_n}{c_n}}{\frac{dp_s}{p_s}} = \frac{\frac{dc_{cpl}}{c_{cpl}}}{\frac{dp_s}{p_s}} \frac{c_{cpl}}{c_n} + \frac{\frac{dc_{cb}}{c_{cb}}}{\frac{dp_s}{p_s}} \frac{c_{cb}}{c_n}.$$

All terms on the right-hand side and the own price elasticity of sustainable milk consumption are available from Chen, Saghaian, and Zheng (2018). The resulting price elasticity is 2.52. That is, a 1 percentage increase in the price of organic milk implies a 2.5% rise in the ratio of unsustainable to sustainable consumption.

The elasticities estimated in Chen, Saghaian, and Zheng (2018) are measured at the average consumer in the sample; therefore, the model is calibrated to match the price elasticity of substitution at the observed average values of consumption and budget shares in the data.

1.B.2 Final calibration step

In the final step of the calibration, I jointly choose effective labor productivity, total factor productivity, and the disutility from labor, χ, by requiring that in the baseline calibrated equilibrium the following target equations

$$\begin{aligned} \text{average annual labor supply} &= \lambda l_{r,base} + (1-\lambda) l_{p,base} \\ \text{income rich} &= z_h w_{base}(1-\tau_l) l_{r,base} + T_{base} \\ \text{income poor} &= z_l w_{base}(1-\tau_l) l_{p,base} + T_{base} \\ \text{unsustainable output} &= A_n H_{n,base} \\ \text{sustainable output} &= A_s H_{s,base} \end{aligned}$$

and the following equilibrium equations hold: labor supply, labor market clearing, firms maximize profits, the government balanced budget, and the complementary slackness conditions for labor supply.

Appendix 1.C Equilibrium definitions and equations

Recall that the model is static.

Social planner equilibrium. The social planner's problem is defined as an allocation $\{c_{sr}, c_{nr}, c_{sp}, c_{np}, l_r, l_p, H_s, H_n\}$ which solves

$$\begin{aligned}
\max_{c_{sr},c_{nr},c_{sp},c_{np},l_r,l_p,H_s,H_n} W^{SP} &= (1-\lambda)U_p + \lambda U_r \\
s.t.\ \lambda c_{nr} + (1-\lambda)c_{np} &= A_n H_n \\
\lambda c_{sr} + (1-\lambda)c_{sp} &= A_s H_s \\
\lambda z_h l_r + (1-\lambda) z_l l_p &= H_n + H_s \\
l_r &\leq L \\
l_p &\leq L.
\end{aligned}$$

Competitive equilibrium. A competitive equilibrium is defined as an allocation $\{c_{sr}, c_{nr}, c_{sp}, c_{np}, l_r, l_p, H_s, H_n\}$, a set of prices $\{p_s, w\}$, and a tax system $\{\tau_n, \tau_l, T\}$ such that
(i) households maximize their lifetime utility subject to their budget and time constraint in each period,
(ii) in each period sustainable and unsustainable firms maximize profits,
(iii) the government maximizes social welfare subject to a balanced budget, and
(iv) markets for the consumption goods and labor clear.

Model equations of the competitive equilibrium.

$$
\begin{aligned}
\text{FOC consumption rich} \quad & U_{csr} = p_s\mu_r \\
& U_{cnr} = \mu_r \\
\text{FOC consumption poor} \quad & U_{csr} = p_s\mu_p \\
& U_{cnr} = \mu_p \\
\text{Labor supply} \quad & \chi l_r^{1/\theta} + \gamma_{lr} = \mu_r w(1-\tau_l)z_h \\
& \chi l_p^{1/\theta} + \gamma_{lp} = \mu_p w(1-\tau_l)z_l \\
\text{Household budgets} \quad & c_{sr}p_s + c_{nr} = l_r w(1-\tau_l)z_h + T \\
& c_{sp}p_s + c_{np} = l_p w(1-\tau_l)z_l + T \\
\text{Profit maximization by firms} \quad & A_n = w(1+\tau_n) \\
& p_s A_s = w \\
\text{Production} \quad & Y_s = A_s H_s \\
& Y_n = A_n H_n \\
\text{Government budget} \quad & T = \tau_n w H_n + \tau_l w(H_n + H_s) \\
\text{Market clearance} \quad & H_s + H_n = \lambda z_h l_r + (1-\lambda)z_l l_p \\
& \lambda c_{sr} + (1-\lambda)c_{sp} = Y_s \\
\text{Complementary slackness conditions} \quad & \gamma_{lp}(L - l_p) = 0 \\
& \gamma_{lr}(L - l_r) = 0
\end{aligned}
$$

The variables μ_i, γ_{li} with $i \in \{r, p\}$ are the Lagrange multipliers in the household problem on the budget and time constraint, respectively. The market for the unsustainable good clears by Walras's law.

Appendix 1.D Primal approach

Throughout an interior solution is assumed. In a competitive equilibrium, the following holds:

$$\begin{aligned}
\text{FOC consumption rich} \quad & p_s = \frac{U_{c_{sr}}}{U_{c_{nr}}} && (1.D.1)\\
\text{FOC labor rich} \quad & w(1-\tau_l) = \frac{-U_{l_r}}{z_h U_{c_{nr}}}, &&\\
\text{Profit max. sustainable sector} \quad & w = A_s p_s &&\\
\text{Profit max. unsustainable sector} \quad & \tau_n = \frac{A_n}{w} - 1 &&\\
\text{Government budget} \quad & T = \tau_l(H_s + H_n)w + \tau_n H_n w, && (1.D.2)
\end{aligned}$$

where $U_{lr} = -\chi l_r^{1/\theta}$. Rich household variables are indexed by an r, and variables referring to a poor household are marked by p.

Using the equations characterizing a competitive equilibrium, see Appendix 1.C, the Ramsey problem can be written as

$$\begin{aligned}
\max_{c_{sr},\, c_{sp},\, c_{np},\, l_r\, l_p,\, H_s,\, H_n} \mathscr{L} =& \lambda U_r + (1-\lambda)U_p\\
&- \mu_{imr}\lambda\left[c_{sr}U_{c_{sr}} + (c_{nr} - T)U_{c_{nr}} + l_r U_{lr}\right]\\
&- \mu_{imp}(1-\lambda)\left[c_{sp}U_{c_{sp}} + (c_{np} - T)U_{c_{np}} + l_p U_{lp}\right]\\
&- \mu_{rc}\left[p_s\left(\lambda c_{sr} + (1-\lambda)c_{sp}\right) + \lambda c_{nr} + (1-\lambda)c_{np} - p_s A_s H_s - A_n H_n\right]\\
&- \mu_{lab}\left[H_n + H_s - (\lambda z_h l_r + (1-\lambda) z_l l_p)\right]\\
&- \mu_{FOCps}\left[ps - \frac{U_{c_{sp}}}{U_{c_{np}}}\right]\\
&- \mu_{FOCw}\left[w(1-\tau_l) - \frac{-U_{lp}}{z_l U_{c_{np}}}\right]\\
&- \mu_{sus.market}\left[\lambda c_{sr} + (1-\lambda)c_{sp} - A_s H_s\right],
\end{aligned}$$

where prices and policy instruments are substituted by equations 1.D.1 to 1.D.2. I further assume that the Ramsey planner's first-order conditions are also sufficient to maximize the objective function.

The first two constraints, following μ_{imp} and μ_{imr}, the *implementability constraints*, ensure that the households budget holds under the optimal allocation. Satisfaction of the resource constraint, following μ_{rc}, and labor market clearing, μ_{lab}, is also ensured. To account for inequality, the first order conditions of the poor household type which include prices are explicitly considered as constraints to the Ramsey problem, following the Lagrange multipliers μ_{FOCps} and μ_{FOCw}, while the respective equations for the rich household type are used to replace prices and policy instruments. In contrast to Barrage (2020), where only one consumption good exists, the market clearing condition for the sustainable market needs to be explicitly considered as a constraint, too; the respective multiplier is $\mu_{sus.market}$. By substituting the optimal allocation from the Ramsey problem into eqs. (1.D.1) to (1.D.2), prices and the optimal policy are determined.

The proofs to show (1) that the resulting optimal allocation can be implemented as a competitive equilibrium and (2) that a competitive equilibrium satisfies the constraints on the Ramsey planner's problem follow Barrage (2020).

Appendix 1.E Social responsibility and redistribution

In a standard model with homogeneous marginal propensities to consume (MPCU), redistribution does not affect the externality. The labor income tax only alters the externality through an efficiency channel. On the contrary, in the baseline model, redistribution to the poor advantageously affects the externality when the MPCU of the rich is higher than that of the poor.

Whether the poor have a lower MPCU, depends on the distribution of income. The Engel curves in figure 1.E.1 illustrate how the MPCU (the slope of the Engel curve) varies with income and social responsibility. Each plot depicts demand as a function of income for two different values of social responsibility: a low one with $\omega = 0.24$ on the left (which corresponds to the calibrated value in 2018) and a high one with $\omega = 0.9$ on the right. The price of the sustainable good is fixed at $p_s = 1.56$, which is in line with a corrective tax equal to zero in the baseline calibration. Demand for the unsustainable good is shown by the dashed graphs and for the sustainable one by the solid one. The thick graphs refer to the baseline model with basic needs. The thin ones refer to the equivalent variable in the standard model. Engel curves for a scenario with a sustainable price below unity are presented in figure 1.E.2.

Externality. Consider, first, the left-hand plot in figure 1.E.1 with $\omega = 0.9$ and a rich and a poor household with an income level of US\$50,256 and US\$25,128, which buy two and one annual unsustainable basic-needs bundle, respectively. In the baseline model, transferring a marginal unit of income lump-sum from the rich to the poor results in a reduction of unsustainable and an increase in sustainable demand on aggregate. The rich household reduces both sustainable and unsustainable consumption to keep the ratio constant. The poor household, in contrast, who is rich enough to cover basic needs with the cheaper alternative, is now able to recompose the consumption bundle towards the more preferred sustainable good: it reduces unsustainable consumption and raises sustainable

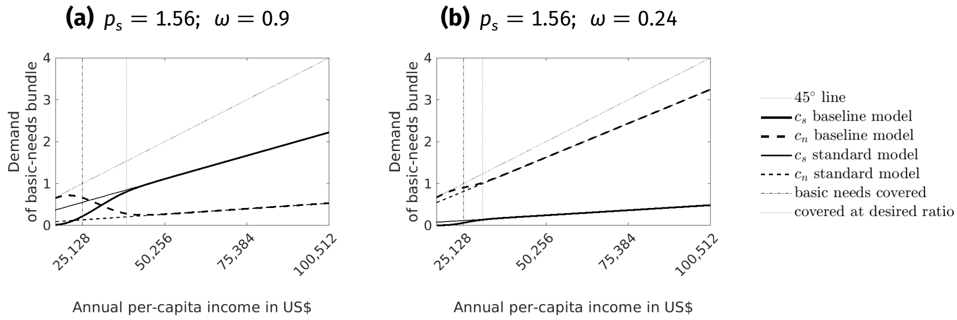


Figure 1.E.1. Engel curves

consumption by more than $\frac{dI}{p_s}$. The unsustainable good is inferior from the perspective of the poor household.[35]

On the other hand, considering an initial income of the poor household sufficiently below the basic-needs threshold, lump-sum redistribution has the contrary effect. In this scenario, the poor household is financially unable to satisfy its basic needs with the cheaper good. An additional unit of income is then mainly spent on the unsustainable, cheaper good. On aggregate, unsustainable production rises. Income of poor households is, therefore, especially important for the size of transfers required to make redistribution negatively affect the externality.

Comparing now the right-hand plot, which depicts Engel curves with $\omega = 0.24$, reveals, first, that the effectiveness of redistribution as a corrective policy instrument strongly depends on households' tastes for sustainability. Lump-sum transferring one unit of income to the poor in the low-responsibility world leads to a negligibly low reduction of unsustainable consumption. The reallocation of consumption bundles is muted as the consumed ratio of goods at an income level below unity is closer to the desired allocation. Moreover, the unsustainable good becomes inferior only after a higher income level than in the high-responsibility world. Hence, redistribution is more effective to lower the externality when social responsibility is high, and the poor are more eager to recompose their budget shares.

Inequality. While social responsibility reduces the externality, its effect on equity is detrimental. To see this, note that the recomposition of the consumption bundle is extended up to a higher income level when social responsibility is high. Thus, a higher income is needed for poor households to align demand with their corrective concerns. Not consuming in line with corrective concerns, in turn, implies a lower

35. Inferiority of the cheaper good at some income levels might seem strange at first glance. However, recalling that the unsustainable and the sustainable good are perfect substitutes in terms of their ability to satisfy consumption needs, the result is plausible. For instance, a household which starts to consume organic milk most likely does not continue buying the same amount of conventional milk as it used to.

composite consumption. Therefore, consumption inequality increases with social responsibility while income inequality remains unchanged.

In addition, as already hinted at in the model section, basic-needs constrained households accept a lower sum consumed the higher social responsibility. Compare the left-hand plot, where already before basic needs are fully satisfied at an income of US$25,128, the household starts to increase its budget share of the more expensive good. This behavior implies a higher disutility from too low consumption through the penalty term. Both observations, a higher consumption inequality and a higher disutility from too low consumption, aggravate inequality and increase the equity-benefits of redistribution.

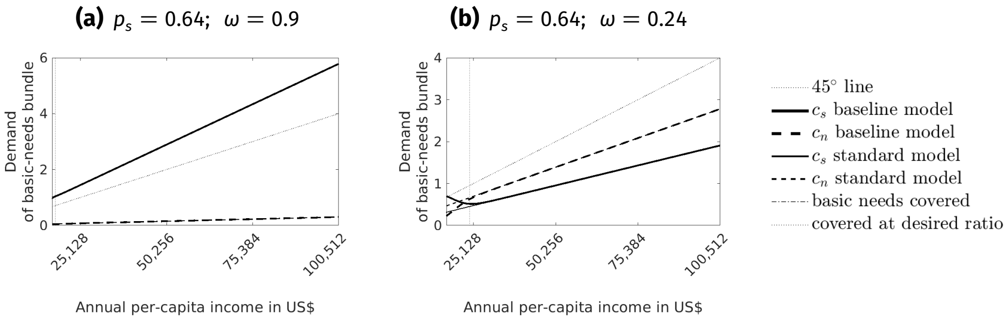


Figure 1.E.2. Engel curves for $p_s < 1$

Appendix 1.F Results

1.F.1 Optimal allocation in the baseline model

Figure 1.F.1 depicts additional variables under the optimal policy in the baseline model. To better understand how the Gini of consumption moves with social responsibility, Panels (a) and (b) show composite consumption by household type. Composite consumption is affected by three factors. First, the change in social responsibility mechanically alters composite consumption as the weight on individual consumption goods changes, and households react to this change in preferences. Absent any policy intervention, this implies that the desired bundle becomes more expensive with social responsibility and, at a constant level of income, composite consumption reduces; compare the laissez-faire allocation in Figure 1.F.2. Second, taking the optimal policy into account, both income (of the rich) and the sustainable good's price become an increasing function of social responsibility; compare Panel (e) and Panel (l) in Figure 1.F.1. This explains the inverted U-shaped behavior of composite consumption of the rich: at the upward sloping part, income is low and the price of the more preferred good is high. As income rises and the unsustainable good becomes less expensive, the composite

consumption of the rich increases. The rise in composite consumption stops once the continuing rise in income is not enough to make up for the desired bundle becoming more expensive again.

Composite consumption of the poor (Panel (b)) is affected by a third factor: basic needs. Not only is their composite consumption lower than that of rich households due to a lower quantity of the composite bundle consumed, but also because they do not allocate their income to maximize composite consumption for the given price. Panel (c) shows how the actual consumption ratio of the poor deviates from the desired one, the dashed-dotted graph. The rich always consume their desired bundle (not shown). When the unsustainable good is more expensive, to the left of the vertical indicator, the poor consume a higher share of the sustainable good; this pattern gets reversed once the unsustainable good becomes the cheaper alternative.

When the unsustainable good is more expensive, a rise in the sustainable price implies convergence of both goods' prices which allows poor households to consume closer to the desired ratio. Once the sustainable good is more expensive, a further rise widens the price differential and the poor consume further away from the desired ratio; at the extreme when prices are identical basic-needs constrained households consume the desired ratio. In addition, when the sustainable good is cheaper, a rise in social responsibility reduces the gap, since the price of the desired bundle falls. In contrast, as the sustainable good is more expensive the rise in social responsibility intensifies the gap. The rise in income of the poor starting at around $\omega = 0.3$ adds to closing the gap between actual and desired consumption.

Since there is a reduction of the gap until the sustainable price exceeds unity, the initial small reduction of composite consumption by the poor is driven by a reduction in income. Roughly, as income starts to rise, the composite consumption of the poor reaches a trough. The fall in the actual-desired consumption gap adds to the rise in composite consumption until the sustainable good becomes more expensive than the unsustainable one. From here on, the widening of the gap amplifies the reduction in composite consumption of the poor relative to the reduction in composite consumption by the rich.

The initial rise of the Gini of consumption is, thus, explained by a reduction of income of the poor while consumption of the rich rises. It reduces once composite consumption of the poor increases faster than that of the rich and the actual-desired consumption gap of the poor declines. As the unsustainable good eventually becomes cheaper, and the gap widens again, consumption of the poor reduces faster, and the Gini of consumption increases.

Aggregate labor supply is shown in Panel (f) followed by household-specific supplies in Panels (g) and (h). Absent any policy intervention, labor supply is constant except for a negligibly small rise in labor supply by the poor; compare

Figure 1.F.2.[36] The movements in labor supply are, therefore, the effect of taxes and transfers.

The initial rise in labor supply by the rich is driven by the strong reduction in the corrective tax. The higher after-tax wage rate (Panel (n)) makes the rich want to work more. The slow down in the reduction of the corrective tax and the rise in labor income taxes diminishes the rise of the after-tax wage. This adds to the decrease in labor supply by the rich. The rise in transfers additionally mitigates work efforts by the rich. As the rise in the after-tax wage accelerates again, labor supply by the rich resurges.

Labor supply of the poor tells a different story. For this household group the penalty term dominates the pattern of labor supply; compare Panels (h) and (i). The high penalty term increases the shadow value of income so that the household is willing to work more. I next explain the movements in the penalty term. Despite the rise in transfers and income with social responsibility, the poor experience a cutback in the sum consumed when the penalty term increases. When the sustainable good is cheaper, the shift in social responsibility towards the sustainable good should imply at most no reduction in the quantity consumed. However, the parallel increase in the sustainable price outweighs this effect. So that the sum consumed falls. After the sustainable good becomes more expensive than the unsustainable good, the penalty term reduces again, although tastes become more expensive. This reduction is, therefore, explained by the accelerated rise in income through transfers. As a response, the poor reduce their labor supply.

36. The rise in labor supply by the poor in the laissez-faire economy is driven by an increase in the penalty term. As social responsibility rises, the poor eventually accept a lower sum consumed at the expense of a higher penalty. This makes them willing to work more.

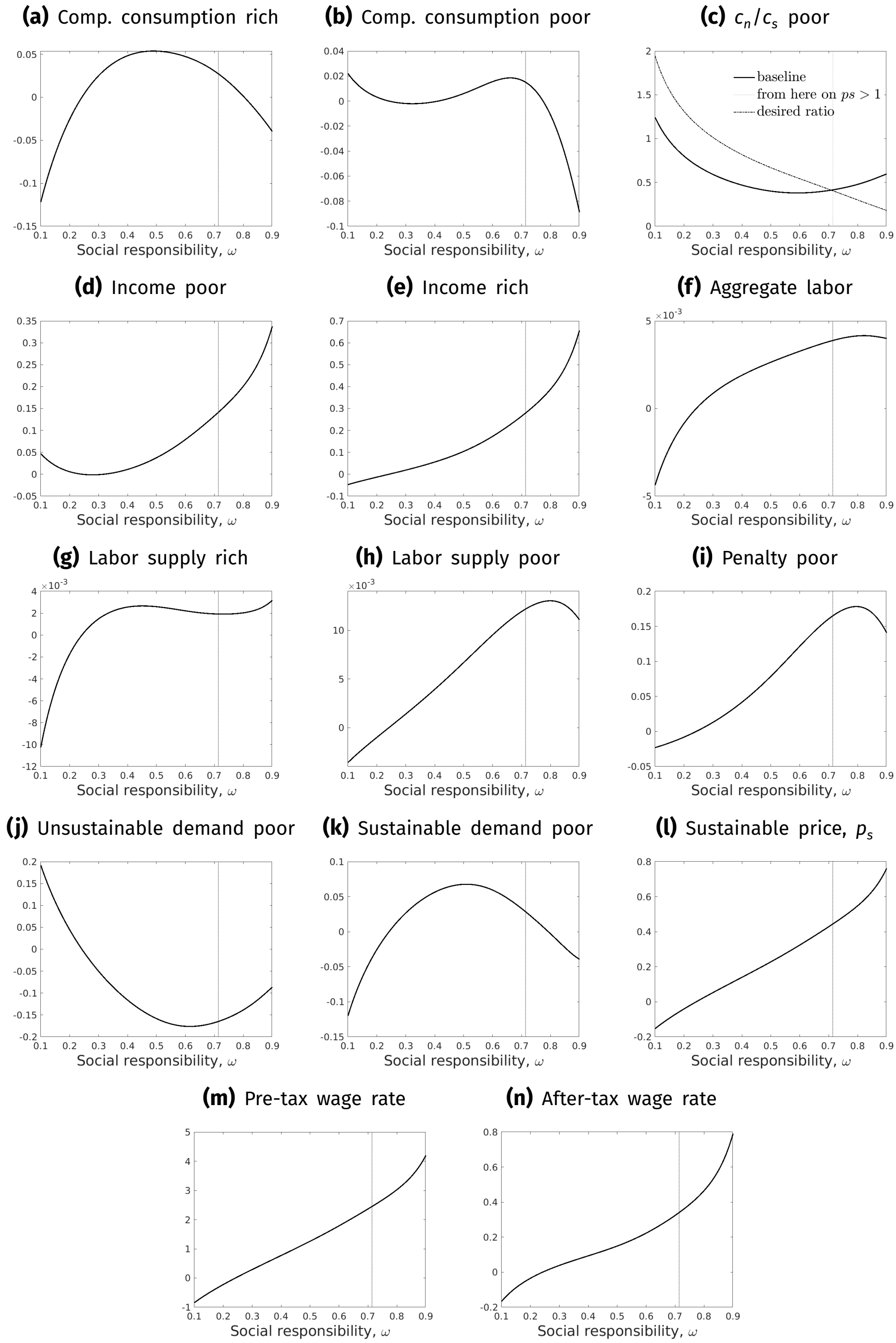


Figure 1.F.1. Optimal allocation: additional variables

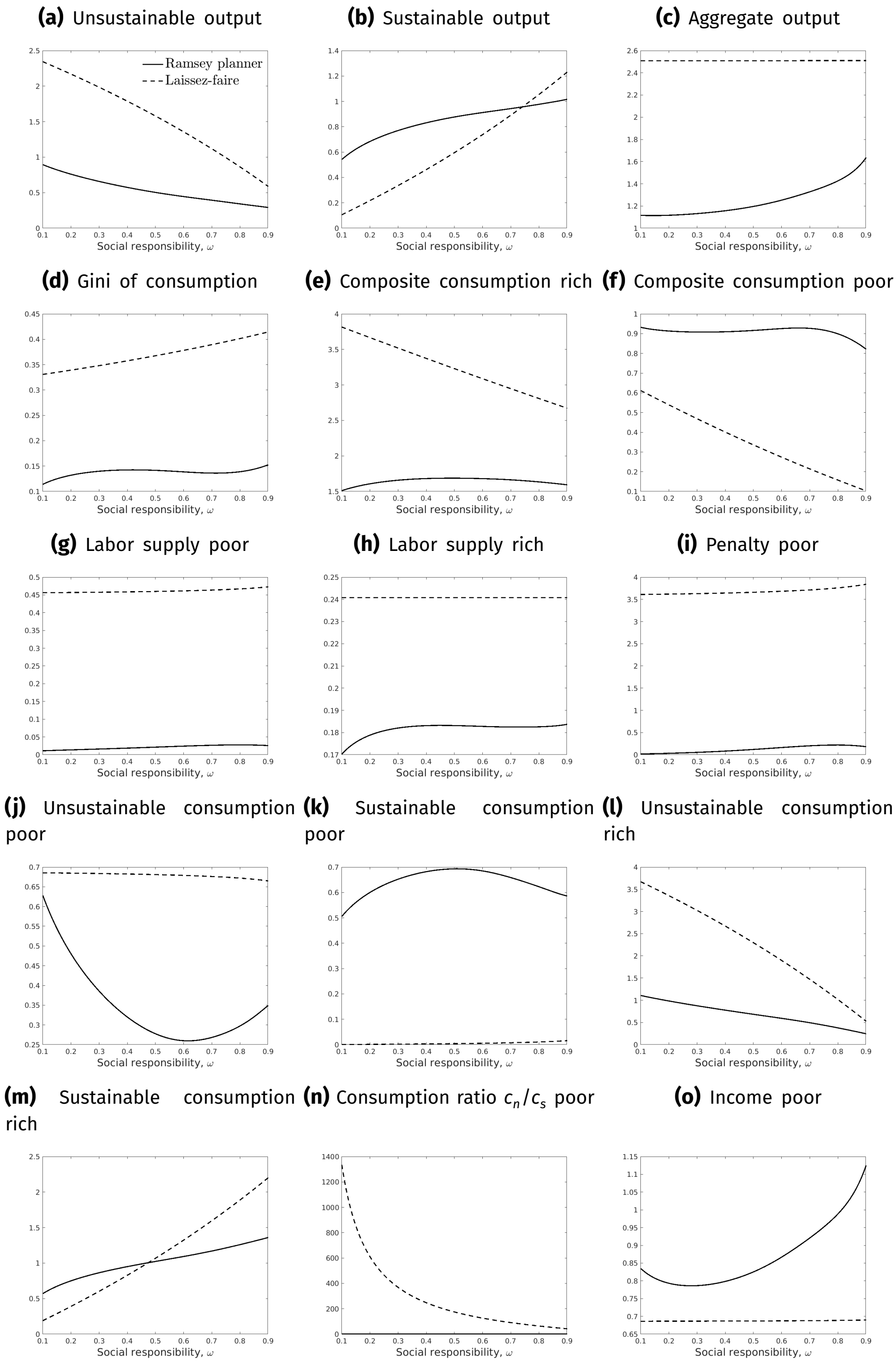


Figure 1.F.2. Optimal and laissez-faire allocation

1.F.2 Results in the standard model

The focus of the optimal policy in the standard model remains on the externality, the dashed line in Panel (a). In fact, the government reduces the externality even more the higher social responsibility due to a lower efficient level of the externality: from -62.5% at $\omega = 0.1$ to -65% at $\omega = 0.9$.[37] In so doing, the government in the standard model accepts a higher level of inequality and a reduction by more than 50% in output for all levels of social responsibility, Panel (c). The initial bigger reduction in inequality is a byproduct of the revenues from corrective taxation.

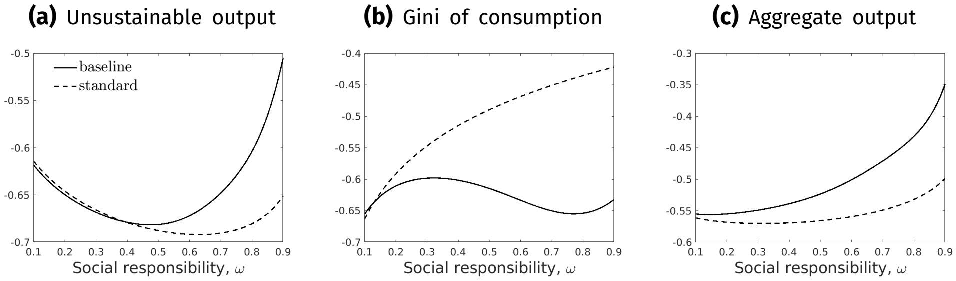


Figure 1.F.3. Effect of government intervention with and without basic needs

1.F.3 Counterfactual policy

Figure 1.F.4 depicts the allocation resulting in the baseline model under a counterfactual, more aggressive environmental tax. As counterfactual policy, I consider the optimal policy chosen in the standard model. In this model, the optimal corrective tax is always higher than in the model with basic needs. With this policy, the government would be able to attain an output ratio closer to the efficient one in the baseline model; see Panel (a). The counterfactual policy considered enforces a sustainable price below unity (so that the poor use the sustainable good to cover their basic needs) for all levels of social responsibility. This causes a lower externality throughout, Panel (b). The cost of this aggressive corrective policy is borne by the poor who see a substantial drop in their unsustainable consumption and a rise in the penalty term, Panels (g) and (h). Consumption of the rich rises for medium to high levels of social responsibility. The Gini coefficient of composite consumption is higher throughout. The increase in inequality is driven by too high efficiency costs of the corrective tax which implies lower output on aggregate (Panel (d)) and transfers (Panel (i)).

37. There is a small decline in the reduction of the externality at very high levels of social responsibility.

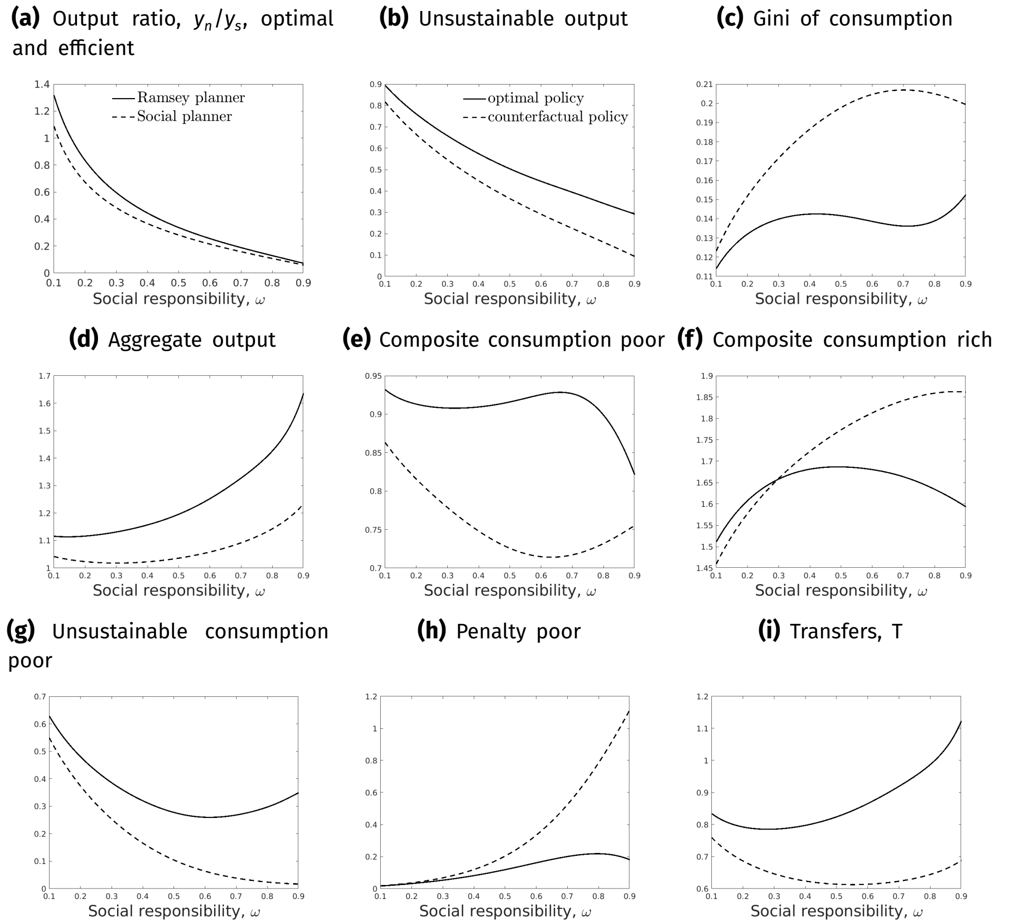


Figure 1.F.4. Counterfactual policy

Notes: Panel (a) compares the allocation under the counterfactual policy to the efficient allocation. All other panels refer to the counterfactual and the optimal allocation.

1.F.4 Representative agent

This subsection discusses the optimal policy in a representative agent version of the model. Figure 1.F.5 displays the results.

Results. When households are alike, a representative agent exists that represents the model economy. Then the model replicates the findings in the literature. First, since there is no requirement on government revenues, the optimal corrective tax equals the Pigouvian rate, aka the social costs of the externality; compare Panel (c) in Figure 1.F.5. A definition of the Pigouvian rate and the derivation of the social cost of the externality (SCE) is given in this section below. The labor income tax is set to zero, as there are no benefits from government funds or redistribution; Panel (b). Hence, when the corrective tax can be set to fully internalize the social costs of the externality, there is no role for labor income taxes as a corrective policy instrument.

The calibration in the representative agent economy is similar to the baseline calibration. Effective labor productivity of both households equals 0.60. The level of social responsibility is slightly lower in the representative agent model, $\omega = 0.23$, because income does not prevent sustainable consumption.

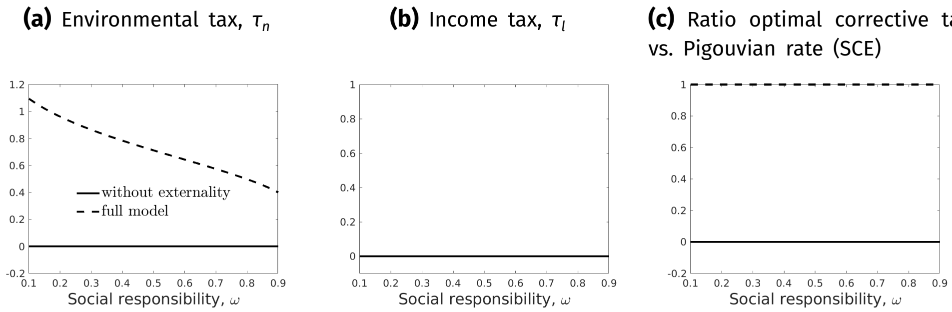


Figure 1.F.5. Optimal policy without inequality

Definition Pigouvian rate. I define the Pigouvian rate, i.e., the SCE, as the aggregate willingness to pay for a marginal reduction in the externality in equilibrium. In contrast to Jacobs and van der Ploeg (2019), I specify the Pigouvian rate as only capturing the marginal social benefits of an externality reduction; it does not account for effects on tax bases. The proposed definition here is closer to the notion of *social costs of the externality* and in line with Barrage (2020). The Pigouvian tax then results from maximizing the average household's problem assuming the existence of a market for the externality. The maximization problem reads

$$\begin{aligned} \max \mathscr{L} =& \lambda U_r + (1-\lambda)U_p + \lambda\mu_r(I_r - c_{nr} - p_s c_{sr} - p_E H_n) \\ & + (1-\lambda)\mu_p(I_p - c_{np} - p_s c_{sp} - p_E H_n). \end{aligned}$$

Note that the total amount paid by unsustainable producers for causing the externality is given by $w\tau_n H_n$ so that

$$\tau^{Pigou} = \frac{-p_E}{w} = \frac{-\frac{\partial g}{\partial h_n}}{\lambda\mu_r + (1-\lambda)\mu_p}.$$

Defined in this manner, the Pigouvian rate can be interpreted as the aggregate willingness to pay by households for the avoidance of a marginal increase in the externality. As regards aggregation, the Pigouvian rate is similar to the one defined in Jacobs and van der Ploeg (2019) when the distortionary tax equals zero.

1.F.5 Quantification of policy effects

In this section, I discuss the mechanisms shaping the effect of each policy instrument resulting from the experiment explained in Section 1.5.2.5. The discussion mainly refers to Figure 1.F.6. The plots show variables in levels in the laissez-faire economy, with vertical markers, after implementation of the corrective tax, the solid graphs, after implementation of the optimal labor income tax but labor supply fixed, the dashed graph, and, finally, as labor supply reacts to the labor income tax, the thin dotted graph.

Environmental taxation. The corrective tax accounts for a reduction in unsustainable output by between 60% and 65% when social responsibility is below $\omega = 0.71$, as shown by the solid graph in Plot (c) in Figure 1.5.7 thereby accounting for the bulk of the impact of corrective policy. The corrective tax affects unsustainable production through two mechanisms: (1) by changing the relative price and (2) by altering households' income. Rendering the sustainable good the cheaper alternative implies a strong response of demand by the poor who now rely on the sustainable good to cover their basic needs; compare the solid graph in Panel (a) in Figure 1.F.6 to the one with vertical lines which shows the laissez-faire allocation.

The additional reduction in unsustainable output on the interval from $\omega = 0.1$ to $\omega = 0.3$ is explained by the demand of poor households. A decrease in transfers, compare Panel (d) in Figure 1.F.6, makes the poor poorer such that these households recompose their budget towards the cheaper, that is, the sustainable good. Transfers reduce due to the cut in the tax rate and the demand-driven reduction in the tax base relative to lower values of social responsibility. Furthermore, the cross-price effect of the sustainable good's price on unsustainable demand by the poor is negative at the marginal corrective tax rate, that is, a fall in the sustainable price implies a rise in unsustainable demand; compare Panel (e) in Figure 1.F.6. How does the negative cross-price effect come about? Being constrained by basic needs implies a small substitution effect in reaction to a marginal change in the relative price. Demand for the cheaper good remains strong so that the income effect of a price change exceeds the substitution effect. Therefore, in sum, demand by the poor for the unsustainable good falls as the sustainable good becomes more expensive. This adds to the importance of the corrective tax for low levels of social responsibility.

The total impact of the corrective tax on unsustainable output reduces as social responsibility rises above $\omega = 0.4$ up to a value equal to $\omega = 0.7$. This is driven by the consumption behavior of the rich; see Panel (b) in Figure 1.F.6. As the environmental tax reduces with social responsibility, the unsustainable good becomes cheaper and the rich recompose their consumption less intensely than in the laissez-faire economy towards sustainable demand; contrast the slopes of the solid graphs and the one with vertical lines. Furthermore, the rich become richer (Panel (f)) as the pre-tax wage rate rises; this adds to the increase of unsustainable demand by the rich.

Once the corrective tax is so low that the sustainable good is more expensive than the unsustainable one, the absolute impact of the corrective tax drops sharply from 60% to roughly above 40%. The main reason is that the price elasticity of demand by the poor is low. What matters most for their demand decision is the ranking of prices and not the relative difference. As long as the unsustainable good is the cheaper alternative, marginal changes in the relative price are of minor importance to the poor; consider Panel (a).

Redistribution channel. Redistribution counteracts the effect of the environmental policy whenever the sustainable good is the cheaper alternative. Consider now the dashed graph. When the unsustainable good is more expensive, until $\omega = 0.71$, redistribution implies a rise in the externality of up to 10% compared to the laissez-faire world in addition to the corrective tax. As the poor demand too high a budget share of the sustainable good relative to the desired bundle, a higher income allows them to recompose their consumption towards the more expensive alternative, i.e., the unsustainable good.[38] In contrast, the rich reduce their unsustainable demand as their income falls.

The picture changes once the corrective tax is set such that the unsustainable good becomes the cheaper one. Now, the marginal propensity to consume the unsustainable good of the poor is, aggregated over the amount redistributed, lower than that of the rich, and the amount redistributed causes a contraction in unsustainable demand on aggregate. The difference in the marginal propensities to consume the unsustainable good across households increases with social responsibility and an increase in the sustainable price. Consequently, redistribution becomes more and more important a corrective policy tool as households' taste for the sustainable good rises. Redistribution accounts for a reduction in the externality rising gradually from 10% to 40% with social responsibility.

Efficiency channel. Finally, the effect of labor income taxation on labor supply adds to the reduction in the externality when social responsibility is relatively low; focus on the thin dotted graphs. Labor supply of both household types (Panels (i) and (j)) decreases in reaction to labor income taxation, and income of both types falls (Panels (f) and (g)), causing a cutback in unsustainable demand relative to the allocation after lump-sum redistribution. However, starting from a level of social responsibility slightly above $\omega = 0.85$, the efficiency channel has a positive additional effect on the externality. This is driven by basic-needs constrained

38. The poor might have a lower MPCU at the initial income level, however, transfers are such that in sum the poor raise unsustainable demand relative to the allocation after only the corrective tax got implemented.

households. The reduction in their income (compare the dashed and the thin dotted graphs in Panel (g)) boosts their unsustainable demand (Panel (a)). To cover basic needs, the poor revert to consume the less preferred but cheaper good.

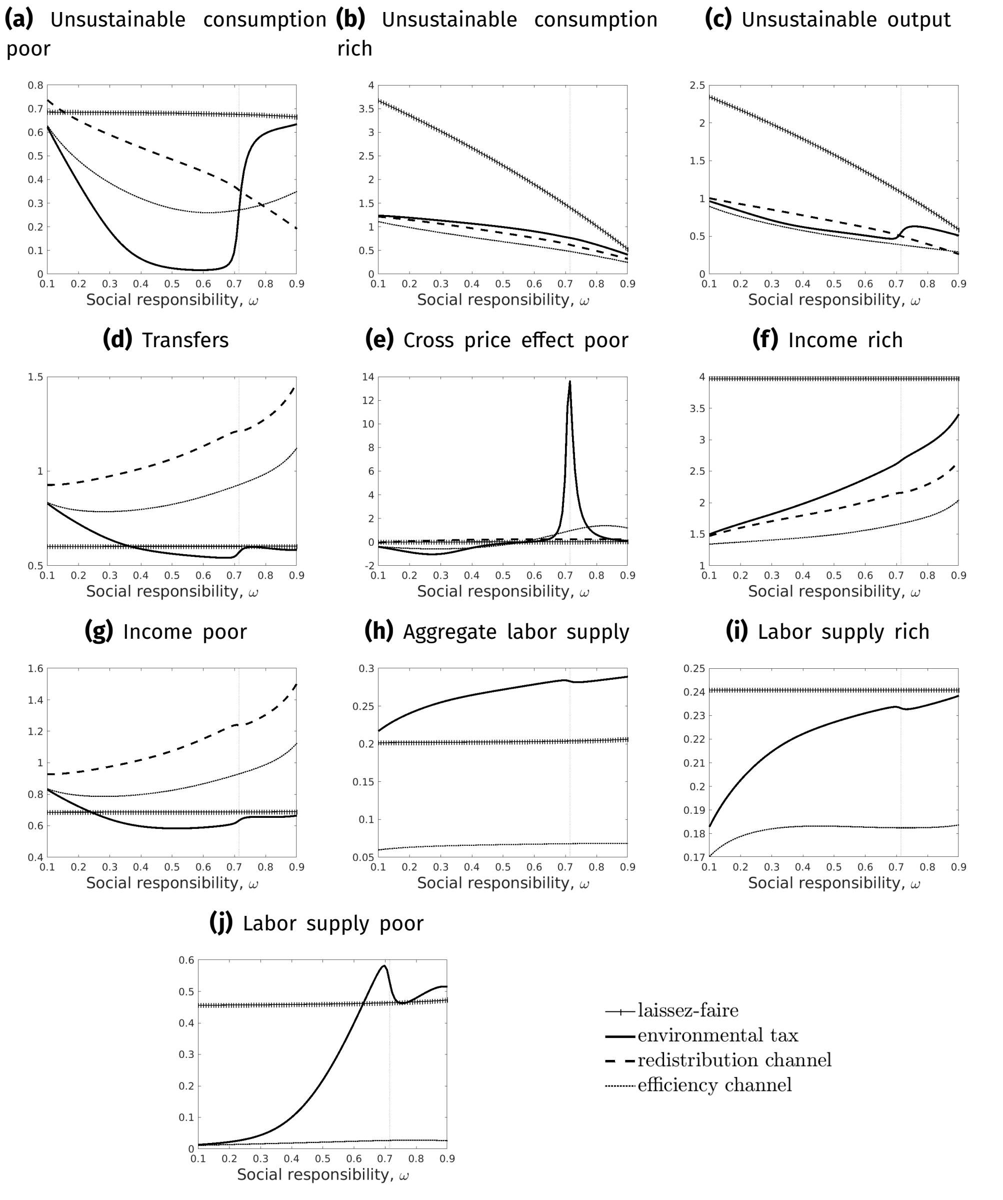


Figure 1.F.6. Policy decomposition baseline model additional variables

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The environment and directed technical change." *American Economic Review* 102 (1): 131–66. [18]

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy*, [10]

Aghion, Philippe, Roland Bénabou, Ralf Martin, and Alexandra Roulet. 2022. "Environmental Preferences and Technological Choices: Is Market Competition Clean or Dirty?" *American Economic Review: Insights* (forthcoming): [9]

Barrage, Lint. 2020. "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy." *Review of Economic Studies* 124 (2): 1–39. [10, 21, 23, 45, 54]

Bartling, Björn, Roberto A. Weber, and Lan Yao. 2015. "Do markets erode social responsibility?" *Quarterly Journal of Economics* 130 (1): 219–66. [5, 9]

Bénabou, Roland, and Jean Tirole. 2010. "Individual and corporate social responsibility." *Economica* 77 (305): 1–19. [9, 11]

Bick, Alexander, Nicola Fuchs-Schündeln, and David Lagakos. 2018. "How do hours worked vary with income? cross-country evidence and implications." *American Economic Review* 108 (1): 170–99. [22]

Boppart, Timo. 2014. "Structural Change and the Kaldor Facts in a Growth Model With Relative Price Effects and Non-Gorman Preferences." *Econometrica* 82 (6): 2167–96. [10]

Bovenberg, A L, and Ruud A De Mooij. 1994. "Environmental Levies and Distortionary Taxation." *American Economic Review* 84 (4): 1085–89. [9, 10, 28, 31]

Bovenberg, A Lans, and Lawrence H Goulder. 2002. "Environmental Taxation and Regulation." In *Handbook of Public Economics*. Edited by A J Auerbach and M Feldstein. Vol. 3, Elsevier Science B.V. Chapter 23, 1471–545. [10]

Bradshaw, Jonathan, Sue Middleton, Abigail Davis, Nina Oldfi, Noel Smith, Linda Cusworth, and Julie Williams. 2008. "A minimum income standard for Britain: What people think." Retrieved from https://www.jrf.org.uk/report/minimum-income-standard-britain-what-people-think. May 2020. [39]

Chen, Bo, Sayed Saghaian, and Yuqing Zheng. 2018. "Organic labelling, private label, and U.S. household demand for fluid milk." *Applied Economics* 50 (28): 3039–50. [20, 23, 40, 41]

Chetty, Raj, Adam Guren, Day Manoli, and Andrea Weber. 2011. "Are micro and macro labor supply elasticities consistent? A review of evidence on the intensive and extensive margins." *American Economic Review* 101 (3): 471–75. [21, 23]

EAT-Lancet Commission. 2019. "Healthy Diets From Sustainable Food Systems Summary Report of the EAT-Lancet Commission." Retrieved from https://eatforum.org/eat-lancet-commission/eat-lancet-commission-summary-report/. May 2020. [7, 37, 38]

Foellmi, Reto, and Josef Zweimüller. 2008. "Structural change, Engel's consumption cycles and Kaldor's facts of economic growth." *Journal of Monetary Economics* 55 (7): 1317–28. [10]

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski. 2014. "Optimal Taxes on Fossil Fuel in General Equilibrium." *Econometrica* 82 (1): 41–88. [10]

Gordon M. Fisher. 2012. "Standard Budgets (Basic Needs Budgets) in the United States Since 2006." Retrieved from https://www.census.gov/content/dam/Census/library/working-papers/2012/demo/udusbd3.pdf. 29/07/2021. [37]

Goulder, Lawrence H. 1995. "Environmental Taxation and the Double Dividend: A Reader's Guide." *International Tax and Public Finance* 2: 157–83. [10]

Herrendorf, Berthold, Richard Rogerson, and Akos Valentinyi. 2014. "Growth and Structural Transformation." In *Handbook of Economic Growth*. Vol. 2, 855–941. [10]

Howe, P., Mildenberger, M., Marlon, J., & Leiserowitz, A. 2015. "Geographic variation in opinions on climate change at state and local scales in the USA." *Nature Climate Change*, [11, 12, 35]

IWPR. 2018. "Basic Economic Security in the United States: How Much Income Do Working Adults Need in Each State?" Retrieved from https://iwpr.org/wp-content/uploads/2020/08/R590_National_finalx.pdf, 29/07/2021. [7, 13, 20, 23, 37, 38]

Jacobs, Bas, and Frederick van der Ploeg. 2019. "Redistribution and pollution taxes with non-linear Engel curves." *Journal of Environmental Economics and Management* 95 (5): 198–226. [10, 15, 18, 31, 54]

Jones, Larry E, Rodolfo E Manuelli, and Peter E Rossi. 1993. "Optimal Taxation in Models of Endogenous Growth." *Journal of Political Economy* 101 (3): 485–517. [21, 23]

Kaplow, Louis. 2012. "Optimal control of externalities in the presence of income taxation." *International Economic Review* 53 (2): 487–509. [15]

Kronthal-Sacco, Randi, Tracy Van Holt, Ulrich Atz, and Tensie Whelan. 2020. "Sustainable Purchasing Patterns and Consumer Responsiveness to Sustainability Marketing Messages." *Journal of Sustainability Research* 2 (2): [5, 21, 23]

Lucas, Robert E, and Nancy L Stokey. 1983. "Optimal Fiscal and Monetary Policy in an Economy without capital." *Journal of Monetary Economics* 12: 55–93. [19]

Matsuyama, Kiminori. 2002. "The Rise of Mass Consumption Societies." *Journal of Political Economy* 110 (5): 1035–70. [10]

McMahon, Shawn, Jessica Horning, and Joo Yeoun Suh. 2018. "The basic economic security tables. Methodology and Supplemental Data." Retrieved from https://iwpr.org/wp-content/uploads/2020/08/US-BEST-Draft-Methodology-Report_Suh1-CH_JC.pdf, 29/07/2021. Institute for Women's Policy Research. [37]

OECD. 2021. "Average annual hours actually worked per worker." Https://stats.oecd.org/Index.aspx?DataSetCode=ANHRS. (Accessed on 11 February 2021). [22, 23]

PSID. 2020. “Produced and distributed by the Survey Research Center, Institute for Social Research, University of Michigan, Ann Arbor, MI, public use dataset.” Retrieved from https://psidonline.isr.umich.edu/Guide/FAQ.aspx?Type=8, 29/01/2021. [39]

Sager, Lutz. 2019. “Income inequality and carbon consumption: Evidence from Environmental Engel curves.” *Energy Economics* 84 (10): [17]

Simon-Kucher & Partners. 2021. “Global Sustainability Study 2021.” Summary to be found here https://www.simon-kucher.com/de/about/media-center/sustainability-study-2021-fast-ein-drittel-der-deutschen-wuerde-fuer-nachhaltige-produkte-mehr-geld-ausgeben, made available upon request. [5]

The Conference Board. 2020. “Consumers’ Attitudes about Sustainability.” Retrieved from https://conference-board.org/pdfdownload.cfm?masterProductID=20499, 11/01/2021. [5, 8, 11]

The Nielsen Company. 2015. “The Sustainability Imperative.” Retrieved from https://www.nielsen.com/wp-content/uploads/sites/3/2019/04/Global20Sustainability20Report_October202015.pdf, 11/01/2021. [5]

USDA. 2021. “Market News Retail Dataset.” Retrieved from https://marketnews.usda.gov/mnp/dataDownload, 11/01/2021. [37]

Vermeir, Iris, and Wim Verbeke. 2006. “Sustainable food consumption: Exploring the consumer “attitude - Behavioral intention" gap.” *Journal of Agricultural and Environmental Ethics* 19 (2): 169–94. [7, 21]

Vona, Francesco, and Fabrizio Patriarca. 2011. “Income inequality and the development of corrective technologies.” *Ecological Economics* 70 (11): 2201–13. [10]

Chapter 2

Meeting Climate Targets: The Optimal Fiscal Policy Mix

2.1 Introduction

To meet climate targets, the Intergovernmental Panel on Climate Change highlights the need to transition to net-zero emissions by 2050 (IPCC, 2022a). The literature to date has largely focused on carbon taxes. Such taxes direct production and R&D towards activities that pollute less.[1] However, other fiscal instruments also affect carbon emissions. Labor taxes, for example, curb the level of production generally thereby diminishing emissions. Conversely, they may stabilize production when carbon taxes are high. Thus, labor income taxes may play a role in optimally meeting emission goals. The question is what fiscal policy mix best supports the transition to net-zero emissions.

To analyze the optimal fiscal mix, I set up a model of directed technical change. The government chooses the dynamic path of labor income taxes and carbon taxes. In so doing, it anticipates that net emissions are limited in the short run and have to be zero at some point in the future. Calibrating the model to the US economy, I can characterize the optimal fiscal mix during the transition toward net-zero emissions and thereafter. My main finding is that when the net-zero emission limit

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1. See, for instance, Acemoglu, Aghion, Bursztyn, and Hemous (2012), Golosov, Hassler, Krusell, and Tsyvinski (2014), or Fried (2018).

is binding, the optimal policy is to tax carbon heavily and to subsidize labor to stabilize production. During the transition phase, the optimal carbon tax is lower. A tax on labor helps reduce emissions by minimizing overall production. This mix allows for a higher productivity of research while meeting emission targets.

The key to the optimal mix of carbon and labor taxes lies in the endogenous allocation of research activity. A knowledge advantage in the fossil sector means that a rapid shift to green research is costly. Cross-sectoral knowledge spillovers from research in the fossil to the green industry enable a steady transition: they ensure that fossil knowledge generated in the short run profits green growth in the long run. Setting a smaller carbon tax, the government engineers a smoother transition of research activity. A tax on labor, in turn, reduces production in the short run to satisfy emission targets. In the long run, only green production and research is feasible. Relying on labor income taxes to reduce emissions by lowering overall production becomes too costly. Therefore, the optimal policy sets an excessively high carbon tax to meet emission limits. The higher carbon tax directs research to the green sector which again stimulates green innovation in the future. Yet, this comes at the expense of lower consumption. Therefore, a labor subsidy optimally mutes the disruption in output.

More in detail, the modeling follows Fried (2018). A final consumption good is produced from energy and non-energy goods. The energy good, in turn, is composed of green and fossil energy. The fossil sector exerts emissions. Imperfectly monopolistic producers of machinery invest in research to increase the productivity of their machines. Machines are used in the intermediate sectors: non-energy, fossil, and green energy. The model builds on the directed technical change framework developed in Acemoglu et al. (2012), where innovation profits from past technology levels within a sector (*within-sector knowledge spillovers*). In addition to their model, returns to research decrease in the number of scientists employed within a sector, and some knowledge spills across sectors (*cross-sectoral knowledge spillovers*).

Relative to the study by Fried (2018), the current paper adds the consideration of an optimal policy. The optimal policy accounts for a gradually declining net emission limit that eventually turns to zero in 2050. Where the literature has mainly focused on carbon taxes (Fried, 2018; Barrage, 2020), the planner in my model chooses (i) a sales tax per unit of fossil energy ("the carbon tax") and (ii) a tax on labor income. The role for the labor income tax does not arise from equity considerations. Rather, the labor tax is an environmental policy instrument next to carbon taxes because it affects the level of production. I solve for the optimal path of carbon and labor taxes using the numerical approach by Jones, Manuelli, and Rossi (1993) and Barrage (2020).

To highlight the importance of endogenous growth for the optimal fiscal mix, I start with a simple pencil-and-paper setting. This has the externality from fossil energy but does away with endogenous growth. In this static setting, optimal fiscal policy only resorts to a Pigouvian carbon tax and lump-sum rebates. The carbon tax adjusts the share of fossil energy in production. Labor taxes do not play a role. The reason for this is that when the carbon tax is set to the Pigouvian level, the wage rate reduces exactly by the social costs from an additional hour worked. These costs arise from more pollution as economic activity rises. Hence, households internalize the externality of work in their labor supply decision.

Then, I turn to the dynamic model with endogenous growth. I first calibrate the model to the US economy in the period from 2015 to 2019. Then, I feed an exogenous emission limit into the model that is based on the path of the global target provided by the IPCC (2022a). The emission limit for the US used in the analysis stipulates a reduction by 84.5% in net emissions in 2020 relative to 2019-levels. The value increases to 85.6% in 2045.[2] In 2050, the emission limit further reduces to net zero. In this setting, I perform two quantitative exercises. First, I calculate carbon taxes that would be necessary to meet the emission limit while keeping the labor income tax fixed. Second, the planner optimally sets the carbon and the labor tax to maximize welfare.

As for the first exercise, I find that the necessary carbon tax is US$889 (in 2022 prices) per ton of carbon in the 2020-2024 period. The tax increases to US$2,951 in the 2070-2074 period. The surge in the necessary tax on carbon over time follows from the tighter emission limit and market forces which direct inputs to the fossil sector, such as cross-sectoral knowledge spillovers. I compare the necessary carbon tax in the calibrated model—which has a distortive income tax—to the necessary carbon tax absent labor income taxes. Without income taxation, the required carbon tax is 7% to 10% higher.

As for the second exercise, results show that the emission limit is best implemented by a combination of carbon and labor income taxes. Before the net-zero emission limit binds, a positive tax on labor optimally accompanies a carbon tax. The carbon tax amounts to US$987 in the 2020-2024 period. It increases steadily to US$1,257 in 2040-2044. The average (income-weighted) marginal income tax rate equals 0.31% in the 2020-2024 period and decreases to 0.01% in the 2040-2044 period.

The role for labor taxation follows from the use of carbon taxes to direct research across sectors. This constitutes a second target for the carbon tax next to adjusting the share of fossil energy in production. The government chooses a lower carbon tax to allow for more research in the fossil sector. Knowledge accumulation in this sector in the past renders fossil researchers particularly productive. Furthermore, decreasing returns to research make a more equal

2. These targets are more than twice as big than the reduction prescribed by the Biden administration amounting to 38% relative to 2019-emissions. Source: https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/, retrieved 14 September 2022.

allocation of scientists more productive. Technological advances in the fossil sector, in turn, benefit green growth in future periods because of cross-sectoral knowledge spillovers. However, as the carbon tax targets the direction of research, it deviates from the Pigouvian rate and the wage rate does no longer fully capture the effect of hours on the externality. Labor supply is inefficiently high. To mitigate the higher level of emissions, the government taxes labor income.

The optimal policy mix changes sharply once the net-zero emission limit has to be implemented. Now, the carbon tax rises steeply to direct research to the green sector. The optimal tax on carbon jumps to US$2,833 per ton in 2050 and gradually increases to US$3,186 in the 2070-2074 period. In addition, the government subsidizes labor. The labor income tax becomes negative already in 2045-2049: the average marginal tax rate is -0.07%. It declines to -0.16% in 2070-2074.

The more stringent emission limit makes it too expensive for the economy to take advantage of more fossil research which would mean using a labor income tax to lower emissions. In this case, encouraging green research becomes optimal in order to benefit from dynamic spillovers within this sector. To do so, the government raises the carbon tax. However, this diminishes the wage rate, and labor supply declines. The subsidy on labor helps to raise labor supply.

Knowledge spillovers are instrumental for the economy to profit from a smooth allocation of researcher. With knowledge spillovers, fossil research in early periods boosts green growth tomorrow. A more productive green sector renders a transition to net-zero emissions in future periods less costly. When knowledge is sector specific, however, the optimal policy should allocate more research to the green sector early on. This fosters green innovation tomorrow as scientists can build on green technology advances today. In this setting, the optimal carbon tax is higher to bolster green research, and the labor income tax subsidizes labor throughout time. While knowledge spillovers to the green sector allow the economy to profit from fossil research, overall, though, knowledge spillovers make a more aggressive environmental policy necessary. The reason is that knowledge also spills to the fossil sector thereby raising the share of fossil energy in production.

Literature. The paper relates to three strands of literature. Firstly, the paper speaks to the literature on environmental policy in endogenous growth models. In general, these papers focus on environmental taxation and analyze settings with inelastic labor supply so that there is no role for labor income taxes in stabilizing or reducing production.

Golosov et al. (2014) investigate the optimal carbon tax in a dynamic stochastic general equilibrium model. Acemoglu et al. (2012) discuss the optimal environmental policy in a tractable model of directed technical change. They highlight the need for green research subsidies to foster green innovation in combination with carbon taxes. Research subsidies serve to correct for the dynamic spillovers of green innovation not internalized by the research sector. They discuss that under a second-best policy, when no subsidies are available, the carbon tax needs to be higher to redirect research. The present paper's exercise directly connects to this case. In my framework, there is no research subsidy, and the government takes into account the effect of the carbon tax on the direction of research. In this scenario, I highlight the need for an additional policy measure—labor income taxes—to correct the level of economic activity when research subsidies are lacking. Fried (2018) extends the framework of the aforementioned paper to a quantitative model. She finds that a constant emission limit can be met at a lower carbon tax when growth is endogenous.

Secondly, this paper is not the first to integrate distortionary fiscal policies into the analysis of environmental policies. However, the role of fiscal policies has in general been passive, and the focus rested on the impact of preexisting fiscal distortions on the environmental policy. One example is the literature focusing on potential double dividends of environmental taxes by generating government revenues (Goulder, 1995; Bovenberg and Goulder, 2002). The present paper closely relates to Barrage (2020) who examines the role of fiscal distortions on the environmental policy in a quantitative framework. She also optimizes jointly over fiscal and environmental policy instruments, but her focus rests on the deviation of the optimal environmental tax from the social costs of carbon.

Thirdly, the paper contributes to the public finance literature. An equity-efficiency trade-off is central to this literature. The benefits of distortive labor taxes arise from redistribution and generating government revenues. (Domeij and Heathcote, 2004; Conesa, Kitao, and Krueger, 2009; Heathcote, Storesletten, and Violante, 2017). To this literature, I add another motive for the use of distortionary fiscal policies: adjusting the level of economic activity as part of the optimal environmental policy.

Outline. The remainder of the paper is structured as follows. Section 2.2 presents the core model and the analytical results. In Section 2.3, I extend and calibrate the model to a quantitative framework. Results are discussed in Section 2.4. Section 2.5 concludes.

2.2 Core model and theoretic results

This section develops a tractable model to derive the theoretic results. I show that scaling the level of production is part of the efficient environmental policy. Yet, absent endogenous growth, this is fully implemented by the use of an environmental tax and lump-sum transfers. There is no role for labor income taxes.

2.2.1 Model

The representative household faces a consumption and labor supply decision. The final consumption good is a composite of a fossil and a green good. Labor is the only input to production. The fossil sector causes an environmental externality.[3] There is no growth, and the model is static.

Representative household. Throughout the paper, the household's decision is static. Each period, the household maximizes its period utility

$$U(C,H;F).$$

The household derives utility from consumption, C, but experiences disutility from hours worked, H. An externality from fossil production, F, decreases household utility. The level of fossil production is taken as given by the household. I assume additive separability of consumption, hours, and the externality. Utility of consumption is increasing and strictly concave. Utility is decreasing and strictly convex in hours worked and fossil production. Utility maximization is subject to a period budget constraint:

$$C \;=\; \lambda(wH)^{1-\tau_\iota} + T_{ls}. \tag{2.2.1}$$

The variable w indicates the wage rate. Lump-sum transfers from the government are denoted by T_{ls}. The government levies income taxes on labor income using a non-linear tax scheme common in the public finance literature (Bénabou, 2002; Heathcote, Storesletten, and Violante, 2017). The tax scheme is characterized by (i) a scaling factor, λ, which determines the level of average tax revenues in the economy, and (ii) a measure of tax progressivity denoted by τ_ι. Heathcote, Storesletten, and Violante (2017) show that whenever $\tau_\iota > 0$, the tax scheme is progressive since the marginal tax rate exceeds the average tax rate irrespective of pre-tax labor income. Hence, average tax payments increase with labor income.[4] With a representative household, τ_ι can be understood as an instrument to regulate labor supply and, thus, the overall level of production. When $\tau_\iota < 0$, the government subsidizes labor, with $\tau_\iota > 0$, it discourages labor.

Production. All sectors of production are perfectly competitive, and production functions have decreasing returns to scale. Intermediate goods, indicated by $J \in \{F,G\}$ for fossil and green, are produced from the labor input good, L_J, using

3. For simplicity, the green sector does not induce any externality; yet, whenever intermediate goods are no perfect substitutes, final good production is never perfectly green.

4. An alternative intuition is that when $\tau_\iota > 0$, the elasticity of post- to pre-tax income is smaller unity for all levels of pre-tax income.

technology, A_J. The variable Y stands in for final output and is the numeraire. Production is given by:

$$Y = Y(F,G), \quad F = F(A_F,L_F), \quad G = G(A_G,L_G). \tag{2.2.2}$$

Government. The government raises income taxes from households and levies an environmental tax, τ_F, per unit of fossil energy bought by final good producers. The environmental tax, thus, is modeled in parallel to a carbon tax which poses a price on emissions. Revenues from the income tax and the environmental tax are treated separately by the government. Income tax revenues are fully redistributed through the income tax schedule. Environmental tax revenues are rebated lump sum to households:

$$\tau_F F = T_{ls}, \quad 0 = wH - \lambda(wH)^{1-\tau_\iota}. \tag{2.2.3}$$

The scaling parameter λ adjusts to balance the income tax scheme.

Markets. Markets for labor and the final good both clear:

$$H = L_F + L_G, \quad Y = C. \tag{2.2.4}$$

Competitive equilibrium. In a competitive equilibrium, household behavior is determined by the budget constraint, eq. (2.2.1), and labor supply which follows from the household's first order conditions and substitution of λ from the government's budget on the income tax:

$$-U_H = U_C(1-\tau_\iota)w. \tag{2.2.5}$$

Firms choose the quantity of input goods to maximize their profits taking prices as given. The following equations describe this behavior in equilibrium:

$$p_G = \frac{\partial Y}{\partial G}, \quad p_F + \tau_F = \frac{\partial Y}{\partial F}, \quad w = p_F\frac{\partial F}{\partial L_F} = p_G\frac{\partial G}{\partial L_G}. \tag{2.2.6}$$

The competitive equilibrium is defined as prices and allocations so that households and firms behave optimally; i.e. eqs. (2.2.1), (2.2.5), and (2.2.6) hold. Production happens according to eqs. (2.2.2). Equilibrium prices and the wage rate adjust to clear markets, eqs. (2.2.4). Finally, the government's budgets are satisfied eqs. (2.2.3). Policy variables τ_F and τ_ι are taken as given.

2.2.2 Theoretic results

Section 2.2.2.1 defines and discusses the efficient allocation. It constitutes a benchmark for the optimal allocation discussed in Section 2.2.2.2.

2.2.2.1 Social planner

Let the share of fossil to total labor be denoted by $s = \frac{L_F}{H}$. The social planner's problem reads

$$\max_{s,H} U(C,H;F)$$
$$s.t. \;\; C = Y.$$

The first order conditions are given by

$$wrt.s \; : \; U_C \cdot \left(\frac{\partial Y}{\partial F} \frac{\partial F}{\partial s} + \frac{\partial Y}{\partial G} \frac{\partial G}{\partial s} \right) = -U_F \frac{\partial F}{\partial s}, \tag{2.2.7}$$
$$wrt.H \; : \; U_C \frac{\partial Y}{\partial H} + U_F \frac{\partial F}{\partial H} = -U_H. \tag{2.2.8}$$

Where U_X denotes the partial derivative of utility with respect to the variable X. These equations determine the efficient or first-best allocation. Absent an externality, $U_F = 0$, the efficient distribution of labor equalizes the marginal product of labor across sectors; compare eq. (2.2.7). Efficient hours balance the marginal utility gain from consumption and the marginal disutility from working, as formalized by eq. (2.2.8).

When there is an externality, the social planner adjusts the allocation in two ways: (i) a compositional adjustment, that targets the share of fossil production, and (ii) a scaling adjustment amending the level of production. The compositional adjustment is determined by eq. (2.2.7). The negative externality of fossil production makes it efficient to alter the share of fossil labor so that a marginal reallocation of labor to the fossil sector would raise output.[5] I show in Appendix 2.A.2 that the social planner reduces the fossil labor share when the aggregate production function features decreasing returns to scale in its labor inputs, L_G and L_F.

The scaling effect is summarized by eq. (2.2.8). First note that eq. (2.2.8) can be rewritten by substituting eq. (2.2.7) and noticing the relation of derivatives

5. Note that $U_F < 0$ by assumption so that the right-hand side is positive and that $\frac{dG}{ds} < 0$. Hence, in the efficient allocation, the marginal product of labor in the fossil sector is higher than in the green sector.

with respect to H and s.[6] The second first order condition becomes:

$$-U_H = U_C \frac{\partial Y}{\partial G} \frac{\partial G}{\partial L_G}. \tag{2.2.9}$$

Hence, the efficient level of the externality lowers hours as if the marginal product of labor was equal to the marginal product of labor in the clean sector.

The recomposition of labor towards the green sector reduces the average marginal product of labor in the economy. An additional unit of labor results in a smaller increase in consumption. This effect has two opposing impacts on the efficient level of labor. On the one hand, there is a substitution effect: as leisure becomes less costly, the efficient amount of hours reduces (note that the right-hand side of eq. (2.2.8) is increasing in H). On the other hand, the economy becomes poorer in terms of consumption, and more work effort might be efficient. This is captured by the term U_C and equivalent to an income effect. Proposition 1 summarizes this discussion.

Proposition 1. Efficient externality mitigation consists of a compositional and a scaling adjustment.

Depending on the importance of the income effect, efficient hours worked may be higher or lower than absent an externality. I will show in the following, however, that there is no role for labor income taxation in implementing the efficient allocation. In fact, under the optimal policy, the wage rate is set so that households internalize the effect of work effort on emissions.

2.2.2.2 Decentralized economy

Governments use tax and transfer instruments to correct for distortions, such as an environmental externality. The question arises if the efficient allocation can be decentralized by the use of taxes and transfers in a competitive economy.

The government is characterized by a Ramsey planner who maximizes utility of the representative household by use of tax and transfer instruments. The behavior of firms and households constrain the government's optimization problem. The Ramsey problem is defined as

$$\max_{s,H} U(C,H;F)$$
$$s.t. \;\; C = Y,$$

6. This is done in more detail for the optimal allocation in Appendix 2.A.5. Relations of derivatives are summarized in Appendix 2.A.1.

subject to the behavior of households and firms. The first order conditions are equivalent to the social planner ones:

$$wrt.\ s\ :\quad U_C \cdot \left(\frac{\partial Y}{\partial F}\frac{\partial F}{\partial s} + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial s}\right) \;=\; -U_F \frac{\partial F}{\partial s}, \tag{2.2.10}$$

$$wrt.\ H\ :\quad U_C \frac{\partial Y}{\partial H} + U_F \frac{\partial F}{\partial H} \;=\; -U_H. \tag{2.2.11}$$

When environmental tax revenues are fully redistributed lump sum, an environmental tax equal to the marginal social cost of fossil production implements the efficient allocation.[7] This observation is known as the *Pigou principle* in the literature. To see this, note that eq. (2.2.10) ensures that the social planner's first order condition, eq. (2.2.7), is satisfied. Rewriting eq. (2.2.7) reveals that the Pigou principle holds:

$$\underbrace{\frac{-U_F}{U_C}}_{\text{marginal social cost of fossil production}} \;=\; \left(1 + \frac{\frac{\partial Y}{\partial G}\frac{\partial G}{\partial s}}{\frac{\partial Y}{\partial F}\frac{\partial F}{\partial s}}\right)\frac{\partial Y}{\partial F} \;=\; \tau_F^*.$$

Where the second equality follows from substituting firms' profit maximization conditions from eqs. (2.2.6).

Absent an externality of production, it is efficient to balance marginal products of labor across sectors. When there is an externality, the social planner lowers the share of labor in the fossil sector. As a result, the marginal product of labor in this sector increases. It falls in the green sector. To sustain this gap between marginal products in the competitive equilibrium, the government has to introduce a corrective tax. Otherwise, market forces would direct labor towards the sector with the higher marginal product. Consequently, the equilibrium wage rate is below the marginal product of labor.[8]

Setting the environmental tax equal to the social cost of fossil production implies that the second first order condition of the Ramsey planner, eq. (2.2.11), is satisfied without use of the income tax instrument: $\tau_\iota^* = 0$. The reason is, that in this case, the wage rate reflects the marginal social costs of hours through raising emissions. I show in Appendix 2.A.5 that the wage rate can be written as:

$$w \;=\; \frac{\partial Y}{\partial H} + \frac{U_F}{U_C}\frac{\partial F}{\partial H}.$$

Since $U_F < 0$, the second summand reduces the wage rate beyond the marginal product of labor in the economy. Therefore, households internalize the marginal

7. I define and derive the social cost of fossil production in Appendix 2.A.3.
8. I formally discuss this statement in Appendix 2.A.4.

social costs of the externality of hours worked in their labor supply decision. Relative to no policy intervention, labor supply declines. Proposition 2 condenses this result.

Proposition 2. The efficient allocation is implemented by an environmental tax and lump-sum transfers. When the environmental tax implements the efficient share of dirty labor, the wage rate fully captures the marginal effect of hours worked on the externality. There is no role for distortive labor income taxation, $\tau_\iota^* = 0$.

Proof: Appendix 2.A.5.

2.3 Quantitative model and calibration

The previous section shows that there is no role for labor income taxation in the optimal policy. However, the model abstracts from endogenous growth. When growth is endogenous, carbon taxes may be used to target the allocation of research across sectors.[9] Then, a motive for income taxation may arise from optimal emission mitigation because the carbon tax deviates from implementing the efficient share of fossil labor. Therefore, Section 2.3.1 extends the core model to a quantitative framework building on Fried (2018). Section 2.3.2 calibrates the quantitative model.

2.3.1 Quantitative model

The main extensions to the core model are endogenous growth, a third, non-energy sector, and skill heterogeneity. The latter allows to capture a skill bias in the green sector (Consoli, Marin, Marzucchi, and Vona, 2016). The government maximizes utility of the representative household under the constraint of meeting an exogenous emission limit. This limit attaches social costs to fossil production and replaces the utility costs of fossil in the core model. Appendix 2.B provides an overview of all equations determining the competitive equilibrium.

Households. A representative household describes the household side. The household chooses hours of high-, h_{ht}, and low-skill workers, h_{lt}, hours of scientists, S_t, and average consumption, C_t, taking prices as given. The share of worker types is fixed with a lower share of high-skill workers, z_h, resulting in a skill premium. The household's problem remains static. Modeling the economy as a representative

9. Acemoglu et al. (2012) argue that to achieve the efficient allocation, a research subsidy needs to complement a carbon tax. In their setting, the subsidy serves to correct for dynamic spillovers in research. Absent a subsidy on green research, the optimal carbon tax is higher to stimulate green growth today. The result in my framework may differ due to knowledge spillovers and decreasing returns to research.

family allows to abstract from inequality as a motive for government intervention while being able to study skill heterogeneity. The total time endowment of workers and scientists is given by $\bar{H}$. The household receives lump-sum transfers from the government: $T_{\pi t}$ and T_{lst} resulting from (i) confiscating firm profits and (ii) the carbon tax. The household behaves according to:

$$\begin{aligned}
&\max_{C_t,h_{lt},h_{ht},S_t} u(C_t, h_{lt}, h_{ht}, S_t)\\
&\quad s.t.\ \ p_t C_t \ \le\ z_h \lambda_t \left(h_{ht} w_{ht}\right)^{1-\tau_{\iota t}} + (1-z_h)\lambda_t \left(h_{lt} w_{lt}\right)^{1-\tau_{\iota t}} + w_{st} S_t + T_{\pi t} + T_{lst},\\
&\qquad h_{ht} \ \le\ \bar{H}, \quad h_{lt} \ \le\ \bar{H}, \quad S_t \ \le\ \bar{H}.
\end{aligned}$$

The variables w_{ht}, w_{lt}, w_{st}, and p_t indicate prices for high- and low-skill labor, for research, and the final consumption good. The government taxes labor income at the skill level. Income of scientists is not taxed because if they were, the planner would use the labor income tax to subsidize research.[10]

Production. Production separates into final good production, energy production, intermediate good production, and the production of machines and the intermediate labor input good. The final sector is perfectly competitive combining non-energy and energy goods according to:

$$Y_t \ =\ \left[\delta_y^{\frac{1}{\varepsilon_y}} E_t^{\frac{\varepsilon_y-1}{\varepsilon_y}} + (1-\delta_y)^{\frac{1}{\varepsilon_y}} N_t^{\frac{\varepsilon_y-1}{\varepsilon_y}}\right]^{\frac{\varepsilon_y}{\varepsilon_y-1}}.$$

I take the final good as the numeraire and define its price as $p_t = \left[\delta_y p_{Et}^{1-\varepsilon_y} + (1-\delta_y) p_{Nt}^{1-\varepsilon_y}\right]^{\frac{1}{1-\varepsilon_y}}$. Energy producers perfectly competitively combine fossil and green energy to a composite energy good:

$$E_t \ =\ \left[F_t^{\frac{\varepsilon_e-1}{\varepsilon_e}} + G_t^{\frac{\varepsilon_e-1}{\varepsilon_e}}\right]^{\frac{\varepsilon_e}{\varepsilon_e-1}}.$$

The price of energy is determined as $p_{Et} = \left[(p_{Ft}+\tau_{Ft})^{1-\varepsilon_e} + p_{Gt}^{1-\varepsilon_e}\right]^{\frac{1}{1-\varepsilon_e}}$. The government levies a sales tax per unit of fossil energy bought by energy producers, τ_{Ft}. This tax is referred to as environmental or carbon tax in this paper.

10. This would also be optimal in a world without emission target. Thus, to focus the analysis on the effect of the labor income tax on labor supply, income of scientists is not taxed. In this case, the optimal policy sets the progressivity of the labor income tax numerically to zero. In a model version where scientists' income is also taxed, the deviation in the optimal labor income tax with and without emission target reflects the findings using this model version.

Intermediate goods, fossil, F_t, green, G_t, and non-energy, N_t, are again produced in competitive sectors using a sector-specific labor input good and machines. The production function in sector $J \in \{F, G, N\}$ reads

$$J_t = L_{Jt}^{1-\alpha_J} \int_0^1 A_{Jit}^{1-\alpha_J} x_{Jit}^{\alpha_J} di.$$

The variable A_{Jit} indicates the productivity of machine i in sector J at time t: x_{Jit}. Capital shares, α_J, are sector specific. Intermediate good producers maximize profits:

$$\pi_{Jt} = p_{Jt} J_t - w_{lJt} L_{Jt} - \int_0^1 p_{xJit} x_{Jit} di,$$

where w_{lJt} is the price of sector J's labor input good, L_{Jt}, and p_{xJit} denotes the price of machines from producer i in sector J.

The labor input good of sector J is produced by a perfectly competitive labor industry according to:

$$L_{Jt} = h_{hJt}^{\theta_J} h_{lJt}^{1-\theta_J}.$$

This additional intermediate industry allows to capture differences in skills by sector and in particular the skill bias of the green sector: $\theta_G > \frac{1}{2}(\theta_F + \theta_N)$.

Machine producers are imperfect monopolists searching to maximize profits. They choose the price at which to sell their machines to intermediate good producers and decide on the amount of scientists to employ. Demand for machines increases with their productivity. This provides the incentive to invest in research. Irrespective of the sector, the costs of producing one machine is set to one unit of the final output good similar to Fried (2018) and Acemoglu et al. (2012). Following the same literature, machine producers only receive returns to innovation for one period. Afterwards, patents expire. Machine producer i's profits in sector J are given by

$$\pi_{xJit} = p_{xJit}(1 + \zeta_{Jt}) x_{Jit} - x_{Jit} - w_{st} s_{Jit}.$$

The government subsidizes machine production by ζ_{Jt} to correct for the monopolistic structure. After production has taken place, machine producers' profits are confiscated by the government to simplify notation.

Research and technology. Technology growth is driven by research and spillovers. The law of motion of technology of machines from firm i in sector J is modeled as

$$A_{Jit} = A_{Jt-1}\left(1+\gamma\left(\frac{s_{Jit}}{\rho_J}\right)^{\eta}\left(\frac{A_{t-1}}{A_{Jt-1}}\right)^{\phi}\right).$$

Aggregate technology levels are defined as

$$A_{Jt} = \int_0^1 A_{Jit}di,$$
$$A_t = \frac{\rho_F A_{Ft} + \rho_G A_{Gt} + \rho_N A_{Nt}}{\rho_F + \rho_G + \rho_N}.$$

The parameters ρ_J capture the number of research processes by sector. This ensures that returns to scale refer to the ratio of scientists to research processes (Fried, 2018). Private benefits of research diverge from social ones for two reasons. First, innovation builds on "the shoulder of giants" introduced through the term A_{Jt-1}, that is, knowledge spills within sectors over time. However, producers do not internalize the effect of today's research on tomorrow's research productivity under one-period patents. Second, they neither consider knowledge spillovers to other sectors captured by the term $\left(\frac{A_{t-1}}{A_{Jt-1}}\right)^{\phi}$ with $\phi \geq 0$. There are no cross-sectoral knowledge spillovers when $\phi = 0$.

The marginal (private) product of research determines the amount of researchers employed. It equals the competitive wage for scientists given by

$$w_{st} = \frac{\eta\gamma\left(\frac{A_{t-1}}{A_{Jt-1}}\right)^{\phi}(1-\alpha_J)\alpha_J s_{Jt}^{\eta-1} p_{Jt} J_t}{\rho_J^{\eta}}.$$

The parameter γ governs research productivity.

The supply of scientists is endogenous in my model. With this choice, I depart from the standard assumption of a fixed supply of scientists in the literature on directed technical change (Acemoglu et al., 2012; Fried, 2018). Modeling the supply of researchers flexibly gives more freedom for the planner to choose lower growth levels: no a-priori fixed amount of research has to be employed. In light of an absolute emission limit, this could be important. There is free movement of scientists across sectors, which seems reasonable given the 5-year duration of one period and certain research skills being applicable across sectors.

Markets. In equilibrium, markets clear. I explicitly model markets for workers, scientists, and the final consumption good:

$$\begin{aligned} z_h h_{ht} &= h_{hFt} + h_{hGt} + h_{hNt}, \\ (1 - z_h) h_{lt} &= h_{lFt} + h_{lGt} + h_{lNt}, \\ S_t &= s_{Ft} + s_{Gt} + s_{Nt}, \\ C_t &= Y_t - \int_0^1 \left(x_{Fit} + x_{Git} + x_{Nit} \right) di. \end{aligned}$$

Government. The government seeks to maximize lifetime utility of the representative household. Each period, the government is constrained by an emission limit, Ω_t, in line with the Paris Agreement. It is characterized as a Ramsey planner taking the behavior of firms and households as given and discounting period utility with the household's time discount factor, β. The planner chooses time paths for environmental taxes and the tax progressivity parameter on the income tax scheme to solve:

$$\max_{\{\tau_{Ft}\}_{t=0}^{\infty}, \{\tau_{\iota t}\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t u(C_t, h_{ht}, h_{lt}, S_t)$$

$$s.t. \quad \omega F_t - \delta \le \Omega_t, \tag{2.3.1}$$

$$z_h \left(w_{ht} h_{ht} - \lambda_t \left(w_{ht} h_{ht} \right)^{1-\tau_{\iota t}} \right) + (1 - z_h) \left(w_{lt} h_{lt} - \lambda_t \left(w_{lt} h_{lt} \right)^{1-\tau_{\iota t}} \right) = 0, \tag{2.3.2}$$

$$\sum_{J \in \{F,G,N\}} \left(\int_0^I \pi_{xJit} di - \zeta_{Jt} \int_0^I p_{xJit} x_{Jit} di \right) = -w_{st} S_t = T_{\pi t}, \tag{2.3.3}$$

$$\tau_{Ft} F_t = T_{lst}. \tag{2.3.4}$$

subject to the behavior of firms and households, and feasibility[11]. Constraint (2.3.1) is the emission limit. The parameter δ captures the capacity of the environment to reduce emitted CO_2 through sinks, such as forests and moors.[12] The parameter ω determines CO_2 emissions per unit of fossil energy produced.

The scale parameter on income taxes, λ_t, adjusts so that all revenues from the labor income tax are redistributed to the household, eq. (2.3.2). The government also generates revenues from confiscating profits which are used to finance the subsidy on machine production. The remainder is rebated lump sum to

11. Feasibility means that the government is constrained by initial technology levels, time endowments of workers and scientists, and production processes prescribed by the model.

12. In the model, sinks are assumed to be constant. I argue for this choice in Section 2.3.2.2.

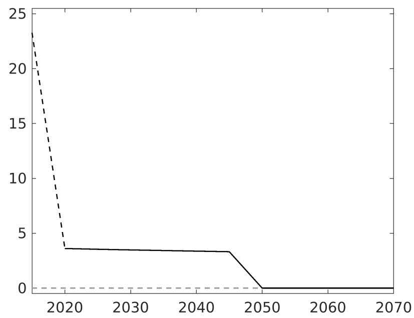

Figure 2.3.1. Net CO_2 emission limit in gigatons (Gt)

households, eq. (2.3.3). Finally, the government redistributes environmental tax revenues lump sum, eq. (2.3.4).

2.3.2 Calibration

Section 2.3.2.1 derives and discusses the emission target. Secton 2.3.2.2 calibrates the remaining model parameters.

2.3.2.1 Emission target

This section calibrates the emission limit. I consider CO_2 emissions only and abstract from other greenhouse gasses since carbon is the most important pollutant with the highest mitigation potential (IPCC, 2022a, p.29). The most recent IPCC report (IPCC, 2022a) formulates a reduction of global CO_2 emissions in the 2030s by 50% relative to 2019 and net-zero emissions in the 2050s as essential to meeting the 1.5°C climate target.[13] Furthermore, the report stipulates a remaining global net CO_2 budget of 510 $GtCO_2$ from 2020 to the net-zero phase starting from 2050 (IPCC, 2022a, p.5, Chapter 3). To deduce an emission target for the US, further assumptions on the distribution of mitigation burdens have to be made. I follow Robiou Du Pont, Jeffery, Gütschow, Rogelj, Christoff, et al. (2017) who consider 5 distinct principles of distributive burden sharing. I use an *equal-per-capita* approach according to which emissions per capita shall be equalized across countries. I plan to conduct sensitivity analyses based on alternative derivations of the emission target. Appendix 2.C details the calculation of the emission target. Figure 2.3.1 visualizes the resulting emission limit for the US starting from 2020. The value for 2015-2019 refers to observed emissions.

13. "*Mitigation pathways limiting warming to 1.5°C [...] reach 50% reductions of CO_2 in the 2030s, relative to 2019, then reduce emissions further to reach net zero CO_2 emissions in the 2050s [...] (*medium confidence*).*" (IPCC, 2022a, p.5, Chapter 3)

Discussion. The reduction in net CO_2 emissions necessary to meet the emission limit relative to 2019 emissions in the US is substantial. It amounts to around 85%. The result is not only explained by the global emission limit but also by the US emitting beyond its population share in 2019. In 2019, US emissions accounted for 10.44% of global net emissions while the population share of the US was 4.3%. Hence, even without an emission limit, the US would have to reduce emissions according to the *equal-per-capita* principle.

The necessary reduction in net CO_2 emissions found in this calibration exceeds political goals. On April 22, 2021, President Biden announced a 50-52% reduction in net greenhouse gas emissions relative to 2005 levels in 2030 and net-zero emissions no later than 2050.[14] However, relative to 2019, the planned reduction for 2030 corresponds to a 38% decline only. The resulting net emissions in the US would then amount to 103.21 Gt.[15] This is 5 times the budget acceptable for the US, if the global remaining carbon budget was allocated on a *equal-per-capita* basis.[16]

2.3.2.2 Model parameters

Functional forms. I assume the following functional form of period utility:

$$u(C_t, h_{ht}, h_{lt}, S_t) = \log(C_t) - z_h \chi \frac{h_{ht}^{1+\sigma}}{1+\sigma} - (1-z_h)\chi \frac{h_{lt}^{1+\sigma}}{1+\sigma} - \chi_s \frac{S_t^{1+\sigma_s}}{1+\sigma_s}.$$

The log-utility of consumption ensures that the scaling parameter of the income tax scheme does not affect hours worked. It cancels from the optimality condition describing labor supply since income and substitution effect cancel which simplifies the analysis.[17]

Parameter values. To calibrate the model, I proceed in three steps. First, I set certain parameters to values found in the literature. Second, I calibrate the remaining variables requiring that equilibrium conditions and target equations hold. Third, parameters relating production and emissions are chosen. Table 2.3.1 summarizes the calibrated parameter values.

14. Source: https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/, retrieved 14 September 2022.

15. This calculation assumes emissions where left at 2019-levels until 2030 and then lowered to the Biden target from 2030 to 2050 and net-zero afterwards.

16. The remaining net carbon budget for the US based on its population share is 20.738Gt for the period from 2020 to 2050.

17. On the other hand, recent research has shown that substitution and income effects of the wage rate most likely do not cancel. Boppart and Krusell (2019) argue for a slightly higher income effect so that hours fall over time as productivity increases. I plan to conduct a sensitivity analysis by assuming the utility specification suggested in their paper.

I calibrate the model to the US in the baseline period from 2015 to 2019. Using this calibration approach, it is not ensured that the economy is on a balanced growth path. However, the goal of this paper is to study necessary interventions to meet an absolute emission limit. Therefore, it is important to capture whether the economy is transitioning, for example, to a higher fossil share. The optimal dynamic policy has to counteract these forces.

In the first step, I mainly rely on Fried (2018) to calibrate the parameters governing research processes, $\eta, \rho_F, \rho_N, \rho_G, \phi$, and production, $\varepsilon_e, \varepsilon_y, \alpha_F, \alpha_G, \alpha_N$. The labor share in the green sector is remarkably low with $\alpha_G = 0.91$. This diminishes the significance of labor supply for green innovation and production. Furthermore, fossil and green energy are no close substitutes with $\varepsilon_e = 1.5$ so that the cap on fossil energy cannot be fully substituted for by green energy. Returns to research are decreasing with $\eta = 0.79 < 1$. This makes extreme distributions of researchers across sectors unproductive. The non-energy sector is the biggest research sector with $\rho_N = 1$ and $\rho_F = \rho_G = 0.01$. The utility parameters, β, σ, are set to 0.984^5 and 0.75^{-1} following Barrage (2020) and Chetty, Guren, Manoli, and Weber (2011), respectively. The business-as-usual policy is set to $\tau_\iota = 0.181, \tau_F = 0$, where I borrow the tax progressivity parameter from Heathcote, Storesletten, and Violante (2017).

In the second step, I calibrate the weight on energy in final good production by matching the average expenditure share on energy relative to GDP over the period from 2015 to 2019 taken from the US Energy Information Administration (EIA, 2022, Table 1.7). The expenditure share equals 6%. The resulting weight on energy is $\delta_y = 0.38$. The data to match the high-skill share in labor production are taken from Table 3 in Consoli et al. (2016). In particular, I derive the share of high-skill labor in the green sector and for the non-green sector. I assume that within the non-green sector, i.e., sectors N and F in the model, high-skill labor shares are the same, $\theta_F = \theta_N$. These three conditions determine $\theta_G = 0.57$ and $\theta_F = \theta_N = 0.42$. The share of high-skill workers, z_h, is chosen to match a skill premium for the period 2005-2016 of $\frac{w_h}{w_l} = 1.9$ following Slavík and Yazici (2020). The disutility of labor, χ, is set to match equilibrium average hours worked to average hours over the period from 2015-2019 drawing from OECD data (OECD, 2021), $\chi = 10.02$. I normalize total economic time endowment for workers and scientists per day, which I set to 14.5 as found in Jones, Manuelli, and Rossi (1993), to 1.

Two more variables determining research remain to be calibrated: research productivity, γ, and the disutility from research, χ_s. To find γ, I force the maximum aggregate growth rate, defined as the growth rate which would obtain, if researchers worked all available hours, to match an annual growth rate of 4%. This value roughly reflects an upper bound for annual growth rates in the US from 2010 to 2019 (compare OECD, 2022). The resulting research productivity is $\gamma = 0.06$. Finally, I set average hours supplied by scientists to 0.34 similar to workers while equilibrium equations have to hold. As a result, the disutility of research is $\chi_s = 0.48$. Initial productivity levels follow from normalizing output in the base period to $Y = 1$ and matching the ratio of fossil-to-green energy utilization over the years 2015-2019 which equals 7.33 according to EIA (2022, Table 1.3). I find that total factor productivities in the baseline period are $A_{N0}^{1-\alpha_N} = 2.8$, $A_{F0}^{1-\alpha_F} = 8.21$, and $A_{G0}^{1-\alpha_G} = 1.27$.

Finally, I calibrate the sink capacity to match the average difference between gross and net CO_2 emissions over the baseline period from 2015 to 2019. Information on emissions comes from the US Environmental Protection Agency (EPA, 2022). Since sinks are relevant for all greenhouse gasses, I only use the proportion of total sink capacity which reflects contribution of carbon dioxide to gross greenhouse gas emissions. The resulting sink capacity per model period is $\delta = 3.19 GtCO_2$.[18] The parameter relating CO_2 emissions and fossil energy in the base period equals $\omega = 217.39$.[19]

2.4 Quantitative results

This section presents and discusses the quantitative results. In Section 2.4.1, I use the model to learn how a constant carbon tax affects the economy and how it interacts with a tax on labor income. Section 2.4.2 calculates how high a carbon tax is necessary to meet the emission limit. I find that an increasing carbon tax is necessary to counter market forces directing production and research towards the fossil sector. Section 2.4.3 goes one step further asking how the government can optimally satisfy the emission limit using carbon and labor income taxes. Results show that a combination of the two instruments is optimal throughout.

2.4.1 A constant carbon tax

We are now equipped to study how a carbon tax equal to US$185 (in 2020 prices) affects the economy. The value reflects the social costs of carbon calculated by a joint research effort led by *Resources for the Future* (RFF), an independent research institution, and the University of Berkeley (Rennert, Errickson, Prest, Rennels, Newell, et al., 2022).[20]

18. I consider this capacity to be constant. This is a simplifying assumption. What is crucial qualitatively is the assumption that sinks are finite. Indeed, natural sinks and carbon capture and storage (CCS) technologies rely on the use of land (Van Vuuren, Stehfest, Gernaat, Van Den Berg, Bijl, et al., 2018) which is in limited supply. In addition, the importance of land for food production makes land even scarcer especially in light of a growing world population.

19. I perceive the fossil sector in the model as source of all CO_2 emissions including, for instance, non-energy use of fuels and incineration of waste.

20. For comparability, the social cost of carbon equal US$203.5 in 2022 prices.

Table 2.3.1. Calibration

Parameter	Target/Source	Value
Household		
(σ, σ_s)	Chetty et al. (2011)	(1.33, 1.33)
z_h	skill premium 2005-2016: $w_h/w_l = 1.9$ (Slavík and Yazici, 2020)	0.21
(χ, χ_s)	average hours worked per economic time endowment by worker: 0.34 (OECD, 2021)	(10.02, 0.48)
β	Barrage (2020)	0.93
$\bar{H}$	14.5 hours per day Jones, Manuelli, and Rossi (1993)	1.00
Research		
η		0.79
(ρ_F, ρ_G, ρ_N)	Fried (2018)	(0.01, 0.01, 1.00)
ϕ		0.50
γ	maximum aggregate growth: 4% per annum (OECD, 2022)	0.06
Production		
ε_y	Fried (2018)	0.05
δ_y	expenditure share on energy (EIA, 2022)	0.38
ε_e		1.50
$(\alpha_F, \alpha_G, \alpha_N)$	Fried (2018)	(0.72, 0.91, 0.36)
Initial total factor productivity		
$(A_{F0}^{1-\alpha_F}, A_{G0}^{1-\alpha_G}, A_{N0}^{1-\alpha_N})$	energy shares (EIA, 2022)	(8.21, 1.27, 2.80)
Labor production		
$(\theta_F,\theta_G,\theta_N)$	share of high skill non-green: 27.55%, green: 40.71% (Consoli et al., 2016)	(0.42, 0.57, 0.42)
Government		
τ_F	-	0.00
τ_ι	Heathcote, Storesletten, and Violante (2017)	0.18
Emissions		
δ	EPA (2022)	3.19
ω	EPA (2022)	217.39

Static effect of a carbon tax. Figure 2.4.1 shows the effect of a constant carbon tax in a world with and without labor income tax represented by the solid and the dashed graphs, respectively. In this and all following figures, the x-axis indicates the first year of the 5-year period to which the variable value corresponds.[21]

Panel (a) depicts how net emissions evolve under the carbon tax. The level of emissions is smaller in presence of a labor income tax with $\tau_\iota = 0.181$. A carbon tax of 185$ per ton diminishes emissions by around 46% initially relative to the business-as-usual (BAU) policy; i.e., without carbon tax. However, net emissions exceed the emission limit derived previously; see the thin dotted line in Panel

21. Figure 2.E.1 in Appendix 2.E.1 shows research related and other variables.

(a) Net CO_2 emissions in Gt

(b) Fossil energy in percentage deviation from business-as-usual

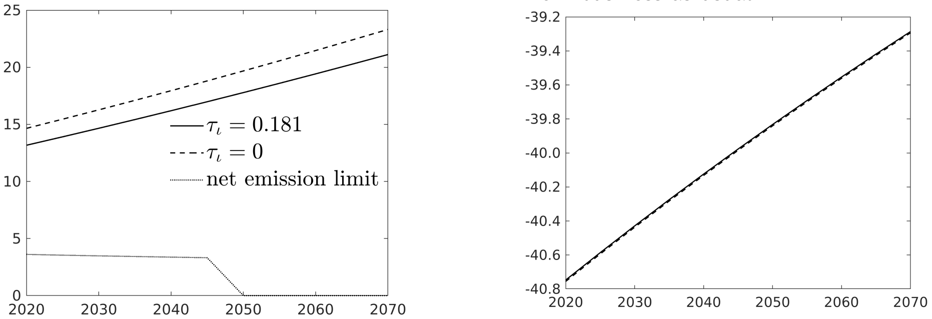

Figure 2.4.1. A constant carbon tax equal to US$185 (2020 prices) per ton of carbon

Notes: Panel (a) shows levels of net emissions under a constant carbon tax equal to US$185 (in 2020 prices) for a world with progressive income taxation at $\tau_\iota = 0.181$, the solid graph, and without income taxation, $\tau_\iota = 0$. The thin dotted graph shows the emission limit suggested by the IPCC. Panel (b) presents the percentage deviation from the business-as-usual policy in the economy (i) with and (ii) without income tax by the solid and dashed graphs, respectively.

(a). Panel (b) shows the percentage deviation from the BAU allocation for fossil energy.

A carbon tax operates as follows. As energy producers face a higher price for fossil energy, they lower demand for fossil and rise demand for green energy. Fossil production falls, and green production rises. The tax on fossil goods also increases the price for energy goods relative to non-energy goods on impact. Final good producers recompose their inputs towards non-energy goods. The energy share to GDP declines. But, the recomposition is limited as energy and non-energy goods are complements.

The shift in demand by energy and final good producers induces a reallocation of research. In the model, the direction of research is determined by a market size effect, a price effect, and knowledge spillovers. A market size effect directs research to the sector with the bigger market; i.e., higher output. A price effect runs in the contrary direction rendering research in more expensive sectors more profitable. Which effect dominates depends on the degree of substitutability of goods (Acemoglu, 2002; Hémous and Olsen, 2021). Cross-sectoral knowledge spillovers make research in less productive sectors more profitable.

Since green and fossil goods are sufficient substitutes, the market size effect dominates the price effect. As demand for the green good increases, profitability of research in this sector rises. In contrast, research in the fossil sector falls. This makes the green good even cheaper contributing to an increase in the green-to-fossil energy ratio. Non-energy research falls because knowledge spillovers to the energy sector direct research away from the non-energy sector.[22]

Dynamics. Over time, the effectiveness of the carbon tax to lower fossil production declines from 40.8% to 39.3%. Hence, to meet a net-zero emission limit, a continuous intervention is necessary. This finding is in contrast to the result by Acemoglu et al. (2012) who abstract from cross-sectoral knowledge spillovers and heterogeneity in labor shares. They conclude that when dirty and clean goods are sufficient substitutes, a temporary intervention suffices to prevent too high pollution. In contrast, in the present model, cross-sectoral knowledge spillovers and heterogeneous labor shares call for a continuous rise in the carbon tax to keep fossil energy from rising.

Consider, first, the effect of cross-sectoral knowledge spillovers. Initially, the carbon tax reduces research in the fossil sector, however, as green technology advances, knowledge spillovers from the green sector make fossil research more profitable again, and demand for fossil scientists resurges. It is not only that a constant amount of researchers becomes more productive but also a change in the equilibrium level of fossil researchers which intensifies the effect of knowledge spillovers. This mechanism explains the quick rise in emissions under a constant carbon tax.[23] Therefore, when knowledge spillovers are strong, reducing emissions to net-zero requires a continues intensification of environmental intervention. In its extreme, growth may have to stop eventually in order to prevent the fossil sector from growing too much.

Consider now the effect of heterogeneous labor shares. The green sector has the smallest labor share. Labor is more important in the fossil and most important in the non-energy sector. This heterogeneity lowers the effectiveness of the carbon tax through a supply-side channel. A reduction in demand for labor in the fossil sector eases labor costs of the green sector. When, however, the green sector only uses a small share of labor, the higher labor supply does not lower green production costs as much, and the green good remains more expensive. The share

22. I examine the effect of a carbon tax on non-energy and energy research in Appendix 2.E.1. Contrary to theory, the price effect does not dominate. It does not direct research to the more expensive good. The reason are heterogeneous labor shares which hamper a supply-side effect. Assume sectors share the same input good. As demand for the more expensive good falls, the cheaper sector can produce even cheaper because of a higher supply of input goods. This amplifies the price difference in goods. When the supply-side effect is muted since sectors have different production functions, the price difference may not be big enough to direct research to the more expensive good. The market size effect dominates directing research to the sector with the bigger market: in this case, non-energy goods. Yet, cross-sectoral knowledge spillovers from the non-energy to the energy sector are pivotal. All in all, the share of energy research increases.

23. Panel (a) in Figure 2.E.2 shows the effect of a constant carbon tax in a model without cross-sectoral knowledge spillovers, $\phi = 0$. The rise in net emissions over time is muted, and a constant carbon tax becomes more effective over time in reducing fossil production. Absent cross-sectoral knowledge spillovers, more research is allocated to the green and non-energy sector.

of green energy and labor rises less. This weakens the effectiveness of directed technical change to foster green energy production. Panel (b) in Figure 2.E.2 displays the behavior of key variables in a model with homogeneous labor shares across sectors.[24]

Panel (c) in Figure 2.E.2 shows the result in a model variation without cross-sectoral knowledge spillovers and with equal labor shares. A constant carbon tax suffices to lower emissions over time. Then, endogenous growth directs research away from the fossil sector so that emissions continuously decline. This finding is consistent with the result in Acemoglu et al. (2012).

Effect of the income tax. A progressive income tax lowers the level of emissions; compare the solid and the dashed graph in Panel (a) in Figure 2.4.1. As labor supply reduces, output shrinks, and emissions fall. However, there are compositional effects of a progressive income tax which (i) affect the economic structure and (ii) interact with the effectiveness of the carbon tax. I will explain each statement in turn.

A progressive income tax lowers the green-to-fossil energy ratio and diminishes the energy share in GDP. The compositional effect of a progressive income tax originates from the asymmetric reaction of high- and low-skill workers. Tax progressivity affects labor supply via an income and a substitution effect. The income effect is similar across skill types due to the family structure of the household side. The substitution effect, in contrast, is more pronounced for high-skill workers. There are two reasons. First, post-tax income falls more the higher pre-tax income as progressivity rises. Second, I assume that the marginal value of leisure rises with hours worked. Since the high skill work more, they require a higher wage rate to be compensated for an additional unit of labor. Hence, as tax progressivity rises, and the after-tax wage rate falls, the high skill reduce their labor supply more. Overall, the high-to-low skill ratio declines.

Now, note that green production is skill biased as opposed to fossil production. As a consequence, green production becomes more expensive, while fossil production gets cheaper when tax progressivity rises. The price of non-energy goods, which are less skill-intense than energy goods, falls, too. Therefore, energy producers substitute fossil for green energy, and final good producers turn to non-energy goods. The former effect raises, the latter diminishes emissions.

Research responds to the change in demand and in prices. First, non-energy research is less profitable due to its smaller price. Since non-energy and energy goods are complements, the amount of non-energy goods does not rise sufficiently to raise machine producers' profits despite the smaller price. As a result, research turns to the energy sector. The share of non-energy researchers reduces, albeit

24. In this counterfactual calibration, I set capital shares equal across sectors to the average in the baseline calibration: $\alpha_g = \alpha_f = \alpha_n = 0.66$.

minimally. Second, focusing solely on the allocation of researchers between the fossil and green sector, the relatively higher supply of low-skill labor raises the market size of the fossil good. Since intermediate energy goods are sufficient substitutes, the market size effect dominates the price effect and research shifts from green to fossil. Although the share of green-to-fossil research drops, the absolute amount of green scientists increases. The reallocation of research to energy goods in general implies a rise in green researchers.

While the labor tax affects the composition of research due to skill heterogeneity, there is no effect on aggregate research activity. To see this, I consider the model with homogeneous skills, then the labor tax has no compositional effect. In this model, the equilibrium amount of scientists remains unchanged by a progressive income tax. Indeed, demand for innovation reduces in response to a progressive income tax since less labor is available to work with technology. However, at the same time, scientists are willing to accept a lower wage rate since consumption of the household reduces. In equilibrium, the reduction in demand is absorbed by a change in the wage rate, and the level of aggregate research remains unchanged.

Interaction of income and carbon taxes. The compositional effect of a tax on labor interacts with the impact of the carbon tax. Quantitatively, the effect of the carbon tax seems largely unaffected by the value of income tax progressivity. Yet, there is a smaller reduction in fossil energy visible in Panel (b) in Figure 2.4.1. This discrepancy emerges from the effect of a carbon tax on skill supply which is affected by the income tax.

The carbon tax changes the skill premium since demand for green-specific high-skill labor increases. High-skill hours in equilibrium rise, while hours of low-skill workers reduce. A progressive income tax lessens the effect of changes in the wage rate on labor supply. The reason is that the elasticity of after-tax labor income with respect to pre-tax labor income diminishes with a higher tax progressivity.[25] This mutes the supply response in the skill ratio to the carbon tax, and production costs of the green good remain high.

2.4.2 Meeting the emission limit

The previous section makes apparent that, first, the carbon tax suggested by the RFF does not cause emissions in line with the IPCC's emission limit. Second, it shows that model dynamics call for an increasing carbon tax. In this section, I calculate the necessary carbon tax to meet the emission limit. I compare the resulting tax and allocations for the policy regimes with labor income tax ("combined policy") to a "carbon-tax-only" policy.

25. Consider Panel (f) in Figure 2.E.1 in Appendix 2.E.1.

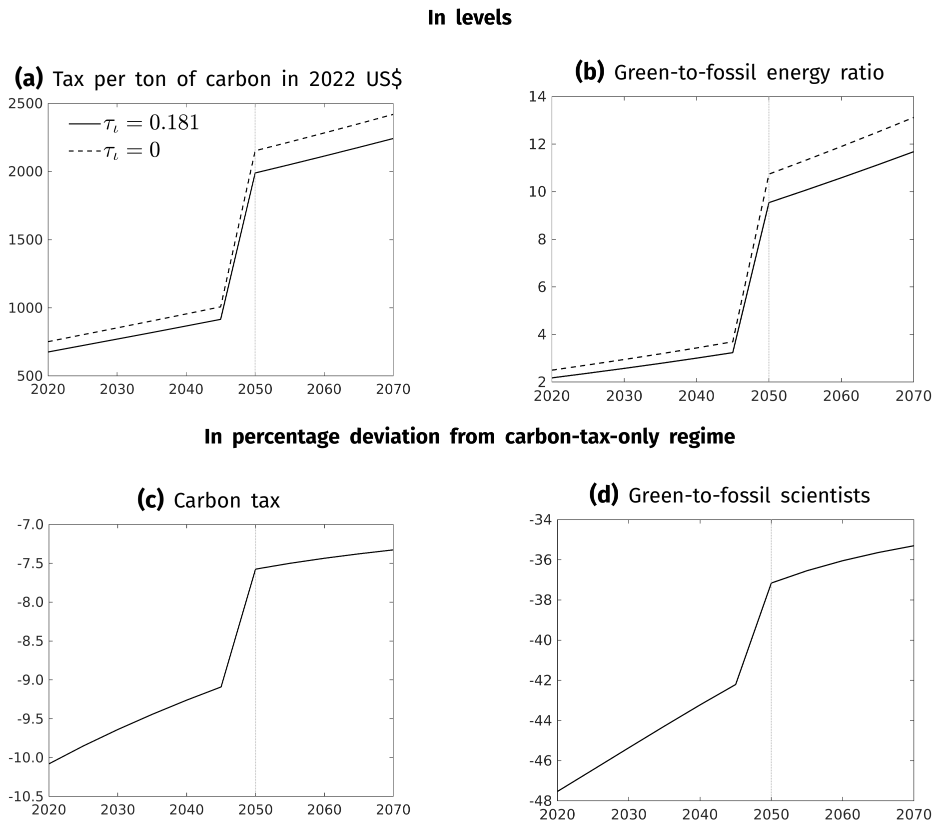

Figure 2.4.2. Meeting the emission limit with and without preexisting labor tax

Notes: Panels (a) and (b) show variables in levels when the emission limit has to be met (i) in a scenario without income tax, $\tau_\iota = 0$, dashed graphs, and (ii) in a scenario with labor income tax, $\tau_\iota = 0.181$, solid graphs. Panel (c) and (d) depict percentage deviation in variables in the combined scenario to the carbon-tax-only scenario. A vertical line indicates when the net-zero emission limit becomes binding.

Figure 2.4.2 shows the results. Consider Panel (a). The necessary carbon tax ranges from US$889 in the 2020-2024 period to around US$2,951 in the 2070-2074 period (both in 2022 prices). The carbon tax is lower when labor is taxed: the deviation of the carbon tax reaches -10% in initial periods but diminishes over time to approximately -7.25% (Panel (c)).[26]

The combined policy results in a lower green-to-fossil energy ratio (Panel (b)) and a higher energy share to GDP. Yet, the reduction in economic activity induced by the labor income tax ensures that the emission limit is satisfied. On the upside, the combined policy enables a smoother distribution of energy scientists (Panel

26. The smaller deviation under the net-zero emission limit results primarily from the tightness of the emission limit itself and not the presence of the labor income tax. Abstracting from all model features discussed earlier, the carbon tax nevertheless approaches the one without progressive income tax as the emission limit gets tighter. Hence, the more stringent emission limit calls for a more aggressive carbon tax despite the reductive effect of labor taxation.

(d)). While the carbon tax induces a shift of researchers to the green sector, the labor tax lowers the green-to-fossil research share. In sum, the combined policy allows for a smoother distribution of scientists across sectors. This diminishes the reduction in scientists' productivity due to the higher research productivity in the fossil sector from within-sector knowledge spillovers.[27]

2.4.3 Optimal policy

This section seeks to answer the question how a benevolent planner optimally attains the emission limit. After showing the results in Section 2.4.3.1, I discuss the motive behind the optimal policy in Section 2.4.3.2. The optimal policy consists of a combination of labor income and carbon taxes. The reason is that when the carbon tax is used to target the direction of research, the wage rate no longer captures the social costs of labor. The labor tax boosts or curbs labor supply to correct for the externality of work through emissions.

2.4.3.1 Results

Figure 2.4.3 depicts the optimal policy. To meet the emission limit suggested by the IPCC, the optimal policy taxes labor until 2044 (Panel (a)). The labor tax turns into a subsidy from 2045 onward, $\tau_{\iota t} < 0$. Consider now Panel (b). The optimal

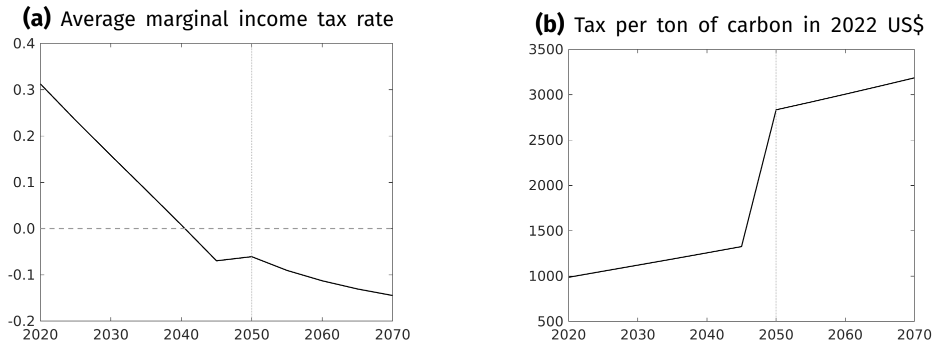

Figure 2.4.3. Optimal policy

Notes: The x-axis indicates the first year of the 5 year period to which the variable value corresponds. A vertical line indicates when the net-zero emission limit becomes binding.

carbon tax increases over time and jumps to a higher level when the net-zero emission limit is introduced in 2050. In 2020, the carbon tax equals US$987 and rises steadily to US$1,326 in the 2045-2049 period. As the emission limit declines to net-zero, the tax rapidly surges to US$2,833 and gradually increases afterwards reaching US$3,2186 in 2070-2074.

27. I discuss the effects of cross-sectoral knowledge spillovers, heterogeneous skills, heterogeneous labor shares, and endogenous growth in Appendix 2.E.2.1.

Figure 2.4.4 presents adjustments of key variables under the first-best (efficient) and the second-best (optimal) policy relative to the laissez-faire allocation.[28] Dashed graphs show the efficient and solid graphs the optimal allocation. The efficient allocation is chosen by a social planner who picks allocations irrespective of market forces. It can be perceived as the allocation the Ramsey planner intents to implement. However, she may not be able to achieve the efficient allocation due to the reliance on (a limited number of) tax instruments and market forces.[29]

The social planner attains the emission limit while increasing consumption and decreasing labor relative to laissez-faire (Panels (a) and (b) in Figure 2.4.4). This allocation is achieved by a higher research effort on aggregate: average hours of scientists roughly double in all periods. The social planner decreases the share of non-energy scientists (Panel (d)). More research effort in the energy sector is efficient. Within the energy sector, a higher level of fossil scientists as compared to green scientists characterizes the efficient allocation (Panels (e) and (f)). As the emission limit becomes stricter, the ratio of green-to-fossil scientists increases. The social planner can sustain high growth rates—especially in the fossil sector—and simultaneously meet the emission limit by choosing a lower energy share to GDP and a higher ratio of green-to-fossil energy (Panel (c)). I will discuss in the next section why this allocation of researchers is efficient.

Under the optimal policy, in contrast, consumption reduces relative to the laissez-faire allocation. Average hours of scientists fall slightly by approximately 0.1%. The optimal policy implements a lower share of energy research, and the number of fossil scientists remains close to zero (Panels (d) and (e)). The ratio of green to fossil scientists tends to infinity. In the competitive economy, a rise in fossil research has to be induced via demand. A higher demand for fossil fuels, however, conflicts with the emission target. A trade-off between growth and emission mitigation exists. In fact, the optimal allocation falls short of both the efficient green-to-fossil energy ratio and the efficient allocation of researchers.

2.4.3.2 Discussion

What explains the optimal policy? To answer this question, I, first, consider the social planner allocation without cross-sectoral knowledge spillovers. Knowing the reasons behind the efficient allocation enables us to better understand the use of policy instruments. Second, I look at how the optimal allocation with labor income tax differs from the optimal allocation when no income tax is available. Finally, I conduct a counterfactual experiment where only the optimal carbon tax

28. I formulate the social planner's problem in Appendix 2.B.2.

29. Figure 2.E.4 in Appendix 2.E.3 shows the laissez-faire, the efficient, and the optimal allocation in levels.

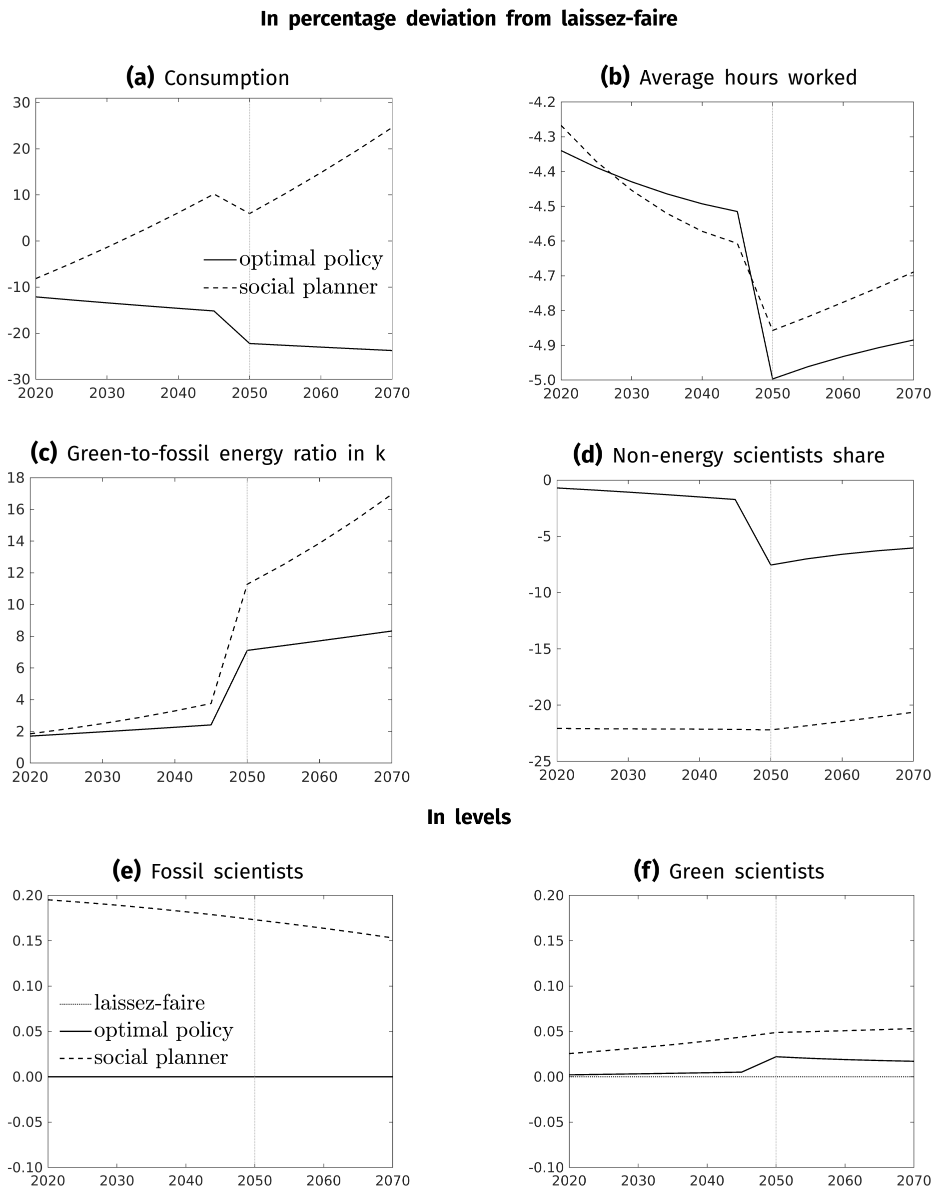

Figure 2.4.4. Efficient and optimal allocation relative to laissez-faire

Notes: Panels (a) to (d) show the percentage deviation of the allocation resulting under the optimal policy, the black solid graph, and the efficient allocation, the black dashed graph, relative to the laissez-faire allocation. Panels (e) and (f) show fossil and green scientists in levels. The dotted graph refers to the laissez-faire allocation. A vertical line indicates when the net-zero emission limit becomes binding.

is implemented. This allows to decompose the effect of the carbon and the labor income tax.

Efficient and optimal allocation without cross-sectoral knowledge spillovers. Figure 2.4.5 depicts deviations of the efficient and the optimal allocation from laissez-faire in the model without cross-sectoral knowledge spillovers. Absent knowledge spillovers, the social planner raises research efforts by a factor of 3.5 compared to 2 in the benchmark model, and hours worked reduce less and increase more over time (Panel (b)). Nevertheless, consumption grows less than in the model with knowledge spillovers (Panel (a)). The reason is that fossil research is no longer valuable in a green future absent cross-sectoral knowledge spillovers.

When knowledge cannot spill from conventional to the green sector, meeting the emission limit requires a strong rise in green relative to fossil research. Almost no energy research happens in the fossil sector (Panel (c)), and the social planner raises green research effort (Panel (d)). Due to the knowledge advantage in the fossil sector, this extreme allocation reduces overall research productivity and, hence, consumption growth. Yet, it is efficient because it takes into account dynamic spillovers in the green sector.[30]

The rise in working hours over time under the social planner reflects the slow down in consumption. Consumption becomes so valuable, that hours have to rise. Hence, knowledge spillovers diminish the costs of implementing the emission limit since they allow to mitigate decreasing returns to research in the green sector.

Comparison to carbon-tax-only policy regime. How is the income tax used to achieve a more efficient allocation? This section analysis the benefits of the policy regime with income tax, the combined regime, as opposed to a carbon-tax-only regime where $\tau_{\iota t} = 0$. Panel (a) in Figure 2.4.7 presents percentage deviations of variables under the combined policy relative to the carbon-tax-only regime. In both regimes, tax instruments are chosen optimally. In the period from 2020 to 2044, the carbon tax is lower when a labor income tax can be used (Panel (a i)). Recall that in the exact same period, the labor income tax is used to tax labor (Panel (a), Figure 2.4.3). From 2045 onward, the carbon tax exceeds its counterpart when no labor tax is available. Now, the government subsidizes labor. Thus, labor income taxes and carbon taxes act as substitutes.

By setting a lower carbon tax and taxing labor, the government achieves a higher share of fossil scientists in the periods before the net-zero emission limit (Panel (a ii)). Hence, in terms of the allocation of research, the optimal policy comes closer to the efficient allocation. Yet, to do so, it forfeits an advantageous green-to-fossil energy ratio.[31] This observation highlights the trade-off between more fossil research and lower fossil demand.

30. Figure 2.E.6 in Appendix 2.E.3 depicts the ratio of green-to-fossil energy and the adjustment in the share of non-energy scientists absent knowledge spillovers. When no knowledge spills to the non-energy sector, the planner raises the share of non-energy scientists initially to boost consumption. Once the net-zero emission limit binds, the social planner reduces the share of non-energy researchers relative to laissez-faire. Then, energy research becomes more important to mitigate the costs of the emission limit.

31. Both, a smaller carbon tax and a tax on labor contribute to the adverse energy ratio. Figure 2.E.5 in Appendix 2.E.3 shows deviations of the green-to-fossil energy ratio.

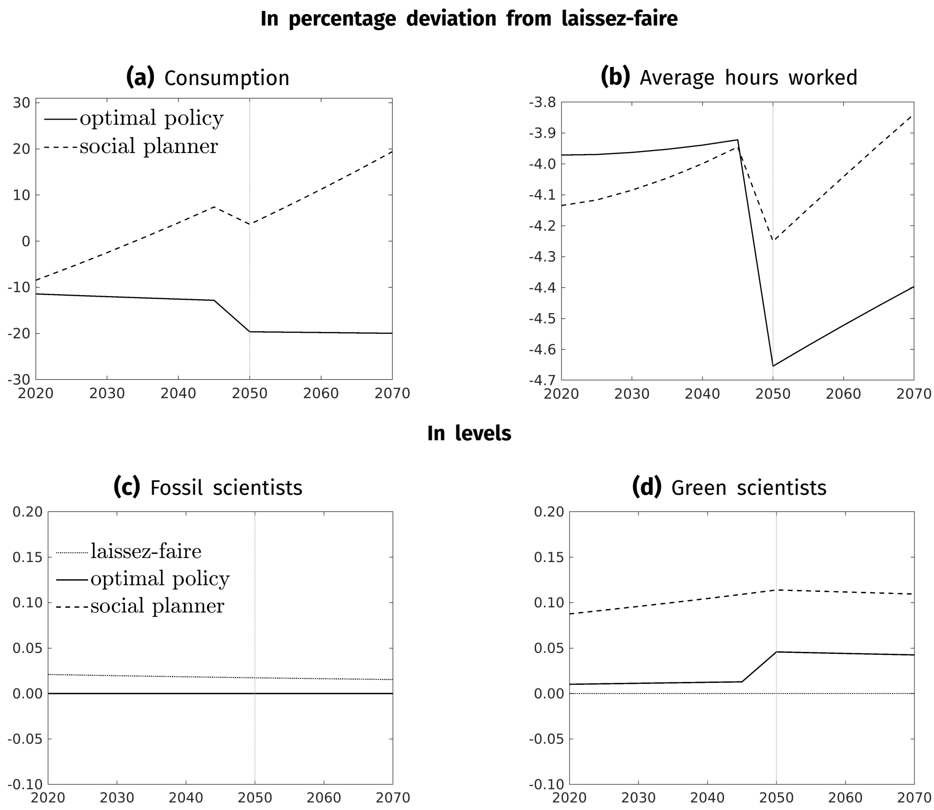

Figure 2.4.5. Efficient and optimal allocation: no knowledge spillovers

When the net-zero emission limit binds, the carbon tax under the combined policy is higher than in the carbon-tax-only scenario. The stricter emission limit makes the use of a labor income tax to lower emission too costly. Therefore, the government cannot engineer a higher share of fossil-to-green scientists but uses the carbon tax to meet the emission limit. Within this limit, it becomes optimal to direct more research to the green sector which is achieved by an even higher carbon tax. This is in spirit of the finding in Acemoglu et al. (2012): absent a research subsidy, the carbon tax is used to take into account the path dependency of research, i.e. the gains from green research today by boosting green productivity tomorrow.

Indeed, the optimal policy in the model without knowledge spillovers subsidizes labor throughout; see Figure 2.4.6. In this case, future green growth does not profit from fossil growth today. Therefore, carbon is taxed higher to foster more green research right from the beginning.[32] By doing so, the optimal policy takes into account the path dependency of research. As regards the level of the carbon tax, it is smaller than in the model with knowledge spillovers. Knowledge

32. The deviation in the carbon tax is minimal. For better visibility, consider Figure 2.E.7 in Appendix 2.E.3.

spillovers to the fossil sector call for a higher and gradually increasing carbon tax.[33]

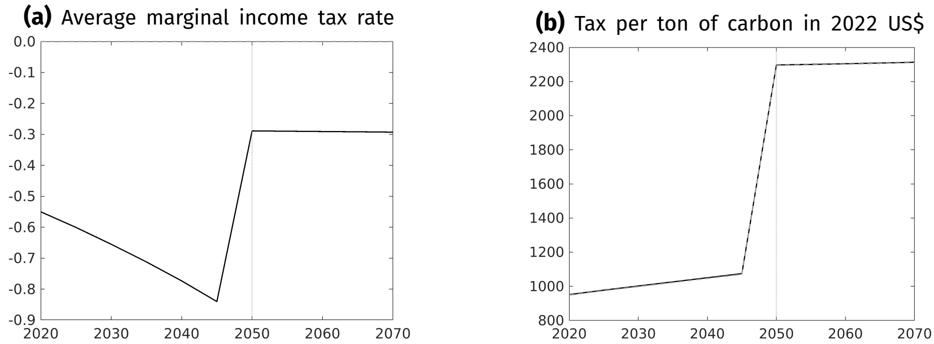

Figure 2.4.6. Optimal policy without knowledge spillovers

Notes: The figure shows the optimal policy in the model without knowledge spillovers. Solid graphs refer to the combined policy regime, and dashed graphs to the carbon-tax-only regime. A vertical line indicates when the net-zero emission limit becomes binding.

In the next two paragraphs, I decompose the effect of the combined policy regime relative to the carbon-tax-only regime into the effect of (i) the adjusted carbon tax, and (ii) the change in the labor income tax.

Effect of adjustment in carbon tax. Panel (b) in Figure 2.4.7 depicts the deviation of the allocation when only the optimal carbon tax is implemented—that is, the labor income tax is fixed at $\tau_{\iota t} = 0$—relative to the carbon-tax-only scenario. The lower carbon tax almost fully accounts for the deviation of the ratio of green-to-fossil research (Panel (b i)). Average hours worked remain largely unchanged by the change in the carbon tax (Panel (b ii)). But, a bigger labor share allocated to the fossil sector raises the externality associated with work. As a result, the allocation with the lower carbon tax alone would violate the emission limit.

Effect of labor income tax. Panel (c) in Figure 2.4.7 compares the allocation under the combined policy to the one where only the carbon tax is set to its optimal value and the labor income tax is kept at zero. The difference is, thus, explained by income taxation.

The labor income tax contributes to a smoother allocation of green-to-fossil scientists albeit minimally (Panel (c i)). Instead, the labor income tax is more important to adjust average hours worked (Panel (c ii)). Before the net-zero emission limit, it reduces labor supply contributing to a reduction in emissions. The smaller carbon tax implies a distortion in the labor market: households do not internalize the negative effect of their work effort on emissions.

33. On this point, see the discussion in Section 2.4.1.

The higher carbon tax under the net-zero emission limit, in contrast, results in too low a wage rate discouraging labor supply. In other words, households act as if their work was associated with more social costs than it actually is. The labor subsidy ensures that labor supply rises. It, thereby, raises fossil production. Yet, the emission limit remains satisfied due to the higher carbon tax.

An alternative explanation for the use of labor income taxes could be to stimulate research activity. Indeed, the progressive income tax fosters fossil research in early periods through its effect on the skill ratio. However, even in a model with homogeneous skills, the labor income tax is part of the optimal policy. Nevertheless, in this counterfactual model, the labor income tax does not affect research effort.[34] The reason is that a higher demand for research is absorbed by a higher wage rate for scientists, as discussed in section 2.4.1.

34. Compare Figure 2.E.8 in Appendix 2.E.3.

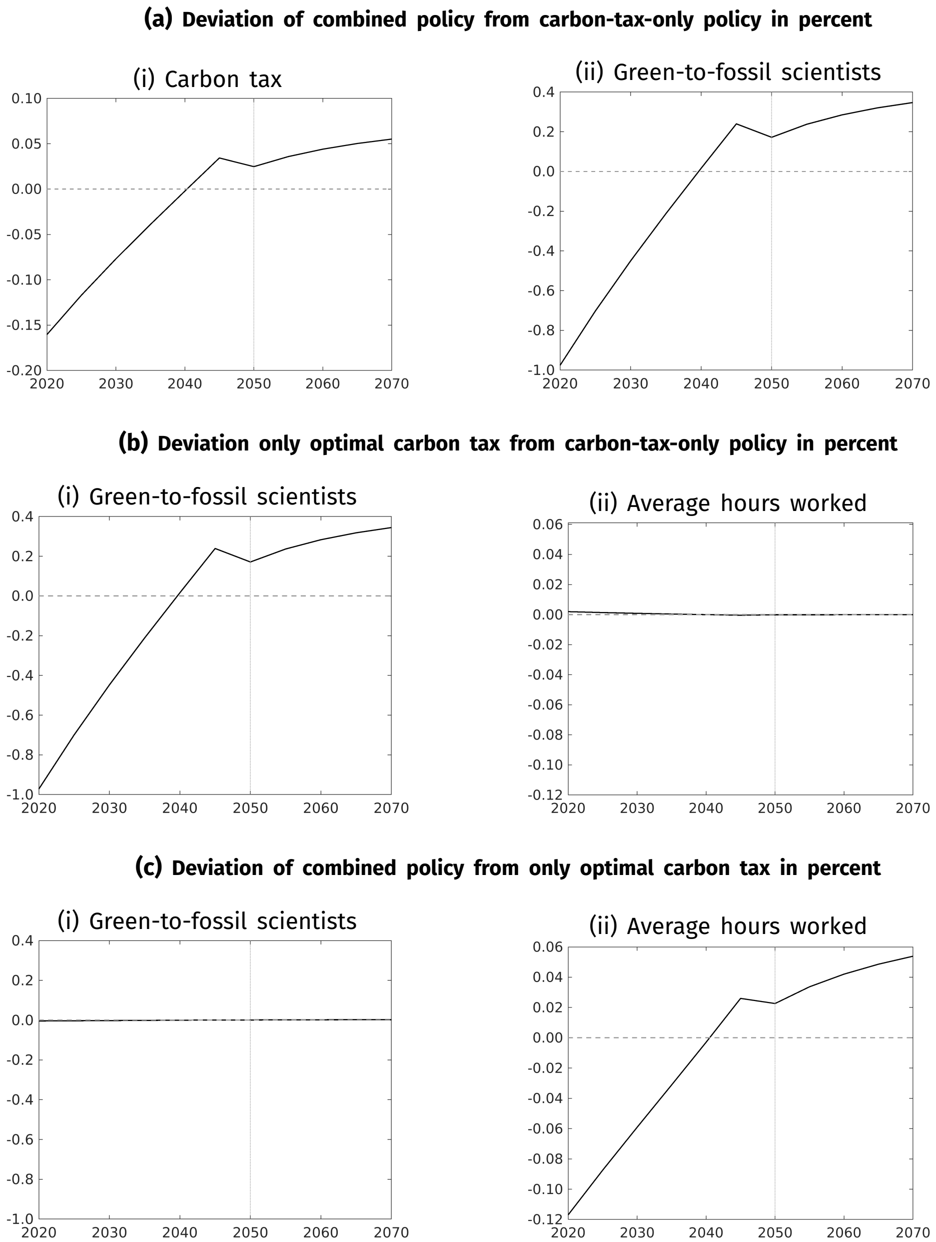

Figure 2.4.7. Decomposing effect of combined policy

Notes: Graphs show the percentage deviations of the variable under the combined policy regime where the planner can choose income tax progressivity and the carbon-tax-only regime where the income tax scheme is non-distortive, $\tau_{it} = 0$. A vertical line indicates the introduction of the net-zero emission limit.

2.5 Conclusion

The latest IPCC report (IPCC, 2022a) stresses the necessity to transition to net-zero emissions in order to meet climate goals. The economics literature has largely focused on the use of carbon taxes to lower emissions. However, labor income taxes may contribute to lowering emissions by affecting the level of production. I ask what is the optimal fiscal mix of taxes on carbon and labor income in a transition toward net-zero emissions?

I build an endogenous growth model in which an emission limit renders fossil energy socially costly. I find that the optimal policy always chooses a combination of carbon and labor income taxes. In the run-up to the net-zero emission limit, the optimal policy chooses a smaller carbon tax that on its own is insufficient to meet the emission limit. A labor tax, therefore, serves to diminish emissions by lowering labor supply and thus overall production. The rationale is that the smaller carbon tax allows the economy to benefit from fossil research. Fossil research is more productive as it can draw from a deep pool of knowledge that has been generated in the past. In addition, fossil knowledge remains valuable in a green future since green innovation can learn from knowledge advances on fossil-based technologies.

Once the net-zero emission limit binds, policy implications differ. Now, the optimal policy taxes carbon extensively. A subsidy on labor serves to stabilize production. Under the more stringent emission target, using a labor income tax to lower emissions becomes too costly. Then, it is optimal to set an even higher carbon tax to foster green research. More green research today stimulates green research tomorrow through dynamic spillovers of knowledge. As a side effect of the higher carbon tax, a more beneficial ratio of green-to-fossil energy is obtained. This allows to boost production overall while meeting the emission limit. The scaling of the economy is achieved by subsidizing labor.

The quantitative results show that the optimal allocation deviates substantially from the efficient one when only carbon and income taxes are available. Absent knowledge spillovers, Acemoglu et al. (2012) point to green research subsidies as an essential tool to implement the efficient allocation. With knowledge spillovers, however, my results suggest that a subsidy on fossil research might be beneficial. An important aspect of a green transition is societal acceptance. Investigating additional instruments to reduce the costs of meeting emission targets, therefore, is an important direction for future research.

Appendix 2.A Derivations and proofs

2.A.1 Useful relations of derivatives

Below relations follow from the definition of s as $s = \frac{L_F}{H}$.

$$\begin{aligned}\frac{\partial F}{\partial H} &= \frac{s}{H}\frac{\partial F}{\partial s} &\quad (2.A.1)\\ \frac{\partial G}{\partial H} &= -\frac{(1-s)}{H}\frac{\partial G}{\partial s} &\quad (2.A.2)\\ \frac{\partial G}{\partial s} &= -H\frac{\partial G}{\partial L_G} &\quad (2.A.3)\\ \frac{\partial F}{\partial s} &= H\frac{\partial F}{\partial L_F} \\ \frac{\partial Y}{\partial H} &= \frac{\partial Y}{\partial s}\frac{s}{H} + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial Lg}\end{aligned}$$

The last equality follows from $\frac{\partial Y}{\partial s} = \frac{\partial Y}{\partial F}\frac{\partial F}{\partial s} + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial s}$. Multiplying by $\frac{s}{H}$, adding and subtracting $\frac{\partial Y}{\partial G}\frac{\partial G}{\partial H}$, and substituting eqs. (2.A.1), (2.A.2), and (2.A.3) yields the result.

2.A.2 Efficient reduction of the dirty labor share

I show in this appendix that a reduction in dirty labor share is efficient under decreasing returns to scale.

Proof. With a negative externality of dirty production it has to hold that

$$\frac{\partial Y}{\partial F}\frac{\partial F}{\partial s} > -\frac{\partial Y}{\partial G}\frac{\partial G}{\partial s},$$

which can be rewritten as

$$\frac{\partial Y}{\partial L_F} > \frac{\partial Y}{\partial L_G}. \quad (2.A.4)$$

In the efficient allocation absent externality, marginal products of dirty and green labor are equalized: $\frac{\partial Y}{\partial L_F} = \frac{\partial Y}{\partial L_G}$. Under decreasing returns to scale, it holds that the left-hand side and the right-hand side of eq. (2.A.4) are decreasing in L_F and L_G, respectively. Hence, the adjustment to satisfy eq. (2.A.4) relative to the efficient allocation without externality requires a decrease in L_F and/or a rise in L_G . This is achieved by reducing the fossil labor share, s, since $L_F = sH$ and $L_G = (1-s)H$. □

2.A.3 The social cost of pollution and the Pigouvian tax rate

The Pigouvian tax is the tax on the externality which equals the marginal social cost of the externality. The social cost of pollution in my model is defined as the price the representative household is willing to pay for a marginal reduction in dirty production. Solving the household problem as if there was a market for the externality yields this price. The household's problem is then determined by

$$\max_{C,H,F} U(C,H,F) - \mu\big(C + \tilde{p}_F F - Y(H)\big).$$

Where μ is the Lagrange multiplier. Taking the derivative with respect to dirty production and with respect to consumption yields

$$\begin{aligned} U_F &= \mu \tilde{p}_F, \\ U_C &= \mu. \end{aligned}$$

Substituting the Lagrange multiplier gives the negative of the equilibrium price, $\tilde{p}_F$, the household is willing to pay for a reduction in dirty production: $\tilde{p}_F = \frac{U_F}{U_C}$. The marginal social cost of fossil production to be added to fossil buyers' price is, hence, $\tau^{Pigou} = \frac{-U_F}{U_C}$.

2.A.4 The wage rate and the marginal product of labor

This appendix shows that the competitive wage rate falls below the marginal product of labor under the optimal environmental policy.

Proof. The aggregate marginal product of labor is defined as

$$MPL = \frac{\partial Y}{\partial H}.$$

This expression can be rewritten using relations of derivatives summarized in 2.A.1 as follows.

$$\begin{aligned} \frac{\partial Y}{\partial H} &= \frac{\partial Y}{\partial F}\frac{\partial F}{\partial H} + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial H} \\ &= \frac{\partial Y}{\partial F}\frac{\partial F}{\partial L_F}s + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G}(1-s) \\ &= \frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G} + s\left(\frac{\partial Y}{\partial F}\frac{\partial F}{\partial L_F} - \frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G}\right). \end{aligned} \tag{2.A.5}$$

The term in brackets is positive under the optimal policy as can be seen from the first order condition with respect to s, eq. (2.2.10):

$$\frac{\partial Y}{\partial F}\frac{\partial F}{\partial L_F} - \frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G} \;=\; \frac{1}{H}\left(\frac{\partial Y}{\partial F}\frac{\partial F}{\partial s} + \frac{\partial Y}{\partial G}\frac{\partial G}{\partial s}\right) \;=\; \frac{1}{H}\left(\frac{-U_F\frac{\partial F}{\partial s}}{U_C}\right) \;>\; 0. \qquad (2.A.6)$$

The inequality holds since the externality of polluting production is negative. Now note that the first summand in eq. (2.A.5) is the competitive wage rate. Hence $w < MPL$.

□

2.A.5 Sufficiency of the environmental tax and lump-sum transfers

This section is to prove proposition 2.

Proof. Noticing that $\frac{\partial Y}{\partial H} = \frac{\partial Y}{\partial s}\frac{s}{H} - \frac{\partial Y}{\partial G}\frac{\partial G}{\partial s}\frac{1}{H}$ and that $\frac{\partial F}{\partial H} = \frac{\partial F}{\partial s}\frac{s}{H}$, and substituting eq. (2.2.10) in eq. (2.2.11) yields

$$-U_C\frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G} \;=\; -U_H. \qquad (2.A.7)$$

Hence, if the environmental tax is set to guarantee that condition (2.2.11) holds and proceeds are redistributed lump sum, optimal hours worked only trade off the disutility from labor and the utility from more consumption.

Substituting U_H from household optimality, eq. (2.2.5), and the clean sectors' profit maximizing condition from eq. (2.2.6) yields

$$1 \;=\; 1 - \tau_\iota^*.$$

Hence, $\tau_\iota^* = 0$ from which follows that $\lambda = 1$ so that the income tax scheme is a flat tax rate equal to zero; the labor income tax is not used in optimum.

The reason for this result is that the competitive wage rate captures the social costs of the externality induced by an additional hour worked when the carbon tax is set so that the planners first order condition, eq. (2.2.10), holds. To see this, substitute the last equality of eq. (2.A.6) in eq. (2.A.5) and solve for the wage rate $w = \frac{\partial Y}{\partial G}\frac{\partial G}{\partial L_G}$:

$$w \;=\; \frac{\partial Y}{\partial H} + \frac{U_F}{U_C}\frac{\partial F}{\partial H}, \qquad (2.A.8)$$

where I replaced the derivative of fossil with respect to s with the derivative with respect to H using the relations in Appendix 2.A.1.

□

Appendix 2.B Quantitative model

This section spells out model equations and the definition of the efficient allocation.

2.B.1 Model equations

Household

$$\text{Period utility} \quad \log(C_t) - z_h \chi \frac{h_{ht}^{1+\sigma}}{1+\sigma} - (1-z_h)\chi \frac{h_{lt}^{1+\sigma}}{1+\sigma} - \chi_s \frac{S_t^{1+\sigma}}{1+\sigma}$$

$$\begin{aligned}
\text{Budget} \quad C_t &= z_h \lambda_t (w_{ht} h_{ht})^{1-\tau_{\iota t}} + (1-z_h)\lambda_t (w_{lt} h_{lt})^{1-\tau_{\iota t}} \\
&\quad + w_{st} S_t + T_{\pi t} + T_{lst} \\
\text{Optimality} \quad C_t^{-1} &= \mu_t p_t \\
\chi h_{ht}^{\sigma} &= \mu_t \lambda_t (1-\tau_{\iota t}) w_{ht}^{1-\tau_{\iota t}} h_{ht}^{-\tau_{\iota t}} - \gamma_{ht}/z_h \\
\chi h_{lt}^{\sigma} &= \mu_t \lambda_t (1-\tau_{\iota t}) w_{lt}^{1-\tau_{\iota t}} h_{lt}^{-\tau_{\iota t}} - \gamma_{lt}/(1-z_h) \\
\chi_s S_t^{\sigma_s} &= \mu_t w_{st} - \gamma_{st}
\end{aligned}$$

where γ_{ht}, γ_{lt}, and γ_{sJt} are Lagrange multipliers on the inequality constraints with respect to time endowment.

Final good and Energy producers

$$\begin{aligned}
\text{Optimality} \quad p_t \delta_y^{\frac{1}{\varepsilon_y}} Y_t^{\frac{1}{\varepsilon_y}} E_t^{-\frac{1}{\varepsilon_y}} &= p_{Et} \\
p_t (1-\delta_y)^{\frac{1}{\varepsilon_y}} Y_t^{\frac{1}{\varepsilon_y}} N_t^{-\frac{1}{\varepsilon_y}} &= p_{Nt} \\
p_{Et} E_t^{\frac{1}{\varepsilon_e}} F_t^{-\frac{1}{\varepsilon_e}} &= p_{Ft} + \tau_{Ft} \\
p_{Et} E_t^{\frac{1}{\varepsilon_e}} G_t^{-\frac{1}{\varepsilon_e}} &= p_{Gt} \\
\text{Definitions prices} \quad p_t &= \left[\delta_y p_{Et}^{1-\varepsilon_y} + (1-\delta_y) p_{Nt}^{1-\varepsilon_y}\right]^{\frac{1}{1-\varepsilon_y}} \\
p_{Et} &= \left[(p_{Ft} + \tau_{Ft})^{1-\varepsilon_e} + p_{Gt}^{1-\varepsilon_e}\right]^{\frac{1}{1-\varepsilon_e}} \\
\text{Production} \quad Y_t &= \left(\delta_y^{\frac{1}{\varepsilon_y}} E_t^{\frac{\varepsilon_y - 1}{\varepsilon_y}} + (1-\delta_y)^{\frac{1}{\varepsilon_y}} N_t^{\frac{\varepsilon_y - 1}{\varepsilon_y}}\right)^{\frac{\varepsilon_y}{\varepsilon_y - 1}} \\
E_t &= \left(F_t^{\frac{\varepsilon_e - 1}{\varepsilon_e}} + G_t^{\frac{\varepsilon_e - 1}{\varepsilon_e}}\right)^{\frac{\varepsilon_e}{\varepsilon_e - 1}}
\end{aligned}$$

Intermediate good producers

$$\text{Production} \quad F_t = x_{Ft}^{\alpha_F} \left(A_{Ft} L_{Ft}\right)^{1-\alpha_F}$$

$$
\begin{aligned}
& & N_t &= x_{Nt}^{\alpha_N}\left(A_{Nt}L_{Nt}\right)^{1-\alpha_N} \\
& & G_t &= x_{Gt}^{\alpha_G}\left(A_{Gt}L_{Gt}\right)^{1-\alpha_G} \\
&\text{Labor demand} & w_{lFt} &= p_{Ft}^{\frac{1}{1-\alpha_F}}(1-\alpha_F)\alpha_F^{\frac{\alpha_F}{1-\alpha_F}}A_{Ft} \\
& & w_{lNt} &= p_{Nt}^{\frac{1}{1-\alpha_N}}(1-\alpha_N)\alpha_N^{\frac{\alpha_N}{1-\alpha_N}}A_{Nt} \\
& & w_{lGt} &= p_{Gt}^{\frac{1}{1-\alpha_G}}(1-\alpha_G)\alpha_G^{\frac{\alpha_G}{1-\alpha_G}}A_{Gt} \\
&\text{Machine demand} & x_{Fit} &= \left(\alpha_F p_{Ft}\right)^{\frac{1}{1-\alpha_F}}L_{Ft}A_{Fit} \\
& & x_{Nit} &= \left(\alpha_N p_{Nt}\right)^{\frac{1}{1-\alpha_N}}L_{Nt}A_{Nit} \\
& & x_{Git} &= \left(\alpha_G p_{Gt}\right)^{\frac{1}{1-\alpha_G}}L_{Gt}A_{Git} \\
&\textbf{Labor producers} & & \\
&\text{Production} & L_{Ft} &= h_{hFt}^{\theta_F}h_{lFt}^{1-\theta_F} \\
& & L_{Nt} &= h_{hNt}^{\theta_N}h_{lNt}^{1-\theta_N} \\
& & L_{Gt} &= h_{hGt}^{\theta_g}h_{lGt}^{1-\theta_G} \\
&\text{Optimality} & h_{hFt} &= \theta_F L_{Ft}\frac{w_{lFt}}{w_{ht}} \\
& & h_{hNt} &= \theta_N L_{Nt}\frac{w_{lNt}}{w_{ht}} \\
& & h_{hGt} &= \theta_G L_{Gt}\frac{w_{lGt}}{w_{ht}} \\
& & h_{lFt} &= (1-\theta_F)L_{Ft}\frac{w_{lFt}}{w_{lt}} \\
& & h_{lNt} &= (1-\theta_N)L_{Nt}\frac{w_{lNt}}{w_{lt}} \\
& & h_{lGt} &= (1-\theta_G)L_{Gt}\frac{w_{lGt}}{w_{lt}} \\
&\textbf{Machine producers} & & \\
&\text{Price setting} & p_{xFit} &= \frac{1}{\alpha_F(1+\zeta_F)} \\
& & p_{xNit} &= \frac{1}{\alpha_N(1+\zeta_N)} \\
& & p_{xGit} &= \frac{1}{\alpha_G(1+\zeta_G)} \\
&\text{Demand Scientists} & w_{st} &= \frac{\eta\gamma A_{Ft-1}^{1-\phi}A_{t-1}^{\phi}\left(\frac{s_{Ft}}{\rho_F}\right)^{\eta}p_{Ft}F_t}{\frac{1}{1-\alpha_F}s_{Ft}A_{Ft}} \\
& & w_{st} &= \frac{\eta\gamma A_{Nt-1}^{1-\phi}A_{t-1}^{\phi}\left(\frac{S_{Nt}}{\rho_N}\right)^{\eta}p_{Nt}N_t}{\frac{1}{1-\alpha_N}s_{Nt}A_{Nt}}
\end{aligned}
$$

$$w_{st} = \frac{\eta\gamma A_{Gt-1}^{1-\phi} A_{t-1}^{\phi} \left(\frac{s_{Gt}}{\rho_G}\right)^{\eta} p_{Gt} G_t}{\frac{1}{1-\alpha_G} s_{Gt} A_{Gt}}$$

Innovation
$$A_{Fit} = A_{Ft-1}\left(1+\gamma\left(\frac{s_{Fit}}{\rho_F}\right)^{\eta}\left(\frac{A_{t-1}}{A_{Ft-1}}\right)^{\phi}\right)$$
$$A_{Nit} = A_{Nt-1}\left(1+\gamma\left(\frac{s_{Nit}}{\rho_N}\right)^{\eta}\left(\frac{A_{t-1}}{A_{Nt-1}}\right)^{\phi}\right)$$
$$A_{Git} = A_{Gt-1}\left(1+\gamma\left(\frac{s_{Git}}{\rho_G}\right)^{\eta}\left(\frac{A_{t-1}}{A_{Gt-1}}\right)^{\phi}\right)$$

Government

$$\begin{aligned} 0 &= z_h(w_{ht}h_{ht} - \lambda_t(w_{ht}h_{ht})^{(1-\tau_{\iota t})}) \\ &\quad + (1-z_h)(w_{lt}h_{lt} - \lambda_t(w_{lt}h_{lt})^{(1-\tau_{\iota t})}) \end{aligned}$$
$$T_{lst} = \tau_{Ft}F_t$$
$$\begin{aligned} T_{\pi t} &= -\int_0^1 \left(p_{xFit}\zeta_{Ft}x_{Fit} + p_{xGit}\zeta_{Gt}x_{Git} + p_{xNit}\zeta_{Nt}x_{Nit}\right)di \\ &\quad + \int_0^1 \left(\pi_{Fit} + \pi_{Git} + \pi_{Nit}\right)di = -w_{st}S_t \end{aligned}$$

with
$$\zeta_{Jt} = \frac{1-\alpha_J}{\alpha_J} \; for \; J \in \{F,G,N\}$$

Markets

$$h_{hFt} + h_{hNt} + h_{hGt} = z_h h_{ht}$$
$$h_{lFt} + h_{lNt} + h_{lGt} = (1-z_h)h_{lt}$$
$$s_{Ft} + s_{Nt} + s_{Gt} = S_t$$
$$C_t + \int_0^1 \left(x_{Fit} + x_{Nit} + x_{Git}\right)d_i = Y_t$$

2.B.2 Social planner allocation

The solution to the social planner's problem is defined as an allocation $\{h_{hFt}, h_{hGt}, h_{hNt}, h_{lFt}, h_{lGt}, h_{lNt}, x_{Nt}, x_{Ft}, x_{Gt}, C_t, h_{ht}, h_{lt}, s_{Ft}, s_{Gt}, s_{Nt}\}$ for each period which maximizes social welfare, $\sum_{t=0}^{T} \beta^t u(C_t, h_{ht}, h_{lt}, S_t) + PV$, subject to the emission limit and feasibility. It holds that $x_{Jt} = \int_0^1 x_{Jit} di$.

Appendix 2.C Calibration of the emission limit

In 2019, global net CO_2 emissions amounted to 44.25Gt (compare Figure SPM1.a p.11 in IPCC, 2022b) yielding a net emission limit in the 2030s of 22.125Gt per annum. The IPCC report is vague on the exact year when the 50% reduction has to be reached. I assume that the net emission limit becomes binding in 2035 and is active until the limit reduces to zero in 2050. To back out the share of the emission limit assigned to the US following the *equal-per-capita* principle, I use population projections from the United Nations (2022). Since the US population share is projected to decline over the period from 2035 to 2050, the emission limit reduces over this period.

Following this approach, the remaining net CO_2 budget for the period 2020-2035 happens to be smaller than total CO_2 emissions equal to the limit between 2035-2050. This conflicts with the downward sloping time path of emissions stipulated by the IPCC (p.3-28).[35] To generate a non-increasing pattern of the emission limit, I set the global emission limit for the period from 2035 to 2050 to half the CO_2 budget. This leaves an equal budget share for the initial 15 years. I assume that in the period from 2020 to 2035 the budget is equally distributed across years to simplify the numeric calculation of the optimal policy. Similar to the derivation for the period from 2035 to 2050, I apply the year-specific population share and sum over those years which form a model period. In sum, this approach amounts to distributing the remaining budget of 510Gt equally over the 30 years until the net-zero limit.

Appendix 2.D Numerical appendix

Since I cannot solve explicitly for the optimal policy over an infinite horizon, I truncate the problem after period T. In the literature, utility in periods after T are approximated under the assumption that policy variables are fixed, and the economy reaches a balanced growth path (Jones, Manuelli, and Rossi, 1993; Barrage, 2020). However, assuming a constant carbon tax would most likely violate the emission limit since the model is designed to reflect market forces describing an economy with green and fossil sectors operating in equilibrium.

I motivate the design of the continuation value by pretending the planner would hand over the economy to a successor after period T. A continuation value, PV, in the objective function captures that the planner cares about utility after period T. This set-up accounts for concerns about economic well-being of future generations in a similar vein than the sustainability criterion proposed by the World Commission on Environment and Development (1987) by attaching some value to the final technology level.[36] I approximate the value of future technology

35. The reason is that global net-CO_2 emissions are so high that a 50% reduction starting from 2035 results in more than half the emissions of the remaining carbon budget.

36. The sustainable development criterion reads "*[...] to ensure that it meets the needs of the present without comprising the ability of future generations to meet their own needs.* " (p.24). This is a vague definition. Dasgupta (2021) p.(332) interprets this criterion as meaning: "*[...] each*

levels by assuming constant growth rates. To mitigate concerns that the choice of the continuation value drives the results, I experiment with the exact value of explicit optimization periods. I truncate the problem once explicitly adding a further period leaves the optimal allocation numerically unchanged. That is the case after $T = 42$, or 210 years. The planner's objective function becomes:

$$\max_{\{\tau_{Ft}\}_{t=0}^{T},\{\tau_{\iota t}\}_{t=0}^{T}} \sum_{t=0}^{T} \beta^t u(C_t, h_{ht}, h_{lt}, S_t) + PV.$$

In more detail, I define the continuation value as the consumption utility over the infinite horizon starting from the last explicit maximization period:

$$PV = \sum_{s=T+1}^{\infty} \beta^s u(C_s, h_{hs}, h_{ls}, S_s).$$

I make three simplifying assumptions to derive the continuation value. First, I assume that the consumption share, c_s, with $C_s = c_s Y_s$, is constant from period $T+1$ onward. Then, consumption grows at the same rate as output. Second, as an approximation to future growth, I assume the economy grows at the same rate as in the last explicit optimization period. Third, hours of workers and scientists remain at their value in the last explicit optimization period. Let $\gamma_{yT} = \frac{Y_T}{Y_{T-1}} - 1$. Under above assumptions, I can rewrite future consumption as $C_s = (1+\gamma_{yT})^{s-T} C_T$. Given the functional form

$$u(C_s) = \frac{C_s^{1-\theta}}{1-\theta},$$

the continuation value reduces to

$$PV = \beta^T \left(\frac{1}{1-\beta(1+\gamma_{yT})^{1-\theta}} \frac{C_T^{1-\theta}}{1-\theta} + \frac{1}{1-\beta} u(h_{hT}, h_{lT}, S_T) \right).$$

Where $u(C_s, h_{hs}, h_{ls}, S_s) = u(c_s) + u(h_{hT}, h_{lT}, S_T)$. When $\theta \underset{\lim}{\rightarrow} 1$, the first summand in brackets becomes

$$\frac{1}{1-\beta} \log(C_T).$$

generation should bequeath to its successor at least as large a productive base as it had inherited from its predecessor. ". However, this cannot be used to derive a sensible condition on the optimization in the present setting since there is no negative growth and technology is the only asset bequeathed to future generations. Thus, successors will always have at least as much productive resources as predecessors left. The relation to the future is instead approximated by a future potential to derive utility from consumption given bequeathed technology levels. Natural needs of the future are accounted for through the emission limit.

Appendix 2.E Quantitative results

2.E.1 A constant carbon tax

Effect on non-energy research. As a side effect of the carbon tax, research in the non-energy sector declines. The reason is that knowledge spillovers from the non-energy sector boost research profitability in the energy sector so that the aggregate effect is a decline in non-energy research. The theory on directed technical change suggests that a price effect directs research to the energy sector since energy and non-energy goods are complements. However, absent knowledge spillovers, the share of non-energy research rises; consider Panel (a) in Figure 2.E.2 which shows the effect of the constant carbon tax in a model without knowledge spillovers. The rise in non-energy scientists without knowledge spillovers—contrary to theory[37]—results from heterogeneous labor shares across sectors. The reduction in labor demand from the energy sector fails to lower non-energy production costs, and the price of non-energy goods remains higher.

The carbon tax raises the price of energy goods. As energy and non-energy goods are complements, demand for the non-energy good reduces, too. The price of non-energy goods falls. For the direction of research the relative change in revenues is essential. It turns out that in the model absent knowledge spillovers, revenues in the energy sector fall more, so that non-energy research increases. However, knowledge spillovers from the non-energy sector, which is the biggest sector and has, therefore, a higher share in aggregate technology, rise profitability of the energy sector so much, that in equilibrium, non-energy research declines in response to the carbon tax.

The result of the theoretic literature on directed technical change is reestablished in the model without knowledge spillovers when labor shares are homogeneous. Then, a supply-side effect makes non-energy goods cheaper: lower labor demand from the fossil sector reduces production costs of the non-energy sector. Lower production costs amplify the reduction in the price of non-energy goods induced by lower demand. As a result, revenues in the non-energy sector fall more and non-energy research declines—in line with the theory—even absent knowledge spillovers; see Panel (c) in Figure 2.E.2 which shows the effects of a carbon tax in a model without knowledge spillovers and with equal labor shares.

37. See, for instance, Hémous and Olsen (2021).

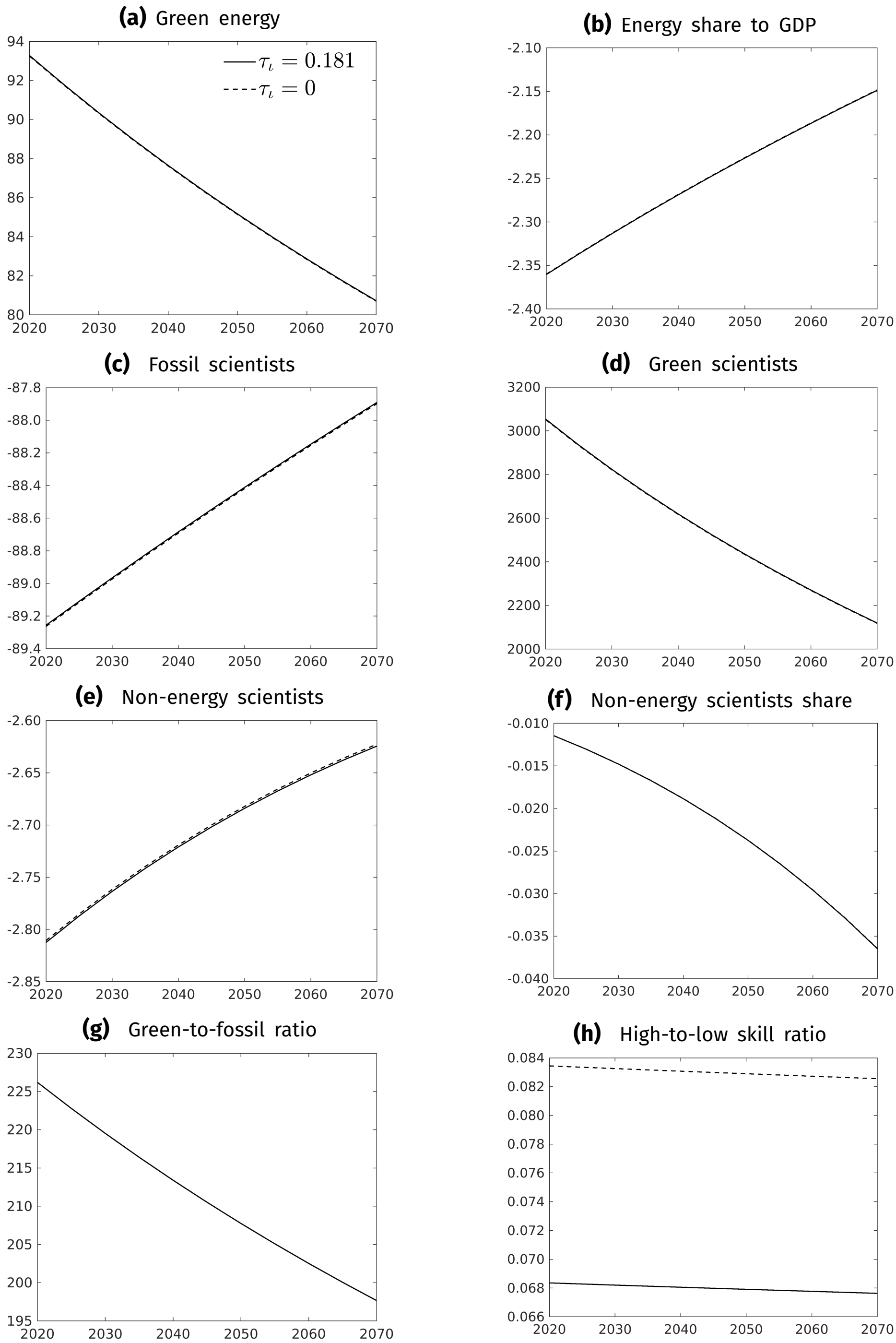

Figure 2.E.1. Effect of a constant carbon tax equal to US$185 (2020 prices) per ton of carbon in percentage deviation from business as usual

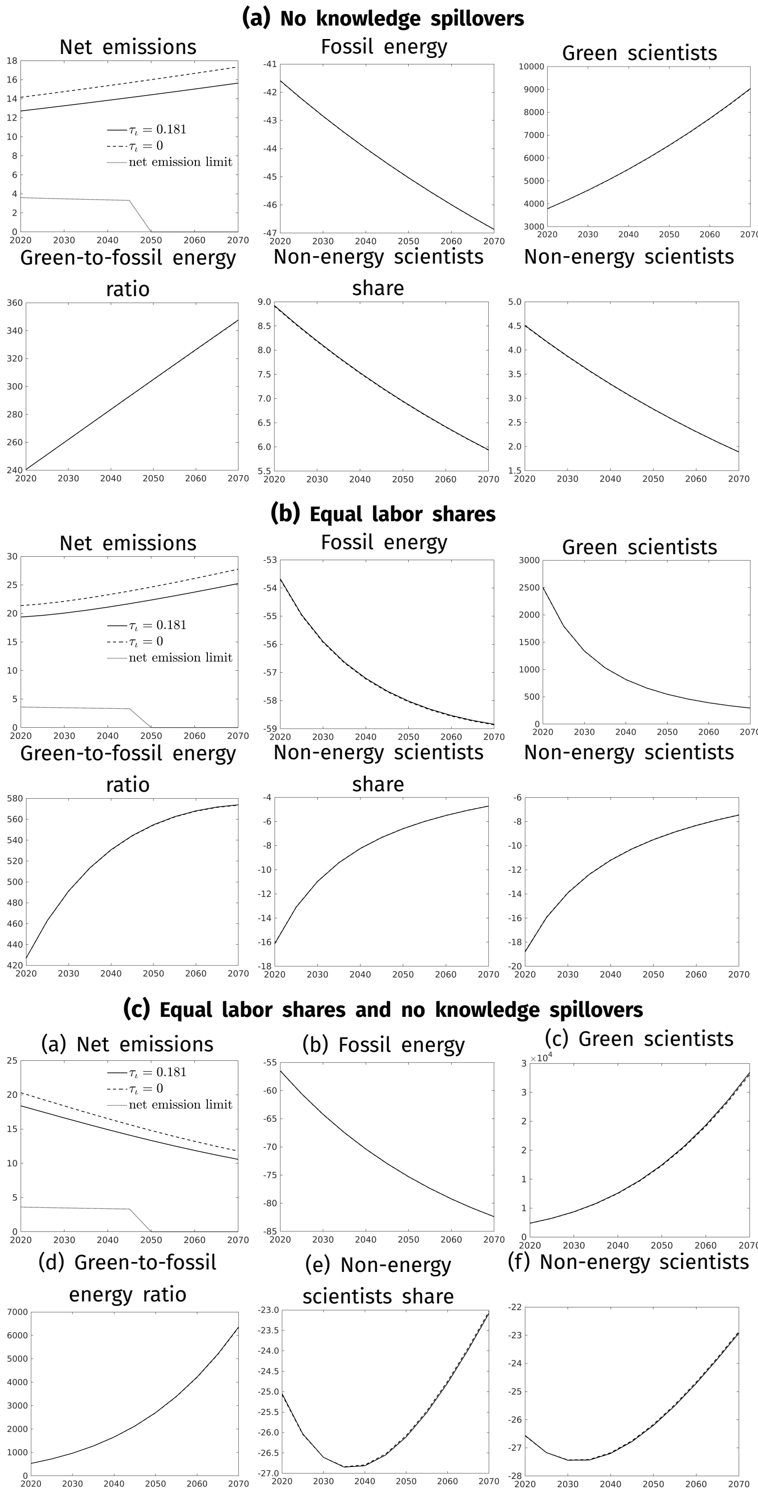

Figure 2.E.2. Effect of a constant carbon tax in model variations

2.E.2 Meeting the emission limit

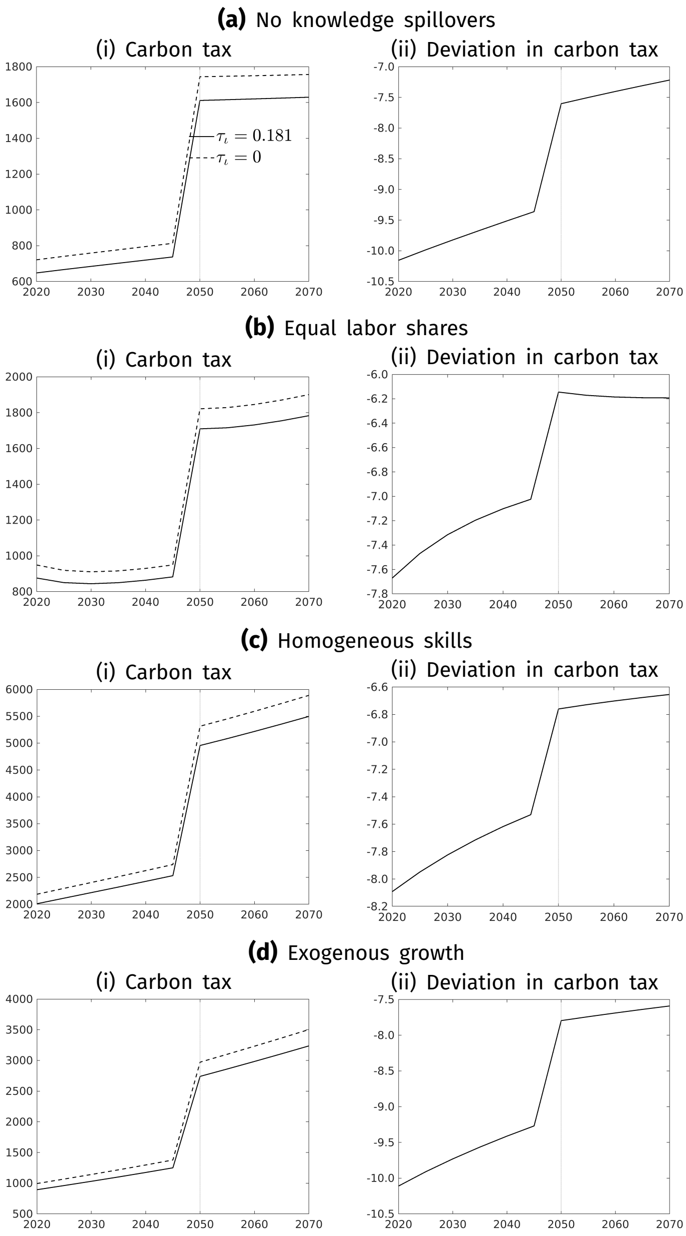

Figure 2.E.3. Necessary carbon tax with and without progressive income tax

2.E.2.1 Effect of model ingredients on necessary carbon tax

This appendix discusses the effect of model ingredients on the necessary carbon tax. The discussion is based on Figure 2.E.3.

Role of cross-sectoral knowledge spillovers. Knowledge spillovers render a higher carbon tax in all periods necessary. This underlines the previous observation that emissions rise faster especially in future periods when knowledge spills from the green and non-energy to the fossil sector.

Role of heterogeneous labor shares. Heterogeneous capital shares increase the necessary carbon tax to meet emission limits since a positive supply side effect is muted. With equal capital shares, the necessary carbon tax is almost half as high as in the benchmark model during the net-zero emission period. As the fossil sector lowers demand for labor, the green sector profits from a higher labor supply, yet, less so under a lower labor share.

With equal labor shares the carbon tax in presence of a progressive income tax is, however, closer to the required carbon tax absent progressive labor taxation. The reason is that the compositional effect of the progressive labor tax on skill supply is less devastating for green production when the green sector relies less on labor. Then, a bigger reduction in the carbon tax is possible while meeting emission limits.

Role of heterogeneous skills. The required carbon tax to meet emission limits is higher when skills are homogeneous. The reason is that the resources for fossil production increase. When skills are homogeneous, labor income tax progressivity has no compositional effect on the economic structure. One might expect, therefore, that a stronger reduction in the carbon tax is admissible. However, the reduction in the carbon tax is smaller when skills are homogeneous.

One explanation is that with homogeneous skills, similar to heterogeneous capital shares, there is no supply side effect triggered by the carbon tax. Instead, labor supply is unaffected. With heterogeneous skills, however, the carbon tax has a compositional effect on labor supply which makes green production less costly. A reduction in the carbon tax does not harm the green-to-fossil energy ratio as much when skills are heterogeneous.

Role of endogenous growth. In line with Fried (2018), I find that a smaller carbon tax is required when growth is endogenous because the shift in research intensifies the effect of the carbon tax.

2.E.3 Optimal policy

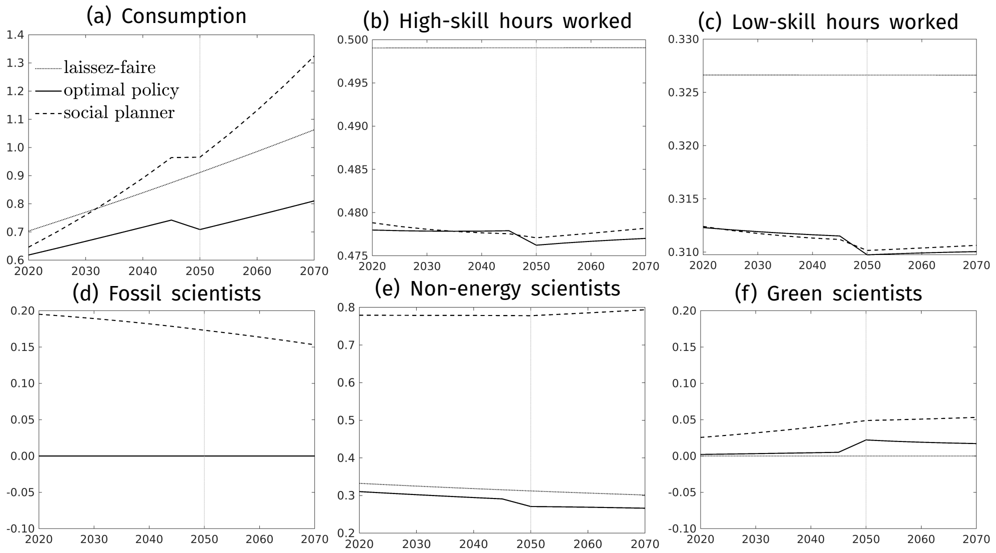

Figure 2.E.4. Laissez-faire, optimal, and efficient allocation in levels

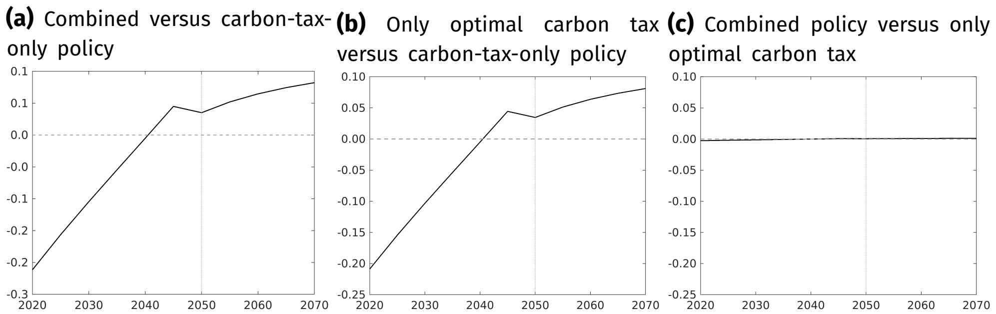

Figure 2.E.5. Deviation of green-to-fossil energy ratio in percent

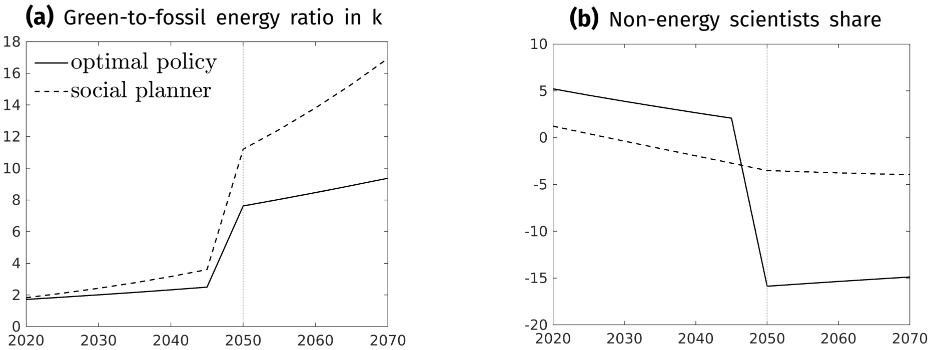

Figure 2.E.6. Efficient and optimal allocation: no knowledge spillovers

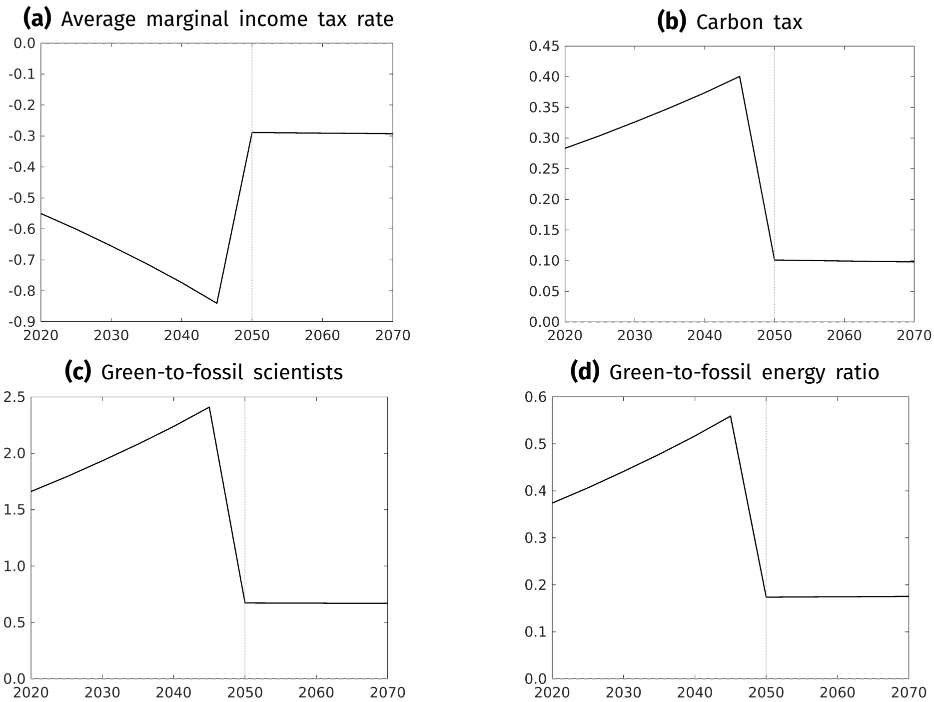

Figure 2.E.7. Deviation of combined policy from carbon-tax-only: no knowledge spillovers

Notes: Panel (a) shows the level of the average marginal income tax rate. Other graphs show percentage deviations of variables under the combined policy and the carbon-tax-only regime without income tax, $\tau_{it} = 0$. A vertical line indicates when the net-zero emission limit becomes binding.

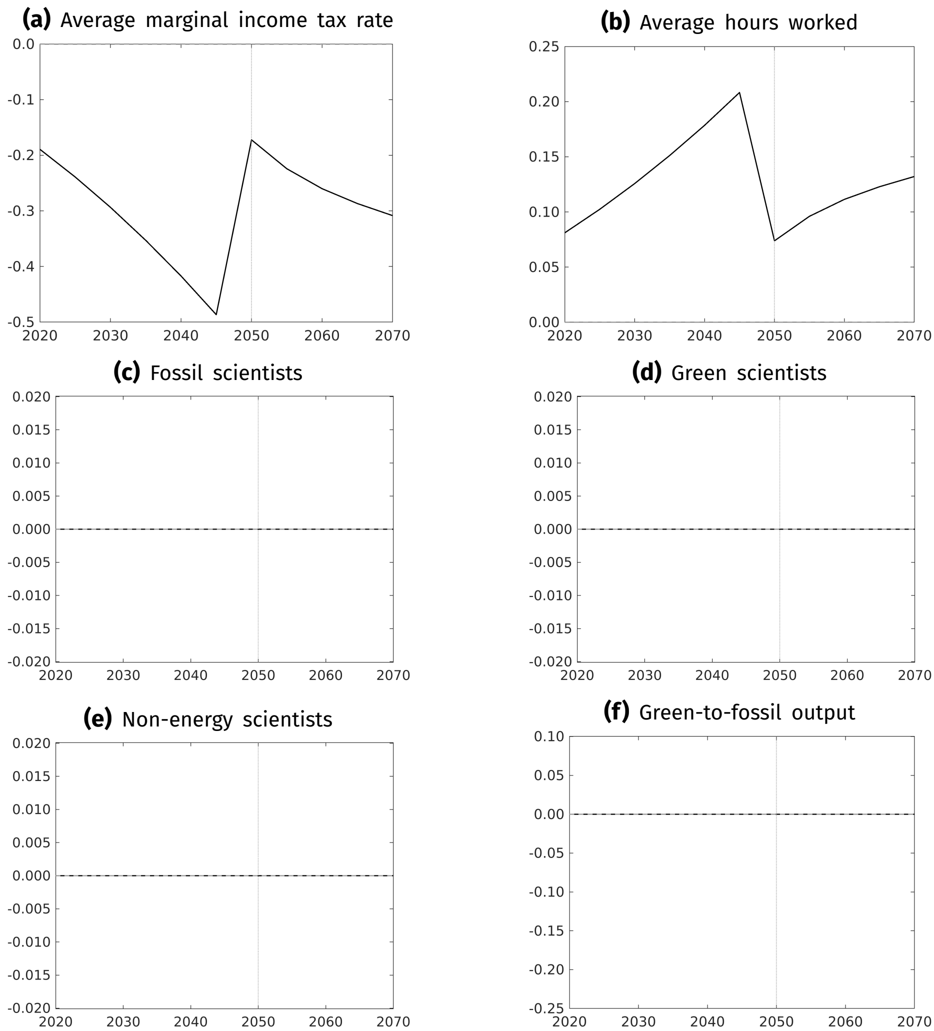

Figure 2.E.8. Optimal combined policy versus only optimal carbon tax: homogeneous skills

References

Acemoglu, Daron. 2002. "Directed Technical Change." *Review of Economic Studies* 69: 781–809. [81]

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The environment and directed technical change." *American Economic Review* 102 (1): 131–66. [61, 62, 64, 71, 73, 74, 82, 83, 90, 94]

Barrage, Lint. 2020. "Optimal Dynamic Carbon Taxes in a Climate-Economy Model with Distortionary Fiscal Policy." *Review of Economic Studies* 124 (2): 1–39. [62, 65, 78, 80, 101]

Bénabou, Roland. 2002. "Tax and Education Policy in a Heterogeneous-Agent Economy: What Levels of Redistribution Maximize Growth and Efficiency?" *Econometrica* 70 (2): 481–517. [66]

Boppart, Timo, and Per Krusell. 2019. "Labor Supply in the Past, Present, and Future: A Balanced-Growth Perspective." *Journal of Political Economy* 128 (1): 118–57. [77]

Bovenberg, A Lans, and Lawrence H Goulder. 2002. "Environmental Taxation and Regulation." In *Handbook of Public Economics*. Edited by A J Auerbach and M Feldstein. Vol. 3, Elsevier Science B.V. Chapter 23, 1471–545. [65]

Chetty, Raj, Adam Guren, Day Manoli, and Andrea Weber. 2011. "Are micro and macro labor supply elasticities consistent? A review of evidence on the intensive and extensive margins." *American Economic Review* 101 (3): 471–75. [78, 80]

Conesa, Juan Carlos, Sagiri Kitao, and Dirk Krueger. 2009. "Taxing capital? not a bad idea after all!" *American Economic Review* 99 (1): 25–48. [65]

Consoli, Davide, Giovanni Marin, Alberto Marzucchi, and Francesco Vona. 2016. "Do green jobs differ from non-green jobs in terms of skills and human capital?" *Research Policy* 45 (5): 1046–60. [71, 78, 80]

Dasgupta, Partha. 2021. "The Economics of Biodiversity: The Dasgupta Review." Working paper. London: HM Treasury. [101]

Domeij, David, and Jonathan Heathcote. 2004. "On the Distributional Effects of Reducing Capital Taxes." *International Economic Review* 45 (2): 523–54. [65]

EIA. 2022. "Monthly Energy Review March 2022." Https://www.eia.gov/totalenergy/data/monthly/. (Accessed on 06 April 2022). [78–80]

Fried, Stephie. 2018. "Climate policy and innovation: A quantitative macroeconomic analysis." *American Economic Journal: Macroeconomics* 10 (1): 90–118. [61, 62, 65, 71, 73, 74, 78, 80, 107]

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski. 2014. "Optimal Taxes on Fossil Fuel in General Equilibrium." *Econometrica* 82 (1): 41–88. [61, 64]

Goulder, Lawrence H. 1995. "Environmental Taxation and the Double Dividend: A Reader's Guide." *International Tax and Public Finance* 2: 157–83. [65]

Heathcote, Jonathan, Kjetil Storesletten, and Giovanni L. Violante. 2017. "Optimal tax progressivity: An analytical framework." *Quarterly Journal of Economics* 132 (4): 1693–754. [65, 66, 78, 80]

Hémous, David, and Morten Olsen. 2021. "Directed Technical Change in Labor and Environmental Economics." *Annual Review of Economics* 13: 571–97. [81, 103]

IPCC. 2022a. "*Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926." [61, 63, 76, 94]

IPCC. 2022b. "Summary for Policymakers. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001." [100]

Jones, Larry E, Rodolfo E Manuelli, and Peter E Rossi. 1993. "Optimal Taxation in Models of Endogenous Growth." *Journal of Political Economy* 101 (3): 485–517. [62, 78, 80, 101]

OECD. 2021. "Average annual hours actually worked per worker." Https://stats.oecd.org/Index.aspx?DataSetCode=ANHRS. (Accessed on 11 February 2021). [78, 80]

OECD. 2022. "Gross domestic product (GDP) (indicator)." Doi: 10.1787/dc2f7aec-en (Accessed on 03 September 2022). [78, 80]

Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff. 2022. "Comprehensive Evidence Implies a Higher Social Cost of CO2." *Nature*, (9): [79]

Robiou Du Pont, Yann, M. Louise Jeffery, Johannes Gütschow, Joeri Rogelj, Peter Christoff, and Malte Meinshausen. 2017. "Equitable mitigation to achieve the Paris Agreement goals." *Nature Climate Change* 7 (1): 38–43. [76]

Slavík, Ctirad, and Hakki Yazici. 2020. "Wage Risk and the Skill Premium." [78, 80]

United Nations. 2022. "World Population Prospects: The 2022 Revision." Https://population.un.org/dataportal/data/indicators/49/locations/900,840/start/2010/end/2100/table/pivotbylocation (Accessed on 04 August 2022). [101]

EPA. 2022. "Trends in Greenhouse Gas Emissions." Https://nepis.epa.gov/Exe/ZyPDF.cgi/P1011XV3.PDF?Dockey=P1011XV3.PDF (Accessed on 02 February 2022). [79, 80]

Van Vuuren, Detlef P., Elke Stehfest, David E.H.J. Gernaat, Maarten Van Den Berg, David L. Bijl, Harmen Sytze De Boer, Vassilis Daioglou, Jonathan C. Doelman, Oreane Y. Edelenbosch,

Mathijs Harmsen, Andries F. Hof, and Mariësse A.E. Van Sluisveld. 2018. “Alternative pathways to the 1.5 °c target reduce the need for negative emission technologies.” *Nature Climate Change* 8(5): 391–97. [79]

World Commission on Environment and Development. 1987. “*Our Common Future*. New York: Oxford University Press.” [101]

Chapter 3

Green Consumer Preferences, Innovation, and Lobbying

Joint with Olimpia Cutinelli Rendina and Antoine Mayerowitz

3.1 Introduction

Households' environmental concerns are rising eventually shifting demand towards cleaner products.[1] How do firms react to such a shift in demand? On the one hand, firms' incentives to innovate clean increase (Aghion, Bénabou, et al., 2022). On the other hand, lower demand for dirty goods diminishes firms' profits thereby reducing their ability to invest in clean R&D. As a result, firms have a heightened incentive to protect their profits. Lobbying qualifies as a potential measure. In this paper, we investigate whether a rise in green consumer preferences also implies an increase in environmental lobbying.

To this end, we compile a novel dataset linking natural catastrophes, environmental preferences, and firm-level data on lobbying and patents in the automobile industry. Our measure of household environmental awareness is based on Google Trends data allowing for a high-frequency and geographically disaggregated measure. We find robust and significant evidence that automotive producers adjust in two dimensions in response to a rise in environmental concerns. First, in line with the literature, the average lobbying firm's value of novel clean patents rises and decreases for dirty ones. Second, this shift in innovative activity is accompanied by an increase in lobbying expenditures

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1. Recently, the phenomenon of an intrinsic willingness to pay for the avoidance of negative externalities has spurred interest in the economics literature; see, for instance: Bénabou and Tirole (2010), Bartling, Weber, and Yao (2015), and Aghion, Bénabou, Martin, and Roulet (2022).

on environmental topics. A one standard deviation increase in environmental concerns implies a rise in environmental lobbying expenditures by a factor of 3, i.e., US$180,000, and the stock of clean innovation by a factor of 2.4, i.e., US$248.29 million, on average.[2]

Using variation in environmental preferences induced by natural catastrophes and controlling for federal policy changes, we interpret our results as identifying a demand-led mechanism. As firms face more clean demand, they innovate cleaner technologies. At the same time, the shift in demand reduces profits of dirtier firms. Fixed costs of research or convex returns to clean innovation render marginal profits more valuable. At its extreme, preventing a further reduction in profits may be vital for the firm to survive the transition toward green production. Then, environmental lobbying emerges as a tool to ensure the survival of the firm.

In more detail, the analysis focuses on the US over the period from 2006 to 2019. We connect several datasets and employ a shift-share instrumental variable approach. First, we construct a novel proxy for household environmental preferences from Google Trends data. Google Trends measures the relative frequency with which certain terms, e.g. *Climate Change*, are searched. In contrast to available survey data, Google Trends comes at a high frequency and fine geographic variation which allows us to build a panel dataset on the state level at a quarterly frequency.

Second, we combine our proxy for green preferences with vehicle registration data of the automobile industry to construct a measure of firm exposure to green consumer preferences.[3] While environmental awareness has increased everywhere, there is significant heterogeneity across the consumers of different firms; both in terms of the speed and the timing of the change.

Third, green preferences are most likely shaped by political and economic surroundings. For instance, exposure to green supply or policies may increase environmental awareness. To rule out that we measure firm responses to confounding factors, we use exogenous variation in green preferences induced by natural catastrophes. Therefore, we construct a novel dataset of state exposure to wildfires using satellite data from NASA. We argue that our instrument is valid to capture the effect of green preferences due to, first, geographic differences

2. Responses and especially the rise in environmental lobbying are huge. Yet, a one standard deviation in the index of environmental preferences means a sizable increase, too. As regards lobbying, we expect the response to be transitory. Going forward, we aim to, first, provide an economically more meaningful interpretation of the rise in environmental concerns, and, second, analyze the dynamics in firm responses using local projections.

3. We focus on the automotive industry in the US for the following reasons. First, the industry produces highly heterogeneous goods in terms of pollution standards, that are easily identifiable (through the distinction between electric, hybrid, and fuel cars). Second, the US sees the highest level of expenditures in both lobbying and innovation, therefore, enabling us to study the trade-off between these two strategies.

in firms' sales and production markets. Second, we include control variables to capture political adjustments in response to natural catastrophes.

We find that firms increase their spending on lobbying on environmental topics as green preferences increase. A one standard deviation increase in environmental awareness causes an increase in the average firm's environmental lobbying expenditures by a factor of 3. Simultaneously, patenting increases for clean and declines for dirty technologies.

Taken together, these results suggest that, on the one hand, greener household preferences urge firms to innovate cleaner technologies. On the other hand, however, firms' returns to lobbying on environmental issues increase. Protecting profits seems to become critical as firms need to finance more clean innovation while returns to dirtier goods decline. A possible explanation is that R&D investment becomes more important when profits are low due to fixed costs of innovation. Another explanation may be first-mover advantages in particular in a market for durable goods.

Interpretation of our results as a response to demand hinges upon the assumption that it is not a shift in policies driving our results: greener household preferences may urge policymakers to discuss greener laws at the state level. Clearly, this provides the opportunity for firms to increase their spending on environmental lobbying. However, our measure of lobbying consists of expenses targeted at federal institutions only, which changes similarly for all firms and not only those affected by greener consumer preferences. Furthermore, our empirical set-up allows us to control for a rise in environmental regulations on the federal level by including time fixed effects. In addition, we find that firms also increase their lobbying expenditures on other topics which constitute margins to protect profits, such as trade and manufacturing, which presumably do not become more important politically in response to a shock in environmental preferences. This observation, thus, lends support to the narrative that protecting profits becomes more vital to firms and it is not an increase in environmental regulations being discussed.

More generally, next to the instrumental variable approach we employ a variety of strategies to alleviate concerns that our patterns arise from omitted factors or through reverse causality. First, the analysis is carried out on first differences within firms in order to identify variations that are not driven by firm-specific fixed observed or unobserved characteristics, such as size or main geographic areas of operation of the firm. Second, we control for period and firm fixed effects, which are to be interpreted as controls for time trends in a linear specification. Thirdly, we control for factors potentially affecting state-level policies and corporate strategies, such as demographics, political preferences, transportation habits, local infrastructure, and local investments in the energy transition of transport.

Literature. This paper brings together two strands of literature: the literature on the relationship between competition, innovation, and lobbying and the literature on households' willingness to pay to avoid negative externalities.

The first literature developed around the seminal paper by Aghion, Bloom, Blundell, Griffith, and Howitt (2005) which discusses the relation between competition and innovation. Aghion, Blundell, Griffith, Howitt, and Prantl (2009) use a Schumpeterian model to show that firms that are able to innovate to differentiate from competition will do so when competitive pressures reach certain levels. Empirical validation thus far focuses on trade shocks to investigate firm responses to increased competition (Bombardini, 2008; Bloom, Draca, and Reenen, 2016; Brandt, Biesebroeck, Wang, and Zhang, 2017; Hombert and Matray, 2018).

Autor, Dorn, Hanson, Pisano, and Shu (2020) find that many firms do not have the possibility to innovate after a competition shock. Based on the intuition that other escape avenues exist in response to competitive pressures, Bombardini, Rendina, and Trebbi (2021) provide evidence that US firms use innovation and lobbying as two alternative strategies to deal with a trade shock. Akcigit, Baslandze, and Lotti (2022) present opposed firm-level correlations on the relationship between market dominance, innovation, and political connections in the framework of Italian firms, further confirming this intuition. In contrast to the existing literature, we focus our analysis on firm responses to a demand shock. Furthermore, our results point to an aggregate complementarity of clean innovation and lobbying: both, clean innovation and lobbying expenditures rise in response to increased competition in one market fragment. Going forward, we aim to study firm characteristics shaping the decision in order to make a statement on the complementarity of these adjustment margins on the firm level.

More precisely, our project connects to studies on firm capacities to modify environmental regulations through political influence. This literature attests high social costs and individual gains from anti-environmental lobbying (Kang, 2016; Meng and Rode, 2019).[4] Adverse environmental lobbying is particularly effective because the strength of lobbying is multiplied when targeted at maintaining the status-quo (McKay, 2012), dirty firms tend to organize more than clean firms resulting in a higher impact on policies (Kim, Urpelainen, and Yang, 2016), and environmental organizations lobby less than what would be considered rational (Gullberg, 2008). We contribute by investigating motives for environmental lobbying. In the framework of the automotive industry, we show that while firms increase their environmental lobbying expenditures in reaction to the shift in green preferences, they also engage in a technological transition through clean innovation.

4. A remarkable study shedding light on the positive impact of lobbying on the discrepancy between voters and legislature decisions is Giger and Klüver (2016) in the context of Swiss referenda.

The second connected literature explores *individual social responsibility* (see, for instance, Bénabou and Tirole, 2010; Bartling, Weber, and Yao, 2015; Falk, Andre, Boneva, and Chopra, 2021). While the phenomenon of social responsibility has been studied in the behavioral economics literature, analyses of the effectiveness of social responsibility to affect market outcomes is scarce. Aghion, Bénabou, et al. (2022) show that clean innovation is one way to escape competition in conventional, non-green markets. Stronger environmental consumer preferences accelerate the mechanism. Other contributions highlight obstacles for social responsibility to impact actual allocations. Income inequality (Vona and Patriarca, 2011; Dobkowitz, 2022), for instance, may keep low-income households from consuming clean products. A perceived quality advantage of conventional goods, a low availability (Vermeir and Verbeke, 2006), or a lack of trust in sustainability claims (Meis-Harris, Klemm, Kaufman, Curtis, Borg, et al., 2021) are other reasons why demand and environmental attitudes diverge. We add to answer the question of whether households can shape the allocation of resources across sectors by focusing on a barrier on the producers' side: lobbying.

Outline. The remainder of the paper is structured as follows. Section 3.2 outlines our data followed by a description of the empirical strategy in Section 3.3. In Section 3.4, we present and discuss our results. Section 3.5 concludes.

3.2 Data

In this section, we describe the data sources, define our sample of interest, and present summary statistics.

3.2.1 Data construction

Vehicle sales: S&P Global. The data on new vehicle registrations is sourced from *S&P Global* covering the years 2006 through 2019.[5] This comprehensive dataset provides quarterly registration details for each US state including information on the make, model, and engine type of each vehicle. We consider registrations in a given state to be equivalent to a sale to a resident of that state.[6] Using this dataset, we can determine the market share of each vehicle make at the state level which we use to assess a make's exposure to green consumer preferences.

5. https://www.spglobal.com/mobility/en/products/automotive-market-data-analysis.html

6. It's generally forbidden to register a vehicle in another state than the state of residency in the United States. Exceptions exists for citizen that are living in multiple states, or working in another state.

Environmental preferences: Google Trends. To proxy consumers' awareness of environmental issues at the state level, we revert to Google Trends data. Google Trends is a free tool that provides time-series indices of search queries made in a certain area. Specifically, it quantifies the percentage of all searches that use a given term. To build our index, we use Google Trends queries on topics related to environmental issues and aggregate them using factor analysis. The selected keywords are *Electric car*, *Recycling* and *Climate Change*. Google Trends normalizes the index by the highest value observed within the time period and areas included in the query. However, Google Trends only allows comparing a maximum of five locations per search so that reference points of normalization vary. To solve this issue, we include the national US index in each query and sequentially normalize each state by the maximum value of the US.[7] Finally, we build a composite index with principal component analysis (PCA).[8]

Google Trends does not provide information on the intention with which a term is searched. Therefore, the search data may not express concerns. However, we observe similar trends comparing Google Trends data to survey data. Figure 3.B.2 shows the evolution of a measure of environmental concerns from the Gallup survey. The series displays a similar trend as our index of environmental preferences derived from Google Trends presented in Figure 3.B.1. Previous work highlights the usefulness of Google Trends to predict near-term economic indicators (Choi and Varian, 2012; Stephens-Davidowitz and Varian, 2014). Vosen and Schmidt (2011) show in the context of private consumption that Google Trends outperforms survey-based indicators in forecasts.

Fires: FIRMS. We measure exogenous shocks to environmental preferences through wildfires. Data on fires comes from the Fire Information for Resource Management System (FIRMS) of the US NASA. The data divides the US into cells of one square kilometer and documents several times a day whether there is a fire in this cell.[9] We apply the following procedure to obtain a map of all fires in the US for each week of the period of analysis. First, we collapse the data at the week level, considering that a cell is alight if a fire was declared in the cell at least once over the week. Second, we determine clusters of fires using the algorithm *dbscan* algorithm (Ester, Kriegel, Sander, Xu, et al., 1996).[10] Third, we draw a convex polygon around each cluster to determine the area of the fire. We then compute our measure of consumers' exposure to fires at the state level by summing over all the fires f:

7. See West (2020) for an extensive discussion of this issue.

8. We extract the first component which accounts for 53% of the total variance.

9. We focus on *presumed vegetation fire* and drop the other types of fires.

10. We focus on clusters to exclude fires that are too small to impact environmental preferences. We choose eps=0.25 and minpts=5 as parameters for the algorithm, that is clusters are composed of at least 5 points at a maximum normalized distance of 0.25.

$$Fire\ \ Exposure_{lt} = \log\left(\sum_{f} \text{intensity}_{it} * \text{surface}_{ft}/\text{distance}^2_{flt}\right)$$

where the *intensity* is proxied by the fire radiative power (in Megawatts) and *surface* refers to the expansion of the fire. Our measure of fire exposure results from division with the square of the distance between the fire and the state to ensure that close populations are exponentially affected.[11]

Lobbying: LobbyView. Following the Lobbying Disclosure Act of 1995, all lobbyists ought to register their lobbying activity with the US Senate Office of Public Records. In particular, they need to declare their client, the amount spent on lobbying, the topics lobbied, and the entity targeted by the lobbying activity. This information is publicly available at the Senate Office of Public Records. We use the clean version *LobbyView* provided by Kim (2018), where firms are matched to standard identifiers, such as the *gvkey* identifier for the Compustat database. We focus on clients that are firms from the automotive industry.

Using this dataset, we derive information on the topic firms lobby on by dividing lobbying expenditures into the nine groups of issues receiving the most expenditures. These groups of issues are manufacturing, trade, tax, labor, environment, consumer safety, trade, finance, innovation, and public expenditures. Last, we deduce information on the targeted entity. We create a variable for the log expenditures targeted at one of the eight institutions subject to the most lobbying (House of Representatives, Senate, White House, Department of Commerce, Environmental Protection Agency, Department of Energy, National Highway Traffic Safety Administration, and Trade Representative). We also aggregate entities following two criteria: first, political institutions versus agencies and, second, according to whether the institution's main mandate is towards environmental questions.[12]

Innovation: Patentsview. We measure innovation through granted patents at the United States Patent and Trademark Office (USPTO). Patents are dated by their year of application to precisely represent the year of their invention. We match patents with firms in our sample using the assignee disambiguation method of PatentsView and manual inspection.[13] Following Aghion, Dechezleprêtre, Hémous, Martin, and Reenen (2016) we categorize patents using their Cooperative Patent Classification (CPC) into *clean*, *dirty*, and *grey* technologies. However, the number of patent applications may not reflect actual investment in R&D. To bypass this

11. The distance is computed between the fire's and the state's center of gravity.

12. We define political institutions (in opposition to independent agencies) as institutions where representatives are elected. The list of targets and their classifications can be found in the appendix.

13. https://patentsview.org/disambiguation

issue, we weight patent applications with an estimation of its private economic value from Kogan, Papanikolaou, Seru, and Stoffman (2017) updated until 2020. Finally, following Hall (2005) and Bloom, Draca, and Reenen (2016), we compute a measure of *knowledge stock*, K_{ist}, according to the recursive identity:

$$K_{ist} \; = \; (1-\delta)K_{ist-1} + R_{ist}$$

Where R_{ist} represents the economical market value of new patents from firm i in technology s. The variable δ captures the depreciation of knowledge. [14]We use K_{ist} in our main analysis to measure changes in innovation activity. Using a stock instead of a flow variable is less prone to arbitrary results due to the choice of lags in the regression.

State-level controls. We control for a series of state trends that may affect corporate strategies responding to shocks to consumer preferences. More specifically, we control for local transportation habits (through the percentage of the population commuting by personal car, by public transportation, and by bike and the percentage of the population working remotely), local investments in the energy transition of transports (measured as the number of alternative fueling stations). We also control for demographic information such as the share active in the labor market and young persons in the population; the share of rural population, and average income. Finally, we control for major political preferences by using the share of votes for Republicans in the past presidential election.

Data on transportation habits, local infrastructure, investment in local infrastructure, and alternative fueling stations come from the Bureau of Transportation Statistics. We use Census data to account for demographic changes and Decennial Census data to measure the share of rural population. Personal income per capita comes from the Bureau of Economic Analysis. Last, we use election data from the MIT Election Data and Science Lab.

3.2.2 Summary statistics

Having specified all main variables of interest, we now briefly discuss the sample and main variables.

Innovation and lobbying. Our dataset is composed of 17 groups, which are the main groups of the automotive sector offering private cars.[15] We focus on groups, that is, aggregates of makes, because the data suggests that both lobbying

14. Following the literature on depreciation of R&D (Li and Hall, 2020), we set $\delta = 0.2$.

15. We remove from the sample groups with less than 30,000 registered cars over the whole period and truck-only companies.

and innovation are determined at the group level.[16] Table 3.A.1 reports the distributions of our main outcome variables. Table 3.A.3 reports average group characteristics.

We document that green technologies represent 57% of patent applications in our period of analysis, grey technologies around 28%, and dirty technologies account for only 16% of applications. Figure 3.B.3 depicts the trends in the different types of patenting since 1976. There was an exponential increase in the number of patents since the late 1990s which was mainly driven by green applications. The number of clean patents rose by a factor of five during the period.[17] The level of dirty patenting remained stable over the period with a peak around the year 2000. Grey patenting followed suit but with milder trends than green patenting until 2010. Afterwards, the number of grey applications plateaued at an intermediate level between green and dirty applications.[18]

There is high heterogeneity in the mix of technologies patented by firms, with makes such as Mazda or Isuzu innovating mainly in grey technologies, and others focusing on green technologies. However, all firms—with the exception of Tesla—innovate in all types of technologies. When studying the heterogeneity in response to consumers' environmental awareness we, therefore, do not compare *green* to *dirty* firms but use a continuous scale of *greenness*.

There are 17 firms in our sample lobby of which 15 engage in lobbying. Lobbying expenditures are substantial.[19] The average expenditure is US$683,000 with a maximal expenditure of more than US$6,3 million.[20] Splitting lobbying expenditures according to targeted topics on the firm level, we observe that on average 13% of lobbying expenditures are directed toward environmental topics. The largest firms in terms of market shares are also the largest spender on lobbying, with General Motors spending around US$2,773,490 by quarter and Ford spending on average US$1786,180 per quarter (see Table 3.A.3). The highest share of lobbying expenditures going to environmental topics are from BMW (32% of total expenditure) and Tesla (30% of total expenditures); in comparison, both General Motors and Ford allocate 18% of their lobbying to environmental issues.

Variation in shock exposure. Figure 3.B.5 compares market shares across makes over the US. A more bluish color means that the area represents a more important

16. The group BMW, for instance, includes the makes BMW, Mini and Rolls-Royce. Similarly, the group General Motors includes the makes Oldsmobile, Hummer, GMC, Buick, Chevrolet, Saturn, Cadillac, and Pontiac. The whole list of groups and makes can be found in the appendix.

17. In our dataset, we only observe patent applications that were accepted by the USPTO. The application process takes a few years, so all applications after 2018 have not been accepted yet. This explains the sharp decrease in patenting we observe in the last quarter.

18. These trends accord with the data presented in Aghion, Dechezleprêtre, et al. (2016) and Aghion, Bénabou, et al. (2022).

19. The two groups that do not lobby are Suzuki and Isuzu.

20. The order of magnitude surpasses by far campaign contributions or other political influence tools.

market for a given make than for other makes. There is important heterogeneity between companies: some are unexceptionably exposed to demand across the US (Ford, Toyota, and Jeep, for instance), while others are more exposed than the average make to some regions. To Tesla, for instance, the West and Washington DC are of superior importance, New England and the West Coast are highly important to BMW, and General Motors is highly exposed to demand in the Midwest and the South. These variations in the importance of specific states for firms are at the heart of our empirical strategy. In the next step, we discuss the second crucial variation: changes in environmental attitudes across states and time.

Trends in environmental awareness and fires. The index of environmental attitudes toward the environment is presented in Figure 3.B.1. It is characterized by a positive trend over the first years followed by a drastic U-shape. While the decrease in environmental concerns is only somewhat discussed in the literature, our trends are congruent with the stark decline in environmental awareness presented in Aghion, Bénabou, et al. (2022) and the trends of the Gallup survey (Figure 3.B.2). In our sample, we observe that the decrease started around 2008. One candidate explanation is the 2008 financial crisis leading to a drop in the salience of climate issues. Importantly for our analysis, there is significant variation at the state level and over time.

Exposure to wildfires. Figure 3.B.6 pictures the index of fire exposure through time. The index is centered with respect to a yearly linear trend and state-quarter fixed effects, similar to our main regression. We observe a high heterogeneity both between states and over time.

3.3 Empirical strategy

In this section, we introduce a quasi-experimental shift-share design to estimate the effects of changes in consumer environmental attitudes on firm behavior.

3.3.1 Research design

To estimate the causal effect of environmental attitudes on lobbying and innovation, the ideal experiment would, all else equal, change random firms' consumer attitudes toward environmental issues. However, consumer preferences are an endogenous object. To approximate the ideal experiment, we employ a shift-share instrumental variable (IV) design. Therefore, we leverage two components: localized shocks to environmental concerns and pre-determined exposure shares to local markets. The analysis is run on the firm-quarter level.

Treatment. We seek to estimate the effect of a change in consumer preferences on a firm i. As discussed earlier, the index based on Google Trends, ENV_{lt}^{GT}, serves as a proxy for household preferences. To derive a measure of firm exposure to consumer preferences, we weigh consumer preferences in state l with the share of firm i's sales in that state, i.e., a measure of the importance of a local market for a firm, s_{ilt}:

$$\Delta ENV_{it}^{GT} = \sum_{l}^{L} s_{ilt} \left(ENV_{lt}^{GT} - ENV_{lt-8}^{GT} \right). \tag{3.3.1}$$

We measure a change in consumer preferences as the difference in the index over a period of 2 years (8 quarters).

Instrument. To ensure that changes in environmental preferences are not driven by firm behavior, for instance, via advertisement, we instrument the change in environmental preferences. As discussed in Section 3.2, exogenous shocks are obtained through the exposure to wildfires. Those shocks are aggregated at the state level l to match the data on firm market shares. We measure the shocks as changes in state exposure to wildfires over a period of 8 quarters.

$$\Delta FIRE_{lt} = Fire \;\; Exposure_{lt} - Fire \;\; Exposure_{lt-8}. \tag{3.3.2}$$

The shift-share design combines this set of local shocks with variations in exposure to local markets. The exposure shares s_{ilt-h} are computed as the share of sales in state l in total sales of firm i lagged by h quarters. Because contemporaneous shares are likely to be subject to reverse causality, we use lagged shares, measured 4 years earlier.[21] Finally, the shift-share instrument, Z_{it}, is built as the weighted average of changes in fire exposure:

$$Z_{it} = \sum_{l}^{L} s_{il,t-h} \Delta FIRE_{lt}. \tag{3.3.3}$$

Specification. Outcomes, y_{it}, are measured as log change over two years. The endogenous variable is the change in the standardized environmental attitudes index, ΔENV_{it}^{GT}, which we instrument with the weighted change in wildfires, Z_{it}. In short, we estimate the following model by 2SLS:

$$y_{it} = \lambda_t + \alpha_i + \beta_{it} \Delta ENV_{it}^{GT} + \gamma X_{it} + \varepsilon_{it}. \tag{3.3.4}$$

Where λ_t is a time fixed effect, α_i is a firm fixed effect, and X_{it} indicates a set of controls. The coefficient of interest is β_{it} which captures the semi-elasticity of the

21. Firms may strategically change their exposure to markets given the shocks, and shocks may affect a firm's market share. By using lagged exposure, we make sure to capture variation that comes only from the shocks.

outcome variable to a change in the index of green environmental preferences, conditional on a set of controls X_{it}.

3.3.2 Identification

The instrument used in this study is a combination of lagged exposure shares and local shocks. Previous studies on shift-share instruments have identified two possible sources of identification in this research design. The first source, as discussed by Goldsmith-Pinkham, Sorkin, and Swift (2020), is identification when the shares are exogenous. The second source, as shown by Borusyak, Hull, and Jaravel (2022), is when the IV identification assumption can be met through quasi-random assignment of shocks. We argue that our study belongs to the latter category. In this section, we discuss the necessary conditions for identification:

Quasi-random shock assignment. This condition requires that $\boldsymbol{E}[\Delta FIRE_{lt}|\bar{\varepsilon}_{lt}, \tilde{X}_{lt} s_{t-h}] = \tilde{X}_{lt}' \cdot \mu$. This implies that shocks are quasi-randomly assigned conditional on shock-level unobservable $\bar{\varepsilon}$, average lagged exposure s_{t-h}, and shock-level observables $\tilde{X}_{lt}$. In our design, it means that shocks are randomly assigned, conditional on state-level characteristics and period fixed effects. Thus, a systematic relation of the occurrence of wildfires and state characteristics would not violate our identification strategy.

Many uncorrelated shocks. This condition states that shocks should not be concentrated in few observations and that average exposure converges to 0 as observations increases. The effective number of shocks leveraged by this research design can be estimated by the inverse of the Herfindhal index HHI of the weights s_{lt-h}, where $s_{lt-h} = \frac{1}{N}\sum_i s_{ilt-h}$, where N indicates the number of firms. We report the related statistics in Table 3.A.4. Our effective sample size is large (above 700) and our largest importance weight s_{lt} is below 1%.[22]

Relevance Condition. The relevance condition states that the instrument has power, that is $\boldsymbol{E}[\Delta Y_{it} \cdot Z_{it}|X_{it}] \neq 0$. This can be checked by computing the first-stage F-statistic which we report in our tables of results. Figure 3.B.4 visualizes the first-stage revealing a strong positive correlation between exposure to wildfires and environmental attitudes. This finding is in line with the literature which establishes that natural disasters strongly affect local public opinion on climate change (Bergquist, Nilsson, and Schultz, 2019).

All results are clustered at the state level, which allows for correlated shocks within a state across time. For example, California especially may expect numerous wildfires throughout our period of analysis. In a shift-share IV design, observation

22. Note that even though we have relatively few treatment groups (50 states), we leverage the quarterly frequency in our data to reach consistency.

cannot be treated as i.i.d. We thus follow Adao, Kolesár, and Morales (2019) and Borusyak, Hull, and Jaravel (2022) to correct standard errors and the first-stage F-statistic.

3.4 Results

This section details our main results, their robustness, and additional analyses.

3.4.1 Main results

Table 3.A.5 displays the main results. The first two panels report results for variables capturing lobbying expenditures as the dependent variable: lobbying expenditures on environmental topics, and total lobbying expenditures.[23] The following three panels use the change in the stock of clean, dirty, and grey patents, respectively, in a firm measured as the knowledge stock detailed in Section 3.2. All outcomes are in two-year log difference and include year-quarter fixed effects, firm fixed effect, and the lagged market share at the firm level.

Table 3.A.5 separates into an OLS regression, columns 1 to 4, and our preferred IV estimates, columns 5 to 8. Consider first the OLS estimates. The first column applies a bare-bone specification that includes no covariates beyond the change in environmental awareness, the specific fixed effects, and the lagged market shares. The estimates of column 1 suggest no significant correlation between the change in consumers' environmental awareness and our dependent variables, with the exception of a negative correlation with grey innovation. In column 2, we augment the long difference model with a set of demographic controls, such as population and income per capita. This tests robustness and handles potential confounders. In the third column, we add controls for transportation habits (the share of the population commuting by personal car and state-level investments in transportation infrastructures). Finally, we control for the score for Republicans in the last presidential elections in column 4. These specifications further address the concern that firms might respond differently to different populations depending on their demographics and income level and the concern that the response of firms runs primarily through public policies and not demand. In all three specifications, the controls leave the results of similar magnitude and significance.

The following four columns repeat the same specifications instrumenting the change in the environmental attitudes index by the change in wildfire exposure.

23. We focus on the intensive margin of lobbying. Lobbying activity has inherent fixed costs rendering it extremely persistent. We thus do not have enough heterogeneity in the extensive margin to measure the impact of environmental concerns on it. Details on how lobbying expenditures are aggregated between issues and institutions can be found in the appendix.

This allows us to exclude confounding factors affecting both household preferences and firm decisions, for instance, political efforts towards more environmental protection. Consider column 5. We don't observe a significant impact of consumer awareness on total lobbying expenditures. However, lobbying on environmental topics increases as a consequence of rising environmental concerns. This suggests a reallocation of the lobbying activity within topics. Also, clean patenting responded positively to contemporaneous exposure to greener consumers, while dirty patenting decreased, and grey patenting didn't react significantly.[24] The results are of the same magnitude after the inclusion of demographic, transportation, and political controls. In five out of six models, the IV estimates are larger than their OLS counterparts suggesting that the instrumentation purges the potential effect of confounders shocks or measurement error (or both).

The results are economically meaningful. A one standard deviation increase in environmental concerns implies a rise in environmental lobbying expenditures by a factor of 3. Moreover, the last two panels suggest that a one standard deviation increase in environmental awareness spurs green innovation on average by a factor of 2.4 and slows down dirty innovation by a factor of 1.1.

Taken together, these results suggest that, on the one hand, greener household preferences urge firms to innovate cleaner technologies. On the other hand, however, firms' returns to lobbying on environmental issues increase. Protecting profits seems to become vital as firms need to finance more clean innovation, while returns to dirtier goods decline. A possible explanation is that R&D investment becomes more important when profits are low due to fixed costs of innovation. Another may be first-mover advantages in particular in a market for durable goods.

Interpretation of our results as a response to demand hinges upon the assumption that it is not a shift in policies driving our results: greener household preferences may urge policymakers to discuss greener laws at the state level. Clearly, this provides the opportunity for firms to increase their spending on environmental lobbying. However, our measure of lobbying consists of expenses targeted at federal institutions only, which changes similarly for all firms and not only those affected by greener consumer preferences. Furthermore, our empirical set-up allows us to control for a rise in environmental regulations on the federal level by including time fixed effects. In addition, as will be discussed below, we find that firms also increase their lobbying expenditures on other topics constituting margins to protect profits, such as trade and manufacturing, which presumably do not become more important politically in response to a shock in environmental preferences. This observation, thus, lends support to the narrative that protecting profits becomes more critical to firms and it is not an increase in environmental regulations being discussed.

24. These results are in line with Aghion, Bénabou, et al. (2022) who find that exposure to greener attitudes fosters clean innovation.

3.4.2 Robustness

To ensure that our results capture the effect of exposure to consumers' environmental awareness, and not some long-run common causal factor behind both the rise in awareness and technological change or lobbying, we conduct a falsification exercise by regressing past changes in innovation and lobbying expenditures on future changes in environmental awareness. The results of the pre-trend falsification tests are presented in Table 3.A.6, where the first two panels focus on lobbying activity and the three following panels on patenting, similarly to our main table of results. Across all five specifications, we cannot reject that there is no relationship between the shocks and our lagged dependent variables on lobbying expenditures and innovation.

3.4.3 Additional analysis

Our results suggest that, while total lobbying expenditures do not increase at the firm level, there is a reallocation within issues and institutional targets towards green topics. To further understand how firms react to environmental concerns, we repeat our estimation exercise looking at lobbying expenditures on different groups of issues, that is, the topic on which firms lobby, and targets, i.e., the institutions lobbied.

Topics lobbied. Table 3.A.7 presents the results for the different issues, where the dependent variable is successively the lobbying expenditures targeted: environmental topics, taxation, trade, innovation, finance, manufacturing, labor, and public expenditures. Apart from environmental topics, the issues toward which there is a clear reallocation in lobbying expenditures are trade and manufacturing. The estimates suggest that a one standard deviation increase in environmental topics results in an increase in lobbying expenditures, respectively, by a factor of 6.5 and 7. The magnitude is economically significant and twice as large as the one on environmental lobbying. These two topics receive a significant share of total lobbying and represent 12% and 38% of total expenditures.

The increase in lobbying is, hence, not concentrated solely on environmental topics. This further suggests that lobbying in general serves to protect profits which become more valuable during a transition to cleaner production. We note no significant decrease in the expenditures allocated to other topics, indicating that there is a high heterogeneity in the topics from which firms reallocate expenditures.

Institutions lobbied. Table 3.A.8 presents the results of the main specification where the dependent variable is the amount of lobbying expenditures targeted at a specific institution. There are over eighty institutions targeted by lobbying from the automotive sector. We first group the institutions into two main categories and then focus on the eight institutions targeted by the largest number of firms. All our results are interpreted taking into account the absence of an effect of household preferences on the *total* amount of lobbying expenditures.

The first panel gathers expenditures at all the targets whose main mandate is related to environmental issues.[25] The second panel focuses on political institutions—that is institutions with elected representatives—in contrast to independent agencies.[26] The following panels focus, respectively, on expenditures targeted at the Department of Energy, the Environmental Protection Agency (EPA), the National Highway Traffic Safety, the Department of Commerce, the Trade Representative, the House of Representatives, the Senate, and the White House.

Panel 1 reveals a positive relationship between environmental concerns and lobbying expenditures on environmental institutions. This result is in line with the previous results on environmental topics. However, we note that the estimates are twice as large, implying that a one standard deviation increase in environmental awareness results in an increase in lobbying expenditures on these targets by a factor of 7.5. Decomposing, we find a modest effect of consumers' attitudes on expenditures targeted at the Department of Energy (Panel 3) and no effect on expenditures targeted at the EPA (Panel 4). These results could be explained by a sample effect or the fact that lobbying expenditures on each individual issue are too noisy to measure the impact of our shocks.

Panel 2 focuses on lobbying targeted at political institutions. Changes in consumers' environmental concerns can be understood as changes in public opinion, and therefore as shifts in the salience of environmental issues for voters. Politicians, therefore, have incentives to adapt to new concerns. On the contrary, independent agencies do not rely on public support and do not see their incentives shift with public opinion. Our estimate suggests that lobbying on political institutions responds positively to contemporaneous exposure to greener consumers. This confirms the intuition that firms are concerned with new environmental regulations, after the shift in environmental attitudes.

3.5 Conclusion

Households' environmental concerns are rising presumably lowering demand for dirty goods. How do firms react to an increase in green preferences? The literature points to the innovation of cleaner technologies as a response (Aghion, Bénabou, et al., 2022). We show that there exists another margin of adjustment: environmental lobbying.

25. These targets are the Environmental Protection Agency, the Department of Energy, the Council on Environmental Quality, and the Federal Energy Regulatory Commission. For simplicity, we refer to this group of targets as environmental institutions in the rest of the paper.

26. The list of political institutions can be found in Appendix 3.C.

More precisely, We examine firm responses in the automotive industry to exogenous changes in household concerns about the environment in the US from 2005 to 2020. Our findings suggest that automotive firms not only innovate cleaner technologies but also increase their lobbying on environmental topics. We argue that the eagerness to innovate clean plus the reduction in profits from dirty goods makes environmental lobbying more valuable to firms. As firms' profits decline, the ability to invest in R&D reduces. Protecting remaining profits becomes especially important for firms to survive a transition to green production. We interpret lobbying on environmental topics as a measure to protect profits and finance research on clean technologies.

In a next step, we plan to scrutinize more closely the heterogeneity of firm responses. We seek to test the hypothesis that the rise in environmental lobbying is driven by firms with a dirtier stock of technologies. Dirtier firms have an increased incentive to prevent stricter environmental regulations in a response to a shift in demand toward clean products. First, those firms are affected more adversely by the shift in demand. Second, these firms need to innovate clean to not lag behind cleaner firms and eventually survive a green transition of the economy. Finally, dirtier firms are hit more by stricter environmental regulation.

Relatedly, we intend to investigate the complementarity and dynamics behind the two dimensions of firm response to a demand shock: clean innovation and lobbying. We expect the initial sizable response in lobbying expenses to decay over time as firms' stock of clean innovation rises. This would confirm our interpretation of lobbying as a means to generate profits in the short run until the firm transitioned to green means of production.

We argue that our results are best explained by a demand channel and not a change in policies. To mitigate concerns that it is in fact a change in regulations on the state level which drives our results, we plan to construct a variable capturing environmental state-level policy changes using public information on state environmental regulations.[27] This dataset will then be available for future research on environmental policies.

27. Information on state-level policies are collected here: https://www.epa.gov/aboutepa/health-and-environmental-agencies-us-states-and-territories.

Appendix 3.A Tables

Table 3.A.1. Summary statistics of the outcomes

	Mean	SD	P25	P50	P75	P95	Max
Lobby (Env. topics) K$	90.04	158.66	0.00	17.61	100.80	394.19	1236.50
Lobby (Total) K$	683.92	842.94	38.01	380.00	1040.01	2237.59	6380.00
K_{clean} (M$)	177.35	347.50	0.00	0.94	141.81	1056.28	1944.64
K_{dirty} (M$)	63.34	141.83	0.00	0.17	18.89	392.75	750.80
K_{grey} (M$)	127.69	305.98	0.00	0.33	31.95	759.65	1641.60

Notes: The table summarizes the main outcomes in our analysis. Data is quarterly average. The first is the average lobbying targeted to environmental topics in thousands of dollars. Second row shows total lobbying expenditures in thousand of dollars. The last three rows are knowledge stock for clean, dirty, and grey innovations, computed using the market value estimation of patents from Kogan et al. (2017) in million of dollars (deflated with CPI). See section 3.2 for a description of the dataset.

Table 3.A.2. Firm lobbying expenditures by target

	Mean	SD	P25	P50	P75	Max
Lobbying	683.92	842.94	38.01	380.00	1040.01	6380.00
- Political Group	555.15	729.38	30.00	261.67	742.51	5224.97
– Senate	253.25	298.55	13.33	136.60	405.14	1725.81
– White House	16.55	41.62	0.00	0.00	5.00	514.61
– House of Representatives	255.33	299.22	13.12	144.93	415.75	1725.81
– Dpt. of Commerce	11.23	23.23	0.00	0.00	10.02	140.91
– Dpt. of Energy	16.33	42.43	0.00	0.00	6.17	531.61
- Agencies	123.03	217.59	0.00	24.44	145.63	1374.44
– EPA	18.61	35.95	0.00	0.00	27.20	431.31
– NHTSA	14.36	30.72	0.00	0.00	10.00	205.86
– USTR	12.38	25.23	0.00	0.00	17.05	347.98

Notes: The table summarizes the distribution of quarterly lobbying expenses for a list of targets in thousands of dollars. The first row reports total lobbying.

Table 3.A.3. Summary statistics by group (quarterly, 2006-2019)

Make	Clean Patents	Dirty Patents	Grey Patents	Lobbying (k$)	Market Share (%)
BMW	10.71	2.52	3.02	131.45	2.32
Daimler	5.12	0.92	2.29	438.45	2.09
FCA	4.46	1.15	1.90	1271.57	11.61
Ford	63.58	25.17	47.96	1786.18	15.03
Geely Automobile Hld.	3.19	0.88	1.83	334.69	0.52
General Motors	47.40	15.48	30.56	2773.49	19.61
Honda	41.50	16.02	11.35	769.56	9.82
Hyundai Kia Automotive Group	79.77	15.35	26.31	437.90	7.01
Isuzu	0.42	0.59	3.76	0.00	0.03
Mazda Motors Gr.	2.00	2.46	9.15	35.57	1.85
Renault-Nissan-Mitsubishi	33.79	6.35	12.58	1115.96	8.46
Subaru Gr.	4.00	0.38	1.00	2.50	2.45
Suzuki	3.69	2.28	0.79	0.00	0.38
Tata Gr.	4.56	0.68	1.26	127.92	0.45
Tesla	3.21			161.07	0.10
Toyota Group	116.10	19.15	43.31	1577.17	15.00
Volkswagen	21.77	3.46	6.67	381.64	3.34

Notes: The table summarizes patenting activity, lobbying, and market share for the make group that we observe in our sample. The first three columns are the average number of patent applications per quarter that are categorized as clean, dirty, and grey. Lobbying is the average lobbying expenses per quarter. The last column reports the average market share of firms over all quarters.

Table 3.A.4. Summary statistics of shocks and exposure shares

Panel A: Shocks summary statistics

	Mean	Std. dev.	p5	p95
$\Delta FIRE_{lt}$	−0.04	0.01	−0.02	0.03
$\Delta FIRE_{lt}$ (w. period FE)	0.00	0.01	−0.01	0.01

Panel B: Shares summary statistics

	Mean	Max
$1/HHI$	719.56	719.56
s_{lt} (%)	0.05	0.44
Treatment Groups	50.00	50.00

Notes: Panel A summarizes the distribution of the instrument (change in wildfire exposure) across states. All statistics are weighted by the average state exposure share s_{lt}. Panel B reports the *effective sample size* computed as the inverse of the Herfindahl index of the average state exposure share s_{lt}. the second line reports exposure statistics in percent. The largest average exposure share is less than 1 percent. Finally, the third row reports the number of treatment groups, which are the 50 states (excluding DC).

Table 3.A.5. Main results

	OLS				IV			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta_8 ln(lobby)$Lobbying (Environment Topics)								
$\Delta_8 ENV^{GT}$	0.34	0.36	0.29	0.27	3.10***	3.08***	3.06***	3.09***
	(0.51)	(0.56)	(0.57)	(0.57)	(0.83)	(0.82)	(0.81)	(0.80)
$\Delta_8 ln(lobby)$ (Total)								
$\Delta_8 ENV^{GT}$	-0.28	-0.60	-0.74*	-0.74*	0.67	0.66	0.70	0.70
	(0.31)	(0.40)	(0.42)	(0.43)	(0.81)	(0.85)	(0.84)	(0.83)
Δ_8 Clean Knowledge Capital								
$\Delta_8 ENV^{GT}$	0.29	0.78	0.93	0.91	2.27***	2.37***	2.33***	2.36***
	(0.39)	(0.62)	(0.57)	(0.56)	(0.71)	(0.65)	(0.66)	(0.64)
Δ_8 Dirty Knowledge Capital								
$\Delta_8 ENV^{GT}$	0.23	0.18	0.13	0.13	-1.09***	-1.11***	-1.09***	-1.08**
	(0.20)	(0.22)	(0.22)	(0.22)	(0.39)	(0.39)	(0.40)	(0.41)
Δ_8 Grey Knowledge Capital								
$\Delta_8 ENV^{GT}$	-1.04***	-0.27**	-0.14	-0.14	0.79	0.77	0.70	0.70
	(0.19)	(0.11)	(0.09)	(0.09)	(0.92)	(0.74)	(0.71)	(0.72)
FE: year-quarter	X	X	X	X	X	X	X	X
Firm Trend	X	X	X	X	X	X	X	X
Lagged Firm Controls	X	X	X	X	X	X	X	X
Lagged Demographic Controls		X	X	X		X	X	X
Lagged Transportation Controls			X	X			X	X
Lagged Political Controls				X				X
N (states - periods)	2000	2000	2000	2000	2000	2000	2000	2000
First-Stage F					46	49	50	50

Signif. codes: ***: 1%, **: 5%, *: 10%

Notes: Column (1) to (4) are OLS, (5) to (8) are shift-share IV estimates. Standard errors clustered at the state level are given in parentheses. all changes are in 2 years differences (8 quarters). ΔENV^{GT} represent the 8 quarters difference in the environmental awareness index that is constructed in Section 3.2. In columns (5) to (8), it is instrumented by the change in exposure to wildfire computed using satellite data from the NASA's FIRMS dataset. Each row is the result of a different regression with a different outcome variable. The unit of analysis are US automotive groups. Outcomes are described in Section 3.2.

Table 3.A.6. Falsification test for the IV regression on lagged patents

	(1)	(2)	(3)	(4)
Lagged $\Delta_8 ln(lobby)$Lobbying (Environment Topics)				
$\Delta_8 ENV^{GT}$	0.61	0.18	-0.27	-0.26
	(0.92)	(0.91)	(1.06)	(1.07)
Lagged $\Delta_8 ln(lobby)$ (Total)				
$\Delta_8 ENV^{GT}$	0.78	-0.11	-0.45	-0.44
	(0.49)	(0.74)	(0.63)	(0.64)
Lagged Δ_8 Clean Knowledge Capital				
$\Delta_8 ENV^{GT}$	0.24	0.54	0.69	0.66
	(0.46)	(0.54)	(0.60)	(0.60)
Lagged Δ_8 Dirty Knowledge Capital				
$\Delta_8 ENV^{GT}$	0.84*	0.72	0.58	0.57
	(0.42)	(0.49)	(0.51)	(0.51)
Lagged Δ_8 Grey Knowledge Capital				
$\Delta_8 ENV^{GT}$	-1.95***	-0.66	-0.46	-0.49
	(0.64)	(0.89)	(0.84)	(0.84)
FE: year-quarter	X	X	X	X
Firm Trend	X	X	X	X
Lagged Firm Controls	X	X	X	X
Lagged Demographic Controls		X	X	X
Lagged Transportation Controls			X	X
Lagged Political Controls				X
First-Stage F	58	53	47	47
N (states - periods)	1500	1500	1500	1500

Signif. codes: ***: 1%, **: 5%, *: 10%

Notes: The table reports coefficients from the shift-share IV falsification tests. We regress the two-year change in the environmental preferences index on lagged changes in outcome. The change in the environmental preference index is instrumented with the change in wildfire exposure computed from NASA's FIRMS dataset. Clustered standard errors at the state level are depicted in parentheses.

Table 3.A.7. OLS and shift-share IV of firms lobbying by topic

	OLS				IV			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta_8 ln(Lobby)$ (Environment)								
$\Delta_8 ENV^{GT}$	0.34	0.36	0.29	0.27	3.10***	3.08***	3.06***	3.09***
	(0.51)	(0.56)	(0.57)	(0.57)	(0.83)	(0.82)	(0.81)	(0.80)
$\Delta_8 ln(Lobby)$ (Taxation)								
$\Delta_8 ENV^{GT}$	-0.93**	-0.84*	-0.87*	-0.88*	1.74*	1.77*	1.81*	1.82*
	(0.45)	(0.43)	(0.45)	(0.46)	(1.00)	(0.97)	(0.94)	(0.94)
$\Delta_8 ln(Lobby)$ (Trade)								
$\Delta_8 ENV^{GT}$	0.67***	0.68**	0.67**	0.67**	6.46***	6.50***	6.49***	6.48***
	(0.25)	(0.28)	(0.29)	(0.29)	(2.04)	(2.02)	(2.02)	(2.03)
$\Delta_8 ln(Lobby)$ (Innovation)								
$\Delta_8 ENV^{GT}$	-0.20***	-0.20***	-0.21***	-0.21***	-0.27	-0.27	-0.27	-0.27
	(0.05)	(0.05)	(0.06)	(0.06)	(0.21)	(0.21)	(0.21)	(0.21)
$\Delta_8 ln(Lobby)$ (Finance)								
$\Delta_8 ENV^{GT}$	0.02	0.02	0.02	0.02	1.09*	1.10*	1.11*	1.11*
	(0.05)	(0.05)	(0.05)	(0.05)	(0.58)	(0.57)	(0.58)	(0.58)
$\Delta_8 ln(Lobby)$ (Manufacturing)								
$\Delta_8 ENV^{GT}$	0.10	0.08	0.08	0.09	6.95***	6.99***	6.95***	6.94***
	(0.13)	(0.11)	(0.09)	(0.09)	(1.54)	(1.52)	(1.53)	(1.53)
$\Delta_8 ln(Lobby)$ (Labor)								
$\Delta_8 ENV^{GT}$	-0.67***	-0.65***	-0.64***	-0.64***	0.65	0.67	0.66	0.65
	(0.19)	(0.18)	(0.19)	(0.18)	(0.48)	(0.48)	(0.47)	(0.47)
$\Delta_8 ln(Lobby)$ (Public Expenses)								
$\Delta_8 ENV^{GT}$	-0.12	-0.08	-0.05	-0.05	-0.16	-0.16	-0.16	-0.17
	(0.08)	(0.08)	(0.07)	(0.07)	(0.22)	(0.23)	(0.23)	(0.23)
FE: year-quarter	X	X	X	X	X	X	X	X
Firm Trend	X	X	X	X	X	X	X	X
Lagged Firm Controls	X	X	X	X	X	X	X	X
Lagged Demographic Controls		X	X	X		X	X	X
Lagged Transportation Controls			X	X			X	X
Lagged Political Controls				X				X
N (states - periods)	2000	2000	2000	2000	2000	2000	2000	2000
First-Stage F					46	49	50	50

Signif. codes: ***: 1%, **: 5%, *: 10%

Notes: Column (1) to (4) are OLS, (5) to (8) are shift-share IV estimates. Standard errors clustered at the state level are given in parentheses. all changes are in 2 years differences (8 quarters). ΔENV^{GT} represent the 8 quarters difference in the environmental awareness index that is constructed in Section 3.2. In columns (5) to (8), it is instrumented by the change in exposure to wildfire computed using satellite data from the NASA's FIRMS dataset. Each row results from a different outcome variable with a different outcome variable. The unit of analysis are US automotive groups. Outcomes are described in Section 3.2.

Table 3.A.8. OLS and shift-share IV of firms lobbying by targeted agency

	OLS				IV			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta_8 ln(Lobby)$ *(All env. Targets)*								
$\Delta_8 ENV^{GT}$	0.18*	0.24**	0.30**	0.31**	7.47***	7.53***	7.49***	7.47***
	(0.10)	(0.12)	(0.12)	(0.12)	(2.04)	(1.98)	(2.00)	(2.00)
$\Delta_8 ln(Lobby)$ *(All Political Inst.)*								
$\Delta_8 ENV^{GT}$	0.10	0.16	0.14	0.13	2.18***	2.19***	2.18***	2.18***
	(0.22)	(0.23)	(0.23)	(0.23)	(0.46)	(0.47)	(0.48)	(0.48)
$\Delta_8 ln(Lobby)$ *(Dpt. of Energy)*								
$\Delta_8 ENV^{GT}$	-0.01	-0.01	0.00	0.00	0.40**	0.41**	0.41**	0.41**
	(0.04)	(0.04)	(0.04)	(0.04)	(0.16)	(0.16)	(0.16)	(0.16)
$\Delta_8 ln(Lobby)$ *(EPA)*								
$\Delta_8 ENV^{GT}$	-0.14*	-0.10	-0.08	-0.08	0.62	0.63	0.64	0.64
	(0.08)	(0.08)	(0.07)	(0.07)	(0.50)	(0.50)	(0.51)	(0.51)
$\Delta_8 ln(Lobby)$ *(NHTS)*								
$\Delta_8 ENV^{GT}$	0.26***	0.35***	0.40***	0.39***	0.20	0.19	0.20	0.20
	(0.07)	(0.08)	(0.07)	(0.07)	(0.61)	(0.60)	(0.61)	(0.62)
$\Delta_8 ln(Lobby)$ *(Dpt. of Commerce)*								
$\Delta_8 ENV^{GT}$	-0.15**	-0.17**	-0.17**	-0.17**	1.19**	1.20**	1.21**	1.21**
	(0.07)	(0.07)	(0.07)	(0.07)	(0.50)	(0.50)	(0.49)	(0.49)
$\Delta_8 ln(Lobby)$ *(Trade Representative)*								
$\Delta_8 ENV^{GT}$	0.07	0.07	0.07	0.07	2.55***	2.57***	2.56***	2.55***
	(0.10)	(0.11)	(0.12)	(0.12)	(0.72)	(0.71)	(0.71)	(0.71)
$\Delta_8 ln(Lobby)$ *(House of Representatives)*								
$\Delta_8 ENV^{GT}$	0.08	0.05	0.00	0.00	2.20***	2.21***	2.21***	2.22***
	(0.15)	(0.16)	(0.15)	(0.15)	(0.68)	(0.70)	(0.71)	(0.71)
$\Delta_8 ln(Lobby)$ *(Senate)*								
$\Delta_8 ENV^{GT}$	-0.10	-0.13	-0.17	-0.17	0.61	0.61	0.61	0.61
	(0.18)	(0.18)	(0.17)	(0.17)	(0.60)	(0.61)	(0.62)	(0.63)
$\Delta_8 ln(Lobby)$ *(White House)*								
$\Delta_8 ENV^{GT}$	0.24	0.24	0.23	0.23	3.20***	3.22***	3.20***	3.20***
	(0.15)	(0.16)	(0.16)	(0.16)	(1.00)	(1.00)	(1.01)	(1.01)
FE: year-quarter	X	X	X	X	X	X	X	X
Firm Trend	X	X	X	X	X	X	X	X
Lagged Firm Controls	X	X	X	X	X	X	X	X
Lagged Demographic Controls		X	X	X		X	X	X
Lagged Transportation Controls			X	X			X	X
Lagged Political Controls				X				X
N (states - periods)	2000	2000	2000	2000	2000	2000	2000	2000
First-Stage F					46	49	50	50

Signif. codes: ***: 1%, **: 5%, *: 10%

Notes: Regression on log change in lobbying expenses categorized by target. (1) to (4) are OLS, (5) to (8) are shift-share IV. Standard errors clustered at the state level are given in parentheses. Independent variable is th change in environmental preferences which is instrumented in columns (5) to (8) by the change in exposure to wildfire computed using NASA's FIRMS dataset. Each row is the result of a different regression.

Appendix 3.B Figures

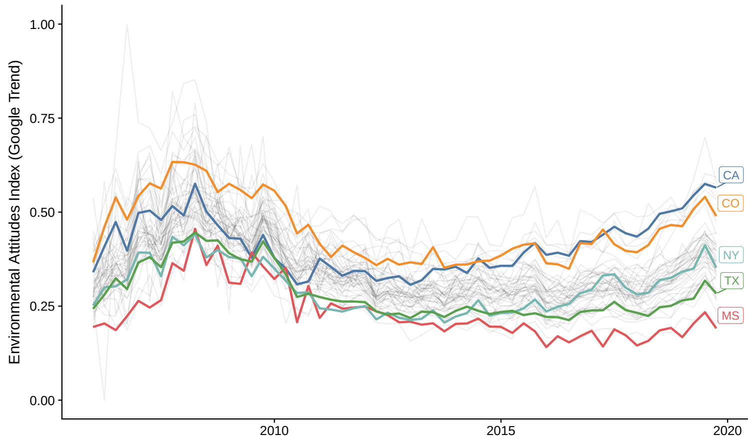

Figure 3.B.1. Environmental preferences index

Notes: This figure shows our measure of environmental preferences build with Google Trends at the state level discussed in Section 3.2. The index is a composite of search frequency for popular keywords related to the environment. Those keywords are *Climate Change*, *Recycling*, and *Electric Car*. Series build on the first component of a principal component analysis. The y-axis is normalized between 0 and 1 for aesthetic purposes.

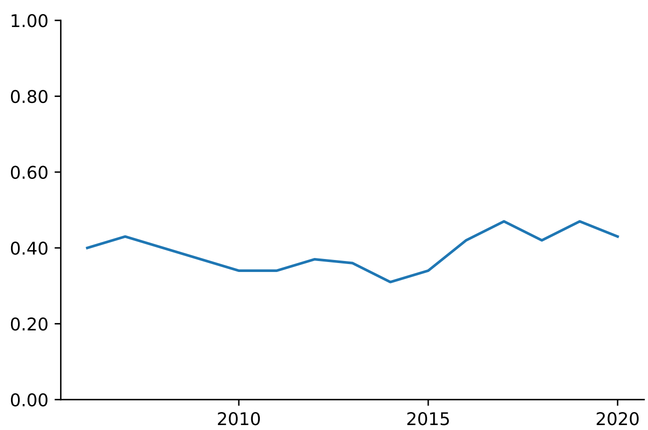

Figure 3.B.2. Gallup survey data: share worried about the environment

Notes: This figure is based on survey data on environmental concerns from the Gallup annual survey for the US (https://news.gallup.com/poll/391547/seven-year-stretch-elevated-environmental-concern.aspx). The precise question asked reads: "For each one, please tell me if you personally worry about this problem a great deal, a fair amount, only a little, or not at all? First, how much do you personally worry about the quality of the environment?" The graph shows the share of participants that worries "a great deal".

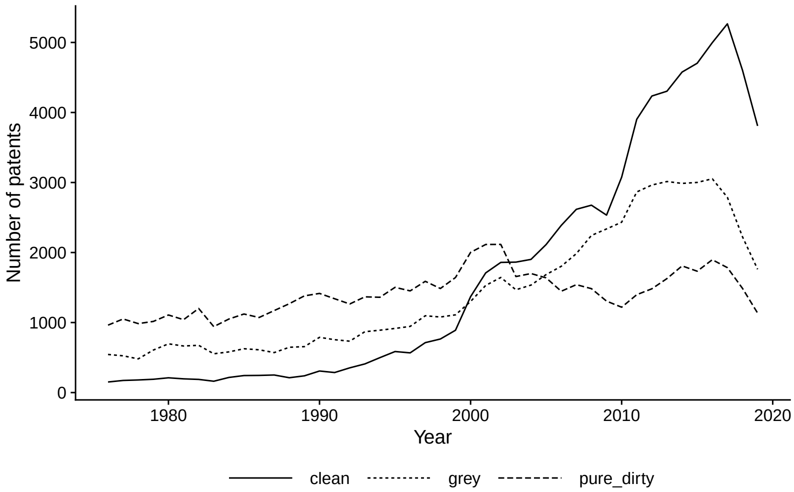

Figure 3.B.3. Number of clean, dirty, and grey patents 1976-2019

Notes: This figure illustrates the number of patent applications filed for 'clean', 'grey', and 'dirty' technologies over time in the US patent office. Dirty patents are defined as innovation related to internal combustion engine, while clean innovations are related to electric, hybrid, and hydrogen vehicle patents. Grey patents are innovations that aim to reduce emissions from fossil fuel vehicles. Source: USPTO, author's calculation

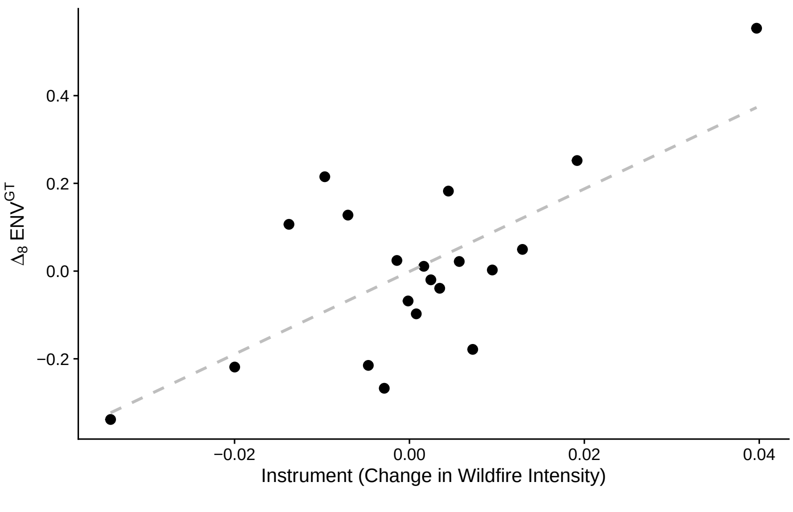

Figure 3.B.4. First-stage estimation shift-share IV

Notes: The figure plots the reduced-form relationship underlying our shift-share IV estimation. It plots the correlation between our instrument (x-axis) and the change in the environmental preference index (y-axis). Each point accounts for 1% of the data. The data is first residualized on a set of firm controls and period fixed-effects. Observations are weighted by the average treatment group exposure share s_{lt}.

Figure 3.B.5. Relative market shares (log Odds-Ratio)

Notes: The figures show a firm's market share s by state relative to the market share of other firms in that very state. We define $p_{il} = P(l|i)$ the proportion of vehicle registered in state l for a make i, and $p_{0l} = P(l|\neg i)$ the proportion of vehicles, not produced by i, registered in state l. Then the log odds-ratio is $r_{li} = log\left(\frac{p_{il}/(1-p_{il})}{p_{0l}/(1-p_{0l})}\right)$. The ratio is positive for makes that are over-represented in a state l and negative if under-represented in the state.

Source: S&P Global, author's calculation

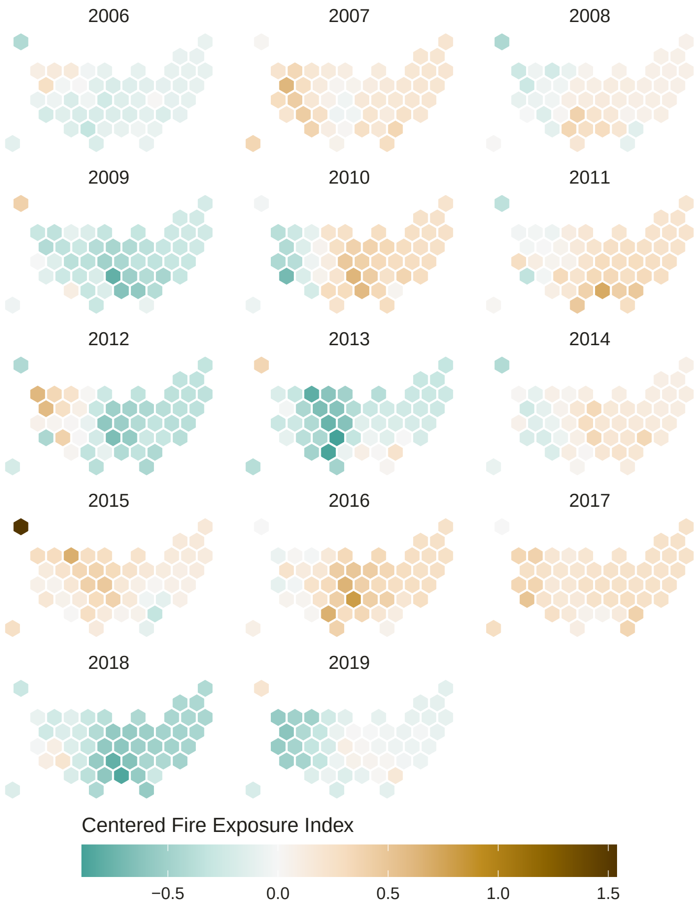

Figure 3.B.6. Centered fire exposure index (yearly average)

Notes: The figures show the wildfire measure. The measure is centered with respect to a yearly linear trend and state×quarter fixed effects. We report the annual average for each state. A brown shade indicates overexposure, blue shades indicate underexposure relative to other states.
Source: NASA's FIRMS, author's calculation.

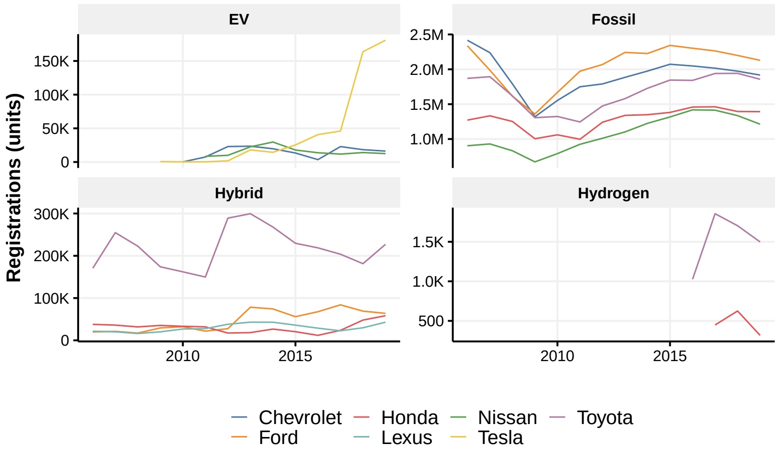

Figure 3.B.7. Number of vehicle registrations in the US

Notes: This figure shows the number of registered vehicle units by quarter in the US. Only makes with more than 5% market share in an engine segment are plotted: top left are electric (EV), top right fossil fuel, bottom left are hybrid (including plug-in hybrid), and bottom right are hydrogen vehicles.
Source: S&P Global, author's calculation

Appendix 3.C Construction of lobbying variables

We find a total of 79 different targets in the lobbying data. We group the relevant issues into the nine following categories:

- Manufacturing: AUT, AVI, TRA, AER, TRU, CPI, MAN.
- Trade: TRD, TAR, FOR.
- Taxes: TAX.
- Environment: ENV, ENG, CAW, FUE.
- Finance: FIN, BAN, BNK, INS.
- Labor: HCR, LBR, IMM MMM, RET.
- Public Expenditures: BUD, DEF, GOV, HOM, ROD, RRR.
- Innovation: CPT, SCI.
- Consumer Safety Product: CSP.

References

Adao, Rodrigo, Michal Kolesár, and Eduardo Morales. 2019. "Shift-share designs: Theory and inference." *Quarterly Journal of Economics* 134 (4): 1949–2010. [127]

Aghion, Philippe, Roland Bénabou, Ralf Martin, and Alexandra Roulet. 2022. "Environmental Preferences and Technological Choices: Is Market Competition Clean or Dirty?" *American Economic Review: Insights* (forthcoming): [115, 119, 123, 124, 128, 130]

Aghion, Philippe, Nicholas Bloom, Richard Blundell, Rachel Griffith, and Peter Howitt. 2005. "Competition and Innovation: an Inverted-U Relationship." *Quarterly Journal of Economics* 120 (2): 701–28. [118]

Aghion, Philippe, Richard Blundell, Rachel Griffith, Peter Howitt, and Susanne Prantl. 2009. "The Effects of Entry on Incumbent Innovation and Productivity." *Review of Economics and Statistics* 91 (1): 20–32. [118]

Aghion, Philippe, Antoine Dechezleprêtre, David Hémous, Ralf Martin, and John Van Reenen. 2016. "Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry." *Journal of Political Economy* 124 (1): 1–51. [121, 123]

Akcigit, Ufuk, Salomé Baslandze, and Francesca Lotti. 2022. "Connecting to power: political connections, innovation, and firm dynamics." Temi di discussione (Economic working papers) 1376. Bank of Italy, Economic Research, and International Relations Area. [118]

Autor, David, David Dorn, Gordon H. Hanson, Gary Pisano, and Pian Shu. 2020. "Foreign Competition and Domestic Innovation: Evidence from US Patents." *American Economic Review: Insights* 2 (3): 357–74. [118]

Bartling, Björn, Roberto A. Weber, and Lan Yao. 2015. "Do markets erode social responsibility?" *Quarterly Journal of Economics* 130 (1): 219–66. [115, 119]

Bénabou, Roland, and Jean Tirole. 2010. "Individual and corporate social responsibility." *Economica* 77 (305): 1–19. [115, 119]

Bergquist, Magnus, Andreas Nilsson, and P. Wesley Schultz. 2019. "Experiencing a Severe Weather Event Increases Concern About Climate Change." *Frontiers in Psychology* 10: [126]

Bloom, Nicholas, Mirko Draca, and John van Reenen. 2016. "Trade Induced Technical Change? The Impact of Chinese Imports on Innovation, IT and Productivity." *Review of Economic Studies* 83 (1): 87–117. [118, 122]

Bombardini, Matilde. 2008. "Firm heterogeneity and lobby participation." *Journal of International Economics* 75 (2): 329–48. [118]

Bombardini, Matilde, Olimpia Cutinelli Rendina, and Francesco Trebbi. 2021. "Lobbying Behind the Frontier." CEPR Discussion Paper DP16390. [118]

Borusyak, Kirill, Peter Hull, and Xavier Jaravel. 2022. "Quasi-experimental shift-share research designs." *Review of Economic Studies* 89 (1): 181–213. [126, 127]

Brandt, Loren, Johannes Van Biesebroeck, Luhang Wang, and Yifan Zhang. 2017. "WTO Accession and Performance of Chinese Manufacturing Firms." *American Economic Review* 107 (9): 2784–820. [118]

Choi, Hyunyoung, and Hal Varian. 2012. "Predicting the present with Google Trends." *Economic record* 88: 2–9. [120]

Dobkowitz, Sonja. 2022. "Labor Income Taxes and Social Responsibility in an Unequal Economy." [119]

Ester, Martin, Hans-Peter Kriegel, Jörg Sander, Xiaowei Xu, et al. 1996. "A density-based algorithm for discovering clusters in large spatial databases with noise." In *kdd*. Vol. 96, 34, 226–31. [120]

Falk, Armin, Peter Andre, Teodora Boneva, and Felix Chopra. 2021. "Fighting Climate Change: The Role of Norms, Preferences, and Moral Values." Working paper. [119]

Giger, Nathalie, and Heike Klüver. 2016. "Voting Against Your Constituents? How Lobbying Affects Representation ." *American Journak of Political Science*, (1): 190–205. [118]

Goldsmith-Pinkham, Paul, Isaac Sorkin, and Henry Swift. 2020. "Bartik instruments: What, when, why, and how." *American Economic Review* 110 (8): 2586–624. [126]

Gullberg, Anne Therese. 2008. "Rational lobbying and EU climate policy." *International Environmental Agreements: Politics, Law and Economics*, (8): 161–78. [118]

Hall, Bronwyn H. 2005. "Measuring the Returns to R&D: The Depreciation Problem." *Annales d'Économie et de Statistique*, 341–81. [122]

Hombert, Johan, and Adrien Matray. 2018. "Can Innovation Help U.S. Manufacturing Firms Escape Import Competition from China?" *Journal of Finance* 73 (5): 2003–39. [118]

Kang, Karam. 2016. "Policy influence and private returns from lobbying in the energy sector." *Review of Economic Studies* 83 (1): 269–305. [118]

Kim, In Song. 2018. " Lobbyview: Firm-level lobbying & congressional bills database." Working paper. *Unpublished manuscript, MIT, Cambridge, MA. A. http://web. mit. edu/insong/www/pdf/lobbyview. pdf Google Scholar Article Location*. [121]

Kim, Sung Eun, Johannes Urpelainen, and Joonseok Yang. 2016. "Electric utilities and American climate policy: lobbying by expected winners and losers." *Journal of Public Policy* 36 (2): 251–75. [118]

Kogan, Leonid, Dimitris Papanikolaou, Amit Seru, and Noah Stoffman. 2017. "Technological innovation, resource allocation, and growth." *Quarterly Journal of Economics* 132 (2): 665–712. [122, 132]

Li, Wendy CY, and Bronwyn H Hall. 2020. "Depreciation of business R&D capital." *Review of Income and Wealth* 66 (1): 161–80. [122]

McKay, Amy. 2012. "Negative Lobbying and Policy Outcomes." *American Politics Research*, (1): 116–46. [118]

Meis-Harris, Julia, Celine Klemm, Stefan Kaufman, Jim Curtis, Kim Borg, and Peter Bragge. 2021. "What is the role of eco-labels for a circular economy? A rapid review of the literature." *Journal of Cleaner Production* 306: 127134. [119]

Meng, Kyle C., and Ashwin Rode. 2019. “The social cost of lobbying over climate policy/.” *Natural Climate Change*, (9): 472–76. [118]

Stephens-Davidowitz, Seth, and Hal Varian. 2014. “A hands-on guide to Google data.” *further details on the construction can be found on the Google Trends page*, [120]

Vermeir, Iris, and Wim Verbeke. 2006. “Sustainable food consumption: Exploring the consumer “attitude - Behavioral intention" gap.” *Journal of Agricultural and Environmental Ethics* 19 (2): 169–94. [119]

Vona, Francesco, and Fabrizio Patriarca. 2011. “Income inequality and the development of corrective technologies.” *Ecological Economics* 70 (11): 2201–13. [119]

Vosen, Simeon, and Torsten Schmidt. 2011. “Forecasting private consumption: survey-based indicators vs. Google trends.” *Journal of Forecasting* 30 (6): 565–78. [120]

West, Robert. 2020. “Calibration of Google Trends time series.” In *Proceedings of the 29th ACM International Conference on Information & Knowledge Management*, 2257–60. [120]