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# Political competition and renewable energy transitions over long time horizons: A dynamic approach☆

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ABSTRACT

Climate change mitigation requires sustainable energy transitions, but their political dynamics are poorly understood. This article presents a general dynamic model of renewable energy policy with long time horizons, endogenous electoral competition, and techno-political path dependence. We calibrate the model with data on the economics of contemporary renewable energy technologies. In doing so, we discover transition dynamics not present in economy-energy models, which ignore politics, or in formal political economy models, which ignore long-term technological dynamics. We show that the largest effects of partisan ideology on policy occur when the competing parties disagree on the importance of energy policy. In these cases, the less ideological party appeases the more ideological one, while the more ideological party attempts to appease the electorate. The results demonstrate that political dynamics could have large effects on the development of renewable energy and carbon dioxide emissions over time, influencing the ability of countries to reach various climate mitigation trajectories.



## 1. Introduction

In the study of environmental political economy, *sustainable energy transitions* have emerged as a central topic of interest (Jacobsson and Lauber, 2006; Schwoon, 2006; Verbong and Geels, 2007; Walz, 2007; Agnolucci, 2008; Schmidt and Marschinski, 2009; Loorbach, 2010; Dangerman and Schellnhuber, 2013). To a surprising extent, such transitions have already begun in forerunner countries, especially in the case of renewable energy.[1] While the International Energy Agency predicted in the year 2000 that renewables will continue to play a negligible role in the energy economy at least until 2020 (IEA, 2000), reality has proven this pessimistic prognosis wrong. According to the World Development Indicators, in 2012 Denmark generated 48% of its electricity from non-hydroelectric renewables. In Germany, the share was 19%. Even in the United Kingdom and the United States, which have begun investing in renewables much more recently, the shares were 10 and 6%, respectively. The rapid growth rates of renewables and the policies underpinning them highlight the importance of transitions to renewable energy as a core theme in political science.

Understanding renewable energy transitions requires paying attention to politics (Torvanger and Meadowcroft, 2011; Aklin and Urpelainen, 2013). Fossil fuels continue to dominate the energy landscape largely because of a market failure, whereby their negative externalities are not priced (Unruh, 2000). Due to centuries of industrial development based on fossil fuels, they enjoy tremendous structural advantages over less mature, sustainable alternatives such as solar and wind power. This problem of "carbon lock-in" is further compounded by fossil fuel subsidies. Therefore, government action is needed for a correction of incentives and to level the playing field (Unruh, 2002; Loorbach, 2010). Indeed, a large body of literature in public policy argues that the promotion of clean technology is a key strategy in climate mitigation (Barrett, 2009; Dangerman and Schellnhuber, 2013; Smith et al., 2014).

The problem of implementing a renewable energy transition is a dynamic one, and governments cannot tie the hands of their future successors. The problems of time-inconsistency and path dependence (see Pierson, 2000; Jacobs, 2011) are widely recognized among scholars as essential for mitigating climate change and promoting renewable energy (Kline, 2001; Sandén and Azar, 2005; Hovi et al., 2009; Laird and Stefes, 2009; Nilsson et al., 2011; Levin et al., 2012). However, government incentives to promote a renewable energy transition are still poorly understood. In particular, the literature does not present models of the long-run political dynamics of renewable energy transitions. Our

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[1] In general, sustainable energy transitions also include other changes, such as energy conservation. Our focus is on renewable energy.

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goal is to present such a model and use it to sharpen the social science of sustainable energy transitions more generally.

How, then, does political competition influence renewable energy transitions over long time horizons? This article presents a dynamic model that can explain the renewable energy policies of different types of governments as circumstances change over long periods of time. The key feature of the model is the inclusion of technological learning and electoral competition between two governments. Similar to Aklin and Urpelainen (2013), one of the governments is 'green' (pro-renewables) and the other 'brown' (anti-renewables). The strength of ideology is defined in terms of a deviation from the cost-minimizing benchmark for renewable energy. For example, the green party is willing to incur some additional energy costs to protect the environment and mitigate climate change.

Governments accede to power through regular elections decided by a majority vote. When in power, each party formulates policy strategies dynamically, taking into account the fact that current policies influence both electoral outcomes and, thanks to technological learning, the future attractiveness of clean energy to the opposing government. Specifically, we model technological learning by assuming that the marginal cost of renewable energy capacity investment decreases with the current share of renewables in the fuel mix. Although governments cannot tie the hands of their successors, current policy decisions can shape future incentives to invest into renewable energy. Therefore, political competition between parties is an important component of strategic renewable energy policy.

To make the model realistic, we use parameter estimates characterizing the economics of energy technologies observed in the U.S. and globally, including the learning curves for wind and solar energy. The dynamic model allows us to simulate energy policy trajectories over long periods of time. In practice, we evaluate outcomes for a period of 50 years. This period is long enough for a dynamic analysis, yet not so long that a scenario analysis is virtually impossible due to unknown and unpredictable factors. Because these calibrations focus on the electricity generation, the model is best suited for an analysis of renewables in the power sector.

Our main finding is that *political competition and partisan ideology exert a powerful influence on renewable energy development when the two parties show different levels of ideological commitment*. To understand this logic, consider the case of a highly ideological green party. Such a green party is ready to make renewable energy investments at very high costs. To prevent a very costly 'crash' program in renewable energy development, the brown party accommodates and compromises by making modest investments into renewable energy when in office. Therefore, the green party's strong political commitment to renewable energy, along with a willingness to impose very high costs on the society, allows it to force the brown party to compromise. Over time, these investments generate technological learning and thus reduce the cost of renewables, further contributing to the energy transition.

This logic is largely robust to endogenous elections, whereby voters consider energy issues in supporting the two political parties. While we see that public opinion about renewable energy can be a powerful incentive for the two parties, the central logic of dynamic strategies remains intact. In this regard, we reaffirm the result in Aklin and Urpelainen (2013) that, even if energy policy is a minor issue for the electorate, political competition is critical to understanding renewable energy transitions. At the same time, we also report the surprising result that strongly ideological parties are often more sensitive to electoral considerations than their less ideological counterparts. While this result appears counter to intuition initially, the logic behind it is powerful: a party with a strong ideological commitment to certain energy policy cannot afford to lose elections, as such a party suffers heavily from any deviations from its preferred energy policy.

These findings are significant for two bodies of literature. First, they add to the analytical study of sustainable energy transitions. There is by now a large body of detailed case studies on this phenomenon, including impressive longitudinal studies that track policy dynamics over many decades (Verbong and Geels, 2007; Hvelplund, 2013; Smith et al., 2014; Rosenbloom and Meadowcroft, 2014). Several scholars have also proposed both analytical (Aidt, 1998; List and Sturm, 2006; Aklin and Urpelainen, 2013; Millner et al., 2014; Schmidt and Marschinski, 2009) and computational (Schwoon, 2006; Fuss et al., 2008; Schwarz and Ernst, 2009; Zeppini and van den Bergh, 2011) models of environmental and energy policy. What we add is a dynamic analysis that captures both political competition and technological change in one unified framework focused on renewable energy. By doing so, our model can prove useful to empirical studies of energy transitions, as it provides guidance as to how we should account for the endogeneity between policy and available technological capabilities. We also shed new light on the ways in which political competition is shaped by long time horizons and processes of path dependence, with potentially important implications for understanding transitions to renewable energy. For example, our result on asymmetric ideological preferences suggests that in two-party systems such as the United States or United Kingdom, a future pro-renewable coalition could achieve significant gains in political bargaining and competition with a less ideological opposition. In today's American politics, where the anti-renewables coalition is itself ideologically committed, the outlook is much less bright.

The findings are also important for the growing body of literature on climate policy. In this literature, the question of domestic political incentives to enact low-carbon policies has drawn a lot of attention, with scholars emphasizing factors from public opinion (Shwom et al., 2010; McCright and Dunlap, 2011; Ansolabehere and Konisky, 2014) to interest groups (Gullberg, 2008; McCright and Dunlap, 2003) and economic side benefits (Rabe, 2004). The decarbonization of energy is an important component of strategies to avoid long-term climate disruption. Our results show how partisan ideology, political competition, and public opinion interact in a dynamic setting over long periods of time. The relative importance and effects of these different variables are modified by dynamic strategies, and our model is flexible enough to allow scholars in various disciplines to explore the dynamic implications of their premises and frameworks.

The article is organized as follows. We first present the key elements of our model, with technical details given in the online appendix. We then present our primary analytical results on the role of political competition in renewable energy transitions over long periods of time. Before we offer a concluding discussion, where we evaluate our analysis and summarize the limitations of the dynamic model, we illustrate the substantive significance of our findings by simulating renewable energy trajectories that are consistent with climate mitigation pathways in the IPCC's Fifth Assessment Report.

## 2. A dynamic model of political competition and renewable energy policy

The technical details of the model are presented in the online appendix, and here we focus on conveying the intuition behind the analysis. To summarize, we consider a model with two parties. Both parties aspire to minimize the costs of energy production, but the "brown party" additionally has an ideological commitment to fossil fuels (for example, a political party could prefer coal because party activists live in communities that depend on coal mining for livelihood) and the "green party" to renewable energy (for example, many party activists could be environmentalists). For example, in the context of American politics today, one could say that Democrats are the green party with a weak ideological commitment to renewable energy, while Republicans are the brown party with a strong ideological commitment to sustaining the fossil-fuel economy. This model of political competition allows us to evaluate the effects of ideological divergence on renewable energy transitions over long periods of time under various electoral settings. Because the model includes technological learning over time, we can also investigate processes of path dependence.

In developing the model, we draw game-theoretic inspiration from Aklin and Urpelainen (2013), who present a two-period model of sustainable energy transitions under political competition. In their model, political parties respond to external shocks, such as energy price surges, by selecting the level of sustainable energy deployment. High levels of sustainable energy deployment produce future political constituencies with a vested interest in renewable energy policy, such as wind turbine and solar panel manufacturers. In terms of the energy-economic model, we draw on the energy-economy specification provided by Fuss et al. (2008). Their model offers a simple but flexible approach to assessing renewable energy and fossil fuel investments in a dynamic setting. The model specification includes capital costs, operating costs, fuel costs, technological change, and path dependence. Finally, our dynamic optimization strategy for the two political parties is based on McKibbin et al. (1987). Their approach allows political parties to consider the economic structure, electoral outcomes, and – most importantly – the political goals and strategies of the other party.

### 2.1. Energy-economy model

The cost of energy production includes the installation and operating costs of power plants. Therefore, it is a function of the share of renewables – actual generation, not just capacity – in the energy mix, and of new investments. The share of renewables at time $t$ is denoted $s_t$. Both fossil fuels and renewable energy carry capital and operating costs, but only fossil fuels require payments for fuels. The energy production costs are realized in each period. Specifically, the energy production cost at any given time $t$ is given by the following:

$$\begin{aligned}\Gamma\left(s_t, q_t, P_t^f\right) = {} & F(1-s_t)QP_t^f \\ & + O^f((1-s_t)Q) + O^c(s_tQ) \\ & + C^c(q_t, s_t) + C^f(q_t)\end{aligned} \tag{1}$$

This is a standard accounting equation, where the first row represents the cost of fossil fuel. The second row represents operating costs and the last row the capital costs. $F$ is the quantity of fossil fuel per unit energy, Q is the total energy production which is assumed to be constant, consumed and $P_t^f$ is the price of fossil fuel inputs, such as coal. Next, $O^f(\cdot)$ and $O^c(\cdot)$ are the operating costs of fossil fuel energy production and renewable energy production, respectively, as a function of the energy production from those sources, as determined by $s_t$, the renewable energy share. Both fossil fuels and renewables have annual operating costs, while only fossil fuels have an additional input cost. The terms $C^f(q_t)$ and $C^c(q_t,s_t)$ represent the total capital costs, respectively, of fossil and renewable energy investment. Endogenous technological learning is captured by the decreasing cost of new clean energy capital, $C^c(q_t,s_t)$, as $s_t$ increases.[2]

Because of technological learning, the installation costs of renewable energy decrease as a function of installed capacity (McNerney et al., 2011). When parties make renewable energy investments, they also reduce the cost of future investments due to economies of scale and learning effects (Jaffe et al., 2005; Klaassen et al., 2005; Nemet, 2006; Jamasb, 2007; Söderholm and Sundqvist, 2007; Shum and Watanabe, 2007). This assumption captures the notion that immature technologies, such as renewable energy, gain competitiveness over time. We calibrate the relationship between accumulated capacity and installation cost using global data of solar and wind power investments and costs provided by Nemet (2006). However, within any given period, we assume capital investments to have an increasing cost on the margin. This assumption reflects both installation capacity constraints and the idea that learning cannot be instantaneous. Crash investments into renewable energy are more costly than gradual investments over time.

In each period, the only decision made by the policymaker – the party in power – is the level of additional investment into (or divestment from) renewable energy capacity. We assume that the policymaker can affect renewable energy production through policy instruments such as subsidies, feed-in tariffs, tendering, and portfolio standards. However, these policy instruments are not explicitly included in the model. Instead, the policymaker simply selects renewable energy investment. Under the assumption of forward-looking policymakers, and reflecting the standard game-theoretic notion of dynamic optimization, these decisions are constructed as comprehensive strategies optimized over every future state of the world. The policymaker selects energy investments in the current period considering how it and the competing political party act in the future. At the same time, the policymaker also discounts those future outcomes relative to the present benefits at a rate $\delta$.[3] In this regard, our model again draws on dynamic game theory.

We use the cost-minimizing path of investment as our economic baseline, computed from a dynamic version of Eq. (1) over 50 years. This baseline can be interpreted as the path that maximizes economic growth in the absence of negative externalities from fossil fuels. The purpose of the baseline is to illustrate the outcome in the absence of any ideological competition between political parties. The cost-minimizing path is based on assumptions and data from the literature about capital costs, operating costs, and fuel prices. Because of technological learning over time, this economic baseline features gradual increase in the share of renewable energy over time. The baseline is not one a welfare-maximizing social planner would choose, however, because it does not consider the social cost of pollution from energy production. Substantively, in the baseline the government of the country is assumed to ignore concerns such as climate mitigation. We consider this baseline useful because it allows us to see when and how a green party's commitment to sustainability can make a difference. Had we instead included these negative externalities to the baseline, the interpretation of the green party's ideological commitment would no longer be clear.[4]

In the model, political parties face elections every four years. In one variant of the model, the election probabilities are exogenous to renewable energy policy; in another variant, voters base their decisions on the incumbent government's energy policy. As it turns out, the main results are not very sensitive to whether elections are exogenous or endogenous. In other words, we shall see that each party's expectations of future changes in power is a more powerful driver of policies over renewable energy.

In the beginning of every period, the party in power – the incumbent – chooses its investment strategy. In the majoritarian democracy we model here, the opposition cannot influence policy. In turn, the incumbent's strategy consists of a series of investment decisions in every possible future state, so that it is optimal given the other party's expected strategy. In a forward-looking fashion, the incumbent prepares for various combinations of electoral defeats and victories over time (Moe, 2005). In this regard, similar to Aklin and Urpelainen (2013) and Hovi et al. (2009), our dynamic model assumes that politicians are self-interested but forward-looking. Each political party understands that it may lose the next election, and considers this critical fact in their decision-making. For example, a green party understands that, in the future, the brown party may show less interest in the renewable energy transition. These dynamic strategies are a key concern for us.

This model of majoritarian democracy is obviously a simplification, but it is useful because it draws on conventional models of voting and

[2] In Section A8 of the appendix, we also allow enhanced learning and improved energy efficiency over time.

[3] Throughout, we keep $\delta$ constant at 5%.

[4] Below, however, we allow voters to hold environmental preferences that deviate from the cost-minimizing benchmark.

policy formulation in political science. In particular, two-party competition has been found a useful and analytically tractable approach in models leading to the "median voter" theorem (Downs, 1957; Stigler, 1972; Besley et al., 2010; Großer and Palfrey, 2014). We adopt this approach, as our goal is to provide a sharp characterization of the implications of political competition between parties for renewable energy transitions. Future extensions of the model could incorporate other interesting aspects of the problem, such as coalition formation and variation in party strategy formulation, as recent computational research on partisan politics has begun to do (Laver and Sergenti, 2011).

To be specific, party $i = G, B$ maximizes the discounted expected value of the following per-period utility function over the 50-year time period:

$$u_t = -\left(s_t - \left(\lambda_i s^i + (1-\lambda_i) s_t^E\right)\right)^2, \quad (2)$$

where $s_t^E$ denotes the cost-minimizing amount of renewable energy at time $t$, as determined by Eq. (1), depending on technological progress, and $s^i$ is the preferred share of renewable energy based on ideology, equal to 0 for the brown party and 1 for the green party. This is a standard loss function that assumes governments try to stay as close as possible to their ideal point, which is composed of their ideological and economic interests, weighted by $\lambda_i$. As the current level of renewable energy capacity moves away from the ideal point, the political party suffers a loss of utility.

In the context of renewable energy transitions, a plausible interpretation of this specification is that the two parties have different material and ideological interests in regard to renewable energy. For the green party, high levels of renewable energy are valuable because these energy sources mitigate climate change and reduce air pollution. In economic models of "impure altruism," for example, individuals may prefer the provision of an environmental public good because it provides prestige, reputational benefits, and "warm glow" (Andreoni, 1989; Andreoni, 1990; Kotchen and Moore, 2007; Cornes and Sandler, 1994). Furthermore, the supporters of the green party could also have a vested material interest in policies that create demand for clean technology (Neumayer, 2003; Michaelowa, 2005; Lewis and Wiser, 2007; Lipp, 2007). Conversely, the brown party could be opposed to renewable energy because its supporters are active in the extraction, transportation, and combustion of fossil fuels (Fisher, 2006; Pahle, 2008; Cheon and Urpelainen, 2013).

In this equation, $\lambda_i \in (0,1)$ is the weight of the parties' ideological component. As the value of this parameter increases, party $i$ becomes increasingly ideological, in the sense of being increasingly bent on promoting its preferred type of energy-producing infrastructure. The green party becomes more interested in renewable energy, whereas the brown party becomes more opposed to renewable energy. Note that the strength of the ideological commitment is allowed to be asymmetric, with one of the parties more ideological than the other. In the extreme, one party is highly ideological while the other party is only interested in cost-minimization. For example, scholars of American politics have noted that ideological conservatives have increasingly managed to influence the positions of the Republican Party (McCright and Dunlap, 2003; Layzer, 2012), which is more hostile to renewables than the Democratic Party, suggesting an increase in the value of $\lambda_B$ in the United States. The parties' payoffs do not directly involve the costs of investments, because costs indirectly enter the valuation due to the fact that the party endures direct disutility if investments represent a departure from economic optimality.

On the basis of Eqs. (1) and (2), we then develop a computation structure that allows each party to select actions and evaluate possible future states of the world in parallel, similar to McKibbin et al. (1987). Each party is characterized by the parameters $\lambda$ (strength of ideology) and $s$ (ideological preference for or against renewable energy) used in its utility function, and by the discount rate used in that party's planning process (which we keep constant and equal for both parties). The states of the world are characterized by which party is currently in power and the current share of renewable energy. Only the party in power is assumed to be capable of making investment decisions, and each party maximizes a discounted sum of the payoffs in Eq. (2) over the long time horizon, taking into account the decisions made by the opposite party in each state of the world in which that party is in power. By dynamic optimization, we then obtain each party's strategy, i.e. the investments it would make in each period if it is in power as a function of the contemporaneous share in renewable energy. From these strategies, we can then compute renewable energy pathways for any given 50-year sequence of election results.

In the variant with endogenous elections, the public is assumed to prefer the following share of renewable energy:

$$s_t^{e*} = \lambda_e + (1-\lambda_e) s_t^E, \quad (3)$$

where $\lambda_e \in (0,1)$ is the public's environmental preference and, conversely, $1-\lambda_e$ represents the public's interest in cost-minimization in the energy sector. As $\lambda_e$ increases, then, the public becomes more supportive of renewable energy. Drawing on work on environmental public opinion (Brechin, 2003; Franzen and Meyer, 2010; Ansolabehere and Konisky, 2014), this specification allows the voters to exhibit varying degrees of concern about environmental quality. Besides their real income, voters are also interested in the benefits of renewable energy, such as improved air quality and contributing to the mitigation of climate change (Rübbelke, 2002). As in the case of political parties, the voters may also value the warm glow benefits of clean energy. Note also that if the cost-minimizing renewable energy share increases, the distance between the public's environmental preference and the weighted average of the environmental and economic preference endogenously decreases.

As described in the appendix, as a party's investment decision moves farther away from the public's ideal point, the expected vote share of the party decreases. Therefore, each political party is punished by the electorate for policies that do not reflect the median voter's preference (Downs, 1957). The two parties consider these electoral punishments as they formulate their strategies. Each party understands that when they are in power, their probability of winning the next election depends on their policy.

The model is solved by backwards induction, using a pair of Bellman equations that capture each party's valuation of future states and the cost of current actions. The state of the world is discretized by renewable energy share, party in power, and the electorate's approval of recent planner actions. In each period, the party in power selects the action that provides the greatest present discounted value. Election outcomes are determined probabilistically and payouts are averaged over possible future states. This process repeats from the last period backwards, until an entire strategy is constructed.

## 3. Computational results

As a political baseline, we explore scenarios where election outcomes are exogenous and the ideological commitments of the two parties are symmetric. In other words, the brown party and green party are equally insistent on their preferred policies ($\lambda_B = \lambda_G$). Next, we let the strength of this symmetric ideological commitment vary and compare outcomes under various scenarios.

### 3.1. Partisan polarization under symmetric ideology

*As the ideological preferences of the two parties intensify and diverge, renewable energy investment strategies increasingly depart from the economic baseline.* The result is illustrated in Fig. 1. In the figure, the $y$-axis shows the per-period, incremental investment (first difference) in terms of the share of renewables in the total energy mix. It is shown

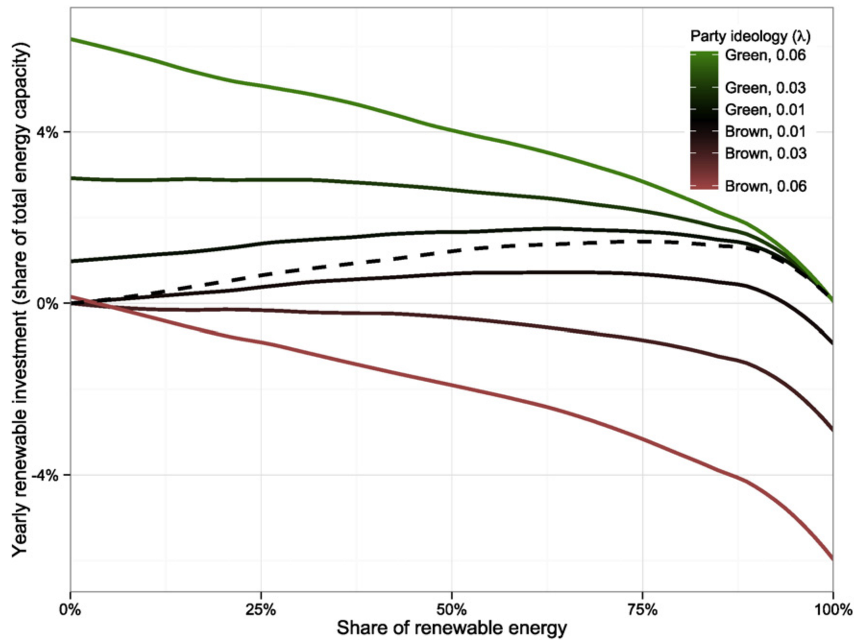


**Fig. 1.** Investment strategies of both parties, for various values of ideological commitment and a moderate fuel price. The dashed line denotes the economically optimal strategy. Green party investments lie above brown party investments.

as a function of the current renewable energy capacity, again as the current share of renewables in the mix. The dashed line provides the cost-minimizing economic baseline.

Except for very low levels of ideological commitment, the brown party invests in new fossil fuel capital across all states of the world. For modest levels of ideological commitment, investments in renewables are monotonically decreasing in the share of clean energy for both parties. The green party invests in renewables most when the existing renewable energy capital is low, while the brown party invests in fossil fuels most when the existing renewable energy capital is high.

These investment strategies are virtually identical to those of hypothetical actors who myopically consider their present-period payoffs without dynamic optimization. Although the energy transition literature emphasizes that long time horizons require complex strategies (Verbong and Geels, 2007; Loorbach, 2010; Aklin and Urpelainen, 2013), if both parties have equally strong ideological preferences, their political strategies reflect their true preferences. The reason is that each party understands that if it increases or decreases the level of investment in renewable energy, the competing party responds with the diametrically opposed strategy.

Notably, the modest role played by partisan polarization in this scenario contradicts some arguments from other studies (Hovi et al., 2009). As long as the two parties are equally ideological, they fully expect the other party to negate their policies in the future. Therefore, partisan polarization itself needs not result in extreme strategies in our model despite the fact that each party has full powers during their rule. Over time, variation in the party in power prompts moderate renewable energy policy and investments. Even without any constraints on policy formulation, such as supermajority requirements or the threat of a filibuster, policies and outcomes remain modest. This lack of polarization effect is important, as it suggests that in a symmetrically charged political environment, relaxing executive constraints may not have much effect on policy outcomes.

In the United States, for example, our result would imply that the Senate filibuster may not be a binding constraint on climate policy. As long as partisan ideological polarization remains symmetric at a high level, the policies of the competing parties will negate each other. Even though a reduction in constraints on policy formulation would allow the incumbent party to enact new policies, these could be easily negated by the opposition when it gains power.

### 3.2. The case of asymmetric ideology

*If one party is more ideological than the other, then both parties deviate from their myopic policies to manipulate their opponent's future behavior.* This result is shown in Fig. 2. For example, if the green party is very concerned about the global negative effects of fossil fuels but the brown party only wants to minimize the cost of energy generation, then the green party will over-invest in renewable energy technology (relative to its myopic preferences) so that it becomes cheaper in the future, which will induce the brown party to then favor renewable energy. Thus, with asymmetric preferences, dynamic strategic incentives arise due to technological lock-in.

A reciprocal dynamic occurs for the brown party. Since the green party's strategy departs further from the economic optimum due to ideology, the brown party is concerned about the excessive costs of an accelerated transition. To forestall this, the brown party also invests in renewables energy when in power, to avoid the costly crash investments coveted by the environmentalists. In more strategic terms, the green party's threat of paying a high cost for renewable energy is sufficiently credible to induce the brown party to compromise. This result is notable in light of the earlier literature, which does not predict that a highly ideological green party can force the other party to accommodate (Hovi et al., 2009; Aklin and Urpelainen, 2013). Our analytical structure prompts a deviating prediction because we consider a very long time horizon and allow the costs of rapid deployment to be high.

For the case of the United States, this result is particularly relevant. In the current political environment, partisan polarization has reached a high level, and this conflict manifests itself in profound disagreements over environmental and energy policy (McCright and Dunlap, 2011). In particular, it is noteworthy that the Republican Party is explicitly hostile to many environmental goals, such as climate mitigation. In such an environment, our model predicts that even a strongly committed Democratic Party might not be able to induce the political right wing to compromise. However, if the

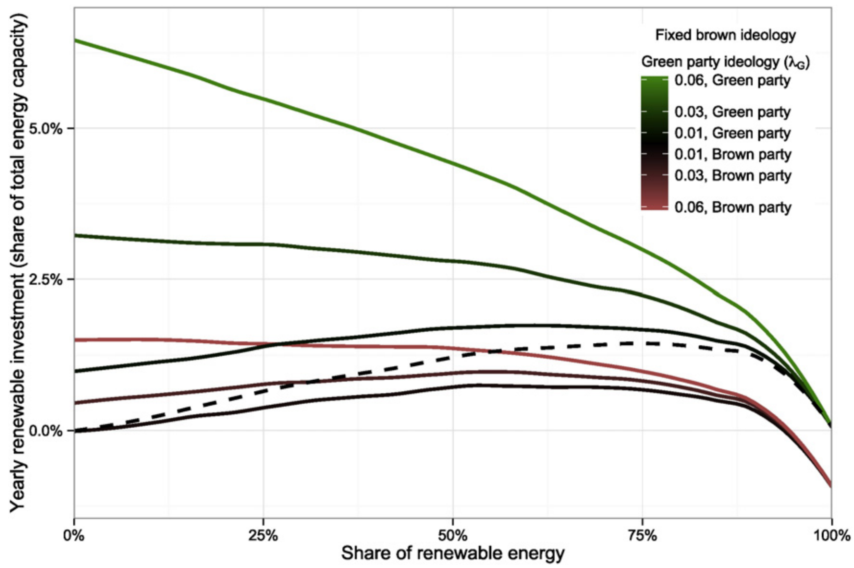


**Fig. 2.** Investment strategies of both parties, for various values of ideological commitment. The dashed line denotes the economically optimal strategy. Green party investments lie above brown party investments. In this asymmetric case, the brown party's ideological commitment is fixed at a low value, while that of the green party varies. In terms of outcomes, asymmetry drives the investment of both parties up.

Republican Party were to become more moderate, be it for strategic or demographic reasons, we would expect to see a stronger association between the Democratic Party's commitment to renewables and federal policy.

### 3.3. Endogenous elections

Qualitatively, the parties' strategies remain unchanged when we make the probability of election endogenous, that is, dependent on energy policy. In this version, voters care about energy policies, as well as other issues, so that electoral outcomes are stochastic. For example, while voters will penalize a party for excessive investments in renewable energy, even a party that over-invests in renewables may win elections. This result is illustrated in Fig. 3. The figure shows the investments of parties when elections are endogenous. We compare cases of electorates with high and low environmental ideologies. As baselines, we use both the cost-minimizing energy trajectory and one where the parties simply invest according to their ideal points, without considering the electoral consequences of this myopic and naive strategy.

Since parties care not only about election, but also the policy outcome, they still manipulate the status quo in order to influence the entire future trajectory. This result, however, does not mean that elections have no effect on strategies. Endogenous elections make the policies responsive to the public's preferences, which are assumed to combine cost-minimization with varying preference for clean energy. Specifically, the brown party's strategy now systematically involves more investment in renewables than without the electoral response. The green party's strategy involves more or less investment in renewables, depending on the relative strength of the electorate's preference. Counter-intuitively, the party that is the most ideological is most influenced by the electorate, since it is the party that is the most motivated to win elections. This is why electoral support for renewable energy is so

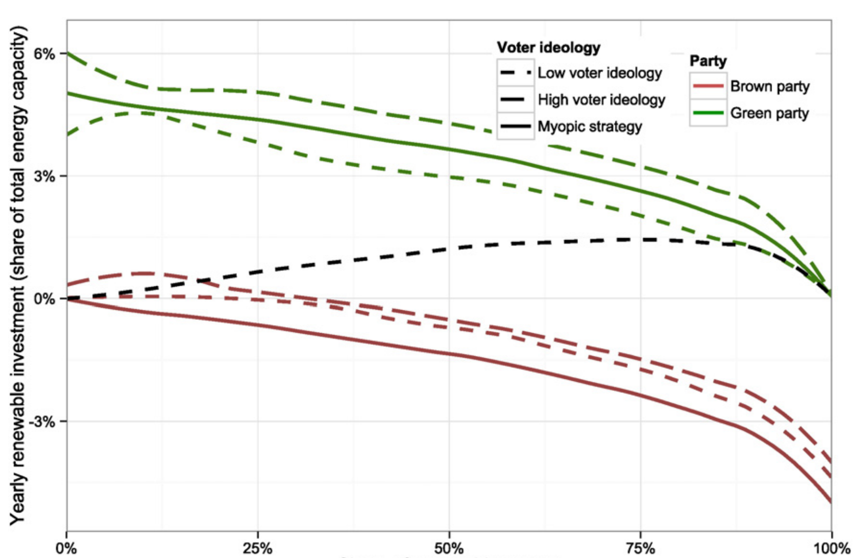


**Fig. 3.** Investments of the parties as a function of the renewable energy share when both parties are equally strongly ideological, for varying values of voters' green ideological commitment. The dashed line represents the economically optimal investments, and black lines represent the myopic (single period preferred) actions of each party.

important for a robust renewable energy transition, as shown in the next section.

These results are important for theories of renewable energy transitions for two reasons. First, they show that electoral competition does not stop parties from dynamically responding to the other party's plans. As long as the two parties are interested in policy, and not only political survival, they continue to adjust their policies in preparation for possible electoral defeats. Second, they also show that the effect of electoral competition on policy interacts with partisan ideology in a complex manner. In particular, high degrees of ideological commitment drive political parties toward the median voter's preference, as highly ideological policy positions make the thought of losing the elections difficult to accept. This surprising result suggests, among other things, that the high degree of partisan polarization in the United States over environmental policies cannot be understood without considering public opinion. Even though McCright and Dunlap (2011) note that partisan ideologies are more sharply diverging than public opinion among Republican and Democrat voters, our model suggests that the sharp partisan polarization may result in policies that reflect the preferences of voters. For example, a strongly anti-environmental Republican must consider carefully the views of the electorate to avoid allowing a Democrat with the opposite ideology to gain power.

### 3.4. Path dependence in the system

Because our model is dynamic, we can use it to investigate "path dependence" in renewable energy investment as a function of government policy. Scholars in the literature on sustainable energy transitions and climate mitigation frequently highlight the dangers and opportunities of path dependence (Unruh, 2000; Laird and Stefes, 2009; Nilsson et al., 2011; Levin et al., 2012; Aklin and Urpelainen, 2013). We investigate the extent to which initial policy decisions by either party have durable effects on renewable energy trajectories over long periods of time.

Technically, we consider two measures of path dependence. First, we measure the variance of the share of renewable energy in 2040 over all paths that have the same number of green electoral terms. Taking a weighted average of these variances, where the weights correspond to the frequency of a given count of green electoral terms in 1000 simulation runs, we obtain a total variance attributable to sequencing. Intuitively, we compare all sequences of political power with the same number of the green party in power, and compare the consequences of early versus late electoral victories. Second, we compare the outcome in 2040 under two radically distinct electoral sequences. Letting G denote green party rule and B brown party rule, these sequences are GGGBBBB (first greens dominate, then browns) and BBBBGGG (first browns dominate, then greens).

The simulations are graphically illustrated in the appendix. To summarize, we find that the degree of path dependence is heavily influenced by the ideological strength of the parties: for there to be substantial path dependence, both parties must be strongly ideological. For example, in the case of equally strong ideological commitment, the change in party sequence is associated with a 15% difference in final outcome, but only 2–8% for the other scenarios. To see why this is the case, consider what happens under the GGGBBBB sequence and the BBBBGGG sequence when both parties are strongly ideological. In the BBBBGGG path, the brown party pursued minor divestments while it was in power because the renewable energy share was still low. Once the green party had a period of sustained control, it aggressively invested. In contrast, in the GGGBBBB sequence, any investments in the early period by the green party is undone by vigorous disinvestments by the strongly ideological brown party. The greater the ideological strength of the parties, the more pronounced the difference between these two paths.

These findings add nuance to earlier arguments and debates in the literature on first-mover advantages in energy policy. A large body of literature emphasizes that technology development is characterized by increasing returns to scale, and this characterization has been proven accurate for the energy sector (Unruh, 2000). Our model shows that political incentives can modify such path dependence. If a party with positive views about the utility of different energy sources governs a country for a long time in the early years of energy technology development, its initial achievements can still be partially undone by later anti-renewables governments, though the increased cost-effectiveness of clean technology mitigates such tendencies. Indeed, once the technology is more mature, a pro-renewables party can relatively rapidly change the energy development trajectory even at a late stage. These results are consistent with the notion that renewable energy is now globalizing and differences across countries shrinking, as even previously uninterested countries have begun to invest into renewable energy development.

## 4. Trajectories for renewable energy transitions

We now explore how partisan strategies unfold in time, producing energy transitions and climate mitigation pathways in the long run. We compare our dynamic outcomes to the renewable energy investment trajectories required by various mitigation pathways simulated by energy–economy integrated models in the IPCC's Fifth Assessment Report (Clarke et al., 2014). The IPCC simulations are based on fixed economic policies and do not account for the political drivers generating these policies. We use the IPCC simulations only as benchmarks for the outcomes but do not assume they have any effect on government policy; the renewable energy transitions are endogenously derived from our models. In other words, we investigate whether national policies can endogenously generate IPCC-consistent renewable energy transitions. We find that a range of political scenarios generate transitions close to the IPCC pathways needed to maintain $CO_2$ levels under 450 ppm by 2100, despite the presence of an opposition party. Other political scenarios fail to generate such a transition.

To generate transition paths, we simulate stochastic elections and use the strategies discussed above to determine the resulting investments and the evolution of the renewable energy share over time. Since renewables do not generate carbon emissions, our analysis of changes in the renewable energy share is naturally related to the degree of carbon abatement required to achieve various IPCC climate trajectories. Because the IPCC scenarios are based on assumptions about the use of renewables, we can see how political factors influence the feasibility of the renewable energy transitions required for various IPCC scenarios. We acknowledge that renewable energy is not the only variable determining climate mitigation pathways, but we also note that the achievement of IPCC mitigation scenarios does depend on national renewable energy transitions. In practice, such renewable energy transitions feature an increase in the use of renewable energy (as represented in Fig. 4). Therefore, our simulations offer important insights into the political dynamics of renewable energy as a contributor to climate mitigation pathways.

Fig. 4 shows the mean and standard deviation of simulated paths for five distinct political scenarios, with the current renewable share of the United States (11%, 2010) as an initial condition. We compare them to the U.S. median trajectory from the energy transition model ensembles used in Clarke et al. (2014), which were run under various policy scenarios (Kriegler et al., 2014). Two baselines are of particular interest: (i) the cost-minimizing baseline from our model, plotted in blue in the first panel, featuring a considerable increase in renewable technologies to 40% in 2060; (ii) the 450 ppm policy, which shows the path of renewable energy that would arise if the world adopted a global price for $CO_2$ compatible with reaching 450 ppm by 2100. The median trajectory for the 450 ppm policy reaches 95% of renewables in 2060 and is our normative benchmark. In the appendix, we present similar plots for European countries.

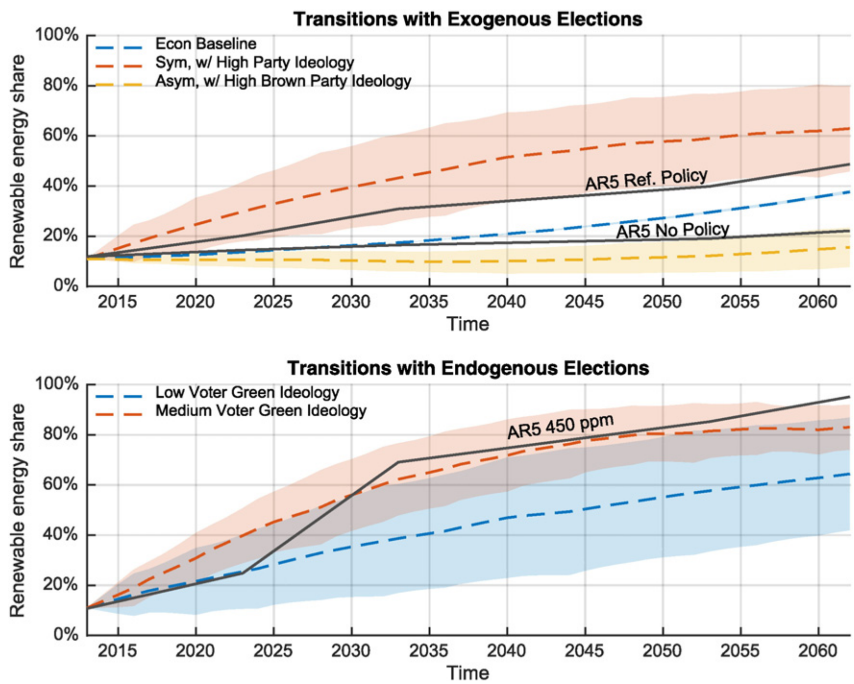


**Fig. 4.** Simulation of renewable energy share in the United States, 2013–2060. The two panels compare our simulations to various mitigation pathways in the IPCC Fifth Assessment Report. The bands represent the trajectories that fall within one standard deviation of the mean of all trajectories (in an ensemble of 1000 simulations). Black lines show AR5 transition trajectories: AR5 No Policy corresponds to a complete absence of climate policy; AR5 Ref. Policy shows the median renewable energy path for the U.S. projected by the AR5 ensemble of models given the country's current policies; and AR5 450 ppm is a transition for the U.S. that is necessary to support a 450 ppm world. Colored lines and prediction bands show mean and standard deviations around modeled scenarios, across different possible election results. In the top panel, the green band is a trajectory where both parties are highly ideological (nonetheless showing a greater transition than the economic baseline), while the red band shows a total lack of energy transitions because only the brown party is ideological. In the lower panel, the electorate either does not value energy policy (blue), or does (green), where strong electorate values produce a trajectory near the 450 ppm curve.

In the red set of paths of the first panel of Fig. 4, both parties are strongly and equally ideological. Despite a brown party that is as staunchly committed to fossil fuels as the green party is to renewables, the mean trajectory reaches about 65% renewables in 2060 from 11% in 2013. *A highly ideological and competitive political game generates a transition that arrives halfway between our cost-minimization and our normative benchmark*. However, the variance is considerable and driven by variation in the number of times the green party is elected, as well as the effect of path dependence on the trajectories. The yellow set of trajectories corresponds to a scenario where the brown party is much more ideological than the green party. In this case, it is impossible to obtain a transition. Not only is the brown party more active, but the green party is reacting to the brown party's stance by minimizing its own investments to remain in a low-renewable energy economy, where the actions of the brown party are more economical.

The "reference policy" path shows the median renewable energy path for the U.S. projected by the AR5 ensemble of models given the country's current policies. Yielding a median trajectory that is a little more than a standard deviation lower than the mean yellow path, current policies qualitatively correspond to what one would expect when two parties are weakly and equally ideological. In contrast, the "No Policy" median path, which corresponds to a complete absence of climate policy, lies below our cost-minimizing baseline and close to the yellow trajectories, adequately reflecting the pro-fossil fuel bias assumed by the scenario generating the yellow trajectories, in which the brown party is more ideological than the green party.

The second panel adds the influence of the electorate, with the two parties as ideological as in the upper trajectories of the first panel. In the blue set of paths, the electorate wants the most economic policy; in the green set, the electorate is strongly pro-renewables. When the electorate is sensitive to cost only, the mean 2050 outcome is similar to that achieved in the exogenous election case, but, interestingly, the trajectories are much more variable because there is more path dependence (since path dependence runs through the changing economic attractiveness of renewables). In contrast, the pro-renewables electorate is able to push the mean 2050 share of renewables to 85%, much closer to our normative 450 ppm benchmark. Additionally, the uncertainty is less in the case of a pro-renewables electorate because the green party has an electoral advantage. This suggests that robust renewable transitions require a vocal pro-renewable electorate.

In producing the results above, we assume that only national policies can affect costs and total renewable energy shares. When policy spillovers or increases in energy efficiency are included, the renewable energy share can reach much higher levels (see Section A8 in the Appendix).

## 5. Conclusion

The unsustainable nature of contemporary energy use highlights the need for sustainable energy transitions, but the political feasibility of this phenomenon remains poorly understood. Because sustainable energy transitions take place over decades, no single government can launch and sustain them. Instead, the government must consider various electoral scenarios over long periods of time. The problem is further complicated by technological change and the effects of energy policy on electoral outcomes. In such a dynamic environment, political parties have to adopt strategies that consider the implications of their policies over long periods of time.

This article contributes to the debate a dynamic model of renewable energy policy with technological learning and electoral competition. In our model, two political parties, one with 'green' and the other with 'brown' preferences, compete for office and select renewable energy policies. The two parties have their ideological preferences, and the strength of these preferences relative to cost-minimization may vary. Each party understands that elections are competitive, and we analyze the model both with and without elections that depend on energy policy. The dynamic simulations highlight the importance of ideological commitment, as a highly ideological party can force a less ideological party to accommodate its preferences. At the same time, highly ideological parties are also sensitive to public opinion, as they find the idea of an electoral defeat particularly unpalatable. Taken together, these dynamic incentives inject a degree of path dependence into the system.

To be sure, the computational model has its limitations. To draw sharp inferences, we have assumed two competing parties in a starkly majoritarian setting without any checks and balances. In parliamentary systems with many smaller parties, this strategy prevents the analysis of coalition formation and may therefore offer limited insights into some dimensions of climate policy. These considerations offer interesting opportunities for future analytical models that add nuance and detail to our general structure. We have also not considered the role of interest groups, such as trade associations, labor unions, and the environmental movement. These interest groups may significantly influence policy even in an environment with political competition. We have also refrained from explicitly modeling the behavior of private investors. Our model suggests that political uncertainty could play an important role in encouraging or discouraging private investments in renewables under different policies. This could be a useful future direction of research, especially in light of empirical findings suggesting that policy uncertainty is indeed a major obstacle to renewable energy investment (Mitchell et al., 2006; Fuss et al., 2008). A more complete analysis of sustainable energy transitions would also capture energy conservation policies.

We have also purposefully refrained from commenting on the international aspects of renewable energy transitions, such as transboundary externalities, global public goods, and the diffusion of clean technology across borders (Brock et al., 2014; Costantini et al., 2013; Ghisetti and Quatraro, 2013). Both technological and political spillovers across borders could facilitate renewable energy transitions. As one frontrunner country makes investments into renewables, others can start deploying wind, solar, and other renewbale sources at a lower cost. If the investments prove profitable, the public image and political feasibility of renewables could also improve. These extensions could be readily incorporated into future extensions of our basic dynamic model.

## Appendix A. Supporting information

Supporting information to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2016.01.019.

## References


Agnolucci, Paolo, 2008. Factors influencing the likelihood of regulatory changes in renewable electricity policies. Renew. Sust. Energ. Rev. 12 (1), 141–161.
Aidt, Toke S., 1998. Political internalization of economic externalities and environmental policy. J. Public Econ. 69 (1), 1–16.
Aklin, Michaël, Urpelainen, Johannes, 2013. Political competition, path dependence, and the strategy of sustainable energy transitions. Am. J. Polit. Sci. 57 (3), 643–658.
Andreoni, James, 1989. Giving with impure altruism: applications to charity and Ricardian equivalence. J. Polit. Econ. 97 (6), 1447–1458.
Andreoni, James, 1990. Impure altruism and donations to public goods: a theory of warm–glow giving. Econ. J. 100 (401), 464–477.
Ansolabehere, Stephen, Konisky, David M., 2014. Cheap and Clean: How Americans Think about Energy in the Age of Global Warming. MIT Press, Cambridge.
Barrett, Scott, 2009. The coming global climate–technology revolution. J. Econ. Perspect. 23 (2), 53–75.
Besley, Timothy, Persson, Torsten, Sturm, Daniel M., 2010. Political competition, policy and growth: theory and evidence from the US. Rev. Econ. Stud. 77 (4), 1329–1352.
Brechin, Steven R., 2003. Comparative public opinion and knowledge of global climatic change and the Kyoto Protocol: the US versus the World? Int. J. Sociol. Soc. Policy 23 (10), 106–134.
Brock, William, Engström, Gustav, Xepapadeas, Anastasios, 2014. Spatial climate–economic models in the design of optimal climate policies across locations. Eur. Econ. Rev. 69, 78–103.
Cheon, Andrew, Urpelainen, Johannes, 2013. How do competing interest groups influence environmental policy? The case of renewable electricity in industrialized democracies, 1989–2007. Pol. Stud. 61 (4), 874–897.
Clarke, Leon, Jiang, Kejun, Akimoto, Keigo, Babiker, Mustafa, Blanford, Geoffrey, Vanden, Karen Fisher, Hourcade, Jean-Charles, Krey, Volker, Kriegler, Elmar, Löschel, Andreas, McCollum, David, Paltsev, Sergey, Rose, Steven, Shukla, Priyadarshi R., Tavoni, Massimo, van der Zwaan, Bob, van Vuuren, Detlef P., 2014. Assessing Transformation Pathways. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2014: Mitigation of Climate Change. Cambridge University Press, New York, NY.
Cornes, Richard, Sandler, Todd, 1994. The comparative static properties of the impure public good model. J. Public Econ. 54 (3), 403–421.
Costantini, Valeria, Mazzanti, Massimiliano, Montini, Anna, 2013. Environmental performance, innovation and spillovers. Evidence from a regional NAMEA. Ecol. Econ. 89, 101–114.
Dangerman, A.T.C. Jérôme, Schellnhuber, Hans Joachim, 2013. Energy systems transformation. Proc. Natl. Acad. Sci. 110 (7), E549–E558.
Downs, Anthony, 1957. An Economic Theory of Democracy. Harper, New York.
Fisher, Dana R., 2006. Bringing the material back in: understanding the U.S. position on climate change. Sociol. Forum 21 (3), 467–494.
Franzen, Axel, Meyer, Reto, 2010. Environmental attitudes in cross-national perspective: a multilevel analysis of the ISSP 1993 and 2000. Eur. Sociol. Rev. 26 (2), 219–234.
Fuss, Sabine, Szolgayova, Jana, Obersteiner, Michael, Gusti, Mykola, 2008. Investment under market and climate policy uncertainty. Appl. Energy 85 (8), 708–721.
Ghisetti, Claudia, Quatraro, Francesco, 2013. Beyond inducement in climate change: does environmental performance spur environmental technologies? A regional analysis of cross-sectoral differences. Ecol. Econ. 96, 99–113.
Großer, Jens, Palfrey, Thomas R., 2014. Candidate entry and political polarization: an antimedian voter theorem. Am. J. Polit. Sci. 58 (1), 127–143.
Gullberg, Anne Therese, 2008. Lobbying friends and foes in climate policy: the case of business and environmental interest groups in the European Union. Energ Policy 36 (8), 2964–2972.
Hovi, Jon, Sprinz, Detlef F., Underdal, Arild, 2009. Implementing long-term climate policy: time inconsistency, domestic politics, international anarchy. Glob. Environ. Pol. 9 (3), 20–39.
Hvelplund, Frede, 2013. Innovative democracy, political economy, and the transition to renewable energy: a full-scale experiment in Denmark 1976–2013. Environ. Res. Eng. Manag. 66 (4), 5–21.
IEA, 2000. World Energy Outlook. International Energy Agency, Paris.
Jacobs, Alan M., 2011. Governing for the Long Term: Democracy and The Politics of Investment. Cambridge University Press, New York.
Jacobsson, Staffan, Lauber, Volkmar, 2006. The politics and policy of energy system transformation: explaining the German diffusion of renewable energy technology. Energ Policy 34 (3), 256–276.
Jaffe, Adam B., Newell, Richard G., Stavins, Robert N., 2005. A tale of two market failures: technology and environmental policy. Ecol. Econ. 54 (2-3), 164–174.
Jamasb, Tooraj, 2007. Technical Change Theory and Learning Curves: patterns of progress in electricity generation technologies. Energy J. 28 (3), 51–71.
Klaassen, Ger, Miketa, Asami, Larsen, Katarina, Sundqvist, Thomas, 2005. The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecol. Econ. 54 (2-3), 227–240.
Kline, David, 2001. Positive Feedback, Lock-In, and Environmental Policy. Policy. Sci. 34 (1), 95–107.
Kotchen, Matthew J., Moore, Michael R., 2007. Private provision of environmental public goods: household participation in green-electricity programs. J. Environ. Econ. Manag. 53 (1), 1–16.
Kriegler, Elmar, Riahi, Keywan, Bauer, Nico, Schwanitz, Valeria Jana, Petermann, Nils, Bosetti, Valentina, Marcucci, Adriana, Otto, Sander, Paroussos, Leonidas, Rao, Shilpa, Currás, Tabaré Arroyo, Ashina, Shuichi, Bollen, Johannes, Eom, Jiyong, Hamdi-Cherif, Meriem, Longden, Thomas, Kitous, Alban, Méjean, Aurélie, Sano, Fuminori, Schaeffer, Michiel, Wada, Kenichi, Capros, Pantelis, van Vuuren, Detlef P., Edenhofer, Ottmar, 2014. Making or breaking climate targets: the Ampere study on staged accession scenarios for climate policy. Technol. Forecast. Soc. Chang. 90 (A), 24–44.
Laird, Frank N., Stefes, Christoph, 2009. The diverging paths of German and United States policies for renewable energy: sources of difference. Energ Policy 37 (7), 2619–2629.
Laver, Michael, Sergenti, Ernest, 2011. Party Competition: An Agent-Based Model. Princeton University Press, Princeton.
Layzer, Judith A., 2012. Open for Business: Conservatives' Opposition to Environmental Regulation. MIT Press, Cambridge.
Levin, Kelly, Cashore, Benjamin, Bernstein, Steven, Auld, Graeme, 2012. Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change. Policy. Sci. 45 (2), 123–152.
Lewis, Joanna I., Wiser, Ryan H., 2007. Fostering a renewable energy technology industry: an international comparison of wind industry policy support mechanisms. Energ Policy 35 (3), 1844–1857.
Lipp, Judith, 2007. Lessons for effective renewable electricity policy from Denmark, Germany and the United Kingdom. Energ Policy 35 (11), 5481–5495.
List, John A., Sturm, Daniel M., 2006. How elections matter: theory and evidence from environmental policy. Q. J. Econ. 121 (4), 1249–1281.
Loorbach, Derk, 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. Governance 23 (1), 161–183.
McCright, Aaron M., Dunlap, Riley E., 2003. Defeating Kyoto: the conservative movement's impact on U.S. climate change policy. Soc. Probl. 50 (3), 348–373.
McCright, Aaron M., Dunlap, Riley E., 2011. The politicization of climate change and polarization in the American public's views of global warming, 2001–2010. Sociol. Q. 52 (2), 155–194.
McKibbin, Warwick, Roubini, Nouriel, Sachs, Jeffrey D., 1987. Dynamic Optimization in Two-Party Models. NBER Working Paper, p. 2213.
McNerney, James, Doyne Farmer, J., Trancik, Jessika E., 2011. Historical costs of coal-fired electricity and implications for the future. Energ Policy 39 (6), 3042–3054.

Michaelowa, Axel, 2005. The German wind energy lobby: how to promote costly technological change successfully. Eur. Environ. 15 (3), 192–199.

Millner, Antony, Ollivier, Hélène, Simon, Leo, 2014. Policy experimentation, political competition, and heterogeneous beliefs. J. Public Econ. 120, 84–96.

Mitchell, C., Bauknecht, D., Connor, P.M., 2006. Effectiveness through risk reduction: a comparison of the renewable obligation in England and Wales and the feed-in system in Germany. Energ Policy 34 (3), 297–305.

Moe, Terry M., 2005. Power and Political Institutions. Perspect. Polit. 3 (2), 215–233.

Nemet, Gregory F., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energ Policy 34 (17), 3218–3232.

Neumayer, Eric, 2003. Are left-wing party strength and corporatism good for the environment? Evidence from panel analysis of air pollution in OECD countries. Ecol. Econ. 45 (2), 203–220.

Nilsson, Måns, Nilsson, Lars J., Hildingsson, Roger, Stripple, Johannes, Eikeland, Per Ove, 2011. The missing link: bringing institutions and politics into energy future studies. Futures 43 (10), 1117–1128.

Pahle, Michael, 2008. Germany's dash for coal: exploring drivers and factors. Energ Policy 38 (7), 3431–3442.

Pierson, Paul, 2000. Increasing returns, path dependence, and the study of politics. Am. Polit. Sci. Rev. 94 (2), 251–267.

Rabe, Barry, 2004. Statehouse and Greenhouse: The Evolving Politics of American Climate Change Policy. Brookings Institution Press, Washington, D.C.

Rosenbloom, Daniel, Meadowcroft, James, 2014. The journey towards decarbonization: exploring socio-technical transitions in the electricity sector in the province of Ontario (1885–2013) and potential low-carbon pathways. Energ Policy 65, 670–679.

Rübbelke, Dirk T.G., 2002. International Climate Policy to Combat Global Warming: An Analysis of the Ancillary Benefits of Reducing Carbon Emissions. Edward Elgar Publishing, Northampton.

Sandén, Björn A., Azar, Christian, 2005. Near-term technology policies for long-term climate targets: economy wide versus technology specific approaches. Energ Policy 33 (12), 1557–1576.

Schmidt, Robert C., Marschinski, Robert, 2009. A model of technological breakthrough in the renewable energy sector. Ecol. Econ. 69 (2), 435–444.

Schwarz, Nina, Ernst, Andreas, 2009. Agent-based modeling of the diffusion of environmental innovations – an empirical approach. Technol. Forecast. Soc. Chang. 76 (4), 497–511.

Schwoon, Malte, 2006. Simulating the adoption of fuel cell vehicles. J. Evol. Econ. 16 (4), 435–472.

Shum, Kwok L., Watanabe, Chihiro, 2007. Photovoltaic deployment strategy in Japan and the USA. Energ Policy 35 (2), 1186–1195.

Shwom, Rachael, Bidwell, David, Dan, Amy, Dietz, Thomas, 2010. Understanding U.S. public support for domestic climate change policies. Glob. Environ. Chang. 20 (3), 472–482.

Smith, Adrian, Kern, Florian, Raven, Rob, Verhees, Bram, 2014. Spaces for sustainable innovation: solar photovoltaic electricity in the UK. Technol. Forecast. Soc. Chang. 81, 115–130.

Söderholm, Patrik, Sundqvist, Thomas, 2007. Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies. Renew. Energy 32 (15), 2559–2578.

Stigler, George J., 1972. Economic competition and political competition. Public Choice 13 (1), 91–106.

Torvanger, Asbjörn, Meadowcroft, James, 2011. The political economy of technology support: making decisions about carbon capture and storage and low carbon energy technologies. Glob. Environ. Chang. 21 (2), 303–312.

Unruh, Gregory C., 2000. Understanding carbon lock-in. Energ Policy 28 (12), 817–830.

Unruh, Gregory C., 2002. Escaping carbon lock-in. Energ Policy 30 (4), 317–325.

Verbong, Geert, Geels, Frank, 2007. The ongoing energy transition: lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). Energ Policy 35 (2), 1025–1037.

Walz, Rainer, 2007. The role of regulation for sustainable infrastructure innovations: the case of wind energy. Int. J. Public Policy 2 (1-2), 57–88.

Zeppini, Paolo, van den Bergh, Jeroen C.J.M., 2011. Competing recombinant technologies for environmental innovation: extending Arthur's model of lock-in. Ind. Innov. 18 (3), 317–334.