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The effect of near-term policy choices on long-term greenhouse gas transformation pathways

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ABSTRACT

To successfully limit climate change, today's greenhouse gas mitigation policies should encourage reductions that will continue for decades. History suggests, however, that some policy reforms lead to societal changes that persist over the long-term while others fade without long-term effect. Current climate policy literature provides little guidance on how today's policy choices can successfully shape long-term emission reduction paths. To address such questions, this paper introduces a new agent-based, game theoretic model designed to compare how near-term choices regarding alternative policy architectures influence long-term emission reduction trajectories. Drawing on political science literature that identifies the characteristics of policies that persist over time, this simulation for the first time integrates the co-evolution of an industry sector, its technology base, and the shifting political coalitions that influence the future stringency of the government's emission reduction policies—all as influenced by the initial choice of policy architecture. An exploratory modeling analysis that represents deeply uncertain phenomena such as the future potential for innovation and the behavior of future governments draws policy-relevant conclusions from this model. The analysis finds that near-term choices regarding the architecture of a carbon pricing policy may affect long-term decarbonization rates significantly. In particular, such rates are higher if program revenues are returned to firms in proportion to their market share, thus, creating a political constituency for continuing the carbon pricing policy. More generally, the analysis provides a framework for considering how near-term policy choices can affect long-term emission transformation pathways within integrated assessment models.

1. Introduction

Limiting climate change requires large-scale transformation of energy and other socio-economic systems (Clarke et al., 2014). To hold global average temperatures within 2 °C of pre-industrial levels would require sustained decarbonization rates of 3–4 percent per year—quite rapid by historical standards (Guivarch and Hallegatte, 2013). Not surprisingly, there exists a large gap between the policies most governments have put in place and the scale of change many argue is needed (Victor et al., 2014). This study offers a decision-analytic, simulation modeling framework for evaluating how politically actionable, near-term policy choices might affect long-term carbon emission trajectories.

Current literature on integrated assessment modeling (IAM) reflects this distance between action and aspiration. IAM analyses can sketch contours of greenhouse gas transformation pathways produced through future technology mixes and deployments which hold climate change within proscribed bounds (Clarke et al., 2014). Such studies can also suggest policy mechanisms that might help drive such transitions over the long-term such as a steadily rising, globally harmonized carbon tax (Nordhaus, 2008). But such work provides little guidance on what today's policy makers might do to cause such pathways to be followed: What choices today might increase the likelihood that any carbon tax would rise over time? Numerous studies also provide guidance on specific policies – such as investments in efficiency and fuel switching – which may reduce near-term emissions. While the reductions achievable from such polices generally fall short of those required to achieve long-term ambitions, the transformation pathways literature suggests that near-term progress can help catalyze subsequent larger changes by reducing the scale of emissions reductions required in the future and reducing near-term investment in high-emitting capital that could "lock-in" future emissions. Nonetheless, other than the reasonable claim that cost-reducing R&D will encourage future technology adoption and the suggestion that policy uncertainty hinders low carbon investment, the current integrated assessment literature does not satisfactorily grapple with the

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mechanisms by which near-term policies might – or might not – shape long-term emission reduction paths.

This study offers a new perspective on this question by combining several strands of literature. First, it adopts a view of longer-term policy analysis that focuses on the long-term consequences of near-term decisions (Lempert et al., 2003, 2009; Lempert and Light, 2009). That is, rather than predicting or characterizing long-term emissions paths, this study employs decision-analytic methods designed to identify and evaluate near-term policy actions that would reduce 21st century emissions over a wide range of plausible futures (Lempert et al., 2006; Lempert and Collins, 2007). Second, this study draws on the political science literature of policy persistence which identifies the attributes associated with policy reforms that persist over long periods of time (Patashnik, 2003). This literature, along with a game-theoretic model describing how competition among firms and the government can shape policy outcomes (Grossman and Helpman, 1994), suggests mechanisms that decision-makers might exploit in the near-term to affect long-term emission pathways. Third, this study uses agent-based, evolutionary economic formalisms (Dosi et al., 2006; Gerst et al., 2013a) to instantiate in simulation models these mechanisms that might relate near-term actions to long-term emission reductions, along with numerous and deeply uncertain socio-economic factors that also affect this connection between action and consequence.

In particular, this study builds on Patashnik's policy persistence work which reviews historical cases of new legislation put into place in areas such as social protection and deregulation during a brief period of focused public concern and identifies the conditions that lead the policy reform to endure over time after public concern dissipates (2003). New policies are more likely to persist when they create supportive and enduring political constituencies.

Our analysis envisions policy makers in a national government with a brief window of opportunity to implement a greenhouse gas (GHG) reduction policy (e.g., pass legislation) with the ultimate goal of eliminating those emissions. Subsequently, the policy will evolve along paths no longer under the control of those initial policy makers as firms and future governments negotiate over the carbon price. We examine how policy makers might use their policy window to choose a policy architecture that increases the chances that their long-term goal will be achieved, in part by causing societal transformations that will yield future conditions supportive of these goals (Lempert et al., 2003; Lempert, 2007).

This study employs an agent-based evolutionary economics model (Ciarli et al., 2010; Nelson and Winter, 1982; Saviotti and Pyka, 2004; Silverberg and Verspagen, 1994), based on that of Dosi et al. (Dosi et al., 2006, 2010), to evaluate the policy-implications of such dynamics. Previous versions are described in detail in two earlier reports (Isley, 2014; Isley et al., 2013). In particular, we have added a game theoretic component based on the work of Grossman and Helpman (1994) which describes the competition among firms as they attempt to influence the stringency of future GHG regulations. The climate policy literature emphasizes the importance of tracking often complex feedbacks among different components of coupled natural and human systems. This study focuses on a generally neglected, but potentially crucial class of feedbacks relevant to the long-term persistence of emission reduction policies—those among the government and political coalitions that results from the interaction of firms, technology, and evolving market structure.

This agent-based simulation both contains many uncertain parameters and aims to project hard-to-predict phenomena such as innovation and evolving political coalitions. To manage such deep uncertainty, we use an exploratory modelling approach (Bankes, 1993) which seems well-suited to the type of simulation employed here (Lempert, 2002). In particular, exploratory modelling regards simulation models not as predictive engines but as tools for mapping assumptions onto consequences without privileging one set of assumptions over another. This study draws analytic methods and concepts from Robust Decision Making (RDM) (Lempert et al., 2003), an exploratory modelling-based approach, to identify near-term policies that increase emission reduction rates over a range of assumptions regarding the future behaviour of firms and the government, future technological opportunities and future economic conditions.

This study contributes to a growing literature on climate-related transformation (Denton et al., 2014) and sustainability transitions (Voss et al., 2009) suggesting that shifting to a low carbon society would not only require large-scale changes in technology but would also disrupt existing political arrangements and ways of life (O'Brien and Sygna, 2013; O'Brien, 2012). In contrasting such transformation to incremental change, this literature notes that some interests may oppose what others see as the vital societal changes needed for sustainability. Similarly, this literature emphasizes the challenges of lock-in, both at the level of technologies as well as at the level of socio-economic regimes, as well as the potential importance of policy windows that offer an opportunity for significant policy change. This study examines such themes albeit in the narrow context of interactions among firms and the government which might witness the restructuring of a previously high-emitting industry sector. In so doing, this study offers two novel contributions. First, we provide a quantitative analysis of mechanisms that may drive and hinder transformation. Second, we take a decision–actor approach in contrast to a systems view. The latter view extends over time and emphasizes the connections among different societal spheres, such as practical, political, and personal (O'Brien and Sygna, 2013) or technical, market, and behavioral, but does not privilege any particular actor in the system. The former, in focusing on how a particular agent, acting at a particular time, can influence the evolution of the system aims to contribute more directly to the evaluation of policy-relevant decision options.

Overall, this work provides an initial, quantitative, decision-analytic evaluation of how near-term choices about greenhouse gas regulatory architectures can affect the long-term co-evolution of technology, market shares, and political coalitions that affect the stringency of greenhouse gas regulation. This study also suggests how this general decision-analytic framework might prove broadly useful to the study of climate-related transformations and sustainability transitions.

Section 2 describes our integrated assessment model, the following describes the analysis and the final section offers some conclusions.

2. An evolutionary, game-theoretic model of firms and the government

This study employs an "XLRM" framework (Lempert et al., 2003) to help organize the structuring of the decision, the factors considered in the analysis and the subsequent model development and exploration. The letters X, L, R, and M refer to four categories of factors to be explored in RDM-related analyses: **Metrics (M)** are measures of merit used to express policymakers' goals; **Policy levers (L)** are near-term actions that policymakers can take to pursue their goals; **Exogenous uncertainties (X)** are factors outside policy makers' control that may determine if their near-term actions achieve their goals; **Relationships (R)**, represented by the simulation model, describe how the policy levers perform, as measured by the metrics, under the various uncertainties. Table 1 summarizes the factors considered in this analysis. We will now use this XLRM structure to describe our modeling activities.

Table 1
Factors explored in this analysis

Exogenous uncertainties (X)	Policy levers (L)
Government: Weight given to different market outcomes; actual valuation of emission reductions. Firms: Carbon price expectations; R&D allocation; capital purchasing decisions; pricing rules. Technology: Favorability of future technology landscape; effectiveness of firms' R&D investments; technology availability to entrants. Economy: Price elasticity of aggregate demand; depreciation rate; initial capital distribution; cost of new capital; entrant characterization; exit conditions; interest rate.	Policy architecture choice: • Carbon tax - Plain - With grandfathering - With LTCRs • Cap and Trade - Full auction - Free incumbent permits - Conditional allocation
Relationships (R)	**Measures (M)**
Evolutionary economics model (Dosi et al., 2006; Gerst et al., 2013a), with new or modified modules to include • Two types of R&D (to improve carbon intensity as well as labor productivity) • Price clearing market • Game theoretic competition among firms and government over carbon price • Stochastic entry/exit mechanism	• Decarbonization rates • Carbon price • Rate of improvement in labor intensity

2.1. XLRM: policy levers

Our analysis assesses the long-term implications of policymakers' near-term choice of policy architecture. We assume at the start that the national government implements a carbon control program wherein the policy architecture is fixed but the value of the underlying market instrument may vary over time. The architecture includes decisions concerning preference for pricing versus quantity-based controls, the treatment of existing capital and how program revenue will be allocated. At each subsequent time step, the government chooses a new carbon tax or permitted carbon cap. For simplicity, this analysis assumes that the government values carbon reductions at a constant price. However, the actual carbon price is influenced by the lobbying activities of market actors who are primarily driven by individual expectations about whether they would benefit from a carbon price higher or lower than the government would otherwise set. Overall, we assume that today's decision makers can choose the policy architecture but that they cannot control the future carbon price which may evolve along a path significantly different than intended.

Table 1 lists six different policy architectures that explore different combinations of price and quantity instruments along with alternative types of incentives for firms to favor a carbon reduction program. Each combination of instruments can help spur emissions reductions and technological innovation (Parson and Kravitz, 2013; Requate, 2005). The first three architectures use price instruments in the form of a carbon tax applied to every unit of emission (plain tax), a grandfathering policy in which the carbon tax is not applied to existing capital for ten years and a carbon tax which includes long term carbon rights (LTCR). With the LTCR policy the government auctions the right to emit an amount of carbon equal to 20% of baseline emissions. Following Polborn (2010), we assume these rights are purchased primarily by the financial sector, which then sells those rights to firms every year and participates in the political competition as an independent lobby. For simplicity, we also assume a single auction in the first period, even though in practice such auctions would occur periodically over time. The analysis also explores three quantity instruments. The first is a fully auctioned cap and trade system; the second distributes free permits to incumbent firms for ten years based on their baseline market share; and the third, a conditional permit allocation, distributes 20% of the government's desired cap to firms based on their prior period market share (Hahn and Stavins, 2010).

Note that the set of price and quantity instruments each consist of an unadorned policy architecture, another with special treatment of capital stock existing at the beginning of the simulation and a third that aims to returns revenues from the carbon price to firms. While clearly a subset of the actual choices facing decision makers, the policy choices considered here help explore much of the interesting dynamics that affect how initial institutional designs may affect the long-term evolution of carbon prices.

2.2. XLRM: metrics

Three measures of merit are used to compare the ability of the alternative policies to achieve long-term goals: (1) the long-term decarbonization rate of the economy (2) the deviation of the carbon price from the desired price and (3) the labor intensity improvement rate. The first measure addresses the ability of alternative policies to catalyze a significant transformation of society's energy system. The second provides a measure of the importance of the political feedbacks in this analysis in shifting the actual carbon price away from the socially optimal value. The third provides a rough indication of tradeoffs between carbon reductions and other social goals.

2.3. XLRM: relationships

The model is designed to evaluate the long-term consequences of the alternative policies by linking modules representing the market, its constituent firms with their technological change, associated lobbies, a bank and the government. Climate impacts only enter the model through the carbon price. The model is stylized and not based on any particular form of representative government. The fundamental assumption is that the government can be represented by a single welfare maximizing entity whose objective function includes possible lobbying contributions from competing market actors.

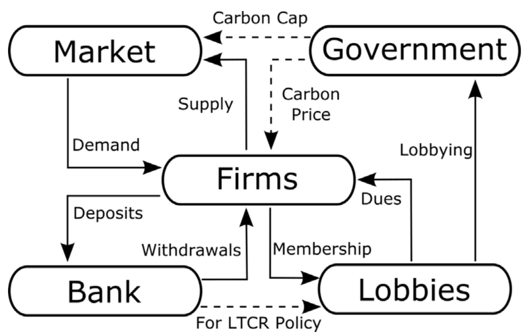

Fig. 1. Model relationships (dashed lines represent policy-specific relationships).

The model, described in detail in Isley (2014) and Isley et al. (2013), is also summarized using the ODD protocol (Grimm et al., 2006, 2010) in an online supplemental. Fig. 1 provides a high level representation of the model components and their relationships. The following events constitute a single time step in the model:

1. New capital is delivered to firms and existing capital is depreciated
2. Firm entry and exit takes place
3. Information on effects of carbon price on current period firm profits is updated
4. Firms choose a lobby and a negotiated carbon tax or permit amount is reached
5. Firm market shares are determined (and the permit market, if it exists, is simultaneously cleared)
6. Firms decide on resource allocation
7. Technological innovations and imitations are awarded
8. The bank assesses interest payments and delinquencies

Each component will be described briefly below with details relegated to the previously mentioned sources.

3. Market, firm and bank dynamics

The market consists of firms with heterogeneous capital and expectations that compete by selling a single final good. For cap and trade policies, the simulation also includes a permit market. Demand for goods is exogenously specified and varies according to a constant elasticity curve. Standard market clearing assumptions determine equilibrium prices. The quantity demanded fluctuates with the equilibrium price which is heavily influence by technological improvements and changes in the carbon price.

Firm behavior follows largely from Dosi et al.'s agent-based, evolutionary formalism (Dosi et al., 2006; Gerst et al., 2013a). Firms produce final goods using one or more capital stocks. Capital is defined by its labor and carbon intensity, with labor a proxy for all non-carbon variable costs. Firms offer to sell at a fixed markup over their non-carbon costs of production.

Firms keep all their financial assets in an independently modeled bank. The bank enforces accounting rules that ensure all transactions are conducted correctly. This is an implementation detail but an important one that helps ensure the model is working as desired. Firms are allowed to borrow from the bank up to a multiple of their prior period revenue with any outstanding debts removed from this sum and account balances added to it. The bank assesses interest due from each firm and any firm with insufficient funds is removed from the simulation.

The evolution of industry structure is influenced by firm entry and exit. Firms exit when they go bankrupt (their available funds become insufficient to pay required expenses) or when their market share falls below a minimum value. The probability of entry is proportional to the expected profits over some exogenous time horizon. Expected profits are strongly influenced by available technologies. This entry/exit process leads to high levels of market turnover when technological change is abundant and relatively low levels when technology is constant. Without decreasing returns to scale, monopolies can form. While they generally do not persist due to technological innovation, a parameter in the model can be set to divide in half any firm that exceeds a threshold market share.

Firms invest in capital in order to meet market demand. Each unit of capital embodies technology that determines the plant's carbon and labor intensity. A firm may have multiple units of capital stock at any given time, each using different technology.

Technological capabilities represent the key factor shaping the environment in which firms compete. Each firm's technology capability consists of available combinations of carbon and labor intensity that can be included in new capital. A firm can increase its set of available technologies by either innovation or imitation, both enabled by the firm's spending on R&D (a firm's capabilities never decrease.) Each time period, firms allocate their innovation R&D between improving labor or carbon intensity based largely on their expectation of future carbon prices which take into account the government's past adherence to its stated carbon price preference. Each new innovation offers an incremental change to a firm's current lowest unit cost technology. The magnitude of this change is determined by random draws from two related beta distributions, one for carbon-saving another for labor-saving innovations. The span of each distribution increases proportionally to the amount the firm invests in carbon and in labor R&D. The maximum possible span for each distribution, attainable only if all resources go towards its dimension, are important exogenous uncertainties that characterize the opportunities for technological advancement in any given future.

Each time period, firms make two key decisions: (1) which technologies to choose for any new capital stock they employ and (2) how to allocate available R&D funds. New capital results from expansion and replacement. When a firm's demand outstrips its supply, it attempts to expand by purchasing additional capital. Firms replace existing capital when more cost-effective new capital passes a simple payback period rule. In either case, firms choose the technology available to them that is expected to yield the lowest production costs given anticipated carbon prices (i.e., the technology with the lowest projected unit cost).

Over time, firms pursue heterogeneous strategies for R&D allocations and achieve diverse R&D outcomes. These in turn yield heterogeneous production costs and thus potentially divergent interests in the level of future carbon prices.

3.1. Lobbying framework

The government sets the carbon price in a game-theoretic negotiation with the firms, modeled as a menu-auction as described by Bernheim and Whinston (1986) and popularized in the context of public policy decision making by Grossman and Helpman (1994) (and see also Lange and Polborn (2012)). Firms and the government are myopic while negotiating and only consider how their welfare is affected by the price of carbon for the current period. All participants have complete and accurate information regarding the effects of carbon prices on their current period welfare, including information about the profit of every agent in the model for any given carbon price.

Each time period, the firms divide themselves into two lobbies, one favoring lower and the other higher carbon prices relative to the government's stated preference. Total demand decreases as the carbon price rises, but the slope of the supply curve can also increase, resulting in higher market-clearing prices and the potential for firms with low carbon intensity to profit from an increased carbon price. When the LTCR policy is in effect, the bank operates as a third lobby with profits increasing linearly in the price of carbon up to the point at which the demand for carbon emissions drops below the bank's supply of LTCR's. Profit then varies with the elasticity of demand for carbon.

The government's welfare is a weighted sum of four monetized market outcomes: (1) emissions reductions valued at the government's preferred carbon price, (2) government revenue derived from the chosen program, (3) production losses (as a proxy for employment) valued as the change in industry revenue caused by the program and (4) increases in the cost of buying the goods at the new equilibrium price. The weights used in this welfare function are important policy parameters; their influence is explored later in this analysis. Because our analysis is from the perspective of today's decision makers and we do not know how future planners may assign priorities, we model these weights as "X"s, exogenous uncertainties in Table 1 rather than "L"s—policy levers. However, the discussion at the end of Section 5 also explores the weights as levers.

Each lobby calculates its willingness to pay for a higher/lower carbon price by summing the change in profit of its members. The menu-auction framework results in the government choosing a carbon price that maximizes the sum of its own welfare combined with that of all the lobbies. The lobbies requisition the funds owed the government from each member firm in proportion to its market share. The amount changes every period and varies with the simulation inputs but is typically only a few percent of revenue for any given firm.

A large and growing body of climate change literature focuses on coalition formation (Hoel and Zeeuw, 2010; Burger and Kolstad, 2009; Brechet and Eyckmans, 2012), in particular the conditions under which coalitions form, the incentives to join them and their stability over time. While consistent with this literature, this analysis differs in focusing on coalitions of firms joining to lobby their national government rather than nations joining international agreements to limit greenhouse gases. In addition, the model assumes firms can shift between the low and high carbon-price lobby at any time but must join one or the other. While chosen for simplicity, this assumption implicitly hold the fruits of lobbying to not be entirely a public good so that members of a lobby could discourage free-riding by excluding nonmembers from benefits not explicitly included in the model. However, the rule specifying which lobby is chosen by a firm is consistent with the finding in the literature that the marginal return of joining a coalition is an important driver of coalition formation (Eyckmans and Finus, 2006).

Most of the model components have already been applied in energy and climate related applications (Gerst et al., 2013a,b). However, since the lobbying component has not been previously applied in this area, we applied it to a geographic and temporally disaggregated model of the U.S. electric power industry and found that it successfully reproduced the lobbying surrounding the 2009 Waxman–Markey climate legislation in the US Congress (Isley, 2014).

The model was written in Java and utilizes the MASON agent-based modeling framework (Luke et al., 2005). Each run took between 5 and 15 s, depending on the complexity. In particular, runs with a lobbying bank or high technological change resulted in longer run times. All runs were performed on Amazon Elastic Cloud Compute (EC2) servers using the c4.8×Large instance type with a processor speed of 2.9 GHz.

3.2. Model limitations

This model clearly has important limitations. First, the policy architecture is set once at the start of the simulation and is then immutable. This is clearly an abstraction, not worse (and perhaps better) than the more usual implicit assumption that a decision maker may optimize an emissions policy over many centuries. Future work might usefully relax the assumption of an immutable policy architecture, for instance considering how lobbying might affect the number of years of grandfathering or of permits distributed freely to firms. Such extensions would exploit the applicability of the menu–auction framework to situations with more than one policy lever.

The lobbying framework neglects the possibility of free-riding. In addition, the government and firms are myopic and only consider current period effects. Having firms consider many periods into the future is possible but would present additional modeling challenges. Firms in the model do forecast future carbon prices by adjusting the government's declared carbon price trajectory based on past observations of the difference between the declared and actual carbon price. An alternative would be to use rational expectations, though it is debatable if this would yield more accurate insights.

We have not included any policies that favor labor or recycle revenue to households (an income tax reduction or household carbon tax credit.) These would require a richer treatment of the political economy than offered by the menu–auction model.

Finally, the only influence of climate change in this model is the presence of a constant, non-zero socially optimum cost of carbon. While this study's results are consistent with our earlier work that considered a rising social cost of carbon (Isley et al., 2013), future work could usefully include a much richer set of interactions including the effects of climate impacts on demand and the preferences of future government authorities, voters, and consumers.

4. XLRM: exogenous uncertainties

In this analysis, thirty-nine parameters govern the model's behavior. These parameters, whose values are uncertain, include those specifying the government's welfare function; the initial distribution of capital and technology; how firms adjust expectations over time, allocate their R&D, and enter and leave the market; the potential for future innovation; and the price elasticity of demand. The simulation results are stochastic to the extent that innovation depends on random draws from distributions describing the potential for R&D improvements. Each set of inputs was repeated 50 times to account for stochasticity (further repetitions did not change the results significantly), with the final outcome ascribed to that input vector being the average over all repetitions. As described in the online supplemental, the variance in decarbonization and labor intensity improvement rates can and do vary with the input parameters, with the main drivers being the size of the carbon and labor R&D beta distributions. The policy results reported here are significant compared to this variance. See Appendix A for the parameter values as well as the online supplemental for the relevant equations.

5. Analysis

We present the modeling results in three stages of increasing complexity. First, we present time series results for a single representative case in order to illustrate the model dynamics. Second, we present a full factorial design over two critical and uncertain parameters to demonstrate the impacts of alternative policy architectures. Then we explore over the entire range of uncertain parameters to complete the policy comparison.

5.1. Representative model run

An example helps demonstrate the simulation's dynamics. Using the inputs noted in Appendix A,Fig. 2a shows the market share evolution for each firm in a representative simulation. Each line, representing one firm, changes color in accordance with the firm's profit maximizing carbon price. A firm that desires a very high carbon price is green, while a firm that prefers low values is red.

Fig. 2b shows the corresponding evolution of prices over time. Due to the technological heterogeneity present at the beginning of the simulation, many firms seek a high carbon price. This causes the price to rise, particularly when a large entrant joins the market near year ten. But with the high price, high carbon intensity firms begin to exit the market. With their exit comes a reduction in heterogeneity and, thus, less chance for the remaining firms to profit from high carbon prices. With less market share to gain from the worst polluters, the remaining firms must instead compete amongst themselves. The high carbon price lobby collapses in years 20–30 of the simulation, along with the carbon price. After this initial shake out, the carbon price gradually rises over the remainder of the simulation as heterogeneity returns to the market. The heterogeneity returns because with low carbon prices the firms' carbon intensity diverges with their differing carbon R&D investment strategies and the differing stochastic outcomes from this investment.

Overall, heterogeneity is a necessary but insufficient condition for higher carbon prices. For instance, large incumbent firms could suddenly encounter firms with equal labor intensity but much improved carbon intensity. Heterogeneity would increase, but carbon prices could drop as the incumbent firms seek to prevent their challengers from benefiting from their low carbon technology. However, a lack of heterogeneity will always lead firms to unanimously lobby for low carbon prices. In order for heterogeneity to lead to an industry preference for higher carbon prices, the profit gained by firms seeking the high price must be greater than that lost by others.

The model's sensitivity to firm heterogeneity is supported by evidence from actual climate change policy negotiations. Markussen and Svendsen (2005) examined the effectiveness of lobbies in influencing the outcome of the European Union cap and trade program. They found that the electric power industry lobby had a much harder time presenting a unified message since some producers were carbon-free (e.g., nuclear and hydroelectric) while others were very carbon intensive. In contrast, the iron and steel industry was relatively homogeneous and presented a unified message. The pulp and paper industry was similarly homogeneous and reacted much like the iron and steel sector.

Fig. 2 displays a pattern that consistently appears in the full set of runs summarized in the Section 5.2—the carbon price is strongly influence by the heterogeneity of carbon intensity among firms. High heterogeneity can create incentives for low carbon intensity firms to seek a high carbon price, but high prices tend to drive high carbon intensity firms out of the market thus reducing heterogeneity and the political constituency for a high carbon price. As discussed below, the heterogeneity among firms is driven by the extent of technological opportunities available from R&D investments to improve carbon and labor intensity. In addition, the impact of firm heterogeneity on the carbon price, and, thus, long-term decarbonization rate, can also depend on the near-term choice of policy architecture.

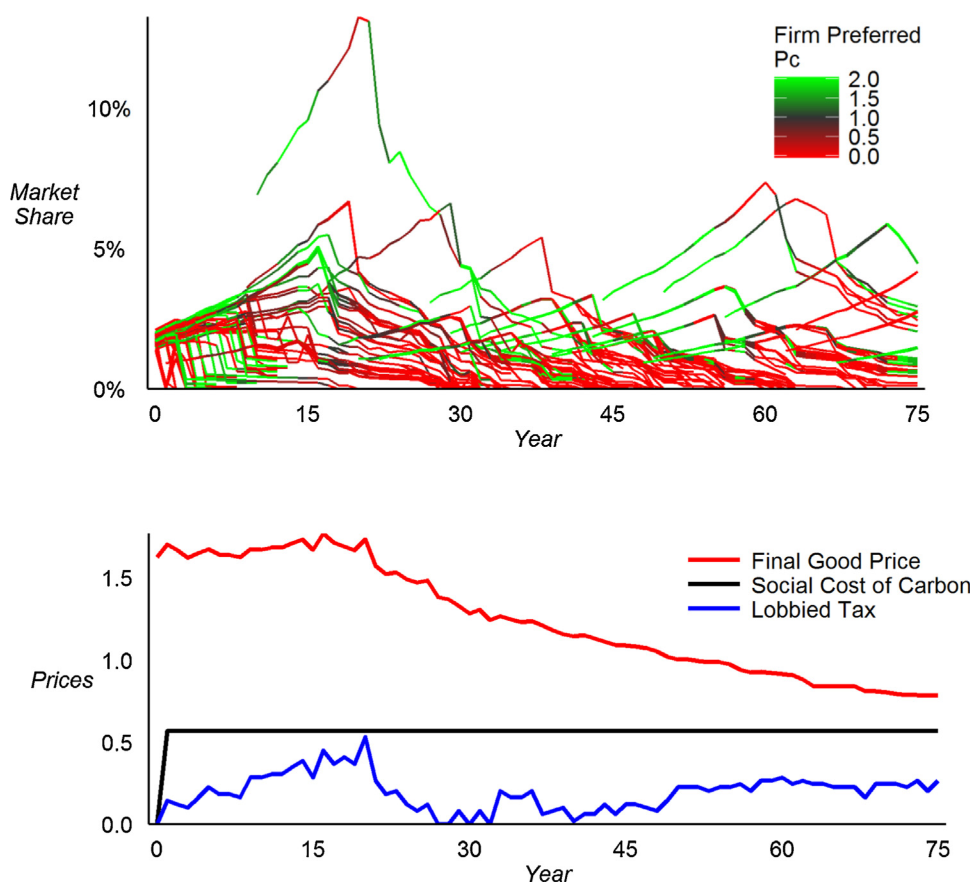

Fig. 2. Upper panel (a) shows market share evolution with each line representing changes in a single firm's carbon price preference; the lower panel (b) shows the evolution of prices for a single representative model run.

5.2. Initial policy comparison

We conducted a scaled regression coefficients sensitivity analysis (Saltelli and Annoni, 2010) to determine the most important parameters using the same 6000 case experimental design described in the Section 5.3. To conduct this sensitivity analysis we scaled all the inputs and outputs (transforming them to have mean zero and unit variance) and then found a simple linear fit to the data. The resulting coefficients provide a rough indicator of the average magnitude and direction of effect of the inputs on the output. Input parameters related to the potential for technology improvements in carbon and labor intensity, the elasticity of demand, and the weights in the government welfare function had the greatest potential effect on long-term decarbonization rates (Isley, 2014).

Based on this sensitivity analysis, Figs. 3 and 4 show the performance of alternative policies over combinations of two of these most important uncertain parameters – the carbon and labor R&D span – holding the other parameters constant at the values shown in the appendix. The carbon R&D span specifies the upper limit of the beta distribution describing the potential for carbon intensity improvements for new innovations. A value of X% means that a new innovation will be at most X% less carbon intensive than the technology upon which the new innovation is based. Actual improvements will be less since a firm's R&D rarely all goes towards carbon intensity innovation and stochastic draws generally occur near the middle of the distribution. The same applies to labor R&D. Each parameter varies over a range of 0–50% in steps of 5% (with 0% replaced by 1% to better bound the plot) resulting in 121 data points. The other uncertain parameters are all held constant at values shown in Appendix A.

Fig. 3 shows the results for these inputs in a cap-and-trade regime in which the lobbying mechanism is disabled. The figure shows the labor intensity improvement rate (LIIR) and decarbonization rate (DCR) for each of the 121 input combinations. The mostly horizontal lines correspond to lines of constant labor R&D opportunity, vertical lines to carbon R&D opportunity. The percentages shown along the edge of the grid denote these R&D levels. The figure is very similar to a traditional contour plot but rather than have inputs on the axes and draw lines of constant output, we have outputs on the axes and draw lines of constant input. For this analysis, the results are much clearer when presented in this manner.

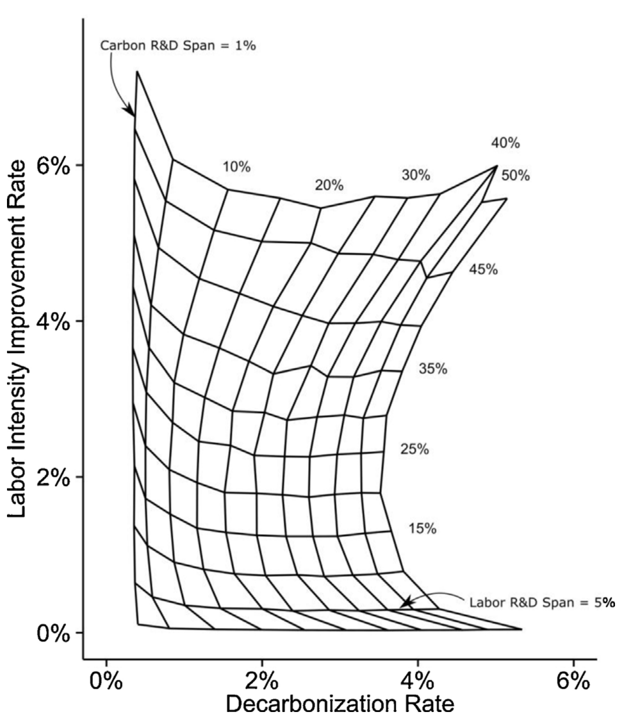

Fig. 3. Intensity improvement rates for futures with no lobbying. Labels on the top and side denote lines of constant carbon and labor R&D span, respectively.

Fig. 4 shows the changes when lobbying is active. The black mesh is a fully auctioned cap and trade system while the grey mesh is a cap and trade system with 20% of permits conditionally allocated to firms based on their prior period market share.

The location and magnitude of lobbying-induced changes in either outcome can be seen by comparing either of the wire mesh policies with the no-lobbying background figure (from Fig. 3). In future with low carbon or labor R&D opportunities, lobbying can significantly reduce the decarbonization rate compared to the case without lobbying. However, when the technological opportunities are sufficiently high, the lobbying has a smaller effect on the decarbonization rate. Note also that in the presence of lobbying, a near-term policy architecture that includes a revenue sharing mechanism can significantly increase long-term decarbonization rates.

5.3. Policy Comparison Over All Uncertainties

The results in Figs. 3 and 4 vary only two of the 39 parameters representing X factors in Table 1. We now evaluate all six policies over a much wider sampling of the uncertainties in order to more comprehensively compare the policies' comparative long-term consequences and the factors on which these consequences most importantly depend. We created an experimental design of 6000 plausible combinations of values for the 39 uncertain model input parameters and repeated the entire design for each of the six policies for a total of 1.8 million runs. Reasonable bounds for some parameters, like the depreciation rate, were found in the literature. Other parameters (e.g., those characterizing new innovations) are specific to this model. The experimental design for these parameters was chosen to yield plausible ranges of important outcomes, such as the decarbonization rate, in the no policy case (Isley, 2014).

In addition to the parameters describing technological opportunity, government welfare function weights and the elasticity of demand also prove important to long-term decarbonization rates. Fig. 5 compares the consequences of the near-policy choices over the full range of uncertain parameters. Note that a fully auctioned cap and trade system and a plain carbon tax have the same outcomes (though modeled separately) and so only the carbon tax results are shown. The figure organizes each of the four components that define the government's preferences into high and low ranges. The upper left cell represents low weight on each of the four components, which indicates a government heavily influenced by lobbying. In contrast, the lower left cell is a government with low weights on revenue and emissions, but high weights on production and avoiding price shocks. Within each cell, the different shapes (circle, box, diamond, upward triangle, and downward triangle) show the combination of long-term decarbonization and labor productivity improvement rates that result from each policy (plain tax and fully auctioned cap, tax with long-term carbon permits, conditional allocation, tax with grandfathering, and free incumbent permits, respectively). The shapes are shown for two demand elasticities: inelastic white (0.1 to 0.5) and more elastic black (0.5 to 2). Each point in the figure is the average of about 185 cases (6000 cases per point, divided into 16 government types and two elasticity bins) and thus averages over the range of technology parameters shown in Figs. 3 and 4.

Note first the range of the DCR axis, whose upper value of 4% can be compared to the fastest ever observed decarbonization rate of

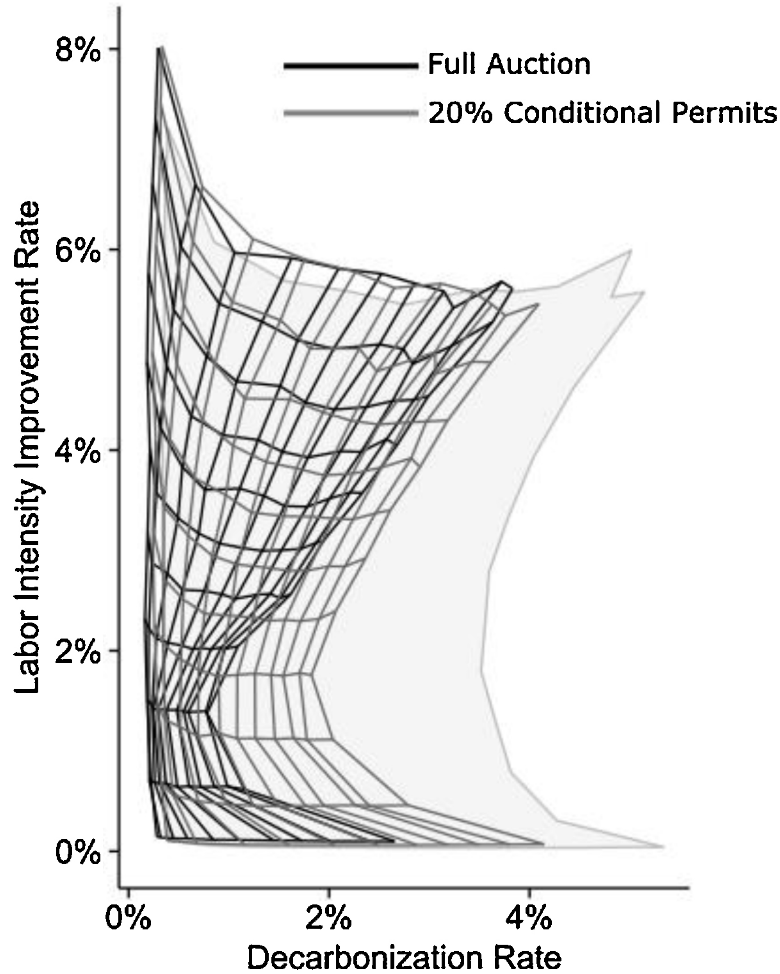

Fig. 4. Intensity improvement rates for futures with no lobbying (grey background), fully auctioned permit system (black grid), and 20% conditional permits (grey grid)

an industrialized country, that of 4.6% annually over a five year period experienced in France from 1980 to 1985 as this country made a rapid shift to nuclear energy (Guivarch and Hallegatte, 2013). The figure also shows the trade-off between DCR and LIIR. The latter decreases as firms direct resources towards carbon R&D.

The spread of symbols within each cell for a given (black or white) elasticity shows the long-term importance of near-term choice of policy architecture. Where the points of the same shading cluster together the near-term policy choice has little long-term consequence. Where they lie apart, near-term choices can have long-term consequences. Consider, for instance, the upper left hand cell in which the government is particularly responsive to lobbying. When total demand is inelastic (white symbols) the two policies that return carbon price revenues to firms, in proportion to their market share (tax with LTCR and conditional allocation), have significantly higher decarbonization rates than the four policies that do not return carbon price revenues to firms. The effect is similar, though less pronounced for futures with more elastic demand.

We had expected that the two policies that exempt capital existing at the start of the simulation from the carbon price (tax with grandfathering and free incumbent permits) to affect the long-term decarbonization rate. But looking across all the cells in Fig. 5 suggests they do not. Depreciation of existing capital, demand growth requiring new capital, and new entrants to the market all reduce the share of existing capital in the industry, reducing the incentives for owners of such capital to join the high carbon price lobby. In addition, new firms without grandfathered capital lobby aggressively to keep the carbon price low. Note that the policy which freely distributes carbon permits to incumbents for ten years in a cap and trade system (free incumbent permits) has decarbonization rates similar to, but slightly higher than the tax policy with grandfathering, because in the cap and trade system the incumbents' permits are transferable, not subject to depreciation, and, thus, persist better over time which gives their owners a larger incentive to favor high carbon prices.

The two policies that return carbon price revenue to firms have the largest influence on long-term decarbonization rates. Similarly to Polborn's (2010) results, the tax with LCTR policy architecture creates long term carbon rights that give investment banks that purchase these rights an incentive to seek higher carbon prices. The cap and trade policy that returns revenue to firms based on market share (conditional allocation) transfers revenue from high carbon intensity to low carbon intensity firms, thus giving the latter a stronger incentive to seek higher carbon prices.

Fig. 5 also indicates that any difference in long-term decarbonization rates resulting from the choice of alternative near-term policy architectures depends strongly on the government's welfare function. The two quartets of graphs in the top left and bottom right of the figure all represent cases in which the government places comparable weight on price stability and on revenue collected from the carbon price. In the top left quartet, the government places low value on both outcomes; in the bottom right the government places high value on both. In the off-diagonal quadrants, the government values price stability and revenue

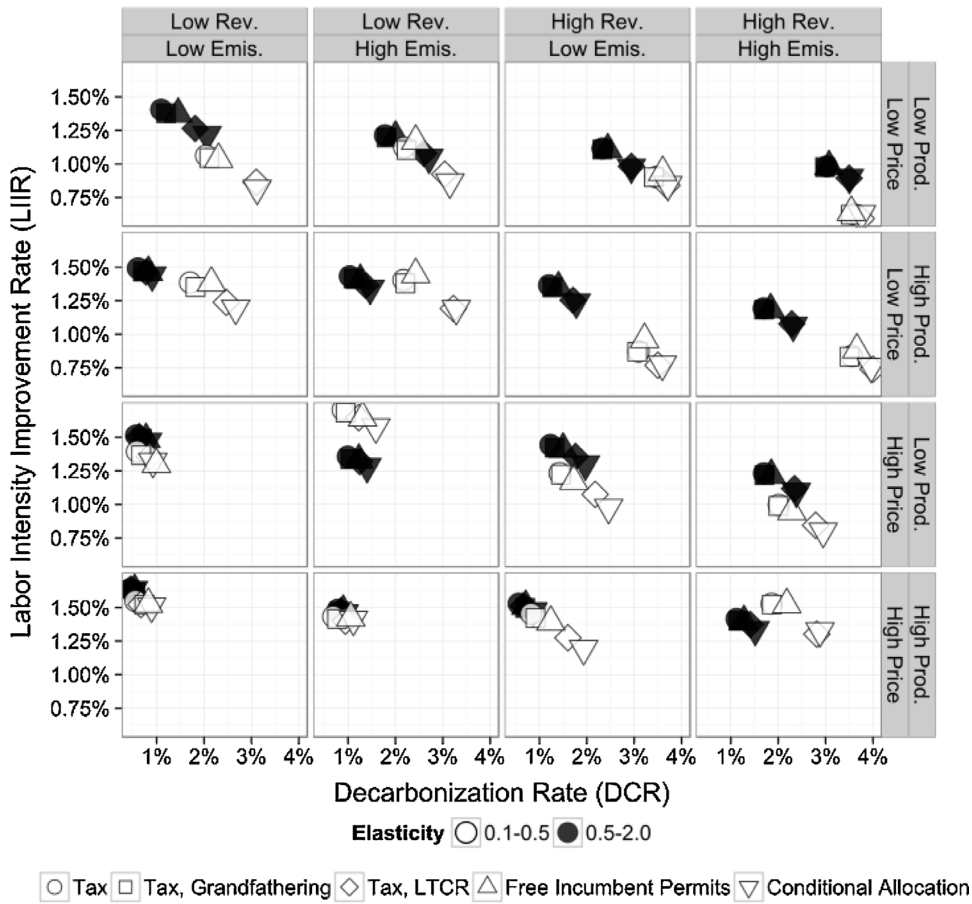

Fig. 5. Long-term rates for decarbonization and labor intensity improvement for each carbon price policy architecture, 16 alternative government welfare functions and two levels of total demand elasticity.

differently, with a high value on revenue in the upper right and a high value on price stability in the lower left.

The figure indicates that the choice among alternative near-term policy architectures influences long-term decarbonization (and labor productivity improvement) rates most when the government values price stability and carbon revenues similarly. When the government values these outcomes unequally, the choice of near-term policy architecture proves less consequential. This results from the asymmetric nature of lobbying with respect to elasticity. As the carbon price increases in an inelastic market, the final good price goes up translating into a large price increase and a small consumption decrease. In this situation, if the government values price and revenue unequally then one component dominates and lobbying is less effective. For elastic markets, the situation would normally reverse—carbon prices would lead to large quantity changes but mild price changes. However, in elastic markets the industry is far more opposed to carbon prices because price increases lead to overall demand reductions making it harder for firms to profit by taking a larger slice of a smaller pie. This makes the skewed nature of the government welfare function less pronounced with regards to the final outcomes. This also explains why across a wide range of government values the choice of near-term policy proves more consequential when total demand is inelastic than when demand is more elastic.

The discussion so far treats the government's welfare function as an exogenous uncertainty. However, it is interesting to also consider the government's welfare function as a potential policy lever. Different government agencies have differing missions, mandates, and organizational cultures which can all be interpreted as differing welfare functions in the context of this analysis. Our analysis considers policy makers to have a brief window of opportunity to choose a carbon-price policy architecture the consequences of which play out over time. One choice available to policy makers is the government agency that will administer the carbon price. While likely pushing the menu-auction framework beyond its intended scope of applicability, we can interpret the different cells of Fig. 5 as representing alternative choices regarding the agency that will administer the carbon price. For instance, the results in the second cell from the right in the upper row, in which the government places high value on emission reductions and low value on revenues, price stability and production, might represent our simulation's best representation of the consequences of giving an environmental agency, such as the U.S. Environmental Protection Agency, authority over the carbon price. In contrast, the neighboring cell to the left, in which the government places high value on revenues and low value on emissions, employment and price stability, might represent our simulation's best representation of the consequences of giving a budget agency, such as the U.S. Treasury, authority over the carbon price.

6. Policy implications

Many recent assessments emphasize a need for near-term action to address climate change (IPCC, 2014). Studies of public opinion measure voters' readiness for such action (Leiserowitz et al., 2011). History suggests, however, that some policy actions taken at a time of public attention result in societal changes that persist for decades, while others fade away without much long-term impact (Patashnik, 2003). Clearly policies aimed at limiting climate change will only meet their goals if they persist for decades. Nonetheless, much of the integrated assessment literature and the policy discussions it informs focus on policies – such as emission reduction targets binding in the long-term or carbon taxes that rise for decades – outside of the direct control of

Table A1
Input values for the analyses conducted.

Parameter name	Example run (Fig. 2)	Full factorial (Figs. 3 and 4)	Range (Fig. 5)	
			Min	Max
Startup				
Ini. firm count	58	75	50	100
Ini. carbon mean	0.66	1	0.5	1.5
Ini. carbon span	0.17	0.5	0	1
Ini. capital span	4.10	2.5	0	5
Ini. labor span	0.09	0.05	0	0.1
Ini. labor mean	1			
Ini. capital mean	10			
Final tick	75			
Initial funds multiplier	2			
Depreciation				
Depreciation	3.5%	5.0%	0%	10%
Entry and exit				
Max steps at min market share	4	3	1	5
Public use delay	8	5	0	10
Entrant recoup horizon	7.42	7.5	1	10
Monopoly limit	83%	60%	20%	100%
Entrant count distribution mean	5.34	7.5	5	10
Minimum entrant capital ratio	0.056	0.075	0.05	0.1
Entrant capital ratio span	0.062	0.075	0.05	0.1
Minimum market share*	0.01%			
Entrant ini. funds	2			
Government forecast				
Entrant generator**	BEG	BEG	BEG	NEG
Lobbying				
Govt. price weight	0.54	1	0	2
Govt. production weight	0.03	1	0	2
Govt. emission weight	1.94	1	0	2
Govt. revenue weight	0.43	1	0	2
Upper limit multiplier	3.57	4	3	5
Govt. desired carbon price	0.57	1	0	2
Market clearing				
Elasticity of demand	0.74	0.5	0.1	2
Capital price	5.76	5.5	1	20
Firm resource allocation				
Utilization	0.94	0.89	0.8	0.98
Payback period	5.98	5.00	1	10
Markup	0.30	0.25	0.1	0.4
Firm Pc memory	0.73	0.795	0.6	0.99
Firm Pc lobby bias	0.48	0.3	0.1	0.5
RD turnover	0.04			
RD split	0.5			
Pc avg. period	2			
Technology				
Ini. innovation ratio	0.59	0.5	0	1
Ini. imitation Ratio	0.40	0.5	0	1
Carbon R&D lower bound	0.00	0	−0.02	0.02
Carbon R&D span	0.24	var	0.1	0.4
Labor R&D lower bound	0.01	0	−0.02	0.02
Labor R&D span	0.06	var	0	0.1
Carbon R&D alpha	4.86	5	1	10
Carbon R&D beta	3.33	5	1	10
Labor R&D alpha	2.43	5	1	10
Labor R&D beta	9.46	5	1	10
Bank				
Debt sales ratio	2.59	2	0	4
Interest rate	3%	5.25%	0.5%	10%
Max consecutive late payments	2			

* This value was divided by the initial number of firms for each run.
** BEG/NEG: Estimate/ignore possible entrants in the forecast.

today's policy makers. These analyses say little about how actions taken today might influence long-term greenhouse gas reduction paths.

This study represents a first attempt at filling this gap. We introduce a novel simulation that considers the coevolution of an industry sector, its technology base, and shifting political coalitions that influence government policy. The analysis considers today's policy choice to be the policy architecture that will set any future carbon price. In particular, we consider how alternative choices regarding the structure of a carbon tax or cap and trade program affect the ongoing, game theoretic competition among the government, with its desired carbon price trajectory, and firms that would benefit from the price being higher and lower than that planned by the government. Each firm also makes investments in research and capital, based in part on their expectations of future carbon prices, that affects what future carbon price would benefit them the most.

The analysis finds that near-term choices about policy architecture can significantly affect long-term decarbonization rates. In particular, a carbon control program in which some portion of revenues are distributed back to firms generates long-term decarbonization rates about a percentage point higher than a carbon price whose revenues are not returned to firms. In both cases, a higher carbon price shrinks the total demand for the firms' output. But a policy architecture that returns revenue to firms allows those with a lower than average carbon intensity to gain market share from a higher price and thus creates a constituency for a rising price. In contrast, some near-term choices about policy architectures have little long-term effect. For instance, grandfathering existing capital has little effect in our analysis because the incumbent firms that benefit are countered by new entrants with new capital that need a low carbon price to compete.

The analysis finds that the elasticity of demand can prove an important influence on the persistence of the policies considered. Policy choice may be particularly important in the electric power industry whose demand is relatively inelastic. Other sectors may yield results different than those in this study. The analysis also suggests that the government's preference among different factors potentially affected by a carbon price – emissions, revenue, price shocks, and employment – may significantly affect long-term carbon prices. This suggests that the near-term choice of which government agency administers the carbon price may also affect its long-term trajectory. As one potential implication, an important difference between a carbon tax and cap and trade policy instruments may thus be the mission and values of the government agency which administers them.

The existence of constituencies favoring a rising carbon price requires heterogeneity in carbon intensity among firms. But a high carbon price drives high carbon intensity firms out of business and thus reduces the heterogeneity. When the carbon price is low, heterogeneity in carbon intensity can return among firms, thus, allowing the price to rise. The government can only keep the price high if a steady stream of technological innovation maintains firm heterogeneity.

This study considers only a narrow range of processes from the transformation and sustainability literature but suggests rich opportunities for further research. Future studies could consider the effects of consumer opinion, along with that of firms, on government policy and could examine how near-term policy choice might affect the formation of political constituencies affecting the persistence of climate policies on the international as well as national level. Such extensions would require richer representations of both the climatological and political environments than were possible in this study. Future research could also include multiple industry sectors, the economic effects of using carbon price revenues to reduce other taxes, mitigation policies beyond those focused on carbon prices and include the effects of uncertain climate impacts on the social cost of carbon (as in Isley et al., 2013). In addition, future studies might evaluate policy architectures by how closely their carbon price hews to the social optimum in any future rather than the decarbonization rate alone.

But most simply, this analysis suggests that the propensity of various constituencies to influence the government's future choices about the carbon price can strongly affect the long-term emissions reduction path and the success of alternative near-term policy choices. This potentially important and policy-relevant feedback is neglected in most integrated assessment models despite that fact that any successful greenhouse gas reduction policy will need to persist for decades and that today's policy makers may have more influence over policy architectures than they do over other factors – such as long-term emission reduction targets and carbon price trajectories – that often represent the focus of much modeling and policy debate.

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Appendix A.

Model Inputs

Table A1 shows the input values used to populate the model and run the analyses discussed in this study. The first column gives the parameter name, the second shows the values used to generate the output shown in Fig. 2, the next column provides the inputs used to create Figs. 3 and 4, while the last two columns provide the endpoints of the ranges used to generate the findings shown in Fig. 5.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2015.06.008.

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