The political logics of clean energy transitions

Hanna Breetz*[1], Matto Mildenberger[2], and Leah Stokes[2]

[1]School of Sustainability, Arizona State University
[2]Department of Political Science, University of California Santa Barbara

Published in *Business and Politics*

Abstract

Technology costs and deployment rates, represented in experience curves, are typically seen as the main factors in the global clean energy transition from fossil fuels towards low-carbon energy sources. We argue that politics is the hidden dimension of technology experience curves, as it affects both costs and deployment. We draw from empirical analyses of diverse North American and European cases to describe patterns of political conflict surrounding clean energy adoption across a variety of technologies. Our analysis highlights that different political logics shape costs and deployment at different stages along the experience curve. The political institutions and conditions that nurture new technologies into economic winners are not always the same conditions that let incumbent technologies become economic losers. Thus, as the scale of technology adoption moves from niches towards systems, new political coalitions are necessary to push complementary system-wide technology. Since the cost curve is integrated globally, different countries can contribute to different steps in the transition as a function of their individual comparative political advantages.

Introduction

Energy economists typically emphasize two factors in energy transitions: prices and quantities. The relationship between these factors is captured with experience or learning curves, which model how production costs fall as technology adoption rises. Experience curves for solar, wind, and batteries have progressed rapidly in recent years and feature prominently in contemporary clean energy discourse, including investor summits, consulting reports, media coverage, and Congressional hearings. But these experience curves are often misinterpreted as telling a simple, causal story—'more deployment leads to more price drops.' The logical implication is that global energy systems are on an inexorable, market-driven path to clean energy.

While experience curves provide important insights into the potential cost trajectory of new energy technologies, they do not account for the political drivers and barriers of deployment. We argue that politics is the hidden dimension of technology experience curves. Policy and politics play a crucial role in constructing both prices and adoption, thus determining how rapidly a new technology progresses down the curve. We cannot understand the clean energy transition without acknowledging this co-evolution of technology, policy, and politics (Schmidt and Sewerin, 2017).

---

[*] Authors contributed equally and are listed alphabetically.

Drawing on a diverse set of North American and European cases, we develop a conceptual framework for the role of policy and politics during different stages of technological maturity. We describe three stylized stages at the top, middle, and bottom of the experience curve. When new technologies' costs are much higher than existing technologies, energy transitions need political coalitions that are willing to nurture new technologies and support initial commercialization, thus creating new economic winners and clean energy constituencies (Meckling et al., 2015). When new technologies become economically competitive, energy transitions can become more contested, and further deployment will often face resistance from incumbent industries who do not want to become economic losers. When new technologies become cheaper than existing technologies, some of the political conflicts are dissipated and the market can drive rapid deployment. We are arguably at this stage now for certain renewable energy sources, such as solar PV and onshore wind, which has led some business leaders to discount the importance of policy and politics. However, scaling up from niche to mass adoption requires further political support for developing complementary technology, infrastructure, and market reforms (Frankfurt School, 2017). Overall, our analysis highlights that the politics of energy transitions are not one-dimensional conflicts between economic winners and losers. Instead, different political logics shape clean energy transitions at different stages of the experience curve. These political dynamics generate evolving pressures for policymaking and demands different levels or types of coalition-building among pro-transition groups.

This framework lays a foundation for several pathways of future research. Since this framework was developed from case studies in advanced industrial democracies, future comparative research could analyze whether similar processes drive and constrain energy transitions in other contexts. Another application of this framework might examine whether different polities have different 'comparative political advantages' in the transition process. For example, some political systems may be more conducive to catalyzing early demonstration and niche adoption, while others may be better suited to supporting large-scale deployment or system evolution. Due to global technology spillovers, this could imply that different countries can best contribute to different stages in the transition.

Our paper proceeds as follows. First, we juxtapose the emerging literature on energy transition politics against a largely apolitical literature on experience curves. Second, we offer a conceptual framework to categorize political incentives and policy choice at different stages of an energy transition. Third, we illustrate the political logics of energy transitions at each stage of the experience curve, drawing from nine brief case studies of electricity, fuels, and vehicle policymaking. Finally, the conclusion draws out implications for future research.

Framing Policy and Politics Along the Experience Curve

In this literature review, we lay the foundation for our framework of politics along the experience curve. We begin with a broad overview of how political science portrays the distributive politics and institutional factors affecting energy policymaking. Next, we introduce experience curves, which typically provide an apolitical portrayal of energy innovation. We identify three stylized stages along these curves and discuss key policies needed at each stage. Lastly, we develop a two-factor typology for categorizing these policies by the type of instrument (prices versus quantities) and targeted industry (incumbents versus new entrants). This enables us to use the experience curve concept to draw linkages between technological maturity, supportive policies, and enabling politics.

Distributive Politics and Energy Policymaking

Distributional losers' capacity to shape policy has long been an active debate in public policy. Early scholars debated *who* controlled the policymaking agenda (Mills, 1956; Dahl, 1961); more recent work emphasizes the conditions under which interest groups influence policymaking. This influence depends on public perceptions of economic strength (Vogel, 1989), the relative unity of the business community (Smith, 2000), groups' abilities to frame policies as being in the public interest (Trumbull, 2012), and the degree of public salience and scrutiny (Smith, 1995).

Distributive politics are highly relevant to clean energy (Aklin and Urpelainen, 2018). Renewable energy provides numerous public benefits, including global climate benefits and local air quality and health benefits (Giang and Selin, 2016). However, the costs are predominantly private and often unequally distributed. The costs include financial investments, which may be passed on to taxpayers or electricity ratepayers (Stokes and Warshaw, 2017), as well as negative externalities or job losses borne by local communities (Stokes, 2016).

Some of the conflicts over clean energy emerge from these mass-level distributive politics. Elite-level politics, involving policy officials and interest groups, are also profoundly important in shaping policy (Aklin, 2018). As new energy industries grow, mature, and form coalitions, they can increase their political influence (Meckling et al., 2015), spurring further investment and growth (Aklin and Urpelainen, 2013). Coalitions combining disparate groups of interests in environmental protection, finance, or real estate can support these new entrants (Hess, 2014). On the other hand, incumbent industries that incur costs from the transition often resist new technologies (Geels et al., 2014; Stokes, 2016; Stokes and Breetz, 2017).

Beyond these simple distributive conflicts, the institutions providing the routines, rules, and frameworks of decision-making also shape policies. Key social and political institutions range from electoral rules to courts to policy design procedures. Institutions emerge from past episodes of distributive conflict even as they continue to structure the relative influence of present-day policy actors (Knight, 1992). Thus the policy status quo reflects compromises from past rounds of policy conflict (Baumgartner et al., 2009). A rich literature on path-dependence in policymaking outcomes emphasizes the subsequent need to trace the co-evolution of institutions and actors over time (Pierson, 2000; Levin et al., 2012; Aklin and Urpelainen, 2013). In this way, political institutions shape the articulation of business interests into climate and energy policymaking processes, shaping the ability of different interests to renegotiate energy and economic routines.

Experience Curves: An Apolitical Perspective on Energy Transitions

Despite political science claims that energy policymaking is a political act, many energy analysts and advocates focus on apolitical 'experience curves'. These curves model production costs or prices as a function of cumulative manufacturing experience. This approach originated with observations of labor productivity in airplane manufacturing (Wright, 1936) and was formalized in a learning curve wherein labor costs decreased through learning-by-doing (Arrow, 1963). Experience curves expand this concept to total costs of production, often aggregated across entire industries. Today the two terms are often used interchangeably, along with the more colloquial term, cost curve.

Experience curves have been analyzed for numerous energy technologies, including incumbent technologies like coal and nuclear (McNerney et al., 2011; Lovering et al., 2016) and new technologies like solar photovoltaics, concentrated solar power, onshore and offshore wind, nuclear, batteries, and biofuels (Weiss et al., 2010; Rubin et al., 2015). Most studies use a one-factor experience curve: $Y = ax^b$, where Y is the unit cost, a is the cost of the first unit, x is cumulative production, and b is the rate of cost reduction. This is often transformed to a log-linear form, $LogY = a + b(logx)$, as shown in Figure 1.

In these models, the learning rate is the cost reduction that occurs with each doubling of production. It's typically a 'black box' rate that aggregates cost reductions due to learning-by-doing, economies of scale, capital investments, product and process innovations, managerial improvements, and reductions in input costs. Learning rates have been widely used since the 1990s to model endogenous technical change in climate and energy models (Nemet, 2006), thus demonstrating the benefit of early deployment, especially for technologies with high learning rates, such as solar PV, and also the necessity of large investments to make clean energy cost competitive (Neij, 1997)

Although learning rates imply a causal relationship between deployment and price reductions, economists often emphasize that experience curves should be interpreted as descriptive, not deterministic, since these two factors are inherently endogenous (Rubin et al., 2015). Yet this acknowledgement of price-quantity endogeneity still obscures how both factors are driven by policy, which itself is driven by politics. This lack

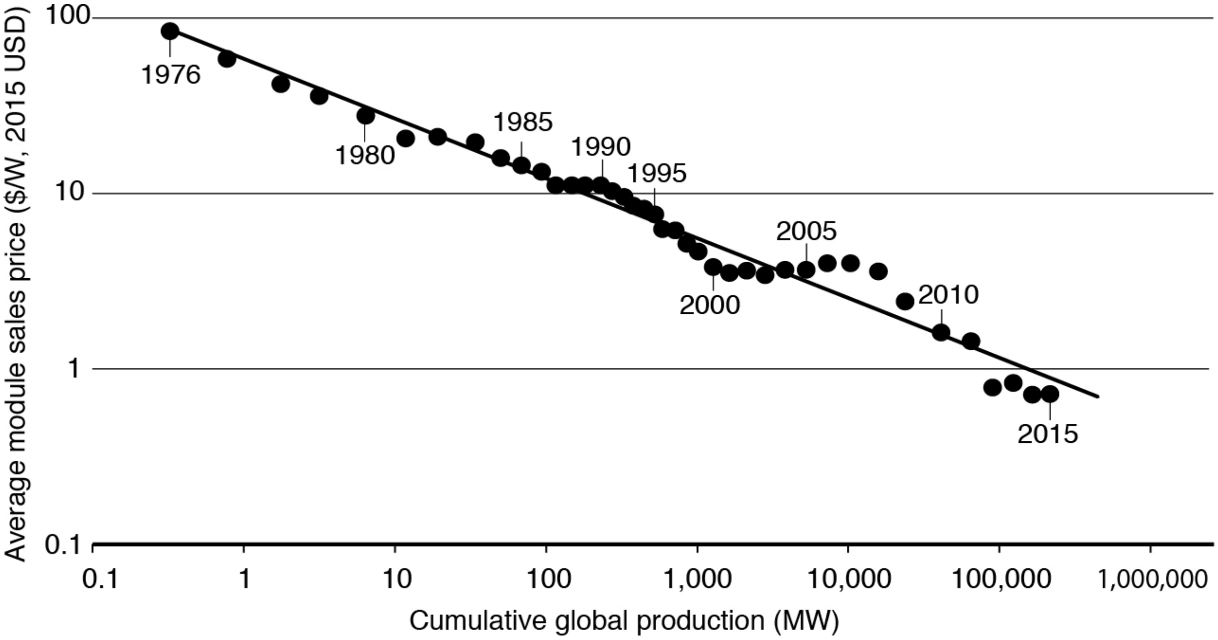

Figure 1: Solar photovoltaics (PV) global experience curve. Adapted from Haegel et al. 2017.

of attention to underlying policy drivers leads some clean energy advocates to invoke experience curves as evidence of virtuous, market-driven cycles. Some even claim that the “unavoidable, almost magical impact of the experience curve” is leading to an “inevitable” future of solar and batteries (Goodall, 2016). This rhetorical use of experience curves belies the role that policy and politics have played in shaping the market for clean energy - thus far, renewable energy has received $2.6 trillion USD in investment (Frankfurt School 2017), including over $750 billion USD in economic incentives (Cozzi et al., 2017) - and downplays how critical they will be in determining the scale and pace of future energy transitions (International Energy Agency, 2016). We argue that a full understanding of energy transitions involves moving beyond prices and quantities to unpack the hidden political dimension of these experience curves.

Policy and Politics Along the Experience Curve

Though public policy may not ‘bend’ the shape of the experience curve, it can change the rate at which technologies advance through the stages of technological maturity (Junginger et al., 2010). In delineating these stages, energy innovation scholars, particularly in the US, typically refer to the sequence of research, development, demonstration, adoption, and diffusion (Lester and Hart, 2012; Gallagher et al., 2012). Energy transition scholars, particularly in Europe, emphasize scalar evolutions: micro-level niches, meso-level regimes, and macro-level systems (Geels, 2002; Markard and Truffer, 2008). We refer to market-oriented stages of technological maturity: research, demonstration, pre-commercial, supported commercial, and fully commercial (Grubb, 2004; Foxon et al., 2005; Balachandra et al., 2010).

To map these onto the experience curve, we further simplify them into three categories (Figure 2): (1) *top of the curve*, when global deployment is very low and the the cost of new technologies is significantly higher than incumbent technologies, corresponding to the stages of research, demonstration, and pre-commercial maturity; (2) *middle of the curve*, when the cost of new technologies has come down enough for niche adoption and initial market formation, corresponding to the stage of supported commercial maturity; and (3) *bottom of the curve*, when new technologies become cost competitive in a fully commercial market.

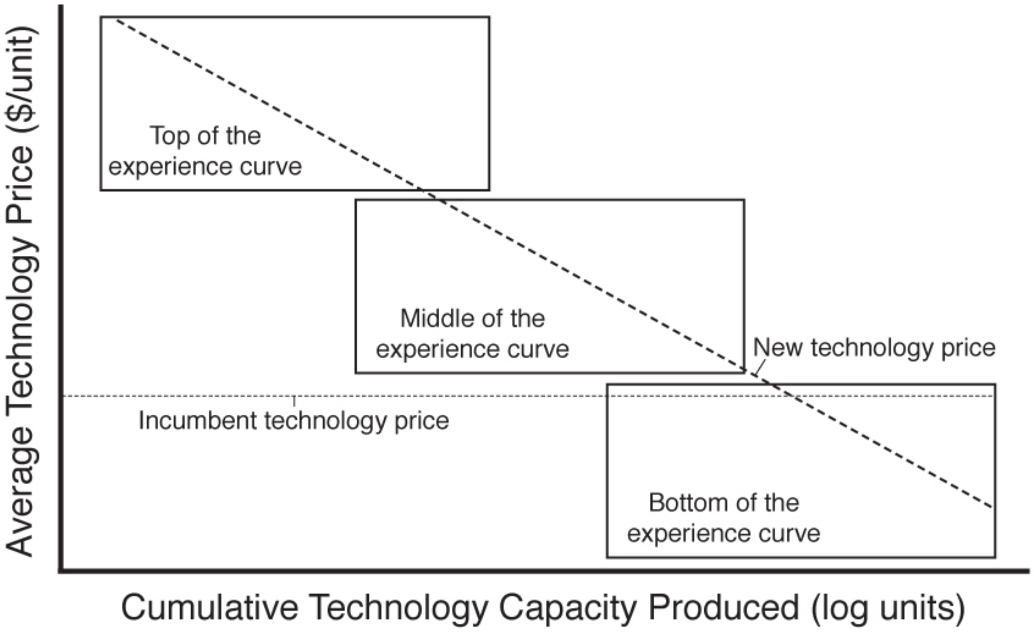

Figure 2: Three stages in a stylized experience curve.

Different stages require different types of policy interventions. At the top of the experience curve, policy must support innovation, prototyping, and pre-commercial installations. Examples of these policies include research funding, knowledge exchange programs, demonstration projects, public procurement, and subsidies for pre-commercial and/or experimental deployments. In the middle of the curve, policies need to cultivate niche markets and catalyze early commercial adoption. This may include fiscal incentives (subsidies, price premiums or guarantees, loan guarantees), regulations (quotas, environmental standards, renewable obligations or portfolio standards), and infrastructure development. For low cost technologies at the bottom of the experience curve, policies need to correct for externalities, ensure market access, and support complementary system-level changes. Examples of policies for this stage may include climate regulations, fossil fuel subsidy reform, utility rate reform, or investments in complementary technologies and infrastructure.

Table 1: Energy transition support strategies

	Price Intervention	Quantity Intervention
Incumbent Tech	Increase cost	Set uptake limits
New Tech	Subsidize cost	Set or enable uptake targets

Table 2: Energy transition opposition strategies

	Price Intervention	Quantity Intervention
Incumbent Tech	Subsidize cost	Protect existing capacity
New Tech	Increase cost	Reduce or limit uptake targets

A two-factor policy typology

Most analyses of energy innovation and transitions do not take the next step of connecting policies to politics. That is, they identify key policies for stimulating clean energy without considering political drivers and constraints. To enable us to make this connection, we categorize policies into functional types. Table 1 summarizes *pro-transition* policies along two dimensions: (1) whether they focus on prices or quantities, and (2) whether they target new or incumbent technologies. This typology builds on the two dimensions of experience curves, while further recognizing that policies can target the progression of either new or incumbent technologies. Figure 3 breaks out these types of policies in further detail.

Of course, political conflict over energy transitions also involves reactionary policymaking that seeks to promote or preserve the incumbent technology. This creates a second suite of policies geared towards *anti-transition* energy transitions. These strategy types, summarized in Table 2, are the inverse of the strategies presented in Table 1. For example, electric utilities threatened by the competitive cost of solar energy have lobbied to impose costs on net metering customers and introduce capacity pricing policies that subsidize fossil-fuel grid capacity. Under the previous net metering rules, customers would be paid the same rate for electricity they sold and purchased. Utilities have argued against this policy and have been remarkably successful and reducing the price customers are paid for their power. As a technology moves down the experience curve and threatens a larger market share, the political incentives to oppose the energy transition become increasingly salient.

Different stages of the experience curve emphasize different quadrants of policy, which in turn correspond to different political logics. Policies at the top of the curve typically fall into the quadrant of subsidies, including price-based interventions for new technologies. They may also involve limited adoption through quantity-based programs such as public procurement or other niche quota policies. Although these policies may have significant budgetary costs, they do not directly threaten incumbent industries. Clean energy technologies may not even need a strong industrial constituency at this stage if politicians, regulators, or the public place a high symbolic value on renewables, or if subsidies can be created without much scrutiny

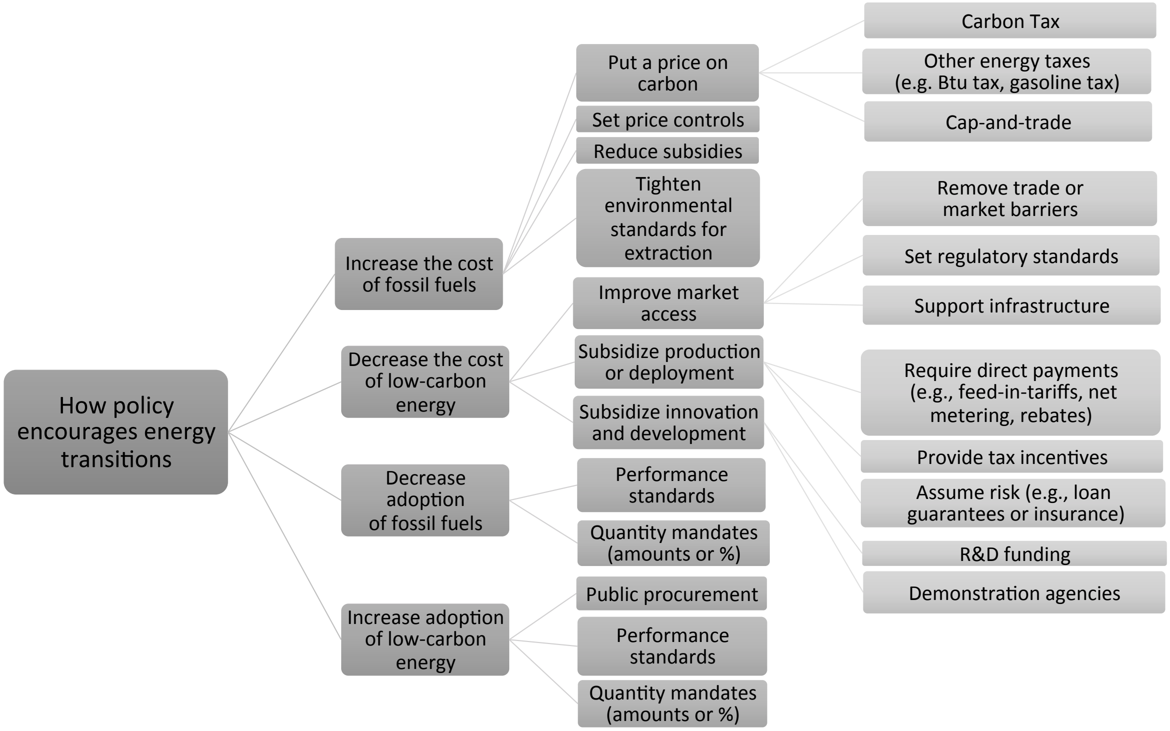

Figure 3: Schematic overview of policy instruments used to promote energy technology transitions

as part of larger policy initiative. Indeed, many programs and policies for renewables managed to fly under the political radar when they were first introduced (Stokes and Breetz, 2017; Stokes, 2016).

As technologies move towards the middle of the curve, they generate more political controversy. Technologies at this stage are still commonly supported by subsidies, and growing clean energy constituencies may help keep some momentum behind these subsidies, but mass political support can wane as deployment increases and the costs of subsidies and technologies become more visible (Stokes and Breetz, 2017; Stokes, 2013; Stokes and Warshaw, 2017). Governments also drive deployment more directly through quantity-based instruments, once the costs come down and markets begin to form. This includes environmental regulations that tend to target incumbent technologies as well as renewable energy standards that target new technologies. As these policies begin to have a larger financial impact on incumbent industries, however, political backlash grows.

As technologies move towards the bottom of the experience curve, subsidies become both unnecessary and politically untenable. For low-carbon technologies that seamlessly blend into existing energy systems (e.g., hybrid cars), further market penetration may be able to proceed without additional policy and political support. For technologies that require more systems-level adaptation at larger levels of penetration (e.g., rooftop solar), achieving unsubsidized mass adoption may require market reforms or environmental policies that directly affect fossil fuels, or alternatively require investments in infrastructure or complementary technologies. The sectoral reforms will likely require broad coalitions of support, while the complementary technologies (e.g., utility-scale battery storage) may require engagement at the top of another experience curve. Thus, over time, policies change technology and costs, which is turn changes energy transition politics.

Political logics along the experience curve

The framework presented in the prior section was developed inductively from our primary empirical research projects, which use within-case process tracing and cross-case comparative analysis to theorize about energy and climate politics (Breetz, 2013; Stokes, 2015; Mildenberger, 2015). This research collectively includes over 300 interviews with policymakers, politicians (including former Prime Ministers and Premiers), bureaucrats, and interest group advocates and opponents engaged in climate and energy policymaking between 2010 and 2015. To further explicate and illustrate our framework, here we provide short case studies of policymaking at various stages of the experience curve: four at the top of the curve (Germany, Norway, California, US), four in the middle of the curve (Arizona, Ontario, Ohio, and California), and one at the bottom of the curve (California). Each case study traces a specific policy debate and draws on secondary literature as well as our own primary research.

In selecting these cases for inclusion in this paper, we adopted a diverse case selection approach, examining a wide range of different policies across different contexts (Seawright and Gerring, 2008). We sought to illustrate political dynamics at different stages of the experience curve, in different countries, using different policy instruments, and affecting a diverse range of technologies. The technologies include wind, solar, CCS, electric vehicles, biofuels, electricity storage and grid expansion—a wide range of technologies that are at various places on their respective experience curves, and that are not typically addressed in a single paper on energy transitions. We cannot make claims about the representativeness of these case studies, as they are merely meant to illustrate the empirical basis of our theory development. That said, we drew upon our collective first-hand knowledge to select cases we believe suggest broader political dynamics. Our cases also reflect variation in the institutions of energy policymaking (Kern, 2011; Kuzemko et al., 2016; Lockwood et al., 2016), given different contexts and variation in energy industries' structure and specialization across different sectors (Fremeth and Marcus, 2016; Nahm, 2017).

Political coalitions at the top of the experience curve

Policies at the top of the experience curve must make winners out of new technologies. Commonly, these policies aim to reduce the costs of new technology or spur pre-commercial adoption of new technologies despite higher costs. The former strategy is usually called ‘subsidies’ while the latter is often pursued through ‘quotas’ or ‘standards.’ However, these terms are not value neutral and are actively contested. If externalities from incumbent technologies are not incorporated into prices, then advocates may argue against the term ‘subsidy.’

At this stage, incumbent technologies typically have a dominant voice in policymaking, with few groups promoting the emergent technology. This imbalance means that policies to limit incumbent technologies’ capacity or increase their costs are typically rare. While the nascency of new industries limits the size of political actors with a direct material stake, clean energy technologies may still have support from coalitions of politicians, publics, or interest groups who see those technologies as solving specific problems. Laird (2016) describes this as a form of institutional “layering,” where new energy technologies are supported without making changes to the existing energy system. In this section, we examine policies on both axes of the experience curve: decreasing new technology’s costs and increasing their quantities.

Decreasing new technology’s cost

Policies that decrease new technologies’ costs include a variety of R&D funding and subsidies. These policies may be challenging to enact at the very top of the experience curve, when there are few stakeholders. They can also be limited by governmental budgets. Nevertheless, early policies have one political advantage: they do not impose direct costs on incumbent industries, at least in the short-term when new technologies have a small market share. In addition, subsidies may bridge intra-coalitional tensions. Here we show these dynamics in two prominent cases of price interventions near the top of the experience curve: Germany and Norway.

Germany’s solar push: In Germany, large-scale subsidization of renewable energy emerged as a strategy to bridge intra-coalitional tensions on the political left. Debate over environmental taxation ignited after the Social Democratic (SPD)-Green Party coalition replaced a long-standing Christian Democratic (CDU) government in 1998. The Greens leveraged their position to achieve several significant environmental reforms. However, the SPD’s industrial base constrained the red-green coalition. Even modest cost imposition proposals divided environment and industrial factions from their labor allies (Schreurs, 2002). Instead, the SPD and Green Party focused on common ground through an environmentally-friendly economic growth strategy. In this way, early pro-reform political coalitions depended on linkage across German political constituencies.

Beginning in 1999, the red-green coalition implemented an ‘ecological tax reform’ that increased taxes on liquid fuels and electricity in exchange for decreased pension contributions. Yet, the reform contained sweeping exemptions to protect industrial actors aligned with the SPD. For instance, energy-intensive industries received up to 80% reductions in the tax rate, plus further rebates if energy tax increases exceeded reductions in corporate pension contributions (Beuermann and Santarius, 2006). While the tax included nuclear it exempted coal because of close relationships between the SPD and German coal unions (Schreurs, 2002).

Instead, the SPD-Green coalition implemented an ambitious energy agenda centered on new technology subsidies. In 2000, the Renewable Energy Act required 12% of German electricity consumption to come from renewables by 2010 and provided subsidies through feed-in-tariffs (FITs) (Jacobsson and Lauber, 2006). This FIT policy, in place from 1990 onwards, paid a higher rate for generators that produced renewable energy power. The Federation of German Industries [BDI] opposed the efforts. In response, energy-intensive industrial producers were exempted from paying reform costs, shifting the burden towards consumers instead of producers (Hughes and Urpelainen, 2015).

German's renewable energy efforts, often called the 'Energiewende', are well known. German subsidies for renewable energy led to major increases in wind and solar, reaching over 30% of the German electricity mix by 2014. What is less well understood is that these reforms were acceptable precisely because they bridged intra-coalitional tensions through generous subsidies for new industrial growth and employment. Critically, the Energiewende did not initially impose any costs on carbon polluters. Thus, Germany provides a clear case of policy at the top of the experience curve that enables cost reduction through subsidies in a fashion that avoided incumbent mobilization.

Norway's CCS investments: Norway took a similar route as Germany, focusing on subsidization rather than cost imposition at the top of the experience curve for carbon capture and sequestration (CCS) technologies. By the early 2000s, industrial carbon reductions in Norway reached the point where further reductions depended on deep process transformations.[1] CCS emerged as a pragmatic way for Norwegian Labor politicians to appease intraparty factions— both those advocating for aggressive climate action and those advocating for industrial expansion (Tjernshaugen and Langhelle, 2009).[2] Harkening back to earlier Labor-led industrial electricity development, union officials and Labor party allies pushed aggressively for research programs that could find new uses for offshore natural gas feedstocks (Kasa and Underthun, 2010)

The Norwegian left's contradictory impulses to protect the environment *and* expand fossil fuel surfaced during a debate over a gas power plant to support the Mongstad oil refinery. Labor Prime Minister Stoltenberg used CCS as a way to resolve internal coalition tensions inside his red-green coalition with the Socialist Left party. Between 2007 and 2012, the Norwegian government invested over 8̃50 million USD in CCS research and development at Mongstad and a second plant at Käarstø. The gas-fired power plant was

---

[1] Interview with senior political official, Oslo, 22 November 2013.

[2] Interview with senior environmental NGO official, Oslo, 11 November 2013.

built on schedule; however, a full-scale CCS facility on the site was abandoned in September 2013 after the Norwegian Auditor General published a high-profile report criticizing cost over-runs and the overall potential for success.[3]

The result was that Norway's red-green coalition authorized a new gas-fired power plant with the promise of massive subsidies for an unrealistic CCS project. Unlike Germany's energiewende, this subsidy policy did not succeed in driving CCS down the experience curve. Nevertheless, the political coalition that supported these policies was rooted in a similar logic.

The critical point in these cases is that when incumbent energy industries have an institutionalized voice, clean energy advocates move to subsidize new technologies rather than increase the cost of incumbent technologies. This resolves (or avoids) domestic distributive conflicts. In some European countries, massive subsidy programs became the political solution to reformer's structural inability to overcome intra-coalition cleavages related to cost imposition. Germany's renewable energy support and Norway's CCS support generated a political "win" for new technology without posing short-term economic threats to incumbents. They made benefits to new technologies visible while keeping a veil of uncertainty over long-term impacts on incumbent technologies. That said, policy did not guarantee technological success: while Germany helped drive down global solar prices, Norway's CCS experiments have proven far less successful.

Increasing uptake of new technology

Quantity-based instruments for new technologies include performance standards, procurement rules, and technology mandates. While these instruments have stimulated efficiency innovations, there are policy examples for pre-commercial electricity technologies, fuels, or vehicles. There are good reasons for not using quantity instruments at the top of the experience curve: commercial success may not materialize, costs may be excessive for regulated industries, and picking winners prematurely runs the risk of 'locking-in' suboptimal technologies (Weiss and Bonvillian, 2009; Hoppmann et al., 2013). There are also political reasons that effective quantity-based instruments may be politically difficult to create: these instruments, if successful, impose private costs on regulated parties, and conflict with current political preferences for flexible, 'technology-neutral' policy (Marchant, 2013).

Instead, when standards and mandates *are* used for new energy technologies, they are often produced by rushed, politically-motivated policymaking processes (Breetz, 2013). Policy entrepreneurs imbue the new technology with important symbolic or instrumental value. Emerging industry actors, far from pushing for

---

[3] Riksrevisjonen. *Riksrevisjonens undersøkelse av statens arbeid med* CO_2*-håndtering.* Dokument 3:14 (2012–2013). 17 September 2013.

risky and over-ambitious mandates, often harbor doubts about a rapid commercial scale-up. Here we show these politics in two US case studies: the California Zero Emission Vehicle (ZEV) mandate and the federal Renewable Fuel Standard (RFS).

California ZEV mandate: California requires automakers to sell a certain percentage of new cars as 'zero emission vehicles,'—vehicles with no exhaust or evaporative emissions. The original 1990 mandate required 2 percent by 1998, 5 percent by 2001, and 10 percent for 2003 onwards. Although the regulatory language is technology neutral, this was a de facto mandate for electric vehicles (EVs) (Bedsworth and Taylor, 2007).

The political impetus came from California's air quality problem, specifically its non-attainment of federal ozone standards, which by the late 1980s threatened the state's federal highway funding. This threat was severe enough that Republican and Democratic state legislators cooperated on major air pollution regulation (Collantes and Sperling, 2008). California's 1988 Clean Air Act charged the California Air Resources Board (CARB) with developing a regulatory solution. CARB developed an extensive Low Emission Vehicle and Clean Fuels program (known as LEV), which included the ZEV mandate.

At the time, EVs were far from commercialization due to batteries' high cost and low capacity. Yet CARB staff were convinced that EVs were needed to meet air quality goals, and were emboldened to mandate them after General Motors unveiled an electric concept car in January 1990 (Kemp, 2005). They had no political coalition pushing for the policy. Nor did they have any substantive technical or economic analysis. The mandate was fundamentally driven by CARB's conviction that EVs *had* to be developed, and reflected that, as a regulatory agency, CARB could set standards but not subsidies. Thus, bureaucrats strongly shaped policy design.

Automakers paid little attention to the mandate during initial adoption, as their attention and lobbying resources were focused on the larger LEV program (Kemp, 2005). Many automakers later fought the ZEV mandate in years of protracted court battles (Marchant, 2013). This was a lagged effect, however, affecting implementation but not enactment. And the opposition arguably dampened over time as some automakers became more cooperative (Wesseling et al., 2015).

In the end, the mandate proved to be overambitious. EVs are finally reaching a supported commerical stage nearly thirty years after the original mandate was passed. But battery technology did not come down the cost curve as rapidly as expected, such that the targets were delayed, adjusted downwards, and revised to accommodate 'partial zero emission' vehicles including hybrids. Moreover, consumer adoption of EVs also necessitated complementary policies such as federal and state tax incentives, ultimately linking the politics of regulations and subsidies (Stokes and Breetz, 2017). The ZEV mandate is one of the most prominent cases of mandating new, uncommercialized technologies. It shows how such a policy can be created 'under the radar' without stirring up distributive conflicts.

US Renewable Fuel Standard: The RFS is a federal biofuel blending mandate. It was developed in two phases. The original RFS (RFS1), enacted by Congress in the Energy Policy Act of 2005, required fuel providers to blend 7.5 billion gallons of biofuels per year by 2012. This merely institutionalized what was already happening as refiners switched from methyl tertiary butyl ether (MTBE) to corn ethanol as an oxygenate–and, indeed, the fuels market quickly exceeded the RFS1 goals. The revised RFS (RFS2), passed in 2007, was a more ambitious mandate requiring 36 billion gallons of biofuels by 2022, including 16 billion gallons of cellulosic ethanol, which had never been demonstrated at commercial scale. We focus on this "cellulosic carve-out" as a mandate at the top of the experience curve.

The policymaking reflected both the macro-politics of the policy agenda and the micro-politics of policy design. In 2006-2007, rising gasoline prices, dependence on foreign oil, and war in the Middle East created growing public pressure to "do something" about oil (Carlisle et al., 2016). Omnibus energy legislation emerged from the competition between the Republican White House and the newly Democrat-controlled Congress to demonstrate leadership on these issues. In 2006, President George W. Bush gave a speech about the nation's 'addiction to oil' and lauded the potential of switchgrass biofuels. In January 2007, he proposed a fuel-neutral mandate of 35 billion gallons, which internal White House analysis suggested would be roughly the functional equivalent of doubling the federal gas tax (Breetz, 2013). In response, Congress 'bid up' the President's proposal and passed a 36 billion gallon fuel mandate, though for a variety of political reasons they kept it as a biofuel-specific RFS.

Congressional staff consulted with investors, interest groups, and inventors, but ultimately this was a number based on political rather than technical assessments. One staffer recalled a meeting where people were tossing numbers around: one person suggested 40, another person said 36. "Our goal cannot be lower than the President's," was how another staffer summarized the Committee's rationale (Breetz, 2013). Notably, neither the biofuels industry nor environmental groups had advocated for such a large RFS prior to the President's policy proposal. Interest groups– including ethanol refiners, corn growers, environmental groups and oil companies–only devoted time to the issue once it was on Congress' agenda.

The cellulosic carve-out was added late in the policy process. The Senate's version of the bill, passed in June 2007, did not differentiate between biofuel types. The version from the House of Representatives added numerous sustainability safeguards, reflecting the close relationship between House Majority Leader Nancy Pelosi (D-CA) and environmental groups (Mondou and Skogstad, 2012). The House bill capped corn ethanol at 15 billion gallons, which was a rule-of-thumb for how much corn ethanol could be produced without affecting food supply, and required 16 billion gallons of cellulosic fuels and 1 billion gallons of biodiesel. The ambitious cellulosic target was described by many policy participants as a "symbolic" and "imaginary" number, rooted in the desire to have cellulosic ethanol beat out corn ethanol (Breetz, 2013).

The ethanol industry publicly assured Congress that this was achievable but privately knew it was unrealistic. To ensure that it did not bring down the entire RFS2, a lobbyist for the advanced biofuel industry helped House staff write a waiver provision (Breetz, 2013). It granted the US Environmental Protection Agency (EPA) authority to waive the cellulosic volumes of the RFS2 if the fuels were not yet available, thus rendering the mandate toothless. This version of the bill was ultimately enacted in December 2007.

In short, the cellulosic mandate in the RFS2 reflected a political competition between elite policymakers. It was politician-driven policymaking, not the result of distributive conflicts between ethanol and oil. The result was a wildly unrealistic mandate that, by necessity, had an enormous loophole. It did not succeed in driving cellulosic fuels down the experience curve; instead, the EPA waived up to 97 percent of the cellulosic mandate in the first several years, and still the regulated parties faced millions of dollars of penalties for not buying an unavailable fuel [4]

This political dynamic is not atypical of mandates at the top of the experience curve. For example, the design of 1970 amendments to the US Clean Air Act were characterized by the same "bid-up" of the mandate to serve symbolic and political rather than technological or economic rationales (Lundqvist, 1980). With no hearings on technical feasibility, and "[w]ithout much attention to the availability of means... [legislators] set goals for a policy that differed radically from the one they had adopted only three years earlier" (pg. 6). Political competition between then Congressman Edmund Muskie and President Nixon generated unachievable mandates and standards that had to be repeatedly adjusted during implementation.

Political coalitions at the middle of the experience curve

Experience curves document that as technology is deployed, its cost typically declines. This can help build larger coalitions of support from potential adopters, who would benefit from subsidized access. Yet new technologies become increasingly competitive, they also become more politically controversial (Stokes and Breetz, 2017). At this point, incumbent industries may feel threatened. They may mobilize to impose costs on new technologies to prevent the transition. If new technologies are eroding profits for existing infrastructure, such as expensive coal plants, they may seek stranded cost payments or try to stall new capacity. In addition, if incumbent utilities are not able to own the electricity system's assets given distributed generation, they may seek to undermine their competition. At the same time, newer technologies are often more established after cost declines, allowing them to contest these new attacks. Thus, the policy conflict becomes two-sided:

---

[4] Wald, Matthew L. January 9, 2012. "A Fine for Not Using a Biofuel That Doesn't Exist." New York Times, B1.

between advocates for new technology and incumbent industries. This shifting economic and political context generates distinct logics associated with energy transition policy compared to early technology at the top of the curve. In this section, we explore these political dynamics taking place in the middle of the experience curve, as new low-carbon technology and cost become more actively contested.

There are a variety of policy strategies both advocates and opponents can use at this point. As before, these strategies still involve cost or quantity interventions. A direct way to reduce or slow new, low-carbon technology's deployment is through increasing its relative costs. This is seen in the case of Arizona, which eliminated incentives and imposed fixed fees on solar customers. Alternatively, incumbent technologies can be subsidized, which we see in California. More subtly, poorly designed subsidies can undermine policy as prices are falling rapidly during the middle of the experience curve, as seen in the Ontario case. Below, we illustrate political efforts to contest the price and quantity of example technologies in the middle of the experience curve. These conflicts often involve many simultaneous policymaking interventions that span most quadrants of Tables 1 and 2. Note, however, that it is rare, at this stage, to see policies designed to spark increased adoption of the opponent, incumbent technologies—although rhetorically politicians may speak about 'reviving the coal industry', in practice the necessary policies to do this are not put into place. Still, the Ohio case below will show that coal utility executives have attempted it. Instead, it is more common to try to decrease the quantity of new technology being deployed, for example by weakening or eliminating an RPS policy. This too is seen in Ohio, which froze its RPS, eliminated its solar RPS and made wind energy more difficult to build by changing setback rules. All of these policies acted to slow the pace of technology deployment in that state.

Overall, political efforts to shape markets in particular industries' favor structure energy transition outcomes at the middle of the experience curve. Outcomes are a function not only of the comparative resources available to each political coalition but also the comparative access each coalition has to government decision-makers. In short, distributive political conflict between economic winners and losers within energy markets construct outcomes in the middle of the experience curve.

Contesting cost

Net-metering in Arizona: Beginning in 2007, Arizona aimed to build upon its nascent renewable energy targets by passing a net energy metering (NEM) policy (Stokes, 2015). This policy was not controversial. At this point in time, the solar leasing model was not yet widely in use, particularly not outside of California. In Arizona, a coalition of environmental groups and renewable energy companies and associations intervened in the net metering proceeding arguing the policy should allow large systems to participate, that there should not be a cap, and that fixed fees should not be used. These provisions would lower the costs for implementing new technologies.

Overall, the utilities did not have major objections to the policy during enactment. The main utility, Arizona Public Service (APS) said it supported the policy, provided only renewable energy and not combined heat and power (CHP) projects could participate. APS went so far as to point out that NEM customers may actually provide benefits to the grid including "voltage support, reliability, lower losses, power quality improvements, and in selective instances, the possible deferral or even avoidance of distribution investment."[5] Indeed, in January 2009, APS would publish a report that valued distributed generation solar between 7-14 cents/kWh in 2025.[6] However, APS also requested additional charges to cover grid costs. Proceedings at the Arizona Corporation Commission (ACC), the state's PUC, noted that other states had not done this, since the goal was to encourage uptake of distributed generation.[7] Consequently, the commission did not approve additional charges in 2008. Further, APS wanted projects to have a maximum size of 100% of the connected facilities peak load; the rule passed with a maximum of 125%. Thus, while the utility attempted to raise the costs of new technology and decrease its deployment scale, during enactment this effort failed. The rule passed in October 2008 with only one out of five commissioners, who were all Republicans, voting against the rule.

After implementation, the NEM policy led to strong growth in residential solar adoption, as the cost of solar PV was declining globally during this time period. In January 2009, APS had only 900 net metering customers.[8] By 2012, growth was approaching 500 systems a month in APS's service area, and by 2013, APS was approaching 16,000 total customers using NEM.[9] However, this strong growth created a significant backlash from APS. In 2012, APS began intervening in elections at the ACC, sending mailers in support of Republican candidates who were anti-solar, despite the company's official position not to participate in ACC elections.[10] After the election, where the anti-solar Commissioners were elected, the ACC undertook a number of policy changes that increased the relative cost of solar compared to other technologies: eliminating $40 million annually in long-standing incentives for commercial and residential solar; and, creating new monthly charges for solar customers. Overall, the opponent coalition, led by a utility, was successful in raising the relative cost of solar. This dramatically reduced the pace of solar deployment in the state. Similar dynamics have also occurred in other states, including Nevada (Davies and Carley, 2017).

---

[5] Arizona Public Service Company's Comments To Staff's Request For Written Comments To Proposed Net Metering Rules, January 4 2008.

[6] R.W. Beck Inc. Distributed Renewable Energy Operating Impacts and Valuation Study. Prepared for: Arizona Public Service. 2009.

[7] ACC Meeting Minutes, "Net Metering Workshop," September 7 2006.

[8] APS application to open NEM docket, July 12 2013.

[9] EIA Form 826 detailed data.

[10] Robert Anglen and Ryan Randazzo, "2 utilities' cash went to 3 ACC campaigns," The Arizona Republic, November 5, 2013.

Ontario's feed-in tariff: As costs are rapidly falling during the middle of the experience curve, uncertainty can create additional challenges for policy that aims to increase new technology deployment. This is seen clearly in the case of Ontario, Canada. Ontario passed a short lived feed-in tariff (FIT) policy in 2006 (Stokes, 2013), which was abandoned in 2012 (Stokes, 2016). In the Ontario case, the renewable energy advocacy coalition was disproportionately empowered during initial policy enactment. As a result of this united coalition in favor of the policy and no opposition, the policy process established highly favorable prices, particularly for small-scale solar PV. During this same time period, global panel prices were falling rapidly. Consequently, some developers collected windfall profits, with an Auditor General report highlighting that projects were receiving 23% returns rather than the targeted 11% (Stokes, 2013). Overall, this poor pricing likely led to almost $1 billion CAD in unnecessary spending. Understandably, these unnecessary costs undermined support for the policy.

In addition, the policy was designed to limit opposition, by requiring that local communities accept any wind projects proposed within their jurisdiction. As a result, more than 50 anti-wind groups ballooned across the province, with numerous unsuccessful court challenges launched. Here again, the lack of bringing opponents into the policy process led to a short-term beneficial policy—requiring acceptance for new technology—which eventually backfired. After these two large problems, the province stopped using the FIT policy in 2012. Instead, it has reverted back to an auction policy, which it relied on earlier. However, this policy may prove less ideal for deployment. As is the case with other jurisdictions, auctions have faced challenges in technology deployment as competitive bidders may underestimate costs.

Contesting capacity

Ohio's RPS retrenchment: In some cases, lowered prices can bring renewed opposition, as incumbent industries are threatened. This is seen clearly in Ohio, where a wide variety of strategies were used to try to reduce quantity targets for new technologies' and decrease incumbent technologies' relative costs. Ohio first passed its RPS policy as part of a restructuring bill in 2008. Although the targets were contested, several Republicans showed strong leadership and it passed both Republican-controlled chambers. Underscoring the environmental nature of the reform, the bill passed the Ohio House unanimously on Earth Day, April 22, 2008. The final law included a solar carve-out and significant targets, given that at the time the state was a relative laggard on renewables.

However, within a few short years, the RPS policy came under significant attack, primarily from electric utilities and large energy consumers. At the time, coal-dominated electric utilities' were facing stranded costs as a result of restructuring. They were seeking subsidies through long-term contracts with fixed prices for their stranded coal plants that were not profitable. New renewable energy capacity would undercut their arguments for long-term coal power purchase agreements. Thus, the utilities pursued a multiple pronged approach—attacking renewable energy targets directly, and seeking fossil fuel subsidies for their aging generation capacity. The utilities were successful in weakening the RPS substantially, and repealing the solar carve out altogether. While they received approval for their long-term coal subsidies at the state level, the Federal Energy Regulatory Commission overturned this decision.

Their attacks on renewable energy targets and ability to increase new technologies' relative costs proved more successful. The renewable energy target was difficult to meet given local resistance to wind projects and the cost of solar in a relatively northern state. By this point, wind energy was competitive in the state. However, anti-wind groups had arisen and gained the ear of a prominent State Senator. Notably, a separate bill also changed the setback rule for wind turbines. This policy change has all but blocked wind energy development in the state. In these ways, even as wind is competitive with coal in the state, new renewable energy development has stalled in Ohio. In this case, we see opponents using the political system to reduce new technology's deployment and raise its relative cost, even as it becomes competitive.

Expanding capacity and falling costs

California's RPS expansion and NEM stability: Although contestation is common during the middle of the curve, as incumbents lose relative power, an alternative dynamic involving positive feedback and path dependence can also develop. We see this in the case of California's NEM and RPS policies (Stokes, 2015). California was an early leader in renewable energy policies. The state's RPS and NEM laws, combined with federal policies, created significant renewable energy companies in the state. These companies gained political clout over time. When the same retrenchment attempts developed in California that we've seen in both Arizona and Ohio, renewable energy advocates managed to defend policies against utility attacks. The renewable energy coalition had developed strong links to politicians, framing their technologies as being able to solve the problems of the day—first resource diversity, then job creation and finally climate change. In part, these advocates were able to resist retrenchment because of the intervener compensation program. Established in 1981, this program pays advocates working in the public interest an hourly rate for their work at the PUC. In other words, these groups have been funded by the state to work on expanding the policy.

In addition, utility opponents were disempowered in California after the electricity crisis and other public failures, such as the San Bruno pipeline explosion. As opponents lost their influence, advocates were able to consistently expand California's policies. At this point, these policies have shaped the environment to such an extent—raising the costs of doing business in the state—that the economy is now changing, with active opponents literally being driven out of the state. Together, these factors have caused California's policy to expand over time, leading to higher targets, covering a greater proportion of the electric utilities, and resulting in a proliferation of related policies. Consequently, the state's renewable energy policies remained stable and even expanded over time.

Political Coalitions at the Bottom of the Experience Curve

One might assume that politics become less important at the bottom of the experience curve when new technology becomes competitive with incumbent technology. The assumption here is that economic incentives are strong enough to drive technology deployment. For some technologies, this is true. For example, consumers have rapidly adopted efficient end-use technologies that require no behavioral or infrastructural changes, such as hybrid vehicles and efficient light bulbs. The increasingly low cost of utility-scale solar and onshore wind suggest that developers are likely to continue to invest in these technologies, even once subsidies are phased out.

However, policy reforms may still be needed to ensure a level playing field. Most obviously, this includes carbon taxes, cap-and-trade programs, or other environmental regulations that account for fossil fuels' externalites, increasing incumbent technologies' costs. Since these policies impose direct costs on incumbent industries, however, they can be politically difficult to enact. When social, behavioral, or informational barriers cause consumers to reject new technologies—even when they make economic sense—there may also a role for policy in overcoming these barriers through quantity-based regulations, labeling, community payments, or market-access programs.

Furthermore, as the scale of deployment expands, many technologies reach a point where new institutions and infrastructure are needed to enable further market penetration (Lenhart et al., 2016). In the transportation sector, EVs are still in the middle of the experience curve, but we can speculate about infrastructural changes that would be needed for them to achieve large-scale diffusion. Today, EVs are predominantly adopted as second vehicles in suburban single-family households with access to private garages or driveways; transitioning from niche to mass adoption will likely require a much larger network of public charging, as well as control systems to ensure that EVs do not exacerbate challenges of peak power demand. In the electricity sector, storage and transmission infrastructure is critical for large penetration of intermittent renewables. Power grids with significant wind or solar are already facing challenges with load balancing, as evidenced by episodes of renewable curtailment and negative power pricing, wherein wholesale rates fall below zero because there is excess supply from facilities with no marginal costs. Low production *costs* do not necessarily drive further deployment in these markets when the *value* of that electricity becomes low—for example, when power exceeds demands at specific times. To address these system-level challenges, policies needed in the electricity sector include utility rate reform, dynamic pricing, demand response programs, and competitive wholesale markets (International Energy Agency, 2016). Large-scale deployment of intermittent and/or distributed renewables will also require substantial investments in complementary technologies and infrastructure: energy storage, high-voltage transmission lines, continental grid interconnections, and smart grid technology.

This is the new frontier of energy policymaking, and it remains to be seen how political coalitions will line up for this system-level transition. As an illustrative case study, here we examine California's attempt to manage new challenges in the electricity system. Similar dynamics are playing out in Europe with complex institutional and infrastructural reforms (Tenggren et al., 2016).

California's electricity storage and regional grid expansion: As the brief case in the previous section showed, California has long been a leader in renewable energy. The state has led in solar deployment, largely resisting attempts to increase the cost of solar through monthly charges on net-metering customers. It was also an early adopter of an RPS policy, which it ratcheted up over time. The current RPS target is ambitious, particularly for such a large state: 50% by 2030. To meet this target, and balance the large amount of distributed generation rooftop solar across the state, California has to increasingly grapple with load and integration challenges.

For example, in 2013 California's independent electricity system operator, CAISO, released a report that highlighted differences between peak demand times and peak electricity provision times under high solar adoption. This so-called 'duck curve' showed that renewable energy resources would be able to meet most electricity demand during the day, but would struggle to serve increasing demand during sunset times. Consequently, other complementary 'flexible' technologies that could increase–'ramp'–quickly would be necessary to keep the grid stable as solar increased in the state. These technological challenges were a direct result of a suite of ambitious state policies to increase renewable energy, particularly solar.

Recognizing the challenges associated with ambitious renewable energy targets, California passed a storage requirement in 2010. Initially, these were simple capacity targets for the state's private utilities. However, in 2016, the California statehouse passed a series of additional laws to further push storage. Some storage technologies, like pumped hydro, are relatively mature. But other technologies, most notably lithium-ion batteries, are still new and expensive. In this way, as one technology matures, the problems it introduces into the technological system requires policymakers to act and address new problems. This can be thought of as a kind of 'spillover' for complementary technology. Such spillovers may also be a function of networks, as we can see for example with the need for charging infrastructure for electric vehicles. Yet, the term spillover, like experience curves, hides the political decisions necessary to create the policy that will drive this new complementary technology down in cost through capacity expansion.

In addition to targeting storage and flexible resources, California began a difficult institutional reform process in 2015 to change the boundaries for its electricity grid operation (Lenhart et al., 2016). Moving from a state Independent System Operator (ISO) to a regional ISO involves complex negotiations with other states and electric utilities. Yet these policy changes have significant benefits for supporting renewable energy technologies. Expanding the grid geographically helps to balance intermittent resources, like wind and solar (MacDonald et al., 2016). This is because small scale weather patterns, like clouds blocking the sun or low-wind, can be balanced out across larger geographic spaces. As this California case shows, even as wind and solar become cost competitive, other complementary system changes are necessary to drive their further adoption.

Conclusion

Learning and experience curves model the relationship between price reductions and technology deployment. Yet both factors are, in part, politically constructed. Efforts to understand the drivers and barriers of energy transitions must therefore move beyond apolitical economic models. Instead, scholars must draw attention to the hidden political dimension of these curves. Our schematic overview of this political dimension emphasizes different political logics at the top, middle and bottom of experience curves. The political institutions and conditions that nurture new technologies into economic winners are not the same that let incumbent technologies become economic losers. These distinct logics are also not fully independent of one another. Actions and policies at one stage of the experience curve shape the actions and policies available at subsequent moments in time. Most importantly, support at the top and middle of the experience curve will ideally nurture the emergence of new political coalitions to support the new technology over time, since the existence of policy defenders can become critical to political conflict in the middle of the experience curve. In some cases, poor policy design way manifest itself during implementation, creating political problems that cascade across different stages of the experience curve. If policies fail to create effective coalitions, they may be retrenched.

In turn, as the scale of technology adoption moves from niches towards systems, new political coalitions may prove necessary to push complementary system-wide technology. Even in cases where innovation may drive long-term movement shifts in cost and capacity, political factors can still shape the timing, if not the direction, of the transition. Such rates of technological transition are extremely consequential for environmental outcomes in the face of global climate change (Levin et al., 2012; Trancik et al., 2013). Of course, once these new entrants become incumbents, if they have sufficient political influence they may seek to hold suboptimal policies in place. This can be particularly problematic if policies are poorly designed, as occurred for example in Ontario's FIT program and the US biofuel mandate. For this reason, governments need to balance policy stability with adaptive management (Stokes, 2013), which at a minimum may include sunset clauses, cost caps, or provisions for phase-downs. In addition, as technologies move down the cost curve, industries are unlikely to invest sufficiently in R&D to create new breakthrough technologies (Hoppmann et al., 2013). Governments also need to continue to invest in R&D (Sivaram, 2018).

Future work could link this framework to institutional variation across countries. Since we focused on advanced, industrialized democracies, we encourage other research that builds on this framework to consider differential political dynamics in developing countries and non-democracies, such as India and China. Future work could also explore multi-scalar connections between global clean energy markets and local policymaking. Although different jurisdictions will likely pursue different resources and policy strategies for their energy transitions—due to differences in factors such as resource endowments, energy demand profiles, institutional capacity, and regulatory structures—the experience curve for a particular technology can be integrated globally. Cost reductions in one place can therefore have spillover effects that reduce costs and spur deployment elsewhere. For example, Germany's feed-in tariff and China's industrial policy contributed to reducing the global costs of solar photovoltaics (Lewis, 2014).

As a final potential extension of this framework, we suggest that it could be used to analyze whether different states have 'comparative political advantages' in support for clean energy transitions. For instance, some scholars suggest that corporatist styles of environmental policymaking may lead to lowest-common denominator policies, since they force policymakers to satisfy a broader range of constituencies (Crepaz, 1995). In this vein, Mildenberger (2015) argues that corporatist policymaking institutionalizes the voices of carbon-intensive economic losers, leading to earlier but weaker climate policies, while pluralist policymaking systems are far more sensitive to consumer interests and may be able to impose stronger direct costs on carbon-intensive industries. Energy scholars could build on this work and use this framework to evaluate questions such as: Do corporatist countries have a 'comparative political advantage' in new technology subsidization? Do pluralist systems suffer from boom-bust investment cycles, as the party in power often changes policies, making them less effective at driving technology down the curve globally? Do non-democratic societies, where government planners are able to directly impose costs on incumbents or create large subsides for new entrants using authoritarian power, have advantages in driving cost reductions? We see this linkage between institutional conditions and political outcomes along the experience curve as a critical next step in the energy politics research agenda.

Actions in one part of the world where political conditions exist to drive shifts in cost or deployment can, in turn, move countries to the middle of the experience curve where top-of-the-curve political incentives did not exist for clean energy transition support. The subsequent emergence of domestic constituencies with material interests tied to the new technology can jump-start distributive conflict over prices and quantity instruments. During these moments, political coalitions must emerge that actively exclude representatives of incumbent industries, such that costs are more directly imposed or tolerated. We believe that careful efforts to elucidate these comparative political advantages and study individual policy transitions through both space and time offers promising avenues for future research on global energy transitions.

References

Aklin, M. (2018). How Robust Is the Renewable Energy Industry to Political Shocks? *Business and Politics*, pages 1–36.

Aklin, M. and Urpelainen, J. (2013). Political competition, path dependence, and the strategy of sustainable energy transitions. *American Journal of Political Science*, 57(3):643–658.

Aklin, M. and Urpelainen, J. (2018). *Renewables: The Politics of a Global Energy Transition*.

Arrow, K. J. (1963). *Social choice and individual values*. Yale University Press.

Balachandra, P., Nathan, H. S. K., and Reddy, B. S. (2010). Commercialization of sustainable energy technologies. *Renewable Energy*, 35(8):1842–1851.

Baumgartner, F. R., Berry, J. M., Hojnacki, M., Leech, B. L., and Kimball, D. C. (2009). *Lobbying and Policy Change: Who Wins, Who Loses, and Why*. University of Chicago Press, Chicago, IL.

Bedsworth, L. W. and Taylor, M. R. (2007). Learning from California's zero-emission vehicle program. *California Economic Policy*, 3(4).

Beuermann, C. and Santarius, T. (2006). Ecological tax reform in germany. *Energy Policy*, 34(8):917–929.

Breetz, H. L. (2013). *Fueled by crisis: US alternative fuel policy, 1975-2007*. PhD thesis, Massachusetts Institute of Technology.

Carlisle, J. E., Feezell, J. T., Michaud, K. E., and Smith, E. R. (2016). *The Politics of Energy Crises*. Oxford University Press.

Collantes, G. and Sperling, D. (2008). The origin of California's zero emission vehicle mandate. *Transportation Research Part A*, 42(10):1302–1313.

Cozzi, L., Gould, T., and Frankl, P. (2017). Commentary: The success of wind and solar is powered by strong policy support. https://www.iea.org/newsroom/news/2017/june/commentarythe-success-of-wind-and-solar-is-powered-by-strong-policy-support.html. Accessed: 2010-09-30.

Crepaz, M. M. (1995). Explaining national variations of air pollution levels. *Environmental Politics*, 4(3):391–414.

Dahl, R. A. (1961). *Who governs?* Yale University Press.

Davies, L. L. and Carley, S. (2017). Emerging shadows in national solar policy? nevada's net metering transition in context. *The Electricity Journal*, 30(1):33–42.

Foxon, T. J., Gross, R., Chase, A., Howes, J., Arnall, A., and Anderson, D. (2005). UK innovation systems for new and renewable energy technologies. *Energy policy*, 33(16):2123–2137.

Frankfurt School-UNEP Centre and Bloomberg New Energy Finance (2017). Global trends in renewable energy investments, 2017. Technical report.

Fremeth, A. and Marcus, A. A. (2016). The role of governance systems and rules in wind energy development. *Business and Politics*, 18(3):337–365.

Gallagher, K. S., Grübler, A., Kuhl, L., Nemet, G., and Wilson, C. (2012). The energy technology innovation system. *Annual Review of Environment and Resources*, 37:137–162.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes. *Research policy*, 31(8):1257–1274.

Geels, F. W., Tyfield, D., and Urry, J. (2014). Regime resistance against low-carbon transitions. *Theory, Culture & Society*, 31(5):21–40.

Giang, A. and Selin, N. E. (2016). Benefits of mercury controls for the United States. *PNAS*, 113(2):286–291.

Goodall, C. (2016). The switch: How solar, storage and new tech means cheap power for all.

Grubb, M. (2004). Technology innovation and climate change policy. *Keio economic studies*, 41(2):103–132.

Haegel, N. M. et al. (2017). Terawatt-scale photovoltaics: Trajectories and challenges. *Science*, 356(6334):141–143.

Hess, D. J. (2014). Sustainability transitions: A political coalition perspective. *Research Policy*, 43(2):278–283.

Hoppmann, J., Peters, M., Schneider, M., and Hoffmann, V. (2013). The two faces of market support—How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. *Research Policy*, pages 1–15.

Hughes, L. and Urpelainen, J. (2015). Interests, institutions, and climate policy: Explaining the choice of policy instruments for the energy sector. *Environmental Science & Policy*, 54:52–63.

International Energy Agency (2016). World energy outlook part b: Special focus on renewable energy. Technical report.

Jacobsson, S. and Lauber, V. (2006). The politics and policy of energy system transformation—explaining the German diffusion of renewable energy technology. *Energy Policy*, 34(3):256–276.

Junginger, M., van Sark, W., and Faaij, A. (2010). *Technological learning in the energy sector: lessons for policy, industry and science*. Edward Elgar Publishing.

Kasa, S. and Underthun, A. (2010). Navigation in new terrain with familiar maps. *Environment and Planning. A*, 42(6):1328.

Kemp, R. (2005). *Zero emission vehicle mandate in California: misguided policy or example of enlightened leadership*. Edward Elgar: Cheltenham, UK.

Kern, F. (2011). Ideas, institutions, and interests: explaining policy divergence in fostering 'system innovations' towards sustainability. *Environment and Planning C: Government and Policy*, 29(6):1116–1134.

Knight, J. (1992). *Institutions and Social Conflict*. Cambridge University Press, Cambridge, UK.

Kuzemko, C., Lockwood, M., Mitchell, C., and Hoggett, R. (2016). Governing for sustainable energy system change. *Energy Research & Social Science*, 12:96–105.

Laird, F. (2016). Avoiding transitions, layering change: The evolution of american energy policy. In Hager, C. and Stefes, C., editors, *Germany's Energy Transition*. Palgrave, London.

Lenhart, S., Nelson-Marsh, N., Wilson, E. J., and Solan, D. (2016). Electricity governance and the western energy imbalance market in the united states: The necessity of interorganizational collaboration. *Energy Research & Social Science*, 19:94–107.

Lester, R. K. and Hart, D. M. (2012). Unlocking energy innovation: how america can build a low-cost, low-carbon energy system. cambridge, mass.: Mit press.

Levin, K., Cashore, B., Bernstein, S., and Auld, G. (2012). Overcoming the tragedy of super wicked problems. *Policy Sciences*, 45(2):123–152.

Lewis, J. I. (2014). The Rise of Renewable Energy Protectionism: Emerging Trade Conflicts and Implications for Low Carbon Development. *Global Environmental Politics*, 14(4):10–35.

Lockwood, M., Kuzemko, C., Mitchell, C., and Hoggett, R. (2016). Historical institutionalism and the politics of sustainable energy transitions: A research agenda. *Environment and Planning C: Government and Policy*, page 0263774X16660561.

Lovering, J. R., Yip, A., and Nordhaus, T. (2016). Historical construction costs of global nuclear power reactors. *Energy Policy*, 91:371–382.

Lundqvist, L. (1980). *The Tortoise and the Hare: Clean Air Policies in the United States and Sweden.* University of Michigan Press, Ann Arbor, MI.

MacDonald, A. E. et al. (2016). Future cost-competitive electricity systems and their impact on US CO2 emissions. *Nature Climate Change*, (January):1–6.

Marchant, G. E. (2013). Technology mandates and socio-behavioral life cycle assessment. *Emerging Technologies: Socio-Behavioral Life Cycle Approaches*, page 41.

Markard, J. and Truffer, B. (2008). Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research policy*, 37(4):596–615.

McNerney, J., Farmer, J. D., and Trancik, J. E. (2011). Historical costs of coal-fired electricity and implications for the future. *Energy Policy*, 39(6):3042–3054.

Meckling, J., Kelsey, N., Biber, E., and Zysman, J. (2015). Winning coalitions for climate policy. *Science*, 349(6253):1170–1171.

Mildenberger, M. (2015). *Fiddling while the world burns: The logic of double representation in comparative climate policymaking.* PhD thesis, Yale University, New Haven.

Mills, C. W. (1956). *The power elite.* Oxford University Press.

Mondou, M. and Skogstad, G. (2012). The regulation of biofuels in the united states, european union and canada. *Canadian Agricultural Innovation and Regulation Network (CAIRN), University of Saskatchewan, Saskatoon, SK, University of Toronto.*

Nahm, J. (2017). Renewable futures and industrial legacies: Wind and solar sectors in china, germany, and the united states. *Business and Politics*, 19(1):68–106.

Neij, L. (1997). Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. *Energy policy*, 25(13):1099–1107.

Nemet, G. F. (2006). Beyond the learning curve: factors influencing cost reductions in photovoltaics. *Energy policy*, 34(17):3218–3232.

Pierson, P. (2000). Increasing returns, path dependence, and the study of politics. *American political science review*, pages 251–267.

Rubin, E. S., Azevedo, I. M., Jaramillo, P., and Yeh, S. (2015). A review of learning rates for electricity supply technologies. *Energy Policy*, 86:198–218.

Schmidt, T. S. and Sewerin, S. (2017). Technology as a driver of climate and energy politics. *Nature Energy*, 2:17084.

Schreurs, M. A. (2002). *Environmental Politics in Japan, Germany, and the United States.* Cambridge University Press, Cambridge, UK.

Seawright, J. and Gerring, J. (2008). Case Selection Techniques in Case Study Research: A Menu of Qualitative and Quantitative Options. *Political Research Quarterly*, 61(2):294–308.

Sivaram, V. (2018). *Taming the Sun: Innovations to Harness Solar Energy and Power the Planet.* MIT Press, Cambridge.

Smith, M. A. (2000). *American Business and Political Power: Public Opinion, Elections, and Democracy.* University of Chicago Press, Chicago.

Smith, R. A. (1995). Interest group influence in the us congress. *Legislative Studies Quarterly*, pages 89–139.

Stokes, L. C. (2013). The politics of renewable energy policies: The case of feed-in tariffs in ontario, canada. *Energy Policy*, 56:490–500.

Stokes, L. C. (2015). *Power Politics: Renewable Energy Policy Change in US States.* PhD thesis, Massachusetts Institute of Technology.

Stokes, L. C. (2016). Electoral Backlash against Climate Policy: A Natural Experiment on Retrospective Voting and Local Resistance to Public Policy. *American Journal of Political Science*, 60(4):958–974.

Stokes, L. C. and Breetz, H. L. (2017). Politics in the U.S. Energy Transition: Policies to Promote Solar, Wind, Biofuels and Electric Vehicles.

Stokes, L. C. and Warshaw, C. (2017). Renewable energy policy design and framing influence public support in the United States. *Nature Energy*, 2(17107).

Tenggren, S., Wangel, J., Nilsson, M., and Nykvist, B. (2016). Transmission transitions: Barriers, drivers, and institutional governance implications of nordic transmission grid development. *Energy Research & Social Science*, 19:148–157.

Tjernshaugen, A. and Langhelle, O. (2009). Technology as political glue: Ccs in norway. In Meadowcroft, J. and Langhelle, O., editors, *Caching the Carbon*, pages 98–124. Edward Elgar Publishing, Cheltenham, UK.

Trancik, J. E., Chang, M. T., Karapataki, C., and Stokes, L. C. (2013). Effectiveness of a segmental approach to climate policy. *Environmental science & technology*, 48(1):27–35.

Trumbull, G. (2012). *Strength in Numbers: The Political Power of Weak Interests.* Harvard University Press, Cambridge, MA.

Vogel, D. (1989). *Fluctuating Fortunes: The Political Power of Business in America.* Beard Books, Frederick, MD.

Weiss, C. and Bonvillian, W. B. (2009). *Structuring an energy technology revolution.* MIT Press.

Weiss, M., Junginger, M., Patel, M. K., and Blok, K. (2010). A review of experience curve analyses for energy demand technologies. *Technological forecasting and social change*, 77(3):411–428.

Wesseling, J., Farla, J., and Hekkert, M. (2015). Exploring car manufacturers' responses to technology-forcing regulation: The case of california's zev mandate. *Environmental Innovation and Societal Transitions*, 16:87–105.

Wright, T. (1936). Learning curve. *Journal of the Aeronautical Sciences*, 3(1):122–128.